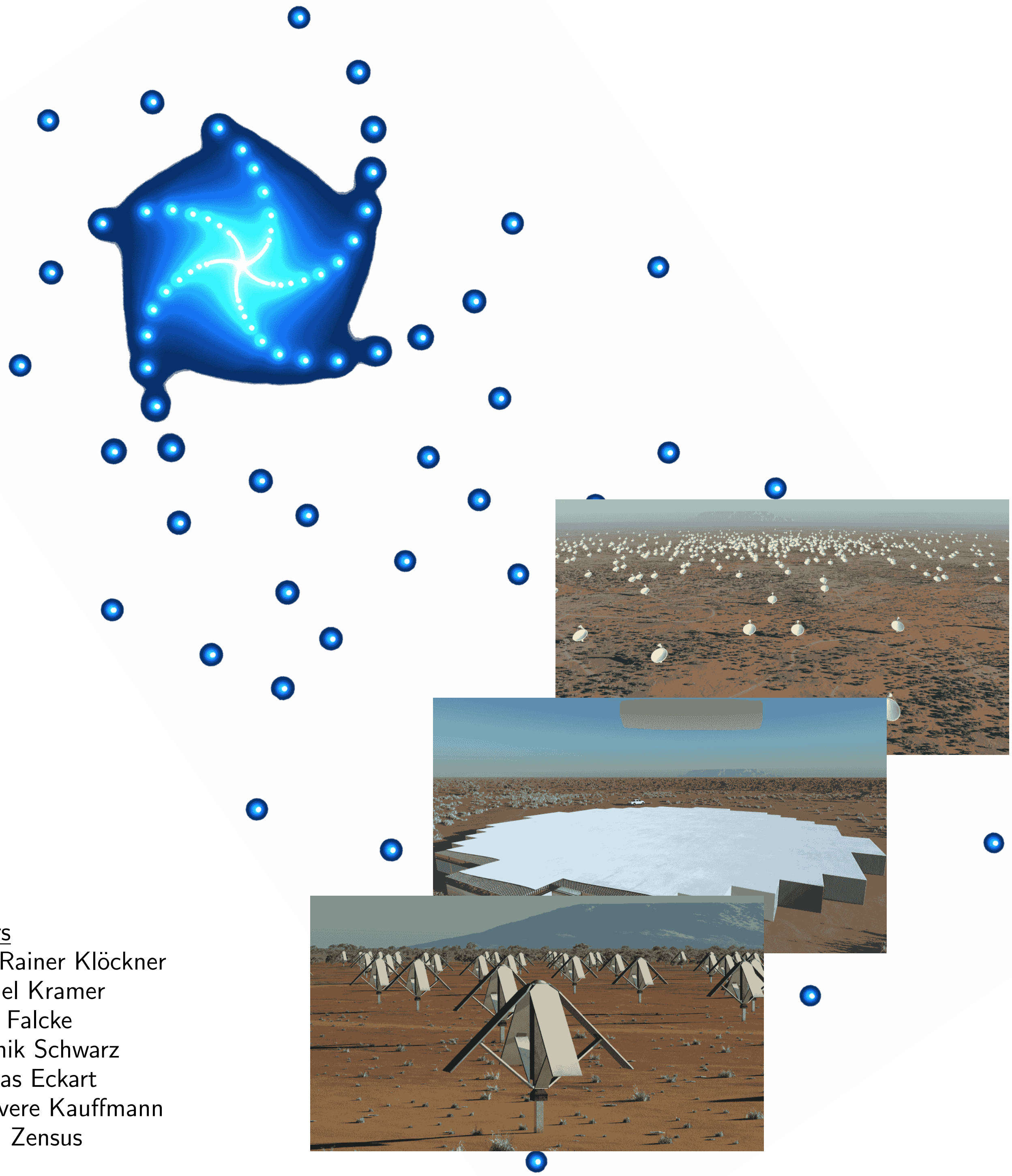
Pathway to the Square Kilometre Array

The German White Paper



Editors

Hans-Rainer Klöckner
Michael Kramer
Heino Falcke
Dominik Schwarz
Andreas Eckart
Guinevere Kauffmann
Anton Zensus

Published by the Max-Planck-Institut für Radioastronomie (MPIfR), Bonn, Germany

Cover:
Cover images show an artist impression of the Square Kilometre Array (SKA) configuration and of the different antenna types used in the SKA.
Images: SPDO/Swinburne Astronomy Productions

Pathway to the Square Kilometre Array

The German White Paper

Editors:
Hans-Rainer Klöckner, Michael Kramer, Heino Falcke, Dominik Schwarz, Andreas Eckart, Guinevere Kauffmann, Anton Zensus

Contributions from:

F. Aharonian [Max-Planck-Institut für Kernphysik Heidelberg], **T.G. Arshakian** [I. Physikalisches Institut der Universität zu Köln], **B. Allen** [Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) Hannover], **R. Banerjee** [Hamburger Sternwarte, Fachbereich Physik, Universität Hamburg], **R. Beck** [Max-Planck-Institut für Radioastronomie Bonn], **W. Becker** [Max-Planck-Institut für extraterrestrische Physik Garching], **D.J. Bomans** [Astronomisches Institut der Ruhr-Universität Bochum], **D. Breitschwerdt** [Zentrum für Astronomie and Astrophysik, Technische Universität Berlin], **M. Brüggen** [Hamburger Sternwarte, Fachbereich Physik, Universität Hamburg], **A. Brunthaler** [Max-Planck-Institut für Radioastronomie Bonn], **B. Catinella** [Max-Planck-Institut für Astrophysik Garching], **D. Champion** [Max-Planck-Institut für Radioastronomie Bonn], **B. Ciardi** [Max-Planck-Institut für Astrophysik Garching], **R. Crocker** [Max-Planck-Institut für Kernphysik Heidelberg], **R.-J. Dettmar** [Astronomisches Institut der Ruhr-Universität Bochum], **D. Engels** [Hamburger Sternwarte, Fachbereich Physik, Universität Hamburg], **T. Enßlin** [Max-Planck-Institut für Astrophysik Garching], **H. Enke** [Leibniz-Institut für Astrophysik Potsdam], **T. Fieseler** [Forschungszentrum Jülich], **L. Gizon** [Max-Planck-Institut für Sonnensystemforschung Katlenburg-Lindau], **E. Hackmann** [ZARM, Universität Bremen], **B. Hartmann** [Jacobs University Bremen], **C. Henkel** [Max-Planck-Institut für Radioastronomie Bonn], **M. Hoeft** [Thüringer Landessternwarte Tautenburg], **L. Iapichino** [Institut für Theoretische Astrophysik, Universität Heidelberg], **D. Innes** [Max-Planck-Institut für Sonnensystemforschung Katlenburg-Lindau], **C. James** [Physikalisches Institut der Friedrich-Alexander Universität Erlangen-Nürnberg], **J. Jasche** [Argelander-Institut für Astronomie, Universität Bonn], **D. Jones** [Max-Planck-Institut für Kernphysik Heidelberg], **V. Kagramanova** [Institut für Mathematik und Naturwissenschaften, Carl von Ossietzky Universität Oldenburg], **G. Kauffmann** [Max-Planck-Institut für Astrophysik Garching], **E. Keane** [Max-Planck-Institut für Radioastronomie Bonn], **J. Kerp** [Argelander-Institut für Astronomie, Universität Bonn], **H.-R. Klöckner** [Max-Planck-Institut für Radioastronomie Bonn], **K. Kokkotas** [Theoretische Astrophysik, Eberhard Karls Universität Tübingen], **M. Kramer** [Max-Planck-Institut für Radioastronomie Bonn], **M. Krause** [Max-Planck-Institut für extraterrestrische Physik Garching], **M. Krause** [Max-Planck-Institut für Radioastronomie Bonn], **N. Krupp** [Max-Planck-Institut für Sonnensystemforschung Katlenburg-Lindau], **J. Kunz** [Institut für Mathematik und Naturwissenschaften, Carl von Ossietzky Universität Oldenburg], **C. Lämmerzahl** [ZARM, Universität Bremen], **K.J. Lee** [Max-Planck-Institut für Radioastronomie Bonn], **M. List** [ZARM, Universität Bremen], **K. Liu** [Max-Planck-Institut für Radioastronomie Bonn], **A. Lobanov** [Max-Planck-Institut für Radioastronomie Bonn], **G. Mann** [Leibniz-Institut für Astrophysik Potsdam], **A. Merloni** [Max-Planck-Institut für extraterrestrische Physik Garching], **E. Middelberg** [Astronomisches Institut der Ruhr-Universität Bochum], **J. Niemeyer** [Institut für Astrophysik der Georg-August-Universität Göttingen], **A. Noutsos** [Max-Planck-Institut für Radioastronomie Bonn], **V. Perlick** [ZARM, Universität Bremen], **W. Reich** [Max-Planck-Institut für Radioastronomie Bonn], **P. Richter** [Leibniz-Institut für Astrophysik Potsdam], **A. Roy** [Max-Planck-Institut für Radioastronomie Bonn], **A. Saintonge** [Max-Planck-Institut für extraterrestrische Physik Garching], **G. Schäfer** [Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena], **J. Schaffner-Bielich** [Institut für Theoretische Astrophysik, Universität Heidelberg], **E. Schinnerer** [Max-Planck-Institut für Astronomie Heidelberg], **D. Schleicher** [Institut für Astrophysik der Georg-August-Universität Göttingen], **P. Schneider** [Argelander-Institut für Astronomie, Universität Bonn], **D.J. Schwarz** [Fakultät für Physik, Universität Bielefeld], **A. Sedrakian** [Institut für Theoretische Physik, Goethe-Universität Frankfurt], **A. Sesana** [Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) Potsdam], **V. Smolčić** [Argelander-Institut für Astronomie, Universität Bonn], **S. Solanki** [Max-Planck-Institut für Sonnensystemforschung Katlenburg-Lindau], **R. Tuffs** [Max-Planck-Institut für Kernphysik Heidelberg], **M. Vetter** [Fraunhofer-Institut für Solare Energiesysteme ISE Freiburg], **E. Weber** [Fraunhofer-Institut für Solare Energiesysteme ISE Freiburg], **J. Weller** [Universitätssternwarte der Ludwig-Maximilians-Universität München], **N. Wex** [Max-Planck-Institut für Radioastronomie Bonn], **O. Wucknitz** [Argelander-Institut für Astronomie, Universität Bonn], **M. Zwaan** [European Southern Observatory Garching],

Contents

Vorwort

Liebe Freunde und Förderer astrophysikalischer Forschung in Deutschland,

als vor nunmehr 10 Jahren die astronomische Gemeinschaft in Deutschland die DFG-Denkschrift "Status und Perspektiven der Astronomie in Deutschland 2003 – 2016" formulierte, sah sie ihre Forschung am Beginn einer "goldenen Epoche", ein Gedanke, der in der 2007 veröffentlichten "Science Vision" der europäischen ASTRONET-Initiative aufgegriffen und weitergeführt wurde. Und es wurde nicht zu viel versprochen! Extrasolare Planeten werden heute routinemäßig entdeckt, die Parameter, die die künftige Entwicklung des Kosmos bestimmen, sind mit einer Genauigkeit von besser als 10% bestimmt, und Studien im hochrotverschobenen Universum dringen in die "dark ages", den Zeitraum zwischen der Rekombination und dem Erscheinen der weitest entfernten Galaxien und Quasare vor. Anekdotenhaft kann dieser Erfolg daran gemessen werden, dass in keiner Dekade so viele Astronomie-orientierte Nobelpreise in der Physik vergeben wurden wie in den vergangenen zehn Jahren und zahlreiche neue, hochrangige und hochdotierte internationale Preise initiiert wurden (mit bemerkenswertem Erfolg von Forschern aus Deutschland).

Maßgeblich für diese Entdeckungen war und ist die Verfügbarkeit der großen, boden- und weltraumgestützten internationalen Observatorien wie das "Very Large Telescope" der ESO, die interferometrische Zusammenschaltung von Radioteleskopen zum VLBI, das Weltraumteleskop Hubble oder wie Satellitenobservatorien in anderen Wellenlängenbereichen wie Chandra, XMM oder Herschel, wobei all diese Observatorien zunehmend synergetisch genutzt werden (als Beispiel seien insbesondere die "deep fields" erwähnt). Aufseiten der Theorie werden diese Unternehmungen durch hochaufgelöste und hochkomplexe Supercomputersimulationen ergänzt und verbunden.

Trotz dieser gewaltigen Fortschritte sind viele zentrale Fragen erst angerissen worden: die Entdeckung eines erdähnlichen Exoplaneten in der habitablen Zone steht weiter aus, die "dark ages" liegen nach wie vor größtenteils im Dunkeln und der dominante Teil des Universums – 23% dunkle Materie, 73% dunkle Energie – ist nach wie vor von mysteriöser Komposition.

Sowohl die DFG-Denkschrift wie auch die ASTRONET "Infrastructure Roadmap" haben deshalb die nächste Generation großer Observatorien am Boden und im Weltall identifiziert, die in den nächsten Jahren ihren Betrieb aufnehmen und die Epoche der "Präzisionsastronomie" initiieren werden. Dies beginnt 2013 mit der Astrometrie-Mission GAIA und führt mit der Inbetriebnahme des E-ELT der ESO sowie des Euclid-Satelliten der ESA in die nächste Dekade. Wie bereits bei den Vorgängermissionen werden diese Projekte zahlreiche technologieorientierte "spin-offs" weit abseits der Astronomie generieren.

Als nunmehr zeitlich letztes in dieser Serie der großen internationalen Observatorien steht nun die Weichenstellung zur Realisierung des "Square Kilometre Arrays" an, um im Multi-Frequenz-Portfolio die kritische Lücke im Bereich langer Wellenlängen zu schließen. Das SKA soll nach derzeitiger Planung 2024 in den Regelbetrieb übergehen. Dieses Weißbuch ("White Paper") ist eine Momentaufnahme der deutschen SKA-Forschungslandschaft und erläutert die verschiedenen Forschungsthemen und -gebiete, an denen Wissenschafter in Deutschland interessiert sind. Das Portfolio beeindruckt hierbei nicht nur durch die Vielfalt und Tiefe der Fragestellungen von der Sonnenphysik bis hin zur Kosmologie, sondern auch durch die Diversität der Autoren – sie reicht von Theoretikern über Astroteilchenphysikern bis hin zu beobachtenden Astronomen verschiedener Spezialisierung. Hierbei sticht ins Auge, dass die traditionell als Radioastronomen bezeichneten Wissenschaftler eher eine Minderheit darstellen. Ein wichtiger Aspekt sind auch technologische Herausforderungen, z.B. die Handhabung von großen Datenmengen oder von Technologien im Bereich der erneuerbaren Energien.

Das wichtigste Kapitel bleibt jedoch im Weißbuch naturgemäß ungeschrieben: Neue, unerwartete Entdeckungen und daraus resultierende neue Forschungsfelder, die sich erst durch die Nutzung der neuen Observatorien ergeben.

Prof. Dr. Matthias Steinmetz
Vorsitzender des Rats deutscher Sternwarten

Zusammenfassung: Das Square Kilometer Array – ein Technologie-Teleskop der Superlative

Das SKA wird als einziges globales Projekt mit bedeutender internationaler Partnerschaft in der ESFRI-Liste aufgeführt und erhielt zusammen mit dem E-ELT die höchste Priorität als künftige bodengebundene astronomische Einrichtung.

Das SKA wird mit einer effektiven Empfangsfläche von einer Million Quadratmeter (m^2) das mit Abstand größte Radioteleskop sein, das in einem Frequenzbereich von 70 MHz bis 10 GHz, oder höher, operieren wird. Das SKA wird in zwei Phasen gebaut werden. Es wird erwartet, dass erste wissenschaftliche Ergebnisse im Jahr 2019 erzielt werden können, während die volle Inbetriebnahme des gesamten Teleskops für 2024 geplant ist. Der niederfrequente Teil des Observatoriums ($70-500$ MHz) wird an dem hierfür optimalen Standort in West-Australien gebaut, während die mittel- und hochfrequenten Teile im südlichen Afrika errichtet werden. Dort werden sie den südafrikanischen SKA-Vorläufer MeerKAT ergänzen und können mit den großen Radioteleskopen in Europa, hier insbesondere das 100-m Effelsberg Radioteleskop in Deutschland, verbunden werden und das europäische "Very Long Baseline Interferometry"-Netzwerk erheblich erweitern.

Das SKA wird das weltweit führende "Imaging und Survey"-Teleskop sein, das aufgrund einer Kombinaton aus beispielloser Vielseitigkeit und Empfindlichkeit neue Türen zu neuen Entdeckungen aufstoßen wird. Es wird sich in einer einzigartigen Landschaft neuer Einrichtungen wiederfinden, mit denen das Universum in elektromagnetischen und anderen Wellenlängen erforscht wird. Dabei wird das SKA nicht nur selbst faszinierende Entdeckungen ermöglichen, sondern auch eine außergewöhnliche Komplementarität bei der Beantwortung unserer fundamentalsten offenen Fragen herstellen. In der Tat wird das SKA Astronomen in die Lage versetzen, Erkenntnisse in allen wissenschaftlichen Schlüsselfragen zu erlangen, wie z.B. nach der Bildung und Entwicklung der ersten Sterne und Galaxien nach dem Urknall, nach der Natur der Schwerkraft und unserer Vorstellung von Raum und Zeit, nach der kosmischen Geschichte des neutralen Wasserstoffs, nach der Rolle des kosmischen Magnetismus und möglicherweise auf die Frage nach außerirdischem Leben. Insbesondere wird uns das SKA erlauben, folgendes zu untersuchen:

– **Das dunkle Zeitalter**, durch die Erforschung der Bildung der ersten Strukturen/Körper zu einer Zeit, als das Universum gerade von einem vorwiegend neutralen Zustand in den heutigen ionisierten Zustand überging, etwa eine Milliarde Jahre nach dem Urknall;

– **Die Galaxienentwicklung, Kosmologie und Dunkle Energie**, durch Untersuchungen der Anordnung, der Verteilung und der Eigenschaften von Galaxien, z. B. durch Messungen des neutralen Wasserstoffs;

– **Tests der Schwerkraft in starken Gravitationsfeldern**, in denen Pulsare verwendet werden, um Einsteins allgemeine Relativitätstheorie und unsere Vorstellung von Raum und Zeit auf die Probe zu stellen;

– **Die Wiege des Lebens**, durch das Studium der bewohnbaren Bereichen von protoplanetaren Scheiben und der Suche nach präbiotischen Molekülen, die auf primordiale erdähnliche Bedingungen hindeuten.

Die Radioastronomie hat einige der größten Entdeckungen des 20. Jahrhunderts produziert, die mit nicht weniger als vier Nobelpreisen für Physik belohnt wurden. Einige dieser Ergebnisse sind die kosmische Hintergrundstrahlung, Pulsare, Gravitationswellen, dunkle Materie, Quasare, Schwarze Löcher, Moleküle und relativistische Plasma-Jets. Von zentraler Bedeutung für diese Entdeckungen waren technologische Innovationen, die die Grenzen des Machbaren in räumlicher, zeitlicher und spektraler Auflösung verschoben haben.

Mit dem Bau des SKA wird mit dieser Tradition der Innovation fortgefahren, durch die Kombination von grundlegenden Neuentwicklungen in der Radiofrequenztechnologie, Informationstechnologie und dem Supercomputing. Dies wird vergleichbare Anstrengungen in anderen elektromagnetischen und nicht-elektromagnetischen Wellenlängenbereichen zum Universum komplementieren. Die Information aus jedem dieser Bereiche ist einzigartig und wichtig, und nur durch die Kombination all dieser Informationen können wir hoffen, die physikalischen Prozesse im Universum verstehen und einige der großen Fragen der Wissenschaft beantworten zu können. Tatsächlich macht es die gebräuchliche (obwohl nie wirklich gültige) Einteilung der Wissenschaftler in Physiker, Hochenergiephysiker, optische Astronomen, Radioastronomen und dergleichen unmöglich, die modernen erfolgreichen Forschungsprojekte dieser Tage korrekt zu beschreiben. In den verschiedenen Beiträgen dieses "Weißbuchs" zeigt sich, dass die einzelnen Astronomen, Institute und Forschungskooperationen heutzutage boden-und weltraumgestützte Instrumente im gesamten elektromagnetischen Spektrum verwenden, nicht-elektromagnetische Fenster nutzen, Supercomputing für numerische Simulationen und Datenanalyse verwenden und eng mit Teilchenphysikern zusammenarbeiten. Die Diskussion der Ergebnisse erfolgt hierbei anhand wissenschaftlicher Fragestellungen und nicht im Rahmen enggefasster Definitionen spektraler Bereiche.

Das SKA ist ein unersetzlicher Teil einer globalen Anstrengung, das Universum, seine Grundgesetze, Herkunft und Entwicklung zu verstehen. Als eines der großen weltweiten Observatorien wird das SKA ein unverzichtbares Werkzeug im gesamten Portfolio der deutschen astronomischen Gemeinschaft sein. Außerdem werden für das SKA Lösungen erarbeitet, um gemeinsam die übergreifenden technologischen Herausforderungen zu meistern, wie zum Beispiel das Problem der Handhabung, Verwaltung und Analyse erstaunlich großer Datenmengen – ein Problem, dass alle neuen Einrichtungen der Spitzenforschung betrifft.

Die technischen Herausforderungen und die anstehenden Anforderungen an die Datenverarbeitung werden die Art und Weise, wie astronomische Forschung heutzutage gemacht wird, grundlegend verändern. Um das SKA zu verwirklichen, brauchen wir einen revolutionären Bruch mit dem konventionellen Design von Radioteleskopen. Das SKA wird insbesondere im Bereich der Informations- und Kommunikationstechnologie die technische Entwicklung vorantreiben. Spin-off-Innovationen in diesen Bereichen werden auch für andere Gebiete in Industrie und Wissenschaft von Nutzen sein, die ebenfalls große Datenmengen von geografisch verteilten Quellen verarbeiten müssen. Die enormen Energieanforderungen des SKA bieten außerdem eine Chance, die Technologieentwicklung im Bereich der skalierbaren Erzeugung erneuerbarer Energien, deren Verteilung sowie Speicherung bei gleichzeitiger Reduzierung des Verbrauchs zu beschleunigen. Bereits heute verfügt die deutsche Gemeinschaft über das benötigte Know-how zur Planung, Konstruktion, Inbetriebnahme und zur wissenschaftlichen Ausbeutung eines solchen Observatoriums. Dies wird demonstriert durch den Bau des "Internationalen LOFAR Teleskops" (ILT) und seiner deutschen Stationen, das bis heute den größten und modernsten SKA-Pathfinder darstellt. Aus diesem Grunde könnte die deutsche SKA-Gemeinschaft erheblich zum SKA und dessen Design beitragen.

Der Bauabschnitt SKA Phase 1 wird wissenschaftlich wie technisch eine Teilmenge der SKA Phase 2 sein. Diese Planung erlaubt es, die technische Reife der verschiedenen Systemkomponenten zu überprüfen und möglicherweise entsprechende Änderungen während der Bauphase des SKA vorzunehmen. Die Zielkosten für das komplette SKA sind auf 1,5 Milliarden Euro festgelegt worden, während die Kosten für Phase 1 auf 350 Millionen Euro begrenzt werden sollen. Die Kostenschätzungen des gesamten SKA-Projekts basieren auf einem Kalkulationsmodell, das speziell für das SKA entwickelt wurde und die Einhaltung der Kosten im Detail und im Ganzen ermöglicht. Damit ist das SKA einzigartig im Vergleich zu anderen internationalen Wissenschaftseinrichtungen bezüglich der Kontrolle der endgültigen Kosten. Durch den modularen Charakter des SKA als ein "Synthese Array" ist es zum Beispiel möglich, bei einer Kostenreduktion (wenn wissenschaftlich begründbar) die Gesamtplanung durch eine Änderung der möglichen Antennenanzahl entsprechend zu verändern.

Die weltweiten Anstrengungen zur Ausarbeitung der wissenschaftlichen Ziele und der technischen Spezifikationen für die nächste Generation von Radioteleskopen bestehen seit 1993. Seitdem wurde das Konzept und die Technologie-Entwicklung für das SKA von einem internationalen Konsortium unternommen, das rund 55 Institutionen in 19 Ländern umfasste. Deutschland war von Beginn an Teil dieser Konsortia. Im Jahr 2011 haben sieben nationale Regierungs-und Forschungsorganisationen aus Australien, China, Italien, den Niederlanden, Neuseeland, Südafrika und dem Vereinigten Königreich eine formale SKA-Organisation gegründet, der vor kurzem Kanada und Schweden beigetreten sind, die als ein unabhängiges, nicht-gewinnorientiertes Unternehmen nach britischem Recht aufgestellt wurde. Ziel der Organisation in dieser "Vor-Konstruktions-Phase" ist es, die Beziehungen zwischen den internationalen Partnern zu formalisieren und die Leitung des SKA-Projekts zu zentralisieren. Die Finanzierung dieser Organisation ist bis 2016 gesichert. Danach soll das Projekt in die Bauphase übergeleitet werden, die von einer neuen unabhängigen Organisation durchgeführt werden könnte und sollte.

Dieses "Weißbuch" versucht, die wissenschaftlichen Interessen an dem SKA-Projekt in Deutschland zu erfassen. Die überwiegende Mehrheit der Beiträge befasst sich mit astronomischen Fragen, aber weitere wichtige Themen wie High Performance Computing, "Daten-Handling, Management und Mining" sowie Energieversorgung sind von großer Bedeutung für die deutsche SKA-Gemeinschaft. Eine konservative Schätzung der Größe der deutschen "SKA-Community" ergibt eine Zahl von mehr als 400 Einzelpersonen, die direkt vom SKA profitieren würden. Um die deutschen SKA-Aktivitäten zu organisieren und koordinieren, hat das "German Long Wavelength Consortium" (GLOW) eine SKA-Arbeitsgruppe gegründet, die als verbindendes Element zwischen der astronomischen Gemeinschaft, der SKA-Gemeinschaft insgesamt sowie den Industrie- und politischen Partnern dienen wird. Dies ist notwendig, da das SKA ein einzigartiges "Welt-Teleskop" sein wird, das eine strategische Allianz von technischen, kommerziellen und wissenschaftlichen Partnern darstellen und gleichzeitig eine hochkarätige Forschungs- und Entwicklungeinrichtung sein wird. Investitionen in das SKA würde einen Wissenstransfer für die Industrie und die Forschung mit Hilfe einer High-Tech-Einrichtung bedeuten, die in einem weltweiten Netzwerk operiert.

Es ist von größter Bedeutung, dass Deutschland sich bei den wichtigen Forschungseinrichtungen wie das SKA, E-ELT und das Cherenkov Telescope Arrays (CTA) engagiert und seine Bemühungen weiter verstärkt. Als solches muss es eine aktive Rolle bei den Entscheidungen im SKA-Projekt einnehmen, um die Interessen der beteiligten deutschen Gemeinschaften zu sichern und die Wettbewerbsfähigkeit (und oft führende Rolle) der astrophysikalischen Forschung sowie technologischen Entwicklung in Deutschland zu erhalten.

Foreword

Dear Friends and Supporters of astrophysical research in Germany,

When the astronomical community in Germany composed the DFG memorandum " Status and Perspectives of Astronomy in Germany 2003−2016", now 10 years ago, it considered its research to be at the beginning of a "golden era" – an idea that was picked up and elaborated on in 2007 in the "Science Vision" of the European ASTRONET initiative. And, they did not exaggerate! Extrasolar planets are today routinely discovered, the parameters that dictate cosmic evolution are determined with an accuracy of better than 10 %, and studies of the high-redshift universe penetrate the "dark ages", the period between the recombination and the appearance of the most distant galaxies and quasars. This success story can be gauged by the fact that in no other decade have there been more astronomy-related Nobel Prizes in Physics than in the last ten years, and many new, high-level and financially substantial awards have been established (with remarkable success of researchers from Germany).

To a large extent these discoveries have been made possible by continued access to the large international, ground- and space-based observatories like the Very Large Telescope of ESO, the interferometric combination of radio telescopes for VLBI, the Hubble Space Telescope, and satellite observatories at other wavelength regimes such as Chandra, XMM, or Herschel. Interestingly, all these observatories are increasingly used synergistically, with the "deep fields" as particularly good examples. On the theory side, these efforts are supplemented by, and combined with, high-resolution and highly complex super-computer simulations.

Despite this tremendous progress, many central questions have thus far only been touched upon: an Earth-like exoplanet in the habitable zone remains to be discovered, the "dark ages" are still mostly in the dark, and the composition of the dominant part of the Universe, i.e. 23 % dark matter and 73 % dark energy, is still a mystery.

Both the DFG memorandum as well as the ASTRONET "Infrastructure Roadmap" have therefore identified the next generation of large observatories on the ground and in space, which will become operational in the next years and which will initiate an era of "precision astronomy". This will start in 2013 with the astrometric mission GAIA and leads with the commissioning of the E-ELT of ESO and the Euclid satellite of ESA into the next decade. As with the predecessor missions, these projects will result in numerous "spin-offs" of technological nature far away from astronomy.

Now it is time to pave the way for the last in this sequence of great international observatories, namely to make the "Square Kilometre Array" a reality in order to close the critical gap in the multi-frequency portfolio at long wavelengths. The completed SKA is planned to go into regular operation in 2024. This "white paper" describes and explains the different research interests and applications of scientists in Germany. The presented portfolio is not only impressive in the variety and depth of the issues, from solar physics to cosmology, but also in the diversity of the authors – ranging from theoreticians via astro-particle physicists to observational astronomers of different specialisation. Only a minority can be considered to be radio astronomers in the traditional sense. Important aspects are also the technological challenges, e.g. the handling of large amounts of data and technologies in the field of renewable energies.

Naturally, the most important chapter in the white paper remains unwritten: new, unexpected discoveries and resulting new research fields that will only be created by the use of the new observatories.

Prof. Dr. Matthias Steinmetz
Chairperson of the Council of German Observatories (RDS)

1 Preamble

The Square Kilometre Array (SKA) is the most ambitious radio telescope ever planned. With a collecting area of about a square kilometre, the SKA will be far superior in sensitivity and observing speed to all current radio facilities. The scientific capability promised by the SKA and its technological challenges provide an ideal base for interdisciplinary research, technology transfer, and collaboration between universities, research centres and industry. The SKA in the radio regime and the European Extreme Large Telescope (E-ELT) in the optical band are on the roadmap of the European Strategy Forum for Research Infrastructures (ESFRI) and have been recognised as the essential facilities for European research in astronomy.

Within the next few years the SKA project will move into a construction phase and important decisions are necessary regarding the telescope design, the infrastructure, and the technical developments. It is of vital importance to both the German science community and industry that Germany will be fully engaged in the SKA project in order to secure German interests in research and development (R&D) and its scientific usefulness.

This "White Paper" outlines the German science and R&D interests in the SKA project and will provide the basis for future funding applications to secure German involvement in the Square Kilometre Array.

2 Executive summary: The Square Kilometre Array – a technology telescope of superlatives

The SKA is listed as the only global project in the ESFRI with significant international partnership and, together with the E-ELT, it received the highest priority for future ground-based astronomical facilities.

The SKA will be a giant radio telescope with an effective collecting area of one-million square metres (m^2) that will operate between 70 MHz to 10 GHz, or more. The SKA will be built in two phases, first science is expected in 2019 and it is planned to be fully operational by 2024. The low-frequency part of the observatory will be built at the optimal site in Western Australia, while the mid- and high-frequency part will be built in Southern Africa where it can be merged with the SKA precursor MeerKAT and connected to the large European and German radio telescopes, enormously extending the European very long baseline interferometry network.

The SKA will be the world's premier imaging and surveying telescope that, with a combination of unprecedented versatility and sensitivity, will open up new windows of discovery space. It will find itself placed in a unique combination of new facilities exploring the electromagnetic and other windows into the Universe, making not only fascinating discoveries on its own but also providing exceptional complementarity in the exploration of the Universe's most fundamental open questions. With these capabilities the SKA will provide astronomers insight into the key science questions such as, the formation and evolution of the first stars and galaxies after the "big bang", the nature of gravity, the history of neutral hydrogen, the role of cosmic magnetism, and possibly life beyond Earth. In particular the SKA enables us to probe:

– **the dark ages**, by studying the formation of the first structures/bodies at a time when the Universe made a transition from largely neutral to its ionised state today;

– **galaxy evolution, cosmology, and dark energy**, by investigating the assembly, the distribution, and the properties of galaxies, e.g. through measurements of neutral hydrogen;

– **strong field tests of gravity**, by using pulsars to challenge Einstein's general relativity and the nature of space and time;

– **cradle of life**, by studying the habitable segment of proto-planetary disks and to search for prebiotic molecules that indicates primordial Earth-like conditions.

Radio astronomy has produced some of the greatest discoveries of the 20th century that have been rewarded with no less than four Nobel Prizes for physics. Some of these findings are the cosmic background radiation, pulsars, gravitational waves, dark matter, quasars, black holes, molecules, and relativistic plasma jets. Central to these discoveries have been innovations in technology pushing the observational frontiers of sensitivity as well as spatial-, temporal- and spectral-resolution. The SKA will carry on this tradition of innovation by combining fundamental developments in radio frequency technology, information technology and high-performance computing, hence complementing comparable efforts in other electromagnetic and non-electromagnetic windows to the Universe. The information of each window is unique and important and only by combining all information from all observational windows can we hope to understand the physical processes at work in the Universe. Indeed, the commonly used (though never really valid) division of scientists into physicists, high energy physicists, optical astronomers, radio astronomers, and the like fails to represent the successful research endeavours performed these days. As also indicated by the various contributions of this "White Paper" individual astronomers, institutes and research collaborations today use ground-based and space-based facilities across the electromagnetic spectrum, exploit non-electromagnetic windows, use high-performance computing facilities for numerical simulations and data analysis, and interact closely with particle physicists, all at the same time. In particular, they discuss their results in terms of science questions, rather than using a narrow definition of spectral windows.

The SKA is an irreplacable part of this global endeveour to explore the Universe and its fundamental laws, its origin and its fate. As one of the great global observatories, the SKA will provide an indispensable tool in the portfolio of the German astronomy community as a whole, sharing also solutions to common technological challenges, such as the handling, management and analysis of a staggering amount of data that is common to most many future top facilities.

The technical challenges and the upcoming data products will dramatically change the way astronomical research is done today and to make the SKA a reality it demands a revolutionary break from the traditional framework of radio telescope design. The SKA will drive technology development particularly in information and communication technology. Spin-off innovations in these areas will benefit other systems in industry and science that process large volumes of data from geographically dispersed sources. The energy requirements of the SKA also present an opportunity to accelerate technology development in scalable renewable energy generation, distribution, storage, and demand reduction. The German community has already developed expertise, in the design, construction, commissioning, and scientific exploration, of the "International LOFAR Telescope" the largest and most advanced SKA pathfinder to date, and therefore could significantly contribute to the SKA and its design.

The SKA Phase 1 will be built first and will be a scientific and technological subset of the SKA Phase 2. This setup allows evaluation of the technical maturity of various components of the system and will guide the decisions made in the course of a full SKA. The target cost of the full SKA has been set to be 1.5 Billion Euros ("1.5 Milliarden Euro"), whereas the cost of Phase 1 will be capped to 350 Million Euros. The cost estimates of the entire SKA project are based on a costing model especially developed for the SKA allowing for detailed cost modelling in order to minimise the uncertainties of the final expenses. The SKA is unique compared to the international flagship facilities in science in terms of controlling the final fiscal cost. Due to the modular nature of the SKA, as a "synthesis array", a cost reduction, if scientifically justified, is possible by alternating the number of telescope stations to match a final targeted cost figure.

Since 1993 a worldwide effort has been established to develop the scientific goals and technical specifications for the next generation of telescope. Since then the concept and technology development of the SKA has been undertaken by an international SKA consortium that includes some 55 institutions in 19 countries. Germany has participated and was involved in this endeavour since the beginning. In 2011, seven national governmental and research organisations from Australia, China, Italy, the Netherlands, New Zealand, South Africa, and the United Kingdom, provided the base to form a formal SKA organisation. Recently, Sweden has joined the organisation, which is an independent, not-for-profit company that has been established to formalise relationships with international partners and to centralize the leadership of the SKA project. The funding of this organisation is secured until 2016 at which point the construction phase will start. It is foreseen that the construction is executed by a new independent organisation that will also run the telescope.

This "White Paper" aims to capture the current science interests in the SKA project in Germany. The vast majority of contributions addresses astronomical questions, but further important subjects like high performance computing, data handling, management and mining, as well as energy provision are subjects of great importance to German scientists. A conservative estimate of the size of the German SKA community results in more than 400 individuals that would benefit from the SKA. In order to organize and coordinate the German SKA activities, the German Long Wavelength Consortium (GLOW) has established an SKA Working Group that will serve as the binding element between the radio astronomical community, the SKA community at large as well as industrial and political partners. This is necessary since the SKA will be a "world-telescope" that build a strategic alliance enabling technical, commercial, and scientific partnerships and research and development in a high-profile project. Furthermore, investing in the SKA would provide knowledge transfer for industry and accademia in a high-tech facility that operates in a worldwide network.

It is of utmost importance that Germany preserve and strengthen its position in the flagship facilities like the SKA, E-ELT, and the Cherenkov Telescope Array (CTA), and takes an active role in the decisions to be made in the SKA project to safeguard the German communities interests and the competitiveness (and often leading role) of astrophysical research in Germany.

3 Radio astronomy and its role in understanding the Universe

Astronomy is an observational science that connects to the human spirit and its curiosity, which drives us forward to explore and venture into new worlds. Indeed, modern astronomy has much to offer. It has dramatically changed over the last century, opening new observational windows to the Universe. Astronomy is essential, since

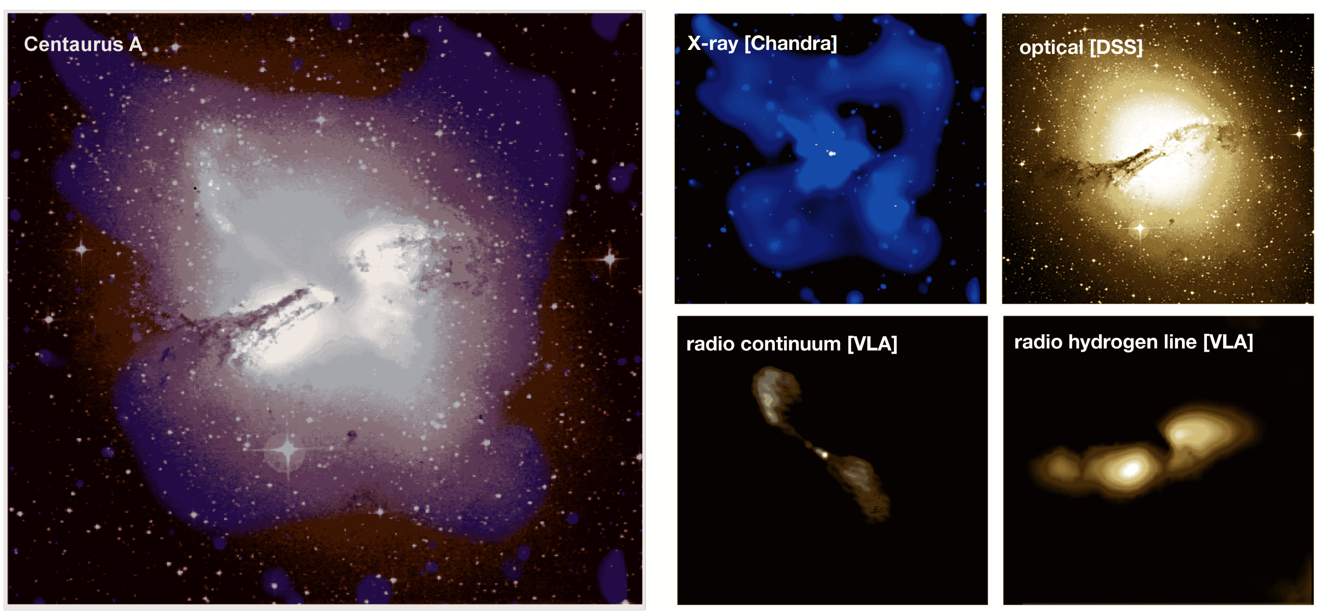


Figure I: Composite image of the extragalactic source "Centaurus A" observed from short wavelengths (X-ray) to long wavelengths (radio). In particular, the radio emission maps out various components of the galaxy. The radio continuum emission traces the outflow-jet structure of the galaxy whereas the neutral hydrogen emission traces the kinematics of the disk like structure seen in the optical image. Furthermore, by using the hydrogen line emission the distance to the galaxy itself can be determine via the redshift relation. (Image credits: see page 136) many of the scientific tests, experiments or hypotheses proposed by theory can only be examined in the cosmic laboratory as many conditions cannot be replicated on Earth. In particular radio astronomy, developed since the 1930s plays an important part and is now a multi-disciplinary science that connects to quantum and high energy physics, general relativity, information technology, chemistry, electrical and mechanical engineering, communication, optics, material science, mathematics, and much more.

Depending on physical conditions, cosmic signals are created in several ways, mostly by matter that emits, reflects, or absorbs energy across the electromagnetic spectrum ranging from very short wavelengths (e.g. gamma rays, X-rays) to very long wavelengths (e.g. infrared, radio waves). Each part of this information is unique and important, and only by combining all information from all observational windows can we hope to understand the physical processes at work. Indeed, it can be shown that multi-wavelength papers, in particular the combination of optical and radio observations, are on average more influential than other publications (Tremble & Zaich 2006). This is a lesson that is very much adopted by the astronomical and physical community as a whole. Hence, dividing scientists into physicist, high energy physicists, optical astronomers, radio astronomers and the like, is a very much a misrepresentation of the research successfully performed these days. As a result, the classical division between users of certain facilities has disappeared. Individual astronomers, institutes and research collaborations today use ground-based and space-based facilities across the electromagnetic spectrum, exploit non-electromagnetic windows, use high-performance computing facilities for numerical simulations and data analysis, interact closely with particle physicists, all at the same time – in particular, they discuss their results in terms of science questions, rather than using an out-dated narrow definition of spectral windows.

For instance, it is clear that the most burning questions about the nature of dark matter and dark energy can only be solved by combining studies in the radio-, optical-, and high-energy windows, paired with results from particle accelerators and vast simulations using the best super-computers in the world. Similarly, all future science facilities have one property in common: they will produce a staggering amount of data that needs to handled, managed and analysed. Solutions to this common problem are likely to come from working together towards a science infrastructure that can handle the storage and, also, energy requirements.

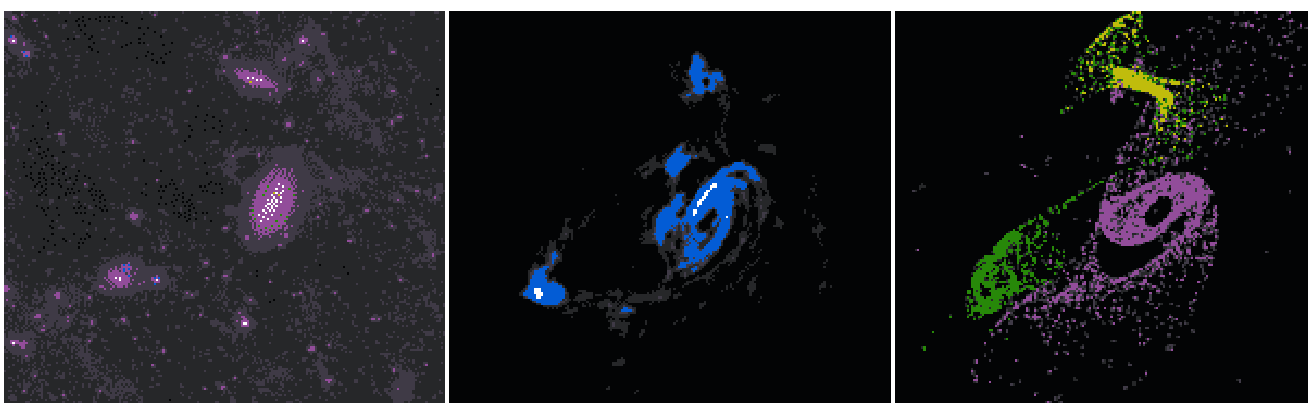


Figure II: An example of modern astronomy, combining multi-wavelength observations with computer simulations. Here shown are the interacting galaxies M 81, M 82, and NGC 3077 in the optical (left) and in neutral hydrogen (H I, middle). The interaction is only observable by the atomic H I gas that connects all three galaxies by filaments. The numerical simulation (right) demonstrates that all H I filaments are the results of tidal interaction among these galaxies. (Image credits: see page 136)

An example of the required combination of information across the electromagnetic spectrum is illustrated in Figure I which shows a composite image of a galaxy and the contributing observations at different wavelengths. Apart from tracing different processes, quite often, energy from one part of the electromagnetic spectrum will be blocked by interstellar matter, interplanetary dust, or Earth's atmospheric constitutes, while energy from other parts of the spectrum will be transmitted freely to the astronomical observatory. For instance, cosmic radio emission has been shown to be less limited by these effects and is even observable during day time. Moreover, even though radio photons may be not very energetic, they often result from highly energetic processes, revealing objects that are otherwise not visible. For example Figure II shows galaxy mergers who's energetic processes are only visible with radio observations. Furthermore, the figure demonstrates the interplay of observations and simulations in modern astronomy. Without doubt the use of radio astronomical techniques will continue to play an important part in this joint endeavour to understand the cosmos and the fundamental laws that govern it. In the accordance with these efforts, despite humble beginnings, radio telescopes have delivered some of the arguably most important discoveries of the last 100 years.

When radio astronomy was "born" in the 1930s, its inventor Karl Jansky was employed at Bell Laboratories, studying the disturbance of radio telephone links. His findings that these were of extraterrestrial origin triggered further "radio" work and, by the early 1950s, radio astronomy had discovered radio emission from the Milky Way, the Sun, and from very distant galaxies. These discoveries challenged the theoretical models of the time, and there were no accepted theories in place to explain these phenomena. However, it was not until the 1960s that radio astronomy began to play its part in the "big science area" on a large, transformational scale (Verschuur 2007). The resulting discoveries were many, including signals from the beginnings of all time and space (i.e. "big bang" background radiation at 3 Kelvin), and have been rewarded with no less than four Nobel Prizes for physics. The discoveries include:

– the cosmic microwave background (CMB), as the remaining signal from the big bang,

– Pulsars, as the remnants of massive stars whose existence proves the validity of quantum mechanical laws in space,

– the existence of gravitational waves using binary pulsars in cosmic clock experiments,

– the existence of gravitational lenses that bend light to form multiple images of distant super-massive black holes,

– the evidence for "Dark Matter" in the rotational properties of galaxies (neutral hydrogen),

– the existence of complicated molecules in space that may well be related to the formation of life (carbon monoxide, ammonia),

– the first extra-solar planets.

As indicated earlier, these discoveries address or have led to fundamental questions that are not exclusive to radio astronomy but which initiated multi-disciplinary research about our origin and fate and that of the Universe, as well as the fundamental laws of physics. Given this important complementarity of the different waveband observations, it is does not come as a surprise that both the Hubble Space Telescope (HST) and the radio interferometer Very Large Array (VLA) remain as the two astronomical facilities with the largest number of publications and citations of a single facility. But it is also true that consistently, publications combining radio and optical data are extremely well cited and typically more influential than single-waveband papers (see e.g. Trimble & Zaich 2006, Trimble & Ceja 2008). The SKA will follow this tradition by providing an indispensable tool in the portfolio of the German astronomy community as a whole.

4 The SKA in the astronomical landscape

The strategic plan for European astronomy described in the " ASTRONET Roadmap" identifies the SKA, together with the European Extremely Large Telescope (E-ELT), as the highest priority project for ground-based astronomy due to the potential for fundamental breakthroughs in a very wide rage of scientific fields. Besides the SKA and the E-ELT three other projects were considered scientifically outstanding but in narrower fields and with lower budgets (see "ASTRONET Roadmap"). In descending order of priority identified, these are the European Solar

Telescope (EST), the Cherenkov Telescope Array (CTA) and the neutrino detector KM3NET – all which have significant German involvement or leadership.

On the same timescale as the realisation of SKA Phase 1 and, certainly, Phase 2, further instruments will be operational or are in preparation, such as ALMA, JWST, ELTs, ATHENA, SPICA, CTA LIGO, eLISA/NGO, LSST, Euclid/JDEM, CMBPOL, GAIA, KM3NeT and the LHC (running in CERN) all covering different wavelength or energy regimes. The SKA provides an important and crucial radio component in the pursuit of the burning science topics that are, for instance, captured by the science questions formulated in the "ASTRONET Science Vision", which are:

– *What is the origin and evolution of stars and planets?*

– *Do we understand the extremes of the Universe?*

– *How do galaxies form and evolve?*

– *How do we fit in?*

As described in the science contributions to this "White Paper", the German interests cover all these areas, and indeed, the SKA will not only contribute to them, but SKA observations will often play a or even *the* decisive role in answering them. A good example is the SKA's role in answering the questions about the nature of dark matter and dark energy. The is already a large German involvement and interest in instruments and projects that address these questions, such as the Sloan Digital Sky Survey (SDSS), WiggleZ, 4MOST, LSST, HETDEX, Pan-Starrs, or DES, others space-based missions such as Euclid. All of them are operating in the optical or near-infrared. In the radio, several SKA pathfinder telescopes are also preparing continuum radio surveys (e.g. LOFAR MSSS, LOFAR Tier1, WODAN, EDU; Raccanelli et al. 2011), while the SKA itself will survey a billion galaxies in redshifted hydrogen, which will automatically provide distances, so that the Universe can be conveniently sliced in redshift bins. This information promises to provide unprecedented and pivotal answers in determining the equation-of-state of dark energy.

In order to understand the role of the SKA for science in the next decades see Figure III or it is perhaps even more enlightening to recast the SKA contribution in the following themes, namely

The laws of nature: Fundamental Physics & Cosmology including

Gravity: Is general relativity our last word in understanding gravity?
What happens in strong gravitational fields?
What are the properties of gravitational waves?
What is "Dark Matter"?
What is "Dark Energy"?

Magnetism: What is the origin of cosmic magnetism?
How did it evolve?
What is its role in the formation and evolution of stars and galaxies?

Strong & weak forces: What are the properties of matter?
What is the nuclear equation-of-state?

Origins: Galaxies across cosmic time, Galactic neighbourhood, stellar & planetary formation including

Galaxies and the Universe: How did the Universe emerge from its Dark Ages?
How did the structure of the cosmic web evolve?
Where are most of the metals throughout cosmic time?
How were galaxies assembled?

Stars, Planets, and Life: How do planetary systems form and evolve?
What is the life-cycle of the interstellar medium and stars? (biomolecules)?
Is there evidence for life on exoplanets (SETI)?

German involvement in related projects is wide-spread and other observatories like LOFAR, ALMA, JWST or the E-ELT and dedicated projects such as LSST and EUCLID will superbly contribute to the pursuit of these science goals. But, in many cases, the science is also unique to the radio band, as for instance in the study of cosmic magnetism.

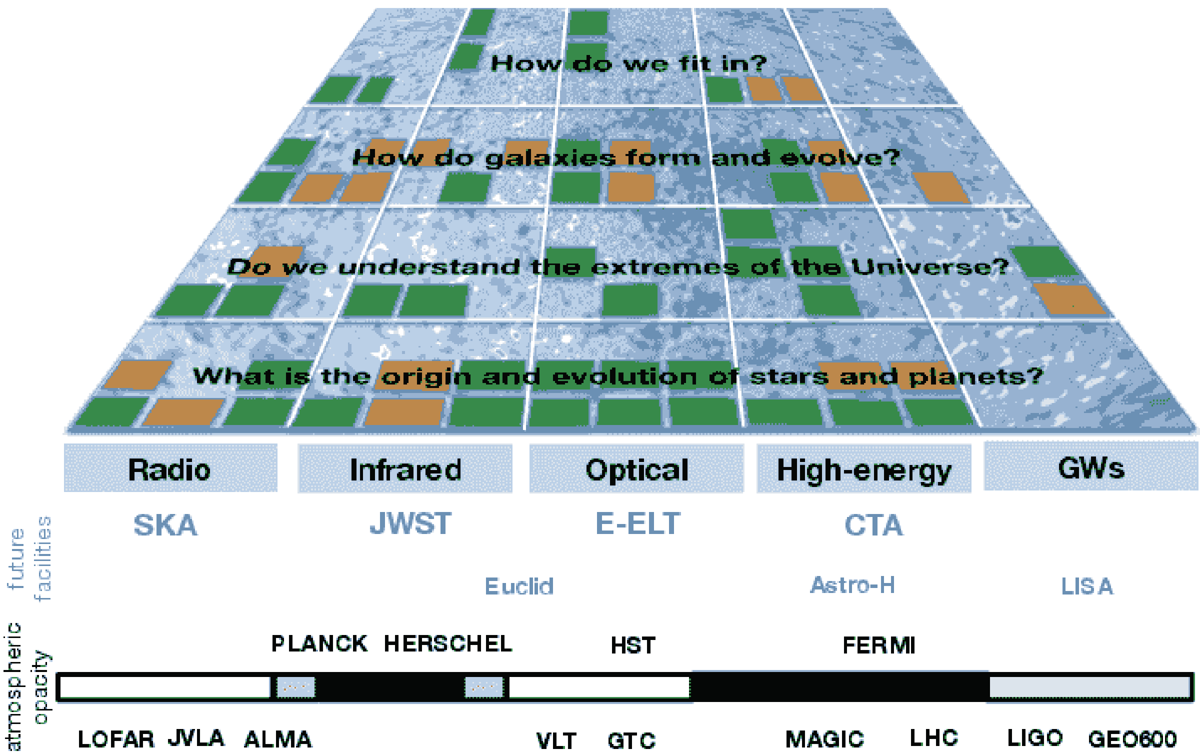


Figure III: Overview of future and recently developed or upgraded astronomical facilities. The upcoming flagship facilities have been related to the science questions and the recommendations of the "ASTRONET Science Vision". The science vision indicates 6 – 7 science goals for each main research area, which has been divided into two classes: Essential (green rectangles), implying that the scientific goal can-not be reached without this facility, and complementary (orange rectangles), where the facility will provide very beneficial information to reach the scientific goal.

The complementarity of the SKA, however, goes far beyond the exploitation of the Universe using the classical electromagnetic windows. Naturally, the SKA will also provide excellent matching insight when studying the gravitational wave sky or when connecting to the Cosmos with particle physics or Cherenkov telescopes. On one hand, radio astronomical techniques provide the only evidence so far that gravitational waves exist, and hence they allow us to study similar but also additional sources expected to be observed with ground- and space-based gravitational wave detectors. The detectors *GEO600, Advanced LIGO* and *VIRGO* will observe gravitational waves from merging compact binary systems like double neutron stars or binary black hole systems, while *LISA/NGO* will observe, for instance, extreme mass-ratio inspirals. By comparison, the SKA will detect and study the gravitational waves from super-massive binary systems (see also contributions in this "White Paper"). Hence, the SKA is a logical step towards securing Germany's leading role in gravitational wave astronomy.

Furthermore, radio photons are those with the lowest energies, but they often result from the most energetic processes known. Radio emission is therefore indeed often associated with those sources that are visible at the highest energies with Gamma-ray satellites like *FERMI* or ground-based Cherenkov-telescopes. Some of the particles observed with such detectors have energies a hundred million times greater than that achievable by terrestrial accelerators, and their observation raises several questions; How can cosmic accelerators boost particles to these energies? What is the maximum energy achievable by galactic sources such as supernova remnants, neutron stars, or micro-quasars? How do they propagate through the Universe? Does the cosmic ray energy spectrum extend beyond the maximum energy a proton can maintain when travelling over large cosmic distances, as they would eventually collide with the omnipresent microwave background? (questions obtained from http://www.aspera-eu.org). These questions can be addressed by new facilities like the *Cherenkov Telescope Array* (CTA) where Germany is also playing a leading role. Indeed, many of the sources for the photons and particles observed with the CTA are indeed uniquely observable with radio telescopes and, in particular, with the SKA. Pending the siting decision for the CTA, there is a large chance that both SKA and CTA will be collocated in Southern Africa, providing unparalleled possibilities in studying the high energy sky. A prime example of such a successful combination of experiments is given by the LOPES array (LOFAR PrototypE Station; http://www.astro.ru.nl/lopes/), that operates radio antennas and photomultipler technology, from particle physics, to perform coincidence measurements of air showers that are produced by cosmic rays when they enter the Earth's atmosphere.

A fundamental question that requires the interplay of radio astronomy, optical astronomy and particle detectors and accelerators is, of course, that about the nature of dark matter. First evidence for dark matter has been obtained from the kinematics of stars in the Galaxy as revealed by ground-based optical observations in the first third of the 20th century (Oort 1932) and the kinematics of galaxies in clusters (Zwicky 1933). Since then, dark matter has become the keystone of the standard cosmology model based on much wider evidence than optical astronomy alone, in particular from hydrogen observations of galaxies in the radio regime. Based on the latest measurements from the *Wilkinson Microwave Anisotropy Probe* (WMAP; satellite operating at infrared- and radio frequencies) only 4 % of the Universe is made of ordinary matter. Whereas 73 % of the cosmic energy budget seems to consist of dark energy and 23 % of dark matter.

The ultimate answer on the nature of dark matter will likely come from the observation the exotic particles that constitute dark matter. These particles may be first observed in subterranean laboratories, by the planned detectors recording the nuclear recoils due to the impact of dark matter particles ("direct detection"). Alternatively, signs of dark matter particles may arise as products of their annihilation in celestial bodies and may be detected by Gamma-ray telescopes (e.g. the Cherenkov Telescope Array) at ground level or in space, by *neutrino telescopes* deep underwater or in ice, or by cosmic ray spectrometers in space ("indirect detection"). Discoveries based on particle physics technology will have immediate consequences on our understanding of the Universe and, vice versa, discoveries in radio astronomy by the SKA will have fundamental impact on theories of the infinitely small. Some of the subjects where the SKA will impact in particle physics is discussed in Section 8.5 on fundamental physics.

In summary, like all new major facilities the SKA will not only boost scientific output it will also impact on astronomy and natural science in general. In addition, the massive increase in sensitivity and survey speed will not only detect every active radio galaxy in the Universe but it will also trigger a revolution in how research is done in radio astronomy that will reverberate in other areas of astrophysics and fundamental science. Overall, Germany's contribution to the SKA will help cement a leading position for Germany's astronomy community.

5 The German SKA community & the GLOW consortium

In order to estimate the size of the German science community that would benefit from the SKA, three different parts to that community are considered. Universities and research institutes that have a radio-astronomical division or sub-division, institutes with radio-astronomical interests or that use radio astronomical instruments, and institutes that would conduct science using the SKA. These different groups are considered and their numbers are discussed below.

In the first group, the number of people can be estimated directly, whereas for the second group individual scientists can be counted, who either directly work on radio data or make use of science results obtained by current radio facilities. In particular, people involved in the "GLOW-Konsortium" can be named. The third group reflects the fact that the SKA will be a general purpose science facility that will be accessible as a general purpose observatory. The third group therefore made out of scientists, who do not consider themselves as astronomers, but who make use of the information and the data provided by the SKA to study fundamental science questions.

The example of ALMA, however, underlines impressively our statement in the previous section that it is not appropriate anymore to divide the astronomical community according to wavebands. Indeed, the number of authors of "ALMA Cycle-0" proposals employed in Germany exceeds the number of people who would be considered as radio astronomers or "classical" ALMA users. It shows that if a new instrument promises to provide new answers to scientific questions, the distinction into the classical observing bands (e.g. optical-, infrared-, or radio-bands) does not hold anymore as, in fact, nowadays a multi-disciplinary approach is needed to answer our science needs. According to our definition above, the current ALMA users could and should be added to our second group of potential SKA users. Following these considerations, we proceed as outlined.

Radio-astronomical institutes or sub-divisions: The following institutes host a "Radioastronomical Group" that either do research in radio astronomy, technical development, or develop/run a radio observatory (in alphabetic order).

- Astronomisches Institut der Ruhr-Universität Bochum
- Max-Planck-Institut für Radioastronomie Bonn
- Geodätisches Institut der Universität Bonn (GIUB is part of FGS)
- Wettzell Observatorium (Forschungsgruppe Satellitengeodäsie (FGS))
- 1. Physikalisches Institut der Universität zu Köln
- Leibniz-Institut für Astrophysik Potsdam

The total size of the group of ~ 270 people is based on counting institute member with a tenture track, postdoctoral, or student position. In addition to this number one could add people working in the ESO ALMA ARC's, which would result in a total of ~ 280 people .

Institutes with radio-astronomical interests: In this group are institutes that make use of radio facilities or run an observatory without technical research and development. In particular institutes of the German Long-Wavelength Consortium (GLOW) are mentioned here:

- Fakultät für Physik, Universität Bielefeld
- Astronomisches Institut der Ruhr-Universität Bochum (not counted again, as counted already above)
- Argelander-Institut für Astronomie, Universität Bonn
- Max-Planck-Institut für Radioastronomie Bonn (not counted again, as counted already above)
- Jacobs University Bremen
- Max-Planck-Institut für Astrophysik Garching
- Exzellenz Cluster "Universum" Garching
- Hamburger Sternwarte, Fachbereich Physik, Universität Hamburg

- Forschungszentrum Jülich
- 1. Physikalisches Institut der Universität zu Köln (not counted again, as counted already above)
- Leibniz-Institut für Astrophysik Potsdam (not counted again, as counted already above)
- Thüringer Landessternwarte Tautenburg

From these institutes an additional ~ 30 people have been counted.

Surveying the publicly available observing schedules of radio telescopes like Effelsberg, EVN, Parkes, VLA and Westerbork a further set of $10-20$ people has been identified who work actively on radio data (e.g. colleagues from the "Landessternwarte Heidelberg" or the "Max-Planck-Institut für Astronomie" are very active users). We consider this latter number as a conservative lower estimate.

Institutes with interests in SKA research and development: The SKA will not only be a general purpose observatory, but with its technical challenges and large-volume data products it will also be a mega-science infrastructure that will dramatically change the way research is achieved. The requirements of the SKA will push toward new research areas in eScience, data handling, as well as digital electronics, and energy consumption and solar energy storage. Despite this wide appeal, at the current time an estimate of the science (and industry) community related to those questions is difficult to give. However, as an extremely conservative lower bound for the size of the third group of the SKA community, we can at least count those colleagues who are interested in fundamental science questions related to research and development in physics and astronomy, who also contributed to this "white paper". Obviously, the real number is likely to be larger by a factor of a few, at least. For now, we count:

- Zentrum für Astronomie and Astrophysik, Technische Universität Berlin
- ZARM, Universität Bremen
- Physikalisches Institut der Friedrich-Alexander Universität Erlangen-Nürnberg
- Fraunhofer-Institut für Solare Energiesysteme ISE Freiburg
- Institut für Theoretische Physik, Goethe-Universität Frankfurt
- Institut für Astrophysik der Georg-August-Universität Göttingen
- Max-Planck-Institut für Kernphysik Heidelberg
- Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena
- Max-Planck-Institut für Sonnensystemforschung Katlenburg-Lindau
- Universitätssternwarte der Ludwig-Maximilians-Universität München
- Institut für Mathematik und Naturwissenschaften, Carl von Ossietzky Universität Oldenburg
- Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) Potsdam
- Theoretische Astrophysik, Eberhard Karls Universität Tübingen

A conservative measure for the number of people who have not been taken into account in any of the previous groups would be of the order of (at least) 50 people.

In conclusion this community is far larger than if one only counts the "classical" radio-astronomical institutes in Germany. Adding the previous estimates and parts of the ALMA community, which partially overlaps, a conservative evaluation of the size of the **German SKA community** results in more than **400 individuals**.

5.1 The German Long Wavelength Consortium and its SKA Working Group [M. Hoeft]

The German Long-Wavelength Consortium (GLOW) aims to foster radio astronomy in Germany. Twelve German astronomy institutes form a consortium for exchanging knowledge, bundling efforts and coordinating activities in radio astronomy. Initially focussing on low-frequency radio astronomy and its exploitation with the *Low Frequency Array* (LOFAR), GLOW has recently formed an SKA working group that will act in a role as an organising entity, seeking to coordinate the overall German SKA interests. Given the impact of the SKA on areas outside radio astronomy or astronomy as a whole, GLOW offers membership in this working group to all interested parties from science and industry.

LOFAR with its core in the Netherlands, is a unique telescope for very long wavelengths. GLOW member institutes strive to enhance LOFAR by building and operating LOFAR stations in Germany and by participating in the LOFAR Key Science projects (KSPs). GLOW coordinates these LOFAR-related activities. Similarly, GLOW will provide a framework for coordinating SKA related activities in Germany.

GLOW is an open consortium which can be joined by any institute which subscribes to the "Memorandum of Understanding" (MoU). As an initial step into the LOFAR project the German "LOFAR white paper" (eds. Brüggen, et al. 2005) was compiled in 2005, summarising the scientific and technical interests in the LOFAR telescope. In 2006 ten institutes, which aimed to extend LOFAR into Germany by building several stations, formed the German Long Wavelength Consortium. Among the founding institutes were "major players" in radio astronomy such as the "Max-Planck-Institut für Radioastronomie" (MPIfR, Bonn) and also "newcomers" such as the Thüringer Landessternwarte (TLS, Tautenburg). At this time only the MPIfR had started to build a LOFAR station while other institutes were planning to do so. Currently, five stations have been completed and are in operation. A sixth station is in preparation. LOFAR crucially relies on information and communication technologies. The Forschungszentrum Jülich (FZJ) is interested in technological aspects of LOFAR, hence, it also joined GLOW. The GLOW members assemble annually for an intense exchange with regard to scientific and technological topics. An Executive Committee, a Science Working Group, and a Technical Working Group conduct the GLOW activities between the annual meetings.

