Advancing Astrophysics with the Square