When the German institutes joined LOFAR they also established two new KSPs, namely one on "Cosmic Magnetism" and one on "Solar Physics and Space Weather". The two KSPs significantly enhance the scope of LOFAR, e.g. the Cosmic Magnetism KSP uses Rotation Measure Synthesis for studying magnetic fields in the cosmos. Hence, suitable methods need to be implemented in the LOFAR data analysis pipelines. A substantial amount of man-power is needed for developing the software, conducting commissioning observations, and analysing the huge amounts of scientific data. GLOW has coordinated efforts for writing proposals. Most of them have been granted, in particular, a DFG research group (FOR 1254, "Cosmic Magnetism") and projects in the framework of the German Verbundforschung (D-LOFAR I+II). The "Verbundforschungs"-grants also allowed two of the German LOFAR stations to be built.

The International LOFAR Telescope (ILT) is based on National Consortia. Therefore, a crucial task of GLOW is to provide the link between the ILT and station owners and KSP members in Germany. For instance, GLOW nominates a representative for the Board of ILT and balances contributions to LOFAR and scientific returns for station owners. Another crucial German contribution to LOFAR – besides building and operating stations – is an archiving facility offered by FZJ to the LOFAR Long Term Archive.

GLOW also strives to educate young scientists in radio astronomy. To this end two schools have been organised (2010 in Hamburg and 2012 in Bielefeld) at which students were introduced to radio interferometry by lectures and hands-on tutorials. Moreover, GLOW members organize scientific meetings focussing on low frequency radio astronomy, e.g. the International LOFAR Workshop in Hamburg (2008) and Splinter meetings at the annual meetings of the German Astronomical Society.

Currently, most activities of GLOW are related to LOFAR. However, GLOW has a more general mission, namely to foster radio astronomy. Consequently, GLOW has established a coordinating SKA Working Group that will serve as the binding element between the radio astronomical community, the SKA community at large as well as industrial and political partners.

6 The SKA project

6.1 History, Governance, Timeline & Top level management structure

Since the early 1980s the need for a bigger telescope has been discussed in the radio astronomical community triggering e.g. the construction of the Giant Metrewave Radio Telescope (GMRT) in India. Around 1990 these plans were developed by considering even larger arrays (Wilkinson 1991; Noordam et al. 1991). Since then the Square Kilometre Array has evolved over the years from a purely "hydrogen array" observing at frequencies of 1.4 GHz and below, to a multi-facetted science facility covering a frequency range from about 50 MHz to 10 GHz or possibly 25 GHz, capable of answering many of the major questions in modern astrophysics and cosmology.

In September 1993 the International Union of Radio Science (URSI) established the Large Telescope Working Group to begin a worldwide effort to develop the scientific goals and technical specifications for a next generation radio observatory. Subsequent meetings of the working group provided a forum for discussing the technical research required and for mobilising a broad scientific community to cooperate in achieving this common goal. In 1997, eight institutions from six countries (Australia, Canada, China, India, the Netherlands, and the USA) signed a "Memorandum of Agreement" (MoA) to cooperate in a technology study programme leading to a future very large radio telescope. In 2000 a "Memorandum of Understanding" (MoU) to establish the "International Square Kilometre Array Steering Committee" (ISSC) was signed by representatives of eleven countries (Australia, Canada, China, Germany, India, Italy, the Netherlands, Poland, Sweden, the United Kingdom [UK], and the USA). This was superseded by a MoA to collaborate in the development of the Square Kilometre Array which came into force in 2005 and which has been extended until 2007. It made provision to expand the ISSC to 21 members (7 members from each: Europe, USA, and the Rest of the World) and to establish the International SKA Project Office (ISPO).

A further international collaboration agreement for the SKA programme was drawn up in 2007, which became effective on 1 January 2008. It was signed by the European, US, and Canadian SKA Consortia, the Australian SKA Coordination Committee, the National Research Foundation in South Africa, the National Astronomical Observatories in China, and the National Centre for Radio Astrophysics in India. This agreement established the SKA Science and Engineering Committee (SSEC) as a replacement to the ISSC. The SSEC acts as the primary forum for interactions and decisions on scientific and technical matters for the SKA among the signatories to the International Collaboration Agreement. A further agreement was drawn up in 2007, a MoA to establish the SKA Program Development Office (SPDO).

In 2011 a call was launched to host the SPDO headquarter. Germany, the Netherlands and the UK applied. Due to the very strong support by their government the United Kingdom was chosen to host the SKA headquarter at Jodrell Bank near Manchester. In April 2011, the Founding Board was formed. The Board members, Germany, the UK, the Netherlands, Australia, New Zeeland, South Africa, China, France and Italy carried out the preparatory work for the SKA Organisation which was formed in November 2011. At that time, seven national governmental and research organisations announced the formation of the SKA Organisation, as an independent not-for-profit company (Ltd.) established to formalise relationships with international partners and centralise the leadership of the Square Kilometre Array (SKA) telescope project. The founding signatories are Australia (Department of Innovation, Industry, Science and Research), China (National Astronomical Observatories, Chinese Academy of Sciences), Italy (National Institute for Astrophysics [INAF]), the Netherlands (Netherlands Organisation for Science Research [NWO]), New Zealand (Ministry of Economic Development), South Africa (National Research Foundation [NRF]) and the United Kingdom (Science and Technology Facilities Council [STFC]) to fund the project in the period leading up to the construction phase which will start in 2016. In March 2012 Canada via the National Research Council (NRC) joined the SKA organisation as a full member and will make financial contributions to the project. In April 2012 India joined the SKA organisation as the first associate member. Sweden joined the SKA organisation as a full member in June 2012. Overall the SKA organisation is the legal entity that will design, built and operate the SKA.

In early 2012 the SKA organisation received the site evaluation report and started the process on a resolution to select a site. The two sites that proposed to host the SKA were:

– South Africa (SA) partnering with Namibia, Botswana, Kenya, Madagascar, Mauritius, Mozambique and Zambia.

– Australia, together with New Zealand.

In the site decision process the members of the SKA organisation which are bidding to host the SKA did not take part. Therefore, of the SKA Organisation the following members were eligible to vote: Canada, China, Italy, the Netherlands, and the United Kingdom. The site decision of the SKA was announced in May 2012: the majority of the members of the SKA Organisation is in favour of a dual-site implementation of the SKA. The evaluation report concludes that a scientifically and technically viable approach is to split the SKA array in frequency space. The long term solution for the "full" SKA will therefore be that the low-frequency array will be hosted in Australia and New Zealand whereas the mid- and high-frequency array will be placed in South Africa. However during the first phase of the SKA (SKA_1) both sides will host different technical realisations of the dish array of the SKA. A full account of the various telescope types and the realisation of the SKA at both sites is discussed in Section 6.2.

While the split-site decision certainly keeps the whole global SKA science and technology community fully engaged, it offers also a number of advantages. Firstly, the large investments in the SKA pre-cursors, MeerKAT and ASKAP, now become integral part of SKA Phase 1. This promises to keep the costs for the first phase under control, as MeerKAT itself already represents a significant fraction of Phase 1's collecting area. Similarly, the low-frequency part of the SKA will now be co-located at the MWA site, which is arguably also the better site for very low-frequency radio astronomy. It was also decided that the final approval for Phase 2 construction depends on the continuing pristine radio interference-free conditions of the sites. Having two sites prepared for Phase 2 constructions promises a reliable path into the future, as one site can always act as a back-up site for the other. Finally, it should be noted that the plan for South Africa to host the high- and mid-frequency array of the SKA will open up an additional science possibility for Germany (and Europe in general) as it will be possible to use very long baseline interferometry, connecting the Effelsberg telescope (the biggest single dish telescope in Europe) with the SKA. It is also worh noting that the European Parliament has called for greater collaboration with Africa in the field of radio astronomy, following its adoption of "Written Declaration 45" on science capacity building in Africa.

Figure IV: SKA overall project timeline

The overall SKA project timeline of the next decade can be divided into six major periodes (see Figure IV). The upcoming pre-construction phase allows the employment of a formal project management structure, enabling a top-level description of work and a breakdown structure of work packages (WP). Furthermore, it will establish the science specifications and system requirements for SKA Phase 1 (SKA_1). In addition, the work in the first two periods ("Preparatory Phase and Pre-Construction Phase") will be carried out on the baseline design and the "Advanced Instrumentation Program" (AIP) with the aim of preparing the international project for the start of construction. The construction of the SKA is planned to start in 2016 allowing for the first science results within this decade. The schedule to extend the frequency coverage to 25 GHz at the high end of frequency range would define the third phase in the construction of the SKA, but up to this point in time there is no defined schedule for SKA_3. A full overview of the individual programmes within the SKA project timeline can be found in the appendix (page 133).

The work of the SKA organisation is overseen by its "Board of Directors" which has the authority to appoint senior staff, to decide on budgets, to admit new project partners to the organisation and to direct the work of the global work package consortia. Every SKA member of the organisation appoints two representatives to the board of directors. Furthermore, the top level management structure of the SKA organisation includes the "director general", "the office of the SKA organisation" ("the office" in the following) and various advisory committees. The SKA project will have a strong central office with management and system design authority, that will not only contract the work of major telescope subsystems but also coordinate a small number of work package contractors. The work package contractors themselves will be consortia of participating organisations (PO) and industrial partners, but could also be individual companies or POs. On overview on the management structure is illustrated in Figure V. The subjects of the individual work packages cover the following 11 areas: management of the pre-construction phase and management support, such as quality assurance, configuration management, and procurement; science; overall system; maintenance and support; dish sub-systems; aperture array sub-systems; signal transport and network; signal processing; software and computing; power; site and infrastructure.

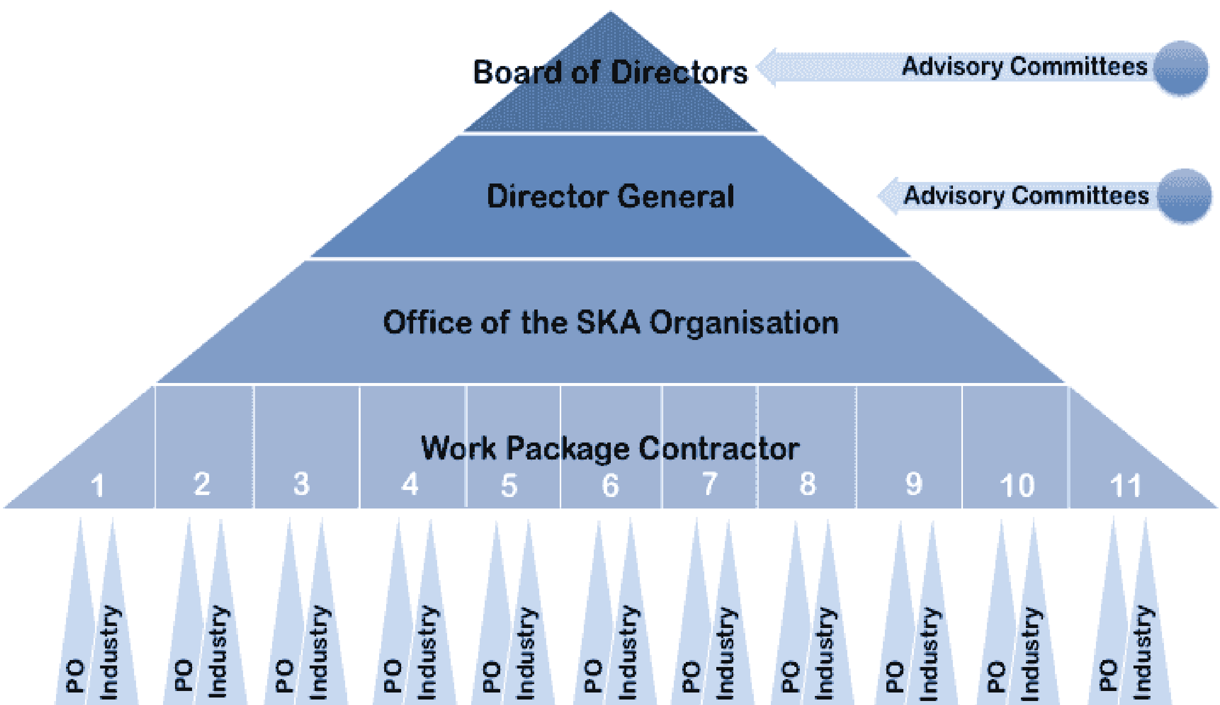


Figure V: Schematic overview of the management structure of the SKA organisation. Contributions to the SKA project from third parties are organised in work packages. The full description of the work packages and their different subjects and are discussed in the text.

In general, the timeline and the overall project management indicates that important decisions will be made in the next years that strongly influence the technical and scientific capability of the SKA and an early involvement of Germany in these decisions is needed to secure their interests in research and development.

6.2 The telescope

The SKA will be the World's premier imaging and surveying telescope with a combination of unprecedented versatility and sensitivity. The SKA will continuously cover most of the frequency range accessible from the ground, ranging from 70 MHz to 10 GHz in the first and second phase of construction and offers the possibility, at a later stage, to extend the frequency range up to 25 GHz to close the frequency gap to ALMA and to be able to observe water masers, ammonia, etc. Having a collecting area of a million square meters ($1\,000\,000\,\mathrm{m}^2$), it will be about $10-100$ times more sensitive than the largest single dish telescope in Arecibo (305 m diameter, Puerto Rico), and fifty times more sensitive than the currently most powerful interferometer, the Karl G. Jansky Very Large Array (JVLA, in Socorro/USA). The enormously wide field of view (FoV) is another major advancement, ranging from 200 square degrees at 70 MHz to at least 1 square degree at 1.4 GHz (for reference the full moon covers 0.25 square degrees). Such a wide field of view will enhance the speed of observations for large parts of the sky, particularly at the lower frequencies, allowing for survey speeds which will be ten thousand to a million times faster than what is possible today.

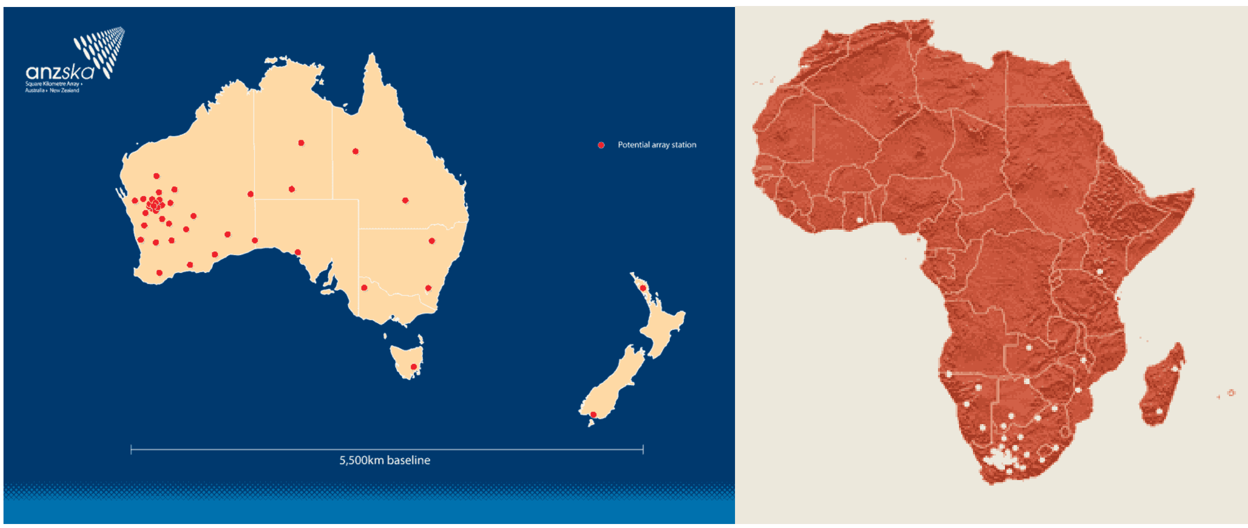


Figure VI: Overview of the overall SKA configuration. The SKA will have 3 central stations that one built of a core of 1 km and an inner region of 5 km in extent. The individual antenna stations are distributed along 5 spiral arms within a region of 180 km. Further stations will be distributed most likely along 3 spiral arms up to a distance of 3000 km from the core. The different configurations are needed to answer the differently motivated science questions, which need to detect weak and diffuse radio emission, but also allow for observations at high angular resolution. (Image credits: see page 136)

In order to achieve both high sensitivity and high-resolution images of the radio sky, the antennas of the SKA will be densely distributed in the central region of the array ("core" and "inner region") and then logarithmically positioned in groups along five spiral arms, such that each group becomes more widely spaced further away from the centre. This configuration will make up the SKA up to distances of several hundreds of kilometres in diametre (~ 200 km)[1]. Beyond this configuration a possible layout of 3 arms, also logarithmically spaced, is anticipated and will extend the SKA baselines up to several thousands of kilometres. Depending on the type of antennas the individual groups of the SKA will be made of either single dipoles or small arrays of dipoles, or single small telescopes. This setup allows a continuous frequency coverage from 70 MHz to 10 GHz. The SKA high frequency dishes will be either equipped with single pixel feeds or, at later stage in the project, with phased array feeds

[1]Note that in SKA_1 this configuration may only range from 50 to 100 km in diametre.

(PAF) to archive a larger FoV for this antenna type. For an overview of the configuration and the antennas types see the figures.

Combining the signals from a single antenna type creates a telescope with a collecting area of about one square kilometre. For example, in case of the high frequency array the SKA would require of the order of $\sim$6000 high frequency dishes each of 15 m in diametre to assemble a collecting area of 1 million m^2.

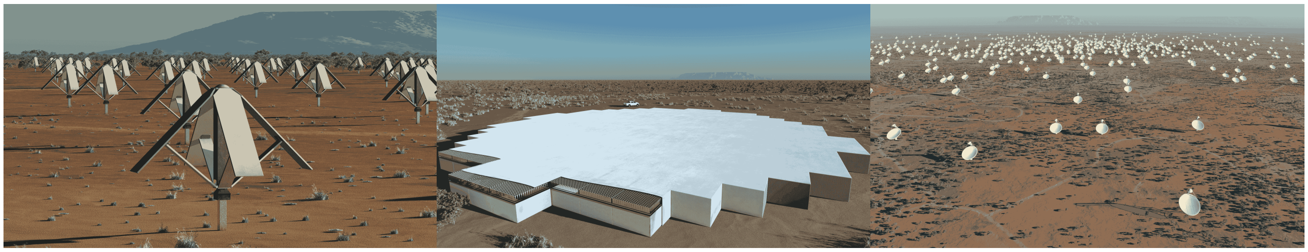


Figure VII: The three different antenna types ("radio wave receptors") of the SKA. From left to right: sparse aperture array (low: 70 – 500 MHz) used in SKA Phase 1 & 2 , dense aperture array (mid: 500 – 1000 MHz) used in SKA Phase 2 only, and high frequency dishes (high: 500 MHz – [3 GHz SKA_1] 10 GHz) used in SKA Phase 1 & 2. Note that the frequency ranges and in particular the edge frequencies of each band will vary in the design process. (Image credits: see page 136)

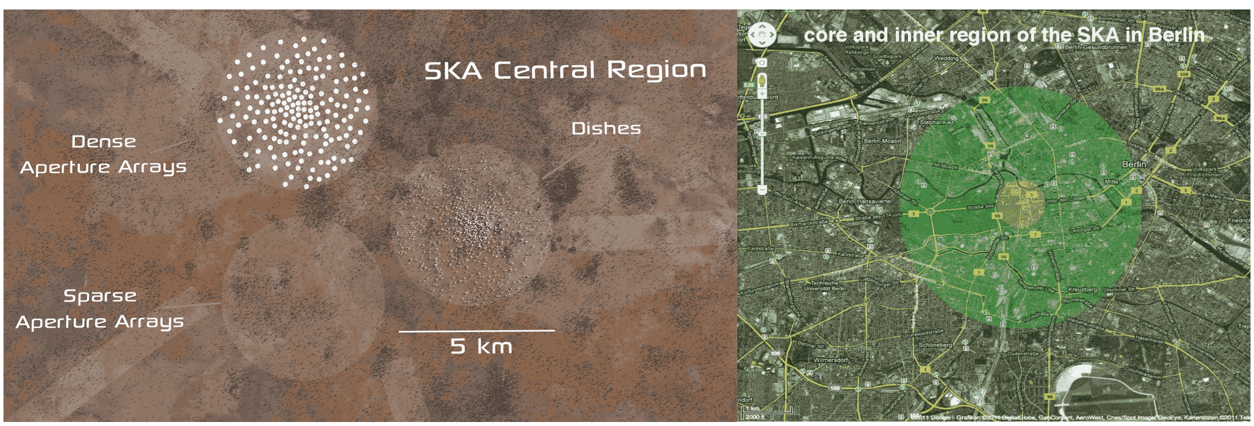


Figure VIII: Left: An example layout of the central region of the SKA. Each of the three central stations are made up of a "core" and an "inner region". The "core" and "inner region" distinguish themselves by different distributions of the antennas, a very dense region within 1 km making up the very sensitive core and a less dense distribution within 5 km. Right: An example of the size and extent of one SKA central station superimposed on Berlin. The station has been centred on the "Deutsche Bundestag" and would cover parts of Berlin Mitte (including the BMBF), Schöneberg, Kreuzberg, and Moabit. The orange region indicates the dense core with a diametre of 1 km, whereas the green area displays a region of 5 km. (Image credits: see page 136)

Realising the SKA telescope in two phases SKA_1 and SKA_2: The construction of a radio telescope with a collecting area approaching one million square metres across a wide frequency range is a major undertaking and is planned to be implemented in phases in order to ensure technical readiness and to spread and control the cost impact. Therefore, the SKA will be built in two distinct phases of which the SKA Phase 1 (SKA_1) is a scientific and technological subset of SKA Phase 2 (SKA_2), the full SKA. Of the three antenna types only the sparse aperture array and the dish array will be built in SKA_1. Each of these sub-arrays will make up 10 % of the full collecting area of the SKA.

In general, radio interferometers (aperture synthesis telescopes) have the advantage over other astronomical facilities (e.g. telescopes operating in the optical band solid mirror are needed) that they can be built out of blocks (e.g. single dishes or sub-arrays) and these building blocks can be integrated into a running system at any possible stage and physical position in the array. Such a setup will allow for an iterative process in which feedback loops ultimately trade performance and cost against science return. Furthermore, the science projects and the technical maturity of various components will guide the design process from SKA_1 to SKA_2 and allows significant progress toward the major science goals of the full SKA. Some key aspect to be defined for SKA_2 is the relative proportion of: dishes (with or without PAF), sparse aperture arrays, and the dense aperture arrays in the final system.

In this light, developments in the Advanced Instrumentation Program (AIP) will be continued into the pre-construction phase in order to develop and elaborate on the technical readiness of PAFs on dishes, ultra-wideband single pixel feeds on dishes, and the mid-frequency aperture arrays. This process may also lead to the construction of a stand-alone demonstrator in the pre-construction phase e.g. for the mid-aperture array, or opening up the opportunity for individual research groups to fund new systems on existing instrumentation relevant to the SKA. The conceptional and technical outcome of this verification programme will provide a good understanding of the system performance, in large volume manufacturing, in deployment and maintenance costs, and risk assessment in order to have mature and cost-effective components incorporated into the final SKA design. Therefore, the design of SKA_1 should also allow for the possibly including PAFs or ultra-wideband feeds, as modular sub-systems, on the SKA_1-dishes to enhance the science impact of SKA_1.

A prototype of a full system design is expected, once the overall SKA system design and costing exercise is completed at the end of 2012, prior to the detailed engineering design in the pre-construction phase (Garrett et al. 2010).

The SKA_1 timeline is planned as follows:

– telescope system design, prototyping and costing (2010 – 2012)

– detailed engineering design & pre-construction phase (2013 – 2015)

– SKA_1 construction, commissioning & early science observations (2016 – 2019)

– SKA_1 Advance Instrumentation Programme (AIP) decision (2016)

– SKA_1 full operation (2020)

It should be noted that the SKA_1 array already represents the essential radio component of a suite of "Origins" and "Fundamental Physics & Discovery" instruments now being planned or under construction, including facilities like ALMA, JWST, ELTs, SPICA, CTA LIGO, eLISA/NGO, LSST, Euclid/JDEM, CMBPOL, GAIA, KM3NeT and the LHC (running in CERN).

The dual-site implementation of the SKA telescope: In May 2012 the majority of the members of the SKA organisations were in favour of a dual-site implementation model which has been proposed by the Site Options Working Group (SOWG). The SOWG work shows that a scientifically justified and technically viable approach is possible, and concludes that in SKA_1, viable dual-site implementations exists that not only maintain, but add to, the scientific appeal of the first stage of the SKA. Taking this into account the SKA organisations agreed on the following dual-site implementation:

	Australia	South Africa
Phase 1	SKA_1 low frequency sparse aperture array SKA_1 mid frequency dish array with phased array feeds (PAF)	SKA_1 mid frequency dish array with single pixel feed
Phase 2	SKA_2 low frequency sparse aperture array	SKA_2 mid/high frequency dish array with single pixel feed SKA_2 mid frequency dense aperture array

For an overview on the various frequency ranges and telescope types see the Figure VII on the previous pages.

6.3 Cost estimation

This section briefly reviews the cost modelling effort in the SKA project. For a project such as the SKA, true costing will be influenced very strongly by political, economic, and commercial considerations. While every cost model attempts to include some aspects of commercial drivers (such as economies of scale), some of the uncertainties can be very large. Therefore, the main focus of the SPO's work during the pre-construction phase is to firmly establish the overall cost envelope, using the detailed input from specialists and potential suppliers. Finally, the SKA's advantage of being an interferometer allows one to essentially constrain the cost by building out the array to only such distances and collecting area, that are consistent with the initial cost estimates.
The first cost modelling methodologies are described in SKA memos[2] 92 and 93 and permit the analysis of the relative cost/performance of the realisations of the SKA system as design parameters are varied. The modelling engine has been developed in a high-level programming language (python) and aspects of system design and details of the cost model are implemented as modules of the costing engine. The modelling also includes a formal uncertainty analysis of these results. However, the results of course depend on the reliability of the input models and do not allow for wholesale changes in the underlying system design. Therefore the initial cost modelling provides a better guide to how costs scale using different technology routes rather than providing a full capital cost figure.

The logical structure of the costing of a specific system design is determined by summing the costs of components by following the signal path through the system. Appropriate cost models are adopted for components such as: – a cost performance model (e.g. cost as a function of dish diameter and surface accuracy), – a simple financial model (e.g. cost as a function of purchase date), – a model for expected performance as function of time (e.g. the cost per operation within computing hardware dropping with Moore's law), and – economies of scale. However a number of aspects were partially or not included at all in the early cost modelling. These include: non recurrent expenditure (e.g. development costs), infrastructure, project delivery, management costs, and operations. Importantly, these constraints mean that it is not possible to consider, for example, total cost of ownership when considering different technology options.

However the initial approach provides a very flexible, robust costing engine with excellent error/consistency checking, Monte Carlo modelling, facilitates cost reduction exercise, and "what if" analysis. The disadvantages are that the underlying cost modules are not easily accessible to the user and input from domain experts is more difficult to obtain and to incorporate. Based on the initial approach *a new cost modelling engine is currently in development*, that will provide cleaner access to different parts of the model by domain experts and designers. To further facilitate this, new interfaces are being developed that clearly separates the tools and the models. Furthermore, the new system will also be able to support many advanced realisations of the system design.

[2] The SKA Memo series is available via the SKA homepage and its www address can be found on page 135.

The underlying philosophy of the *new costing strategy* is that cost estimation will be an ongoing and iterative process throughout the design, the development and the construction stages of the SKA. The confidence levels attributed to cost estimates are predicated on both the maturity of the SKA design and the substantiating evidence in support of the cost estimate. Therefore, in the pre-construction phase confidence levels in cost estimations for SKA_1 will be high as the design matures to the point that formal invitation to tender documentation is prepared. Further work will be required to increase confidence levels in cost estimations for SKA_2. The work involved in estimating the project costs will include studies and comparison of costs against analogous systems as well as verification against precursors and pathfinders (e.g. MeerKAT, ASKAP, LOFAR). It will furthermore include, extraction of cost estimations from POs and industry and the analysis, assessment and administration of that data. As the project moves forward, cost estimates will be gathered at opportunities such as design- and project-reviews. These data will be integrated into the full SKA estimate with the aim to continuously refine the uncertainty in the cost estimate.

At the moment, the costing for SKA Phase 1 is being updated, since the engineering work is expected to generate input to the costing models within the preparatory- and pre-construction phase. In any case, the design of interferometers allows to break down the arrays into building blocks of individual receptors (e.g. dishes) and therefore reducing the cost by reducing the number of building blocks could be an option to fix a targeting cost. However this option will influence the sensitivity of the SKA_1 and, if required, needs to be evaluated with the scientific scope of SKA_1.

The capital cost of the SKA Phase 1 is fixed at 350 MEuro, including a significant element of contingency. The targeted cost of the full SKA Phase 2 system is estimate to 1.5 Billion Euro ("1.5 Milliarden Euro"), once there are good estimates of costs for all aspects of the SKA project a trade-off analyses will be done at all system levels ensuring a detailed cost calculation, including uncertainty estimates.

Risk Strategy and Risk Management: As an advanced technology project, the SKA faces many risks and uncertainties but also opportunities, the identification and the management of uncertainties and opportunities will have to be a focus within the project management scheme in order to fulfil the project goals.

Risk management is already an integral part of the management of the project in the "Preparatory Phase" and will continue to occupy a central position throughout the project lifecycle. Currently, the risk management programme is being established at all levels and within all domains of the project. It will be maintained and managed by the project managers and system engineers. As the SKA project progresses, the nature of the risks and the context and environment in which they will have to be managed will change, and therefore this risk management process will be reviewed and adapted on a regular basis. An overall and integrated risk register/database will be established and maintained and will be the central source of information on the status of risks and will be used for management as well as for internal and external communication purposes. The level and detail of these communications will vary and it will be the responsibility of "the office" management to ensure that the correct level of communication is achieved with relevant stakeholders. Regular risk focus events will be conducted such as: brainstorming sessions, risk assessment workshops, work sessions during technical design reviews, external review(s) of risk register/database, structured or semi-structured interviews with experts, using knowledge, expertise and experience of team, failure mode and effect analysis (FMEA), and fault tree analysis (FTA).

In combination with other aspects such as the management and engineering processes, this setup of risk management enhances visibility into the project activities, strengthens decision making and facilitates the project goals.

6.4 The SKA key science case

The expected science return of an observatory like the SKA will be overwhelming. To maximize it, the expected science needs to be captured and translated into science requirements/specifications. This has been achieved at different times in the life of the project (e.g. SKA Memo 3, 45, 83; the memo series can be found via the link provided in Section 14). The international community has developed a full ensemble of SKA experiments and a detailed and compelling science case for the SKA, as described in detail in New Astronomy Reviews, volume 48 (Carilli & Rawlings 2004).

Following an extensive period of consultation with the international community, the SKA science case has been built around five key science areas that are either unique to the SKA or where the SKA will provide the essential knowledge to answer them. Based on these topics five Key Science Projects (KSPs) have been identified, each of which contain unanswered questions in fundamental physics, astrophysics, or cosmology.

The following describes the major objectives of each of the KSPs. Additional targets may be found in e.g. the science case, the SKA Memo 100 and references therein.

Probing the dark ages will focus on the formation of the first structures/bodies at a time when the Universe made the transition from a largely neutral to its largely ionised state today.

> – Mapping out redshifted neutral hydrogen (H I) from the epoch of reionisation (EoR) –
>
> The SKA will use the emission of neutral hydrogen to trace the most distant objects in the Universe. The energy output from the first energetic stars and the jets launched near young black holes (e.g. in quasars) started to heat the neutral gas, forming bubbles of ionised gas as overall structure emerged. This is called the epoch of reionisation and it should be possible to map out the signatures of this exciting transition phase. The frequency range of the SKA will allow us to detect hydrogen up to redshifts of 20, and therfore enables us to trace the evolution of the EoR starting with the footprint of the transition up to a neutral to an ionized Universe, and hence provide a critical test of our present-day cosmological model.

Galaxy Evolution, Cosmology and Dark Energy will aim to probe the assembly, the distribution and the properties of the Universe's fundamental constituent, galaxies.

> – Dark energy via baryonic oscillations traced by the 3-d galaxy distribution in the Universe –
> – Galaxy evolution as a function of cosmic time (H I observations in emission and absorption) –
>
> The expansion of the Universe is currently accelerating. This phenomenon is not understood but described as the result of a mysterious "Dark Energy" that vastly dominates the energy content of the Universe. One important method of distinguishing between the various explanations for dark energy is to compare the distribution of galaxies at different epochs in the evolution of the Universe to the distribution of matter at the time when the cosmic microwave background (CMB) was formed. Small distortions in the distribution of matter, called baryon acoustic oscillations (BAO), should persist from the era of CMB formation until today. Tracking if and how these distortions change in size and spacing over cosmic time can then tell us if one of the existing models for dark energy is correct or if new theories are needed. For this purpose a deep all-sky survey is needed to detect hydrogen emission from Milky Way-like galaxies out to redshifts of about 1 and hydrogen emission and absorption from other galaxy types up to redshifts of 3 and beyond (redshift is equivalent to lock back time)[a]. Using a "1-billion galaxy survey" the SKA will "slice" the Universe into different redshift (time) intervals and hence will reveal a comprehensive picture of the Universe's history.
>
> The same data set will provide unique information about the evolution of galaxies, how the hydrogen gas was concentrated to form galaxies, how quickly it was transformed into stars, and how much gas galaxies from intergalactic space acquire during their lifetime.
>
> [a] The todays age of the Universe is $\sim$13.8 Giga-years (Gyrs) and observing galaxies at a redshift of unity allows to look back in time and investigate the Universe at an age of $\sim$5.9 Gyrs. At a redshift of 3 the Universe has an age of 2.1 Gyrs.

Strong Field Tests of Gravity aims to probe fundamental physics, challenge general relativity and the nature of space and time.

– Tests of theories of gravity via binary pulsars with neutron star and black hole companions –

– Detection of nano-Hertz gravitational radiation using pulsar timing arrays –

Pulsars are ideal probes for experiments in the strong gravitational fields around black holes. We expect that almost all pulsars in the Milky Way (those pointed towards Earth) will be detected with the SKA, while several 100s of bright pulsars will be detected in nearby galaxies. The SKA will search for and find radio pulsars orbiting black holes (stellar black holes as well as Sgr A*) that we can use to trace the extremely curved space with high precision, and hence enable us to probe the limits of General Relativity that would not be possible otherwise.
Regular high-precision observations with the SKA of a network of pulsars with periods of milliseconds opens the way to the detection of gravitational waves with wavelengths of many parsecs, as expected, for example, from two massive black holes orbiting each other with a period of a few years (resulting from galaxy mergers in the early Universe). When such a gravitational wave passes by the Earth, the nearby space-time changes slightly at a frequency of a few nHz (about 1 oscillation per $5-20$ years). This wave can be detected as apparent systematic delays and advances of the clock-like pulsar in particular directions relative to the wave propagation on the sky.

The Origin and Evolution of Cosmic Magnetism aims to understand how magnetic fields form, evolve over cosmic times, stabilise galaxies, influence the formation of stars and planets, and regulate stellar activity.

– The rotation measurement grid –

Synchrotron radiation and Faraday rotation have revealed magnetic fields in our Milky Way, nearby spiral galaxies, and in galaxy clusters, but little is known about magnetic fields in the intergalactic medium. Furthermore, the origin and evolution of magnetic fields is still unknown. The SKA will measure the Faraday rotation towards several tens of million polarised background sources (mostly quasars), allowing us to derive the magnetic field structures and strengths of the intervening objects, such as, the Milky Way, distant spiral galaxies, clusters of galaxies, and in intergalactic space. This will provide essential information to interprete the apparent source locations of high energy sources observed with particle detectors.

The Cradle of Life will investigate all aspects of astrobiology.

– Planet formation in proto-planetary disks –

The SKA will be able to probe the habitable segment of proto-planetary disks and to detect the thermal radio emission from centimetre-sized "pebbles", which are thought to be the first step in assembling Earth-like planets. The prebiotic chemistry - the formation of the molecular building blocks necessary for the creation of life - occurs in interstellar clouds long before that cloud collapses to form a new planetary system. Therefore observing prebiotic molecules as a probe for primordial Earth-like conditions and generating movies of planet growth and hence informing on our origins is in reach with the SKA.

In addition to the KSPs the **Exploration of the Unknown** is very much a theme that will be pursued by constructing the SKA as a multi-purpose observatory. If history is any example, the most exciting science done with the SKA may not come from answering the known science questions listed above, but by addressing new questions raised by unexpected discoveries enabled by a paradigm change of observations made possible with the SKA.

The large German interests in the SKA science scopes were established and recognised very early in the project and resulted in the leadership of SKA KSP programmes and key science topics. In addition to these research programmes, Chapter 8 provides a full record of the scientific interests of the German SKA community.

6.4.1 The major science goals for SKA Phase 1

The SKA will undergo a significant construction phase. While many aspects of the SKA Key Science projects require the capability of the full SKA, Phase 1 of the SKA will already provide a world-class facility that is unrivalled in its capabilities. For this reason and thanks to the modular nature of radio interferometers, important science topics that do not require the sensitivity, angular resolution nor frequency coverage of the full array have been identified as "headline science topics" for SKA_1. This ensures early breakthrough science in the project, but the truly transformational science return across all the Key Science projects will need the full capabilities of the SKA_2.

The following **headline science topics** which drive the technical specifications for the SKA Phase 1 have been identified:

– Understanding the history and role of neutral hydrogen in the Universe from the dark ages to the present-day.

– Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity (including General Relativity and quantum gravity), to detect gravitational waves from cosmological sources, and to determine the equation of state of super-dense matter.

In case of the **neutral hydrogen** (H I) the expected transition from SKA_1 to SKA_2 science is such that the SKA_1 will make the first statistical detection of the epoch of reionisation (EoR) and delineate the H I content in galaxies in the post-EoR Universe. The statistical measurements of the power spectra of galaxies between redshift $z = 7$ and $z = 0$ will rival, and potentially exceed that of other techniques, and it will provide the only measurements of large-scale structure in the dark ages ($z = 13$ to 20).

In the EoR and dark ages studies, the chief SKA_2 science driver will be to move from the limited resolutions and sky areas observable with SKA_1 to higher resolution (that needed to map ionised structures directly associated with quasars and star-forming galaxies) over a large fraction of the sky, requiring the significant ($\sim 10-100$) planned gains in mapping speed. This will provide a definitive, in parts cosmic-variance-limited, map of the EoR and "dark ages", just as WMAP has provided and Planck will soon provide for the CMB allowing for a battery of new cosmological tests.

In the post-EoR Universe, the main science driver will be to use the results of the advanced instrumentation programme (AIP) to, in going from SKA_1 to SKA_2, enhance the mapping speed of the $z \sim 2$ Universe by a factor $\sim 100-10\,000$ (depending on the adopted AIP technology). This will allow the "all-sky" and thresholded ($\sigma > 5$) "billion galaxy" surveys needed to address key questions such as neutrino mass, that is measurable to the lowest limit allowed by particle physics experiments at SKA_2 sensitivity, and sub-per-cent accuracy on the dark energy w parameter; both are provided by SKA_2 galaxy power spectra (in several independent redshift bins) achieving high signal-to-noise-ratio on features due to Baryon Acoustic Oscillations (BAO), and allowing marginalization over galaxy bias through accurate measurement of velocity-space distortions.

In the **pulsars** case, the main science driver for going from SKA_1 to SKA_2 is to achieve the full planned increase in sensitivity. For pulsar surveys, SKA_2 will then deliver the full census of $\sim 30\,000$ normal and ~ 3000 millisecond pulsars in our galaxy, with the concomitant increase in chances of finding the rare "holy grail" systems, and almost certainly the first known pulsar-black hole system. Such systems can be used to make definitive tests of the "Cosmic Censorship Conjecture" and the "No-Hair Theorem". In this context, the highest-frequency coverage of the SKA_2 is crucial to detect pulsars in the vicinity of the Galactic Centre and allows for precision timing of pulsars orbiting Sgr A*. Pulsar timing experiments will also probe the equation of state of nuclear matter at extreme densities. The increase in timing precision of SKA_2 over SKA_1 is the main science driver here because the sensitivity increase needs to allow timing (every $\sim 10-20$ days) of all the millisecond pulsars to the ~ 100 ns time-of-arrival precision needed for their use in a Pulsar Timing Array (PTA). The science that can be done with such as "SKA_2-PTA" can go far beyond detection of a cosmic background of gravitational waves (that should be already within reach of SKA_1): e.g. experiments to measure or constrain the spin and mass of the graviton; and, crucially, the ability to pinpoint individual gravitational wave sources, with this capability requiring astrometry to provide distances, and hence long (few-1000 km) SKA_2 baselines.

Appart from the major science goals, the SKA_1 offers the possibility for the **magnetism** KSP to directly image close-by galaxies and to piggy-back on the EoR surveys in order to map rotation measures from individual galaxies or our Milky Way at low spatial resolution. Whereas the additional sensitivity and resolution of SKA_2 (cf. SKA_1) will enable far denser grids of rotation measures to be observed, allowing higher spatial sampling of the magnetic field structure in both external galaxies and clusters of galaxies, as well as the Milky Way. In addition it will provide a sensitive probe of the small scale structure in the outflows of nearby giant radio galaxies, AGN and protostellar objects, as well as increasing sensitivity to magnetic structure in the high redshift Universe. These considerations are crucial not only for magnetism science but also for successful completion of other Key Science, such as constraining the EoR where accurate characterisation and correction of polarised foregrounds is key. In addition, the magnetic field KSP places high demands on the calibration and the polarisation performance of the full SKA such that it will impact on the other KSPs.

In the case of the **cradle of life** KSP the system specifications of the SKA Phase 1 offers only very limited science return. The main science driver of this KSP is to probe the terrestrial planet zones in the nearest circumstellar disks in order to map out the distribution of complex organic and potentially biological molecules. Therefore this KSP requires the largest frequency coverage (potentially up to 25 GHz) and the highest sensitivity capabilities of the SKA. This enables us to detect the molecules and together with the best possible angular resolution, on (sub-)milliarcsec scale (which requires dishes separated by a few thousand of kilometres), enables us to probe the terrestrial planet zones in the nearest circumstellar disks in order to generate movies of planet growth and hence provide information about our origins.

7 German involvement in technical and scientific pathfinder programmes of the SKA

In the different phases of the SKA project various organisations have been or are currently involved in precursor and organisation studies such as SKADS, PrepSKA, GO-SKA and in pathfinder telescope projects like LOFAR, ASKAP, or MeerKAT in order to investigate many of the technical design issues underlying the SKA system design, and to develop some of the science themes and techniques necessary for the SKA. In addition, the SKA-relevant design greatly benefits from the knowledge that is generated by the newly upgraded facilities like the JVLA, eMERLIN, and eEVN.

Here a basic overview of these SKA studies and the pathfinder telescopes with German involvement is given.

7.1 SKA pathfinder programmes

7.1.1 The SKA design study (SKADS)

SKADS was an EC funded design study for the SKA running from 2005 nominally for 4 years, which was completed at the end of 2009. SKADS received EC-FP6 10.4 MEuro funding with national matching such that was brought to a total of $\sim$38 MEuro. Participation included many European countries: The Netherlands, United Kingdom, Germany, France and Italy, plus contributions from Australia, South Africa and Canada.

SKADS covered multiple aspects of SKA research and design including science simulations, configuration, communications, and costing plus technical development and technology road mapping to implement mid-frequency phased aperture arrays. The scientific outcomes of SKADS are 43 scientific memos and an internationally well-recognised simulation of the radio Universe (SKA Simulated Skies S^3). This is a set of computer simulations of the radio and (sub)millimeter Universe primarily dedicated to the preparation of the SKA and its pathfinders. The physical outcome of SKADS was the construction and testing of three demonstrators: 1- EMBRACE – a 144 m^2 aperture array with RF beam-forming; 2- 2-PAD – a 9 m^2 entirely digital aperture array tile; and 3- BEST – a focal line installation on the Northern Cross radio telescope in Italy (Medicina). The results from SKADS have been highly influential for the SKA and are discussed in parts in the mid-term SKADS science conference proceedings (Klöckner et al. 2006), in detail in the final conference proceedings (Torchinsky et al. 2009) and in the "SKADS white paper" (Faulkner et al. 2010).

In summary, SKADS was very successful at taking advanced engineering concepts and reviewing potential implementations of the SKA to maximise the scientific output. SKADS also formed a major collaboration between many countries and institutions, which is continuing in the PrepSKA phase of the project. The principal conclusion of SKADS is that an SKA implementation based on aperture arrays operating from 70 MHz to 1.4 GHz observing frequency, with dish based receivers above 1 GHz is achievable, affordable and a highly desirable solution in the SKA timeframe.

7.1.2 Preparatory phase proposal for the SKA (PrepSKA)

PrepSKA is a consortium that consists of 24 partners from around the world including Germany and acts as a coordinating body for much of the technical and policy work currently underway for the SKA. It is a 35 MEuro programme running from 2008 to possibly the end of 2012, that has been funded by the EC with 5.5 MEuro.

There are several issues that need to be addressed before construction of the SKA can start, these are: design, location, legal framework and governance, procurement and funding. This preparatory study for the SKA is designed to address all these points. Furthermore, PrepSKA is coordinating and integrating worldwide R&D work to develop the costed design for Phase 1 of the SKA (SKA_1). The main deliverable will be an implementation plan forming the basis of a funding proposal to governments to start construction. The principal objectives of PrepSKA are:

1) to produce a deployment plan for the full SKA, and a detailed costed system design for Phase 1 of the SKA. The technical development work is being carried out in Work Packages that are informed by the SKA Precursor and Pathfinder projects and the Design Studies;
2) to further characterise the two candidate SKA sites in Southern Africa and Australia and to analyse the various risks associated with locating the SKA at each of the sites;
3) to develop options for viable models of governance and the legal framework for the SKA during its construction and operational phases;
4) to develop options for how the SKA should approach procurement and how it should involve industry in such a global project;
5) to investigate all aspects of the financial model required to ensure the construction, operation and, ultimately, the decommissioning of the SKA;
6) to demonstrate the impact of the SKA on society, the economy and knowledge.
7) to integrate all of the activities, reports and outputs of the various working groups to form an SKA implementation plan.

7.1.3 Global organisation for the SKA (GO-SKA)

The global project organisation for the SKA is a coordination action funded by the European Commission and designed as a follow-up of PrepSKA whose aim was to formulate an implementation plan that forms the basis of a funding proposal to governments to start the construction of the SKA. The decisions and the ensuing developments will have a significant impact on the organisation of the SKA project and raise new topics to be investigated, in order to narrow down and implement the governance, funding and procurement options delivered by the PrepSKA policy work packages. The purpose of GO-SKA is to investigate and provide guidance at policy-level to the SKA Organisation, so that it will be optimally prepared for the construction and operation of the SKA in 2016. The project period is from 2011 to the end of 2014 and has a total cost of 1.2 MEuro, the EU will contribute 0.9 MEuro. Whereas PrepSKA has assembled the best options for the SKA, GO-SKA will focus on the further development and implementation during the next stage of the SKA Project. The principal objectives of GO-SKA will be:
to broaden and strengthen the involvement of funding agencies and governments around the globe;
to establish world-wide partnerships between industry and the SKA;
to prepare the establishment of global governance for the SKA organisation;
to develop strategies to further define the conditions by which non-scientific benefits from large-scale research infrastructures can best be integrated into investment decision-making.

Germany is partner in this project via the MPIfR as the leader of work package 5: "Developing SKA as a tool to address global challenges". Their main responsibility is to identify global challenges and main innovation drivers of the SKA that have a direct impact on society and socio-economic structures. In order to reach this goal a strategic forum is going to be build and established.

7.2 SKA pathfinder telescopes

7.2.1 e-MERLIN (UK)

e-MERLIN is a cm-wavelength telescope array, spanning 217 km baselines connected by a new dark fibre network. It was the first full-time array to be connected at 10 Gb/sec using a combination of specially installed fibre cable (90 km in total) and trunk dark fibre (600 km in total) leased from a number of providers. SKA pathfinding activity includes: 1) Low-cost techniques of cable installation and the experience of procuring, managing and maintaining this dark fibre network are valuable for the SKA. The data transmission equipment follows the JVLA/ALMA design (in which Manchester/e-MERLIN staff participated), but e-MERLIN has extended this approach to more than ten times the maximum link used in these arrays, by using multiple amplification/regeneration sites. e-MERLIN will provide useful experience in operating this type of link over these distances. 2) As part of the SKADS project e-MERLIN has been used to demonstrate optical phase transfer links over >100 km and with multiple hops, allowing this approach to be extended to hundreds of km, if required. The system is based on an optical implementation of the pulsed ~ 1 GHz band link system designed for MERLIN, over the installed e-MERLIN optical fibre network. 3) e-MERLIN science tested for the SKA in the high-resolution study of the SKA populations using gravitational lensing and in the high-resolution follow-up of radio transients.

German scientists are involved in the commissioning and the legacy proposal programme of e-MERLIN.

7.2.2 e-European VLBI network (eEVN)

The EVN is a consortium of institutes operating an interferometric network of radio telescopes on a global scale from Europe to China to Puerto Rico and South Africa. The eEVN is a development programme to transfer data in real-time from the remote EVN telescopes to the central processing facility via optical fibre cables to replace the "traditional" implementations of VLBI in which the data are first recorded at the telescopes on magnetic media (tapes or discs) and then physically delivered to the processor. Over the last four years, fibre links have been established to most of the EVN telescopes. Data rates achieved currently are 1 Gbits/sec per VLBI station, but the expectation is that this will increase to 16 Gbits/sec/station. Its SKA knowledge transfer will be: 1) The eEVN will serve as a test-bed for the SKA for long distance signal transmission across national boundaries. 2) eEVN science pathfinder for the SKA in separating AGN and starburst emission in distant sources and obtaining ultra-high-resolution follow-up of radio transients.

The Effelsberg telescope in Germany is the biggest telescope in Europe and German scientists and engineers have played a major role in the development of the eEVN array.

7.2.3 Karl G. Jansky Very Large Array (JVLA)

The JVLA is a 27-element array of 25-m diameter dishes located in Socorro, New Mexico. Technical areas of interest to the SKA are: High-rate data transmission (120 Gbits/s from each of 27 antennas) over an internally installed and maintained fibre network. SKA pathfinding activity includes: 1) 2:1 bandwidth receivers with low system noise temperatures and high polarisation purity; 2) RFI-tight designs and detailed radio frequency interference (RFI)-testing protocols to prevent self-interference that can limit the dynamic range of a large array; 3) Data archiving and default image production in real-time or near-real-time; 4) Wide field-of-view imaging by means of new imaging algorithms that involves parallel processing; 5) Remote operations, including dynamic scheduling of the array in short scheduling blocks (an hour and shorter) to take optimal advantage of atmospheric conditions; 6) JVLA science pathfinding for SKA includes the first surveys for galaxies in the EoR via low CO transitions and studies of cosmic magnetism.

German scientist make frequent use of the JVLA which was discussed in the section "German SKA community" and are principle investigators of large surveys such as THINGS (http://www.mpia-hd.mpg.de/THINGS/) or COSMOS (http://www.mpia-hd.mpg.de/COSMOS/).

7.2.4 Aperture tile in focus (APERTIF)

The "APERture Tile In Focus" system (APERTIF) is a Phased Array Feed (PAF) that is being developed for the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands to increase its survey speed by a factor ~ 20. APERTIF will operate in the frequency range from 1000 to 1750 MHz, with an instantaneous bandwidth of 300 MHz, a system temperature of 55 K and an aperture efficiency of 75 %. The goal is to generate 37 beams on the sky for an effective field of view of 8 square degrees. The current horn feeds have a 30 K system temperature, 55 % aperture efficiency and 160 MHz bandwidth. The PAF will reduce the sensitivity of a single beam observation compared to the current horn feeds, but in terms of survey speed this is more than compensated by the 37 times larger field of view. Each PAF consists of a dual polarised antenna arrays of 121 tapered slot elements with Low Noise Amplifiers and a Uniboard-based digital beamformer. The APERTIF correlator may be based on Uniboard technology. APERTIF is an important SKA pathfinder in the following ways: 1) Demonstrating the capabilities for PAF technology on an existing, well-characterized telescope array; 2) Measurements with the first APERTIF prototypes (called DIGESTIF) already demonstrate the unique capabilities of PAFs in practice: wide field of view (scan range), low system temperature, excellent illumination efficiency, synthesis imaging and a significant reduction of the reflector-feed interaction; 3) APERTIF provides a clear performance and cost benchmark for PAF technology. 4) APERTIF science will include medium-deep H I surveys aimed at measuring evolution in the number density and cosmological bias of the H I population.

German scientists are involved in the Expression of Interest (EoI) programme of the APERTIF-WSRT project. Furthermore, MPA and ASTRON scientists have now teamed up to carry out the "WSRT Bluedisk project" which can be regarded as a pilot study for upcoming APERTIF surveys.

7.2.5 Australian SKA pathfinder (ASKAP)

ASKAP the Australian SKA Pathfinder is a CSIRO project being built at the Murchison Radio-astronomy Observatory (MRO), Australia's SKA location. It is a facility to trial wide-field-of-view high-dynamic-range technologies for the SKA, deliver cutting edge science, and develop the MRO as a world-class observatory. ASKAP will be operational by mid-2013, while early hardware is already available to test technology and science since 2011. Many of the technical developmental aspects to be addressed in the SKA design are included in the ASKAP design: 1) The inexpensive sky-mount telescopes represent one possible configuration and allow one to directly measure the effects of parallactic rotation of the image. Aspects of cooling and other environmental effects are being investigated; 2) The phased array feed (PAF) represents one possible implementation for the SKA. ASKAP provides a platform to trial PAFs in an array configuration, and the group is working with other teams around the world to jointly develop the best PAF for science; 3) Given the vast amounts of data to be transported, ASKAP signal transport and network developments are directly relevant to the SKA. ASKAP is looking at a variety of signals over optical fibre as well as networking protocols. 4) The ASKAP digital system represents architectures and developments directly related to the SKA. Digital hardware studies to scale the beamformer for SKA cost and energy goals will be pursued, as well as correlator architectures for the SKA; 5) ASKAP software, calibration, imaging and temporal solutions will have direct relevance to the SKA. Scaling studies to the SKA are also being pursued; 6) Power and communication solutions appropriate for the SKA are being investigated and implemented; 7) System engineering, life-cycle studies, operations planning, logistics engineering management plan and cost models are all being developed and evaluated; 8) ASKAP will deliver cutting edge science to inform the SKA science case and development. Examples: large sky area, low-redshift H I surveys to measure the galaxy power spectra and hence cosmological biases of the galaxy populations; large sky area continuum surveys to trace the evolution of black holes to high redshift, and star-forming galaxies to moderate redshift. The "Science Survey Team" process instituted by CSIRO has been an effective way to involve the broader international community effectively at an earlier stage.

German scientists are involved in science simulations and the planned legacy programmes of the ASKAP project.

7.2.6 MeerKAT

MeerKAT will be built in South Africa and is an array of 60 13.5-metre offset-feed dishes with single pixel wideband feeds, and is therefore closely related to a major component of the SKA baseline design.

Technologies being developed and used for MeerKAT that have direct relevance to the SKA include: 1) One-piece moulded reflectors fabricated using composite materials. Costing and performance information resulting from the design, construction and operation of these composite dishes will be made available to the international project; 2) Electromagnetic modeling of feed and dish optics. Simulations of the MeerKAT feed and dish optics aimed at optimising Ae/Tsys and sidelobe characteristics will be made available to the international project; 3) High fidelity single pixel octave bandwidth digital receivers.

The specific components and technologies relevant to the SKA include: novel feed horns, OMTs and LNA coupling, low cost, low maintenance and high reliability cryogenic systems based on Stirling cycle refrigerators, integrated RF chain systems, wide bandwidth ADCs, temperature stabilization, and RFI shielding. Packet-switched architectures for radio astronomy signal processing applications.

MeerKAT will test the scalability of the CASPER packet-switched architectures for digital signal processing applications for radio astronomy. 4) Calibration, imaging and time-domain processing. 5) System Engineering: life-cycle studies, operations planning, logistics engineering management plan and cost models. 6) MeerKAT will deliver science on the pathway to the SKA. Examples are: deep H I surveys to establish the cosmological evolution in H I to redshift $z \sim 1.4$ and, potentially piggybacked, a deep continuum survey to reach (with stacking) the populations likely to dominate SKA surveys; pulsar timing for fundamental physics as precursor to SKA pulsar KSP. The call for large proposals issued by SKA South Africa has motivated early involvement by a broad international community.

German scientists are involved in early science proposals and the legacy proposal programmes of the MeerKat project, including a PI-ships for selected key science projects. In addition, German scientists are leading a pilot project on the MeerKAT precursor telescope KAT–7.

7.3 Low frequency array [LOFAR] [M. Hoeft]

LOFAR is the newest European radio telescope being constructed by ASTRON in the Netherlands. It is a low-frequency aperture array operating at two largely unexplored frequency bands: 15 − 80 MHz and 110 − 240 MHz. LOFAR leads the way for a new generation of radio telescopes, like the SKA. It will consist of about fifty antenna fields each comprising a multitude of small and cheap antennas without moving parts. The signal of all antennas is digitally processed and combined at each field. Resulting data are send via fast links to a supercomputer in Groningen (NL). Since the data processing is fully implemented in software, LOFAR is an extremely flexible instrument. For instance LOFAR can be operated as interferometer with a large field of view but it is also used to detect cosmic rays.
LOFAR will consist of at least of 40 stations in the Netherlands, 6 stations in Germany, and one station in each of United Kingdom, France and Sweden. More international LOFAR stations are planned in the UK, Poland, Italy and Ukraine. The first German station was completed in 2009 next to the 100-m Effelsberg radio telescope, the second in Tautenburg (Thüringen) was completed later that year, the third German stations near Garching (Unterweilenbach) in 2010, the fourth and fifth stations in Bornim near Potsdam and in Jülich in 2011. The sixth station is planned near Hamburg.
The large collecting area (about 0.1 square kilometre) and the variety of operating modes is reflected by the diversity of the six "Key Science Projects", which drive the design of the hardware and the software of LOFAR:

– The epoch of reionisation
– Extragalactic surveys
– Transient radio phenomena and pulsars
– High energy cosmic rays
– Cosmic magnetism (German leadership; http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html)
– Solar physics and space weather (German leadership; http://www.aip.de/groups/osra/sksp/)

Thus far almost forty stations have been built and validated in the Netherlands, five in Germany, and one each in the UK and France. LOFAR operates in a largely unexplored frequency regime, it has a very large field of view, the operation needs to extremely flexible to account for transient phenomena, and it produces tremendous amounts of "raw" data after correlation. Hence, LOFAR needs newly software tools new strategies for calibration. Currently, the hardware and software are being commissioned. First scientific results verify the high quality of the data obtained with LOFAR.

The German LOFAR activities (www.lofar.de) are organised and coordinated by the GLOW consortium, which is described in Chapter 5.

7.3.1 LOFAR – long baselines [O. Wucknitz]

Long baselines of low-frequency arrays pose particular calibration challenges. Beyond baseline length of approximately 30 km, the stations probe independent patches of the ionosphere, which introduces considerable phase fluctuations that have to be accounted for. At the same time the signal is reduced on long baselines, because most sources (targets and calibrators) start to be resolved.

LOFAR will have 11 "international stations" outside of the Netherlands, with baselines up 1000 km and more. The flux density detected on international baselines is typically at least an order of magnitude lower compared to short baselines. Together with the rapid phase fluctuations (in time and frequency), this implies that more sophisticated calibration schemes have to be applied. Even standard fringe-fitting techniques developed for VLBI are not sufficient for LOFAR because of the large dispersion in the ionosphere and the strong differential Faraday rotation between stations.

The development of the long baselines for LOFAR is organised by the Long Baseline Group at the AIfA, University of Bonn. Preliminary simplified methods are currently used to analyse commissioning data and produce the first science results on long baselines. As of autumn 2011, long-baseline results have exclusively originated from these efforts. The implementation of long-baseline calibration methods as part of the general pipeline will be pursued by the same team together with a postdoc/developer appointed at AIfA.

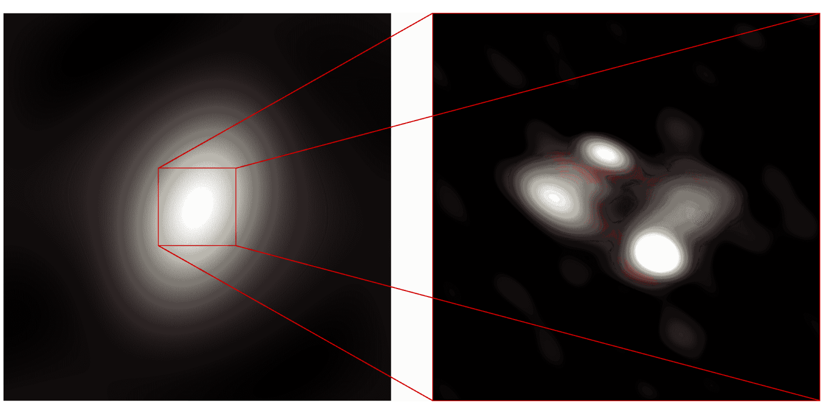


Figure $1_{\rm Wu}$: LOFAR image of the extragalactic source 3C 196 showing the radio emission at 30 – 80 MHz. Left: Radio emission of 3C 196 using only the stations in the Netherlands (35 x 22 arcsec angular resolution). Right: Radio emission of 3C 196 including all Dutch and international stations (1.5 x 0.9 arcsec angular resolution).

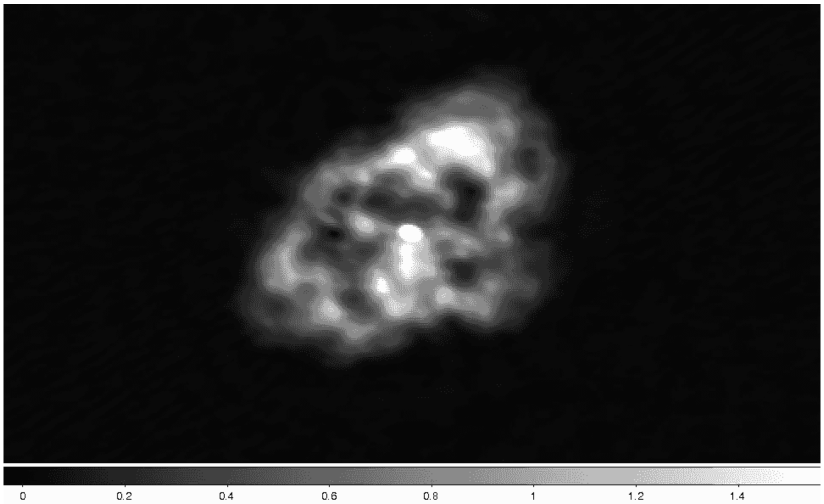


Figure 2_{Wu}: The first LOFAR image of the Crab Nebula, the calibration only made possible by the international baselines.

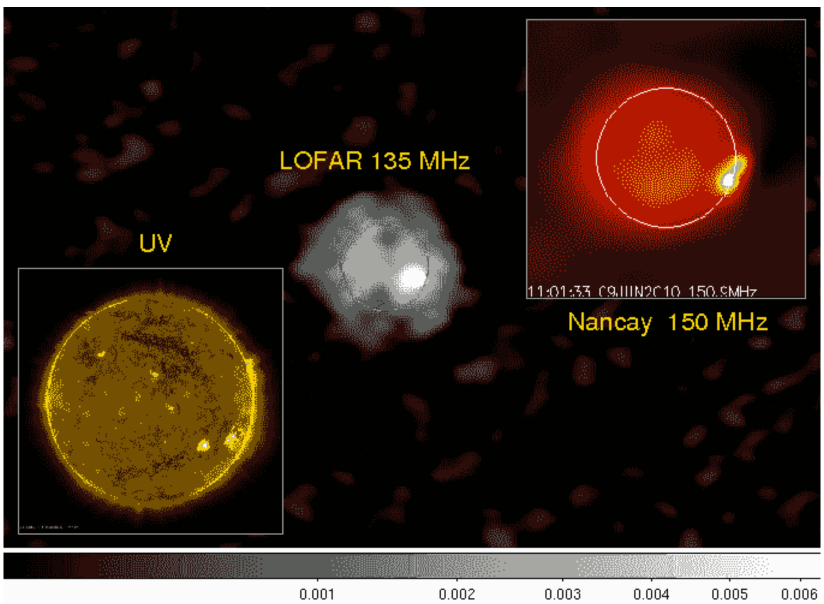


Figure 3_{Wu}: The first LOFAR images at 135 MHz of the Sun, compared to radio observations at 150 MHz (Nançay, France) and an ultra-violet image of the Sun.

8 The German astrophysical science interests

The SKA will be one of the fundamental pillars in the exploration of the Universe. With its enormous collecting area, that will be around $10-100$ times more sensitive than todays largest single dish telescope, and with its survey speed, allowing to survey the sky a million times faster than what is possible today, the SKA will significantly impact on current science programmes and offer opportunities in exploring new science scopes. To gather the German community and to guarantee that their scientific interests are well represented on a national and international level, a call for contributions was initiated in autumn 2011 and a splinter session was organised at the AG Tagung in Heidelberg 2011 ("A fresh view of the radio sky: science with LOFAR, SKA, and its pathfinders").

In order to allow for an unbiased approach to the science potential of the SKA no particular guidelines have been given and therefore the nature of these contributions are widely spread, ranging from general overviews of specific science areas of interest, to direct observing experiments, up to descriptions of new concepts of future scientific and technology studies.

8.1 Cosmology

8.1.1 Cosmology with the SKA [D.J. Schwarz]

Introduction: The SKA will allow us to study the Universes inventory of neutral hydrogen (H I) and trace its evolution from the dark ages (long before the very first stars and galaxies light the sky) to the present ages. In doing so, the SKA will put cosmology on more fundamental grounds. Since the turn of the millennium we speak about precision cosmology, but so far that term is only justified for the observations of the spectrum and the intensity anisotropies of the cosmic microwave background (CMB) radiation. The SKA will bring the study of large-scale structures in the Universe to the realm of precision cosmology.
Hydrogen is the most common atom in the Universe. The SKA will map the 21 cm emission from neutral hydrogen throughout the visible and dark Universe and is therefore able to trace atomic matter in the most remote places of the Universe. This is due to

- a large sky coverage (approximately $2\,\pi$)
- a deep sky coverage (H I clouds shall be observed out to redshifts of 20 to 30)
- a broad frequency coverage (70 MHz to 25 GHz)

The SKA will allow us to probe cosmic H I in two ways. It will map the H I density field (non-thresholded SKA), similar to how we map the CMB temperature anisotropies. But in contrast to the CMB, the SKA will resolve the H I density field in three dimensions (two angles and a redshift). This is most suited for studying the dark ages of the Universe when most of the ordinary matter in the Universe is neutral hydrogen.
Alternatively we might use SKA observations to generate an H I galaxy redshift survey (thresholded SKA). This second possibility is well suited for the visible Universe at redshifts below 6, as counting point sources is less sensitive to foreground and RFI issues. The SKA is likely to be the first telescope that will be able to map H I intensities at redshifts > 6 and will be the first radio telescope to produce a huge galaxy redshift survey.
Besides observing the H I inventory, the SKA will also be well suited for an exquisite continuum radio survey.
Before highlighting some of the cosmological issues attacked by the SKA, let us shortly review the status of modern cosmology.

Status of modern cosmology and the role of the SKA: Modern cosmology rests upon the cosmological principle, which states that the Universe is isotropic and homogeneous at the largest scales. A further key assumption is the validity of Einsteins theory of general relativity. Both assumptions will be tested by the SKA.
The observed isotropy of the cosmic microwave background (CMB) radiation at a temperature of 2.7 K, the relic radiation from the epoch of the formation of the first atoms in the Universe, holds in 1 part in 1000. If we account the observed dipolar temperature anisotropy (3 mK) to the proper motion of the Local Group and remove some

foreground emission of the Milky Way, isotropy holds to in 1 part in 100 000. The remaining tiny temperature anisotropies (of order 10 μK) are believed to be due to quantum fluctuations generated during an early epoch of cosmological inflation and have been studied by several ground, balloon borne and space CMB missions (among them COBE, Toco, Boomerang, Maxima, WMAP, ACT, SPT and Planck).

The analysis of the CMB allows us to measure the curvature of space and to model the matter and energy content of the Universe (Komatsu et al. 2011). It turns out that the Universe is spatially flat, in agreement with the prediction from cosmological inflation, but surprisingly it turns out that we are missing most of the Universes matter and energy density in our labs. Only 4 % of the Universe seems to be made out of atomic matter, up to one per cent might be contributed by neutrinos the most elusive particles known by particle physics so far. The vast amount in the universal energy budget seems to stem from a cosmological constant or a component called dark energy (70 %) and about 25 % are attributed to dark matter. The presence of dark energy originally has been inferred from the observation of supernovae of type Ia at redshifts up to order unity. These supernovae are standardizeable candles and can be used to measure the acceleration and rate of the expansion of the Universe.

The search for dark matter and dark energy is one of the most urgent problems in modern physics and cosmology. The SKA will contribute to this search by further constraining the properties of dark energy and dark matter. Sections 8.1.2, 8.2.5, and 8.2.6 describe further aspects of the contribution of the SKA to the solution of the dark energy puzzle and Section 8.5.1 elaborates on the identification of dark matter.

The tiny temperature anisotropies in the CMB reflect density fluctuations, which seed the formation of the large-scale structure of the Universe. Due to the action of gravity these tiny fluctuations grow and eventually collapse to from gravitationally bound structures like sheets, filaments and clusters of galaxies, in between them void regions of enormous extend (of the order of 100 Mpc). The study of large-scale structure has so far be driven by optical galaxy redshift surveys, pioneered by the CfA slices, more recently by the 2dF (two degree field) galaxy redshift survey, the Sloan Digital Sky Survey (SDSS), WiggleZ, and is currently continued by BOSS. A large number of surveys is in preparation, many of them ground based, such as 4MOST, LSST, HETDEX, Pan-Starrs, or DES, others space based such as Euclid. All of them in the optical or near-infrared. In the radio, several SKA pathfinder telescopes are preparing continuum radio surveys (e.g. LOFAR MSSS, LOFAR Tier1, WODAN, EDU; Raccanelli et al. 2011).

Galaxy redshift surveys so far allowed us to measure the power spectrum of the galaxy distribution and to identify the scale of the baryon acoustic oscillations (BAO) a relic of the plasma oscillations in the primordially hot Universe. Tracing the power spectrum as a function of the redshift (or even better as a function of time) would allow us to directly measure the growth of structure and use that to constrain the properties of dark matter and neutrinos, as well as dark energy and would allow us to test the action of gravity. Identification of the BAO as a function of redshift (or time) allows us to measure the geometry and expansion history of the Universe. The H I galaxy surveys that Apertif, Meerkat, and ASKAP are going to provide will give us a first glimp (Camera et al. 2012) on the possibilities the SKA will offer. Sections 8.1.3 and 8.1.4 illuminate in several aspects of the study of large-scale structure.

A prediction of cosmological inflation is the Gaussian distribution of primordial density fluctuations. Tiny departures from Gaussianity are expected from the non-linear growth of structures and from models of cosmological inflation that involve several dynamical degrees of freedom and/or depart significantly form the slow-roll regime. A survey covering cosmologically large volumes is able to test both aspects (see Section 8.5.2 for more details).

Modern cosmology is based on exquisite observations of the CMB, which provide information from redshifts of order 1000, large-scale structure surveys, SN and cluster studies, providing information on redshifts up to order unity so far. There are pieces of information form deep surveys and quasar surveys out to redshifts of about 6, but we miss information from the Universe at redshifts > 6. This is due to the fact that, according to our current model, there was almost no visible light at those redshifts.

We know from the so-called Gunn-Peterson test that the present Universe is ionized out to redshifts of about 6. However the small optical depth of the CMB tells us that this cannot hold true up to a redshift of 1000 and we believe that the Universe was in fact filled with neutral hydrogen between a redshift of 1000 and somewhere between 15 to 30. This epoch is the so-called dark age of the Universe. An instrument that can map H I at high redshifts is what is needed to reveal to origin of stars, galaxies etc. We expect that the very first stars and galaxies produce UV light that eventually reionizes the Universe by a redshift around 10. However, there might also be other mechanisms of reionization like the injection of energy by annihilation or dark matter particles or by the decay of metastable particles (Natarajan & Schwarz 2009). These and more aspects concerning the dark ages and the epoch of reionisation (EoR) are elaborated in Section 8.1.6.

Returning to the cosmological principle, the second part of it, homogeneity, is not tested very well. One of the key challenges of observational cosmology is to devise means to test it. The problem is, that the most naive method to directly test homogeneity, would be to observe the Universe from another place, which is not possible at all. Thus we have to rely on information from other places in the Universe that sample a past light cone different from ours. The observation of local temperatures at other places offers such a possibility. The spin temperature observable via the 21 cm brightness allows us to think about such a test. Alternatively also molecular lines can be used, to measure the CMB temperature at other places in the Universe.

High-fidelity observations of the CMB have revealed several anomalies at the largest angular scales (Bennett et al. 2011, Copi et al. 2011). Among them a lack of angular correlation on scales larger 60 degrees, compared to the prediction of inflationary cosmology. Such a lack of power might point towards a non-trivial topology of the Universe or to short epoch of inflation, such that we are able to actually observe the pre-inflationary Universe at the largest scales. The SKA will be able to further investigate the physics of these anomalies and confirm or rule out the primordial origin of these anomalies.

A new class of fundamental test will be come possible by means of the superb frequency resolution of the SKA, which will allow us to directly see the expansion of the Universe based in the redshift drift of individual objects. Thus the SKA will be able to do real time cosmology, as described in more detail in Section 8.1.7.

Continuum radio surveys at SKA: We still know surprisingly little about the vicinity of the Local Group. A badly understood issue is the motion of the Local Group with respect to the CMB. A dipole component in the CMB is commonly interpreted as the Doppler effect due to the motion of the Local Group through the Universe at a speed of 600 $\mathrm{km\,s^{-1}}$. This hypothesis cannot be tested by CMB observations, the only way to test it, is to confirm it via another background which is supposedly at rest w.r.t. the CMB. The background of radio galaxies out to a redshift of order 1 would be such a reference frame (Blake & Wall 2002, Crawford 2009).

For this analysis a sample of about a billion point sources from a continuum SKA survey over all of the observable sky could bin down the dipole component at an accuracy matching the CMB dipole. As redshift information is not necessary for this test, this measurement could already be completed by the SKA_1.

Number counts and measurements of the angular auto-correlation will allow us to constrain cosmological parameters, but will be less powerful than the thersholded H I survey (see below). A useful and powerful probe will be the cross-correlation of a continuum survey with Planck's CMB maps enabling us to probe dark energy and modified gravity via the integrated Sachs-Wolfe effect (Raccanelli et al. 2011). We expect that errors on the dark energy equation of state and modified gravity parameters can be constrained at the few per cent level with an exquisite control of systematic errors, due to the broad frequency coverage of the SKA.

Flux limited H I radio surveys at SKA (thresholded SKA): The H I point source power spectrum at several redshift shells could directly reveal the onset of cosmic acceleration from the study of the growth rate of large-scale structures and constrain our models of dark energy. The measurement of the BAO scale with an unseen accuracy will allow us to measure the geometry and the expansion rate of the Universe. A combination of SKA results and CMB results from Planck is expected to constrain all cosmological parameters of the concordance model and a few new ones (such as the dark energy equation of state) at well below the per cent level. This will enable us to confirm or rule out the cosmological constant with high confidence. However, the full power of the SKA will only be obtained with SKA_2.

Beyond the two-point correlation function, the SKA is ideal to search for huge structures like voids of order 100 Mpc and more, that could be the reason for several anomalous cold spots observed by WMAP (Bennett et al. 2011) and look for counterparts of the SDSS Great Wall, a 400 Mpc long structure that fills about a third of the volume of the SDSS. As structures that large have been a surprise and have not been predicted by the concordance model of cosmology, it is important to find out how frequent they are in the Universe.

H I intensity mapping with the SKA (non-thresholded SKA): In order to study the intergalactic medium in the late Universe, the epoch of reionisation and the dark ages of the Universe, a three dimensional intensity mapping of the 21 cm line will allow us to trace all structures that contain neutral hydrogen (see e.g. Paciga et al.2011). We hope to learn about the very first stars, the very first galaxies, understand how the central galactic black holes form and further constrain the properties of dark matter. Dark matter annihilations and decays would affect the spin temperature during the dark ages, to name just two effects that could not be observed otherwise. The intensity mapping of the 21 cm line promises an enormous information gain, but is challenged by astrophysical (and terrestrial) foregrounds (similar to the CMB). First steps will be possible with SKA_1, but to fully explore the potential of the SKA, SKA_2 will be required to complete this task.
There are many more cosmological issues to address, let me just mention the genesis of cosmic magnetic fields (see Sections 8.1.3 and 8.1.6).
The technological challenge to handle and analyse the huge cosmological data volume will require a world wide and concentrated effort, which will be worth its return, as our understanding of the Universe will certainly be very different from today once the SKA has been realised.

References:
Abdalla F.A., Rawlings S., 2005, MNRAS, 360, 27; Abdalla F.A., Blake C., Rawlings S., 2010, MNRAS 381, 1313; Bennett C.L., et al., 2011, ApJS, 192, 17; Blake C., Wall J., 2002, Nature, 416, 150; Camera et al. 2012arXiv:1205.1048; Copi C.J., et al., 2010, Adv. Astron. 2010, 847541 ; Crawford F., 2009, ApJ, 692, 887; Komatsu et al., 2011, ApJS, 192, 18; Natarajan A., Schwarz D.J., 2009, Phys. Rev. D 80, 043529; Paciga G., et al., 2011, MNRAS, 413, 1174; Raccanelli A., et al., 2011, preprint arXiv:1108.0930

8.1.2 Dark energy with the SKA [J. Weller]

One of the largest puzzles in modern cosmology is the explanation of the observed accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1997). The simplest way to incorporate accelerated expansion into Einsteins equations of general relativity is the introduction of a cosmological constant, whose energy density can be associated with a constant vacuum energy, which comprises about 75 % of the energy budget in the Universe. However this requires an extreme fine-tuning of initial conditions to 120 orders of magnitude. Hence, dynamical models, which introduce a new scalar field, are considered (Wetterich 1988; Ratra 1988; Zlatev 1998). In general these models allow at late times a slow variation of the energy density in the Universe, which is be encoded in the equation of state of the associated fluid. One of the holy grails of observational cosmology today is the measurement of this equation of state, expressed as the ratio of pressure and density in the fluid, $w = p/r$. Further possibly explanations of the observed accelerated expansion, are that Einsteins theory of relativity requires extensions at very large distances. This can be achieved by higher order gravity models (Starobinsky 1980) or for example with the introduction of extra dimensions (Dvali 2000). These models typically leave an imprint how large-scale structures form over time.
In recent years it has emerged that one of the most promising ways to measure cosmological parameters are so called "Baryon Acoustic Oscillations" observed in the matter distribution in the Universe (Eisenstein 2005). These features are imprints in for example the galaxy distribution from the time before $z = 1100$, when baryonic matter and photons, were tightly coupled together and allowed the propagation of pressure waves. At the time of decoupling some regions in space were overdense in baryons and some underdense. This influenced the distribution of dark matter, which seeds the large-scale matter and galaxy distribution, in a sense that there is a bump at a scale of 110 Mpc (Eisenstein 2005).
The SKA can measure these baryon acoustic oscillations by observing the galaxy distribution with the 21 cm line. So far the observation of the 21 cm line of distant galaxies has been nearly impossible because of the lack of sensitivity. The SKA will change this situation with its large collecting area. Since the wavelength of the 21 cm is redshifted due to the expansion of the Universe, the SKA will allow drawing a 3 dimensional picture of the cosmic web. The SKA has the potential to find a billion galaxies out to redshift $z = 1.5$. For example, if we parameterize the equation of state with two parameters: w_0 for the value today and w_a the linear evolution, these parameters can be measured together with the information provided by the Planck cosmic microwave background measurement, to 5 % resp. 15 % accuracy (Abdalla 2005). In addition the SKA is the best suited instrument to

map out the history of the equation of state (Tang et al. 2011), This in turn will allow to severely constrain the space of possible dark energy models. As mentioned above another possible explanation of accelerated expansion is the extension of gravity on large scales. Via the measurement of redshift space distortions (Guzzo 2008), the SKA will also be able to address this question. In summary the SKA will most likely be the most powerful and precise instrument to reveal the nature of dark energy.

References:

Riess A., et al. 1998, AJ, 116, 1009; Perlmutter S., et al. 1997, ApJ, 483, 565; Ratra B., Peebles P.J.E., 1988, PR, D37, 2406; Wetterich C., 1998, Nucl. Phys., B302, 668; Zlatev. I., Wang L., Steinhardt P.J., 1999, PRL, 82, 896; Starobinsky A.A., 1980, Phys. Lett, B, 91, 99; Dvali G., Gabadadze G., Porrati M., 2000, Phys. Lett. B, 485, 208; Eisenstein D.J., et al, 2005, ApJ, 633, 560; Abdalla F.B., Rawlings S., 2005, MNRAS, 360, 27; Tang J., Abdalla F.B., Weller J., 2011, MNRAS, in press, preprint astro-ph/0807.3140; Guzzo L. et al., 2008, Nature, 451, 541

8.1.3 Large-scale structure [M. Brüggen]

One of the fundamental problems in modern cosmology is the fact that stars, neutral atomic and molecular gas, and the diuse hot gas within clusters of galaxies account for only a third of the baryon density in the local Universe as predicted from Big Bang nucleosynthesis (Fukugita et al. 1988) and fluctuations in the microwave background (Spergel et al. 2003). Some fraction of the missing baryons lies in the Lyman-alpha forest at low redshift (e.g. Penton et al. 2000), but much is believed to reside in a warm ($T = 10^{5-7}$ K), low-density intergalactic medium (Cen & Ostriker 1999, Dave et al. 2001, Cen et al. 2001, Tripp et al. 2000).
The temperature and low density of the WHIM leave it nearly undetectable in emission. There are three approaches by which the SKA can detect the WHIM and the cosmic web:

– map the distribution of low column density neutral hydrogen. Although the gas in these inter-galactic filaments is moderately to highly ionized, QSO absorption lines have shown that the surface area increases dramatically in going down to lower H I column densities. With moderate integration times, the necessary resolution and sensitivity can be achieved out to distances beyond the Virgo cluster. When combined with targeted optical and UV absorption line observations, the total baryonic masses and enrichment histories of the cosmic web will be determined over the complete range of environmental over-densities (Braun 1994).

– use giant pulses from "Crab-like" pulsars in nearby galaxies to measure the dispersion across the local filaments and voids of the cosmic web. The SKA can detect giant pulses from pulsars in more than 30 bright galaxies within 7 Mpc of the Milky Way. As described by Lazio et al. (2004) the sensitivity of the SKA will allow for the detection of giant pulses originating in galaxies as distant as the Virgo cluster. It will also be possible to detect giant pulses from extragalactic pulsars on the other site of the Local Void, allowing for measurements for the first time of the baryon density of voids in the cosmic web. While this technique is limited to a relatively small number of line of sights determined solely by the number of giant pulses within a given galaxy, it offers the advantage of directly measuring the electron density of the baryons in the cosmic web, something ultraviolet and X-ray absorption line studies can only infer.

– utilize the tremendous sensitivity and large field of view of the SKA to map the cosmic web via imaging of diffuse synchrotron emission arising from the infall of baryons onto the large-scale structure of the Universe. The formation of the large-scale structure of the Universe is thought to be marked by large-scale shocks as baryons accrete onto collapsing structures. Typical shock velocities of $500-1000$ km/s can be expected for reasonable cosmological properties. Such infall velocities are sufficiently high that the infalling particles can be accelerated to total energies of $10^{18}-10^{19}$ eV. In the presence of even a weak magnetic field in which the energy density of the magnetic field accounts for only 1 % of the total post-shock energy density, the growth of structure should be accompanied by the emission of diffuse synchrotron radiation coincident with accretion shocks (e.g. Vazza et al. 2010). Thus, the detection of diffuse synchrotron emission associated with these external shocks offers us the opportunity to accurately map the cosmic web, while at the same time measuring the electron density and energy distribution and inferring the strength of primordial magnetic fields associated with large-scale structure (Brüggen et al. 2005, Dolag et al. 2005).

One of the key techniques used to obtain information about the strength and structure of cluster magnetic fields is the analysis of Faraday rotation from polarised radio sources located behind and within clusters. The sources' intrinsic polarisation need not be known, as the effect can be observed as a characteristic wavelength-dependent rotation measure (RM) signature. Observations of a few nearby clusters have established the presence of magnetic fields with typical strengths of few micro Gauss (μG) in non-cool core clusters and in excess of 10 μG in the centres of cool core clusters (Carilli & Taylor 2002, Feretti & Giovannini 2008, Bonafede et al. 2010). Detailed high-resolution RM images of radio galaxies in merging and cooling-core clusters indicate that the RM distribution is characterised by patchy structures of a few kpc in size (e.g. Enlin & Vogt 2003, Murgia et al. 2004, Guidetti et al. 2008, Laing et al. 2008).
As shown in Krause et al. (2009), in a shallow 100 hours survey, the SKA array will detect over a million clusters with at least one background source each, and allow detailed field structure determination (>1000 clusters with more than 100 background sources each) with a deep survey. If the cosmological evolution of the rotation measures is proportional to $(1 + z)^n$, the SKA would be able to measure n to an accuracy of 0.3 (Krause et al. 2009). Compared to the few RMs known for a few nearby clusters today, this will revolutionize our knowledge of magnetic fields in large-scale structure. It will allow us to study the physics of cosmic plasmas, by for example probing the field geometry inside clusters. This can test models for anisotropic thermal conduction in the intra-cluster medium, as well as the distribution of cosmic rays.
Provided the electron densities can be measured via the Sunyaev-Zel'dovich effect at high redshift, we can expect to follow the build-up of cosmic magnetism with the SKA.
Finally, the SKA will be able to solve the mystery of radio halos and relics. Radio halos and relics are Mpc-scale, diffuse synchrotron source in galaxy clusters whose origin is unclear. Their existence indicates the presence of magnetic fields and relativistic electrons. Radio halos are always found in clusters with merging signatures, and their power at 1.4 GHz correlates with the X-ray luminosity of the host cluster (Liang et al. 2000). The origin of radio halos is still debated (see e.g. Pfrommer et al. 2008, Cassano et al 2009). Models proposed so far can be divided into two classes: – re-acceleration models: in which electrons are re-accelerated by turbulence in-situ through second-order Fermi mechanism (Petrosian et al. 2001, Brunetti et al. 2001); – secondary models: in which electrons originate from hadronic collisions between the long-living relativistic protons in the ICM and thermal ions (Dennison et al. 1980).

References:
Bonafede A., et al., 2010, A&A, 513, 30; Braun R., 1994, New Astronomy Reviews, 48, 1271; Brüggen M., et al., 2005, ApJ, 631, 21; Brunetti G., et al., 2001, NewA, 6, 1; Carilli C.L., Taylor G.B., 2002, ARAA, 2002, 40, 319; Cassano R., et al., 2009, arXiv:0902.2971; Cen R., Ostriker J.P., 1999, ApJ, 514, 1; Cen R., et al., 2001, ApJ, 559, 5; Dave R., et al., 2001, ApJ, 552, 473; Dennison B., 1980, ApJ, 239, 93; Dolag K., et al., 2005, MNRAS, 364, 753; Enßlin T., Vogt , 2003, A&A, 401, 835; Feretti L., Giovannini G., 2008, arXiv:astro-ph/0703494; Guidetti D., et al., 2008, A&A, 483, 699; Krause M. et al., 2009, MNRAS, 400, 646; Lazio J.,et al., 1994, New Astronomy Reviews, 48, 1439; Laing R., et al., 2008, MNRAS, 391, 521; Liang H., et al., 2000, arXiv:astro-ph/0012166; Murgia M., et al., 2004, A&A, 424, 429; Penton S.V., Shull J.M., Stocke J.T., 2000, ApJ, 544, 150; Petrosian V. , 2001, ApJ, 557, 560; Pfrommer T.,et al., 2008, 385, 1211; Spergel D.N., et al., 2003, ApJS, 148, 175; Tripp T.M., Savage B.D., Jenkins E.B., 2000, ApJ, 534, 1; Vazza F., Brunetti G., Gheller C., Brunino R., 2010, New Astronomy, 15, 695

8.1.4 Baysion cosmography [J. Jasche]

According to the current cosmological paradigm, all observable structures in the Universe stem from microscopic primordial quantum fluctuations generated at the very beginning of the Universe. In the following ∼13.8 billion years of cosmic history, these seed perturbations grew via gravitational amplification and formed the presently observed matter distribution consisting of clusters, filaments and voids. The processes of cosmic structure formation have been governed by a variety of exciting physics ranging from quantum field theory, general relativity to the dynamics of collision less dark matter and dark energy as well as the behavior of baryons in the formation of galaxies and stars. All these processes left their imprints on the three dimensional matter distribution of the Universe. For this reason, mapping and analyzing the cosmic large-scale structure from observations has the potential to answer outstanding questions of modern cosmology, such as the nature of a possible dark matter and dark energy component and also provide us with a powerful laboratory to test fundamental physics. However, contact between theory and observation cannot be established directly since observational data is subject to a variety of systematic effects and strongly coupled uncertainties, such as noise, survey geometry, galaxy biases, redshift space distortions, selection and light cone effects. The Bayesian large-scale structure inference framework HADES (HAmiltonian Density Estimation and Sampling) addresses these problems and permits unprecedentedly accurate inference of cosmological information and corresponding uncertainties from probes of the large scale structure (Jasche et al. 2010a, Jasche et al. 2010b, Jasche & Wandelt 2011). Specifically, the HADES cosmography framework provides high precision maps of the three dimensional matter distribution of the Universe in the linear and non-linear regime together with corresponding uncertainties and statistical properties of the large-scale structure. This is achieved by exploring the highly non Gaussian and non linear large-scale structure posterior distribution via an efficient implementation of a hybrid Markov Chain Monte Carlo method (Jasche et al. 2010a). The application of the HADES algorithm to the Sloan Digital Sky galaxy survey demonstrates the ability of Bayesian cosmography to build precise and detailed maps of the cosmological large-scale structure (see Figure $1_{\rm Ja}$ for a slice through the three dimensional large-scale structure inferred from the Sloan Digital Sky Survey, SDSS).

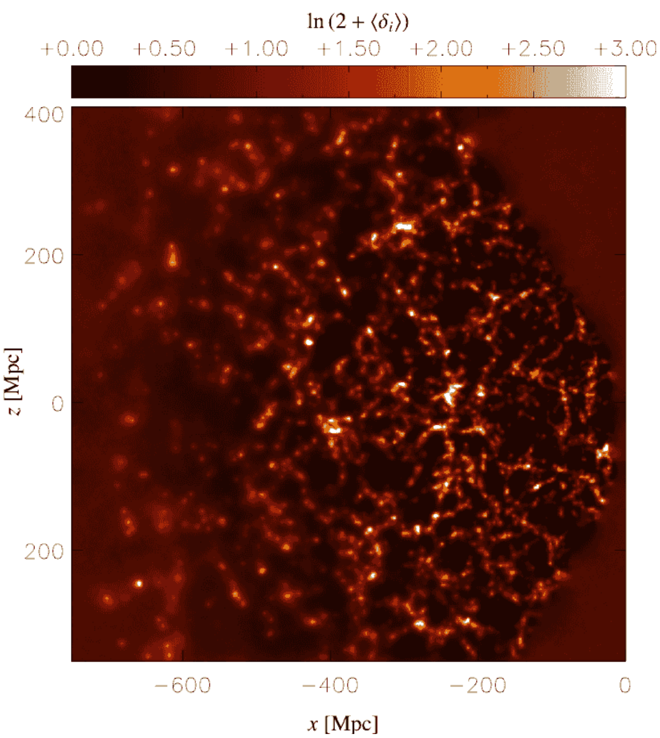


Figure $1_{\rm Ja}$: Slice through the three dimensional ensemble mean density field, estimated from 40 000 density samples. The plot demonstrates the results of the application of the HADES algorithm to the SDSS Data Release 7 (for details see Jasche et al. 2010b). As can be seen, the large-scale structure consisting of filaments, clusters and voids, has been recovered to great detail.

These three dimensional maps constitute the basis for a variety of subsequent scientific analyses. In particular, these maps enable us to study the processes of structure and galaxy formation in the linear and non-linear regimes and will help to identify the relation between the properties of galaxies and their large-scale structure environments. Furthermore, the maps can be used to predict observations in complementary cosmological probes such as the Cosmic Microwave Background (CMB) or weak lensing (for an example see see Figure $2_{\rm Ja}$). In particular, the possibility of straightforward non-Gaussian and non-linear error propagation will significantly aid the detection of weak signals such as the integrated Sachs-Wolfe effect in the CMB.

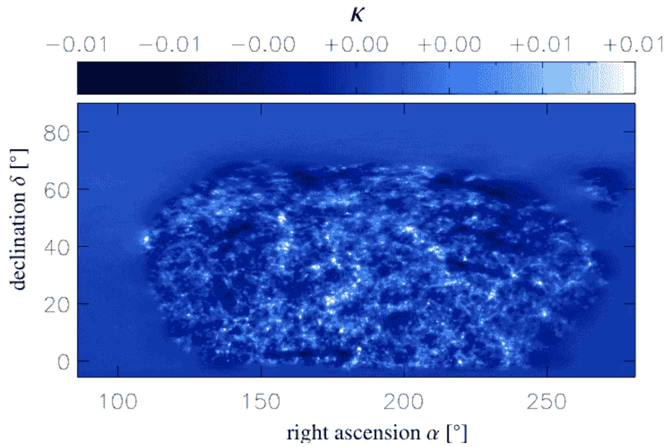


Figure 2_{Ja}: Weak lensing convergence κ projection of the density field, inferred from the SDSS, onto the sky. This plot serves as an example for the possibility to predict physical observations in complementary data sets from the inferred density fields. Furthermore, this plot also demonstrates the degree of detail to which the Bayesian cosmography framework HADES recovers the three dimensional large-scale structure.

In general, scientific results obtained with this cosmography framework, permit to constrain the nature of the initial conditions from which cosmic structures formed; extract information about the nature of dark energy and dark matter; illuminate the relationship between the distribution of dark matter and the different types of galaxies detected in surveys; and provide the community with reconstructions of the cosmic density and velocity fields including a detailed treatment of the uncertainties inherent in such reconstructions.

References:

Jasche J., Kitaura F.S., 2010, MNRAS, 407, 29; Jasche J., Kitaura F.S., Li C., Enßlin T., 2010, MNRAS, 409, 355; Jasche J., Wandelt B.D., 2011, preprint astro-ph 1106.2757

8.1.5 Turbulence and magnetic dynamo in the cosmological large-scale structure [L. Iapichino]

The formation and evolution of the large-scale structure, which proceeds through the process of hierarchical clustering, plays a key role for the conversion of potential gravitational energy into kinetic and internal energy in galaxy clusters and groups. In this process, cluster mergers induce bulk motions in the intra-cluster medium (henceforth ICM), with velocities up to $1000\ \mathrm{km\ s^{-1}}$ (e.g. Paul et al. 2011). The shearing instabilities associated with the merger events and the ubiquitous shock waves in the ICM are thus expected to stir the gas and make the flow turbulent.

Turbulence is an important link between the thermal history of the cosmic baryons and the non-thermal phenomena, such as cosmic ray acceleration and amplification of magnetic fields. In particular, the small-scale, turbulent dynamo is often invoked in the framework of the evolution of galaxy clusters (Brüggen et al. 2005, Subramanian et al. 2006). The resulting magnetic fields have magnitudes of the order $1 - 10\ \mu$G in the ICM, and $0.1\ \mu$G or less in the cluster outskirts and filaments (Ryu et al. 2008).

Observationally, magnetic fields in the cosmological large-scale structure can be probed by Faraday rotation measures (RM) of background sources. This approach is already extensively used for the study of cluster cores (Murgia et al. 2004, Bonafede et al. 2010) and has been proposed for the study of the magnetisation of the cosmic web using upcoming instruments, like the SKA and its precursors (for example, Akahori & Ryu 2010).

We argue that the SKA will be able to probe the magnetic fields in the outer regions of galaxy clusters in much more detail than currently possible, because it will trace the outer regions by using background galaxies and their measured Faraday rotation (Krause et al. 2009). These regions are extremely interesting, because they start being explored only recently by deep X-ray observations using *Suzaku* (Urban et al. 2011, Simionescu et al. 2011). Hydrodynamical simulations (Burns et al. 2010, Vazza et al. 2011) suggest that the cluster outskirts are not efficiently settled in hydrostatic equilibrium and have a substantial turbulent pressure support. However, the volume-filling factor of turbulence in these regions is still debated (Iapichino et al. 2011).

Recent analytical estimates (Iapichino & Brüggen 2012) show that, if the outer ICM is turbulent, a moderate level (10 to 30 per cent) of non-thermal pressure support can amplify the magnetic field to values around $2.5\,\mu$G at a central distance of $0.5\ R_{\rm vir}$. This estimate, combined with a simple model for the RM dispersion in idealised clusters (Felten 1996), predicts values for $\sigma_{\rm RM}$ of the order of $\sigma_{\rm RM} = 10\,{\rm rad\ m^{-2}}$. This prediction is within reach of future SKA observations, which might probe the amplification of magnetic fields that are related to propagating merger shocks and diffuse radio emission in the cluster outskirts (radio relics). The SKA will be able to shed light on non-thermal processes in regions of the ICM whose study is, both theoretically and observationally, otherwise very challenging or even impossible.

References:

Akahori T., Ryu D., 2010, ApJ, 723, 476; Bonafede A., et al., 2010, A&A, 513, A30; Brüggen M., et al. 2005, ApJL, 631, L21; Burns J.O., Skillman S.W., O'Shea B.W., 2010, ApJ, 721, 1105; Felten J.E., 1996, ASPC Conference Proceedings, 88, 271; Iapichino L., Brüggen M., 2012, MNRAS, in press: 1204.2455; Iapichino L., et al., 2011, MNRAS, 414, 2297; Krause M., et al., 2009, MNRAS, 400, 646; Murgia M., et al., 2004, A&A, 424, 429; Paul S., et al., 2011, ApJ, 726, 17; Ryu D., et al., 2008, Science, 320, 909; Simionescu A., et al., 2011, Science, 331, 1576; Subramanian K., Shukurov A., Haugen N.E.L., 2006, MNRAS, 366, 1437; Urban O., et al., 2011, MNRAS, 414, 2101; Vazza F., et al., 2011, A&A, 529, A17

8.1.6 Neutral hydrogen and the epoch of reionisation [B. Ciardi]

The epoch of reionisation (EoR) sets a fundamental benchmark in cosmic structure formation, corresponding to the birth of the first luminous objects that act to ionize the neutral intergalactic medium (IGM). Observations at near-IR wavelengths of absorption by the IGM in the spectra of the highest redshift quasars (e.g. Becker et al. 2001, Fan et al. 2006, Mortlock et al. 2011) and the radio wavelengths of the electron scattering optical depth for the cosmic microwave background (Komatsu et al. 2011) imply that we are finally probing into this key epoch of galaxy formation at $z > 6$.

Theoretical modeling based on the above existing observational constraints give the impression conveyed in the following figure of an IGM that becomes filled with growing ionized bubbles on a range of size scales. With the passage of time, the bubbles finally punch through the walls separating each other, to leave behind an almost fully ionized IGM, which remains such to the present.

The SKA and the pathfinder telescopes which will precede it will provide critical insight into the EoR in a number of ways. The ability of these telescopes to perform a study of the neutral IGM in neutral hydrogen (21 cm) emission/absorption will be a unique probe of the process of reionization, and is recognized as the next necessary and fundamental step in our study of the evolution of large-scale structure and cosmic reionization. The applications of radio technologies to probing the EoR form the basis for several chapters in the book "*Science with a Square Kilometre Array*" (Carilli & Rawlings 2004).

The attention dedicated to 21 cm studies in cosmology has mainly focused on the feasibility of tomography, which would ideally provide a 3-d mapping of the evolution of neutral hydrogen (e.g. Madau et al. 1997 Tozzi et al. 2000, Ciardi & Madau 2003, Mellema et al. 2006, Santos et al. 2008, Lidz et al. 2008, Morales & Wyithe 2010). This is an extremely exciting prospect which suffers though from several severe difficulties, the most relevant being foreground and ionospheric contamination and terrestrial interference (e.g. Shaver et al. 1999, Di Matteo et al. 2004, Jelić et al. 2008, Bowman et al. 2009). As tomography of the reionization history will require approximately one square kilometre of collecting area, this will most probably not be feasible by the pathfinders, which will instead concentrate on statistical studies of the 21 cm signal. But more than a statistical analysis, IGM tomography offers an invaluable tool to discriminate between different ionization sources and to follow the spatial and temporal evolution of the reionization process. Thus, despite the challenge of the observations, also the SKA_1 should include them among its goals.

Similarly, while the construction of radio maps of individual ionized bubbles with the pathfinder arrays will be feasible at best (if at all) after several years of observations, the SKA_1 will have the sensitivity to deliver their direct detection. The ability of the telescope for effective survey of large areas of sky will lead to the identification of targets for subsequent follow up at other wavelengths. For example, the SKA_1 will be well suited to the direct observation of ionized bubbles (giant Strömgren spheres) around luminous QSOs in a still significantly neutral IGM (e.g. Tozzi et al. 2000, Wyithe et al. 2005). If QSO Strömgren spheres can be discovered, and their structure studied, this will be an invaluable source of information on the supermassive black hole population at high redshifts, the nature of the ionizing spectra responsible for the reionization of the Universe and the abundance of neutral hydrogen in the IGM at those redshifts.

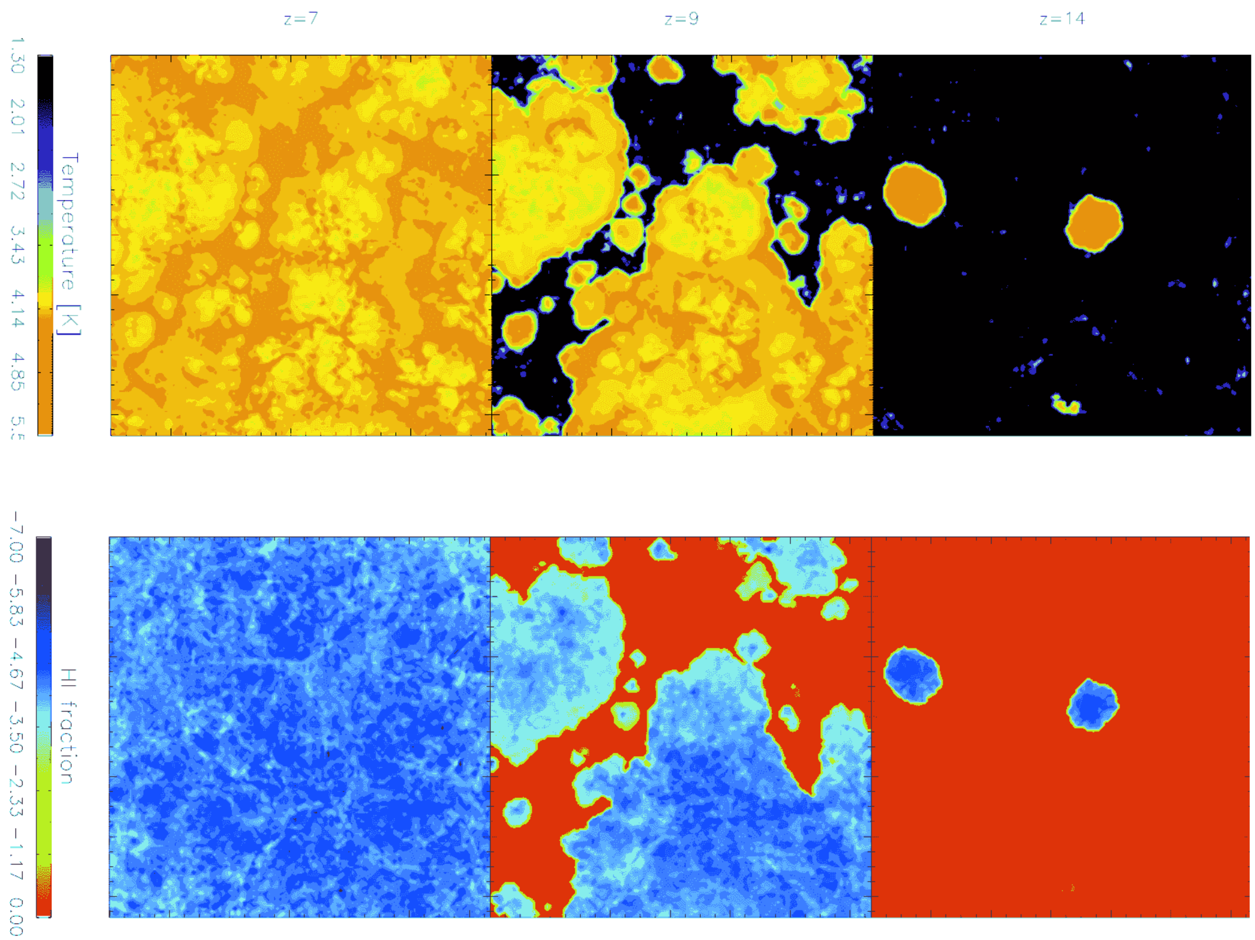


Figure 1_{Ci}: upper panel:maps of gas temperature at redshift $z=7$ (left panel), 9 (middle panel) and 14 (right panel) as obtained in simulation $\mathcal{E}1.2-\alpha1.8$ by Ciardi et al. (2012). Each map represents the central slice of the simulation box.
lower panel: as upper panel for H I fraction.

A valid alternative to tomography is looking at the 21 cm lines generated in absorption against high-z radio loud sources by the neutral IGM and intervening collapsed structures, i.e. to search for the 21 cm forest (e.g. Carilli et al. 2002, Furlanetto 2006, Xu et al. 2009, Mack & Wyithe 2011, Xu et al. 2011). Analogous to the extensively studied case of the Lyman-alpha forest, the 21 cm forest signal can be detected in the spectra of high-z radio sources and results from the absorption produced by the H I intervening along the line of sight. Despite the great challenge posed by the detection of such extremely rare target sources, the 21 cm forest is particularly appealing as it naturally bypasses some the main limitations expected for 21 cm tomographyc measurements.

References:
Becker R.H., et al., 2001, AJ, 122, 2850; Bowman J.D., Morales M.F., Hewitt J.N., 2009, ApJ, 695, 183; Carilli C.L., Gnedin, N.Y., Owen, F. 2002, ApJ, 577, 22; Carilli C.L., Rawlings S., 2004, New Astronomy Reviews, 48, 979; Ciardi B., et al., 2012, MNRAS, 423, 558; Ciardi B., Madau P., 2003, ApJ, 596, 1; Di Matteo T., Ciardi B., Miniati F., 2004, MNRAS, 355, 1053; Fan X., et al., 2006, AJ, 132, 117; Furlanetto S. R., 2006, MNRAS, 370, 1867; Jelić V., et al., 2008, MNRAS, 389, 1319; Komatsu E., et al., 2011, ApJS, 192, 18; Lidz A., Zahn O., McQuinn M., Zaldarriaga M., Hernquist L., 2008, ApJ, 680, 962; Mack, K. J., Wyithe, J. S. B., 2011, ArXiv e-prints; Madau P., Meiksin A., Rees M. J., 1997, ApJ, 475, 429; Mellema G., Iliev I.T., Pen U., Shapiro P.R., 2006, MNRAS, 372, 679; Morales M. F., Wyithe J.S.B., 2010, ARA&A, 48, 127; Mortlock D. J., et al., 2011, Nature, 474, 616; Santos M. G., et al., 2008, ApJ, 689, 1; Shaver P.A., Windhorst R.A., Madau P., de Bruyn A.G., 1999, A&A, 345, 380; Tozzi P., Madau P., Meiksin A., Rees M. J., 2000, ApJ, 528, 597; Wyithe J.S.B., Loeb A., Barnes D.G., 2005, ApJ, 634, 715; Xu Y., Chen X., Fan Z., Trac H., Cen R., 2009, ApJ, 704, 1396; Xu Y., Ferrara A., Chen X. 2011, MNRAS, 410, 2025

8.1.7 A direct measure of the expansion rate of the Universe [H.-R. Klöckner]

Abstract: In the last recent years cosmology has undergone a revolution, with precise measurements of the comic microwave background radiation (CMB), large galaxy redshift surveys, and the discovery of a recent accelerated expansion of the Universe. All these details has boosted our understanding of the Cosmos, its evolution and the models describing it are entering a new phase of precision.

In this light the SKA will provide an opportunity to directly measure the expansion rate of the Universe via a rather simple experiment by observing the neutral hydrogen (H I) content within and also toward galaxies at two epochs. Due to the accelerated expansion of the Universe these signals encounter a shift in redshift space and hence provide a real time measure of the cosmological expansion rate. The accuracy of these measurements, together with other probes of cosmological parameters, allows us to constrain our current understanding of the Universe and may help to distinguish between alternative cosmological models.

Introduction: The Big Bang concept of our Universe seems to be well established as "the standard model of cosmology", but currently the observational data cannot tighten constrains on the physics of the very early phase of the Universe. In this current picture 13.8 billion years ago the Universe was hot and dense, and it has expanded and cooled ever since. The content of the universe has evolved and observations specify a census of the type of matter and energy in its development. In the very early phase, it began to be dominated by an energy field with a negative pressure, which drove an early period of acceleration expansion, "the inflation" phase. It was then dominated by radiation, and later by matter. Based on this understanding the expansion of the Universe should decelerate if it is dominated by baryonic and cold dark matter [3]. However by using type Ia supernova (SNIa), as standard candles, a surprising discovery has been made, that the expansion of the Universe encounters a second epoch of acceleration (Riess et al. 1998, Perlmutter et al. 1999, this research was awarded a the Nobel prize in physics 2011). The reason for the recent accelerated expansion is still a mystery and points again to a new negative pressure contribution of the mass-energy field and a possible modification of Einstein's general relativity. Therefore, understanding the nature of the current acceleration is the essential step in our understanding of the inflation phase and the mechanism in place in this phase.

Measuring the expansion history of the Universe include distances, the linear growth of density perturbations, and a combination of both observed at different epochs. The observations at different epochs allows for a direct measure of the expansion history, whereas SNIa surveys, weak lensing (Heavens 2003) and Baryon Acoustic Oscillations in the galaxy power spectrum (BAO; Wang 2006) are generally considered to be indirect probes of the acceleration. The results of the indirect probes are uncertain because the extracted information requires a

[3] Baryons are composite subatomic particles made up of three quarks and participate in the strong interaction force. Cold dark matter is a hypothetical from of matter that interacts weakly with electromagnetic radiation and most of whose particles move slowly compared to light. Possible candidates of "cold dark matter"-objects are MACHOs, RAMBOs, and weakly interacting massive particle (WIMP) and axions. Such constitutes lead to a "bottom-up" scenario of structure formation in the Universe. Dark matter is undetectable by its radiation, but its presence can be inferred from gravitational effects (e.g. rotation curves in galaxies).

priory knowledge of the cosmological model and even simple parameterisations of dark energy properties can result in misleading conclusions (e.g. Bassett et al. 2004, Shapiro & Turner 2006).

Thus model-independent measurements are needed and using observations at different epochs, as direct probes, will provide strong evidence on the expansion history of the Universe.

The experiment: will make use of the direct change of observable properties of galaxies over an extended periods of observing time. In general, the changes in source brightness, apparent angular size, and redshift constrains the parameter needed in describing the expansion history of the Universe (see e.g. Gudmundsson & Björnsson 2002). The change of the first two properties will not be discussed here and only the latter is considered to be feasible with the SKA.

Already in the 1960s the model-independent approach that measures the expansion rate directly was first explored by Sandage. At these time limitations in technology made these measurements out of reach, e.g. for a ten years period assuming a ΛCDM cosmology ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$) the maximum change in redshift is of the order of $\Delta z = 2\,10^{-10}$. This idea was revisited by Loeb in 1998 discussing the use of Lyman-alpha absorption lines toward quasars to measure the expansion rate. The author concluded that the signal might be marginally detectable by observing approximately 100 quasars over 10 years with a 10-m class telescope (Loeb 1998). Since then new plans have emerged to build a giant optical telescope the E-ELT, a 40-m class telescope, with a specially equipped spectrograph to perform the "Cosmic Dynamics Experiment" (CODEX). The CODEX experiment is based on the Loeb test and will make use of a specially designed spectrograph to detect the expansion rate of the Universe via Lyman-alpha absorption lines (Pasquini et al. 2005; Liske et al. 2008a). Feasibility studies suggest observations of at least 20 targets for a total observing time of 4000 hours to reach a 3.1σ detection of the velocity shift of 2.34 cm s^{-1} over 20 years (Liske et al. 2008b). This experiment is limited by the fact that the Lyman-alpha forest is only accesible from the ground for $z \geq 1.7$ and it is most likely that a direct measure of the recent acceleration might not be possible with the CODEX experiment.

Like the CODEX experiment a similar type of observation can be achieved with the SKA and instead of observing the Lyman-alpha forest one could use a H I absorption spectra toward a radio loud active galaxy at redshift prior to reionisation epoch (Carilli et al. 2002). In their simulation, the authors showed that at redshifts above 8 a Cygnus A-type galaxy would show numerous H I absorption line features in their spectra that are suitable to measure the velocity shift. However like the Lyman-alpha absorption systems these sources are difficult to find and in case of the radio counterpart have not found yet, but it is not unreasonable to expect the SKA to be able to find these.

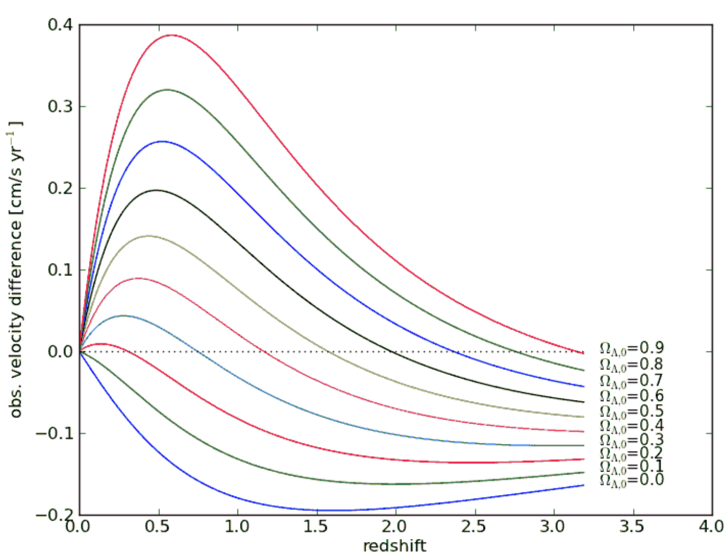


Figure 1_{Kl}: The expected velocity shift for various ΛCDM cosmologies ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.0$ ... 0.9) assuming two epochs of observations within 1 year. Note that the velocity shift depends linearly on the observing period, therefore for $\Omega_\Lambda = 0.7$ a maximum velocity shift of ~ 2.5 cm would be expected for an observing period of about ten years.

Here a new experiment is proposed to directly measure the recent acceleration of the Universe. Using the spectra, with high spectral resolution (approx. 0.1 cm^{-1} per channel), of millions of galaxies enables us to detect an isotropic and average velocity shift up to a redshift of 1. Depending on the available number of galaxies per redshift bin even tracing the functional dependence might be possible. The figure shows the expected velocity shift within one year of observing for various cosmological models with $\Omega_m = 0.27$ and varying Ω_Λ. Depending on the contribution of Ω_Λ a positive velocity shift would be expected up to redshifts of 3, after that the velocity of the Cosmos will slow down. Only in the case of the existence of dark energy does the velocity shift show a pronounced functional dependency up to a redshift of 1−2 and a maximum between z = 0 and 0.6. This redshift range is ideal for the SKA to measure the velocity shift, because the anticipated sensitivity limits of the SKA allows observations of the H I signal (in emission) from Galaxy-like systems up to a redshift of 1. Based on the SKADS simulations, for a flux limit of 3 μJy the expected number of H I emitting sources at redshift 1 are of the order of 7000 sources per square degree (Klöckner et al. 2009). Assuming a "halve-of-the-sky " H I survey and no evolution of the H I-luminosity function the expected number of sources is of the order of 150 Million. This high number of sources will compensate the channel sensitivity drop of the SKA telescope and therefore enables us to carry out a statistical detection of the velocity shift. For lower redshift bins the number of sources will increase and allows for a further sample of the redshift dependency of the velocity shift. The statistical detection of the velocity shift would come from, instead of averaging the individual line features of the Lyman-alpha or 21 cm forest, by averaging the subtracted 2-epoch spectra of each individual galaxy.
In general, the H I emission line surveys performed with the SKA offers the ability to directly measure the recent acceleration of the Universe. In addition, observations of high redshifted radio sources and the measurements of the CODEX experiment on the E-ELT could provide further constrains on the functional dependency of the velocity shift at larger redshifts, and enables us to investigate the parameter space of modified cosmological models of our Universe.

Summary: A new experiment is proposed using the SKA to measure the real-time expansion of the Universe using H I emission line surveys at two different epochs. In addition, a twin experiment to the CODEX programme in the radio regime was discussed. Such measurements are still out of reach for current telescopes, but it is within reach for future facilities such as the SKA or the E-ELT. However the key issue in this research will be the accuracy to which one can determine the velocity shifts and which system parameters will cause systematic effects (e.g. gravitation shifts due to our planetary system; Klöckner in prep.).

References:

Bassett B.A., Corasaniti P.S., Kunz M., 2004, ApJL, 617, 1; Carilli C.L., Gnedin N.Y., Owen F., 2002, ApJ, 577,22; Gudmundsson E.H., Björnsson G., 2002, ApJ, 565, 1; Heavens A., 2003, MNRAS, 343, 1327; Klöckner H.-R., et al., 2009, PoS(SKADS 2009), 009; Loeb A., 1998, ApJL, 499, 111; Liske J., et al., 2008a, The Messenger, 133, 10; Liske J., et al., 2008b, MNRAS, 386, 1192; Pasquini L., et al., 2005, The Messenger, 122,10; Perlmutter S., et al., 1999, ApJ, 517, 565; Riess A.G., et al., 1998, AJ, 116, 1009; Sandage A., 1962, ApJ, 136, 319; Shapiro C., Turner M.S., 2006, ApJ, 649, 563; Wang Y., 2006, ApJ, 647, 1

8.2 Extragalactic astronomy

8.2.1 Neutral hydrogen [M. Zwaan]

What do we know about the evolution of neutral hydrogen in galaxies? Frankly, compared to the enormous advances made over the last few decades in the study of the stellar content of galaxies, our knowledge of the neutral gas evolution is still very limited. Obviously, the main reason for this is that the H I 21 cm emission line is extremely weak and prohibitively long integration times are required on existing radio facilities to measure the H I content of galaxies at redshifts beyond $z \sim 0.2$. A few studies have now published H I emission line detections of a few dozen galaxies at redshifts $z = 0.1$ to 0.2 (e.g. Catinella et al. 2008, Freudling et al. 2011). But for a real understanding of the role of gas in galaxy evolution, the SKA and its pathfinders are required.

Understanding the formation and evolution of galaxies can only be complete by including their most fundamental ingredient: gas. Primordial hydrogen gas dissipates energy when it falls into dark matter halos, loses energy to collapse to a neutral hydrogen reservoir in which denser regions further cool and form molecular clouds, which in turn produce stars. Much of the properties of galaxies are determined by the amount of gas they contain, and specifically, how efficient they are in converting their innate gas content into stars. The neutral gas is the basic fuel for the build up of stellar mass.

But the innate gas is only part of the story. Throughout galaxies' lifetimes, they must continue to accrete gas somehow, as without tanking for new fuel, they will exhaust their supplies within a few Giga years (e.g. Hopkins 2008, Bigiel 2011). At the same time, galaxies also lose part of their neutral gas, either through interactions with other galaxies and the intra-cluster medium, or through ionization of the lower column densities and the formation of molecular gas at the higher column densities. Modeling this delicate balance of gaining and losing neutral gas is extremely complicated (e.g. Lagos 2011). In order to understand these processes, it is essential that we measure the gas content of a large number of galaxies over a large redshift range and determine how the neutral gas is distributed over galaxies with different masses as a function of, e.g. redshift, environment, luminosity etc. Only the SKA will be able to do just that.

For example, Abdalla et al. (2010) calculate that a one year long integration with the full SKA, using a field of view of 10 deg^2, would result in the detection of $2\text{x}10^4$ galaxies per deg^2 per unit redshift at $z = 1$. Of course, these numbers depend strongly on the specifications of the SKA at frequencies between ~ 400 to ~ 1400 MHz, in particular the available instantaneous bandwidth and field-of-view. Also, they are strongly dependent on the assumed model for the evolution of the H I mass function as function of redshift, which is exactly what we wish to measure.

At present, the H I mass function is only measured with high precision in the $z = 0$ Universe. The largest surveys to date, HIPASS and ALFALFA, produced consistent H I mass functions over the mass range $10^{6.5}$ to 10^{11} $M_\odot$ (Zwaan et al. 2005, Martin et al. 2010). However, the survey volumes are still small resulting in large variations of the measured space density across the sky. Also, as an example of the current limitations, controversy still surrounds the magnitude and sign of the density-dependence of the H I mass function, possibly due to depth and cosmic variance issues with existing shallow surveys. Compared to HIPASS an ALFALFA, the SKA can detect low mass galaxies over volumes hundreds time larger and is therefore much less sensitive to cosmic variance.

Of course, once a large sample of H I selected galaxies is available, we can go much beyond studying the gas properties of galaxies. For example, the clustering properties of gas-rich galaxies can be studied as was done for HIPASS by Meyer et al. (2007). Then, using the halo occupation distribution formalism, the distribution of galaxies within dark-matter halos can be studied (Wyithe et al. 2009), giving insights into how galaxies grow over cosmic time. The large number of galaxies detected by SKA surveys allow accurate measurements of the baryon acoustic oscillations signal, which can be compared with the results of other large-scale facilities (Abdalla et al. 2010). Also, since 21 cm surveys deliver H I velocity widths, the Tully-Fisher relation can be studied over a large range in cosmic time, using the same method at $z = 0$ and at higher redshifts. The velocity widths can also be used to construct the rotational velocity function, which provides a direct comparison with CDM predictions (Zwaan et al. 2010, Papastergis et al. 2011).

Going beyond the detection of individual galaxies, stacking experiments will allow the measurement of statistical gas properties of galaxies with redshift measurements acquired in the optical (see Khandai 2011). For example, the stacked 21 cm signal of Lyman-alpha detected galaxies at redshifts $z = 2$ to 3 should be easily detectable. In "HI intensity mapping" the cumulative 21 cm intensity fluctuations from large numbers of galaxies are measured, without the need to catalogue these galaxies individually (see e.g. Chang et al. 2010). The H I power spectrum and the cosmic mass density of neutral hydrogen can be measured at redshifts beyond where individual galaxies can be detected.

References:

Abdalla F.B., Blake C., Rawlings S., 2010, MNRAS, 401, 743; Bigiel, F., et al., 2011, ApJ, 730L, 13; Catinella B., et al., 2008, ApJ, 685L, 13; Chang T., Pen U., Bandura K., Peterson J.B., 2010, Nature, 466, 463; Freudling W. et al., 2011, ApJ, 727, 40; Hopkins A. M., McClure-Griffiths N. M., Gaensler B. M., 2008, ApJ, 682L, 13; Khandai N., et al., 2011, MNRAS, 415, 2580; Lagos C. et al., 2011, arXiv1105.2294; Martin A.M., et al., 2010, ApJ, 723, 1359; Meyer M. J., et al., 2007, ApJ, 654, 702; Papastergis E., Martin A. M., Giovanelli R., Haynes M. P., 2011, arXiv1106.0710; Wyithe S., Brown M. J. I., Zwaan M. A., Meyer M. J., 2009, arXiv0908.2854; Zwaan M. A., Meyer M. J., Staveley-Smith L., Webster, R. L., 2005, MNRAS, 359L, 30; Zwaan M. A.; Meyer M. J., Staveley-Smith L., 2010, MNRAS, 403, 1969

8.2.2 Observational studies of gas in galaxies [G. Kauffmann, B. Catinella, A. Saintonge]

An international team of astronomers [Key members: Barbara Catinella (MPA), Silvia Fabello (MPA), Reinhard Genzel (MPE), Tim Heckman (JHU), Guinevere Kauffmann (MPA), Carsten Kramer (IRAM), Sean Moran (JHU), Amelie Saintonge (MPE), David Schiminovich (Columbia University), Linda Tacconi (MPE), Jing Wang (MPA)] have been carrying out two ambitious surveys (GASS and COLD GASS) to measure the atomic and molecular gas content of around 1000 galaxies with stellar masses greater than $10^{10} M_\odot$ using two of the largest radio telescopes in the world. The results of this programme will yield precious insight into how the interplay between gas and star formation shapes the evolution of galaxies in the local Universe.

Galaxies are well known to divide into two large families: red, old ellipticals and blue, star-forming spirals. While this distinction has been known for a long time, recent work based on the Sloan Digital Sky Survey (SDSS) has shown that in the local Universe, the division into these two large families occurs abruptly at a particular mass and density. Theoreticians have postulated a diverse set of mechanisms to explain the characteristic scales evident in the galaxy population. Most of these mechanisms involve processes that either eject substantial amounts of gas from the galaxy (often referred to as "quenching"), or that regulate the rate at which gas is able to accrete onto the galaxy from its external environment.

The aim of the surveys being carried out by the MPA/MPE groups is to gain new insight into the physical processes that regulate the present-day growth of galaxies with stellar masses greater than $10^{10} M_\odot$ by surveying their gas content. Neutral hydrogen (H I) is the source of material that will *eventually* form stars; it thus may represent a key ingredient in understanding the rate at which galaxies are gaining mass by accretion. The molecular gas, as traced by carbon monoxide (CO) emission, probes "birth clouds" in which stars are currently forming. By studying the interplay between atomic gas, molecular gas and young stars, one hopes to gain insight into internally-driven processes that regulate the conversion of gas to stars in galaxies (see figure below).

In order to understand how such processes operate across the galaxy population as a whole, one requires large, *unbiased* samples of galaxies. The galaxies in the GASS and COLD GASS surveys have been selected from the SDSS. The survey was one of the most ambitious optical surveys of the sky ever undertaken. Over 8 years of operation, it obtained multi-colour images covering more than a quarter of the sky and created 3-dimensional maps containing around a million galaxies. The data obtained by the SDSS provide a wealth of information about stellar content of nearby galaxies. Multi-colour images yield information about stellar ages and masses, while the emission and absorption lines in the spectra allow astronomers to derive estimates of metallicities and star formation rates, and to assess whether or not material was accreting onto central supermassive black holes. Although this data provided a wealth of new information about stellar populations in nearby galaxies, lack of information about the associated gas has prevented real progress in disentangling accretion and quenching processes.

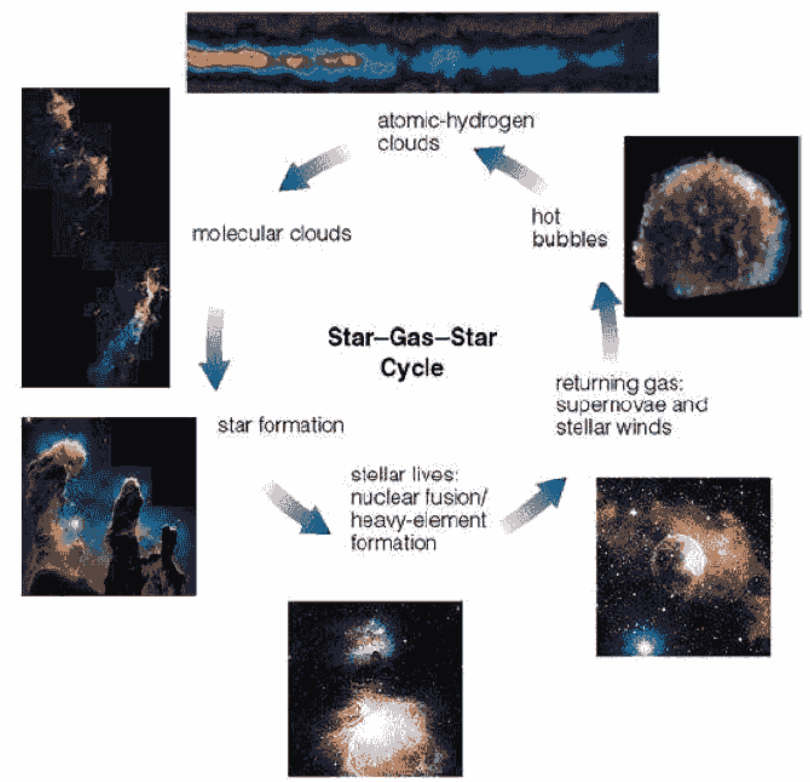


Figure 1_{Ka}: Overview of the star formation cycle in galaxies.

GASS (http://www.mpa-garching.mpg.de/GASS) probes the relationship between stars and gas by linking SDSS observations (which probe the visible light from galaxies), with those from the space-based Galaxy Evolution Explorer satellite (which probes light from the youngest stars) and from Arecibo, the largest radio telescope in the world. The Arecibo observations started in 2008 and are on-going. A thousand targets will be observed until they are detected or an H I gas mass fraction limit of few percent is reached. A subset of these targets are being followed up by the IRAM 30 m telescope in Granada, Spain, in order to measure molecular gas mass fractions down to the same limit (see http://www.mpa-garching.mpg.de/COLD_ GASS/).

The two surveys have already yielded a number of interesting new results, which have been written up in a series of 9 papers. One of the first striking results was that H I gas fraction can be predicted accurately from two optically-derived parameters. The H I fraction increases in proportion to colour/star formation rate, but it also decreases as a function of stellar density (Catinella et al. 2010). Disk galaxies are believed to form from gas that cools within massive dark matter halos. As gas cools, it loses pressure support and falls to the centre of the halo until it becomes rotationally supported. The smaller the initial angular momentum of the gas, the more it contracts. Because the star formation rate in a galaxy increases in proportion to the density of the gas in its interstellar medium, denser galaxies use up their available fuel quickly and become gas-poor. Red, high density galaxies are thus expected to have low H I fractions, as observed.

Although the majority of galaxies in the sample lie on a tight "plane" defined by colour and density, around 10 % of the sample deviate significantly in having higher H I content than inferred from their optical properties. These unusually gas-rich galaxies are of considerable interest, because they may have recently accreted H I from their surroundings. GASS team members have carried out extensive investigations of the properties of these objects. One interesting finding is that unusually H I-rich galaxies have unusually blue *outer* disks (Wang et al. 2011). Follow-up long slit spectroscopy on the Multi-Mirror Telescope in Arizona reveals that the blue outer disks harbour young (<1 Gyr), metal-poor stellar populations (Moran et al. 2010). This lends credence to the idea that present-day disk galaxies are forming from the "inside out". According to theory, high angular momentum

gas accretes later than low angular momentum gas. Although this paradigm has commonly served as the basis of semi-analytic models of the formation of disks in the context of "Cold Dark Matter" cosmologies, this is the first time that direct supporting evidence has been found.
Unusually H I rich galaxies have regular rotation curves and light profiles that are symmetric. Their star formation rates are on average no higher than similar galaxies without excess gas (Schiminovich et al. 2010). This suggests that most of the gas is accreted smoothly, and not in the form of condensed satellites, which would strongly perturb the disk, drive gas into the central regions of the galaxy and result in "bursts" of star formation. In normal spirals, H I gas in the outer disks is probably transported inwards over timescales of many Gyrs. As gas flows inwards, its density increases until the ultraviolet radiation produced by young stars is no longer able to penetrate into the densest regions. These are the conditions under which H_2 molecules begin to assemble, leading to the formation of giant molecular cloud complexes, which are the nurseries in which stars are born.
Are the stellar nurseries of all galaxies alike? What is the fraction of the available molecular gas that is turned into stars before the birth cloud is destroyed by energetic output from hot young stars in the form of radiation and outflows? Does this fraction differ from galaxy to galaxy in the local Universe, and was it different in galaxies in the early Universe? These are some of the most topical questions facing astrophysicists who attempt to understand the physical processes that regulate the rate at which galaxies form their stars.
Recent results from the COLD GASS survey indicate that the molecular gas depletion time (defined as the time taken for a galaxy to exhaust its supply of molecular gas at its current rate of star formation) may not be constant, but may vary systematically from one galaxy to another (Saintonge et al. 2011). More actively star forming galaxies harbour molecular clouds in which star formation is more efficient. For many years, this was understood to apply only to the most extreme star-bursting galaxies known, the so-called Luminous Infrared Galaxy population. Most of these galaxies exhibit signs of recent or continuing interactions. It was thus hypothesized that their interstellar medium properties could be quite different from those of quiescent spirals like our own Milky Way. The COLD GASS results now link these two populations by showing that molecular gas depletion times vary smoothly as gas surface density and star formation increase.
The main fascination of galaxies since the time of Edwin Hubble has been the intricately interwoven system of correlations or "scaling laws" that relate properties such as mass, size, age and metallicity to each other. The GASS and COLD GASS surveys are currently extending this knowledge to the *global* interplay between gas and stars in nearby galaxies. The challenge for the future will be to link phenomena that operate on vastly different physical scales: from the dense cores of molecular clouds to the diffuse ionized gas between galaxies. Meeting this challenge will undoubtedly require new technologies and new surveys. Our experience in the construction of GASS and COLD GASS has prepared us well for many new discoveries to come with the SKA and its pathfinder telescopes.

As a first step the MPA and ASTRON scientists have teamed up early 2012 to carry out the "WSRT Bluedisk project" (http://www.mpa-garching.mpg.de/GASS/Bluedisk/). This project is studying gas accretion in nearby galaxies by obtaining H I maps of galaxies where there is evidence of recent growth of the outerdisk. The observing configuration is similar to upcoming large surveys that will be carried out using the APERTIF focal plane array. The Bluedisk survey can be regarded as a "pilot study". The MPA/ASTRON team is using it as a means to develop the necessary automated data reduction and H I parametrisation software than can later be applied to the very large samples that will be available from 2015 onwards. In addition, the H I data will be linked to a variety of multi-wavelength data sets, including the Sloan Digital Sky Survey, UV imaging from GALEX and IR imaging from WISE.

References:

Catinella B., et al., 2010, MNRAS, 403, 683; Saintonge A., et al., 2011, MNRAS, 415,61; Schiminovich D., et al., 2010, MNRAS. 408, 919; Moran S.M., et al., 2010, ApJ, 720,1126; Wang J., et al., 2011, MNRAS, 412, 1081

8.2.3 Constraining the neutral gas accretion rates of low-redshift galaxies with SKA [P. Richter]

One crucial aspect of galaxy formation and evolution concerns the continuous infall of intergalactic gas onto galaxies. While it is clear that galaxies do accrete substantial amounts of gas from intergalactic space to power star formation, the exact way of how galaxies get their gas is still a matter of debate. In the conventional sketch of galaxy formation and evolution gas is falling into a dark matter (DM) halo and then is shock-heated to approximately the halo virial temperature (a few 10^6 K, typically), residing in quasi-hydrostatic equilibrium with the DM potential well (Rees & Ostriker 1977). The gas then cools slowly through radiation, condenses and settles into the centre of the potential where it forms stars as part of a galaxy ("hot mode" of gas accretion). It has been argued, however, that for smaller DM potential wells the infalling gas may radiate its acquired potential energy at much lower temperatures ($T < 10^{5.5}$ K, typically), so that one speaks of the "cold mode" of gas accretion (White & Rees 1978). For the cold mode of gas accretion the star-formation rate of the central galaxy is directly coupled to its gas-accretion rate (White & Frenk 1991). Numerical simulations indicate that for individual galaxies the dominating gas-accretion mode depends on the mass and the redshift (e.g. Keres et al. 2005). The general trend for $z = 0$ is that the hot mode of gas accretion dominates for massive galaxies with DM-halo masses $> 10^{12}\,M_{\rm sun}$, while the cold accretion mode dominates for galaxies with smaller DM-halo masses (e.g. van de Voort et al. 2011).
Independently of the theoretically expected gas-accretion mode of galaxies it is known since a long time that galaxies at low and high z are surrounded by large amounts of neutral and ionized gas that partly originates in the IGM. This material is complemented by neutral and ionized gas that is expelled from the galaxies as part of galactic fountains, galactic winds, and from merger processes (see e.g. Richter 2006). Because the interplay between these circumgalactic gas components is manifold and the gas physics of such a turbulent multi-phase medium is complex, the circulation of neutral and ionized gas in the inner and outer halos currently cannot be modeled in full detail in hydrodynamical simulations. To improve current models of galaxy evolution models it is of imminent importance to quantify the amount of cool, neutral gas in and around galaxies from observations and to search for obsvervational strategies to separate metal-deficient infalling intergalactic gas from metal-enriched gaseous material that is circulating in the circumgalactic environment of galaxies as a result of fountain processes and galaxy mergers.

We therefore intent to use the SKA to investigate in detail the distribution of neutral hydrogen in the entended halos of low-redshift galaxies to constrain the distribution and amount of cool gas in galaxy halos and to estimate the infall rate of neutral gas onto galaxies in the local Universe. With its superb sensitivity the SKA represents a particularly powerful instrument for this task, as it allows us to map the gaseous environments of a very large number of galaxies down to very low H I column densities of a few $10^{16}\,\mathrm{cm}^{-2}$ at sufficient linear resolution for the local galaxy population. Having such a large sample of galaxies is of great importance to pinpoint possible differences in the radial distribution of neutral halo gas in galaxies of different morphological types and in different large-scale environments (clusters, groups, isolated galaxies). The data will further allow us to study the infall and outflow characteristics of neutral and partly ionized gas in the inner and outer galaxy halos and to estimate the gas-accretion rate of individual galaxies, which then can readily compared with the galaxies' star-formation rates. Finally, deep SKA observations of the faint gaseous outskirts of galaxies will enable us to investigate, how individual galaxies and galaxy groups are connected to the intergalactic medium.

In summary, the above outlined SKA observations will help to better understand the ongoing formation and evolution of galaxies in the local Universe and their connection to the cosmic web.

References:

Kereš D., et al., 2005, MNRAS, 363, 2; Rees M.J., Ostriker J.P., 1977, MNRAS, 179, 541; Richter P.,2006, RviMA 19, 31; van de Voort F., et al., 2011, MNRAS 414, 2458; White S.D., Rees M.J., 1978, MNRAS, 183, 341; White S.D., Frenk C.S., 1991, ApJ, 379, 52

8.2.4 Extragalactic water-vapour maser [C. Henkel]

Background: The physical conditions in active galactic nuclei (AGN) are unique in the cosmos. Stellar and gas densities are very large, and enormous amounts of angular momentum and energy are released as material accretes onto massive black holes. Stellar and interstellar gas constitute reservoirs of accreting material. Studies of the structure, kinematics, and excitation of this material is the sole means available to investigate massive compact objects, which are otherwise not directly visible. While stars close to the massive black holes are difficult to detect because of obscuration and crowding, emission and absorption by the neutral atomic, ionized, and molecular components of the interstellar medium (ISM) may be readily studied at radio wavelengths, applying interferometry.

The role of the ISM in the vicinity of active nuclei is an important one because it feeds the central engines, thus determining their masses and angular momenta. In addition, the ISM directly affects the overall appearance of AGN. This (1) determines the degree of shielding from various viewing angles (recognition of which motivated the formulation of the AGN unification paradigm) and (2) results in intense emission of electromagnetic radiation from radio to X-ray bands, which has an impact on the ISM structure and energetics in parts of the parent galaxies and provides a handle for the study of matter under truly extreme conditions (e.g. Morganti et al. 2005).

More than 100 type-2 active galactic nuclei contain known sources of H_2O maser emssion ($\nu_{\rm rest} \sim 22$ GHz). Radio interferometric studies of these "nuclear" masers are the only means by which structures < 1 pc surrounding supermassive black holes can be mapped directly. Investigations of the first few such sources have demonstrated that H_2O maser emission traces hotspots on Keplerian orbits in warped accretion disks at galactocentric radii of $0.1 - 2$ pc, surrounding nuclear engines with characteristic masses of $10^6 - 10^8$ $M_\odot$.

Key Science: Interferometric observations of H_2O masers allow us to obtain information of the sub-pc morphology of the ISM surrounding highly obscured AGN (Miyoshi et al. 1995, Reid et al. 2009, Braatz et al. 2010). Because of the high gas density required to support H_2O maser action, disks that cross the lines-of-sight to central engines are ready substitutes for the obscuring tori featured in the AGN unification paradigm. From the 2-d images and the kinematical information contained in the spectroscopic data, 3-dimensional shapes of nuclear accretion disks can be derived. Such accretion disks may be warped (e.g. Miyoshi et al. 1995). However, the warping mechanism (e.g. radiative torques) is not certain. Tests of warp models require a sample of sources with different luminosities and accretion rates. Another important item is the thickness of the disks, which is critical to calculations of accretion rate and identification of accretion modes (advective, convective or viscous)

H_2O jet-masers may arise not from the circumnuclear tori of AGN but from a shocked region at the interface between an energetic nuclear jet and an encroaching molecular cloud (e.g. Peck et al. 2003). Reverberation measurements of the nuclear continuum and H_2O line emission can provide information on the distance between their flaring components on spatial scales even well below those of the interferometric measurements.

Observations of H_2O disk-masers also allow us to derive precise dynamical masses of the supermassive back holes (BHs), through an analysis of Keplerian disks. These masses, compared with those of the galactic bulges, will yield essential information on BH - bulge mass correlations, improving our understanding of galaxy formation and providing urgently needed data for targets with less massive central engines than the otherwise almost exclusively studied giant early type galaxies (Greene et al. 2010, Kuo et al. 2011).

As a complement to observations of the cosmic microwave background, an accurate measurement of the Hubble constant (H_0) will provide the best single constraint on models of dark energy, because H_0 is a "local" parameter, referring to a time where dark energy has truly become dominant. This will also improve our knowledge on the geometry of the Universe, i.e. its observationally so far poorly constrained flatness. Making use of the morphology and kinematics of the maser disks, direct geometric distances and radial velocities can be determined. To give an example: For 100 such galaxies with distances measured to an accuracy of $\sim 10\,\%$, H_0 could be determined with a precision of $\sim 1\,\%$.

The impact of the SKA: Because of its enormous sensitivity, the SKA will contribute substantially to the detection and mapping of H_2O maser sources in AGN. While so far only the few strongest sources could be analyzed in detail, with the SKA a much larger number of targets can be analyzed. In particular, the SKA will be sensitive enough to observe a significant number of masers at high redshift. Following Impellizzeri et al. (2008), the mean volume densities and luminosities of H_2O masers is much higher in the early Universe than locally. With the SKA, thus it will be for the first time possible to investigate the evolution of nuclear maser properties as a function of redshift.

Although the SKA will substantially increase the number of known H_2O maser sources, most Key Science (apart from statistical studies of detection rates for different samples) will require high resolution imaging. The simplest solution would be operation of outrigger stations in combination with the core of the SKA, which itself would best be operated as a phased instrument.

References:

Braatz J.A. et al., 2010, ApJ 718, 657; Greene J. et al., 2010, ApJ 721, 26; Kuo C. et al., 2011, ApJ 727, 20; Impellizzeri C.M.V. et al., 2008, Nature 456, 927; Morganti R. et al., 2005, New Astron. 48, 1195; Miyoshi M. et al., 1995, Nature 373, 127; Peck A.B. et al. 2003, ApJ 590, 149; Reid M. et al. 2009, ApJ 695, 287

8.2.5 Measuring the evolution of the galaxy merger rate with extragalactic hydroxyl masers [A. Roy, H.-R. Klöckner]

Introduction: The galaxy population evolves over cosmological history due either to the evolution of galaxy luminosities, galaxy number density or both. Density evolution is a key prediction of models of galaxy formation and one can test it if one can break the observational degeneracy between luminosity and density evolution, for example by measuring the rate of galaxy mergers versus redshift. The environment of mergers provides the conditions needed for hydroxyl megamaser (OHMM) emission and hence OHMM are perfect tracers for galaxy mergers. The SKA and its pathfinder telescopes would be ideal to undertake an OHMM survey to study the evolution of the merger rate at cosmological distances and this study could be conducted by mining the data products produced by the SKA H I surveys.

Background: Extragalactic hydroxyl mega-maser (OHMM) emission has been detected in the highest luminosity far infrared (FIR) galaxies (e.g. luminous (LIRG) and ultra-luminous infrared galaxies (ULIRG)), which are found to have massive star formation often resulting from mergers or interactions. Their OH main-line (showing a strong 1667 MHz and a weaker 1665 MHz) luminosities are 2 to 4 orders of magnitude greater than those of Galactic OH masers reaching above $10^4\,L_\odot$, which makes them detectable over cosmological distances. Typical line profiles vary from $100\,\mathrm{km\,s^{-1}}$ up to $1000\,\mathrm{km\,s^{-1}}$ with broader profiles exhibiting multiple components.

The major surveys for OH megamasers to date are Baan & Haschick (1983), Baan (1989 and references therein), Staveley-Smith et al. (1992), and the Arecibo OH megamaser survey (Darling & Giovanelli 2000, 2001, 2002), and Klöckner (2004). Fifty-five sources were detected in earlier targeted surveys of FIR luminous sources. The targeted survey of Darling & Giovanelli at Arecibo is the deepest survey to date and contained 311 targets selected based on IRAS 60 μm fluxes. It spanned $z = 0.1$ to 0.23 and excluded redshifts near 0.174 due to contamination by Galactic H I emission. Fifty-two OH MM were found and 1 OH absorber, which gives a detection rate of 16 % at the high luminosity end but this ratio decreases towards lower FIR luminosities. Typical OH megamasers found had flux densities near the survey flux-density limit, as expected for any flux-limited survey.

Evolutionary scenarios of galaxy merging rates parameterized by $(1 + z)^m$, with m between 0 (no evolution) and 8 (extreme evolution), predict a factor of 100 difference in the volume density of masers at redshift 1 and so are rather easy to distinguish if the survey extends that far (Briggs 1998). The Arecibo survey went only to $z = 0.23$ where the difference in volume density is a factor of five, which could not be distinguished statistically because of too few detections. These models can be well constrained given enough OH megamaser detections to determine the luminosity function with redshift with good precision. Already, surveys of sub-mm galaxies suggest $m = 3.5$ at low redshifts and clearly rule out the no evolution case (Aretxaga et al. 2007).

The dependence of maser properties on host galaxy properties shows a strong correlation with IR luminosity, going as $\mathrm{L_{OH}} \sim \mathrm{L_{OH}^{2.29\pm0.1}}$ (Klöckner 2004) and no correlation with any other galaxy properties was found. This confirms our understanding of the basic physical processes and has been recognised early on in the study of OHMM (Baan 1989). The luminosity function of Darling & Giovanelli (2002) was found to have the rather flat power-law dependence on luminosity of 10^{-5} ($L_{\rm OH}$ / $L_\odot$) - 0.64 $\rm Mpc^{-3}\,dex^{-1}$, and a high upper luminosity cutoff of $10^{4.4}\,L_\odot$. In contrast, the luminosity function found by Klöckner (2004) was based on twice the number of sources and had the steeper power-law index of -1.1 and an exponential cutoff above $10^{3.58}\,L_\odot$. This turnover at the upper end of the LF is still ill-determined because of the small number of sources, but also predicts the small number of detections in the local volume ($\sim$110 for moderate evolution). Surveys at low redshift among luminous FIR galaxies have been rather complete and have produced about 100 sources with only two gigamaser sources at redshift $z > 0.2$. This number is consistent with our predictions for the nearby Universe. This result is also consistent with the results of the HIPASS survey, where no new masers were found within redshift window 0.17 and 0.22 (Kanekar & Staveley-Smith, personal communication).

Most of the OHMM emission is confined within the nuclear region of less than a kilo-parsec in size showing starburst and AGN-type nuclear phenomena. The clear association of the OH emission with the infrared emission indicates that OH is a good tracer of the dusty circum-nuclear environment. This dusty environment plays an central role in the unification scheme of active galaxies where a dusty circum-nuclear torus or thick disk is used to explain the various emission appearance of their nuclear regions (Antonucci & Miller 1985). The existence of such nuclear structures follows from detailed studies of the OH Megamasers Mrk 231, Mrk 273 and III Zw 35, IRAS 17208–0014 (Klöckner et al. 2003, Klöckner & Baan 2004, Pihlström et al. 2001, Momjian et al. 2006) showing systematic velocity gradient of a rotating disk or torus at scale sizes of about a few hundred of parsecs. The modelling also allows to estimate the enclosed dynamical masses indicating, in some cases, the presence of a super massive black hole (SMBH).

The powerful OHMM in the southern hemisphere, IRAS 20100-4156 (at $z = 1.29$ and $L_{\rm OH} = 10^{3.96}\,L_\odot$; Stavely-Smith et al. 1989) clearly displays both the 1667 MHz and 1665 MHz components. On the other hand, the two highest luminosity sources, IRAS 14070+0727 (Baan et al. 1992) and IRAS 12032+1707 (Darling & Giovanelli 2001) (respectively at $z = 0.265$ and 0.217 and with $L_{\rm OH} = 10^{4.15}\,L_\odot$ and $10^{4.13}\,L_\odot$), show broad and narrow components that cover a velocity width of more than 2000 $\rm km\,s^{-1}$. Therefore, we may find a broader emission profile at higher redshifts. Such luminous OH megamasers would be detectable out to $z = 3.5$ assuming a sensitivity achievable already in the pathfinder telescopes (e.g. 0.2 mJy 3σ in a 100 kHz channel) and so megamasers have the potential to be used for cosmological studies.

Conclusions: The SKA H I surveys can be used for data mining to search for extragalactic hydroxyl emission (OH) at cosmological distances. Based on the current knowledge data mining to search for the OH mainlines at 1667 MHz and 1665 MHz (restframe) seems to be most promising. The main science driver for OH studies is to measure the rate of galaxy mergers versus redshift. By doing so one can break the observational degeneracy between density and luminosity evolution, since galaxy merger events reduce the volume density of galaxies and so the merger rate is the first derivative of the galaxy volume density with respect to time. Models of density evolution take the present comoving volume density of galaxies and scale as $(1 + z)^m$ into the past, with m between 0 (no evolution) and 8 (extreme evolution), with existing observations yielding values over the wide range of $3 < m < 8$. The result can place constraints on models of galaxy formation, which bears on cosmological parameters.
In addition to the main science driver the following studies of OHMM sources at cosmological distances enables us to:

– **study the nuclear condition** – Observations to image the structure and extent of OH emission relative to the continuum emission on angular scales offered by $\rm SKA_1$, $\rm SKA_2$ and possibly SKA+VLBI enables us to study the nuclear composition, the nuclear kinematics and the extreme physical conditions of the nuclear environment.

– **estimate the redshifts of sub-mm galaxies (SMGs)** – Most of the distant, luminous systems seen by LABOCA and SCUBA have no optical counterparts and lack detectable optical or infrared spectroscopic signatures, and so their redshift distribution and hence their possibly dominant contribution to star formation history is poorly constrained. Search for CO emission has been successful in a few and showed them to be massive and gas-rich systems. However, redshift-blind CO search involves searching bandwidths of ~ 100 GHz, which is beyond current capabilities. Alternatively, Townsend et al. (2001) suggest that redshifts might be obtainable from OHMM searches in these systems, assuming that SMGs are also ultra-luminous infrared galaxies with similar high probability (50 %) of producing detectable OH megamaser emission as in the local ULIRG population with $L_{\rm FIR} > 10^{11-12}\,L_{\odot}$.

– **investigate the evolution in the maser luminosity function** – The luminosity function of OHMM might evolve with redshift, for example if cosmic downsizing also affects the OHMM population. The OHMM population may thus show density and luminosity evolution independently from the evolution of the parent ULIRG/SMG population. Given sufficient detections, these effects may be studied by constructing the luminosity function in redshift bins and by using the methods used to measure separately the density and luminosity evolution of QSOs (see Boyle et al. 1988; Schmidt et al. 1995). Even in the case of no detections at high redshift, this would rule out most of the evolutionary models used today for OH Megamaser modelling.

– **determine a possible upper luminosity cutoff** – It is unknown whether an upper-luminosity cutoff affects OHMM. The large volume of space surveyed in a wide and deep SKA survey will vastly improve the chances of detecting rare high-luminosity megamasers and so explore the presently unexplored high-luminosity end of the luminosity function. The cutoff luminosity can be studied by constructing luminosity functions in redshift bins and looking for changes with redshift. The number of detections expected in an OH megamaser survey is extremely sensitive to the (uncertain) location of the cutoff and one could potentially find very many sources.

References:

Aretxaga I., et al., 2007, MNRAS, 379,1571; Baan W. A., 1989, ApJ, 338, 804; Baan W. A., et al., 1992, ApJ, 396, L99; Baan W. A., Haschick A. D., 1983, AJ, 88, 1088; Boyle B. J., Shanks T., Peterson B. A., 1988, MNRAS, 235, 935; Briggs F. H., 1998, A&A, 336, 815; Darling J., Giovanelli R., 2000, AJ, 119, 3003; Darling J., Giovanelli R., 2001, AJ, 121, 1278; Darling J., Giovanelli R., 2002, ApJ, 572, 810; Klöckner H.-R., 2004, PhD thesis; University of Groningen; Klöckner H.-R., Baan W.A., 2004, A& A, 419, 887; Klöckner H.-R., Baan W.A., Garrett G.A., 2003, Nature, 421, 821; Momjian E., Romney J.D., Carilli C.L., Troland T.H., 2006, ApJ, 653, 1172; Pihlström Y.M., et al., 2001, A& A, 377, 413; Robishaw T., Quataert E., Heiles C., 2008, ApJ, 680, 981; Schmidt M., Schneider D. P., Gunn J. E., 1995, AJ, 110, 68; Staveley-Smith L., et al., 1992, MNRAS, 258, 725; Stavely-Smith, L., et al., 1989, Nature, 537, 625; Townsend, R. H. D., et al., 2001, MNRAS, 328, L17

8.2.6 Gravitational lenses [O. Wucknitz]

Gravitational lenses are unique probes of the Universe from high redshift down to our cosmic neighbourhood. As predicted by general relativity, light is deflected by gravitational fields. Depending on the geometry, this effect leads to weak distortions of image shapes (weak lensing) or even the formation of multiple images (strong lensing), often with strong magnifications. Gravitational lensing by the Sun was the first test of general relativity and still has the potential to study any possible deviations from these fundamental laws of physics. At the same time the effect is regularly used as a very versatile tool for a wide area of astrophysical research.

Natural telescopes: Lensing by galaxies or clusters of galaxies often leads to magnifications by one or even several orders of magnitude so that they can be seen as natural extensions of our instruments to increase the resolution significantly. At the same time, because surface brightness is conserved, they also amplify the flux densities to boost the sensitivity limits. At the highest magnifications, a gravitational lens can effectively turn the SKA into a TSKA (Thousand Square Kilometre Array). Both effects are used extensively to search for high-redshift sources and to study their properties as detailed as otherwise only possible at much smaller distances.

Cosmology: The best-known application of lensing for cosmology is the measurement of the Hubble constant using time delays between lensed images. The age of the Universe approximately equals the inverse Hubble constant and scales directly with the measured time delays. The only significant uncertainty in this relation is the mass distribution of the lenses themselves (see below). Lensing provides a one-step path to cosmological scales and completely avoids the many sources of systematical errors that are inherent to classical distance-ladder methods. Together with current CMB measurements, these results can constrain all relevant cosmological parameters.

Weak lensing (see also Section 8.2.7), the statistical study of small image distortions, can provide additional and independent information about cosmological parameters, particularly about the equation of state of dark energy. So far, weak lensing has only been studied at optical wavelengths, because radio surveys have not reached the required combination of source density and resolution. This will change with the SKA, and pilot studies will already be possible with LOFAR.

Mass distribution of lenses: The image configuration of strong lenses provides invaluable information on the mass distribution (luminous and dark) of the lensing galaxies (or clusters). This is the only way to determine mass distributions of high-redshift objects and study the formation of galaxies and clusters in detail. This knowledge is essential for our understanding of the properties of dark matter.

Subjects of particular interest are the large-scale mass profiles, the small-scale clumping predicted by CDM structure formation simulations, and the central density peaks of galaxies and clusters. Lensing is the only way to study these aspects at high redshifts.

Propagation effects: Lensing can provide several images of one and the same source, with the same intrinsic spectrum, structure and polarisation properties. Any observed differences between the images (e.g. different spectrum or polarisation) can be used to study differential propagation effects happening on the way, typically in the lensing galaxy itself. This makes such studies independent of arbitrary assumption on the intrinsic properties of the source. Typical features are dust extinction and reddening in the optical and scatter broadening, free-free absorption and Faraday rotation in the radio regime, all of which provide information about the physical conditions in distant galaxies.

Radio observations of lenses: Observations at radio wavelengths offer a number of advantages. They are independent of dust absorption in the lenses, one of the major source of systematic errors and selection effects in optical studies. In addition, radio flux measurements are not affected by microlensing, which is a major perturbing factor for optical measurements. Because measured flux ratios are very sensitive to small-scale mass clumping, important information is lost in the optical. Instrumentally, radio interferometry is the only technique providing information on all scales, from degrees down to milli-arcsec and even below. Luckily, radio sources show structures on all these scales, so that e.g. lens mass distributions can be studied on scales from megaparsecs down to parsecs. This is not possible with any other technique.

So far, no efficient instruments are available to survey large fractions of the radio sky with the required resolution in the sub-arcsec range to find lensed radio sources. Only about 40 of such systems are known at the moment, compared to hundreds in the optical. LOFAR as a pathfinder for the SKA is just about to reach the required resolution (with international baselines) and imaging capabilities for large-scale radio lens searches. It has the potential to increase the number of radio lenses by an order of magnitude. The experience gained in the preparation and execution of LOFAR lens searches will be essential to prepare for much larger SKA projects.

Koopmans et al. estimated the number of lenses that the SKA can see in a half-sky general-purpose survey as 10^6, of which 10^5 can be identified easily. Even though the exact numbers will depend on the final design, it is clear that the SKA will increase the number of known radio lenses by several orders of magnitude, which will allow us to do new kinds of science. The properties of the SKA (high resolution and sensitivity, wide spectral coverage) will make the identification of lenses much easier than with current instruments. The resolution is sufficient to identify typical lensing geometries directly, without follow-up observations. The spectral information will be invaluable to identify which parts of a multiple-image configurations correspond to the same part of the source, which makes the modelling much more robust. Algorithms to model the mass distribution and (unlensed) source structure simultaneously, while accounting for the interferometric measurement process properly, are already available (Wucknitz 2004). They are currently being extended and improved for LOFAR and e-MERLIN projects.

Given the resolution of the SKA and the expected number of lenses, we will not only obtain a large sample for statistical analyses, but will also find a number of very exotic lens systems and configurations, e.g. lensing by dwarf galaxies and many structures distorted by mass-clumps. In the latter case, the local mass distribution can be "mapped" directly from the observations.

References:
Koopmans L.V.E., Browne I.W.A., Jackson N.J., 2004, New Astronomy Reviews, 48, 1085; Wucknitz O., 2004. MNRAS, 349, 1

8.2.7 Weak gravitational lensing with the SKA [P. Schneider]

The statistical weak gravitational lensing effect caused by the inhomogeneously distributed matter in the Universe leaves an imprint on the observable shapes of images of distant galaxies. Among the most important applications of the weak lensing effect are:

– reconstruction of the two-dimensional total (dark + luminous) mass profiles of individual galaxy clusters,

– the determination of the mean mass profile around classes of objects, such as galaxies and galaxy groups, to study the mass–luminosity relation and to probe for a 'universal' density profile,

– a direct determination of the correlation between luminous objects, such as galaxies, and the underlying total mass distribution, i.e., the bias of these objects as a function of, e.g. luminosity, redshift and object type,

– the study of the geometry of the Universe and the large-scale structure of its matter content, which is used in particular to determine cosmological parameters. In fact, the "Dark Energy Task Force" in the US and the ESA-ESO Working Group on "Fundamental Cosmology" concluded that weak lensing is potentially the most powerful tool to study the equation-of-state of "Dark Energy".

The principle of weak lensing is to measure correlations between the ellipticities of distant sources with either the position of foreground objects (galaxies, groups or clusters), or correlations between image ellipticities. Based on the fact that no direction is singled out in the Universe, so that the intrinsic orientation of sources is statistically isotropic, these correlations measure the strength of the accumulated tidal gravitational field along the line-of-sight to these sources. Since the projected brightness distribution of extended astronomical sources is not circular, there is a lower bound on the noise in such measurements, given by the ellipticity dispersion of the sources. Therefore, to achieve a large signal-to-noise for such measurements, one needs a high number density of these sources on the sky. For this reason, weak lensing has been applied almost exclusively to faint galaxies found in optical wide-field images, as these provide the highest number density. Furthermore, in order to beat sample variance, large areas of the sky need to be imaged. The state-of-the-art is defined by the CFHTLenS survey, a 5-band imaging survey over $\sim 150\,\mathrm{deg}^2$ with a density of galaxies that can be used for shape measurements of about $\mathrm{n} \sim 20\,\mathrm{arcmin}^{-2}$. The most ambitious project currently planned for weak lensing is the ESA Euclid mission, a "Dark Energy" satellite which will map half the sky with a galaxy number density of $\mathrm{n} \sim 35\,\mathrm{arcmin}^{-2}$.
There are several technical difficulties of weak lensing measurements, in particular the necessity to correct the measured ellipticities for the influence of the point-spread function. For ground-based observations, the PSF is typically of the same size as the sources, so that the PSF causes a strong smearing of the brightness profile of the images. Corrections to account for this smearing necessarily amplify the noise in measured ellipticities. Furthermore, the PSF is in general not circular, and hence imposes an additional ellipticity to the images. To correct for these effects, the PSF, which varies with the angular position on the sky and is different for exposure to exposure, needs to be known with very high accuracy. It can be measured at the location of stars – i.e., point sources – but must then be interpolated to the positions of the individual galaxy images.
A further difficulty lies in the necessity to measure redshifts of the objects, not only to increase the measurement sensitivity of weak lensing, but mainly to correct for systematic effects which are due to intrinsic alignments of galaxy shapes – for example, the same tidal field that causes a lensing distortion of a light bundle can lead to an alignment of galaxies with regards to the orientation of the tidal field. These systematics can be detected and removed due to their characteristic redshift dependence, but for this purpose, redshifts need to be known. For optical weak lensing surveys, this needs to be done using photometric redshift techniques.

The SKA will open totally new opportunities for weak lensing, mainly due to five different routes:

1. The sensitivity of the SKA will populate the radio sky with a substantially larger number of (resolved) sources than is possible with existing or planned optical telescopes, either from the ground or from space (with the possible exception of the JWST which, however, has a very small field-of-view and is therefore unable to conduct efficient weak lensing surveys).

2. The large instantaneous field of view will allow for surveys covering significant fractions of the sky on short time scales.

3. The PSF of the SKA is small, so that PSF effects play a substantially smaller role for the determination of image shapes. This implies that much smaller corrections to the observed image ellipticities need to be applied.

4. The PSF of the SKA is supposed to be perfectly reconstructible from the locations of the individual antennas. This will remove the largest current uncertainty in weak lensing measurements; in particular, one will be able to reliably apply more sophisticated methods for PSF corrections which appear to be less robust on optical images, most likely due to remaining uncertainties in the knowledge of the PSF.

5. HI measurements will allow us to determine secure redshifts of (a significant fraction of) the source population, which will provide a tremendous enhancement over the uncertainties associated with photometric redshifts.

Together, these points will render the SKA an enormously powerful weak lensing machine. Whereas the Euclid mission will be close to the "perfect" weak lensing survey possible in the optical wavelength regime, the SKA will allow for better surveys in terms of image density, ability to control the PSF, and the ratio of PSF-to-image size which will lead to far smaller corrections that need to be applied. Furthermore, the exquisite image quality expected from the SKA will allow us to measure shape parameters of images beyond the ellipticity, for example the flexion. Given that flexion turns out to be notoriously difficult to measure on optical images, mainly due to uncertainties in the exact profile of the PSF and the relative sizes of PSF and image, this will provide an important additional channel for weak lensing measurements. The as yet unmatched promise of the Euclid mission – in particular to measure the equation-of-state parameter w of Dark Energy to within $\sim 1\,\%$ accuracy – can probably be topped by future SKA weak lensing studies.

Finally, in addition to individual objects, the patchy hydrogen ionization which can be observed with the SKA provides a large number of statistically isotropic source screens which in principle can be used for measuring weak lensing effects to very high redshifts.

8.2.8 Radio continuum as a measure for dust-unbiased star formation across the Universe [E. Schinnerer, V. Smolčić]

Radio continuum emission is widely used as a dust-unbiased tracer for measuring the recent massive star formation activity in galaxies - both in the local and distant Universe. Based on the locally observed tight relation between infra-red and radio emission, the conversion of radio flux density into star formation has been derived and widely applied. However, the underlying physical reasons for this tight relation still remain elusive. Progress has been slow due to the lack of adequate data at both mid- to far-infrared wavelengths as well as the radio regime. In order to reveal the underlying mechanisms causing the emission and how they are related sensitive images spatially resolving nearby galaxies are essential to disentangle contributions from different sources such as young nascent star forming region, HII regions, and older stellar populations forming the interstellar radiation field (ISRF).
New observations from the infrared Spitzer and particularly the European Herschel space observatories have the necessary angular resolution to allow not only for a spatial separation of the different environments present in nearby galaxies but also to model the full spectral energy distribution of the dust emission using realistic models

of the dust composition such as Draine & Li (2007). With the dramatically increased sensitivity and almost contiguous frequency coverage the Karl G. Jansky Very Large Array (JVLA) can provide the equivalent data at radio frequencies. The combined radio and infrared datasets are prone to shed more light onto the physical bases of the radio-infrared relation, and thus ultimately, the usefulness of the radio continuum as a star formation tracer. However, mapping a moderately sized sample over the full JVLA frequency range is excessively demanding in observing time.

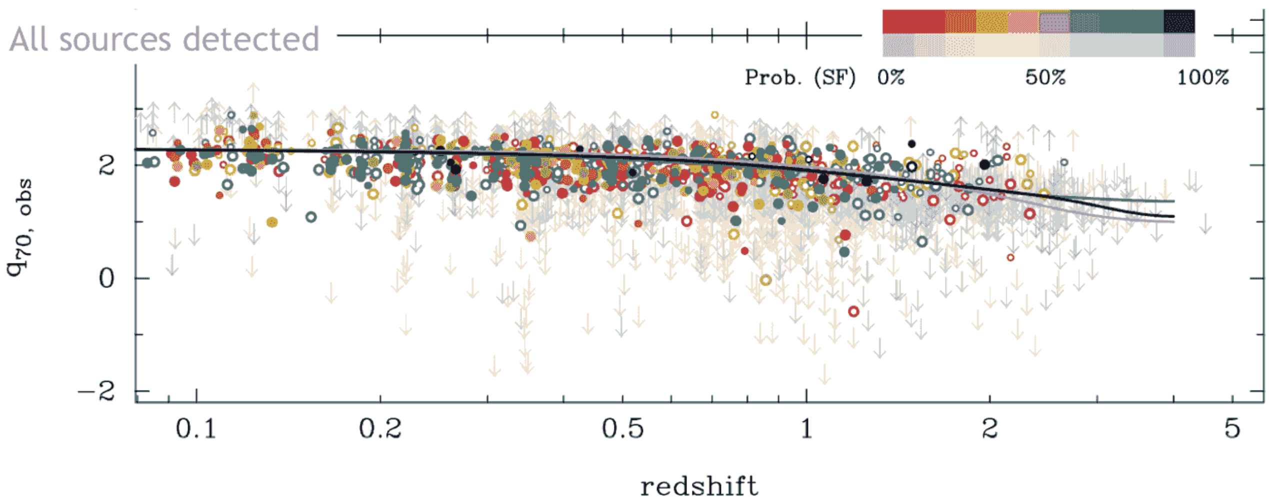


Figure 1_{Sm}: Monochromatic radio-IR relation as a function of redshift (from Sargent et al. 2010a, b). The points show the observed, i.e. not K-corrected, 70 μm to 1.4 GHz ratio. The gray and black curves show the expected evolution of the ratio q based on Chary & Elbaz (2001) SEDs. The filled points are ratios detected at both bands while the colour coding defines the probability that the radio emission of a given object is due to star formation. No evolution of the radio-IR relation out to z$\sim$3 is obvious.

New science highlights that have already emerged from such combined studies is the finding that the radio-infrared relation can become sub-linear in certain galactic environments such as the inter-arm regions in a spiral galaxy (e.g. M51, Dumas et al. 2011; M33, Tabatabaei et al. 2011). The diffusion length of cosmic ray electrons is not exactly the same in all galaxies but shows a variance based on the star formation activity suggesting that refreshment of the cosmic ray electron reservoir is important (Murphy et al. 2006, 2008). Several authors have shown that the radio-infrared relation typically breaks below a few 100 pc scales (e.g. Tabatabaei et al. 2011, Dumas et al. 2011) except for the nearby dwarf galaxy LMC (Hughes et al. 2005). There is tentative evidence now that the nature of the magnetic field, i.e. its ordered large-scale structure versus the small-scale turbulence) could play an important role (Tabatabaei et al. 2012). Clearly, observations of the 3-dimensional structure of the magnetic field would provide information of an important component of the interstellar medium. Another aspect is the potentially important role that could be played by the interstellar gas in enhancing the radio emission as proposed by Thompson et al. (2006).

While JVLA will clearly make significant contributions to advance our understanding of the physics underpinning the radio-infrared relation, only the SKA can obtain high quality data for a representative sample of nearby galaxies that probe all environment present in the local Universe. Such a dataset with a spatial resolution of few 10 to 100 pc which is close to the constituents of the interstellar medium, i.e. (giant) molecular clouds, and star forming sites, i.e. HII region, will provide the information required to test the different relations that have been put forward recently (e.g. Lacki et al. 2010).

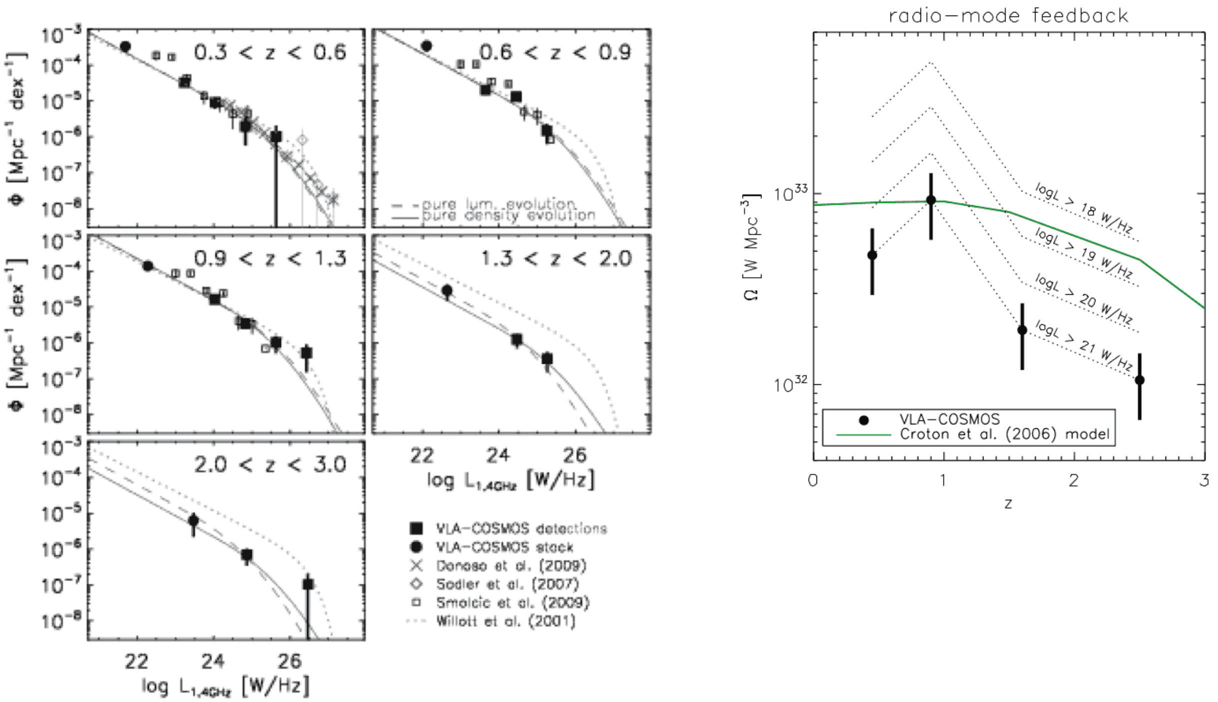


Figure $2_{\rm Sm}$: Radio luminosity functions (LFs) for low-radio power AGN in COSMOS out to z $=3$ (left panel; Smolčić et al. in prep; see also Smolčić et al. 2009b). Curves correspond to the analytical LFs best fit to the COSMOS data (assuming pure density evolution). Right: The comoving volume averaged radio-AGN heating done by low-radio power AGN in COSMOS (points and dotted and dashed lines), compared to predictions from cosmological models (full line). The dotted lines illustrate the strong dependence of the observationally derived curve on the faint end of the radio luminosity function. If the LF continues rising with decreasing radio luminosity the observationally derived radio-mode heating will systematically rise. The way to constrain the faint end of the LF is via deep observations, as possible with the SKA.

A good physical understanding of the relation between radio continuum emission and star formation is the foundation to widely exploit the unique angular resolution that will be offered by the SKA compared to infrared telescopes. In nearby galaxies, ALMA will provide unprecedented insights into the distribution and nature of the molecular clouds thus lying the foundation to unveil the onset and process of star formation within galaxies. In order to uncover the sites of star formation radio continuum emission can provide the missing information as the dust continuum will be almost impossible to be observed across galactic disks even for ALMA at cloud scale resolution. Hence radio continuum might be the only means to identify and quantify star formation in nearby galaxies at a resolution of only a few parsec. These observations are critical to develop a consistent understanding on how molecular gas is transformed into stars in a galactic environment and what the main drivers for this process are.

The high angular resolution afforded by the SKA in combination with its order of magnitude increase in sensitivity will allow for the study of the cosmic star formation history in unprecedented detail. Recent work revealed a strong relation between the star formation rate and the stellar mass of galaxies in the local Universe (e.g. Brinchmann et al. 2004). This relation holds out to high redshift (z $\sim$3), but is evolving in the sense that the average star formation rate for a given mass is increasing with look-back time (e.g. Karim et al. 2011). To-date, only the assembly properties of normal star forming galaxies living at the peak of star formation at z $\sim$2$-$3 can be probed via stacking at either radio or infrared wavelengths. This is preventing deeper insights into the drivers of star formation. Is it only stellar mass or does the galactic environment play a role as well? Also the tightness of the relation is unknown. Therefore probing down to normal star forming galaxies with star formation rates of a few solar masses per year at high redshifts will be essential to better constrain the star formation process in the early Universe. Recently, Karim et al. (2011) showed that the characteristic mass of the star forming galaxies is basically constant out to z $\sim$3 while they saw tentative evidence that the galaxies below the characteristic mass might approach an upper limit for the star formation rate per stellar mass. A possible explanation for this exciting finding might be the gas accretion rate onto the galaxies that is renewing the reservoir for star formation. The only means to push forward on this interesting front of research are ultra-deep radio observations and the SKA will be the only instrument that has the required sensitivity at sub-arsecond resolution. In addition, only the SKA can image the radio continuum emission in distant galaxies well below sub-kpc resolution providing a direct view onto the sites of star formation. Knowing the distribution of the star forming sites is key to understand if galaxy interactions, such as major mergers are important or if secular evolution of disk-like systems is dominating the cosmic star formation density. Finally, in conjunction with ALMA observations of the molecular gas content tests of any locally derived star formation laws or prescriptions could be tested.

Other applications include a full census of the radio-infrared relation in the local Universe to test the universality of the detailed studies done on nearby galaxies and a probing of the radio-infrared relation out to the early Universe. Current studies are consistent with no redshift evolution of the radio-infrared relation (e.g. Sargent et al. 2010, see Figure $1_{\rm Sm}$). However, they are biased towards highly luminous and thus highly star forming systems. Such systems are expected to harbor strong magnetic fields and could thus minimize the impact of the CMB onto the emitted radio emission (e.g. Murphy 2010).

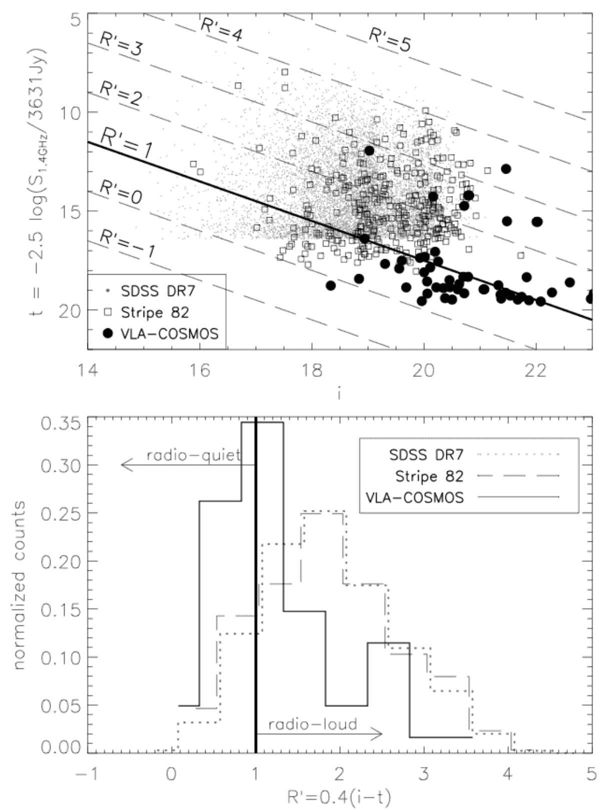


Figure $3_{\rm Sm}$: Top: i-band vs. 1.4 GHz radio magnitude (t) distribution for optically selected quasars (i.e. broad line AGN) drawn from current state-of-the-art surveys: SDSS DR7 - FIRST ($\sim$9000□°, $\rm S_{1.4GHz} \gtrsim 1\,mJy$; Schneider et al. 2010), Stripe 82 (92□°,$\rm S_{1.4GHz} \gtrsim 260\ \mu Jy$; Hodge et al. 2011), and COSMOS (2□°, $\rm S_{1.4GHz} \gtrsim 12\ \mu Jy$; Schinnerer et al. 2007, 2010; Lilly et al. 2007, 2009). The bottom panel shows the distribution of radio loudness, $R' = 0.4(i - t)$, for quasars in these three surveys.

Low-power radio-AGN: Relevance for feedback in massive galaxy formation
Within our standard model of galaxy evolution radio-mode AGN feedback has by now become a standard ingredient in cosmological models that allows reproducing the observed galaxy properties well (e.g. the galaxies' stellar mass function; Croton et al. 2006, Bower et al. 2006). Radio AGN outflows are thought to be the main source that heats the halo gas surrounding a massive galaxy, and thereby quenches its star formation and limits growth to create overly high-mass galaxies. However, from an observational perspective this process is far less clear.

The first observational support for AGN feedback has been found by Best et al. (2006), who quantitatively showed that in the local Universe radio outflows may indeed balance the radiative cooling of the hot gas surrounding elliptical galaxies. Furthermore, it has been both theoretically postulated and observationally supported that this "radio mode" heating occurs during a *quiescent phase of black-hole accretion* (presumably via advection dominated accretion flows), that is reflected in *low-power radio AGN activity* ($\mathrm{L}_{1.4\mathrm{GHz}} < 10^{25}$ W/Hz; Evans et al. 2006, Hardcastle et al. 2006, 2007, Kauffmann et al. 2008, Smolčić et al. 2009b, Smolčić 2009, Smolčić & Riechers 2011). Thus, studying low-power radio AGN and their evolution is paramount for understanding galaxy formation! However, only with the recent advent of simultaneously deep and relatively wide radio surveys could this population be comprehensively studied for the first time. The 20 cm luminosity function of low-power radio AGN, and its evolution out to z = 3 (based on VLA-COSMOS data; Schinnerer et al. 2004, 2007, 2010; Smolčić et al. 2008, 2009, in prep) provided the first quantitative insight into the plausibility of "AGN feedback" beyond the local Universe ($0.1 \leq z \lesssim 3$; see Figure 2_{Sm}). However, these results, crucial for constraining cosmological models, strongly depend on the faint end of the low-radio power luminosity function, which is (beyond the local Universe) unconstrained with current data (see Figure 2_{Sm}). Furthermore, to construct the radio luminosity function of such faint sources with high precision out to the highest redshifts it is paramount to observe large sky areas to unprecedented depth as possible only with the SKA.

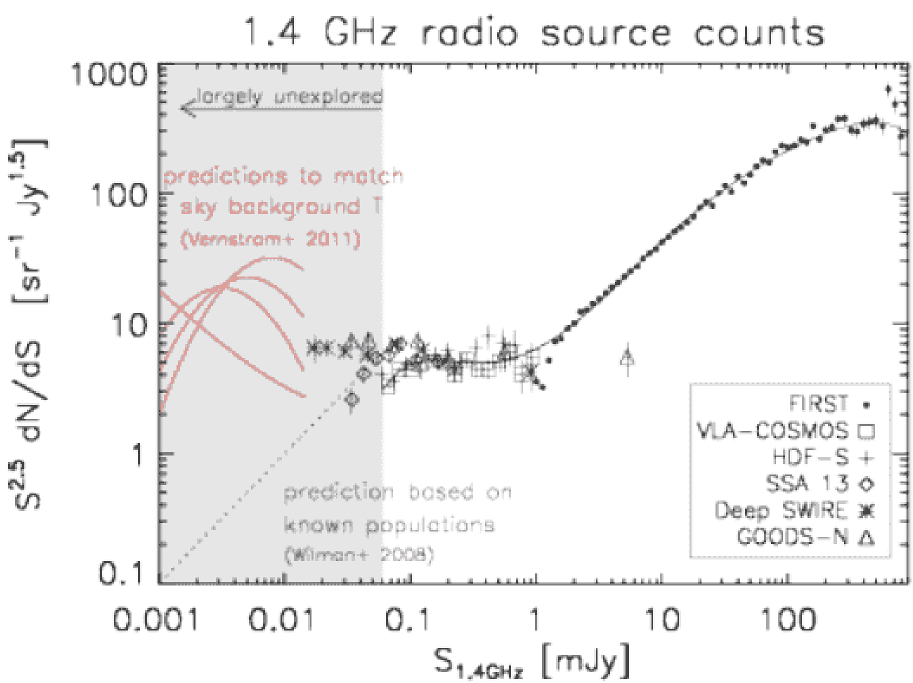


Figure 4_{Sm}: 1.4 GHz source count data (symbols), and predictions for the lowest flux densities (lines). The red full lines show the predictions that produce the background temperature necessary to match the ARCADE 2 result (Vernstrom et al. 2011). In contrast, the blue dotted line shows the generally assumed slope of faint radio source counts. The shaded area designates the flux regime largely unexplored by data. For example, the faintest point to date (Owen & Morrison 2008), is affected by completeness corrections greater than a factor of 4 as it is drawn from a very small field (Deep SWIRE, 0.44□°) with non-uniform rms (2.7 μJy/beam only in the centre). Deep SKA observations will settle this issue.

Radio-quiet quasars: Testing the Unified Model for AGN: Contrary to low-radio power AGN occurring in a quiescent phase of SMBH accretion and thought to be responsible for suppressing further stellar mass growth in massive galaxies (see previous Section), Type 1 (broad line) AGN (quasars hereafter) reflect the most intense SMBH growth in galaxies and are thought to possibly quench their star formation by expelling a fraction of the gas from the galaxy via quasar winds (so called "quasar mode AGN feedback"; e.g. Hopkins et al. 2006). The existence of two physically distinct – radio-loud and radio-quiet – quasar populations is a long debated issue that has far-reaching implications onto astrophysical problems, from unified schemes of AGN to the evolution of galaxies in the Universe. Although the quasar radio-loudness (R') distribution has been carefully studied in many different quasar samples over the past decades (e.g. Strittmatter et al. 1980, Ivezić et al. 2002, 2004, White et al. 2000, 2007, Cirasuolo et al. 2003, Baloković et al. 2011), to date there is still no clear consensus on the existence of a bimodality which would imply two physically distinct types of quasars in the Universe (pointing to e.g. different SMBH accretion/spin mechanisms and/or geometries; e.g. Fanidakis et al. 2010). To get a full census of AGN and to understand the role of quasars in galaxy formation and evolution it is paramount to understand the radio-loud and radio-quiet quasar populations.

To date this cosmologically important issue is still open mainly due to the overwhelmingly high fraction of radio-quiet quasars that are regularly undetected in radio surveys. As show in Figure $3_{\rm Sm}$ all current radio surveys (even the deepest ones) only "scratch" (the loudest end of the) radio-quiet part of the distribution. Hence, as only $\sim 10\,\%$ of optically selected quasars are radio loud (e.g. Ivezić et al. 2000), this means that roughly $90\,\%$ of quasars still remain undetected and unexplored at radio wavelengths. Observations of large areas on the sky to depths reachable with the SKA will directly reveal the radio properties of roughly $90\,\%$ of optically detected quasars.

The quest for a missing population of μJy radio sources: The radio source counts – the most straight-forward information drawn from a radio survey and commonly used to predict source counts in future deeper surveys – flatten below 1 mJy and are generally expected to decrease again at fainter fluxes (see dotted line in Figure $4_{\rm Sm}$; e.g. Hopkins et al. 2000, Wilman et al. 2008). Recent evidence, however, based on a comparison of the sky brightness temperature measured by the ARCADE 2 experiment and that derived from the integral of the observed radio source counts (Vernstrom et al. 2011), points instead to a rise of the counts at these levels (see full lines in Figure $4_{\rm Sm}$). This could possibly be explained by a new IR-faint (thus AGN) radio population so far missed by existing radio surveys due to its faintness (Vernstrom et al. 2011) and/or a mix of various AGN and star forming populations (e.g. Smolčić et al. 2008, Rigby et al. 2011). The SKA will directly test the unconstrained, $< \mu$Jy, levels of the source counts.

References:

Best, P. N., Kaiser, C. R., Heckman, T. M., & Kauffmann, G. 2006, MNRAS, 368, L67; Bower, R. G., Benson, A. J., Malbon, R., et al. 2006, MNRAS, 370, 645; Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151; Chary, R., & Elbaz, D. 2001, ApJ, 556, 562; Cirasuolo, M., Celotti, A., Magliocchetti, M., & Danese, L. 2003, MNRAS, 346, 447; Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11; Draine, B. T., & Li, A. 2007, ApJ, 657, 810; Dumas, G., Schinnerer, E., Tabatabaei, F. S., et al. 2011, AJ, 141, 41; Evans, D. A., Worrall, D. M., Hardcastle, M. J., Kraft, R. P., & Birkinshaw, M. 2006, ApJ, 642, 96; Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2006, MNRAS, 370, 1893; Hodge, J. A., Becker, R. H., White, R. L., Richards, G. T., & Zeimann, G. R. 2011, AJ, 142, 3; Hopkins, A., Windhorst, R., Cram, L., & Ekers, R. 2000, Experimental Astronomy, 10, 419; Hopkins, P. F., Somerville, R. S., Hernquist, L., et al. 2006, ApJ, 652, 864; Hughes, A., Wong, T., Ekers, R., et al. 2006, MNRAS, 370, 363; Ivezić, Ž., et al. 2002, AJ, 124, 2364; Ivezić, Ž., et al. 2004 Proceedings of IAU Symposium No. 222, p. 525 (also astro-ph/0404487); Karim, A., Schinnerer, E., Martínez-Sansigre, A., et al. 2011, ApJ, 730, 61; Kauffmann, G., Heckman, T. M., & Best, P. N. 2008, MNRAS, 384, 953; Lacki, B. C., & Thompson, T. A. 2010, ApJ, 717, 196; Lilly, S. J., Le Fèvre, O., Renzini, A., et al. 2007, ApJS, 172, 70; Lilly, S. J., Le Brun, V., Maier, C., et al. 2009, ApJS, 184, 218; Murphy, E. J., Helou, G., Braun, R., et al. 2006, ApJL, 651, L111; Murphy, E. J., Helou, G., Kenney, J. D. P., Armus, L., & Braun, R. 2008, ApJ, 678, 828; Murphy, E. J. 2009, ApJ, 706, 482; Rigby, E. E., Best, P. N., Brookes, M. H., et al. 2011, MNRAS, 416, 1900; Sargent, M. T., Schinnerer, E., Murphy, E., et al. 2010, ApJL, 714, L190; Schinnerer, E., Carilli, C. L., Scoville, N. Z., et al. 2004, AJ, 128, 1974; Schinnerer, E., Smolčić, V., Carilli, C. L., et al. 2007, ApJS, 172, 46; Schinnerer, E., Sargent, M. T., Bondi, M., et al. 2010, ApJS, 188, 384; Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360; Smolčić, V., Schinnerer, E., Scodeggio, M., et al. 2008, ApJS, 177, 14; Smolčić, V., Schinnerer, E., Zamorani, G., et al. 2009a, ApJ, 690, 610; Smolčić, V., Zamorani, G., Schinnerer, E., et al. 2009b, ApJ, 696, 24; Smolčić, V. 2009, ApJL, 699, L43; Smolčić, V., & Riechers, D. A. 2011, ApJ, 730, 64; Strittmatter, P. A., Hill, P., Pauliny-Toth, I. I. K., Steppe, H., & Witzel, A. 1980, A&A, 88, L12; Tabatabaei, F. S., Schinnerer, E., Murphy, E., et al. 2011, arXiv:1111.6252;

Thompson, T. A., Quataert, E., Waxman, E., Murray, N., & Martin, C. L. 2006, ApJ, 645, 186 Vernstrom, T., Scott, D., & Wall, J. V. 2011, MNRAS, 415, 3641; White, R. L., et al. 2000, ApJS, 126, 133; White, R. L., Helfand, D. J., Becker, R. H., Glikman, E., & de Vries, W. 2007, ApJ, 654, 99; Wilman, R. J., Miller, L., Jarvis, M. J., et al. 2008, MNRAS, 388, 1335

8.2.9 The radio continuum view of galactic scale feedback [D.J. Bomans, R.-J. Dettmar]

A key parameter for the formation and evolution of galaxies is the stellar and AGN feedback of the (proto-)galaxy onto the gas in the galaxy and onto the infalling gas from the circumgalactic or intergalactic medium (e.g. Oppenheimer & Dave 2008). While most of the large simulations treat this as pure hydrodynamical process, it is clear from observations that magnetic fields play a significant role in this process. Observations of the halos of local spiral galaxies with strong star formation show ordered magnetic fields in their halos, which are clearly affected by outflows/galactic winds (e.g. Tuellmann et al. 2000, Heesen et al. 2009, Soida et al. 2011). Here an interaction of a large scale dynamo in massive galaxies and the flow pattern of the gas is at work. Actually, a working dynamo seems to require the presence of a magnetised halo (Hanasz et al. 2006, Gressel et al. 2008) or even a magnetised wind (Brandenburg & Subramanian 2005). It is interesting to note, that galaxies at $z \sim 2$ exhibit very high starfomation rates but are generally not merging galaxies (like the most strongly starforming galaxies in the low redshift universe), but rather very gas-rich disk galaxies (e.g. Genzel et al. 2012). The effect of this spatially very extended starformation on the magnetic field and outflow structure, its kinematics, and its interaction with the infalling gas in cold filaments (e.g. Keres et al 2006, Dekel & Birnboim 2006) is unexplored yet.

Surprisingly, dwarf galaxies with significant star formation rate also show large-scale ordered magnetic fields in their disks and out into their halos (e.g. Klein et al. 1996, Kepley et al. 2010, 2011, Chyzy et al. 2000, 2003, 2011). In these cases a different kind of dynamo is needed (Siejkowski et al. 2010) which sensitively reacts to the local star formation rate. Simulations clearly show that magnetic field amplification is possible in strongly starforming dwarf irregular galaxies and that in this case a significant part of the magnetic flux can escape the potential well (Siejkowski et al. 2010, 2012).

Observations of spiral galaxies with nuclear starbursts and even galaxies with moderately high starformation rate distributed over the disk show magnetized outflows and galactic winds. These galaxies therefore enhance and distribute magnetized plasma into their surrounding intergalactic medium. Due to their abundance dwarf-like galaxies, or more precisely low mass proto-galaxies at high redshift, for which the local dwarf irregular galaxies can serve as proxies (e.g. Dekel & Silk 1986), the magnetized winds of these galaxies were proposed to fill the intergalactic medium with magnetic fields (Kronberg et al. 1999, Bertone et al. 2006, Dubois & Teyssier 2010). The contribution of more massive galaxies has not been explored and on the observational side the whole issue is open due to lack of data sensitive enough to discuss such effects for local proxies or high redshift galaxies.

Not only the local wind zones of individual galaxies can be seeded with magnetic fields, also the collision of magnetized winds can (due to field line compression) lead to further enhanced magnetic field. First hints of such a process are visible in some galaxy groups, but conclusive observations are limited by the sensitivity of current instruments.

The huge plus in sensitivity provided by the SKA will allow to explore the conditions at lower starformation rates in search of the threshold (either locally or globally) for the creation of magnetized halos, similar to the threshold for the presence of ionized gas halos discussed in Rossa & Dettmar (2003). The same holds true for dwarf galaxies for which the higher sensitivity will allow for a much larger sample size to explore the parameter space (e.g. mass, morphology, environment, etc.). The sensitivity and broad wavelength coverage will enable us to map a much larger extent of polarized (and total power) radio-continuum emission into the halo and therefore the study cosmic ray transport and the interaction of the wind with the surrounding intergalactic medium.

In galaxy groups containing several starforming galaxies, interaction of the outflows/winds and the effect of the magnetization of the intra-group medium and maybe even the intergalactic medium in filaments of the large-scale structure can be studied, most probably via RM grid techniques. The plus in sensitivity of the SKA implies also enough signal to noise (at SKA angular resolution) to investigate the details of the magnetic field at the base of galactic outflows and winds, where high ISM density and pressure create special conditions for thermal gas kinematics and cosmic ray propagation.

Finally, the measurement of total power radio continuum at several frequencies will give estimates of starformation rate and turbulent magnetic field strength of intermediate to high redshift galaxies (see Murphy 2009). In deep fields there is even the possibility of reaching the phase of galaxy formation. Again the link to the magnetization of the intergalactic medium appears and may be tested with RM grid together with global properties and distribution of the starbursting and/or highly starforming galaxy population at different redshift intervals.

References:

Bertone S., Vogt C., Ensslin T., 2006, MNRAS, 370, 319; Brandenburg A., Subramanian K., 2005, Phys. Rep., 417, 1; Chyży K.T., Beck R., Kohle S., Klein U., Urbanik M., 2000, A&A, 355, 128; Chyży K.T., Knapik J., Bomans D.J., et al., 2003, A&A, 405, 513; Chyży K.T., Weżgowiec M., Beck R., Bomans D.J., 2011, A&A, 529, A94; Dekel A., Birnboim Y., 2006, MNRAS, 368, 2; Dekel A., Silk J., 1986, ApJ, 303, 39; Dubois Y., Teyssier R., 2010, A&A, 523, A72 Gaensler B.M., Haverkorn M., Staveley-Smith L., et al., 2005, Science, 307, 1610; Genzel R., Newman S., Jones T., et al., 2011, ApJ, 733, 101; Gressel O., Elstner D., Ziegler U., Rüdiger G., 2008, A&A, 486, L35; Hanasz M., Otmianowska-Mazur K., Kowal G., Lesch H., 2006, AN 327, 469; Heesen V., Beck R., Krause M., Dettmar R.-J., 2009, A&A, 494, 563; Kereš D., Katz N., Weinberg D.H., Davé R., 2005, MNRAS, 363, 2; Kepley A.A., Mühle S., Everett J., et al., 2010, A&A, 712, 536; Kepley A.A., Zweibel E.G., Wilcots E.M., Johnson K.E., Robishaw T., 2011, ApJ, 736, 139; Klein U., Haynes R.F., Wielebinski R., Meinert D., 1993, A&A, 271, 402; Klein U., Hummel E., Bomans D.J., Hopp U., 1996, A&A, 313, 396; Kronberg P.P., Lesch H., Hopp U., 1999, ApJ, 511, 56; Murphy E., 2009, in: Panoramic Radio Astronomy: Wide-field 1-2 GHz Research on Galaxy Evolution, eds.: G. Heald & P. Serra, 29; Oppenheimer B.D., Davé R., 2008, MNRAS, 387, 577; Rossa J., Dettmar R.-J., 2003, A&A, 406, 493; Siejkowski H., Soida M., Otmianowska-Mazur K., Hanasz M., Bomans D.J., 2010, A&A, 510, A97; Siejkowski H., Otmianowska-Mazur K., Soida M., Bomans D.J., Hanasz M., 2012, in prep.; Soida M., Krause M., Dettmar R.-J., Urbanik M., 2011, A&A, 531, A127; Tüllmann R., Dettmar R.-J., Soida M., Urbanik M., Rossa J., 2000, A&A, 364, L36

8.2.10 Active galaxies – a science perspectives [A. Lobanov]

Outflows an feedback in AGN: The SKA will yield detailed imaging of extended outflows and lobes in radio galaxies and quasars, providing an excellent tool for probing physical conditions in low-energy tail of outflowing plasma which is believed to carry the bulk of kinetic power of the outflow. This will enable detailed quantitative studies of evolution and re-acceleration of non-thermal plasma in cosmic objects and provide essential clues for understanding the power and efficiency of the kinetic feedback from AGN and its effect on activity cycles in galaxies and cosmological growth of supermassive black holes. Such studies are critically needed for making a detailed assessment of the role played by AGN in the formation and evolution of the large-scale structure in the Universe.

Galactic mergers and supermassive black holes: High-resolution and high-sensitivity radio observations with the SKA will provide arguably the best AGN and SMBH census up to very high redshifts. This will enable cosmological studies of SMBH growth, galaxy evolution, and the role played by galactic mergers in nuclear activity and SMBH evolution. Most powerful AGN are produced by galactic/SMBH mergers. Direct detections of secondary SMBH in post-merger galaxies are the best way to the evolution of black holes and galaxies together. Some of the secondary black holes may be "disguised" as ultra-luminous X-ray objects accreting at a very small rate, and hence remaining undetected even in deep radio images at present. The SKA would be a superb tool for detecting and classifying such objects, thus providing an essential observational information about them SMBH evolution in post-merger galaxies and its influence on the galactic activity, formation of collimated outflows and feedback from AGN.

Radio relics and AGN cycles: Nuclear activity in galaxies is believed to be episodic or intermittent, but relics of previous cycles of nuclear activity are difficult to detect at centimetre wavelengths because of significant losses due to expansion and synchrotron emission. At centimetre wavelengths, such relics decay below the sensitivity limits of the present-day facilities within 10 − 100 thousand years after the fuelling of extended lobes stops. The SKA, working below 1 GHz, would be able to detect such relics for at least 10 million years after the fuelling stops, and this would make it possible to assess the activity cycles in a large number of objects, searching for signs of re-started activity in radio-loud objects and investigating "paleo" activity in presently radio-quiet objects. This information will be essential for constructing much more detailed models of evolution and nuclear activity of galaxies.

8.2.11 Active galactic nuclei [A. Merloni]

Introduction: Soon after their discovery in 1963, it was realised that Quasars (QSOs) were a strongly evolving class of cosmological sources, which could effectively be used as tracers of the structural properties of the Universe and the cosmological parameters (Longair 1966). The physical understanding of QSOs and of their lower-luminosity counterparts (both generally called Active Galactic Nuclei, AGN) as accreting supermassive black holes (SMBH) immediately led to speculations about the presence of their dormant relics in the nuclei of nearby galaxies, with Soltan (1982) first proposing a method to estimate the mass budget of SMBH based on the demographics and evolutionary paths of observed QSO/AGN. In the last decade, it has emerged that tight scaling relations between the central black holes mass and various properties of their host spheroids (velocity dispersion, σ^{*}, stellar mass, M, luminosity, core mass deficit) characterize the structure of nearby inactive galaxies (Tremaine et al. 2002). These correlations have revolutionized the way we conceive the physical link between galaxy and AGN evolution. Together with the fact that supermassive black holes (SMBH) growth is now known to be due mainly to radiatively efficient accretion over cosmological times, taking place during active phases (Marconi et al. 2004; Merloni & Heinz 2008), all this led to the suggestion that most, if not all, galaxies went through a phase of nuclear activity in the past, during which a strong physical coupling (generally termed "feedback") must have established a long-lasting link between hosts and black holes properties. From the cosmological point of view, the crucial aspect is that the growth of supermassive black holes through accretion (and mergers) is accompanied by the release of enormous amounts of energy which can be either radiated away, as in Quasars and bright Seyfert galaxies, or disposed of in kinetic form through powerful, collimated outflows or jets, as observed in radio galaxies. Direct evidence of AGN feedback in action has been found in the X-ray observations of galaxy clusters showing how black holes deposit large amounts of energy on kpc scales in response to radiative losses of the cluster gas (Fabian et al. 2006; Allen et al. 2006). From these (and other) studies of the cavities, bubbles and weak shocks generated by the radio emitting jets in the intra-cluster medium (ICM) it appears that AGN are energetically able to balance radiative losses from the ICM in the majority of cases (Best et al. 2006). On the other hand, numerical simulations of AGN-induced feedback have recently shown that mechanical feedback from black holes may be responsible for halting star formation in massive elliptical galaxies, explaining the bimodality in the colour distribution of local galaxies, as well as the size of the most massive ellipticals (Springel et al. 2005). At a global level, these models hinge on the unknown efficiency with which growing black holes convert accreted rest mass into kinetic and/or radiative power. Constraints on these efficiency factors are therefore vital for the models and for our understanding of galaxy formation. As well as a more detailed understanding of the triggering mechanisms of AGN activity. Here we discuss a few key contributions that the SKA will be able to make in the field. The list is far from being exhaustive and focuses on specific areas of AGN research best served by multi-wavelength synergetic surveys.

What the SKA will achieve:

– A global view of the evolving radio galaxies: AGN population studies can be used to reach the above mentioned goal by combining the evolution of the bolometric luminosity function AGN, obtained via optical, IR and X-ray surveys, with that of radio selected AGN. Thanks to its unprecedented combination of wide area and depth, SKA continuum surveys will be able to identify "typical" (L^{*}) radio AGN well beyond the epoch of major black hole growth ($z \sim 2$). While the bolometric AGN luminosity function evolution provides a mean of computing the evolution of the black hole mass function, the census of radio AGN will be fundamental in order to assess the overall amount of energy released by growing black holes in kinetic form (Merloni and Heinz 2008).

– The duty cycle of radio activity: By identifying the radio counterparts of large, statistically significant, and highly significant populations of active galaxies selected via their accretion power indicators (optical emission lines, X-ray emission, etc.). The SKA will be able to unambiguously address the long-standing question of the radio-loud vs. radio-quiet AGN dichotomy. A particularly powerful synergy is envisaged with the eROSITA all-sky X-ray survey (see e.g. Predehl et al. 2010), as an hypothetical SKA "all-sky" survey with 1 μJy sensitivity will be deep enough to identify essentially all the $\sim 10^6$ X-ray detected AGN in the eROSITA sky, both obscured and un-obscured, above a flux limit of $\sim 10^{-14}$ erg/s/cm^2 (see Padovani 2011).

– AGN hosts: Where do they get their gas?: The SKA will also allow a complete census of galaxies by detecting their H I emission out to z $\sim$ 1.5. Ancillary AGN surveys (mainly in IR and X-rays) will then reveal in which of them nuclear activity is the strongest. For the first time we will then be able to assess in a systematic way, and with high statistical accuracy, the physical connection between cold gas content and nuclear activity in galaxies spanning a wide range of masses, redshift and star formation activity.

References:

Allen et al. 2006, MNRAS, 372, 21; Best et al. 2006, MNRAS, 368, L67; Fabian et al. 2006, MNRAS, 366, 417; Longair, 1966, Nature, 211, 949; Marconi et al., 2004, MNRAS, 351, 159; Merloni and Heinz 2008, MNRAS, 388, 1011; Padovani et al. 2011, MNRAS, 411, 1547; Predehl et al. 2010, Proceedings of the SPIE, Volume 7732, pp. 77320U; Soltan, 1982, MNRAS, 200, 115; Springer et al. 2005, ApJ, 620, L79; Tremaine et al. 2002, ApJ, 574, 740

8.2.12 Disentangling AGN from starbursts: VLBI wide field imaging [E. Middelberg]

Since the invention of the VLBI technique in the 1960s, observations using it have almost exclusively been limited to the study of carefully selected, small samples of objects. There are two fundamental reasons for this: first, the need to record the raw data on tape or disk for later correlation, and second, the limitation of the field of view because of limited processing power. Whilst both effects also affect connected-element interferometers, the long baselines and consequently high spatial resolution of VLBI observations limit the field of view to around one arcsecond. Therefore traditional VLBI observations are helplessly unsuitable for surveys of large fractions of the sky.

However, with the advent of more and more powerful computers at their disposal, astronomers have begun to image sources approximately 10 years ago. Whilst imaging large numbers of objects is still far away from being mainstream, wide-field VLBI observations have become easier, and calibration has been streamlined and improved. The SKA is designed to be a survey telescope, and it is expected that its enormous computing power will easily facilitate production of wide-field VLBI data. The scientific impact of such observations can be summarised as follows.

Identifying AGN: AGN make up a significant fraction of the faint radio sky. Whilst they dominate the radio source population at high flux densities, their incidence, activity, and origin at fainter flux density levels are not understood. How many radio-emitting AGN are there at sub-mJy levels, how did they evolve into their observed form, and what is their activity – these questions can not yet be answered satisfactorily. Because of the relatively high brightness temperatures required for a detection, VLBI observations are excellent AGN filters. Furthermore, they provide the high resolution to image sub-kpc-scale structures at any redshift, yielding further clues about the interplay between the AGN and its host galaxy. The enormous sensitivity of the SKA, combined with baselines of up to 3000 km and GHz frequencies will enable detection of much fainter AGN, at larger distances, to study the role of AGN throughout the Universe.

Star formation and AGN activity: Particularly at high redshift and faint flux density levels, both AGN and star formation processes are likely to be important in a large fraction of galaxies. Such "hybrid" objects are amongst the most interesting wide-field VLBI observations can reveal, since they defy the common wisdom of a star-formation/AGN divide, and they will occur plentiful in wide-field SKA/VLBI surveys. Observations of such objects at any one wavelength will be misleading, since they are heavily obscured, and only high-resolution radio objects can reliably identify the inner emission mechanisms. Another application to the study of star-formation and AGN is the radio-infrared relation, which is a linear relation between the radio and infrared flux densities of galaxies over many orders of magnitude. It can be used to identify AGN when there is a large radio excess, since the relation is thought to arise from star-forming activity. However, a small fraction of AGN-dominated galaxies show a radio excess, but many lower-power AGN appear to obey this relation. Using the SKA, observations of VLBI cores in millions of objects will allow one to investigate the effect of AGN on this relation beyond the local Universe, and to calibrate it more accurately.

The evolution of AGN: Existing observational evidence suggests that low-luminosity radio sources correspond to a distinct type of AGN, accreting through a radiatively inefficient mode (the so-called "radio mode"), rather than the radiatively efficient accretion mode typical of optically or X-ray selected AGN (the so-called "quasar mode"). The physical reasons behind these two different accretion modes are unclear, but it is possible that "quasar mode" AGN accrete cold gas, and that they contribute significantly to the buildup of super-massive black holes predominantly in young (bluer) galaxies. Traditional VLBI observations mostly target well-selected (and bright) samples of objects, for example FRI and FRII galaxies, quasars and blazars, but also weaker objects such as Seyfert galaxies. In all these cases, a pre-selection has been made based on other known properties of the objects, and so such surveys are limited to particular classes of object. Sensitive, wide-field SKA/VLBI surveys will contribute substantially to this issue, providing an unbiased view on the pc-scale radio Universe as it evolves from $z \sim 3$ to the present day.

Studies of particular classes of object; serendipity: Surveying the sky with high resolution and high sensitivity will enable studies of particular classes of object, which alone would not warrant the required observing time. Many traditional VLBI surveys target samples of tens of objects, which must be sufficiently bright so that detections can be made in reasonable times. Such studies will benefit substantially from wide-field SKA/VLBI surveys because of the large number of objects with generally much lower flux densities (which therefore are more distant and younger). Furthermore, surveys exploring new volumes of the parameter space have always returned new, unexpected, and unpredictable results. We do not know what we are going to find, but we are confident some of it is going to be unexpected, interesting, and puzzling.

8.2.13 Magnetic field amplification with the small-scale dynamo model: Implications for the SKA

[D.R.G. Schleicher, R. Banerjee]

Probing the origin of magnetic fields: Due to the ubiquity of magnetic fields in the local Universe (e.g. Beck et al. 1996), the origin of magnetic fields is a subject of considerable interest. With the SKA, this topic can be explored by probing magnetic fields at higher redshifts and at higher resolution. If high-redshift magnetic fields have a primordial origin (e.g. Grasso & Rubinstein 2001), one might expect them to be coherent on rather large scales. However, even in the absence of strong primordial fields, the small-scale dynamo may produce strong small-scale fields already at high redshift (Beck 1996, Arshakian et al. 2009, Schleicher 2010). These possibilities and the implications for the SKA are discussed in the sections below.

Astrophysical magnetic fields: The small-scale dynamo: In the absence of strong primordial fields, astrophysical mechanisms for the production of seed magnetic fields need to be considered. Such possibilities include in particular the Biermann battery (Biermann 1950), which may create seed fields of the order 10^{-15} G in the first star-forming halos (Xu et al. 2008). In the presence of shocks, which are expected to occur during structure formation and the virialization of halos, additional and potentially stronger fields may be generated by the Weibel instability (Schlickeiser & Shukla 2003, Medvedev et al. 2004, Lazar et al. 2009).
Regardless of the origin of the seed, rapid amplification is expected in the presence of turbulence. The latter is released during the virialization of the halo from the gravitational energy, giving rise to a scenario termed

"gravity-driven turbulence" (Elmegreen & Burkert 2010, Klessen & Hennebelle 2010). The presence of sub-sonic turbulence is visible in numerical simulations of the first star-forming halos (e.g. Abel et al. 2002, Turk et al. 2009), while supersonic turbulence is found in simulations of larger primordial galaxies (Wise & Abel 2007, Greif et al. 2008).

Model	B_0 [nG]	f_*
1	0	0.1 %
2	0.02	0.1 %
3	0.05	0.1 %
4	0.2	0.1 %
5	0.5	0.1 %
6	0.8	0.1 %
7	0.8	1 %

Table $1_{\rm Sc}$: The models used in the figure to calculate the redshift evolution of the mean 21 cm brightness temperature. Given are both the co-moving field strength B_0 and the star formation efficiency f_*. We refer to (Schleicher et al. 2009) for further details.

The theory of turbulent field amplification was originally proposed by (Kazantsev 1968), and further refined by (Subramanian 1998). The theory suggests magnetic field amplification on the timescale of turbulent eddies at the resistive scale. This timescale is considerably smaller than the dynamical timescales of the system, providing a rapid amplification mechanism. It has been explored and tested using numerical simulations at high resolution (Haugen et al. 2004a, b). While the initial studies typically explore subsonic turbulence, it was recently shown that the small-scale dynamo operates under a large range of conditions, even at highly supersonic turbulence (Federrath et al. 2011), as well as during gravitational collapse (Sur et al. 2010, Federrath et al. 2011).

The SKA provides a unique opportunity to compare this prediction with observations in a variety of systems. In the local Universe, dwarf galaxies may resemble the conditions at high redshift and show a magnetic field structure that is tangled on small scales. While magnetic fields have indeed been detected in these systems (Chyży 2011), the SKA provides the unique opportunity to increase the resolution by an order of magnitude. In particular, one may then attempt to infer the slope of the power spectrum. While for a saturated field, a scaling of $\sim k^{-1/3} - k^{-1/2}$ is expected for Kolmogorov or Burgers type turbulence, the characteristic Kazantsev slope of $k^{3/2}$ would occur during the kinematic phase of the small-scale dynamo.

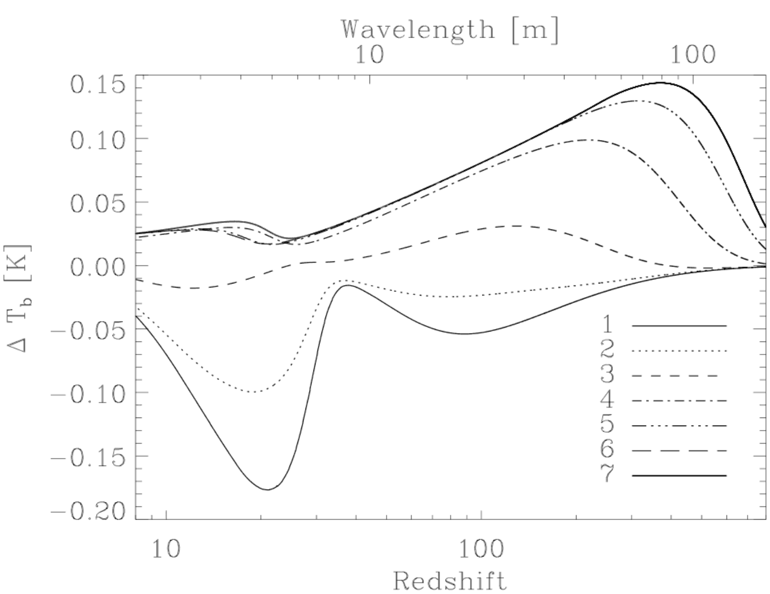


Figure $1_{\rm Sc}$: The evolution of the mean brightness temperature fluctuation as a function of redshift, in the presence of primordial magnetic fields (Schleicher et al. 2009). The models are listed in the table.

Another opportunity to explore the implications of turbulence is provided by galaxy interactions, which were recently shown to considerably amplify the tangled component of the magnetic field (Drzazga et al. 2011). Also in this case, higher-resolution observations with the SKA would provide a unique opportunity to probe these magnetic structures on much smaller scales, in order to infer characteristic properties of the small-scale dynamo and MHD turbulence.

Finally, we would like to point out that the small-scale dynamo was also suggested to operate on large cosmological scales (e.g. Ryu et al. 2008), and drive the magnetic field amplification in galaxy clusters (Dolag et al. 1999, Subramanian 2006). The study of galaxy clusters is another topic of intense study with the SKA, which will shed additional light on the questions discussed here.

Primordial magnetic fields: Constraints from the epoch of reionisation: An alternative scenario for the origin of magnetic fields is the generation of primordial fields in the early Universe (Grasso & Rubinstein 2001). In the presence of an inverse cascade, their integral scale can be shifted to kpc-scales due to the conservation of magnetic helicity (Christensson et al. 2001, Banerjee & Jedamzik 2003, Banerjee & Jedamzik 2004). Strong primordial fields were even suggested to influence the process of structure formation in the Universe (Wasserman 1978, Kim et al. 1996) and could have a considerable impact on the epoch of reionisation (Sethi & Subramanian 2005, Tashiro & Sugiyama 2006). As suggested by (Schleicher et al. 2008), such effects can be used to derive constraints on the primordial field strength. A recent analysis based on the observed UV luminosity functions suggests a 2σ constraint of $2-3$ nG due to the reionization optical depth (Schleicher & Miniati 2011).

A more sensitive probe is provided with the SKA, which will measure the 21 cm signal during reionization up to z $\sim$18. The presence of strong primordial fields could heat the high-redshift intergalactic medium to temperatures up to 10^4 K via ambipolar diffusion (Sethi & Subramanian 2005, Tashiro & Sugiyama 2006, Schleicher et al. 2008), which is reflected in the spin temperature and thus the H I brightness temperature from reionization (Tashiro et al. 2006, Schleicher et al. 2009, Sethi & Subramanian 2009). The evolution of the mean 21 cm signal as a function of redshift, and its dependence on the primordial field strength, is shown in the following figure. Additional characteristic signatures may be inferred from the 21 cm power spectrum from reionization. The SKA activities on the epoch of reionisation will thus shed additional light on the presence of primordial fields, and may help to infer stronger upper limits or potential signatures. We are thus entering an exciting epoch both with respect to the formation of the first structures and the origin of magnetic fields.

References:

Abel T., Bryan G.L., Norman M.L., 2002, Science, 295, 93; Arshakian T.G., Beck R., Krause M., Sokoloff D., 2009, A&A, 494, 21; Banerjee R., Jedamzik K., 2003, Physical Review Letters, 91, 251301; Banerjee R., Jedamzik K., 2004, PRD, 70, 123003; Beck R., et al., 1996, ARA&A, 34, 155; Biermann L., 1950, Zeitschrift Naturforschung Teil A, 5, 65; Christensson M., Hindmarsh M., Brandenburg A., 2001, PRE, 64, 056405; Chyży K.T., Weżgowiec M., Beck R., Bomans D.J., 2011, A&A, 529, A94; Dolag K., Bartelmann M., Lesch H., 1999, A&A, 348, 351; Drzazga R.T., Chyży K.T., Jurusik W., Wiórkiewicz K., 2011, A&A, 533, A22; Elmegreen B.G., Burkert A., 2010, ApJ, 712, 294; Federrath C., et al., 2011, PRL, accepted; Federrath C., et al., 2011, ApJ, 731, 62; Grasso D., Rubinstein H.R., 2001, Phys. Rep., 348, 163; Greif T.H., Johnson J.L., Klessen R.S., Bromm V., 2008, MNRAS, 387, 1021; Haugen N.E.L., Brandenburg A., Dobler W., 2004a, PRE, 70, 016308; Haugen N.E.L., Brandenburg A., Dobler W., 2004b, ApSS, 292, 53; Kazantsev A.P., 1968, Sov. Phys. JETP, 26, 1031; Kim E.-J., Olinto A.V., Rosner R., 1996, ApJ, 468, 28; Klessen R.S., Hennebelle P., 2010, A&A, 520, A17; Lazar M., Schlickeiser R., Wielebinski R., Poedts S., 2009, ApJ, 693, 1133; Medvedev M.V., et al., 2004, Journal of Korean Astronomical Society, 37, 533; Ryu D., Kang H., Cho J., Das S., 2008, Science, 320, 909; Schleicher D.R.G., Banerjee R., Klessen R.S., 2008, PRD, 78, 083005; Schleicher D.R.G., Banerjee R., Klessen R.S., 2009, ApJ, 692, 236; Schleicher D.R.G., et al., 2010, A&A, 522, A115; Schleicher D.R.G., Miniati F., 2011, ArXiv e-prints 1108.1874; Schlickeiser R., Shukla P.K., 2003, ApJL, 599, L57; Sethi S.K., Subramanian K., 2005, MNRAS, 356, 778; Sethi S.K., Subramanian K., 2009, JCAP, 11, 21; Subramanian K., 1998, MNRAS, 294, 718; Subramanian K., 2006, Astron. Nachr., 327, 403; Sur S., et al., 2010, ApJL, 721, L134; Tashiro H., Sugiyama N., 2006, MNRAS, 368, 965; Tashiro H., Sugiyama N., Banerjee R., 2006, PRD, 73, 023002; Turk M.J., Abel T., O'Shea B., 2009, Science, 325, 601; Wasserman I. M., 1978, PhD thesis, Harvard University; Wise J.H., Abel T., 2007, ApJ, 665, 899; Xu H., et al., 2008, ApJL, 688, L57

8.2.14 The origin and evolution of cosmic magnetism [R. Beck]

Magnetism is one of the four fundamental forces. However, the origin of magnetic fields in stars, galaxies and clusters is an open problem in astrophysics and fundamental physics. When and how were the first fields generated? Are present-day magnetic fields a result of dynamo action, or do they represent persistent primordial magnetism? What role do magnetic fields play in turbulence, star formation, cosmic ray acceleration and galaxy formation? The SKA can deliver superb data which will directly address these currently unanswered issues. The key data base is an *all-sky survey of Faraday rotation measures*, in which Faraday rotation towards about 10^7 background sources will provide a dense grid for probing magnetism in the Milky Way, in nearby galaxies, and in distant galaxies, galaxy clusters and protogalaxies. Using these data, we can map out the evolution of magnetized structures from redshifts $z > 3$ to the present epoch, can distinguish between different origins for seed magnetic fields in galaxies, and can develop a detailed model of the magnetic field geometry of the intergalactic medium and of the overall Universe. With the unprecedented capabilities of the SKA, the window to the Magnetic Universe can finally be opened.

Understanding the Universe is impossible without understanding magnetic fields. They fill intracluster and interstellar space, affect the evolution of galaxies and galaxy clusters, contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation, control the density and distribution of cosmic rays in the interstellar medium (ISM), and affect the propagation of the highest-energy cosmic rays which enter the Milky Way. But in spite of their importance, the *evolution*, *structure* and *origin* of magnetic fields are all still open problems in fundamental physics and astrophysics. Specifically, we still do not know how magnetic fields are generated and maintained, how magnetic fields evolve as galaxies evolve, what the strength and structure of the magnetic field of the intergalactic medium (IGM) might be, or whether fields in galaxies and clusters are primordial or generated at later epochs. Ultimately, we would like to establish whether there is a connection between magnetic field formation and structure formation in the early Universe, and to obtain constraints on when and how the first magnetic fields in the Universe were generated.

Most of what we know about astrophysical magnetic fields comes through the detection of radio waves. *Synchrotron emission* measures the total field strength, while its *polarisation* yields the orientation of the regular field in the sky plane and also gives the field's degree of ordering (see figure). *Faraday rotation* of polarisation vectors provides a measurement of the mean direction and strength of the field along the line of sight. Together this yields a full three-dimensional view. Nevertheless, measuring astrophysical magnetic fields is a difficult topic still in its infancy, still restricted to nearby or bright objects. The Square Kilometre Array (SKA) has the power to revolutionise the study of "Cosmic Magnetism".

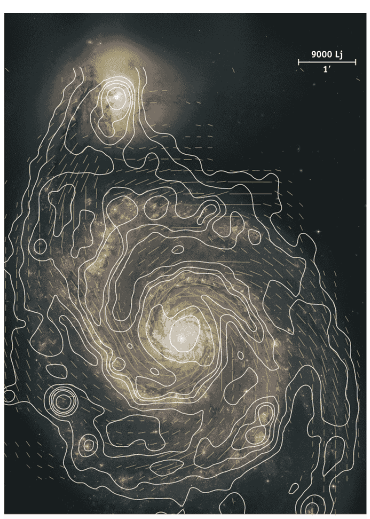


Figure $1_{\rm Be}$: The magnetic field of the grand design spiral galaxy M 51. The image shows an optical *HST* image, overlaid with contours showing the radio total intensity emission at 5 GHz. The vectors show the orientation of the magnetic field, as determined from 5 GHz linear polarisation measurements. Faraday rotation is small at this frequency (from Fletcher et al. 2011).

Much of what the SKA can contribute to our understanding of magnetic fields will come from its *polarimetric capabilities*. The main SKA specifications which enable this capability will be **high polarisation purity** and **spectro-polarimetric capability**. Another important requirement is a field of view at 1.4 GHz of at least 1 deg^2 which can be fully imaged at 1 arcsec resolution. At an observing frequency of 1.4 GHz with a fractional bandwidth of 25 %, a 1-min SKA observation of a source with a linearly polarised surface brightness of $\approx 10\,\mu$Jy beam^{-1} will yield a RM determined to an accuracy $\Delta\mathrm{RM} \approx \pm 5$ rad m^{-2}, and its intrinsic position angle measured to within $\Delta\Theta \approx \pm 10°$. Measurements of this precision will be routinely available in virtually any SKA observation of a polarised source. Currently $\sim$1200 extragalactic sources and $\sim$300 pulsars have measured RMs. These data have proved useful probes of magnetic fields in the Milky Way, in nearby galaxies, in clusters, and in distant Lyman-alpha absorbers. However, the sampling of such measurements over the sky is very sparse, and most measurements are at high Galactic latitudes.

A key platform on which to base the SKA's studies of cosmic magnetism will be to carry out an **All-Sky RM Survey**, in which spectro-polarimetric continuum imaging of 10 000 deg^2 of the sky can yield RMs for approximately 2×10^4 pulsars and $\times10^7$ compact polarised extragalactic sources in about a year of observing time (Gaensler et al. 2004). This data set will provide a grid of RMs at a mean spacing of $\sim$30 arcmin between pulsars and just $\sim$90 arcsec between polarised extragalactic sources. In our **Milky Way**, the large sample of pulsar RMs obtained with the SKA, combined with distance estimates to these sources from parallax or from their dispersion measures, can be inverted to yield a complete delineation of the magnetic field in the spiral arms and disk on scales ≥ 100 pc (e.g. Stepanov et al. 2002). Small-scale structure and turbulence can be probed using *Faraday tomography*, in which foreground ionised gas produces complicated frequency dependent Faraday features when viewed against diffuse Galactic polarised radio emission. Magnetic field geometries in the Galactic halo and outer parts of the disk can be studied using the extragalactic RM grid (Sun et al. 2008). In **external galaxies**, magnetic fields can be directly traced by diffuse synchrotron emission and its polarisation (Beck et al. 2004, see also contribution by Marita Krause).

In **clusters of galaxies**, magnetic fields play a critical role in regulating heat conduction (Chandran et al.1998, Narayan & Medvedev 2001), and may also both govern and trace cluster formation and evolution. Estimates of the overall magnetic field strength come from inverse Compton detections in X-rays, from detection of diffuse synchrotron emission, from cold fronts and from simulations, but our only direct measurements of field strengths and geometries come from RMs of background sources. Currently just $\sim$1$-$5 such RM measurements can be made per cluster; only by considering an ensemble of RMs averaged over many systems can a crude picture of cluster magnetic field structures be established. With the SKA, the RM grid can provide $\sim$1000 background RMs behind a typical nearby galaxy cluster; a comparable number of RMs can be obtained for a more distant cluster through a deep targeted observation (see contribution by Martin Krause). These data will allow us to derive a detailed map of the field in *each* cluster. With such information, careful comparisons of the field properties in various types of cluster (e.g. those containing cooling flows, those showing recent merger activity, etc.) at various distances can be easily made. Furthermore, detailed comparisons between RM distributions and X-ray images of clusters will become possible, allowing us to relate the efficiency of thermal conduction to the magnetic properties of different regions, and to directly study the interplay between magnetic fields and hot gas.

Galaxies at intermediate redshifts $(0.1 \leq \mathrm{z} \leq 2)$ are representative of the local population but at earlier epochs. Measurements of the magnetic field in such systems thus provides direct information on how magnetised structures evolve and amplify as galaxies mature. As the linearly polarised emission from galaxies at these distances will often be too faint to detect directly, Faraday rotation thus holds the key to studying magnetism in these distant sources. A large number of the sources for which we measure RMs will be quasars showing foreground Lyman-alpha absorption; these absorption systems likely represent the progenitors of present-day galaxies. If a large enough sample of RMs for quasars at known redshift can be accumulated, a trend of RM vs z can potentially be identified. The form of this trend can then be used to distinguish between RMs resulting from magnetic fields in the quasars themselves and those produced by fields in foreground absorbing clouds; detection of the latter effect would then directly trace the evolution of magnetic field in galaxies and their progenitors. At yet **higher redshifts**, we can take advantage of the sensitivity of the deepest SKA fields, in which we expect to detect the synchrotron emission from the youngest galaxies and proto-galaxies. The tight radio-infrared correlation, which holds also for distant infrared-bright galaxies, tells us that magnetic fields with strengths similar or even larger than in nearby galaxies existed in some young objects, but the origin of these fields is unknown. The total intensity of synchrotron emission can yield approximate estimates for the magnetic field strength in these galaxies.

Fundamental to all the issues discussed above is the search for **magnetic fields in the intergalactic medium**. All of "empty" space may be magnetized, either by outflows from galaxies, by relic lobes of radio galaxies, or as part of the cosmic web structure. Such a field has not yet been detected, but its role as the likely seed field for galaxies and clusters, plus the prospect that the IGM field might trace and regulate structure formation in the early Universe, places considerable importance on its discovery. To date there has been no detection of magnetic fields in the IGM; current upper limits on the strength of any such field suggest $|B_{\rm IGM}| \leq 10^{-9}$ G. Indirect evidence for weak IGM fields of $|B_{\rm IGM}| \geq 10^{-16}$ G comes from bright galactic nuclei (blazars) which have been detected in the TeV γ-ray regime, but not in the GeV regime, possibly due to scattering of secondary particles in the IGM field (Neronov & Vovk 2010). Using the SKA, this all-pervading cosmic magnetic field may finally be identified through the RM grid. If an overall IGM field with a coherence length of a few Mpc existed in the early Universe and its strength varied proportional to $(1+z)^2$, its signature may become evident at redshifts of $z > 3$. The RM distribution can provide the magnetic power spectrum of the IGM as a function of cosmic epoch and over a wide range of spatial scales. Averaging over a large number of RMs is required to unravel the IGM signal. The goal is to detect an IGM magnetic field of 0.1 nG strength, which needs an RM density of ≈ 1000 sources deg^{-2} (Kolatt 1998). Such measurements will allow us to develop a detailed model of the magnetic field geometry of the IGM and of the overall Universe.

The SKA can provide exciting new insights into the origin, evolution and structure of cosmic magnetic fields. The sheer weight of RM statistics which the SKA can accumulate will allow us to characterize the geometry and evolution of magnetic fields in galaxies, in galaxy clusters and in the IGM from high redshifts through to the present. We may also be able to provide the first constraints on when and how the first magnetic fields in the Universe were generated. Apart from these experiments which we can conceive today, we also expect that the SKA will discover new magnetic phenomena beyond what we can currently predict or even imagine.

References:

Beck R., Gaensler B.M., 2004, in *Science with the Square Kilometre Array*, eds. C. Carilli and S. Rawlings, New Astr. Rev., 48, 1289; Chandran B.D.G., Cowley S.C., 1998, Phys. Rev. Lett., 80, 3077; Fletcher A., et al., 2011, MNRAS, 412, 2396; Gaensler B.M., Beck R., Feretti L., 2004, in *Science with the Square Kilometre Array*, eds. C. Carilli and S. Rawlings, New Astr. Rev., 48, 1003; Kolatt T., 1998, ApJ, 495, 564; Narayan R., Medvedev M.V., 2001, ApJ, 562, L129; Neronov A., Vovk I., 2010, Science, 328, 73; Stepanov R., et al., 2008, A&A, 480, 45; Sun X.H., et al., 2008, A&A, 477, 573

8.2.15 Evolution of magnetic fields in galaxies and testing the galactic dynamo theory [Marita Krause]

Future deep field observations of the synchrotron emission with the SKA will make it possible for the first time to probe the radio continuum emission of normal star forming galaxies out to the edge of the Universe. Further, deep field polarisation observation will give us for the first time the possibility of tracing the magnetic field evolution and structure across cosmic time. From observations in the nearby Universe we know that radio continuum emission and far infrared emission are very tightly related to each other (known as "radio-FIR correlation") which is still not fully understood. While the radio emission depends on the magnetic field, the FIR emission is an indicator of star formation. It is also known that magnetic fields are needed for star formation and that star formation and its evolution has important influences on the dynamo action which is regarded to be the most important mechanism for magnetic field amplification and structure formation. Hence, deep field radio continuum and polarisation observations of star forming galaxies as planned with the SKA will give the unique chance to follow both, star formation and magnetic field evolution far backwards in time and by this will open a new door in understanding their interplay.

Polarised synchrotron emission from galaxies is a sign of large-scale, coherent magnetic fields, even when the galaxies remain unresolved. Stil et al. (2009) showed that the degree of polarisation of unresolved spiral galaxies depends on inclination, uniformity of the magnetic field, and galaxy luminosity (see Figure $_{\rm Kra}$). This result implies that distant normal disk galaxies with flux densities ≤ 100 microJy will be an important population of polarised radio sources for the SKA at frequencies ≥ 1 GHz. The polarisation angle of an unresolved spiral galaxy with an axisymmetric magnetic field will be oriented along the apparent minor axis of the disk, thus creating a polarised source with a (nearly) constant polarisation angle despite significant internal Faraday rotation. RM synthesis (Brentjens & de Bruyn 2005), however, of unresolved spiral galaxies will allow a reconstruction of the distribution of RMs in the disk even though the polarisation angle of the integrated emission is constant. The polarisation properties of a large sample of galaxies as a function of redshift at the same rest frame frequency reveal the evolution of magnetic fields and Faraday depolarisation in these galaxies. The polarisation quantities of these galaxies can be related to other observations to connect the evolution of the magnetic field to the global star formation rate and other tracers of galaxy evolution. Disk galaxies are common up to $z \sim 1$, and exist up to $z > 3$ (e.g. Elmegreen et al. 2007). Observational evidence for the existence of magnetic fields in galaxies up to $z = 2$ has been found from increased RM values for quasars with strong Mg II absorption lines at a smaller redshift than the quasar itself (Bernet et al. 2008, Kronberg et al. 2008).

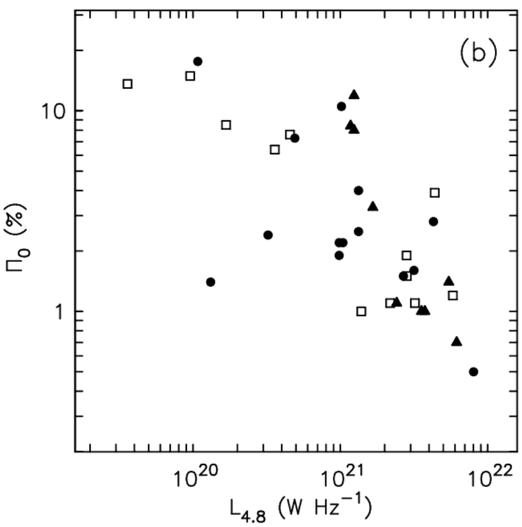


Figure $1_{\rm Kra}$: Radio luminosity at 4.8 GHz and degree of linear polarisation of unresolved spiral galaxies in the local Universe (Stil et al. 2009).

The existence of large-scale, coherent magnetic fields in galaxies are only predicted by dynamo theory, according to which the axisymmetric magnetic field structure in the galactic disk is expected to dominate (e.g. Beck et al. 1996). This field structure has indeed mainly been observed in the disk of nearby spiral galaxies. Large-scale dynamos can order magnetic fields in Milky Way type galaxies on kpc scales for redshift $z \leq 3$. The regular field strength depends on galaxy parameters and is expected to remain almost unchanged –with little evolution– until present (Arshakian et al. 2009). RMs from intervening galaxies up to $z = 2$ towards background sources (Kronberg et al. 2008, Bernet et al. 2008) indeed imply magnetic field strengths of a few μG, similar in strength to the large-scale fields found in spiral galaxies today. At redshift $z \leq 3$ significant evolutionary effects are only expected for the magnetic field structure, as the coherence scale varies as $(1+z)^{-1.5}$ (Arshakian et al. 2009). Fully ordered magnetic fields in Milky Way type galaxies should be observed only at much more recent times ($z < 0.5$). Major mergers with other galaxies can distort the field order and slow down the establishment of large-scale magnetic fields. The polarisation deep field as planned with the SKA will test the dynamo theory by tracing the emergence of fully ordered magnetic fields in galaxies as a function of redshift and galaxy size for more than a million galaxies. Observations of polarised emission from galaxy disks and RMs of background polarisation sources will allow direct observational evidence for the emergence of coherent magnetic field structures in galaxies over cosmic time.

References:

Arshakian T.G., Beck R., Krause M., Sokoloff D., 2009, A&A, 494, 21; Beck R., et al., 1996, ARA&A, 34, 155; Bernet M.L., et al., 2008, Nature, 454, L302; Brentjens M.A., de Bruyn A.G., 2005, A&A, 441, 1217; Kronberg P.P., et al., 2008, ApJ, 676, 70; Stil J.M., Krause M., Beck R., Taylor A.R., 2009, ApJ 693, 1392

8.2.16 Magnetic fields in spiral galaxies [R. Beck, Marita Krause]

The role of magnetic fields in the dynamical evolution of galaxies and of the interstellar medium (ISM) is not well understood. Radio astronomy provides the best tools to measure galactic magnetic fields: synchrotron radiation traces fields illuminated by cosmic-ray electrons, while Faraday rotation allow us to detect fields in all kinds of astronomical plasmas, from lowest to highest densities. Fundamental new advances in studying magnetic fields in nearby galaxies can be made through observations with the SKA. Mapping of diffuse polarised emission in many narrow bands over a wide frequency range will allow us to carry out *Faraday tomography*, yielding a high-resolution three-dimensional picture of the magnetic field, and allowing us to understand its coupling to the other components of the ISM. The combination with Faraday rotation data will allow us to determine the magnetic field structure in these galaxies, and to *test both the dynamo and primordial field theories* for field origin and

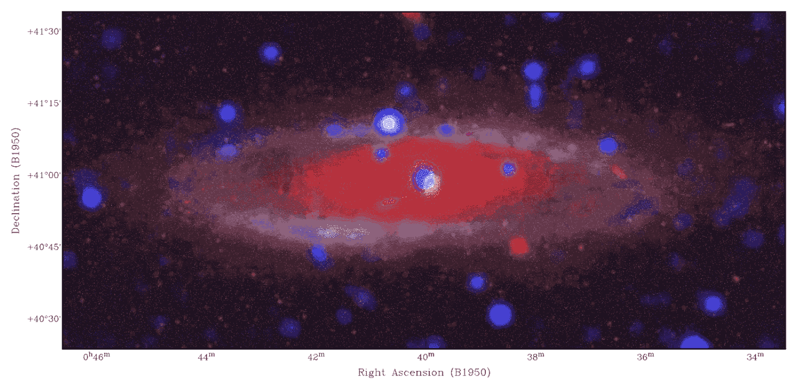


Figure 1_{Bec}: Simulation of RMs towards background sources (white points) in the region of M 31 observable with the SKA within 1 hour. Optical emission from M 31 is shown in red, diffuse radio continuum intensity in blue and diffuse polarised intensity in green (from Bryan Gaensler, priv. comm.).

A full understanding of the structure and evolution of galaxies is impossible without understanding magnetic fields. Magnetic fields fill interstellar space, contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation, and control the density and distribution of cosmic rays in the interstellar medium (ISM). New insights into galactic magnetic fields can be provided by the unique sensitivity, resolution and polarimetric capabilities of the SKA.

Magnetic fields can be detected via synchrotron emission only if there are cosmic-ray electrons to illuminate them. Cosmic rays are probably accelerated in objects related to star formation. However, the radial scale length of synchrotron emission in nearby galaxies is much larger than that of the star formation indicators like infrared or CO line emission (Beck 2007). Magnetic fields must extend to very large radii, much beyond the star-forming disk. Field strengths in the outer parts of galaxies can only be measured by Faraday rotation measures of polarised background sources. Han et al. (1998) found evidence for regular fields in M 31 out to 25 kpc radius. However, with only a few detectable polarised sources per square degree at current sensitivities, no galaxies beyond M 31 could be mapped in this way. The observation of large-scale RM patterns in many galaxies (Beck 2005) proves that the regular field in galaxies has a *coherent direction* and hence is not generated by compression or stretching of irregular fields in gas flows. In principle, the dynamo mechanism is able to generate and preserve coherent magnetic fields, and they are of appropriate spiral shape (Beck et al. 1996) with radially decreasing pitch angles.

However, the physics of dynamo action is far from being understood. Primordial fields, on the other hand, are hard to preserve over a galaxy's lifetime due to diffusion and reconnection because differential rotation winds them up. Even if they survive, they can create only specific field patterns that differ from those observed. The widely studied *mean-field $\alpha\Omega$ dynamo model* needs differential rotation and the α effect (see below). Any coherent magnetic field can be represented as a superposition of modes of different azimuthal and vertical symmetries. The existing dynamo models predict that several azimuthal modes can be excited (Beck et al. 1996), the strongest being $m = 0$ (an axisymmetric spiral field), followed by the weaker $m = 1$ (a bisymmetric spiral field), etc. These generate a Fourier spectrum of azimuthal RM patterns. The axisymmetric mode with even vertical symmetry (quadrupole) is excited most easily. Primordial field models predict bisymmetric fields or axisymmetric fields with odd (dipole) symmetry. The SKA will dramatically improve the situation. Within the fields of M 31, the LMC or the SMC (a few square degrees each), a deep observation could provide $> 10^5$ polarised background sources (Figure $1_{\rm Bec}$), and thus allow fantastically detailed maps of the magnetic structure. The SKA will be able to confidently determine the Fourier spectrum of dynamo modes from high-resolution RM maps of the diffuse polarised emission. An RM grid of background sources is even more powerful: Already 10 RM values are sufficient to identify a single dominating dynamo mode (Stepanov et al. 2008). With the SKA, galaxies out to about 100 Mpc distance become observable. RM grids towards nearby galaxies will allow a 3-d reconstruction of the field pattern.

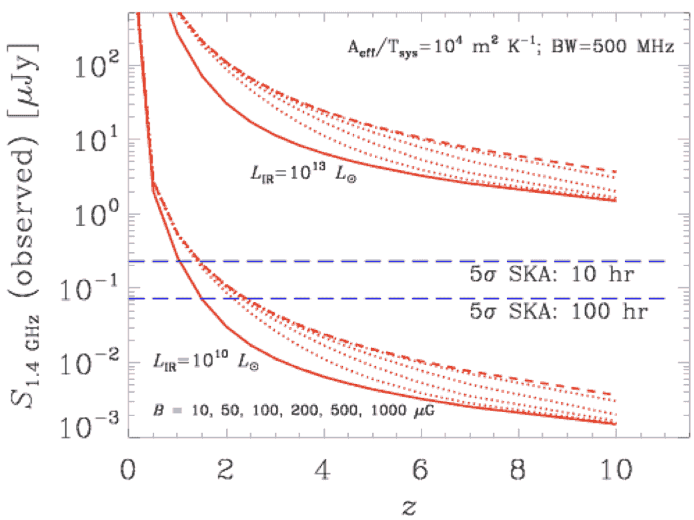


Figure $2_{\rm Bec}$: Synchrotron emission at 1.4 GHz as a function of redshift z and magnetic field strength B, and the 5σ detection limits for 10 and 100 hrs integration time with the SKA (from Murphy 2009).

The SKA has the potential to increase the galaxy sample with well-known field patterns by up to three orders of magnitude. The conditions for the action of galactic dynamos can be clarified. For example, strong density waves are claimed to support the $m = 2$ mode while companions and interactions may enhance the bisymmetric $m = 1$ mode. A dominance of bisymmetric fields over axisymmetric ones would be in conflict with existing dynamo models and would perhaps support the primordial field origin. The lack of a coherent magnetic field in a resolved galaxy would indicate that the timescale for dynamo action is longer than the galaxy's age (Arshakian et al. 2009), or that the mean-field dynamo does not work at all. The detailed structure of the magnetic fields in the ISM of nearby galaxies and in galaxy halos can be observed. The turbulence power spectra of the magnetic fields can be measured. Direct insight into the interaction between gas and magnetic fields in these objects will become possible. Faraday rotation in the direction of bright quasars allows us to determine the strength and pattern of a regular field in an intervening galaxy. This method can be applied to distances of young quasars (z $\simeq$ 5). Mean-field dynamo theory predicts RMs from regular galactic fields at z $\leq$ 3 (Arshakian et al. 2009). Unpolarised synchrotron emission, signature of turbulent magnetic fields, can be detected with the SKA out to very large redshifts for starburst galaxies, depending on luminosity and magnetic field strength (Figure $2_{\rm Bec}$). However, for fields weaker than $3.25\ \mu$G $(1+z)^2$, energy loss of cosmic-ray electrons is dominated by the inverse Compton effect with CMB photons, so that their energy appears mostly in X-rays and not in the radio range. On the other hand, for strong fields the energy range of the electrons emitting at a 1.4 GHz drops to low energies, where ionization and bremsstrahlung losses may become dominant. In summary, the mere detection of synchrotron emission at high redshifts will constrain the range of allowed magnetic field strengths.

References:

Arshakian T.G., Beck R., Krause M., Sokoloff D., 2009, A&A, 494, 21; Beck R., et al., 1996, ARA&A 34, 155; Beck R., 2005, Astronomische Nachrichten, 326, 608; Beck R., 2007, Advances in Radio Science, 5, 399; Han J.L., Beck R., Berkhuijsen E.M., 1998, A&A, 335, 1117; Stepanov R., et al., 2008, A&A, 480, 45; Murphy E., 2009, ApJ, 706, 482;

8.2.17 Structure and evolution of magnetic fields in star-forming galaxies [T.G. Arshakian]

Presently, the magnetic fields of only few tens of nearby galaxies are studied due to limited sensitivity of present-day radio telescopes. With capabilities of the SKA it will become possible to investigate the structure of magnetic fields in local star-forming (SF) disk galaxies and evolution of magnetic fields in distant SF galaxies.

Faraday rotation measures (RM) of polarised background sources towards SF galaxies is shown to be a powerful tool to *recognise* and *reconstruct* the regular magnetic field patterns in galaxies, characterised by the spiral pitch angle (Stepanov et al. 2008). Single and mixed modes, the amplitude of the regular field, and the azimuthal phase can be recognised from a limited sample of about 15 RM measurements of polarised background sources. Galaxies with strong turbulence and small inclination angles need more background sources for a reliable recognition. Future all-sky RM survey with the SKA at about 1 GHz would allow field recognition of about tens of thousands SF galaxies up to a distance of 100 Mpc.

A reliable reconstruction of the field structure would require at least 20 RM values on a cut along the projected minor axes, which translates into thousands RM measurements towards a galaxy. The reconstruction method is superior for galaxies inclined at $\gtrsim 70$ degrees and is possible for the nearest galaxies up to 10 Mpc (M 31, M 33, IC 342, NGC 6946, etc.) but it will require tens to a hundred hours of integration time to achieve a sufficient detection limit of polarised intensity at 1.4 GHz (Stepanov et al. 2008).

It follows to note that the integration time of the SKA to detect polarised background sources strongly depends on the slope of the number count function (uncertain by now) and on Faraday depolarisation, which becomes stronger at lower radio frequencies (Arshakian & Beck 2011). Hence, high radio frequencies ($\gtrsim 1$ GHz) are preferable for the reconstruction and recognition of field structures.

Very little is known about regular magnetic fields and their evolution in distant galaxies. Dynamo theory is able to describe the amplification and ordering of regular magnetic fields to a level seen in present day starforming (SF) galaxies (Arshakian et al. 2009a). Simulations of the total intensity, polarisation, and Faraday depth of an evolving SF disk galaxy are shown in Figure $1_{\rm Ar}$ (Arshakian et al. 2011). These simulations predict patchy field structures and field reversals of regular fields, asymmetric and inhomogeneous RM structures in younger galaxies (less than a few Gyrs); a weak regular field and small ordering scale in young galaxies; polarisation patterns and asymmetric structures in older galaxies, that are frequency dependent due to depolarisation effects at low radio frequencies; complicated field pattern in interacting and merging galaxies. Predictions of present dynamo models (Arshakian et al. 2011, Moss et al. 2012) and future sophisticated models can be tested with upcoming/future sensitive radio telescopes such as ASKAP and the SKA. Radio continuum and polarisation observations of distant disk and dwarf galaxies will allow the merging rate, history of field reversals, change of the magnetic field strength and coherence to be determined up to a redshift z $\approx$ 3. Observations of RMs against distant background polarised quasars (Kronberg et al. 2008) can be applied to study the evolution of regular fields in SF disk galaxies (identified by optical spectroscopic observations of absorption line systems, see Bernet et al. 2008) even to high redshifts of z $\approx$ 5.

Another promising tool to study the evolution of regular fields in distant galaxies is the observation of RM of background sources against gravitational lens systems (Narasimha & Chitre 2004). The power of this method is that the observed difference of RMs of a lens system originates in the magneto-ionic medium of a lens galaxy and it does not depend on Faraday rotation of our Galaxy and intergalactic medium. A large number of lens systems is needed for a meaningful statistics of RM differences. Thousands of lens systems per square degree will be detected with the SKA down to a limiting rms sensitivity of 1 μJy (Koopmans et al. 2004). Many SF galaxies and radio-quiet AGN are expected to be lens galaxies. This will allow the cosmological evolution of magnetic fields in these galaxies to be probed beyond z$\approx$1 (Arshakian et al. 2009b).

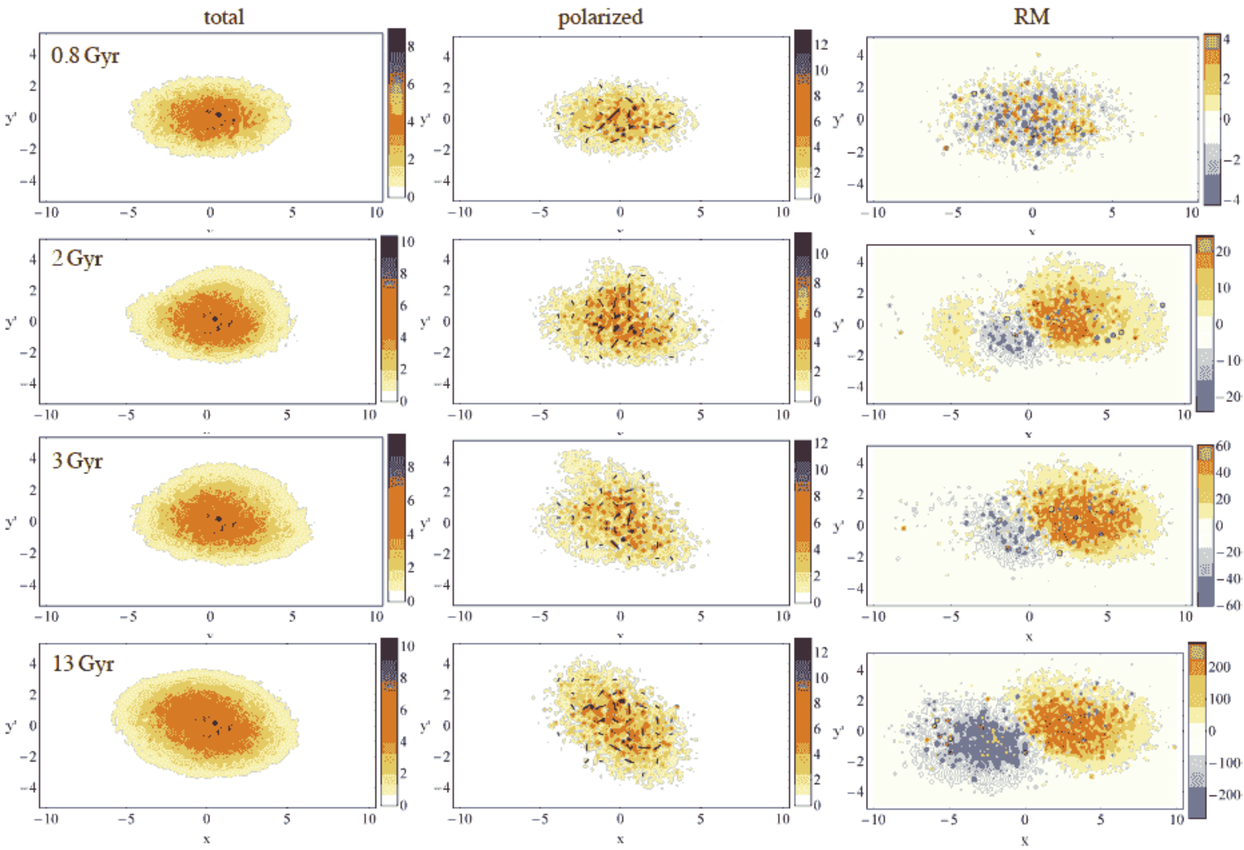


Figure 1$_{\rm Ar}$: Simulations of a SF disk galaxy are shown at 0.8 Gyr, 2 Gyr, 3 Gyr, and 13 Gyr after disk formation. The simulations are based on an evolving dynamo model. The observed total intensity (*left panel*), polarisation (*middle panel*), and Faraday rotation (*right panel*) at 150 MHz are simulated for a galaxy with an inclination angle of 60° and star-formation rate of 10 $M_\odot$ yr^{-1}. The frame units are given in kpc. The colour bars in the first and second columns (total and polarised intensity) are given given in arbitrary units. The colour bar of the third column (Faraday rotation measure) is given in units of rad m^{-2}.

This research will be done in close collaboration with the magnetic field research group of the "Max-Planck-Institut für Radioastronomie" in Bonn.

References:

Arshakian T.G., Beck R., 2011, MNRAS, 418, 2336; Arshakian T.G., et al., 2011, Astronomische Nachrichten, 332, 524; Arshakian T.G.,et al., 2009a, A&A, 494, 21; Arshakian T.G.,et al., 2009b, in: Wide Field Astronomy and Technology for the Square Kilometre Array, eds. S. A. Torchinsky et al., p. 103; Bernet, M.L., et al.,2008, Nature, 454, 302; Koopmans L.V.E., Browne I.W.A., Jackson N.J., 2004, New Astronomy Review, 48, 1085; Kronberg P.P., et al., 2008, ApJ 676, 70; Moss D., et al.,2012, A&A, 537, A68; Narasimha D., Chitre S.M., 2004, Journal of Korean Astronomical Society, 37, 355; Stepanov R., et al.,2008, A&A, 480, 45

8.2.18 The SKA and the plasma Universe – new insights into radio galaxies and galactic outflows

[Martin Krause]

Since the Cosmic re-ionisation at high redshift, the Universe is predominantly ionised and therefore a plasma, carrying currents and magnetic fields. In order to understand the physics of this plasma, including the transport of heat and Cosmic Rays, magnetohydrodynamics, turbulence and mixing with other gas phases, measurements of both, particles and the magnetic fields are required. Ionised gas is now being seen in X-rays and emission lines out to redshifts beyond unity. The magnetic field is mainly accessible via synchrotron emission and Faraday rotation in polarised radio emission. Currently, we have this information essentially only for a few very nearby clusters and groups at redshift $z < 0.1$ (Krause et al. 2009), with a few notable exceptions of rotation measures towards luminous high redshift radio sources (O'Sullivan 2011, Broderick 2007).

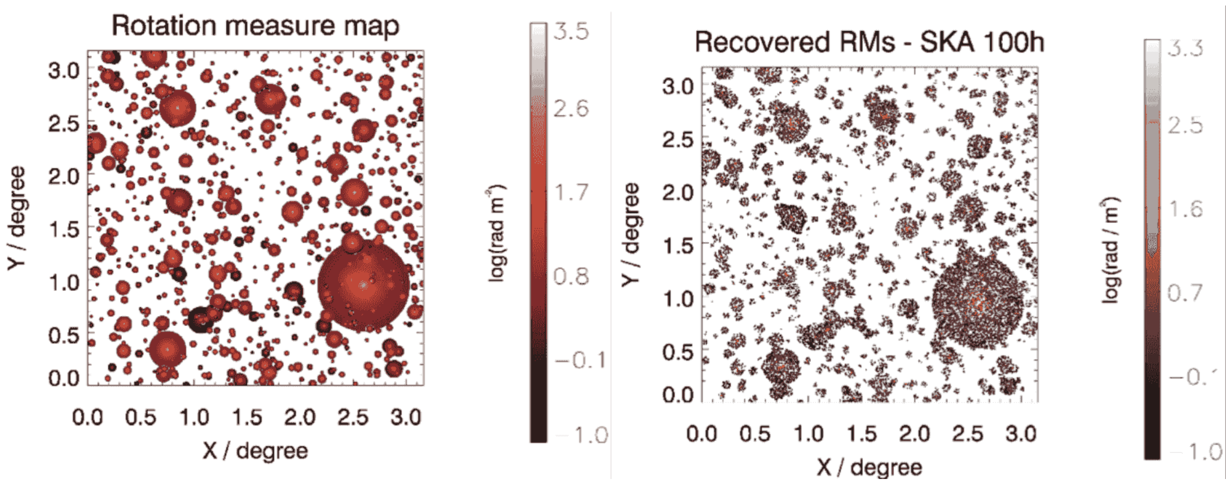


Figure 1_{Kra}: left: Distribution of rotation measures from a Cosmological model.
right: Recovered rotation measure distribution for a simulated SKA observation using specs appropriate for the proposed mid-frequency array (AA-high, Schilizzi et al. 2007, Faulkner et al. 2010). Figures are from Krause et al. 2009.

The Square Kilometre Array (SKA) has the potential to revolutionise the field, providing much more detailed information on the magnetic field in nearby groups and clusters (Krause et al. 2009), and extending the magnetic horizon out to beyond a redshift of unity, comparable with current and planned capabilities of X-ray missions. The impressive recovered rotation measure distribution from a Cosmological calculation is shown in Figure 1_{Kra} (Krause et al. 2009). A 100 hrs SKA observation should yield about 10 000 polarised sources per square degree, resulting in an RM grid with a spacing of about half a minute of arc. This will allow us to follow the evolution of magnetic fields in the dense structures of the Universe. One expectation is that magnetic fields originate in galaxies and are brought to the intra-cluster/group medium (and possibly beyond) by galactic outflows. They are then further amplified due to the gas kinematics (e.g. Ryu et al. 2008), which may be partly due to the same outflows, but probably largely due to the Cosmic flow. The outflows themselves will be a target of the SKA.

Both, star-forming galaxies and outflows related to the jets of Active Galactic Nuclei are radio emitters. I focus here on the latter. Massive galaxies at high redshift frequently have powerful radio jets (Miley & de Breuck 2008). They are associated with gaseous outflows, the so-called emission line or Lyman-alpha halos, which remove a significant amount of ionised gas from the host galaxies. Neutral hydrogen is frequently found in absorption. A successful model that explains all the currently available data is the following (Krause et al. 2005): First, intense star formation with 100s of solar masses per year produces a galactic wind. The wind shell cools and hydrogen recombines. Then the jet is started, hits the shell and is impeded for a while. During that time it fills the wind shell (Figure 2_{Kra}).

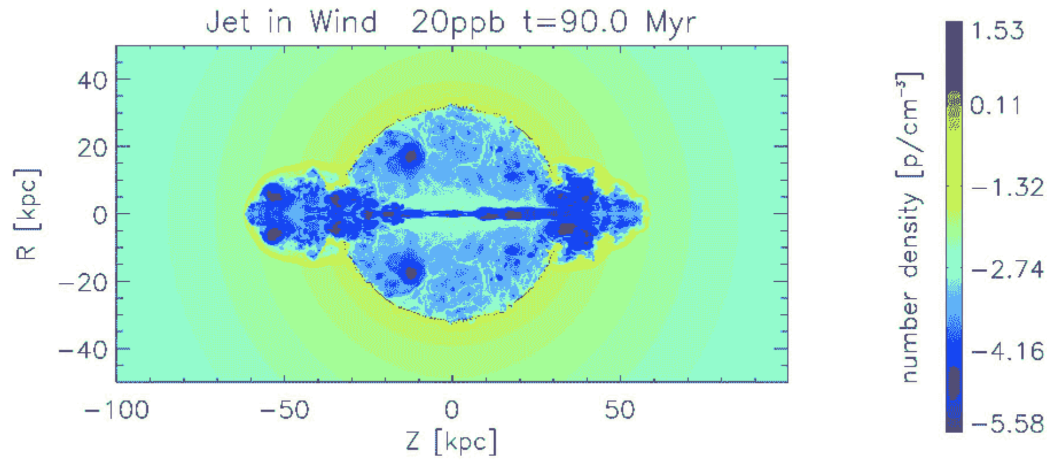


Figure 2_{Kra}: This figure displays the simulation of an extragalactic jet breaking through the shell of a galactic wind caused by supernova activity (Krause 2005). The blue regions are radio emitting plasma, the thin red almost circular region is the galactic wind shell, which provides a screen for Faraday rotation. When the jet first hits the wind shell, it is considerably impeded, and the radio lobes quickly fill the wind shell. Radio sources of this kind are known at redshifts of 1−5, have polarised fluxes of order 10 mJy, and angular diameters of a few to tens of seconds of arc. They will thus be well resolved and easily detected with the SKA.

The acceleration by the excess pressure destroys the wind shell, explaining why the corresponding absorbers are only found in small radio sources. Faraday rotation of about 10^4 rad / m^2 has been measured for the source PKS B0529-549 at redshift z = 2.6. The source also has a prominent local neutral hydrogen absorber, which could be due to such a wind shell. The rotation measure is consistent with a line of sight magnetic field of 10 μG and a neutral fraction of a few per cent within the wind shell. The Faraday rotation could also be due to the general interstellar medium in the host galaxy. The polarised radio flux of PKS B0529-549 is about 10 mJy, no issue for SKA with a 1-hour sensitivity better than 1 μJy. Such a source will therefore be resolved by the SKA in polarised flux. The SKA will therefore be able to tell us

– if the shape of the radio emission is reminiscent of a wind shell

– if the absorbing column of neutral hydrogen agrees with the measurements from Lyman-alpha absorption

– if the column density increases, and the bulk velocity of the absorbers decrease towards the edges, as expected for wind shells

– if the rotation measure increases towards the edges as expected from the mainly tangential field geometry expected in a compressed layer (compare with Huarte-Espinosa et al. 2011)

Thus, we will be able to see and quantify the ejection of magnetised plasma directly.

In nearby clusters, cold fronts could be mapped out (Alexander et al. 2007), and thus the SKA would be able to confirm, if the necessary reduction in conductivity is really due to a tangential magnetic field, as we would expect. Traditional radio sources still present serious problems to plasma physics: While having a mean free path which exceeds the source size by many orders of magnitude, they are able to displace the surrounding cluster gas. Their lobe kinematics seems to be describable by stretching and magnetohydrodynamic turbulence (Huarte-Espinosa

2011b). The magnetic field at their boundaries must be exactly tangential, otherwise the heat flux to the cluster gas would not allow the radio lobes to grow. New plasma physics simulations beyond ideal magnetohydrodynamics are required to understand these issues. The SKA will provide the required high resolution polarisation observations to compare with a regular magnetic field along the line of sight. Extragalactic radio sources confine their heat and particle content almost perfectly, a quality that is intensely sought-after in laboratory fusion plasma research (e.g. Wolf 2003). While one would hardly expect that the solution for the problems in the lab will be found in space, one should keep in mind that progress is being made in related areas of physics, with possibilities of cross-fertilisation.

References:

Alexander P. et al. , 2007, Proceedings of Science (MRU) 052, 068, 525; Broderick J. W., De Breuck C., Hunstead R. W., Seymour, N., 2007, MNRAS, 375, 1059; Faulkner A. et al., 2010, SKA Memo, 122; Huarte-Espinosa M., Krause M., Alexander M., 2011, MNRAS, 417, 382; Huarte-Espinosa M., Krause M., Alexander M., 2011b, MNRAS, 418, 1621; Krause M., et al., 2009, MNRAS, 400, 646; Krause M., 2005, A&A 436, 845; Miley G., de Breuck C., 2008, A&ARv, 15, 67; O'Sullivan S. P., Gabuzda D. C., Gurvits L. I. 2011, MNRAS, 415, 3049; Ryu D., Kang H., Cho J., Das S., 2008, Science, 320, 909; Schilizzi R.T. et al. , 2007, SKA Memo, 100; Wolf R.C., 2003, Plasma Phys. Control. Fusion, 45, R1- R91

8.3 Galactic astronomy

8.3.1 Neutral hydrogen in the Milky Way and the local Universe [J. Kerp]

Abstract: Our aim is to create a major data base for galactic astronomy for the next decade. We propose to combine all-sky surveys from the worlds largest single dish telescopes with SKA data for velocities -1000 $\mathrm{km\,s^{-1}} < |v| <$ 6000 $\mathrm{km\,s^{-1}}$. This range covers the whole Milky Way neutral hydrogen (H I) radiation as well as all members of the local Galaxies, where zero spacing correction is urgently needed to provide a comprehensive view of the complex gas physics.

We propose to use SKA data acquired during wide-field area surveys to generate an all-purpose database on the H I distribution in the Milky Way and the local Universe at an angular resolution of half an arcmin. This database will comprise all declinations below +30 degree, unbiased and homogeneous in its coverage. Because of the proximity of the objects of interest, most of the warm gaseous phase of the H I distribution will not be included within the SKA data. Combining the SKA survey with the Parkes (HIPASS and GASS) and Effelsberg (EBHIS) data will provide an unbiased physical view of the Milky Way, the accretion history of the local group and the local large-scale structure.

A Galactic H I database is urgently needed for the exploration of the warm hot intergalactic medium (WHIM). The WHIM is thought to host about 80 % of the total baryonic budget of the Universe. Due to the structure formation shocks heat the gas of the Lyman-alpha forest to coronal temperatures in the range of 10^6 K. It is difficult to observe this gas phase because its radiation (E $\sim$ 0.2 keV) is strongly attenuated by photoelectric absorption traced by the H I distribution. According to this, the nature of the WHIM in the local group and around the Milky Way, in particular the spatial distribution on arcmin scales, is currently nearly unexplored. The team aims to correlate the eROSITA soft X-ray survey with high resolution short spacing corrected H I data. The strength of the photoelectric absorption is determined by the amount of warm neutral gas, while the cold neutral gas causes strong but spatially well defined (arcmin scales and below) X-ray shadows. H I data covering all spatial frequencies up to the arcmin scale are needed to open the window to the distant Universe.

The exploration of the early Universe at high redshifts an SKA H I survey is even more important. The proposed SKA H I survey database will open for the first time large areas of the sky for X-ray astronomers. Future X-ray observatories like IXO will have a significant fraction of their detection power in the soft X-ray energy range below 1 keV. The emission of active Galactic nuclei at high redshifts (z $\sim$ 10) or the faint emission of clusters of galaxies at moderate redshifts (3 $\leq$ z $\leq$ 5) is shifted ($\mathrm{E} = \frac{E}{1+\mathrm{z}}$) to the soft X-ray band where photoelectric absorption strongly modulates the X-ray intensity of the objects. It is not possible to analyze the X-ray data quantitatively without knowing in detail the distribution of the Galactic ISM. The SKA will overcome the present situation that X-ray astronomy are focused predominantly towards two low H I column density windows of the Milky Way (HDF, CDFS). To overcome the "cosmic conspiracy" it is necessary to open the whole high Galactic latitude sky to X-ray astronomy. ASKAP, with short spacing data based on LAB, GASS and EBHIS will provide an ideal data base for this purpose.

Investigations of the accretion history of the Milky Way halo gas will need SKA H I data. This includes a search for stream-like H I structures, HVCs, and IVCs. Within a research project our team could demonstrate that optical and UV absorption line measurements correlated with single dish and interferometric H I data disclose the physical similarity of HVCs and IVCs with absorption line systems at cosmological distances. Here, excitation conditions and chemical composition appear to be pretty comparable. This offers the opportunity to study in great detail, because of the proximity, dynamics and structure of the metal-absorption line systems and connecting the accretion history of the Milky Way to the cosmological evolution of the Universe as whole.

8.3.2 Hydroxyl masers in the Milky Way and local group galaxies [D. Engels]

In the Milky Way maser emission is often observed in the circumstellar shells of red giant stars and in the surroundings of young stellar objects. These are environments, which are cool enough to form molecules and provide sufficient velocity coherence and density, so that the masers naturally are excited. The strongest stellar masers are those of oxygen-bearing molecules like hydroxyl (OH), water (H_2O) and silicium-oxide (SiO). Methanol (CH_3OH) and to lesser extent ammonia were detected in addition close to star-formation regions. The major maser lines accessible with the SKA will be from OH, at frequencies of 1612, 1665 and 1667 MHz after completion of SKA_1 construction and the CH_3OH maser line at 6.7 GHz later on. Other prominent maser lines at higher frequencies such as from H_2O at 22 GHz and from CH_3OH at 12.2 GHz will not be accessible during the first two construction phases.

Currently >2000 stellar (Engels et al. 2010) and several hundred interstellar OH masers are known in the Milky Way. Most were discovered by surveys with single-dish radio-telescopes with typical survey limits of several hundred mJy, but the ATCA-VLA survey (Sevenster 2002) already showed that the number of detections still increases strongly with decreasing sensitivity limits. The known OH masers are typically located in the Galactic Plane at distances $2-8$ kpc from the Sun. Typical peak luminosities of stellar OH masers are 3×10^{13} Watt/Hz. Their characteristic double-peaked profiles allow the determination of the radial velocity of the star and the expansion velocity of the circumstellar shell with high accuracy. OH masers have been used to infer the presence and strength of magnetic fields in the outer regions of the circumstellar shells of AGB stars (Vlemmings 2007).

With the SKA several thousand OH maser sources can be discovered already in SKA_1 with shallow surveys (~ 100 mJy). Such surveys will uncover the population of OH masers beyond the Galactic Centre (GC), allowing the study of the structure and the kinematics of stellar populations in the parts of the Milky Way opposite to the Sun. As the OH maser lifetimes might be limited (Engels & Jimenez- Esteban 2007), repeated sensitive surveys along the Galactic Plane will unearth lower-luminosity and only temporarily present masers. With SKA's sensitivity, polarisation studies of the OH maser lines of large samples of AGB stars are feasible. The physical mechanism responsible for the launch of the strong winds on the AGB and of non-axisymmetric winds in the post-AGB phase is still not understood, and such polarisation studies will help to understand the role of magnetic fields for launching and shaping the winds. SKA studies of the OH maser lines and ALMA studies of higher frequency masers (f.e. SiO, H_2O) in the mm and submm wavelength will be complementary, as sources showing maser lines from one molecule often have maser emission from the other molecules as well.

Only few maser sources with luminosities similar to their Galactic analogs are known outside the Milky Way. In the Large Magellanic Cloud about 10 OH masers (1612 MHz) with peak-flux densities $17-600$ mJy are known in late-type stars (Marshall et al. 2004), and the number of star-formation sites with interstellar masers is of the same number (Ellingsen et al. 2010). In the Local Group M 31, M 33 and IC 10 a few intrinsically bright H_2O masers belonging to star-formation regions are known (Darling 2011). Taking advantage of the compactness of maser sites, Brunthaler et al. (2005) have shown that with VLBI and phase-referencing techniques, the proper motions of local group galaxies can be measured on scales of tens of microarcseconds per year. This technique will be applicable to the OH and CH_3OH maser sources alike. Galactic analog OH masers at the distance of M 31 are expected to have flux densities of $\sim$400 microJy, extending up to $\sim$15 mJy for the brightest. The bright end of the maser population can be detected at the 5 sigma level already in SKA_1 in $\sim$400 s (bandwidth 5 kHz), while the average Galactic analog OH maser will be detectable in SKA_2 in $\sim$40 min. SKA surveys for OH masers in Local Group galaxies will provide sufficient targets for proper motion studies of the galaxies and provide key insight into the Local Group's historic and future dynamical evolution. The detection of the maser population is also helpful for modelling of their stellar populations in general, because the maser properties can be used to clarify the nature of those stars, which currently evolve in an optically obscured, infrared bright phase, either as young stars or as late-type giants.

References:

Brunthaler A., Reid M.J., Falcke H., et al., 2005, Science 307, 1440; Darling J., 2011, ApJ 732, L2; Ellingsen S.P., Breen S.L., Caswell J., et al., 2010, MNRAS 404, 779; Engels D., Jimenez-Esteban F., 2007, A&A 475, 941; Engels D., Bunzel F., Heidmann B., 2010, Database of Circumstellar Masers v2.0, http://www.hs.uni-hamburg.de/maserdb ; Marshall J.R., van Loon J.T., Matsuura M., et al. 2004, MNRAS 355, 1348; Sevenster M.N., 2002, AJ, 123, 2772; Vlemmings W.H.T., 2007, in IAU Symp. 242, Eds. J.M. Chapman & W.A. Baan. p. 37

8.3.3 The Galactic magnetic field [W. Reich]

Magnetic fields are an importent constituent of the interstellar medium. Magnetic fields could not be directly observed, but are traced by changing the propagation of cosmic-rays or the polarisation plane of electro-magnetic waves in the presence of thermal gas. Radio polarisation provides the key information to reveal the properties of the Galactic magnetic field. Intensive efforts were made in the past employing various observing techniques to trace its small-scale turbulent components on sub-parsec scales and its large-scale regular components on kpc-scales. Synchrotron emission dominates the radio sky at low frequencies, where its intensity depends on the strength of the magnetic field component perpendicular to the line-of-sight. The direction in the plane of sky is observed by linear polarisation when corrected for Faraday rotation effects. The measured linear polarisation percentage is significantly lower than its intrinsic value due to irregular magnetic fields, Faraday depolarisation and also beam averaging effects. Faraday rotation traces the magnetic field along the line-of-sight. Combining all data should in principle provide a 3-d reconstruction of the magnetic field and its properties. The following figure shows a currently widely accepted model of a regular axisymmetric-field with one proven reversal revealed by pulsar RM observations, which seems to agree qualitatively with almost all presently available observations.

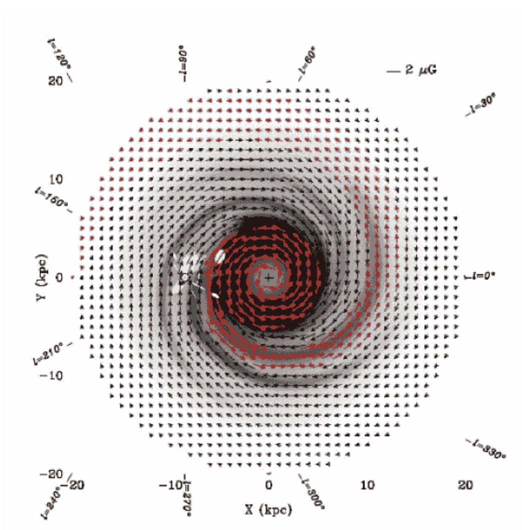


Figure $1_{\rm Re}$: The regular Galactic magnetic field when seen face-on as modeled by Sun et al. (2008). The magnetic field follow the spiral arms based on the NE2001 model of the Galactic thermal electron density distribution by Cordes & Lazio (2002). The position of the Sun is indicated and also some thermal features accounted for in the NE2001 model.

However, we know from magnetic field observations of nearby galaxies, that clear deviation exists from a simple spiral pattern assumed for the Galaxy. Discrete sources like supernova remnants and HII-regions highly influence the magnetic field structure locally on scales up to a hundred parsec or more. Only recently passive Faraday screens were revealed as objects with strongly enhanced regular magnetic fields on scales of tens of parsecs and often have a reverse direction to the Galactic large scale field. They must be known and taken into account when talking about the large scale field, but so far little is known about their number and origin. The turbulent magnetic field component at least as strong as the regular field, but its spectrum is not very well constrained. More high quality data are needed and are expected to be provides by the SKA. Most important is the SKA L-band Rotation Measure (RM) survey, which will result in several million RMs of extragalactic sources at about 1 arcsec angular resolution (Beck & Gaensler, 2004). This RM survey will improve available datasets by two orders of magnitude. Combining extragalactic RM data with arcsec SKA polarisation observations of diffuse Galactic emission will allow to separate any faint intergalactic magnetic field component from the Galactic foreground component. The Galactic foreground needs also to be taken into account when studying magnetic fields of resolved galaxies or cluster of galaxies by polarised emission. Extensive high resolution polarisation simulations were made by Sun & Reich (2009) within SKADS at 1.4 GHz. Galactic emission patches at various Galactic latitudes were simulated, which were based on the 3-d Galactic emission model by Sun et al. (2008). These global models are based on total intensity and polarisation all-sky maps together with extragalactic RM data. The turbulent magnetic field clearly dominates on arcsec scales and was assumed to be of Kolmogorov-type, where the outer scale and the length of the line-of-sight determine the slope of the polarisation maps structure function. By changing the parameters the statistical properties can be adapted to those observed. The SKA is expected to provide a major step towards the understanding of the properties of the Galactic magnetic field.

References:

Cordes J.M., Lazio, T.J., 2002, astro-ph/0207156; Sun X.H, Reich W., Waelkens A., Ensslin T.A. 2008, A&A, 477, 573; Sun X.H., Reich W. 2009, A&A, 507, 1087

8.3.4 Pulsars and the Galactic magnetic field [A. Noutsos]

One of the important but missing components of Galactic astrophysical research is a reliable description of the free-electron density of the Milky Way. Next-generation, low-frequency arrays (e.g. LOFAR) and ultimately the SKA will play a major role in the reconstruction of the warm ionised medium (WIM) using an array of observable effects like Faraday rotation, interstellar dispersion and scattering of pulsar radio emission, scintillation, angular broadening and extreme scattering events, neutral and ionised hydrogen emission, and latest astrometric results and information on the Galactic spiral arm structure. Using a combination of proven and new algorithms to analyse the largest possible set of input data will enable researchers to construct the most complete picture of the Galactic ionised ISM, yet. The derived model will shed light on poorly understood aspects of the turbulent ISM, but will also find applications in improving our knowledge of the Galactic magnetic field, distance estimates for pulsars and transients and guide the exploration of current and future telescopes. One of the advantages of this multi-disciplinary project, is the demand for a close and frequent interaction between different research groups, which would therefore allow for important cross-fertilisation between groups interested in the interstellar medium and its physics.

Introduction: Understanding the most basic properties of galaxies requires understanding the interstellar medium (ISM) that fills the seemingly empty space between the stars. It means to understand the composition, the physical processes and the interplay between the different constituents, the radiation fields and the galactic magnetic field. In particular, the exchange of energy via turbulent processes between different length scales plays an important role in determining the properties of the ISM that are linked through the cycle of matter in the galaxy, from the formation to the death of stars. Many of these properties and processes are still not fully understood or known, even though the highly dynamical ISM is crucial for the interpretation of many astrophysical phenomena such as star formation in general, the energy-mass feedback from evolved stars or the threading of the magnetic field with interstellar matter.

The understanding of the ISM in the Milky Way is of primary importance for studying the properties, formation and evolution of external galaxies. However, the present knowledge of the Galactic ISM is still limited and constrains, for example, our ability to obtain precise distance estimates based on interstellar dispersion, or to accurately correct effects of interstellar weather in pulsar timing data, which in turn hampers efforts to detect gravitational waves. A particularly interesting constituent of the Galactic ISM that manifests itself in many astrophysical observations is its free electron content. We need to understand it for reasons both related to comprehending the physical processes ongoing in the ISM, as well as for its use in astrophysical applications, including:

– to decipher the fundamental turbulence processes and the distribution of energy from the largest to the smallest scales, (see, e.g. You et al. 2007).

– to characterise the "interstellar weather" to take it into account during many experiments, (e.g. You et al. 2007)

– to reveal the structure of the Milky Way including its small- and large-scale magnetic field (as done by Noutsos et al. 2008, amongst others),

– to use it for precise distance measurements via an interaction of the ISM with electromagnetic radiation (as used, amongst others, in Verbiest et al. 2010) and,

– to help compare and constrain "Dark Matter" models of the Milky Way disc (as was done, amongst others, by Kalberla 2003, Kalberla et al. 2007).

Free electrons are a component of the diffuse warm ISM. Separated from their atoms, the electrons can interact with electromagnetic radiation via a large number of observable effects, including Faraday rotation, dispersion and scattering of pulsed radio emission, scintillation, angular broadening and extreme scattering events (excellent reviews can be found in Rickett 1977, Rickett 1990, Backer et al. 1998). The average number density lies at only 0.03 cm^3, but the distribution is far from homogeneous (see e.g. Walker et al. 2008), with clumps and both local maxima (e.g. HII regions) and minima. Given their many astrophysical manifestations, it is of utmost importance to understand the distribution of free electrons on small and large scales. Still, the available models for the free electron density distribution (in particular Cordes & Lazio 2003) are incomplete and insufficient.
The desired outcome is the derivation of an improved electron density model of our Galaxy, taking into account a wide range of (old and new) observations and detailed investigations of the turbulent processes that lead to the inhomogeneities in the distribution, the measurable phenomena related to those and the Galactic distribution of ISM constituents other than free electrons.
A full Galactic ISM free electron model will not only shed light on little understood aspects of the ISM, but will also aid in solving a large number of astrophysical questions. It will find applications in improving our knowledge of the Galactic magnetic field, it will help to understand the local ISM, it will allow precise distance estimates for pulsars and transients and it will reveal the location of astrophysically interesting objects like the location of unknown HII regions and star forming regions, which are potential hiding places of pulsar-black hole binaries. A reliable ISM model can be used to derive the most promising observing strategies for delivering the Key Science proposed for the future Square Kilometre Array (SKA).
The modelling of the free-electron ISM requires input from a diverse range of observables. On the front of Galactic magnetism, one can use pulsar-polarisation data to perform fits to multi-parametric models and derive the optimal set of parameters for various models of the Galactic magnetic field (Noutsos et al. 2008). Another aspect is pulsar timing, which can be used to measure parallax distances. Measuring pulsar distances independently of an ISM model will be crucial as to actually measure the column density along the line of sight (Verbiest et al. 2008, Verbiest et al. 2010).

In addition, measurements of the neutral and ionised hydrogen as well as hydroxyl (OH) maser measurements will be important contributors. With a combination of H I and OH ($\lambda = 21$ cm and $\lambda = 18$ cm) absorption measurements, one can obtain the neutral (H I and H2) column densities. Together with dispersion measures of pulsars, one can derive the fractional ionisation of the intervening ISM, which is not only important for the free-electron model but also an astrochemically interesting quantity.

Moreover, data from other disciplines like stellar dynamics, based on maser velocities and an assumed Galactic gravitational potential, have revealed bar-like features and voids in the ISM of the inner Galaxy. Such features are important and must be included in the next ISM model of the Galaxy.
Invaluable contributions to independent distance measurements can also come from trigonometric parallaxes of methanol masers: parallax distances up to 10 kpc with an accuracy of $\sim 10\,\%$ have been measured (Rygl et al. 2010). Such measurements can be expanded to pulsar distances, where VLBI can yield much more accurate distances that will be an input to the model.

Many interstellar effects are stronger at low frequencies. The next-generation low-frequency telescopes such as LOFAR are expected to play an important role in ISM modelling efforts.

The revised distances and velocities from a new free-electron density model will have direct implications on the kick-velocity distribution of core collapse supernovae. Moreover, using the model predictions will identify the most probable galactic regions to find previously hidden sources of particular astrophysical interest, such as pulsar-black hole binaries.

References:

Backer D.C., et al., 1998, AAS, 30, 1151; Cordes J.M., Lazio T.J.W., 2002, arXiv:astro-ph/7156; Kalberla P.M.W., 2003, ApJ, 588, 805; Kalberla P.M.W., 2007, A&A, 469, 511; Noutsos A., Johnston S., Kramer M., Karastergiou A., 2008, MNRAS, 386, 1881; Rickett B.J., ARA&A, 1977, 15, 479; Rickett B.J., ARA&A, 1990, 28, 561; Rygl K.L.J., et al., 2010, A&A, 511, 2; Verbiest J.P.W., et al., 2008, ApJ, 679, 675; Verbiest J.P.W. , Lorimer D.R., McLaughlin M.A., 2010, MNRAS, 405, 564; Walker M.A., et al., 2008, MNRAS, 388, 1214; You X.P., et al., 2007, MNRAS, 378, 493

8.3.5 Linking theoretical aspects of the interstellar and intergalactic medium to radio observations

[D. Breitschwerdt, M.A. de Avillez]

High resolution simulations: The Interstellar Medium (ISM) of star forming galaxies is a highly turbulent and compressible medium (v. Weizsäcker 1951). This leads morphologically to a coupling of structures on all scales and to a filamentary (see left figure below) gas distribution (e.g. Avillez and Breitschwerdt 2004).

It can be shown that the main driver of turbulence is supernova (SN) explosions (MacLow and Klessen 2004), and to a lesser extent stellar winds. Energy is fed in at an integral scale of about 75 pc (Avillez and Breitschwerdt 2007) and, in purely hydrodynamical turbulence, cascading down through an inertial range until dissipation takes place on the viscous scale. Heating and cooling give rise to a multiphase medium, as thermal instability controls the evolution of the gas. However, contrary to classical textbook models (e.g. McKee and Ostriker 1977), a significant amount of mass resides in thermally unstable regions, again a consequence of turbulence. The complexity of the thermal structure of the ISM is increased due to the difference in atomic time scales ionization and recombination. As a consequence the gas is in general not in ionization equilibrium (NEI), leading e.g. to an overionized appearance of gas because of delayed recombination. This also modifies the cooling function, which now varies in space and time. This important aspect has been neglected in large-scale ISM simulations until now (Avillez et al. 2011). In addition, the electron density distribution (see right figure above) in the ISM is different for an NEI plasma. Radio observations at high spatial resolution together with pulsar dispersion measures can give important constraints. Preliminary calculations point to a bimodal overall probability density function (pdf), with individual temperature range pdfs, such as the warm neutral medium (WNM) being lognormally distributed, in agreement with observations (Berkhuijsen and Fletcher 2008).

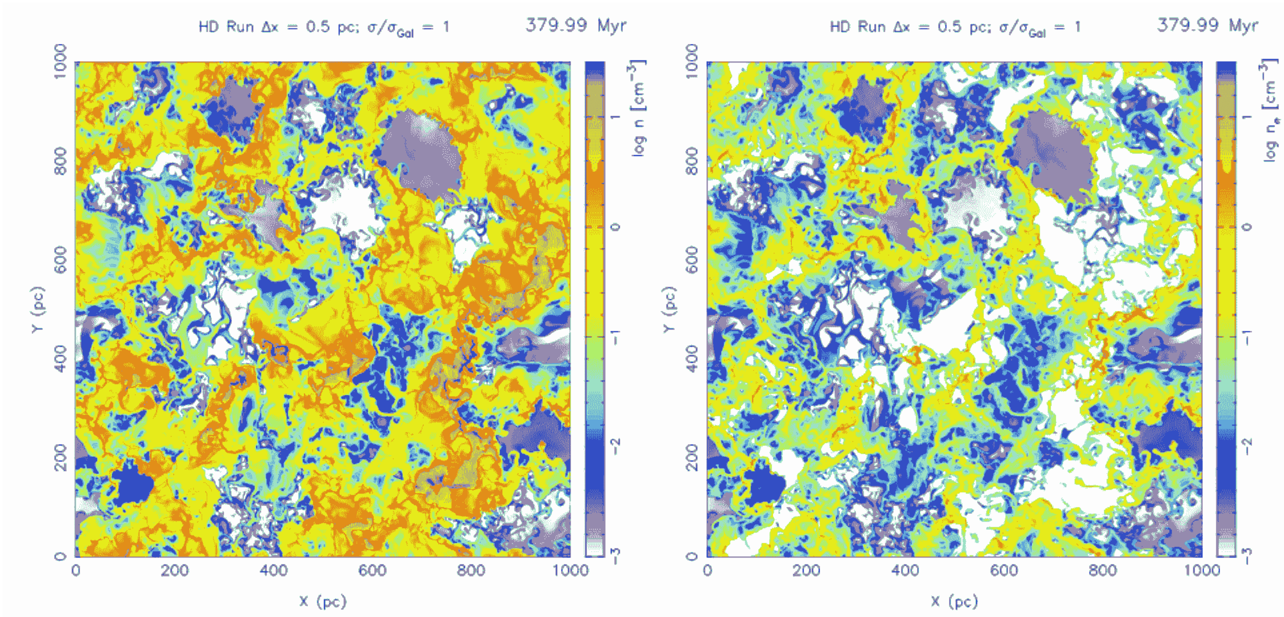


Figure 1_{Br}: High resolution simulations of an ISM plasma in non-equilibrium ionization (NEI), showing slices through the Galactic mid-plane with a highest resolution of 0.5 pc (left panel: total number density, right panel: electron density) after 380 Myr of evolution (Avillez and Breitschwerdt 2011).

Radiocontinuum emission from galactic halos: Combined SN activity in star clusters can generate an outflow perpendicular to the galactic disk, which is driven by hot plasma and cosmic rays (CRs; see Breitschwerdt et al. 1991). High resolution simulations show that the flow is ram pressure dominated, and the magnetic field lines are drawn out into the halo (see Avillez and Breitschwerdt 2005). High resolution and high sensitivity radio observation will be able to reveal the field topology in and off the disk. CR nucleons escape the galaxy eventually together with electrons, which suffer strong synchrotron and inverse Compton losses, thus making them an ideal tracer of the halo profile. CR transport calculations show that a wind advects electrons further out into the halo, resulting in a shallower radio spectral index. Thus SKA observations will be able to unveil the dynamical structure of galactic halos. If the wind interacts with the intergalactic gas, resulting shocks accompanied by particle acceleration may be observed as well.

References:

Avillez M.A., Breitschwerdt D., Manoel N.C. 2011, A&A (submitted); Avillez M.A., Breitschwerdt D., 2007, ApJ 665, L35; Avillez M.A., Breitschwerdt D., 2005, A&A 436, 585; Avillez M.A., Breitschwerdt D., 2004, A&A 425, 899; Berkhuijsen E.M., Fletcher A., 2008, MNRAS 390, 19; Breitschwerdt D., McKenzie J.F., Völk H.J., 1991, A&A 245, 79; MacLow M.M., Klessen R.S, 2004, RvMP 76, 125 ; McKee C. F., Ostriker J. P., 1977, ApJ 218, 148; von Weizsäcker C. F., 1951, ApJ 114, 165

8.3.6 Magnetic field structures and statistics: Unraveling the inner workings of magnetic dynamos [T. Enßlin]

Abstract: The three-dimensional structures of cosmic magnetic fields in our Galaxy, external galaxies, galaxy clusters and the inter-galactic medium were shaped by dynamo processes, turbulent gas motions and shock waves. The fields are remnants of violent hydrodynamical processes, and need to be studied in great detail in order to unravel the field's origin. The SKA, with its unprecedented combination of sensitivity, resolution, and frequency coverage, will play a leading role in charting magnetic structures via polarimetric measurements. Detailed two- and three-dimensional information on field configurations in various galactic and intergalactic environments resulting from synchrotron continuum measurements, Faraday rotation grids, and Faraday rotation synthesis will become available. A number of statistical analysis methods tailored to be applied to such data

are already developed, largely by the German community. These methods include the measurement of magnetic power spectra as a signature of turbulent cascades, the statistics of magnetic tension forces as a window into the inner workings of magnetic dynamos, the testing for magnetic helicity as a key ingredient in galactic large-scale field generation, and the reconstruction of the three-dimensional magnetic field of the Milky Way as a key input for astronomy with ultra-high energy cosmic rays.

Introduction: The observed cosmic magnetic fields in galaxies, clusters of galaxies and the yet to be detected fields in the wider intergalactic medium are believed to be produced by magnetic dynamos. Two broader classes of dynamos have to be distinguished, the small-scale and the large-scale dynamo. Direct proof of their influence, and observations of their detailed inner working, are unfortunately still sparse. The SKA is expected to change this situation dramatically.

The small-scale dynamo amplifies magnetic fields by random field line stretching, and thereby imprints properties of the driving turbulence into the magnetic field statistics. In particular, there should be similarities between the magnetic power spectrum and the hydrodynamical power spectrum driving the dynamo. This seems already to been observed in the Kolmogorov-like magnetic spectrum as inferred for the cool core region of the Hydra-A galaxy cluster (Enßlin & Vogt 2003, Vogt &Enßlin 2005, Kuchar & Enßlin 2011). There, the magnetic power spectrum was measured with novel inference methods exploiting the correlation structure in the extended Faraday rotation maps of the Hydra A radio galaxy. The probed fields reside in front of the radio emitting plasma and therefore are typical for the cool core region of this cluster, but not representative for its wider intra-cluster medium. Other Faraday rotation based magnetic spectrum estimates in less central regions of galaxy clusters are also consistent with Kolmgorov-like magnetic spectra (Bonafede et al. 2010). However, due to a less uniform probing of the cluster volume in these cases, the picture is far from being conclusive (Govoni et al. 2006).
The SKA will provide dense grids of Faraday rotation measurements through many clusters of galaxies. This will allow for the inference of the magnetic field power spectra, not only in a large number of clusters, but also as a function of cluster position (core region, outer region, cool cores) and dynamical state (relaxed cluster, merging cluster). Studies of the magnetic part of cluster weather phenomena will provide unique insight into the interior of the largest virialized objects in the Universe.

The large-scale dynamo: The more ordered large-scale galactic fields are believed to result from some sort of mean field dynamo, which relies on the differential rotation in spiral galaxies. Although various scenarios for these dynamos have been proposed, a common key ingredient of all theories seems to be magnetic helicity (Brandenburg 2009, Shukurov et al. 2006, Sokoloff 2007). The build-up of large-scale helicity must be accompanied by the dissipation or expulsion of small-scale helicity, due to helicity conservation in magnetohydrodynamics. Any way to study magnetic helicity on large or small galactic scales would therefore be extremely important to unravel the inner workings of the Galactic dynamo.
Since magnetic helicity manifests itself in all three components of the magnetic field instantaneously, those have to be probed simultaneously. Suitably constructed combinations of Faraday rotation and synchrotron polarisation data probe parallel and perpendicular field components in such a way as to be sensitive to magnetic helicity (Kahmiashvili & Ratra 2005, Junklewitz & Enßlin 2011). A straight-forward application of such a helicity sensitive statistic to galactic Faraday rotation data (Taylor et al. 2009) and synchrotron polarimetric data (Page et al. 2007) has not yet revealed the presence of magnetic helicity (Oppermann et al. 2012). However, this was expected since the highly structured galactic thermal electron distribution severely affects these measurements and requires correction.

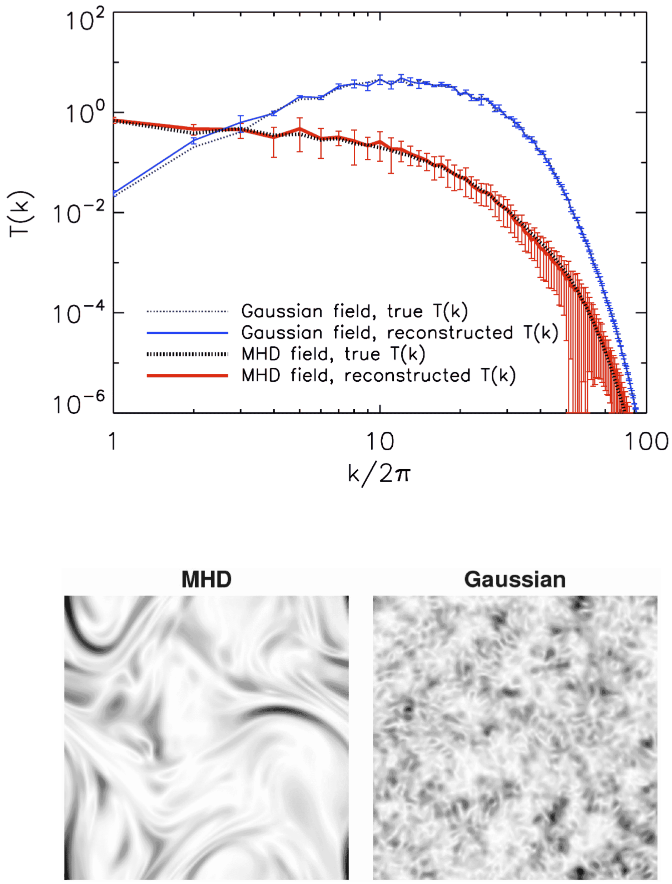


Figure 1_{En}: Top: tension force spectrum reconstructed from mock polarimetry data using the method of Stokes correlators (from Waelkens et al. 2009b). The Gaussian random field was constructed to exhibit the same magnetic energy spectrum as the magneto-hydrodynamical simulation, but it has a different fourth-order statistic as measured by the Stokes correlators.

Bottom: slices through the tension force fields in the two cases, showing that the Gaussian field has more small-scale tension forces than the more realistic MHD simulation, although both have the same magnetic energy spectra.

The SKA will significantly increase the sensitivity of such tests for helicity. It will provide a much denser grid of Faraday rotation measurements, high resolution polarimetric observations, and, most importantly, exquisite data on the galactic thermal electron structure from pulsar observations. The latter will allow for the construction of an accurate, three-dimensional model of the thermal electron distribution that can be used to correct for the impact of the electron structure in tests for magnetic helicity.

The tension force spectrum of turbulent magnetic fields highlights the back-reaction of the magnetic fields on the hydrodynamics. Tension forces should be especially strong in the saturated states of magnetic dynamos, since their action on the gas flows should compensate for the otherwise exponential increase of magnetic energy. Tension force spectra should therefore be very sensitive to the specific dynamo scenario in operation. Tension force spectra are encoded in high resolution radio polarimetry data (Waelkens et al. 2009b) as well as ordinary power spectra (Spangler 1983, Spangler 1982, Junklewitz & Enßlin 2011, Eilek 1989, Eilek 1989b). The SKA will be a powerful tool to discriminate between different magneto-hydrodynamical scenarios (see Figure 1_{En}).

3-d Galaxy: The three-dimensional magnetic field structure of our galaxy can be reconstructed tomographically using the combination of several data sets. The following data sets will substantially improve with SKA measurements:

- Faraday rotation probes by extragalactic sources provide the line-of-sight (LOS) integrated LOS magnetic field component (weighted with the thermal electron density), see Figure 2_{En}.
- Faraday rotation probes by galactic pulsar emission provide similar information, but for shorter path-lengths through our Galaxy. This allows for the discrimination between magnetic structures at different physical depths.

– Pulsar measurements also provide dispersion measures, i.e. LOS integrated thermal electron densities. This is important auxiliary information if one hopes to identify the specific contribution of magnetic fields to Faraday rotation measurements.

– Galactic radio synchrotron emission in total intensity and polarisation (at high, Faraday-rotation-free frequencies) shows the LOS projected perpendicular magnetic field components (see Figure 3_{En}).

– Polarised galactic synchrotron emission at low frequencies, which is affected by intrinsic galactic Faraday rotation (see Figure 3_{En}), carries depth information about the different emission regions. Using the novel Faraday synthesis method to reconstruct the emission as a function of Faraday depth results in 3-d images of polarised intensity (Brentjens & de Gruyn 2006, Brentjens & de Gruyn 2005).

– The most prominent features expected in such 3-d Faraday synthesis images are Faraday caustics (Bell et al. 2011). These sheets of singularities in the polarised emissivity are caused by physical regions in which the LOS component of the magnetic field is close to zero, i.e. due to a field reversal. Since all polarised radiation emitted in this region has basically the same Faraday depth, the Faraday caustics appear as boundaries of galactic regions with opposite polarity (with respect to the LOS).

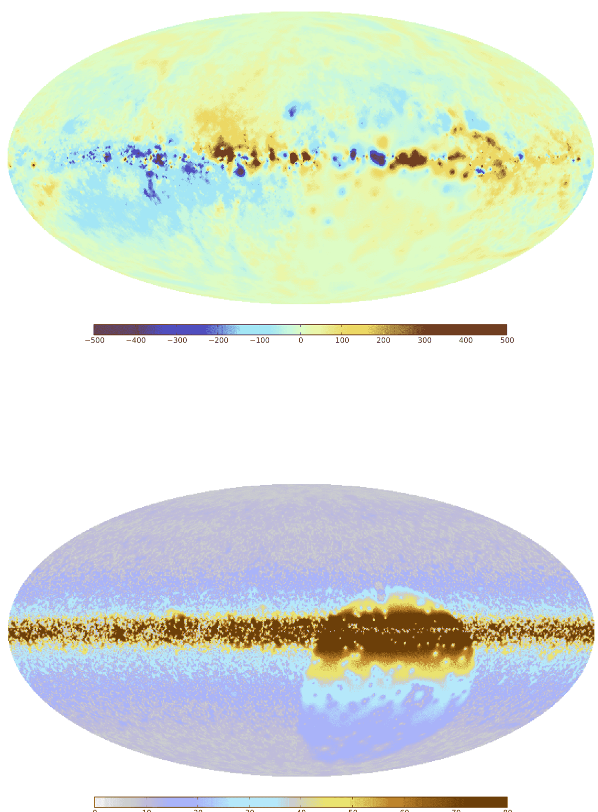


Figure 2_{En}: Faraday sky (top) and its uncertainty (bottom) from extragalactic Faraday rotation measurements (Oppermann et al. 2012, Taylor et al. 2009).

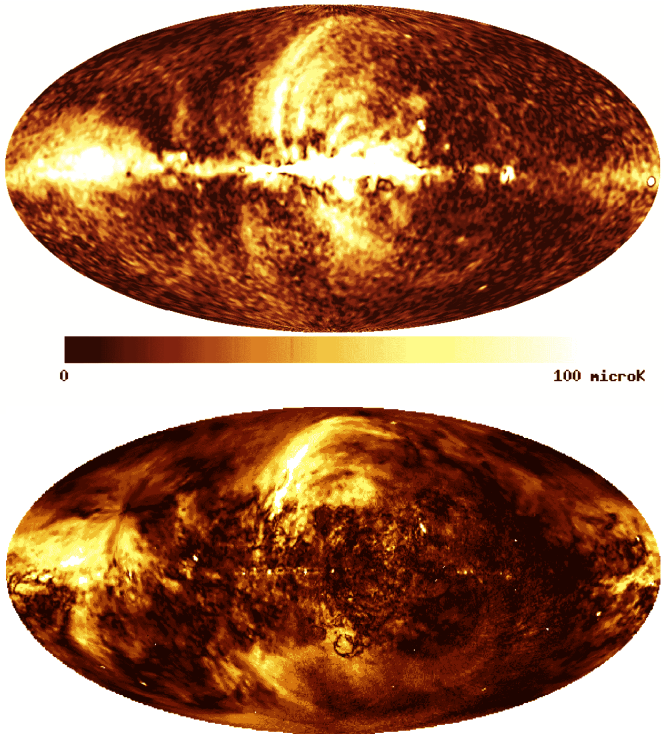


Figure $3_{\rm En}$: The WMAP 22.8 GHz all-sky polarised intensity map (upper panel) and the 1.4 GHz all-sky polarised intensity map (lower panel). The polarised intensities are shown greyscale coded from 0 to 100 μK for 22.8 GHz and from 0 to 570 mK for 1.4 GHz. Galactic Faraday-depolarisation structures are visible in the lower frequency map. Data from (Wolleben et al. 2006, Page et al. 2007, Testori et al. 2008) and figures from (Sun et al. 2008).

There has been substantial progress in combining such data sets into coherent pictures of the 3-d galactic magnetic field structure, although a unique model has not yet been reached (Sun et al. 2008, Waelkens et al. 2009, Jaffe et al. 2010, Jiang et al. 2010, Pshirkov et al. 2011, Sun & Reich 2010). However, with the superb data expected from the SKA, a detailed mapping of our magnetic galaxy will become feasible.

This will not only be important for understanding the large-scale dynamo operating in our galaxy, or to reveal the role magnetic fields play in the galactic metabolism of hot gas, cold clouds and star formation, but it will also be essential for the correction of the galactic magnetic screen that inhibits extragalactic astronomy with high energy charged particles (Sigl & Lemoine 1998, Waelkens et al. 2009, Giacinti & Semikoz 2011b, Giacinti & Semikoz 2011).

References:

Bell M.R., Junklewitz H.,Enßlin T.A.., 2011, arXiv:1105.2693; Bonafede A., et al., 2010, A&A, 513, 30; Brandenburg A., 2009, Plasma Physics and Controlled Fusion, 51(12):124043; Brentjens M.A., de Bruyn A.G., 2005, A&A, 441, 1217; Brentjens M.A., de Bruyn A.G., 2006, Astronomische Nachrichten, 327, 545; Eilek J.A., 1989, AJ, 98, 244; Eilek J.A., 1989b, AJ, 98, 256; Enßlin T.A., Vogt C., 2003, A&A, 401, 835; Giacinti G., Semikoz D.V., 2011, Phys. Rev. D, 83(8), 083002; Giacinti G., Semikoz D.V., 2011b, arXiv:1107.2356; Govoni F., et al., 2006, A&A, 460, 425; Jaffe T.R., et al., 2010, MNRAS, 401, 1013; Jiang Y.-Y., et al., 2010, ApJ, 719, 459; Junklewitz H., Enßlin T.A., 2011, A&A, 530, 88; Kahniashvili T., Ratra B., 2005, Phys. Rev. D, 71(10), 103006; Kuchar P., Enßlin T.A., 2011, A&A, 529, 13; Oppermann N., et al., 2012, A&A, 542, A93; Page L., et al., 2007, ApJS, 170, 335; Pshirkov M.S., Tinyakov P.G., Kronberg P.P., Newton-McGee K.J., 2011, arXiv:1103.0814; Shukurov A., Sokoloff D., Subramanian K., Brandenburg A., 2006, A&A, 448, 33; Sigl G, Lemoine M., 1998, Astroparticle Physics, 9, 65; Sokoloff D., 2007, Plasma Physics and Controlled Fusion, 49, 447; Spangler S.R., 1982, ApJ, 261, 310; Spangler S.R., 1983, ApJL, 271, 49; Sun X.-H., Reich W., 2010, Research in Astronomy and Astrophysics, 10, 1287; Sun X.-H., Reich W., Waelkens A.H., Enßlin T.A., 2008, A&A, 477, 573; Taylor A.R., Stil J.M., Sunstrum C., 2009, ApJ, 702, 1230; Testori J.C., Reich P., Reich W., 2008, A&A, 484, 733; Vogt C., Enßlin T.A., 2005, A&A, 434, 67; Waelkens A.H., et al., 2009, A&A, 495, 697; Waelkens A.H.,, Schekochihin A.A., Enßlin T.A.,2009b, MNRAS, 398, 1970; Wolleben M., Landecker T.L., Reich W., Wielebinski R., 2006, A&A, 448, 411

8.3.7 Accurate distance measurements: Astrometry [A. Brunthaler]

The SKA will have even better astrometric capabilities than current Very Long Baseline Interferometry (VLBI) arrays (see Fomalont & Reid 2004). Since systematic errors from the atmosphere or the array geometry (e.g. antenna positions, earth orientation parameters) scale directly with the angular separation of the reference and target sources on the sky, it is essential to use as close as possible reference sources. The superior sensitivity will allow the use of much weaker (and therefore much closer) background reference sources.

Trigonometric Parallaxes: Many astrophysical properties of objects in star forming regions, like the size, luminosity, and mass, depend strongly on the distance. Therefore, a true understanding of star formation and a detailed comparision of theoretical models and observations is only possible if accurate distances are known to star forming regions. Current galactic distance estimates are often affected by dust obscuration (photometric distances) or highly model dependend (kinematic distances). A completely unbiased method to estimates distances is the trigonometric parallax, which requires extremely precise astrometric measurements in the range of a few micro-arcseconds (μas). While GAIA will measure parallaxes of a billion stars in the Galaxy, it will not probe parts of the Galaxy that are obscured by dust, i.e. large parts of the plane of the Milky Way beyond 1 or 2 kpc inward from the Sun and in particular not the deeply obscured regions where new stars are forming. However, radio observations at cm-wavelengths are not hindered by dust and can provide a view of the Milky Way that is complementary to GAIA.

Currently, astrometric radio observations of methanol and water masers in star forming regions with VLBI surveys like the "Bar and Spiral Structure Legacy" (BeSSeL) survey (e.g. Brunthaler et al. 2011) can reach parallax accuracies of up to 6 μas (Reid et al. 2009a, Hachisuka et al. 2009). Therefore, these observations have the potential to measure accurate distances of most Galactic star forming regions, to map the spiral structure of a large part of the Milky Way, and to determine important parameters such as the rotation velocity and the distance to the Galactic centre with high accuracy (Reid et al. 2009b).

The SKA in Phase 1 can observe the important 6.7 GHz methanol maser line. This line is a tracer of high mass star formation, widespread in the Galaxy, and has been already used for astrometric observations (Rygl et al. 2010). In Phase 3 (for which up to this point is no defined schedule), the SKA will also cover the 22 GHz water maser line, the strongest maser line in star forming regions. Furthermore, the large continuum sensitivity of the SKA allows the observation of radio stars at much larger distances than the few hundred parsec currently possible (Menten et al. 2007, Loinard et al. 2007). With parallax accuracies approaching $\sim 1\,\mu$as, the SKA can measure distances to sources in 10 kpc with 1 % accuracy.

Since the Large Magellanic Cloud (LMC) is known to host many methanol and water masers, the SKA can even measure a 5 % accurate trigonometric parallax to this important first step on the extragalactic distance ladder. Since the LMC is receeding with $\sim 280\,\mathrm{km\,s^{-1}}$ from the Sun, the separation between masers on different sides of the galaxy will shorten at a rate of a few 10 $\mu\mathrm{as\,yr^{-1}}$. Since this apparent motion will be easily detectable with the SKA, one can see the LMC shinking as it recedes.

Galaxy Motions: Most galaxies in the Universe are not isolated objects, but are found in groups or clusters. Thus, large-scale structure formation and galaxy formation are closely connected topics. In the concordance ΛCDM cosmological model, galaxies grow hierarchical in mass by accreting smaller galaxies. This cosmic cannibalism can be witnessed even today: Small galaxies falling into the gravitational potential of the dark matter halo of a more massive galaxy experience strong tidal interactions that can lead to strong disturbances or even tearing apart the smaller galaxy. Having a detailed description of this process is therefore a key ingredient in understanding galaxy formation and evolution.

Nearby examples of galaxy interactions are found in the Local Group (LG) and in nearby galaxy groups and clusters. However, a description of galaxy interactions cannot be complete without knowing the full 3 dimensional space motions of the interacting galaxies. Additionally, the flow of galaxy groups and clusters is strongly connected to the distribution of matter in large-scale structures. For example, it is widely believed that the motion of the Milky Way relative to the cosmic microwave background (CMB), which is of the order of $500\,\mathrm{km\,s^{-1}}$, is induced by mass concentrations within 150 Mpc of the LG, but there is a discrepancy between the direction of the motion and the distribution of visible mass in the local Universe (see e.g. Loeb & Narayan 2008, and references therein).

While current VLBI arrays are already able to measure proper motions of galaxies througout the Local Group (Brunthaler et al. 2005, Brunthaler et at. 2007), the SKA can go far beyond this and measure motions of galaxies with smaser emission or weak AGN in nearby galaxies groups and even nearby galaxy clusters (e.g. Virgo, Fornax). Therefore, the SKA will be able to measure the large-scale 3-d velocity field of galaxies out to nearby clusters.

References:
Fomalont E., Reid M., 2004, NewAR 48, 1473; Brunthaler A., et al., 2011, AN, 332, 461; Reid M., et al., 2009a, ApJ, 693, 397; Hachisuka K., et al., 2009, ApJ, 696, 1981; Reid M., et al. , 2009b, ApJ, 700, 137; Rygl K.L.J., et al., 2010, A&A, 511, A2; Menten K., et al., 2007, A&A, 474, 515; Loinard L., et al., 2007, ApJ, 671, 546; Loeb A., Narayan R., 2008, MNRAS, 386, 2221; Brunthaler A., et al., 2005, Science, 307, 1440; Brunthaler A., et al., 2007, A&A, 462, 101

8.3.8 Prospects for accurate distance measurements of pulsars [N. Wex, M. Kramer]

Parts of the following contribution are taken from Smits et al. 2011.

The Square Kilometre Array (SKA) will be an ideal instrument for measuring the distances of pulsars, having a very high sensitivity as well as baselines extending up to several thousands of kilometres. In particular, the SKA will be able to perform parallax measurements on a great number of pulsars either by direct parallax measurements or, in case of millisecond pulsars, timing observations, allowing accurate determination of their distances from the Earth.

The determination of accurate pulsar distances is vital for various physical and astrophysical reasons. Just to give a few examples:

i) In this way, the interstellar electron model can be calibrated and will not only provide reliable estimates of the DM distances of pulsars without a parallax measurement in return, but will simultaneously provide a map of the free electron content in the Milky Way that can be combined with H I and HII measurements to unravel the Galactic structure and the distribution of ionised material. Combined with Faraday rotation measurements of the same pulsars, the Galactic magnetic field can also be studied in much greater detail as today, since the precise distance measurements potentially allow us to pinpoint field-reversals occurring with some accuracy.

ii) The determination of accurate pulsar distances is also important for those pulsars that are part of binary systems, in particular for those with another compact object, such as the "Double Pulsar" (Burgay et al. 2003; Lyne et al. 2004). Relativistic effects can be used to determine the distance to some of these systems when the validity of general relativity is assumed. In reverse, to perform precision tests of general relativity, kinematic effects have to be removed for which it is often required to know the distance precisely (Lorimer & Kramer 2005).

iii) The SKA has the potential of detecting the gravitational waves from individual super-massive binary black hole systems, and determining the location of the source in the sky with high precision. For this it is important to properly account for the "pulsar term" in the gravitational wave signal, i.e. the impact of the gravitational wave on the emission of the pulsar signals at the pulsar. This is only possible if the distance between Earth and pulsar is known with high precision (Lee et al. 2011).

Imaging parallax: The straightforward method for measuring the parallax of pulsars is by measuring the position of the pulsar on the sky over time by means of imaging. Fomalont & Reid (2004) estimate that the astrometric accuracy that the SKA can potentially obtain is 15 μas at the frequency of 1.4 GHz and a 3000 km SKA baseline. However, for many pulsars the limiting factor will be given by the limited SNR of the pulsar detection. Smits et al. (2011) find that the SKA can potentially measure the parallaxes for $\sim$9000 pulsars with an error of 20 % or smaller. This includes pulsars out to a distance of 13 kpc. The imaging parallax depends only on the observed strength of the radio emission, not the rotation characteristics of the pulsar.

Timing parallax: A second set of methods of performing astrometry of a pulsar involves accurate timing of the pulse time-of-arrival (TOAs) at the telescope. These methods are a) parallax measurements using the Earth orbit, b) parallax measurements for binary pulsars using the Earth orbit and that of the pulsar and c) distance estimates of binary pulsars based on the comparison of observed orbital parameters with those predicted by general relativity.

The "classical" timing parallax measurement (a) utilises the fact that the wave front curvature of a pulsar signal is directly related to the distance of the source. The curvature of the wavefront introduces an annual periodic change in the apparent direction, hence a six-monthly periodicity in the TOAs (Lorimer & Kramer 2005). The apparent change in direction is more easily measurable for low ecliptic latitudes — in contrast to an imaging parallax. For millisecond pulsars, Smits et al. (2011) show that timing observations of pulsars with the SKA can yield a parallax precision that exceeds that of an imaging parallax by at least an order of magnitude in terms of both relative and absolute precision. Such timing precision suggest that distances can be measured with a precision of at least 10 % to a distance of about 10 kpc.

If a pulsar happens to be in a binary system, the pulsar orbit will be viewed under slightly different angles from different positions of the Earth's annual orbit. The result is a periodic change in the observed longitude of periastron and the projected semi-major axis. This effect, known as the annual orbital parallax (b), depends on the distance and therefore can also lead to an accurate pulsar distance measurement for a binary pulsar (Kopeikin 1995). It will require the timing precision of the SKA, to convert this effect into a precise distance measurement of the binary system (Smits et al. 2011).

If the intrinsic decay rate of the orbital period P_b of a binary pulsar is determined purely by gravitational wave damping, one can predict a change in P_b if the pulsar and companion masses are obtained via pulsar timing thanks to the measurement of post-Keplerian parameters. For a pulsar at a finite distance d with an observed proper motion in the sky, the predicted change in P_b will differ from the observed one due to the the kinetic contribution of the Shklovskii term (Lorimer & Kramer 2005), which is proportional to d. The superb timing precision of the SKA will allow for high precision measurements of the binary parameters and the pulsar's proper motion in the sky. Using general relativity to calculate the intrinsic change of P_b, the Shklovskii term can be determined with high precision, which converts into a very accurate distance estimation (c), which can easily supersede the "classical" timing parallax (Smits et al. 2011).

Summary: From the above, it is clear that the SKA will become a superb astrometry instrument for pulsars, providing high precision pulsar distances. These measurements feed directly back into astrophysical questions, for instance, related to the distribution of the ionised gas in the Galaxy and the structure of the Galactic magnetic field. Imaging and timing parallax measurements can help us significantly with precision tests of general relativity to correct for kinematic effects. This is of vital importance for tests of the fundamental properties of gravity, like the emission of gravitational waves and a time dependent gravitational constant. Furthermore, accurate pulsar distances are key parameters in a pulsar timing array to study the emission of nano-Hertz gravitational waves by super-massive black hole binaries.

References:

Burgay M., et al., 2003, Nature, 426, 531; Fomalont E., Reid M., 2004, NewAR 48, 1473; Kopeikin S., 1995, ApJ, 439, L5; Lee K., et al., 2011, MNRAS, 414, 3251; Lorimer D., Kramer M., 2005, Handbook of Pulsar Astronomy (Cambridge Univ. Press, Cambridge, UK); Lyne A. G., et al., 2004, Science, 303, 1153; Smits R., et al., 2011, A&A, 528, A108;

8.3.9 The dynamic radio sky [M. Kramer, E. Keane, D. Champion]

The radio sky reveals variable and transient phenomena which are relevant for a huge range of (astro-) physical questions. Repeated monitoring can reveal new, previously unseen objects which are important for understanding cosmic explosions, population studies or the connections between radio and high-energy processes. Often radio observations can trigger searches and studies in other observational windows. Perhaps one of the most exciting such possibilities is the triggering of gravitational wave searches for neutron star oscillations after the detection of a pulsar glitch.

Excellent recent examples for the scientific potential still hidden in the dynamic Universe are the discovery of Rotating Radio Transients (RRATs, McLaughlin et al. 2006) or the discovery of radio bursts of potential extragalactic origin (Lorimer et al. 2007). Whether in these examples these objects are indeed representing a completely different class of neutrons stars or whether they are really at cosmological distances, respectively, is

not only interesting but similar studies promise a huge potential in changing our mindset about processes in the Universe.
Radio monitoring with good cadence is clearly essential to discovery new phenomena and to eventually study the implications. Indeed, when attempting to extract the extreme physics from the observed signals, it is important to not only obtain a snapshot of the sky but to follow the transient sky systematically. With its multi-beam capability to observe vastly different areas of the sky simultaneously, the SKA will be a unique instrument in studying transient phenomena and their physics over a wide range of radio frequencies. In oder to demonstrate this, we consider as an example the discovery that radio pulsars appear to be able to change the structure of current flow in the magnetosphere in an seemingly instantaneous way. This recognised class of "intermittent pulsars" (Kramer et al. 2006), seem to be active for a period of time before switching off completely for a further period of time, where the change in observed radio output is correlated with a change in pulsar spin-down rate. In the case of PSR B1931+24, if the pulsar is emitting radio waves, the spin-down rate is about 50 % larger than when the pulsar is off. This faster spin-down rate is caused by an extra torque that is given by the electric current of the plasma that also creates the radio emission. If some or all of the plasma is absent, the radio emission is missing together with the additional torque component, so that the spin-down is slower.
Recently, Lyne et al. (2010) realised that intermittent pulsars are actually the extreme form of a more common phenomenon, in which the restructuring of the plasma currents does not necessarily lead to a complete shutdown in the radio emission, but can be observed as changes between distinct pulse shapes. Lyne et al. showed that particular profiles are indeed correlated with specific values for the spin-down rates, confirming the previous picture. The times when the switch in the magnetospheric structure occurs are for some pulsars quasi-periodic but in general difficult to predict. The resulting change between typically two spin-down rates leads to seemingly random timing residuals that have been in the past classified as "timing noise". The observations by Lyne et al. therefore simultaneously connect the phenomenon of timing noise to that of intermittent pulsars and that of "moding" and "nulling" (see e.g. Lorimer & Kramer 2005). An interesting aspect is the possibility of determining the exact times of the switch between magnetospheric changes by precisely measuring the pulse shapes with high-sensitivity, high-cadence monitoring with the SKA. In this case, the changes in spin-down rate can be taken into account and the pulsar clock can be "corrected". This would offer the opportunity to use not only the MSPs for timing experiments, but to utilize also the 20 000 to 30 000 normal pulsars that will be discovered in a Galactic census described below. Even though the precision will not be as high as for MSPs, the large number of pulsars may help to detect, for instance, gravitational waves.
Monitoring specifically radio pulsars can also lead to the discovery of pulsar "glitches". A pulsar glitch is a sudden increase in spin frequency of the neutron star caused by an internal reconfiguration of the star's interior structure (e.g. Lyne & Smith 2004). The relaxation of the glitch gives information about the super-fluid interior of the pulsar and enables us to do neutron star seismology. It is expected that such an event may also cause the neutron star to oscillate, which for certain vibration modes, should result in the emission of gravitational waves (e.g. van Eysden & Melatos 2008). Knowing the exact moment of the glitch through dense radio monitoring, gravitational wave data can be searched accordingly. The statistical information obtained from such radio monitoring with the SKA will be used to study the glitch mechanism and to answer questions as to whether a possible bimodal distribution of the glitch sizes means that two different types of glitch processes are acting (e.g. Espinoza 2010).

Overall, the SKA will revolutionize our understanding of cosmic time variable processes by providing us with a snapshot of this dymamic and non-static Universe.

References:
McLaughlin M.A., et al., 2006, Nature, 439, 817; Lorimer D.R., et al., 2007, Science, 318, 777; Lyne A.G., Smith F. G. , 2004, *Pulsar Astronomy, 3rd ed.* (Cambridge University Press, Cambridge, 2004); van Eysden C.A. , Melatos A., 2008, Classical and Quantum Gravity, 25, 225020; Espinoza C., 2010, PhD thesis, University of Manchester, UK; Kramer M., et al., 2006, Science, 312, 549; Lyne A., et al., 2010, Science, 329, 408; D. R. Lorimer D.R., Kramer M., 2005, *Handbook of Pulsar Astronomy* (Cambridge University Press, Cambridge, 2005)

8.3.10 Multi-wavelength astronomy in the age of the SKA and CTA [D.I. Jones, F.A. Aharonian, R.M. Crocker]

Introduction: The past decade has seen an explosion in the number of sources detected at very high energies (VHE; E $\geq$ 0.1 GeV) as what was a promising new window on the electromagnetic spectrum has metamorphosised into a fully-fledged observational science. This transformation has primarily been brought about by construction of a new generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the High Energy Stereoscopic System (HESS). These telescopes collect Cherenkov photons produced by the interaction of astrophysical gamma-rays with the Earth's atmosphere. With the planned construction of the Cherenkov Telescope Array (CTA), VHE gamma-ray astronomy is moving into its second "golden age" at a time when – serendipitously – radio astronomy is also planning a renaissance. In this section, we point out the synergies that such a fortuitous happenstance can bring from (i) the standpoint of the detection of supernova remnants (SNRs) and (ii) the study of phenomena at the Galactic centre (GC). These are, of course, just two examples of many such problems that a coordinated approach to astrophysics in truly broadband terms can explore.

Telescope	Resolution [arcsec FWHM]	Sensitivity [erg cm^{-2} s^{-1}]	Field of view [deg at FWHM]
JVLA	<1	10^{-18}	0.5
ATCA	~ 1	10^{-17}	0.5
ASKAP	10	10^{-19}	30
SKA	$<<1$	10^{-20}	200
HESS	678	10^{-13}	5
VERITAS	678	10^{-13}	5
CTA	120	10^{-14}	3 – 4

Table 1_{J}: The characteristics of present and future IACT and radio telescopes in common units. The sensitivity for the radio is the r.m.s. sensitivity for 1 hr integration, whereas the gamma-ray sensitivity is for 50 hrs (and assuming a 5σ detection). For the resolution, the figures are the best available for the frequency (energy) range covered, as well as for the sensitivity both of which are frequency (energy) dependent for the radio (gamma-ray) telescopes. The sensitivity is computed at a frequency of 1 GHz and include the best available bandwidth for the radio telescope. Note that the figures for ATCA are for the recent Compact Array Broadband Backend (CABB) upgrade and the SKA and ASKAP FoV values are actually in units of square degrees.

Connecting Galactic supernova detection in VHE gamma-rays and radio domains: Since low-frequency radio emission (i.e. $\lesssim$2 GHz) traces the MeV – GeV part of the Galactic CR spectrum through synchrotron emission, it has long been the method-of-choice for the detection of SNRs. The past few decades has begun to change this due the advent of sensitive, (relatively) high resolution gamma-ray astronomy. The new generation of radio and gamma-ray telescopes promises to change this view. Given the imminent construction of telescopes such as the CTA and the SKA pathfinders, such as ASKAP, it is instructive to connect the search for SNRs at radio frequencies, with the search for SNRs with VHE gamma-ray telescopes. It is well-known that the number of SNRs detected in the radio domain is generally much less than that expected statistically (we expect $\gtrsim$1000 Galactic SNRs – based on pulsar birth rates, OB star counts, Fe abundance, etc; (Brogan et al. 2006) and know of 274; (Green 2009)). This suggests that there is a population of faint SNRs that radio surveys are blind to. Indeed the traditional way of searching for SNRs – based on their low frequency radio continuum emission – skews the statistics so that we only observe the brightest remnants (Green 2009). Therefore, the limited availability of time on high-resolution, large collecting area telescopes, such as the VLA, has limited our ability to identify SNRs to large angular sizes, and down to a surface-brightness limit, $\Sigma_1 \sim 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1}, measured at a fiducial frequency of 1 GHz (Green 2009 and references therein). The SKA (and to a lesser extent its pathfinder instruments such as LOFAR and ASKAP), with its mammoth collecting area and huge instantaneous fields of view (FoV; see table), will change this.

A new era of SNR detection: simultaneous SNR surveys in the radio and gamma-rays bands: The table shows the present and future capabilities of radio and gamma-ray telescopes. It illustrates that although gamma-ray telescope sensitivities are improving (e.g. the order-of-magnitude improvement in sensitivity between HESS/VERITAS and CTA), there is still a gulf between gamma-ray and radio telescopes in this regard.
However, there are important lessons to be learnt from the gamma-ray communitys treatment of SNRs which is to think of them in terms of the SNR evolution, that is, a particle physics view of a particular SNR. Specifically, consideration of the evolutionary stage of a particular remnant in terms of the particle acceleration and diffusion shows that gamma-ray telescopes, such as HESS, are very good at observing very young SNRs. This follows because higher energy particles radiate their energy more quickly than those at lower energies.
The above statement is, in fact, a logically equivalent to the argument in the preceding section that radio continuum surveys miss a population of SNRs because of observational biases. Therefore, in the coming era of large, sensitive gamma-ray and (low-frequency especially) radio telescopes, there is a very compelling argument to undertake simultaneous searches at GHz and TeV frequencies and energies using telescopes such as the SKA and CTA. This will uncover many in this hitherto unknown population and thus close the gap between the expected and observed number of SNRs within our Galaxy.

Synergy between SKA and gamma-ray telescopes and high-energy particle astrophysics; applications to understanding the Galactic nucleus: The SKA will offer an unprecedented sensitivity to extended, low-surface-brightness features in the low frequency radio sky. Such large but relatively dim structures are features of:

– The local ISM e.g. nearby supernova remnants whose detection/characterization is important for a full understanding of the local cosmic ray spectrum, particularly that of cosmic ray electrons and positrons

– The Galaxy-at-large e.g.the recently-discovered "Fermi Bubbles" (Su et al. 2010; and described in detail below)

– Extra-galactic structures like giant radio galaxy lobes, galaxy cluster radio halos, etc, which are, again, important potential sources of cosmic rays at the highest energies.

The SKA will provide crucial new data on the non-thermal particle populations of these disparate regions (through low-frequency radio continuum observations of synchrotron emission from relatively low-energy electrons) in addition to their ISM conditions (magnetic field strength and structure, gas density, etc). In any case, aside from the intrinsic interest they hold, understanding all these features of the "local" Universe is, of course, important to properly understanding the "foregrounds" to cosmological measurements.
There is a great and continuing interest in the Galactic centre and the apparently-related Fermi Bubbles. The latter were discovered in gamma-ray data collected at $\sim$GeV energies by the orbiting Fermi gamma-ray telescope and extend fully 10 kpc north and south from the Galactic plane above the Galactic centre. These structures are coincident with a non-thermal microwave "haze" found in WMAP data and an extended region of X-ray emission detected by ROSAT. In the broadest terms, the Bubbles, while enigmatic, are likely related to the nuclear feedback processes that have acted to limit star-formation in the inner Galaxy and ultimately control the size of the Galactic bulge.
The SKA will contribute vitally to understanding the Bubbles, their relationship to processes occurring in the Galactic centre (the sustained star-formation activity that has occurred there, potential Seyfert-like outbursts of the resident super-massive black hole), and to the wider Galaxy. Crucially-important characteristics of the instrument in this connection are its southern location, sensitivity, and wide field-of-view (up to tens of degrees). The SKA will significantly contribute in at least three ways, namely, by offering the capability to perform:

1. Sensitive rotational measure synthesis studies of background polarised radio sources that could be used to interrogate the magnetic field structure of the Bubbles;

2. Very high resolution low frequency radio continuum morphology studies that show the detailed connection between the Galactic centre and the Bubbles (i.e. that can probe whether the radio continuum spurs visible to current instruments extend down to the super-massive black hole in particular or, rather, originate in star-forming regions in the Galactic centre);

3. Low frequency radio continuum spectral studies of synchrotron emission that could be used to constrain the low-energy component of the cosmic ray electron population inhabiting the Bubbles. This latter is of particular relevance for the question of whether the Bubbles non-thermal emission is generated by electrons or protons. In the proton case, the observed, hard-spectrum, non-thermal microwave emission (at tens of GHz) from the Bubbles is due to secondary electrons created in *pp* collisions. For kinematic reasons the spectrum of such secondaries begins to diverge from a pure power below ~ 1 GeV in electron energy finally cutting off below ~ 100 MeV in electron energy. The primary electron distribution, on the other hand, would display no such features. The low-energy secondary electron spectral features are mapped by synchrotron emission on to the radio continuum spectrum produced by these particles which starts to diverge from a pure power law at frequencies below 100 MHz ($B/10\,\mu$G).

Beyond these particular applications, we would also like to draw attention here to the possibilities that may open up with the simultaneous analysis of data taken by the SKA and that taken at other wavelengths (and with quite different instrumental modalities, such as IACT observations discussed above). For instance, again in the context of the Galactic centre, we were recently able to demonstrate (Crocker et al. 2010) a novel technique for measuring magnetic field amplitude through the simultaneous and self-consistent analysis of GHz radio continuum data with GeV gamma-ray data.

The future and conclusions: We have shown here, that both the fields of gamma-ray and radio astronomy are entering new, "golden ages" simultaneously. We have shown that, using a coordinated approach, fundamental astrophysical questions – such as the number and distribution of SNRs within our Galaxy or the nature and origin of the Fermi Bubbles – may be answered in the near future. This is, of course, over and above the exciting discoveries that one, as yet, cannot anticipate.

References:

Brogan C. L., et al., 2006, ApJL, 639, 25; Green D. A., 2009, Bull. Astr. Soc. India, 37, 45; Su M., Slatyer T. R., Finkbeiner D. P., 2010, ApJ, 724, 1044; Crocker R. M., et al., 2010, Nature, 463, 65

8.4 Solar system science

8.4.1 The Sun [G. Mann]

The Sun is an intense radio source in sky. During solar eruptions as flares and coronal mass ejections (CME), the intensity of the solar radio emission is strongly enhanced over a broad spectrum from the GHz down to the MHz range. Just this frequency range is covered by the SKA (70 MHz – 10 GHz). Therefore, the SKA will be of great interest for solar physics.

The observation of the solar radio radiation is of great importance for studying the flare process. Observationally, a flare is defined as a sudden enhancement of the Sun's emission of electromagnetic radiation covering a broad spectrum from the radio up to the γ-ray range. That can be demonstrated by the example of the solar event on October 28, 2003.

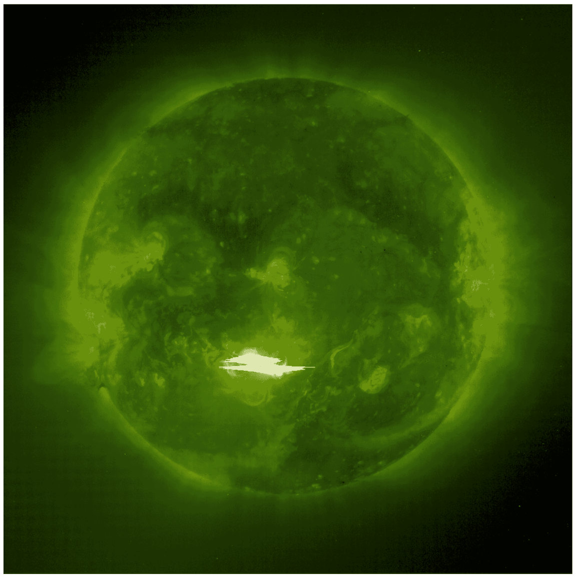


Figure 1_{Ma}: The Figure shows an EUV image of the Sun at the solar event on October 28, 2003. The location of the flare is seen as the flash in the EUV light.

It was one of the hugest solar eruptions ever observed. The Figure 1_{Ma} shows the image in the EUV range. The flare is obviously seen on the disc of the Sun by a local flash in the EUV range. The temporal behaviour of the hard X- and γ-ray photon flux is presented at the top of the Figure 2_{Ma} for the same event. The simultaneous radio spectrum in the range $200-400$ MHz is shown at the bottom of Figure 2_{Ma}. During the impulsive phase of the flare, i.e. at 11:02 UT, the emission of the electromagnetic radiation from the radio ($200-400$ MHz) up to the gamma-ray ($7.5-10$ MeV) range is strongly enhanced. Thus, there is a strong correlation between the radio and the hard X-ray radiation. That indicates the generation of energetic electrons during solar flares. It is one of the basic questions in solar physics, how a huge number of electrons (i.e. 10^{36}) are accelerated up to high energies (i.e. > 30 keV) per second during solar flares. Solar radio observations are an important tool for answering this question.

During solar flares, a huge amount of stored magnetic field energy is suddenly released and transferred into a local heating of the coronal plasma, mass motions (e.g. jets) and particle acceleration (solar energetic particle; SEP). Furthermore, a large amount of coronal material can be ejected in to the interplanetary space. That is usually called coronal mass ejections. All these phenomena of solar activity have their special signatures in the Sun's radio radiation. Thus, the study of the solar radio radiation provides very important information on

- magnetic energy release
- electron acceleration
- plasma jets
- coronal shock waves
- coronal mass ejections
- transport of energetic particles from the Sun into the interplanetary space
- solar energetic particle events

It should be emphasised that all these processes also happens at other places in space, e.g. in other stellar coronae, supernova remnants etc., but they can studied in the best way anywhere than on the Sun as our nearest star.

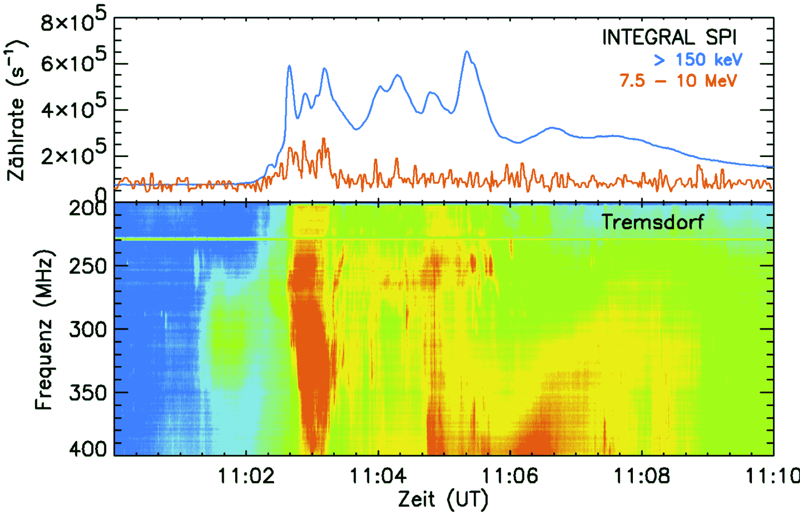


Figure 2_{Ma}: At the top, the temporal behaviour of the photon count rates are presented for the energies > 150 keV (blue line, hard X-rays) and $7.5-10$ MeV (red line, γ-rays). The simultaneous dynamic radio spectrum in the range $200-400$ MHz is shown at the bottom. The radio intensity is colour coded.

The activity of our Sun is influencing our Earth's environment and technical civilization. For instance, solar flares are affecting the global communication. That is usually called *Space Weather*.

The solar radio emission is emanating from the corona. Especially in the dm- and m-wave range, the radio radiation of the Sun is generated by plasma emission, i.e. it is emitted at the local electron plasma frequency and/or its harmonics. Due to the gravitational density stratification the radio waves at different frequencies come from different heights in the corona. Since the SKA will be able to provide radio maps of the Sun at different frequencies (70 MHz – 10 GHz), the SKA will allow a 3-d tomography of the solar activity in the corona. Because of the large SKA dishes and the high precision of the polarisation measurements, the SKA will enable the measurement of the longitudinal component of the magnetic field in the corona. That will also allow magnetic measurements to be extended beyond sunspots.

In summary, the SKA is a very important radio facility of solar physics. It can deliver complimentary information of the Sun in close collaboration to other solar facilities as, for instance, GREGOR on ground as well as Hinode, SDO, and Proba 3 in space.

8.4.2 Ionospheric science and space weather [D. Innes, L. Gizon, N. Krupp]

Space weather: The radio sources on the Sun change from day to day and the most interesting, flares and coronal mass ejections occur with at most three days warning. This makes solar observations of flares difficult to schedule. It is nevertheless urgent to understand the origin and signatures of solar energetic particles (SEPs) and CMEs, not only to get at the heart of these fascinating features and events, but also because they are the principle causes of space weather responsible for changing the properties of the Earths ionosphere and thus affecting satellite orbits and global communications. Flares and shocks are thought to be the primary sources of SEPs but neither source can explain recent STEREO detections of SEPs with an angular spread of 180 degrees from single flares (Innes & Buick 2011). The SKA will be able to image the source and propagation of high energy electrons as they travel trough the corona with unparalleled high resolution maps of $1-10$ GHz bursts. In addition to the high resolution, the sensitivity of the SKA will enable the direct imaging of CME plasma, visible through its gyroresonance and free-free emission. Analysis of the radio spectra gives plasma density, temperature, magnetic morphology and propagation speed in all three dimensions. The aim would be to see where and when particle acceleration occurs in relation to shocks and the bulk plasmas density and magnetic configuration. Less spectacular but more frequent and involving the same basic physics are active region jets and their associated radio bursts. It has recently been suggested that the electron beams responsible for interplanetary radio bursts originate in reconnection regions above sunspot umbra and may be triggered by running penumbral waves (Innes et al. 2011). The SKA can observe the sunspot waves at high frequency (> 5 GHz), the onset of the jets (500 –

100 MHz) and track their propagation using images at lower frequencies.

Magnetic field measurements: The main hindrance to progress in coronal physics is the relative lack of measurement of the coronal magnetic field. Observations in the radio wavelength range provide great promise to change this frustrating situation. The large SKA dishes and high polarisation precision will enable the measurement of the longitudinal component of the coronal magnetic field in weak field (10 G) regions using observations of freefree emission above 10 GHz. This will allow magnetic field measurements to be extended beyond sunspots and the most active regions (to which current measurements are restricted) to the quieter parts of the solar atmosphere.

Future complementary solar facilities in space: The SKA will be operational at a time when we hope that the Proba3 coronagraph will be giving uncontaminated white light images of the solar corona from as close as 1.05 solar radii. This innovative mission will have two spacecraft flying in formation with the sunward spacecraft carrying the occulter and the other the detectors. Combining the coronagraph images with SKA observations will give valuable insight into how and where electron acceleration occurs with respect to the bulk plasma.

References:

Innes D. , Cameron , Solanki, 2011, A&A 531, L13; Innes and Buick, 2011, EGU General Assembly

8.4.3 Determining the masses of the planets [D. Champion]

For the most stable pulsars, pulsar timing can predict the time of arrival (TOA) of a pulse at the Solar System Barycentre (SSB) to within a few 100s of nanoseconds. To convert these to arrival times at the observatory a Solar System ephemeris is used to determine the relative positions of the SSB and Earth. If the Solar System ephemeris was incorrect this would lead to an unmodelled signal in the pulsar timing, this can be effect can be reversed to measure the masses of the planets. This analysis was done using the four longest and most precise data sets taken for pulsar timing (Champion et al. 2010), in all cases, these measurements are consistent with the best-known measurements. For the Jovian system, the measurement improves on the *Pioneer* and *Voyager* spacecraft measurement and is consistent with the mass derived from observations of the *Galileo* spacecraft. Pulsar timing has the potential to make the most accurate measurements of planetary system masses and to detect currently unknown solar system objects such as trans-Neptunian objects.

Pulsars are extremely stable rotators and any effect that causes a delay or advance of their TOA can be measured precisely. The pulses observed during a single observation are added together to produce a single, high signal-to-noise ratio pulse profile. The number of complete rotations between these pulses is then determined using a model. The difference between the model and the observations is minimised by fitting for the model parameters. This technique produces a phase-connected timing solution which accounts for every rotation of the pulsar over the span of the data set, of ten many years.

Before the pulsar model can be fit, the effect of the Earth's orbit must be removed. Depending upon the position of the pulsar there may be as much as 16 mins light travel time delay over the orbit of the Earth. This is equivalent to 500 000 pulses for a fast pulsar. To remove this delay the time of the pulse arrival at the observatory is converted to the arrival time at the SSB. To do this a Solar System ephemeris is used to determine the position of the Earth relative to the SSB, the most common used being from NASA's Jet Propulsion Laboratory.

These ephemerides are constructed by numerical integration of the equations of motion and adjustment of the model parameters to fit data from optical astrometry, astrolabe measurements, observations of transits and occultations of the planets and their rings, radar ranging of the planets, radio astrometry of the planets using very long baseline interferometry, radio ranging and Doppler tracking of spacecraft, and laser ranging of the Moon. These observations constrain the motion of Solar System bodies with respect to the Earth, however they do not tightly constrain the planetary masses. This is reflected in the fact that the planetary/solar mass ratios are normally held fixed in the fit.

If the relative positions of the SSB and observatory are not correctly calculated then an unmodelled signal will be present in the residuals of the fit. For example, an underestimation of the mass of the Jovian system will result in

sinusoidal timing residuals with a period of Jupiter's orbit. The identification of such residuals therefore provides a method to limit or detect planetary mass errors in the ephemeris.
This technique was used by Champion et al. 2010 to measure the masses of the planets from Mercury to Saturn using data taken as part of the International Pulsar Timing Array project (Hobbs et al. 2010). The four pulsars were selected based upon the precision of their measured TOAs, the magnitude of timing irregularities and on the length of the data set. The resulting mass measurements are listed in the table.

System	Best-Known Mass ($M_\odot$)	Ref.	This Work ($M_\odot$)	δ_j/σ_j
Mercury	1.66013(7)$\times10^{-7}$	1	1.6584(17)$\times10^{-7}$	1.02
Venus	2.44783824(4)$\times10^{-6}$	2	2.44783(17)$\times10^{-6}$	0.05
Mars	3.2271560(2)$\times10^{-7}$	3	3.226(2)$\times10^{-7}$	0.58
Jupiter	9.54791898(16)$\times10^{-4}$	4	9.547921(2)$\times10^{-4}$	1.01
Saturn	2.85885670(8)$\times10^{-4}$	5	2.858872(8)$\times10^{-4}$	1.91

(1) Anderson et al. 1987; (2) Konopliv et al. 1999; (3) Konopliv et al. 2006; (4) Jacobson et al. 2000; (5) Jacobson et al. 2006.

All these results were consistent with the best current measurements. Our current data sets are sensitive to mass differences of approximately $10^{-10}\,M_\odot$, independent of the planet. Consequently, our most precise fractional mass determination is for the Jovian system. While the result for the Jovian system is more precise than the best measurement derived from the *Pioneer* and *Voyager* spacecraft by a factor of $\sim$4, the result from the *Galileo* spacecraft is still better by a factor of $\sim$20.

To improve upon these results requires higher precision of the TOAs and longer data sets for more pulsars. For example, after $\sim$7 years of observations a pulsar timing array of 20 pulsars, regularly sampled every two weeks, with an rms timing residual of 100 ns will surpass the *Galileo* measurement for Jupiter; see the figure below. With $\sim$13 years of data, the uncertainty of the current *Cassini* measurement for Saturn is reached. Although it is unlikely that this timing precision will be reached for 20 pulsars using current telescopes the SKA will be able to time large numbers of pulsars to better than 100 ns and will likely find even more stable pulsars that can be used as part of the array.

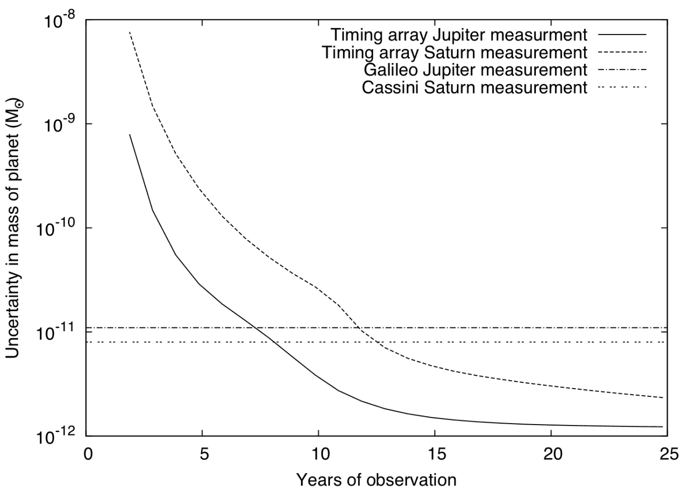


Figure $1_{\rm Ca}$: Mass uncertainties for the Jovian and Saturnian system using simulated data from an array of 20 pulsars sampled every 14 days, timed with an rms timing residual of 100 ns for different data spans. Also plotted are the current best mass measurements for Jupiter (Jacobson et al. 2000) and Saturn (Jacobson et al. 2006).

Although spacecraft measurements provide precise mass measurements for most of the planets, it should be noted that the pulsar measurements are independent with different assumptions and sources of uncertainty. Independent methods are particularly important for high-precision measurements where sources of systematic error may not be well understood. In addition, the spacecraft measure the mass of the body being orbited and do not measure

the mass of the whole planetary system (planet and any satellite masses). When combined with the spacecraft measurements this can provide a measure of the mass undetermined by spacecraft observations.
The pulsar timing technique is also sensitive to currently unknown masses in the Solar System, e.g. trans-Neptunian objects (TNOs). Pulsar timing arrays comprising a large number of stable pulsars with a wide distributions on the sky will be sensitive to any error in the Solar System ephemeris, including those induced by currently unknown TNOs.

References:

Champion D.J., et al., 2010, ApJ, 720, 201; Hobbs G., et al., 2010, Classical and Quantum Gravity, 27, 084013; Anderson J.D., et al., 1987, Icarus, 71, 337; Konopliv A.S., Banerdt W.B., Sjogren W.L., 1999, Icarus, 139, 3; Konopliv A.S., et al., 2006, Icarus, 182, 23; Jacobson R.A., Haw R.J., McElrath T.P., Antreasian P.G., 2000, J. Astronaut. Sci., 48, 495; Jacobson R.A., et al., 2006, AJ, 132, 2520

8.5 Fundamental physics

8.5.1 Fundamental physics with weakly interacting particles [A. Lobanov]

Modern physics finds itself on the brink of a whole new understanding of the most fundamental laws governing particles and forces in the Universe. Investigations of dark matter, dark energy, and new particles span across many fields of research, from accelerator experiments, to astroparticle physics studies, and astrophysical observations.

Most extensions of the standard model of particle physics predict the existence of a "hidden" sector of particles which interact only weakly with the visible sector particles (standard model particles): with the weakly interacting massive particles (WIMP, with masses $m \gtrsim 100$ GeV; e.g. neutralinos with masses in the GeV to TeV range) and ultralight weakly interacting sub-eV particles (WISP; e.g. axions, axion-like particles and hidden photons with masses in the sub-eV range) positioned as the most promising candidates for the dark matter (DM) and dark energy (DE) particles.

Providing observational evidence for WIMP and WISP or setting limits on their physical properties are of paramount importance for modern cosmology, particle physics, and fundamental physics — and the SKA will bring an enormous impact on this field. Dedicated SKA studies will provide an excellent potential for detecting directly the electromagnetic signatures of neutralinos, axions, and hidden photons, and for exploring truly unique areas of the parameter space for each of these particles.

WIMP neutralinos. Recent observations of excess cosmic ray $e^{\pm}$ flux (cf., Aharonian et al. 2008, Abdo et al. 2009) provide compelling arguments for decaying or self-annihilating dark matter and put forth WIMP neutralinos as leading dark matter candidates. For both hadronic and leptonic final states of neutralino annihilation, electromagnetic (EM) signatures are expected to be detectable in the high-energy regime through inverse-Compton emission and in the radio band through synchrotron emission from $e^{\pm}$ annihilation products (Colafrancesco et al. 2007).

The annihilation signal is expected to be very compact in the high-energy bands, while in the radio band it should manifest itself as a smooth and extended halo. This brings a unique advantage for radio observations with the SKA which would be capable of resolving spatially the annihilation signal, hence obtaining much more strignent constraints on mass distribution in DM halos and clumps.

SKA searches for the EM signature of DM annihilation can be made in a number of astrophysical objects, including the Galactic Centre, globular clusters, diffuse galactic emission, nearby dwarf spheroidal and spiral galaxies, and in galaxy clusters. Dwarf spheroidal (dSph) galaxies feature the largest mass-to-light ratios of all these objects (indicative of being dominated by dark matter). The dSph galaxies also have the smallest contamination by astrophysical sources (star formation, SNR, interstellar gas), making them attractive targets for DM searches. Due to an almost two order of magnitude sensitivty improvement provided by the SKA, even non-detection of the annihilation signal will enable a substantial improvement of the limits on the annihilation cross-section and ruling out particular classes of the DM halo models.

An estimate made for arguably the most difficult case (a globular cluster with $M_{\rm cl} = 10^5\,M_\odot$, $M_{\rm cl}/L_{\rm cl} = 5$, $r_{\rm cl} = 10\,$pc located at $d_{\rm cl} = 10\,$kpc) yields a total 1 GHz flux density of $\sim 50\,$mJy distributed over a solid angle of $\sim$0.1 degrees (assuming a magnetic field $B = 1\,\mu$G, a neutralino mass $m_\chi = 100\,$GeV and an annihilation cross-section $\langle \sigma_a v\rangle = 3\times10^{-23}\,{\rm cm^3\,s^{-1}}$. For the compact core of the SKA, this yields a peak brightness of $\sim$2 mJy/beam. With the imaging sensitivity of the SKA reaching a $\sim 1\,\mu$Jy/beam, the DM signal could therefore be detectable even for much smaller (and more physically plausible) values of $\langle \sigma_a v\rangle$.

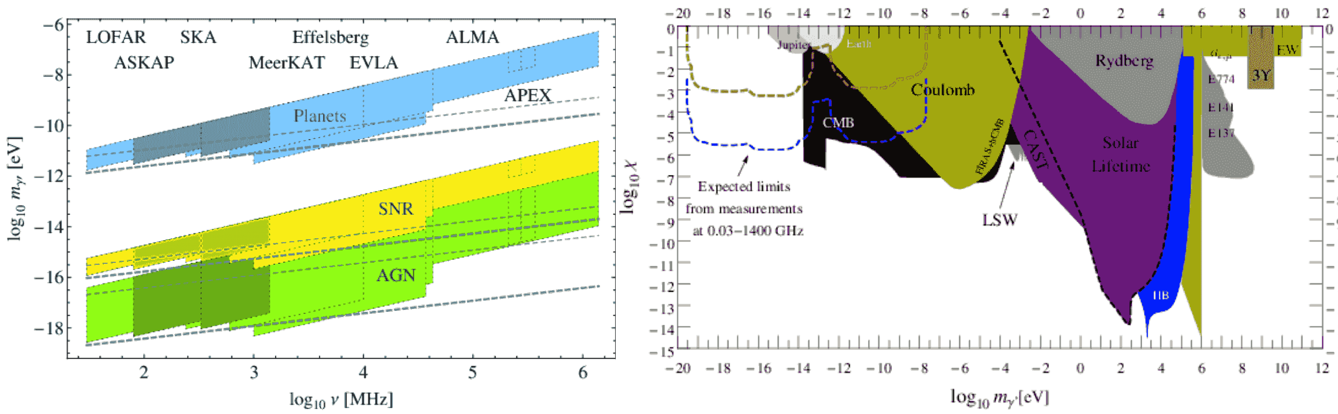


Figure $1_{\rm Lo}$: *left:* Ranges of hidden photon mass, $m_{\gamma'}$, that can be probed by different radio astronomical instruments at different observing frequencies and with different targets. For each colour, darker shades mark the mass ranges accessible to the SKA. The calculations assume typical instrumental setups and generic ranges of distances to planets (0.5 – 10 au), supernova remnants (1 – 10 kpc) and active galaxies (0.02 – 3 Gpc). For each group of targets, dotted lines show minimum detectable $m_{\gamma'}$ as a function of highest observing frequency and distance to a given target, ranging from the minimum (thin lines) to the maximum (thick lines) distances used in the calculation. Actual sensitivity of measuerements and resulting bounds on χ may vary substantially between different instruments and different observing bands. *right:* Ranges of hidden photon mass $m_{\gamma'}$ and kinetic mixing parameter χ excluded by various experiments. The best cumulative bounds expected to be obtained from observations in the radio regime are shown with dashed-line curves for single object (red) and stacked (blue) observations of a number of objects. The SKA measurements provide the best bounds for hidden photon with masses of $10^{-10} - 10^{-12}$ eV and below 10^{-14} eV (frame adapted from Jaeckel & Ringwald 2010).

WISP axions/ALPs and hidden photons. Compelling evidence for existence of ultralight (sub-eV) particles arises from a number of recent experiments, with axions and axions-like particles (ALPs; Raffelt & Stodolsky 1988, Jaeckel et al. 2007), and massless or light, hidden *U*(1) gauge bosons (hidden photons; Okun 1982, Jaeckel & Ringwald 2010) positioned as plausible candidates.

A fundamental feature predicted for WISP is the possibility of their mixing with normal photons. Following this prediction, photons should oscillate between their normal state (γ) and a "hidden" state (γ') in which they propagate along time-like geodesics but do not interact with any normal matter (hence properties of a hidden photon can be completely described by its mass $m_{\gamma'}$ and the kinetic mixing parameter, or mixing angle, χ; with $\chi \ll 1$ expected). The axions can convert to photons in the presence of an ambient magnetic field, with the conversion strength determined by the axion-photon coupling constang $g_{\rm a}$. Experiments and measurements performed so far have yielded bounds on the electro-magnetic coupling for a range of axion masses extending down to $m_{\rm a} = 1\times10^{-15}$ eV (Arias et al. 2010) and hidden photon masses down to $m_{\gamma'} = 2\times10^{-14}$ eV (Redondo 2010).

Radio astronomy measurements made with the SKA will extend axion searches to masses below $\sim 10^{-9}$ eV and probe the axion coupling strength down to $g_{\rm a} = 10^{-14}$ GeV^{-1} (cf., Chelouche et al. 2008). This will expand the experimentally probed range of parameters by about five orders of magnitude.

For hidden photons in particular, SKA observations at frequencies below 3 GHz will offer an excellent (if not unique) tool for placing bounds on χ for $m_{\gamma'} < 10^{-14}$ eV. Oscillations of flux density induced by the hidden photons and occurring at fractional frequency intervals $\Delta\nu/\nu = 2\,\nu\, m_{\gamma'}^{-2} L^{-1}$ will enable detecting kinetic mixing with $\chi \geq \sigma_{\rm rms}^{1/2}$ up to a distance $L_{\rm m} = 2(\nu\,\Delta\nu)^{1/2} m_{\gamma'}^{-2}\sigma_{\rm rms}^{-1}$. For radio observations made with a spectral resolution $\Delta\nu/\nu$ and reaching $\sigma_{\rm rms}$, this implies $\chi(\nu) = (\nu\,\Delta\nu)^{1/4} m_{\gamma'}^{-1} L^{-1/2}$. Improvements of $\sigma_{\rm rms}$ (factor of $\sim$100) and $\Delta\nu/\nu$ (factor of $\sim$100) that will be provided by the SKA, as well as the extension (factor of $\sim$10) to lower frequencies, will enable exploring a new range of $m_{\gamma'}$ below 5×10^{-16} eV and obtaining substantially better bounds on the kinetic mixing of hidden photons with masses below 10^{-14} eV and (as illustrated in the figure; Lobanov et al. in prep.).

References:

Abdo A.A. et al., 2009, Phys. Rev. Lett., 102, 181101; Aharonian F., et al., 2008, Phys. Rev. Lett., 101, 261104; Arias P. et al., 2010, Phys. Rev. D, 82, 5018; Chelouche D., et al., 2009, ApJS, 180, 1; Colafrancesco S. et al., 2007, Phys. Rev. D, 75, 023513; Jaeckel J. et al., 2007, Phys. Rev. D, 75, 013004; Jaeckel J., Ringwald A., 2010, ARNPS, 60, 405; Okun L.B., 1982, Sov. Phys. JETP, 56, 502; Raffelt G., Stodolsky L., 1988, Phys. Rev. D, 37, 1237; Redondo J., 2010, arXiv:1002.0447

8.5.2 Measuring neutrino masses and primordial non-Gaussianity [J. Niemeyer]

The statistical distribution of cosmological structures contains a wealth of information about the history, geometry, and matter inventory of the Universe. It also serves as a valuable probe of the laws of gravity and the physics of inflation during which, according to currently favored theories, the primordial fluctuations were produced. Much of our knowledge to date has been gained from observations of the cosmic microwave background (CMB; e.g Komatsu et al. 2008), combined with galaxy redshift surveys (e.g. Tegmark et al. 2004) and investigations of the Lyman-alpha forest (e.g. McDonald et al. 2006). There are plausible reasons to believe that future radio surveys of neutral hydrogen (H I) emission, especially in combination with planned optical or near-IR redshift surveys (such as BOSS, BigBOSS, HETDEX, Euclid, etc.), will be an ideal probe of fundamental physics during the next two decades. Apart from sharpening constraints on the time dependence of dark energy using BAO features in the cosmological power spectrum (see Section 8.1.1 and 8.1.2), measuring the neutrino mass and determining the extent of primordial non-Gaussianities are among the most prominent goals for future cosmological precision measurements.

Cosmological redshift surveys are ultimately limited by sampling variance, i.e. the number of independent modes accessible for statistical analysis. A non-thresholded H I-survey, or H I intensity mapping, by the SKA can probe a 3-d volume instead of the 2-d surface seen in the CMB, and it can extend to redshifts z$\sim$6 far exceeding those of optical or IR galaxy surveys (z$\lesssim$3$-$4). Hence, the uncertainties in determining the power spectrum can theoretically become as low as $O(10^{-4})$ (Loeb & Wyithe 2008, Rawlings 2011), i.e. more than an order of magnitude improvement over current limits. Furthermore, at redshifts z$\lesssim$1, H I-surveys are expected to detect a sufficiently large number density of emitters to measure the power spectrum with negligible shot noise errors (Abdalla et al. 2010). These forecasts rely on estimates of the evolution of the H I mass fraction in galaxies obtained from semi-analytic models (Marin et al. 2010, Power et al. 2010, Kim et al. 2011) or hydrodynamical cosmological simulations (Duffy et al. 2011a). Observations of the SKA pathfinder programmes, combined with advances in theoretical modeling and available computing power, are likely to produce substantial progress in our understanding of the systematic uncertainties of the cosmological evolution of neutral hydrogen before the onset of SKA operations (Duffy et al. 2011b).

The effect of neutrinos on the power spectrum is well understood: neutrino free streaming produces a mild suppression of the power spectrum on small scales, depending on the time when the neutrinos became non-relativistic and on their total energy density. The effect is difficult to predict precisely at low redshifts, since the scales whose growth is suppressed are in the weakly to fully nonlinear regime where the power spectrum cannot be reliably computed by perturbation theory. Full N-body simulations that explicitly include neutrinos as an additional particle component are still extremely challenging (Brandbyge et al. 2008). Current constraints from cosmological data yield a sum over neutrino masses of about 0.3 eV (Thomas et al. 2010), while experimental bounds from neutrino oscillations show that at least one neutrino has a mass of at least $\sim$0.05 eV. An SKA H I-galaxy survey out to z$\sim$ 2 combined with CMB data would be sensitive to the entire allowed mass range at the 3σ level, and it would allow measuring the number of massive neutrinos (and hence distinguish between a normal and inverted hierarchy) down to 0.25 eV (Abdalla & Rawlings 2007). At higher redshifts, z$\sim$2$-$3, most of the scales affected by neutrinos are still in the linear or weakly nonlinear regime accessible to perturbative calculations; here, cross-correlation of SKA observations with optical surveys such as HETDEX could yield a signal-to-noise ration of $\sim$300 at z$=$2 (Rawlings 2011). Determining the power spectrum at z$>$2 is also interesting for a cleaner separation of curvature and dark energy, which becomes dominant at lower redshifts.

The standard assumption for the statistics of primordial perturbations is a Gaussian distribution, i.e. the power spectrum contains the entire available information. It is well justified for the simplest (single field, slow roll) models of inflation which predict an unmeasurable level of primordial non-Gaussianity (not to be confused with non-Gaussianities produced by gravitational collapse in the nonlinear regime). A clear detection of primordial non-Gaussianity could therefore falsify an entire class of inflationary models. Furthermore, different classes of extensions beyond the simplest model produce unique signatures in the bispectrum which in principle allow to distinguish between e.g. multi-field, DBI, or excited initial state scenarios. It has recently been shown that primordial non-Gaussianity gives rise to a scale-dependent bias in the galaxy power spectrum that is strongest on large scales, i.e. outside of the nonlinear regime (Dalal et al. 2008). Using this effect, galaxy surveys have a potential to constrain $f_{\rm nl}$ (the commonly used dimensionless amplitude of primordial non-Gaussianity of the local type) that is already competitive with bounds from the CMB (Slosar et al. 2008). Current 1σ bounds on $f_{\rm nl}$ are of the order of 25. Large galaxy redshift surveys may become sensitive to $f_{\rm nl}$ of order unity by optimally using the information in the galaxy power spectrum and bispectrum (Jeong & Komatsu 2009). Again, for H I surveys with the SKA an improved observational and theoretical understanding of the clustering properties of H I emission at different redshifts will be crucial. Roughly speaking, the effects of primordial non-Gaussianity are strongest for the most strongly biased tracers of the density field. The current estimates for the bias of H I-emitting galaxies of $b\sim1.5$ at z$\sim$2 (Kim et al. 2011) make it seem plausible that the SKA can significantly contribute to the search for primordial non-Gaussianity. Moreover, combining multiple sets of differently biased tracers, such as BigBOSS or Euclid and SKA galaxies, further enhances the sensitivity by canceling the sampling variance (Seljak 2009).

Neutrino properties and primordial non-Gaussianities are only two prominent examples from fundamental physics that can be explored with the SKA. Aside from dark energy, further fundamental questions that are potentially accessible include modifications of General Relativity measured by the cosmological growth rate (e.g. Daniel & Linder 2010) or other forms of warm dark matter (Viel et al. 2011). The degree to which the SKA will contribute to the determination of these parameters will depend on its final realisation. In the optimistic case that an all sky H I "billion galaxy" survey will become feasible, its constraining power will be competitive with, or even superior to, other planned cosmology probes, e.g. the Euclid mission (Myers et al. 2009).

References:

Abdalla F., Rawlings S., 2007, MNRAS, 381, 1313; Abdalla F., Rawlings S. , 2010, 2010, MNRAS, 401, 743; Brandbyge J., Hannestad S., Haugbølle T., Thomsen B., 2008, J. Cosmology Astropart. Phys. 8:20; Dalal N., Doré O., Huterer D., Shirokov A., 2008, Phys. Rev. D., 77(12); Daniel S.F., Linder E.V., 2010, Phys. Rev. D., 82(10); Duffy A.R., et al., 2012, MNRAS, 420, 2799; Duffy A.R., Moss A., Staveley-Smith, 2011, arXiv:1103.3944; Jeong D., Komatsu E,, 2009, ApJ, 703, 1230; Kim H.-S., et al., 2011, MNRAS, 414, 2367; Komatsu E., et al., 2008, ApJS, 192, 18; Loeb A., Wyithe J.S.B., 2008, Phys. Rev. Letters, 100(16); Marin F.A., Gnedin N.Y., Seo H.-J., Vallinotto, A., 2010, ApJ, 718, 972; McDonald P., et al., 2006, ApJS, 163, 80; Myers S.T., et al., 2009, arXiv:0903.0615; Power C., Baugh C.M., Lacey C.G., 2010, MNRAS, 406, 43; Rawlings S., 2011, arXiv:1105.6333; Seljak U., 2009, Phys. Rev. Letters, 102(2); Slosar A., et al., 2008, J. Cosmology Astropart. Phys. 8:31; Tegmark et al., 2004, Phys. Rev. D. 69(10); Thomas S.A., Abdalla F.B., Lahav O., 2010, Phys. Rev. Letters, 105(3); Viel M., Markovič K., Baldi M.,Weller J., 2012, MNRAS, 421, 50

8.5.3 Ultra-High-Energy particles: Neutrinos and cosmic rays [C. James]

Introduction: The mystery of what is producing the highest-energy particles in nature, the ultra-high-energy[4] cosmic rays, remains unsolved. These extreme particles impact the Earth only once per km^2 per century, and detectors even larger than the 3000 km^2 Pierre Auger experiment are required to gather enough statistics to determine their origin (The Pierre Auger Collaboration 2007). UHE neutrinos – the long-predicted by-products of UHE cosmic-ray acceleration and propagation – are also thought to hold the key. As-yet unobserved, these elusive particles also require the advent of a larger detector to allow their discovery, and to shed light on the UHE cosmic-ray mystery.

By using the "Lunar technique" (Askar'yan 1962, Askar'yan 1965, Dagkesamanskii & Zheleznykh 1989) the SKA promises to do both. The Lunar technique utilises ground-based radio-telescopes observing the Moon to search for UHE particle interactions in the Moon's outer layers. Via the Askaryan effect (Askar'yan 1962, Askar'yan 1965), the interactions of these particles will produce coherent pulses of radio-wave radiation, which can escape the Moon if the interaction is near the surface. Thus the entire visible surface of the Moon can be used as a 10 000 000 km^2 particle detector.

The Benefit of the SKA: Several previous attempts have refined Lunar the technique, but so far no observations have successfully identified a UHE particle signal. This is because only a telescope with the raw sensitivity of the SKA – here, the figure of merit is the product of collecting area and instantaneous bandwidth - will be able to detect the known flux of UHE cosmic rays and beyond, and test models of the flux of "cosmogenic" neutrinos (James & Protheroe 2008).

The size of Lunar cascades (of order 10 cm in width and 3 m in length, Alvarez-Muniz & Zas 1998) means that signal coherency can extend up to a few GHz, but for typical geometries, the coherency will extend to a maximum frequency $\nu_{\rm max}$ of only a few hundred MHz or less due to absorption and decoherence effects. Given that peak signal power increases as $\nu_{\rm max}$, high frequencies are best suited to detecting a larger flux of lower energy particles, and low frequencies to a rarer flux at higher energies. Since the UHE neutrino flux, and the UHE cosmic-ray particle flux above few 10^{20} eV, is currently unknown, the broad frequency coverage of the SKA is critical to maximising discovery potential.

As well as increasing the sensitivity, the large instantaneous bandwidth of the SKA will enable the detection of spectral downturns in detected pulses, which can then be used to gauge the observer's angle to the shower axis. The long SKA baselines will also be able to pinpoint the position of signal origin on the Lunar limb. Combined with the observed signal polarisation, this information can be used to reconstruct the nature and arrival direction of the primary particle, and the cascade energy (James & Protheroe 2009). These properties are also critical for the confidant rejection of radio-frequency interference (RFI). Taken together, this will enable the SKA not only to be a UHE particle detector, but also to perform true UHE particle astronomy.

Detection Technique: Observing nanosecond-scale pulses with a giant radio array however requires novel techniques. Only tied-array beams (coherent addition of signals from each element) at full time resolution will achieve the necessary sensitivity to detect signals coming from the Moon. Each of these beams must be "de-dispersed" to account for the effects of the Earth's ionosphere. Due to computational constraints, only the inner part of the array will be used to form real-time detection beams: small segments of data from the outer stations will be returned upon the detection of a candidate event. This detection paradigm is currently being developed by the NuMoon collaboration for LOFAR's "UHEP" mode (Singh et al. 2012), and the LUNASKA collaboration using Parkes and ATCA (James et al. 2010). However, enabling the SKA to work in such a unique observation mode poses one of the great challenges of this technique.

Summary: Using the Lunar technique, the SKA will be a superb instrument of UHE particle astronomy. If

[4]Commonly, UHE is used to refer to events above 10^{18} eV. Here, the main region of interest is at and above approximately 5 10^{19} eV, where the GZK mechanism is expected to kick-in for protons, and the Pierre Auger observatory sees the greatest statistical anisotropy (The Pierre Auger Collaboration 2007).

the full SKA can be utilised, the known flux of UHE CR will be observable (James et al. 2011, ter Veen et al. 2010) with an event rate at least ten times greater than for Pierre Auger South (Dagkesamanskii & Zheleznykh 1989). Lunar observations would be a significant undertaking for the SKA. If the more pessimistic predictions of a cosmogenic neutrino flux prove true, then of order 2000 hours of observations may be required to detect perhaps only a handful of neutrino events. The likely payoff? Solving the UHE cosmic-ray mystery, and the opening of a new high-energy window on the Universe.

References:

Alvarez-Muniz J., Zas E., 1998, Phys. Lett. B, 434, 396; Askar'yan G.A., 1962, Sov. Phys. JETP, 14, 441; Askar'yan G.A., 1965, Sov. Phys. JETP, 48, 1988; Dagkesamanskii R.D., Zheleznykh I. M., 1989, Sov. Phys. JETP Let. 50, 233; James C.W. , Protheroe R.J., 2008, Astropart. Phys., 30, 318; James C.W., Protheroe R.J., 2009, Astropart. Phys., 31, 392; James C.W., et al., 2010, Phys. Rev. D, 81, 042003; James C.W., Falcke H., Huege T., Ludwig M., 2011, Phys. Rev. E., 84, 056602; Singh K., et al., 2012, Nuclear Instruments and Methods in Physics Research Section A, 1, 171; ter Veen S., et al., 2010, Phys. Rev. D, 82, 103014 M1; The Pierre Auger Collaboration, 2007, Science, 318, 938

8.5.4 Neutron star science with combining radio and X-ray data [W. Becker]

Neutron stars represent unique astrophysical laboratories which allow us to explore the properties of matter under the most extreme conditions observable in nature (although black holes are even more compact than neutron stars, they can only be observed through the interaction with their surroundings). Studying neutron stars is therefore an interdisciplinary field, where astronomers and astrophysicists work together with a broad community of physicists. Particle, nuclear and solid-state physicists are strongly interested in the internal structure of neutron stars which is determined by the behavior of matter at densities above the nuclear density $\rho_{\rm nuc} = 2.8 \times 10^{14}$g cm^{-3}.

Neutron stars are observable as pulsars, i.e. rapidly spinning, strongly magnetized neutron stars which are radiating at the expense of their rotational energy. With some more basic assumptions (cf. Becker 2009) this allows one to estimate a neutron star's age by measuring its period and period derivative. Knowing the age of this objects then supports to study all kinds of evolutionary effects like the thermal evolution of neutron stars.

Neutron stars are formed at very high temperatures of $\sim 10^{11}$ K, in the imploding cores of supernova explosions. Much of the initial thermal energy is radiated away from the interior of the star by various processes of neutrino emission (mainly, Urca processes and neutrino bremsstrahlung), leaving a one-day-old neutron star with an internal temperature of about $10^9 - 10^{10}$ K. After ~ 100 yrs (typical time of thermal relaxation), the star's interior (densities $\rho > 10^{10}$ g cm^{-3}) becomes nearly isothermal, and the energy balance of the cooling neutron star is determined by the following equation:

$$C(T_i)\,\frac{\mathrm{d}\,T_i}{\mathrm{d}\,t} = -L_\nu(T_i) - L_\gamma(T_s) + \sum_k H_k,$$

where T_i and T_s are the internal and surface temperatures, $C(T_i)$ is the heat capacity of the neutron star (cf. Becker 2009). Neutron star cooling thus means a decrease of thermal energy, which is mainly stored in the stellar core, due to energy loss by neutrinos from the interior ($L_\nu = \int Q_\nu\,\mathrm{d}V$, Q_ν is the neutrino emissivity) plus energy loss by thermal photons from the surface ($L_\gamma = 4\pi R^2 \sigma T_s^4$). The relationship between T_s and T_i is determined by the thermal insulation of the outer envelope ($\rho < 10^{10}$ g cm^{-3}), where the temperature gradient is formed. The cooling rate might be reduced by heating mechanisms H_k, like frictional heating of superfluid neutrons in the inner neutron star crust or some exothermal nuclear reactions.

The fact that the thermal evolution of neutron stars is very sensitive to the composition and structure of their interiors, in particular, to the equation of state at super-nuclear densities means that measuring surface temperatures of neutron stars is an important tool to study super-dense nuclear matter. Since typical temperatures of such neutron stars correspond to the extreme UV – soft X-ray range, the thermal radiation from cooling neutron stars can be observed best with X-ray detectors sufficiently sensitive at $E \lessapprox 1$ keV.

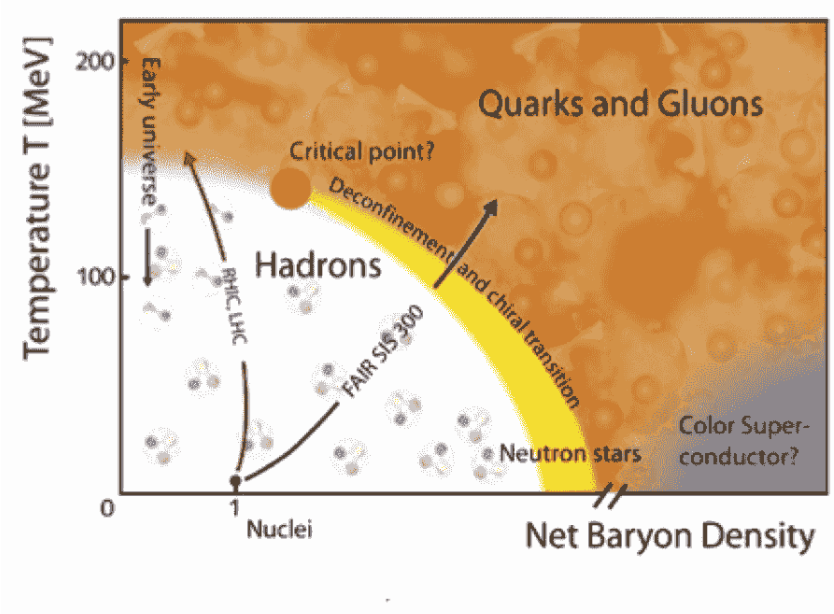


Figure 1_{Beck}: Density vs. Temperature of cold condensed matter. Neutron stars probe the low temperature high density region of the QCD phase diagram. Fundamental questions in physics like: what is the equation of state of matter at sub-nuclear density?, what is the nuclear interaction potential of nuclei at this density? And whether Quarks are able to maintain colour superconductivity can be answered by exploring this density region in e.g. studying the thermal evolution of neutron stars. Todays laboratory experiments (LHC, RHIC, FAIR) will not reach this density level at this low temperature.

Of the 2000 radio pulsars known today only about $1-2\,\%$ turn out to be suitable to study cooling effects using X-ray telescopes. This is mostly because pulsars which are best suited to study cooling effects should be nearby and in the age bracket between $(0.5-1)\ 10^6$ yrs. With a telescope like the SKA the number of radio pulsars expected to be found is about 15 times the number of pulsars detected today. Among them will be a large fraction of middle-age pulsars well suited to study their thermal evolution. The SKA thus will help to enlarge the sample of cooling neutron stars by a significant factor and thus improving todays results which are limited by small number statistics of the detected objects.

Pulsar research also has its application in autonomous spacecraft navigation, by making use of the pulsar's characteristic timing information (cf. Bernhard et al. 2011 and references therein). Rotation-powered pulsars, especially millisecond pulsars, are particularly interesting for two reasons: First, they provide characteristic temporal signatures that can be used as natural navigation beacons; second, the stability of their rotation frequencies is comparable to, or even better than, the timing stability of atomic clocks, which is most important because the temporal resolution is the limiting factor for the performance of this navigation technique.

A pulsar-based navigation system in principle can be designed for any energy band of the electromagnetic spectrum, but X-rays are preferable for several reasons: Whereas radio pulsars are usually very faint and, therefore, are observed by large radio antennas with diameters of typically 50 to 100 metres, X-ray telescopes can be built relatively compactly. Furthermore, radio waves are subject to interstellar dispersion, an effect that degrades the temporal resolution of pulsar data due to pulse smearing. In contrast, X-ray propagation through the interstellar medium does not affect pulsar timing.

A sensitive spacecraft navigation system based on the X-rays observation of millisecond pulsars relies on having suitable pulsars in the field of view, regardless of the direction the instrument is pointed to in the sky. Currently, however, only about $10\,\%$ of the radio pulsars are millisecond pulsars, giving tight constrains to this navigation approach. The SKA is supposed to increase the number of radio millisecond pulsars by a factor of more than 10 compared with the number detected today. This in turn will allow more millisecond pulsars to be detected in the X-ray domain which will be of great advantage for using these sources as natural navigation beacons in space craft navigation.

In view of the observational capabilities previous instruments provided so far, and the intense neutron star research made over a period of more than 42 years, there are still fundamental questions which have not be answered. Questions like "How are the different manifestations of neutron stars related to each other?", "What are the physical parameters which differentiate AXPs/SGRs/CCOs/XDINs and rotation-powered pulsars?", "What is the maximal upper bound for the neutron star mass and what is the range of possible neutron star radii?", "Is there any exotic matter in neutron stars?", "Do strange stars exist?", and "What are the physical processes responsible for the pulsars' broad band emission observed from the infrared to the gamma-ray band?" are just the most striking ones. They all can be addresses with multi-wavelengths observations using telescopes like the SKA in the radio and future X-ray observatories in the high-energy band. New observatories are supposed to bring a major improvement in sensitivity, making them even more suitable for pulsar and neutron star astronomy than the instruments we have available today.

References:

Becker, W., 2009, Astrophysics and Space Science Library, Vol.357, Springer; Bernhardt, M.G., Becker, W., Prinz, T., Breithuth, F.M., Walter, U. 2011, "Autonomous Spacecraft Navigation Based on Pulsar Timing Information" in IEEE proceedings of 2nd International Conference on Space Technology", Athens, Greece, 2011, Editors M. Petrou, M. Gargalakos, N. Uzunoglu, ISBN 9 7811457 718724

8.5.5 Testing theories of gravity with binary pulsars and black holes [M. Kramer, N. Wex, K. Liu, G. Schäfer]

Previous experience has proven that finding a large number of new pulsars will inevitably lead to the discovery of rare objects which push our understanding of their formation or which can be used as unique laboratories for fundamental physics. Currently, we know of about 2000 radio pulsars of which about half were discovered in a single survey, i.e. the Parkes Multibeam Survey for Pulsars (Manchester et al. 2001). In comparison, the SKA's combination of sensitivity and field-of-view will provide a Galactic census of pulsars, which will essentially include every pulsar (visible from the SKA location) that is beaming towards Earth. The 20 000 to 30 000 pulsars to be discovered should join the about 2000 millisecond pulsars (most of which will be in binaries), about 100 relativistic binaries and eventually the rare objects like pulsar-black hole systems (Kramer et al. 2004, Smits et al. 2009).

In binary pulsars hosting a pulsar and a compact companion, we essentially encounter two gravitational test masses of which (at least) one is fitted with a precise cosmic clock. By tracing the motion of this clock in the curved spacetime of its companion, we can test the predictions of general relativity (GR) and alternative theories of gravity. The advantage of using binary pulsars lies in the combination of having access to a system of compact masses that only interact gravitationally, so that their motions should be fully explained by the theory of gravity to be tested, and the ranging capabilities of a pulsar timing experiment. As a result, binary pulsars already provide the best tests of theories of gravity for strongly self-gravitating bodies (Kramer et al. 2006).

With the full SKA, we can expect an improvement in timing precision by a factor of ~ 100. Consequently, we expect that tests of theories of gravity with binary pulsars will greatly surpass the precision of current gravity tests. Concerning the known systems, in particular the continued observations of the Double Pulsar will derive important constraints for testing alternative theories of gravity and the validity of specific concepts in strong gravitational fields (Kramer & Wex 2009). Moreover, this improvement in precision will for many of the relativistic effects allow to probe higher order and spin contributions predicted by GR (e.g. Damour & Schäfer 1988; Blanchet & Schäfer 1989).

Most importantly, however, with the SKA we will be able to probe the properties of black holes and compare those to the prediction of GR for Kerr black holes. With pulsars orbiting the super-massive black hole in the Galactic centre and the discovery of binary pulsars with stellar-mass black hole companions, we will be able to measure the mass, spin and quadrupole moment of the black holes. These measurement will allow us to test the *cosmic censorship conjecture* as well as the *no-hair theorem* (Wex & Kopeikin 1999, Kramer et al. 2004).

The cosmic censorship conjecture states that every astrophysical black hole, which is expected to rotate, has within GR an event horizon that prevents us from looking into the central singularity. However, the event horizon disappears for a given value of the black hole spin, so that we expect the measured spin to be below the maximum allowed value. The no-hair theorem makes the powerful statement that the black hole has lost all features of its progenitor object, and that all black hole properties are determined by only the mass and the spin (and possible charge). Therefore, if the no-hair theorem is valid, the expected quadrupole moment of the black hole can be

uniquely determined from the mass and the spin. With a measurement of all three quantities, this theorem can be tested (Kramer et al. 2004, Liu 2012).
With the chance to perform these experiments with the super-massive black hole in the Galactic centre, stellar black holes and, possibly, intermediate mass black holes in globular clusters, a whole black hole mass range can be studied. As already pointed out by Damour & Esposito-Farèse (1998), a pulsar-black hole system will be a superb probe of gravity, even for theories which make the same predictions for black holes as GR.
In particular, the discovery of radio pulsars in compact orbits around Sgr A* would allow an unprecedented and detailed investigation of the spacetime of the supermassive black hole. Timing of even a single pulsar could provide novel tests of GR. Recently, Liu et al. 2012 presented a method that uses a phase-connected timing solution to enable the determination of the mass of Sgr A*, the frame dragging caused by its rotation, and its quadrupole moment. They show that a simultaneous measurement of the mass, the spin (magnitude and orientation), and the quadrupole moment of Sgr A* is possible by observing a single pulsar in a six months orbit over a period of a few years. Due to the strong pulse broadening caused by the interstellar medium near Sgr A*, only rather slow pulsars are expected to be discovered in surveys, even at frequencies above 10 GHz. Considering a pulsar with 0.5 s spin period we show that the optimal timing frequency is above 15 GHz, and that uncertainties of 100 μs in the arrival times are realistic with the SKA. If Sgr A* is spinning rapidly, weekly timing observations over five years would lead to a measurement precision of 10^{-3} for the spin and 10^{-2} for the quadrupole moment, if the orbital period of the pulsar is a few months. These numbers convert directly into a 1 % test of the no-hair theorem for Kerr black holes. This method is capable of identifying perturbations caused by distributed mass around Sgr A*, thus providing high confidence in these gravity tests.
In summary, with its unique sensitivity the SKA will push the current binary pulsar strong-field tests to unprecedented levels. More importantly, however, with the abilities of the SKA to also find more extreme systems and pulsars orbiting black holes, the observatory will also provide new tests that are qualitatively very different from what is possible today. In particular, the SKA will be able to test GR's description of black holes with precise measurements, providing one of the best tests of gravitational theories imaginable.

References:
Blanchet L., Schäfer G., 1989, MNRAS, 239, 845; Cordes J. M., et al., 2004, New Astr., 48, 1413 Damour T., Esposito-Farèse G., 1998, Phys. Rev. D, 58, 1; Damour T., Schäfer G., 1988, Nuovo. Cimento, 101, 127; Kramer M., et al., 2004, New Astr., 48, 993; Kramer M., et al., Science, 314, 97; Kramer M., & Wex N., Class. Quantum Grav. 26, 073001; Liu K., 2012, PhD thesis, Manchester University; Liu K., et al., 2012, Astrophys. J., 747, 1 ; Manchester R. N., et al., 2001, MNRAS, 328, 17; Smits R., et al., 2009, A&A, 493, 1161; Wex N., Kopeikin S., 1999, ApJ, 514, 388;

8.5.6 Magnetars [K. Kokkotas]

High-density equation of state is a holy grail for astrophysics, relativity and nuclear physics. There is a continuous effort to use all available data from observations of neutron stars in radio, X- or gamma-rays in order to constrain the neutron star parameters and to unveil their internal structure (Lattimer & Prakash 2007). Apart from observations in the electromagnetic spectrum, the elusive gravitational waves offer an alternative opportunity window (Andersson & Kokkotas 1998, Gaertig & Kokkotas 2011).
An alternative/complementary way to reach this is through the study of oscillations from magnetars (Colaiuda & Kokkotas 2011). These oscillations can be observed in the gamma and X-ray part of the spectrum but radio observations can not be excluded while it is possible to observe them via gravitational waves. Two such events have been observed up to now, that is the giant flare of the 2004 December 27 from SGR 1806-20, observed with the X-Ray Timing Explorer (RXTE) and the 1998 giant flare of another magnetar the SGR 1900+14.
Magnetars are thought to be neutron stars with very strong ($> 10^{14}$G) surface magnetic fields. 21 of them have so far been observed in X-rays (http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html). A groundbreaking discovery was made recently by Gavriil et al. (2008) who found that the outburst of a rotation-powered pulsar in Kes 75 (PSR J1846-0258) was typical of magnetars. This was evident through the sudden and significant change in braking index and glitch in its timing behavior (Kuiper & Hermsen 2009). Also five magnetar-like X-ray bursts

were observed during this outburst, making this a promising candidate for observing oscillations when sensitivity is high enough (Gavriil et al. 2008). After the outburst the source went back to normal rotation-powered activity, with radio pulses being however still absent from this system (Archibald et al. 2008).

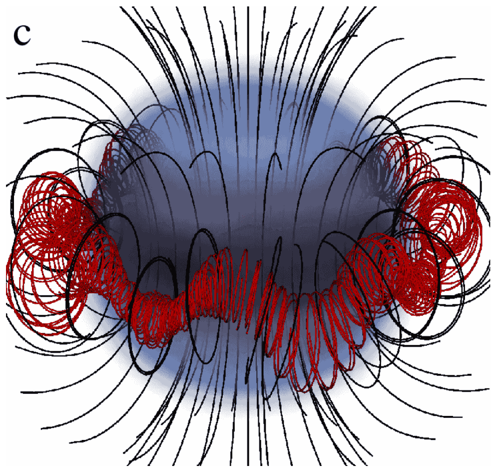


Figure 1_{Ko}: The growth of an MHD instability in the magnetar interior as depicted by the non-linear simulation in (Lasky et al. 2011). This type of instabilities maybe responsible for the catastrophic rearrangement of the magnetic field and even the production of weak gravitational waves.

Observing this type of systems with a next generation radio telescope, like the SKA, will provide important insight in the behavior of this type of enigmatic sources. The fact that such events are not very long lasting provides food for speculation that this source (PSR J1846-0258) is not an exception and more rotation-powered pulsars show magnetar like activity (Ng & Kaspi 2010). This may be supported by the radio pulsations seen from three magnetars (Rea & Esposito 2011). These pulses have some different characteristics than the typical ones for rotation-powered pulses but also some similarities (Kramer et al. 2007). Searches and observations with the SKA could determine the origin of the emission and clarify this open question. Monitoring known pulsars with the SKA and discovering new ones will enlarge this population and expectedly discover other sources with switching behavior. This will extend the number of known magnetars and allow for a deeper study of their activity. Near-simultaneous observations of these sources in X-rays and radio waves will be critical for these studies.

References:

Andersson N., Kokkotas K.D., 1998, MNRAS, 299, 1059; Archibald A.M., et al., 1998, ApJ, 688, 550; Colaiuda A., Kokkotas K.D., 2011, MNRAS, 414, 3014; Gaertig E., Kokkotas K.D., 2011, Phys. Rev. D, 83, 064031 Gavriil F. P., et al., 2008, Science, 319, 1802; Kramer M., et al., 2007, MNRAS, 377, 107; Kuiper L., Hermsen W., 2009, A&A, 501, 1031; Lasky P.D., Zink B., Kokkotas K.D., Glampedakis K., 2011, ApJL, 735, L20; Lattimer J.M., Prakash M., 2007, Phys. Reports, 442, 109; Ng C.Y., Kaspi V.M. 2010, arxiv:astro-ph.HE, 1010.4592; Rea N., Esposito P., 2011, in *High-Energy Emission from Pulsars and their Systems*, eds. D.F.. Torres and N. Rea, 247

8.5.7 The SKA and compact objects [J. Schaffner-Bielich, A. Sedrakian]

The structure and composition of compact objects is uniquely determined by the equation of state (hereafter EoS) of matter in their interior. This is strictly true if General Relativity is the correct theory of gravity. We need to keep in mind, however, that alternative theories of gravity may become an option if we find a drastic disagreement between theory and observations. Then, for any given equation of state, one can compute the so-called global (or integral) parameters of an compact star, typically the mass, the radius, and the moment of inertia.

Among the global parameters of neutron stars their masses are most sensitive to the equation of state at high densities. Therefore, pulsar mass measurements provide one of the key experimental constraints on the theory of ultra-dense matter. The masses measured in the pulsar binaries, after the discovery of the first millisecond pulsar (MSP) in 1982, are clustered around the value 1.4 $M_\odot$ and have been considered as "canonical" for a long time. However, in recent years mounting evidence emerged in favor of substantially heavier neutron stars with $M \geq 2M_{\odot}$. In particular, the recent discovery of a compact star with a mass of $1.97\ M_{\odot}$ through the measurement of Shapiro delay provides an observationally "clean" lower bound on the maximum mass of a compact star. This single result revolutionises our view on the dense matter and provides a clear evidence that the EoS of dense matter is stiff.

Indeed, theoretically, it is now well established that emergence of new degrees of freedom at high densities softens the EoS of matter. For example, allowing for hyperons to appear in dense matter can reduce the maximum mass of a sequence of compact stars below the canonical mass $1.4\,M_{\odot}$. A similar reduction in the maximum mass occurs if kaon condensation takes place. The situation for quark matter is less clear, as it constitutes a new form of matter and not an additional degree of freedom. An extended mixed phase of normal matter and quark matter will reduce the maximum mass, but quark matter can also help to stabilize massive compact stars by providing an additional counterpressure in the core. The observation of a $2M_{\odot}$ mass neutron star is certainly an evidence that the ultra-dense matter in neutron stars can not be soft, *i.e.*, agents that will substantially soften the equation of state are potentially excluded. In particular, this observation already rules out models of dense matter which advocate kaon condensation with typical maximum masses of around $1.5\,M_{\odot}$. Also, model parameters for quark matter being potentially present in the core of compact stars start to be substantially constrained.

The fact that the SKA will be able to measure a large number ($\sim$3000) of MSPs, a considerable fraction of which will certainly be in a binary orbit, will largely increase the chance to observe objects drawn from the high-mass tail of the pulsar mass distribution. It is important to note that a single "clean" observation of a high-mass MSP could strongly constrain the EoS. Such constraints will have profound impact on our understanding of dense matter and on the problem of deconfinement transition from nuclear matter to quark matter - one of the "holy grails" of elementary particle physics. For example, it has been demonstrated that the observation of "twins" - stars having same mass but different moments of inertia - could be a clear signal in favor of hybrid configuration, i.e., stars featuring quark matter in their interiors. The high-density EoS serves as a crucial input for simulations of core-collapse supernovae and neutron star mergers which are considered to be the prime sites for the nucleosynthesis of heavy elements in our Universe. The investigation of the high-density and high temperature EoS is a key for our understanding of the early Universe shortly after the big bang and relativistic heavy-ion collisions, as probed by the Relativistic Heavy Ion Collider (RHIC), the Large Hadron Collider (LHC) and the Facility for Antiproton and Ion Research FAIR at GSI Darmstadt.

We can go on and ask what if accurate measurements of a pair of global parameters were possible? The discovery of the double-pulsar system PSR J0737-3039 already focused our attention on the possibility of simultaneous measurements of the pulsar masses and moment of inertia. A single such measurement could place a point on the mass versus moment of inertial graph through which any candidate EoS should pass. The moment of inertia is roughly proportional to the product of the star's mass and its radius squared, therefore such measurement will give us also an estimate of the radius of the star. Observations of several pairs of global parameters for different pulsar masses will allow us to map out portions of the mass versus moment-of-inertia diagram and thus even further constrain the EoS. In fact, some have argued that the nuclear equation of state can be reconstructed (inverted) from the mass versus radius (or equivalently moment of inertia) observations (Lindblom 1992). Although such reconstruction will not give us the EoS chosen by nature per se, it will provide an extremely useful guidance in the studies of dense matter; we can anticipate that the number of models of dense matter, which is inflated today up to a few tens will narrow down to a few. Furthermore, there is a potential of discovering a new branch of compact objects - self-bound strange stars - which have a mass-radius (or mass-moment of inertia) dependence that is different from the one of the objects bound by gravity.

As compared to other channels of observation of compact objects the SKA programme is extremely valuable because of the precision at which the global parameters of compact objects can be measured. These could be compared with e.g. the constraints on neutron star radii from x-ray bursters and thermal radiation from cooling neutron stars that are relatively weak by itself.

Our current knowledge suggests that the pulsar masses in binaries have a certain distribution which has its origin either in the long-term evolutionary processes (mass accretion from a companion) or short-term dynamics (e.g. creation in a collapse.) The promise held by the SKA to observe a large number ($\sim$3000) MSPs and about 100 relativistic binaries will lead to a potential break-through in our understanding of the evolutionary path undergone

by MSPs. Large statistics will allow us to build and test statistical models of the evolution of MSPs, to find reliable statistical correlations between different parameters, such as the mass, moment of inertia, B-field, spin and its derivatives. These observations could improve our understanding of pulsar genesis and evolution in the $P-\dot{P}$ diagram, i.e., either confirm the present paradigm of spin-up of millisecond pulsars by accretion or suggest new evolutionary avenues.
Increasing the statistics of millisecond pulsars through the SKA programme means increased probability of finding fast rotating pulsars. Each EoS has its unique mass-shedding limit frequency for each fixed mass star. The limit refers to the frequency beyond which the centrifugal forces cannot be balanced by the gravity and a mass loss starts from the equator. Thus, some models can be excluded on the basis of an observation of a stable, rapidly rotating millisecond pulsar. An increase in the currently observed maximal frequency by a factor of two will already place strong constraint on the EoS. Measuring a pulsar close to its Keplerian frequency together with its mass can provide constraints of the same quality as those provided by the mass versus radius or mass versus moment of inertia measurements.

References:
Lindblom L., 1992, ApJ, 398, 569

8.5.8 Motion of particles and light rays in strong gravitational fields [C. Lämmerzahl, E. Hackmann, M. List, V. Perlick, D. Puetzfeld, J. Kunz, V. Kagramanova, B. Hartmann]

Expertise: The expertise of the Bremen and Oldenburg gravity groups is (a) to find analytical and also numerical black hole solutions of the Einstein equations in standard Einstein General Relativity as well as in generalized gravitational models, and (b) also to find analytical and numerical solutions of the equations of motion for a large class of axially symmetric space- times. For the analytical solutions of the geodesic equation this includes the equation of motion of charged particles and for light rays in the whole class of Plebański-Demiański space-times (Hackmann & Lämmerzahl 2008a, Hackmann & Lämmerzahl 2008b, Hackmann et al. 2009). Also the motion of particles in space-time geometries with cosmic strings has been treated by us. We are also solving equations of motion for particles with spin (Obukhov & Puetzfeld 2011) and are also approaching solutions for test particles with mass quadrupole moment (Steinhoff & Puetzfeld 2010), all are described by the Mathisson-Papapetrou-Dixon equations. Our method can be applied to the effective one-body formalism describing binary systems in GR in terms of a power series, too. We also started to consider the motion of test particles including the influence of the gravitational self force.

Research programme: We are very interested in applying our theoretical expertise to astrophysical observations of the SKA. By that we would like to (i) confront analytical results for observables for orbits of test objects in gravitational fields with high precision observations, (ii) to calculate orbits taking into account the emission of gravitational waves whose form we also would like to calculate, and (iii) use high precision observations for tests of alternative theories of gravity.

I. Orbits of stellar objects in strong gravitational fields: It is only by the observation of test particles (realised by light rays and small astrophysical objects like stars or not too big black holes) that one can determine the space-time geometry. This space-time geometry influences the timing, frequency, and direction of the emitted radio and gravitational waves. This has to be taken into account in the analysis of radio data. Since objects are not only pointlike but in general have an internal structure (in astrophysics all stellar objects are rotating and, thus, possess spin and also axisymmetric higher order mass multipole moments), the influence of these internal structures on the motion also has to be taken into account. Once the gravitational field is known one can calculate and interpret further effects with light rays and radio waves which then are used for consistency considerations. What we would like to treat in detail is: a. Analytic calculation of orbits and orbital effects like perihelion shift, Lense-Thirring effect, light bending, etc. (e.g. Hackmann & Lämmerzahl 2012) b. Influence of the spin of test particles on the orbits and on the mentioned orbital effects. For particular configurations like parallel spin which might be realised in astrophysics, one may find analytic solutions and analytic expressions for the orbital effects. Otherwise we would like to study chaos which in general occurs for the motion of particles with internal structure. c. The same holds for the influence of (axially symmetric) mass quadrupole effects on orbits and the orbital effects. Again, analytic solutions in particular cases and also study of chaos is aimed for. Topic b and c also represent a test of the Mathisson- Papapetrou-Dixon equation for spinning and extended objects. d. As one further application of the bending of light we consider the analytical calculation of the shadow of black holes, or higher order images (also called relativistic images). From this one can deduce the properties (mass, rotation parameter) of black holes. e. We would like to derive analytic expressions for timing formulas, based on the analytic representation of orbits and light rays. This should in particular be applicable to binary pulsar systems and compared with high precision observations. With these analytic representations we can test approximation results and also can compare it with results from numeric calculations. f. Also the structure and the behaviour of an accretion disc of a dense object results from the dynamics of particles in strong gravitational fields. In this context the Jacobi equation (dynamics of the relative distance of neighbouring points) plays an important role. This is also a starting point for an analytical treatment of the disruption of objects in strong gravitational fields.

II. Orbits and the emission of gravitational waves: The motion of masses in general will create gravitational waves. These emitted gravitational waves directly depend on the orbits of the masses (also obtained in the first part of this study) and also influence the motion of the body through the loss of energy and angular momentum of the system. Therefore a consistent picture has to be obtained for the motion of the bodies and the form of the gravitational waves. This can be treated in the extreme mass ratio inspiral (EMRI) case where one of the objects is nearly a test particle, or within the effective one-body formalism. Here we would like to calculate: a. The inspiraling orbits and the correspondingly emitted gravitational waves through orbiting EMRI objects. From that the orbital parameters and effects and the timing formulae and other features can be calculated and compared with observations. b. The inspiraling orbits and the created gravitational waves for near equal mass binary systems in the framework of the effective one-body formalism. c. The inspiraling orbits as well as created gravitational waves for a particle which spirals into a boson star. From the measured data of gravitational waves one can identify the object's mass, spin and multipole moments. Due to these physical properties especially their ratio towards each other one should be able to distinguish a boson star from a black hole as the central gravitating object. The resulting orbits then can be observationally confirmed through the observation of orbital parameters or of the timing of pulsar signals. The effect of the radiated gravitational waves also should be compared with results from self-force calculations for the motion of near test particles in gravitational fields.

III. Testing alternative gravitational theories: Any motion of particles and light rays can be used for testing alternative theories of gravitation. Here we restrict to particular tests including black holes and similar high density objects and objects with spin polarisation. We aim at considering three aspects through the observation of the motion of test particles and light rays: (i) To proof the validity of certain properties of black holes encoded in the famous uniqueness and scrutinize boson stars (which might be a consequence of the standard model of particle physics). (ii) To compare the motion of particles and light rays in black hole space-times versus the motion in space-times obtained for boson stars in order to decide how good high density objects which today are considered to be black holes may also be represented by boson stars (which may be a consequence of the standard model of particle physics). (iii) To search for unusual properties of black holes related to generalized theories of gravity where we have, for example, black holes pierced by cosmic strings (Hackmann et al. 2010), black hole with hairs (including scalar hairs), counterrotating horizons etc. These properties of black holes also can be tested using the motion of test particles, light rays, and radio waves in the vicinity of black holes, see e.g. Enolski et al. (2012). a. One way to investigate properties of black holes is to analyze higher order images (intensity, angular sequence, ...) at mostly axisymmetric black holes as well as the shadow of black holes (Kerr black hole, black holes pierced with cosmic string, ...), and boson stars (Perlick 2012). Here we expect major information concerning the very interesting issue of clearly characterising black holes and boson stars from observations of a central object due to their physical properties e.g. mass, spin and multipole moments. b. We aim to test the no-hair theorem through adding not only mass multipoles but arbitrary axisymmetric perturbations to standard General Relativity and also of generalized gravity models. Then the motion of test bodies and light rays within these black hole geometries could be determined. Additionally tests of black holes with hair, including scalar hair, for generalized theories of gravity are considered as they are predicted e.g. from low energy effective Lagrangians from resulting from string theory. c. In the context of the issue of looking for a possibility of boson stars mimicking black holes numerical methods have to be used. Boson star solutions of the Einstein field equations can be obtained only through numerical methods – no analytical solution is known. Correspondingly, the motion of test particles and light rays in these space- times also has to be calculated numerically (Kleihaus & Kunz 2005, Kleihaus & Kunz 2008). The results for the orbits, the orbital parameters, the light rays in terms of shadows, higher order images, etc. have to be compared with measurements and could lead to a better understanding and specification of gravitating sources.

References:

Enolski V., et al.,2012 , J. Math. Phys., 53, 012504; Hackmann E., Lämmerzahl C., 2008a, Phys. Rev. Lett., 100, 171101; Hackmann E., Lämmerzahl C., 2008b, Phys. Rev. D, 78, 024035; Hackmann E., Kagramanova V., Kunz J., Lämmerzahl C., 2009, Phys. Rev. D, 81, 044020; Hackmann E., Lämmerzahl C., Hartmann B., Sirimachan P., 2010, Phys. Rev. D, 82, 044024; Hackmann E., Lämmerzahl C., 2012, Phys. Rev. D, 85, 044049; Kleihaus B., Kunz J., List M., 2005, Phys. Rev. D, 72, 064002; Kleihaus B., Kunz J., List M., Schaffer I., 2008, Phys. Rev. D, 77, 064025; Obukhov, Y., Puetzfeld D., 2011, Phys. Rev. D, 83, 044024; Perlick V., 2004, Living Rev. Relativity, 7, 9; Steinhoff J., Puetzfeld D., 2010, Phys. Rev. D, 81, 044019

8.5.9 Gravitational wave astronomy: Precision pulsar timing [K.J. Lee, N. Wex, M. Kramer]

The observed orbital decay in binary pulsars detected via precision timing experiments so far offers the only evidence for the existence of gravitational wave (GW) emission. Intensive efforts are therefore on-going worldwide to make a direct detection of GWs that pass over the Earth. Ground-based detectors like GEO600, VIRGO, and LIGO use massive mirrors, the relative distance of which are measured by a laser interferometer set-up, while the future space-based LISA detector uses formation flying of three test-masses that are housed in satellites. The change of the space-time metric around the Earth also influences the arrival times of pulsar signals measured at the telescope, so that high-precision timing of millisecond pulsars (MSPs) can also potentially directly detect GWs. Because pulsar timing requires the observations of a pulsar for a full Earth orbit before the relative position between pulsar, Solar System Barycentre and Earth can be precisely determined, only GWs with periods of more than a year can usually be detected. In order to determine possible uncertainties in the used atomic clocks, planetary ephemerides used, and also since GWs are expected to produce a characteristic quadrupole signature on the sky, several pulsars are needed to make a detection. The sensitivity of such a "Pulsar Timing Array" (PTA) increases with the number of pulsars and should be able to detect pulsars in the nano-Hz regime, hence below the frequencies of LIGO ($\sim$kilo-Hz and higher) and LISA ($\sim$milli-Hz). A number of PTA experiments are ongoing, namely in Australia, Europe and North America (see Hobbs et al. 2010 for a summary). The currently derived upper limits on a stochastic GW background (e.g. Jenet et al. 2006, Ferdman et al. 2010) are very close to the theoretical expectation for a signal that originates from binary super-massive black holes expected from the hierarchical galaxy evolution model (Sesana et al. 2008, Sesana & Vecchio 2010).
Demonstrating the power of PTA experiments, Champion et al. 2010 recently used data of PTA observations to determine the mass of the Jovian system independently of the space-craft data obtained by fly-bys. Here, the idea is that an incorrectly known planet mass will result in an incorrect model of the location of the Solar System Barycentre (SSB) relative to the Earth. However, the SSB is the reference point for pulsar arrival time measurements, so that a mismatch between assumed and actual position would lead to a periodic signal in the pulsar data with the period being that of the planet with the ill-measured mass. This measurement technique is sensitive to a mass difference of two hundred thousand million million tonnes – just 0.003 % of the mass of the Earth, and one ten-millionth of Jupiter's mass.
While progress is currently made, GW astronomy using pulsars really requires the SKA (Kramer et al. 2004). A first detection is virtually guaranteed with Phase 1 of the SKA. But the science that can eventually be done with the full SKA goes far beyond simple GW detection – a whole realm of astronomy and fundamental physics studies will become possible. For instance, it will be possible to study the properties of the graviton, namely its spin (i.e. polarisation properties of GWs) and its mass (note that in general relativity the graviton is massless, Lee et al. 2008, Lee et al. 2010a). This is achieved by measuring the degree of correlation in the arrival time variation of pairs of pulsars separated by a certain angle on the sky. A positive correlation is expected for pulsars in the same

direction or 180° apart on the sky, while pulsars separated by 90° should be anti-correlated. The exact shape of this correlation curve obviously depends on the GW polarisation properties (Lee et al. 2008) but also on the mass of the graviton (Lee et al. 2010a). The latter becomes clear when we consider that a non-zero mass leads to a dispersion relation and a cut-off frequency $\omega_{\rm cut} = m_{\rm g}c^2/\hbar$, below which a propagation is not possible anymore, affecting the degree of correlation possible between two pulsars. With a 90 % probability, massless gravitons can be distinguished from gravitons heavier than 3×10^{-22} eV (Compton wavelength $\lambda_{\rm g} = 4.1 \times 10^{12}$ km), if bi-weekly observation of 60 pulsars are performed for 5 years with pulsar RMS timing accuracy of 100 ns. If 60 pulsars are observed for 10 years with the same accuracy, the detectable graviton mass is reduced to 5×10^{-23} eV ($\lambda_{\rm g} = 2.5 \times 10^{13}$ km; Lee et al. 2010a).
In addition to detecting a *background* of GW emission, the probability of detecting a *single* GW source increases from a few percent now to well above 95 % with the full SKA. We can, for instance, expect to find the signal of a single super-massive black hole binary. Considering the case when the orbit is effectively not evolving over the observing span, we can show that, by using information provided by the "pulsar term" (i.e. the retarded effect of the GW acting on the pulsar's surrounding space time), we can achieve a rather astounding source localization. For a GW with an amplitude exceeding 10^{-16} and PTA observations of 40 pulsars with weekly timing to 30 ns, precision one can measure the GW source position to an accuracy of better than $\sim$1 arcmin (Lee et al. 2010b). With such an error circle, an identification of the GW source in the electromagnetic spectrum should be easily feasible. We note that in order to achieve such a result, a precise distance measurement to the pulsars is needed, which in turn can then be improved further during the fitting process that determines the orbital parameters of the GW source. Fortunately, the SKA will be a superb telescope to do astrometry with pulsars (discussed in Section 8.3.8).
Astrometric parameters can be determined in two ways for pulsars. Firstly, using the telescope array as an imaging interferometer, the pulsar can be treated as point source while boosting the signal-to-noise ratio by gating the correlator to use only signals during the few percent duty cycle when the pulsar is actually visible. With images spread over a period of time, it will be possible to measure parallaxes for nearly 10 000 pulsars with an accuracy of 20 % or less (Smits et al. 2010). Secondly, pulsar timing can also be used for a precise determination of the position, proper motion and parallax as all these parameters affect the arrival time of the pulsars at our telescope on Earth. Here, MSPs with their higher timing precision can be used more readily. Distances are retrieved via a "timing parallax" which essentially measures the variation in arrival time at different positions of the Earth is orbit due to the curvature of the incoming wavefront. In contrast to an imaging parallax, the sensitivity is highest for low ecliptic latitudes and lowest for the ecliptic pole. Interestingly, it is still possible to measure a parallax with finite precision at the ecliptic pole, in contrast to first expectations. The origin of this is the small eccentricity of the Earth orbit which allows us to still detect a variation of the arrival time at different times of the year (Smits et al. 2010). We expect that we can measure distances of 20 kpc with a precision better than 20 % for about 300 MSPs, while for some sources distances of 20 to 40 kpc can be measured to 10 % or better, enabling the single GW source studies described above.

In summary, the SKA will be a superb observatory for GW astronomy with numerous exciting applications in fundamental physics.

References:

Kramer M., et al., 2004, New Astr., 48, 993; Smits R., et al., 2009, A&A, 493, 1161; Hobbs G., et al., 2010, Classical and Quantum Gravity, 27, 084013; Jenet F.A., et al., 2006, ApJ, 653, 1571; Ferdman R.D., et al., 2010, Classical and Quantum Gravity, 27, 084014; Sesana A., Vecchio A., Colacino C.N., 2008, MNRAS, 390, 192; Sesana A., Vecchio A., 2010, Classical and Quantum Gravity, 27, 084016; Champion D., et al., 2010, ApJL, 720, L201; Lee K.J., Jenet F.A., Price R.H., 2008, ApJ, 685, 1304; Lee K.J., et al., 2010a, ApJ, 722, 1589; Lee K.J., et al., 2010b, MNRAS, 424, 325; Smits R., et al., 2010, A&A, 528, 108

8.5.10 Gravitational waves with the SKA [A. Sesana]

In the next decade gravitational wave (GW) astronomy will open a new window on the Universe. While signals coming from compact stars and binaries fall in the observational domain of operating and planned ground based interferometers (such as LIGO, VIRGO, GEO and the proposed Einstein Telescope (ET)), massive black hole (MBH) binaries are expected to be among the primary actors on the upcoming low frequency stage, where the $10^{-4} - 10^{-1}$ Hz window could be probed by the European Laser Interferometer Space Antenna (eLISA). Precision timing ($\lesssim 100$ns) of an ensemble of millisecond pulsar (forming a so called pulsar timing array, PTA) will offer the unique opportunity to detect GWs in the $10^{-9} - 10^{-7}$Hz frequency window (e.g. Detweiler 1979), complementing eLISA observations (see the figure below). Infact, while eLISA will be sensitive to individual mergers of relatively light binaries, PTA observations will probe the genuine MBH ($M \gtrsim 10^8 M_\odot$) at low redshift ($z < 1$) in their GW driven inspiral phase. Although current PTA projects, such as the EPTA (Janssen et al. 2008), the PPTA (Manchester 2007), NANOGrav (Jenet et al. 2009), and the IPTA (Hobbs et al. 2010), may succeed in the quest of detection, but it is the SKA that makes GW astronomy at nHz frequencies at all possible (e.g. using MBH binaries).

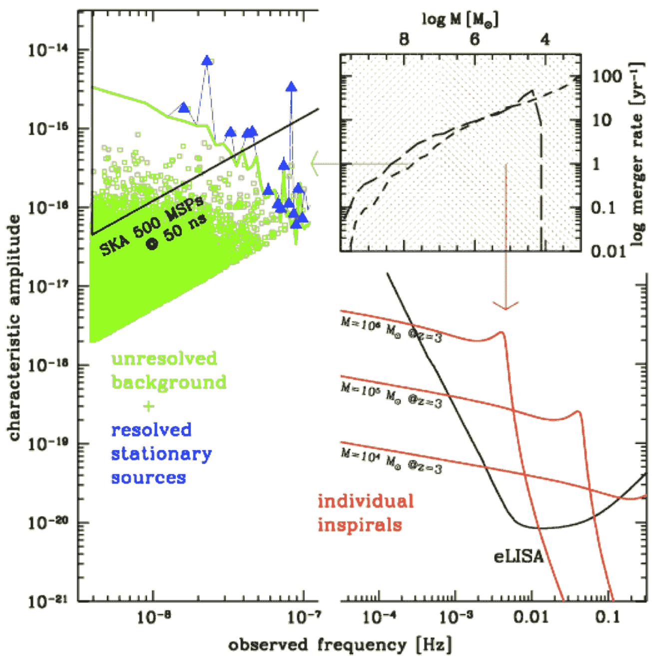


Figure 1_{Se}: The MBH binary landscape in the GW window. Individual inspirals (red solid lines) could be traced by eLISA (black solid line) in the mHz frequency band. At much lower frequencies, the unresolved background (green solid line) generated by the superposition of the signal coming from the cosmic population of MBH binaries (green opens squares) will be detected by the SKA (solid black line). Particularly bright sources (blue triangles) will be individually resolvable. The upper right inset shows the mass function of merging MBH binaries, demonstrationg the complementarity of eLISA and SKA observations: the former will probe the infancy of MBH binaries by detecting light binaries mostly at $z > 3$ (red shaded area); the latter will detect the genuine MBH binaries at low redshift (green shaded area).

By combining observations of hundreds of millisecond pulsars with a timing accuracy of ~ 50 ns the SKA will achieve a spectacular nominal sensitivity of few ns. At such level, the confusion noise generated by the superposition of the signal coming from the cosmic population of MBH binaries will be easily detected and characterized (Sesana 2008), and several sources will be individually resolved (Sesana et al. 2009, Boyle & Pen 2010). The latter will offer the unique opportunity of combining GW and conventional electromagnetic observations, opening a new multimessenger astronomy era, based on the synergy between radio observations, GW detections and Optical/X-ray followup monitoring. Counterparts to GW sources can be identified through periodicity or peculiar spectral features (Sesana et al. 2011, Tanaka et al. 2011), both in Optical/UV and in X-ray by upcoming all sky surveys such as LSST (LSST Science Collaborations et al. 2009) and eRosita (Predehl et al. 2010). The identification of the host galaxy of a MBH binary merger will (i) improve our understanding of the nature of the galaxy hosting coalescing MBH binaries (e.g. galaxy type, colours, morphology, etc.); (ii) help to reconstruct the dynamics of the merging galaxies and of their MBHs; and (iii) offer the possibility of studying accretion phenomena onto systems of known mass and spin (which, also in PTA observations, can be measured from the

GW signal e.g. Sesana & Vecchio 2010, Corbin & Cornish 2010).

References:

Boyle L., Pen U., 2010, arXiv:1010.4337; Corbin V., Cornish N.J., 2010, arXiv:1008.1782; Detweiler S.L. 1979, ApJ, 234, 1100; Hobbs G., et al., 2010, Classical and Quantum Gravity, 27, 084013; Jenet F. et al., 2009, arXiv:0909.1058; Janssen G.H. et al., 2008, in *40 YEARS OF PULSARS: Millisecond Pulsars, Magnetars and More. AIP*, Conference Proceedings, Volume, 983, 633; LSST Science Collaborations, et al., 2009, arXiv:0912.0201; Manchester R.N., 2008, in *40 YEARS OF PULSARS: Millisecond Pulsars, Magnetars and More. AIP*, Conference Proceedings, Volume, 983, 584 Predehl P. et al., 2010, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series of Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, 7732; Sesana A., Vecchio A., Colacino C.N., 2008, MNRAS, 390, 192; Sesana A., Vecchio A., Volonteri M., 2009, MNRAS, 394, 2255; Sesana A., Vecchio A., 2010, Phys. Rev. D, 81, 104008; Sesana A., Roedig C., Reynolds M.T., Dotti M., 2011, arXiv:1107.2927; Tanaka T., Menou K., Haiman Z., 2011, arXiv:1107.2937

9 The SKA high performance computing challenge: A German perspective

The SKA will be the World's premier imaging and surveying telescope with a combination of unprecedented versatility and sensitivity. The technical challenges and the upcoming data products will dramatically change the way astronomical research is done and to make the SKA a reality demands a revolutionary break from the traditional framework designs. The SKA will drive technology development particularly in information and communication technology.

In that respect the SKA is truly a next generation software telescope, in which high performance computing (HPC) is an essential part, allowing the handling and the processing of measurements in real time. The data rates produced by the SKA can not be handled by today's HPC facilities. In the following these aspects are considered by: a first view of the challenge, the future technical development, and the basic consideration to address the aspects of the upcoming demands.

9.1 The challenge [B. Allen]

The data analysis for the SKA is a significant computational and organisational challenge. This comes about for two reasons. First, the total volume of SKA data is very large. Second, the total number of computations which must be performed to extract the science from the data is also very large. So it presents two challenges, one of which is data distribution and storage, and the second of which is data reduction and analysis.

The total volume of data from SKA can only be estimated, because the instrument configuration is not yet frozen. However one can estimate that the order-of-magnitude is about 4 Terabytes (Tb) per second in the initial configuration, and a factor of a few more in the final configuration. Moreover, this data rate is not "peak" but "average", since the instrument is expected to be operating on a 24 hours times 7 days basis. To put this into perspective, at the time that this contribution was written (fall, 2011) the market price for a 2 Tb consumer storage disk is about 100 Euros. The raw SKA data would fill one of these disks every 4 seconds; the raw disk costs alone would be about 90 000 Euro/hour. Over the past 8 years the unit cost of disk storage has dropped by a factor of 25; if similar improvements take place over the coming 8 years, then by 2019 this storage would cost about 40 000 Euro/hour or of order 30 million Euro/year. Note that this does not include the cost of electrical power, the systems hosting the disks, etc. This means that it is impractical to store all the data. The data can only be stored for some period of time, and must be analysed and processed within that window.

The computational challenge arises in two ways. First, simply distributing and accessing such a large data set is a computational challenge. To set the scale, the data rate is several times larger than the data rate passing through the Amsterdam Internet Exchange, the largest data hub in Europe. Second, the computational work that needs to subsequently be done on the data is very significant. Synthesising the beams (summing together the data streams from the different antenna elements) is a Petaflop-scale problem that would challenge the largest supercomputers available today. And searching all of these beams (for example to locate all of the radio pulsars in the Galaxy) is an Exaflop-scale problem. If computing power continues its exponential growth for the coming 8 years, we can expect that the largest purpose-built supercomputers might be capable of handling this load.

At the moment, the growth in computer power (the so-called "Moore's Law") is being maintained by the development of multi-core computing architectures, such as Graphics Processor Unit systems containing 1000 cores and capable of Teraflops/s of computation, and the newly announced Intel Many Integrated Core (MIC) architecture, which has about an order-of-magnitude fewer compute cores but broader vector floating-point units. It is expected that over the coming 8 years, these systems will continue to envolve and improve, though it is also clear that exponential growth in compute capacity at fixed power and cost can not continue indefinitely. However to use these systems effectively for SKA data analysis, a new generation of programming methodologies and software must be developed.

The challenges of SKA data distribution and storage, and data reduction and analysis, contain many interesting research problems and possible creative solutions. To cite one example, estimates indicate that it might be possible to solve both of these problems by adopting a "Public Volunteer Computing" such as the one that has been used by Einstein@Home during the past 6 years. Here, the data would be stored (redundantly) on computer

hosts which were "signed up" by the general public; the computing could also be done on those machines. If the number of volunteers were about one order of magnitude larger than the number who are active in Einstein@Home, this would provide a very cost-effective solution to both these challenges!
More conventional solutions require advances in networking, data storage, and power infrastructure in remote locations; these present a variety of other interesting research challenges.

9.2 Technological developments toward the SKA [T. Fieseler]

Over the past years, several precursor and pathfinder telescopes have been designed and setup to prepare SKA technology and to serve as design studies. In these experiments, the current network, storage, and computing technologies to transport, process and store data are pushed their limits and new technologies are applied. Even these smaller sized experiments like the LOFAR telescope will exhaust large amounts of resources in the final stage of expansion. Current requirements for LOFAR are about tens of Gigabytes (Gb) per second network bandwidth, tens of Petabytes (Pb) of disk and tape storage and a few Petaflops/s computation power. These requirements are not static but will grow with the development of the experiment, as the surveys and analysis which will be performed during the life cycle of the telescope will constantly seek the boundaries of the resources which are available at the time. The requirements of the SKA will be an order of 100 or 1000 higher than the requirements of experiments like LOFAR. In this respect, the SKA will rely on the most powerful High Performance Computing (HPC) technologies which are available. The order of magnitude of the requirements will be in the TB/s range for network bandwidth, in the Exabyte range for disk and tape storage and in the Exaflop/s range for computing. The provision of resources fulfilling these requirements will be a challenge for the following years. The Jülich Supercomputing Centre (JSC) hosts leadership-class supercomputing systems with different architectures. The current Blue Gene installation JUGENE was Europe's first petaflop system and will be further extended to a few Petaflop/s in the near future. The general purpose supercomputer JUROPA is a co-development of the JSC and industrial partners, based on INTEL processors. Furthermore, special cluster solutions like the Cell based cluster QPACE or GPU enhanced clusters are developed and operated. The investigation and operation of a variety of different architectures is the key to finding the best-suited architectures for the SKA challenges. Today, it is unknown which architectures will be the best choice in 10 to 15 years, when the telescope is fully operational. Thus, it is mandatory to gain experience and expertise with all promising candidates of architectures for the SKA. Apart from the mere provision of resources in these huge dimensions, the energy efficiency of the resources will be one of the limiting factors. At present the energy consumption of a Petaflops/s system is about a few megawatts. For example, the power consumption of the 1 Petaflop/s Blue Gene system JUGENE is about 2 megawatt (MW). The leading system of the June 2011 Top 500 list has a power consumption of 10 MW for a peak performance of 8 Petaflops/s. With the current technologies, an Exapflop/s system would have a power consumption in the gigawatt scale, an order of magnitude which would require a dedicated power station for the operation of the supercomputer. Therefore, the development of energy efficient architectures for exascale supercomputing systems is crucial for SKA computer system candidates. Developments like the QPACE cluster (rank 1 in the Green 500 November 2009 and June 2010) and the upcoming BlueGene/Q systems (rank 1 in the Green 500 lists since November 2010) are examples of architectures with an outstanding low power consumption. The development of energy efficient supercomputing systems requires an holistic approach optimising the energy efficiency at all levels. This includes the use of energy efficient processor architectures, whose performance can be optimally exploited by the given application, the reduction of losses in power conversion and distribution as well as the implementation of energy efficient cooling concepts at system level. The research in this direction will dominate the development of prototype systems which could evolve into future SKA technologies. An example is the European exascale research project DEEP coordinated by Jülich. This project aims to exploit the performance of a new type of many-core processors which provide a significantly higher computing performance within a power envelope similar to current multiprocessor nodes.

9.3 SKA data processing and management: Basic considerations [H. Enke]

LOFAR as a starting point: From LOFAR[5] a basic design schema for a software radio telescope emerges:

– distributed antennae stations with on-site compute power to reduce the station signals,

– a fiber optics network for signal transportation to a central processing facility (CPF),

– the CPF for correlating the station signals and various basic observation modes,

– additional compute and short term storage facilities for more sophisticated post processing,

– a long term storage facility for the science ready data,

– distributed facilities for scientific work on the data.

The above list only names the key hardware elements of the system (Begeman et al. 2011). Control and management components have to be added. For the LOFAR project, these components are implemented in a hierarchical design, which consists of three "tiers". Since the basic schemas for the SKA are similar to LOFAR, a similar schema can be applied. Dedicated data processing centres (DPC) can be considered the building blocks in this context. For the SKA, the geographical location of the DPC needs careful consideration.

Tier 0 Data Processing Centre ($\mathbf{DPC_0}$): The SKA-CPF has to be located onsite, near the antennae stations, and connected to them by custom fiber optics network. With an estimated data flow of a few Terabytes/s from the stations to the CPF there is no feasible alternative to this setup. Also, the control and management components of the SKA need to be co-located with the CPF, and thus located onsite as well.

LOFAR-CPF requires processing power of many Teraflop/s (for full operation), for the SKA this scales to many Petaflop/s or even more. The DPC_0 will consist of a PetaScale computer for correlation and a file server with sufficient storage capacity to take the short term data products and for buffering the raw data for special processing modes (pipelines).

Tier 1 Data Processing Centre ($\mathbf{DPC_1}$): The data produced by DPC_0 has to be transferred from the CPF into a dedicated storage facility. The data proces sing within DPC_0 might reduce the amount of data to store by a factor of 100 or 1000, but still requires a bandwidth of the order of some 100 Gbit/s from DPC_0 to DPC_1. The storage capacity of the DPC_1 archive should be able to store the whole data product of DPC_0 for one year or more. In addition, it might be used as a buffer for reprocessing data at DPC_0. Therefore the DPC1 needs a dedicated low latency fiber optics network connection to DPC_0.

For efficiency, the DPC_1 should feature compute facilities with suitable environments for the scientists to remotely work with the data. The technology to provide such environments on demand (virtual machines with customized scientific tools, collaborative virtual infrastructures) is currently maturing.

Tier 2 Data Processing Centre ($\mathbf{DPC_2}$): The SKA data has to be distributed and replicated. Not all of the scientific interesting processing can be done at DPC_1. For the various key science areas, specialized archives will store only the particular subset of data the project is working on and offer additional processing capabilities. Parts of the data might need reprocessing on a long term basis, combining data from various observations. Additional data products will result from the key science areas, which will be located at more than one DPC_2. Another reason for replication is to insure against data loss.

Several DPC_2 will be located all over the world. The transport of the data to these locations will have lower demands on network bandwidth than from DPC_0 to DPC_1. The network connection, however, remains a challenging task with the given intercontinental network structure. Furthermore, the DPC_2 can provide access to SKA data to all interested parties and act as provider for data publication.

[5]See page 31 were LOFAR is referred to as a precursor for SKA.

A distributed structure makes the data output of the SKA manageable, but requires in turn careful procedures for bookkeeping of the data sets, keeping their integrity etc. Cataloguing and validating the archived data, as well as tracking their replications in other archives could become a shared responsibility of DPC_1 and DPC_2.

Since both DPC_0 and DPC_1 have to be co-located with the antennae field, one of the challenges will be to build these facilities onsite, where the supply chains for hardware and skilled labor is very different from Europe.

Conclusion This distributed schema for the SKA data processing flow would allow to decouple the demands on network bandwidth for "real-time" processing of the incoming antennae data, getting first results on the one hand, and on the other hand transporting the (reduced) data to DPC_2 facilities in Europe and all over the world for scientific processing on longer time scales.

References:

Begeman K., et al. , 2011, *LOFAR Information System in Future Generation Computer Systems*, 27, Elsevier B.V., 319

10 The SKA and industry interaction

Radio astronomy provides a demanding, yet open, development and test environment for state-of-the-art devices, systems and algorithms. Construction of the SKA over a 6-year period is the equivalent of building and commissioning a 100-m radio telescope every 20 days, a task far beyond the World's astronomical community. Large industry contracts will therefore be necessary to build the SKA. Even before the construction phase, many of the R&D programmes needed for SKA demonstrators require industry know-how, especially in crucial areas such as economic mass production and system engineering. The scale of the project makes it certain that industry collaboration will be significant for the SKA in general and can be divided into 4 phases in which interaction between science and industry are crucial: 1. Test, Development & Design, 2. Engineering & Manufacturing, 3. Construction, 4. Exploitation.

The SKA has the opportunity to lead in the development of new techniques for mega-project management and effective global research collaboration, being an enabler for improved global-science-industry links for German industry. The nature of the project will inspire individuals, research groups, industrial partners and governments to be part of a global endeavour that will endure beyond their involvement. Furthermore, the profit and benefits to all those involved will be realised over a long timescale and in the broadest sense, building capacity and kudos for those who engage. Effective collaborations have demonstrated pathways for talented individuals and institutions to develop skills and capacity that can be applied domestically and globally. Links and co-locations (technology parks) between industry and science foster innovation and commercially exploitable patents, bring wealth and create jobs.

The SKA project, and its associated national and international consortia programmes, welcomes interest from potential industry partners. In general terms, any joint research and development is viewed as a shared-risk endeavour, with SKA consortia and industry each contributing to defined activities.The SKA has an agreed policy on intellectual property (IP) developed under its aegis. Broadly, industry partners exploit their own IP contributions in arenas outside the SKA project, but innovations are available to the SKA project free of any licensing charge.

SKA's potential business opportunities:

- technological overview of the SKA telescope
- system integration
- telescope mass production
- telescope controlling, monitoring and maintenance
- infrastructure development
- complete electrical solutions for the SKA infrastructure
- chip design & electronics
- software development
- high performance & GRID Computing
- data transport, management, storage, processing and analysis
- energy production and distribution
- operational expenses and sustainability

In order to gain visibility of the SKA project for industry an expression-of-interest (EoI) process was launched in May 2012. Based on the EoI process a formal request for business proposals will be issued mid 2012.

During first steps of the EoI process, various collaboration opportunities have been engaged to build a German collaboration that may form a consortia.

10.1 A global model for renewable energy [M. Vetter, E. Weber]

Abstract: The energy consumption of the SKA telescope and its infrastructure will be of the order of 50–100 megawatt (MW). Such energy demands has to be provided at locations with little or no access to a power grid. While such demands could only be produced by atomic power plants some 50 years ago, it is now within the reach of photovoltaic systems. Regardless of the numerous challenges to be met to power the SKA via a solar energy solution the promised rewards are manifest. In particular, the future location, the practical demands, and the technical requirements of the SKA are ideal to pioneer strategies of green power production and handling. Such studies would impact and accelerate technology development in the areas of scalable energy generation and storage, distribution, efficiency and demand reduction, and furthermore provide a launch pad for commercialisation of innovative green energy technologies. Especially in the developing nations the spin-off benefits of such a project will impact on human quality of life (e.g. 1.5 billion people are not connected to the power grid). The economics of remote communities will thrive and prosper with access to cheaper (renewable) power. In particular it will push the development of infrastructure directly improving the public transport, the education, and the medical health care.
A study of a pathfinder project, to investigate the possibilities to generate, supply, and store renewable energy of the order of 100 MW, has been initiated by CSIRO Astronomy and Space Science involving the Fraunhofer Institute of Solar Energy and the "Max-Planck-Institut für Radioastronomie" (MPIfR).

Introduction: A common problem for private, public and large-scale industrial consumers all over the world is that they are often situated far from the grid, or are not supplied with sufficient or permanent energy capacity. Concepts to supply and distribute power that seems to work for the German or for large parts of the European grid infrastructure, turns out to be not applicable to remote locations and less developed countries in the world.

To cope with an inefficient power supply it is common practise to use diesel generator sets to power e.g. the ALMA array in Chile or the mines in Australia. However the use of fossil fuel has a negative impact on the CO_2 footprint of these countries. In addition, the increasing and at the same time fluctuating fuel costs do not only constitute an extremely high cost factor, but it turns out to be an unpredictable element. The Indonesian fish-processing industry may serve to illustrate this issue: most of the fish canneries are run far from the grid (Indonesia consists of more than 17 000 islands, which would be comparable to the number of individual stations of the SKA telescope). In times of very high crude oil prices the factories have stopped production directly affecting the life of thousands of people in the region.

The energy needed to run the SKA is of the order of 100 MW which needs to be available 24 hours every day, since radio observatories compared to optical observatories can observe day and night. Due to the SKA infrastructure 50 % of the energy needs to be distributed within the central region, whereas the other 50 % needs to be distributed to remote stations up to 1000 km distant. Building a central power plant and a grid infrastructure to power the SKA is on economic reasoning not the preferred solution (e.g. 10 % of the power could be lost during transport). Instead, using solar photovoltaic systems to power the SKA seems to be possible. Figure IX shows the intensity of the solar radiation on the earth. Both SKA sites in South Africa and in Australia are placed in regions of highest solar radiation impact and are very well situated to cover a large fraction of the energetic needs via solar energy.

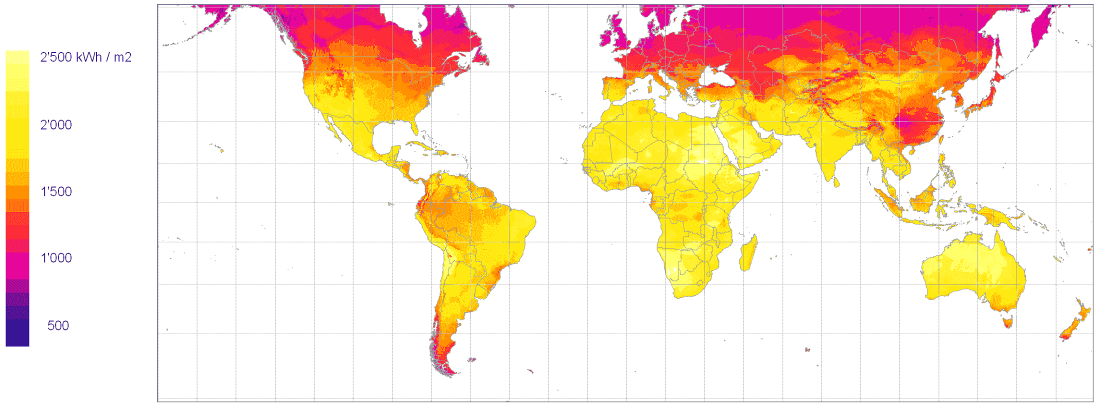


Figure IX: Earth with solar radiation impact shown in colour. The radiation impact is based on the yearly sum of the direct normal irradiance obtained between 1981 to 2000. (Image credit: © METEOTEST; based on [www.meteonorm.com])

The power requirements and the special setup of the SKA are an ideal testbed to develop cost efficient power management infrastructure for remote locations, that could also be applied to remote societies. Such a renewable strategy would accelerate technology development in the areas of scalable energy generation and storage, distribution, efficiency and demand reduction and provide a launch pad for commercialisation of innovative green energy technologies.

Pathfinding: The challenges to power the SKA via a solar energy solution are numerous, but the low running costs unaffected by fluctuations in global fuel price, and the technical benefits and know-how transfer is worth investigation. A Memorandum of Understanding (MoU) to foster collaboration between the Fraunhofer Institute of Solar Energy, the "Max-Planck-Institut für Radioastronomie" and Australian CSIRO Astronomy and Space Science was signed on 7 April 2011 in Berlin during a workshop on "Renewable Energy Concepts for Mega-Science Projects demonstrated by the SKA and its Pathfinders". A key focus of this MoU is to promote scientific and research cooperation in renewable energy capture, storage and management for the SKA between Australia and experts from Germany and the rest of the world. The MoU also looks to advance collaboration between Fraunhofer ISE, the MPIfR and CSIRO in the development of renewable energy systems for the Murchison Radio-astronomy Observatory (MRO) and the Australian SKA Pathfinder (ASKAP) instrument as an SKA precursor facility.

The main aims and R&D challenges can be summarised as follows:

– assessment of energy storage possibilities (thermal or electric)
– developing concepts of concentrated solar power (CSP) and concentrating photovoltaic (CPV) coupling
– developing concepts of electric storage systems with CPV
– developing concepts to include thermal storage
– development of a reliable energy management system; including strategies for operational management of CPV-CSP hybrid systems to cope with high electrical and thermal loads.
– development and testing of highly reliable and efficient power electronics
– evaluation of the electronic needs of an astronomical observatory with respect to the day and night phases in order to minimise the needed electronic storage

One of the major keystones of the MoU is to develop a test concept that will be evaluated on the Effelsberg site to investigate the practicality of the concepts within an astronomical RFI sensitive environment.

Summary: The specific requirements of the SKA will challenge current green-power-generation concepts and will pioneer the continuous use of renewable energy and its remote generation. The main aim of the project is to develop concepts to use solar energy to provide a reliable and stable power solution for the SKA. These concepts will be tested during the development phases of the SKA and in particular in their pathfinder instruments like MeerKAT and ASKAP.

10.2 Connecting Europe: High data transport rates via satellites [J. Kerp]

Astrophysical research suffers on a "digital divide". The most advanced present and future observatories will be located on the Earth's southern hemisphere, like the SKA, while most of the scientific community as well as the high-tech computing facilities are located in the north e.g. in Northern America, Europe, Japan, or China. The daily amount of data needed to be scientifically analyzed increased by two magnitudes in just the last decade. Today most of the observational data is roughly inspected by searching for known objects. Only these "post stamps" are stored and transfered for serious scientific analyses, but data mining for the "exploration of the unknown" is currently out of reach.

This digital divide needs to be overcome by linking the high-performance-computing centres to the observatories by using state-of-the-art satellite communication systems. Today the satellite market is underdeveloped and deep-sea fiber connections transfer more than 90 % of the data. This technology is cost intensive and subject for distortions due to terrestrial events like earth-quakes, wars etc. The financial value of scientific data is unknown and considered to be insignificant. Because of this, fiber connections between the upcoming next generation observatories like the SKA and the super computer facilities on the northern hemisphere are not considered. However high frequency satellite communication could be considered a "key" to change this situation entirely, using data transfer at 60 GHz to 400 GHz radio frequencies to transfer hundreds of gigabytes within the next decade. The low photon energy of the radio radiation allows us to transfer –at a high signal-to-noise– large amounts of data with a minimum of energy. This is feasible by combining multi-feed ground stations and sophisticated data compression technologies with high radio frequency inter-satellite links. Such inter-satellite links use frequencies between 100 GHz and 400 GHz, which is standard technology for astrophysicists and just needs to be adapted to the requirements of the SKA and possible industrial useage.

Using today's latest scientific equipment in radio astronomy it is feasible to transfer this technology to the commercial market. Here, the technology needs to simplified (i.e. from cooled to uncooled systems) and make use of the "of-the-shelf" systems. The new to open commercial market is huge, because ground stations are easy to maintain and can be located in nearly all environments. In combination with the long term evolution (LTE) on the mobile communication standard it is feasible to make these data accessible world wide.

11 Positive impact on human capital development and employment

Astronomy is the study of everything beyond Earth and it is a science that enters our daily lives directly. As a science it is driven by observations, with links to mathematics, physics, chemistry, computer science, geophysics, material science and biology. Astronomy is important for society and culture, and helps attract young people into natural science and technology.

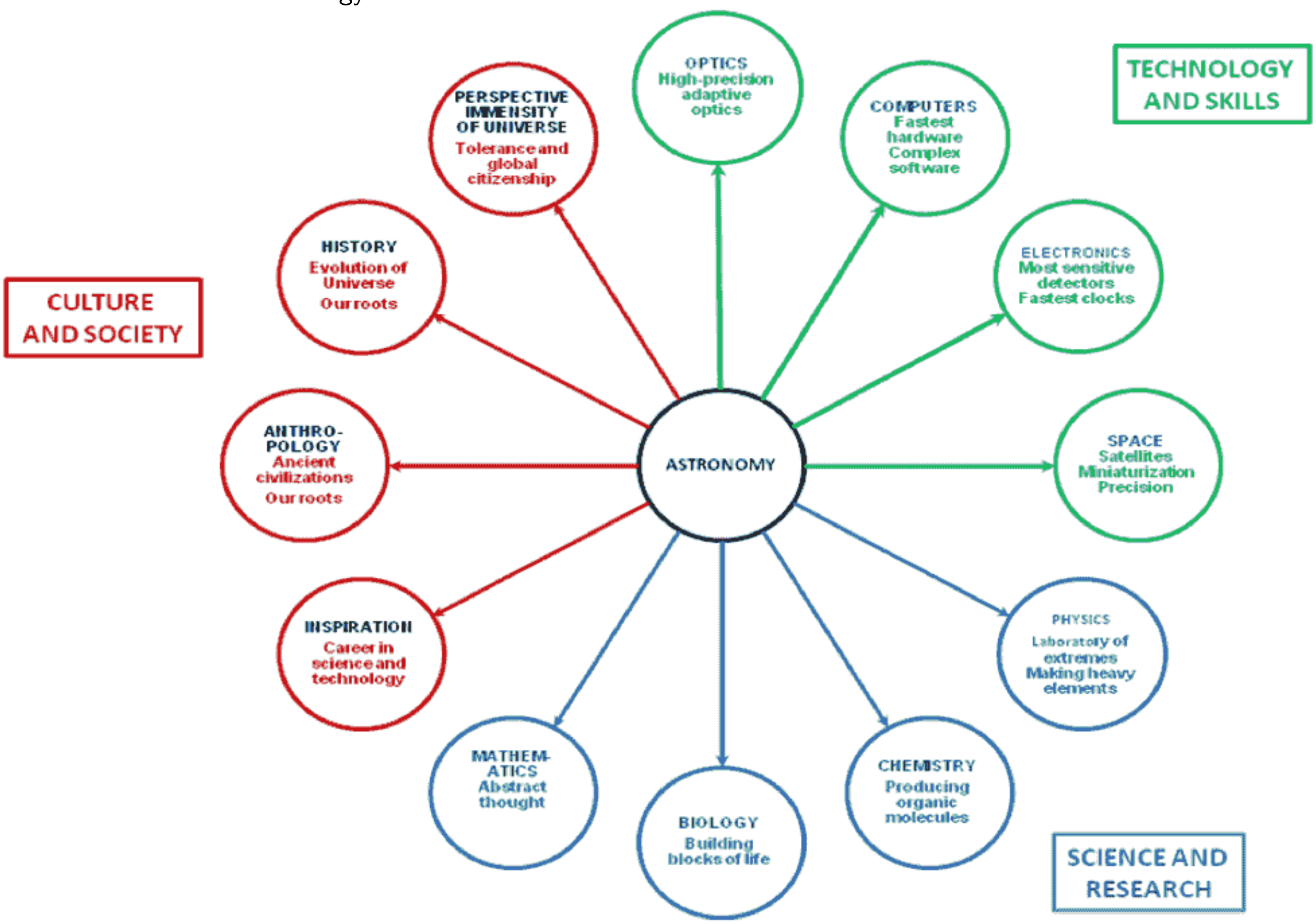


Figure X: Overview on how astronomy impacts on science & research, technology & skills, and culture & society (credit: SKA Project Execution Plan).

In the last two decades astronomy has made particularly impressive advances, technically, observationally and theoretically. In spite of a downturn in intake for natural sciences at university level in general, young students have continued to enter the field at steady rate, driven by their innate curiosity, and motivated to contribute directly to advances in knowledge. Excited by astronomy, young and gifted minds are frequently attracted to related scientific disciplines, so that astronomy acts as a springboard and catalyst for wider scientific enquiry. A summary on how astronomy has been integrated into our society is shown in the Figure X.

In this spirt the SKA, with its scale and scope, has the potential to inspire generations of young people with natural science. It can do so not only because astronomy appeals to our natural curiosity but also because it is a stepping stone to many other fields of science and technology development including computing, engineering, aerospace, mathematics and natural sciences.

The SKA can provide long-standing benefits to society, proportional to the long-term investment it requires. Furthermore, the construction and operation of the SKA facilities will impact on local and regional skill developments in all fields of science.

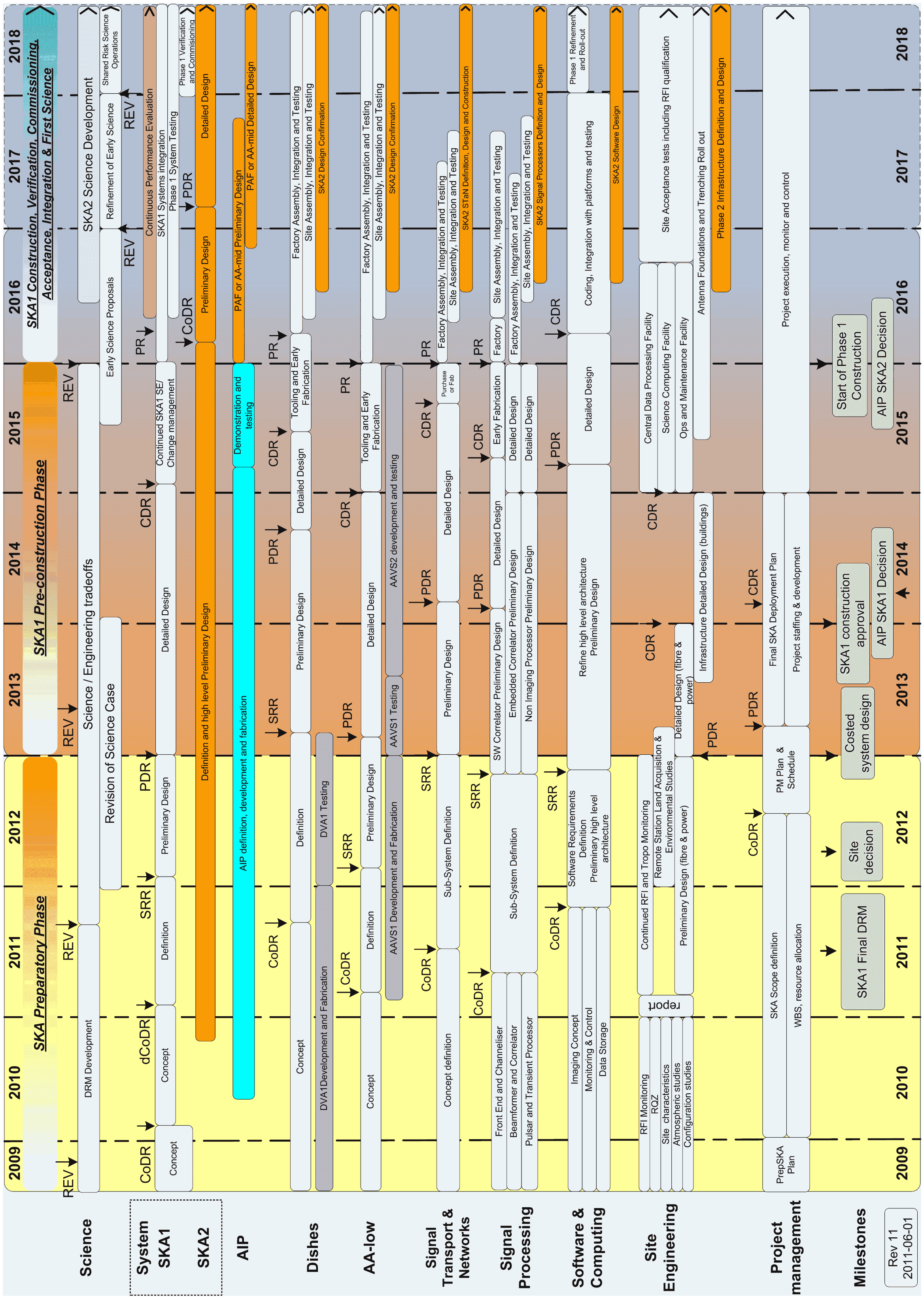
12 Abbreviations

The list of abbreviations covers most of the acronyms used in the SKA project and in this “white paper”.

ACT	Atacama Cosmology Telescope
AGN	Active Galactic Nuclei
AIP	Advanced Instrumentation Program
ALMA	Atacama Large Millimeter/submillimeter Array
ALP	Axions-like Particle
APERTIF	APERture Tile In Focus
ASKAP	Australian SKA Pathfinder
AXP	Anomalous X-ray Pulsar
BAO	Baryon Acoustic Oscillation
BH	Black Hole
BOSS	Baryon Oscillation Spectroscopic Survey
CABB	Compact Array Broadband Backend
CCO	Central Compact Object
CDFS	Chandra Deep Field-South
CDM	Cold Dark Matter
CMB	Cosmic Microwave Background
CMBPOL	CMB POLarisation
CME	Coronal Mass Ejection
CO	Carbon Monoxide
COBE	Cosmic Background Explorer
CODEX	Cosmic Dynamics Experiment
COSMOS	Cosmic Evolution Survey
CPV	Concentrating Photovoltaic
CR	Cosmic Ray
CSP	Concentrated Solar Power
CTA	Cherenkov Telescope Array
DE	Dark Energy
DES	Dark Energy Survey
DM	Dark Matter
DPC	Data Processing Centres
EBHIS	Effelsberg Bonn H I Survey
E-ELT	European Extremely Large Telescope
eEVN	European VLBI Network
EM	Electro Magnetic
e-MERLIN	Multi-Element Radio Linked Interferometer Network
EMRI	Extreme Mass Ratio Inspiral
EoS	Equation of State
EoR	Epoch of Reionisation
EoI	Expression of Interrest
eROSITA	X-ray & gamma-ray satellite programme
ESA	European Space Agency
ESFRI	European Strategy Forum for Research Infrastructures
ESO	European Southern Observatory
ET	Einstein Telescope
Euclid	ESA Cosmic Space Mision
EUV	Extreme Ultraviolet
EVLA	Expanded Very Large Array - re-named in 2012 to Karl G. Jansky Very Large Array (JVLA)
FoV	Field of View
FR	Fanaroff Riley Galaxy (type I and II)
GAIA	ESA Cosmic Space Mision
GC	Galactic Centre
GEO600	Gravitational Wave Detector
GLOW	German LOng Wavelength
GO-SKA	Global Organisation for the SKA
GR	General Relativity
GW	Gravitational Wave
HDF	Hubble Deep Field
HETDEX	Hobbly-Eberly Telescope Dark Energy eXperiment (optical)
HI	Neutral Hydrogen
HII	Ionised Region (Strömgren spheres)
HIPASS	H I Parkes All Sky Survey
HPC	High Performance Computing
HST	Hubble Space Telescope
HVC	High Velocity Clouds
ICM	Inter Cluster Medium
IGM	Inter Galactic Medium
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory
IP	Intellectual Property
ISSC	International SKA Steering Committee
ISM	Interstellar Medium
ISPO	International SKA Project Office
ISRF	Interstellar Radiation Field
IVC	Intermediate Velocity Clouds
JDEM	Joint Dark Energy Mission (space mission)
JWST	James Webb Space Telescope
JVLA	Karl G. Jansky Very Large Array see EVLA
KSP	Key Science Project
KM3NeT	A Multi-km^3 sized Neutrino Telescope
LF	Luminosity Function
LG	Local Group
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational Wave Observatory
(e)LISA	(European) Laser Interferometer Space Antenna
LMC	Large Magellanic Cloud
LOFAR	Low Frequency Array
LoS	Line Of Sight
LSST	Large Synoptic Survey Telescope
LTE	long term evolution
MeerKat	Karoo Array Telescope
MHD	Magnetohydrodynamics
MIC	Many Integrated Core
MM	MegaMaser
MoA	Memorandum of Agreement
MoU	Memorandum of Understanding
MSP	Millisecond Pulsar
NEI	Non-Equilibrium Ionisation
OH	Hydroxyl
PAF	Phased Array Feed
PO	Participating Organisations
PrepSKA	Preparatory phase proposal for the SKA
PSF	Point Spread Function
PTA	Pulsar Timing Array
QCD	Quantum Chromodynamics
QSO	Quasi Stellar Object (quasar)
R&D	Research and Development
RFI	Radio Frequency Interference
RHIC	Relativistic Heavy Ion Collider
RM	Rotation Measurement
RRAT	Rotating Radio Transient
SEP	Solar Energetic Particles
SETI	Search for Extraterrestrial Intelligence
SDSS	Sloan Digital Sky Survey
SF	Star Forming
SGR	Soft Gamma Repeater
SKA	Square Kilometre Array
SKADS	SKA design study
(S)MBH	(super) massive black hole
SMC	Small Magellanic Cloud
SMG	Sub-Millimetre Galaxies
SN(R)	Supernova(remnants)
SOWG	Site Options Working Group
SPDO	SKS Program Development Office
SPICA	ESA Cosmic Space Mision
SPT	South Pole Telescope
SSB	Solar System Barycentre
SSEC	SKA Science and Engineering Committee
TNO	Trans-Neptunian Objects
TOA	Time Of Arrival
UHE	Ultra High Energy
(U)LIRG	(Ultra) Luminous Infrared Galaxies
URSI	International Union of Radio Science
UV	Ultraviolet
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
WHIM	Warm-Hot Intergalactic Medium
WiggleZ	dark energy survey
WIM	Warm Ionised Medium
WIMP	Weakly Interacting Massive Particle
WISP	Weakly Interacting Sub-eV Particle
WMAP	Wilkinson Microwave Anisotropy Probe
WNM	Warm Neutral Medium
WP	Work Package
WSRT	Westerbork Synthesis Radio Telescope
XDIN	X-ray Dim Isolated Neutron Stars

13 Appendix

Figure XI: Overall SKA project timeline (release v11 01-06-2011, credit: SKA Project Execution Plan)).



14 Bibliography, References, & Image credits

Bibliography

Most of the SKA particulars shown and discussed in this "white paper" are based on the information given in numerous SKA documents and memos, which are available via the SKA homepage:

www.skatelescope.org/publications

General information about the SKA can be found via:

http://www.scholarpedia.org/article/Square_kilometre_array

The SKA project receives globale recognition in the media. Also several German newspapers have covered the SKA project and the side discussion of the SKA. A record of newspaper articles, online interviews, and further information can be found via:

http://www3.mpifr-bonn.mpg.de/public/pr/links-ska.html

Information on the German SKA collaboration can be obtained via:

www.mpifr-bonn.mpg.de/seso/GESKA/GeSKA.html

References

The following documents are listed because they are references, are mentioned in the text, or are of particular interest for a general understanding of the SKA project and its impact.

Carilli C., Rawlings S., 2004, New Astronomy Reviews, Elsevier, 48

Dewdney P., et al., 2010, SKA Memo, 130

Faulkner A.J., et al., 2010, "SKADS white paper"

Garrett M.A., et al., 2010, SKA Memo, 125

Klöckner H.-R., Rawlings S., Jarvis M., Taylor A., Editors of "Cosmology, Galaxy Formation and Astroparticle Physics on the Pathway to the SKA", 2006, ASTRON, ISBN 978-90-805434-4-7

Noordam J.E., Braun R., de Bruyn A.G., 1991, ASTRON Notes, https://www.astron.nl/documents/Notes/ASTRON-NOTE-585.pdf

Brüggen M., Falcke H., Beck R., Enßlin T., Editors of "German LOFAR - white paper", 2005, Max-Planck-Institut für Radioastronomie Bonn, http://www.mpifr-bonn.mpg.de/public/pr/white.paper.oct6.pdf

Oort J.H., 1932, Bulletin of the Astronomical Institutes of the Netherlands, 6, 249

Trimble V., Ceja J.A., 2008, Astron. Nachr., 329, 6, 632

Schilizzi R.T., et al., 2011, SKA document, Project Execution Plan

Schilizzi R.T., et al., 2007, SKA Memo, 100

Torchinsky S.A., van Ardenne A., van den Brink-Havinga, van Es A.J.J., Faulkner A.J. Editors of "Wide Field Astronomy & Technology for the Square Kilometre Array", 2009, ASTRON, ISBN 978-90-805434-5-4

Verschuur G.L., 2007, 2nd Edition, "The Invisible Universe", Springer, New York, USA

Wilkinson P.N., 1991, Astronomical Society of the Pacific, "Radio interferometry: Theory, techniques, and applications: Proceedings of the 131th IAU Colloquium", 428

de Zeeuw P.T., Molster F.J., Editors of "A Science Vision for European Astronomy", 2007, ASTRONET, ISBN 978-3-923524-62-4, "ASTRONET Science Vision"

Yun M.S., Ho P.T.P, Lo K.Y., 1994, Nature, 372, 530

Yun M.S., 1997, "Galaxy Interactions at Low and High Redshift: Proceedings of the 186th IAU Symposium, Editor D. Sanders"

Zwicky F., 1933, Helvetica Physica Acta, 6, 110

Image credits

SKA related telescope and array images are obtained from the SKA homepage and are produced by SPDO/Swinburne Astronomy (cover page and Figures VI, VII, VIII).

The image in Figure VIII of the SKA core and inner region within Berlin is based on Goggle Maps.

The images in Figure I are based on the images provided via (http://chandra.harvard.edu/photo/2002/0157/) Credit: X-ray (NASA/CXC/M. Karovska et al.); neutral hydrogen image (NRAO/VLA/ van Gorkom, Schminovich et al.), radio continuum image (NRAO/VLA/ Condon et al.); optical image (Digitized Sky Survey U.K. Schmidt Image/STScI).

The images in Figure II are based on the optical image by J. Gallego [www.astrosurf.com/jordigallego], the H I image is reproduced, based on data by Yun et al. 1994, and the simulation image is from Yun 1997).

The image in Figure X is a copy of Figure 11 of the SKA Project Execution Plan (MGT-001.005.005-MP-001).

The image in Figure XI is a copy of the figure in the Appendix 3 of the SKA Project Execution Plan (MGT-001.005.005-MP-001).

The images of the individual science articles are provided by the authors themselves and, if necessary, the image credits are given in the individual figure captions.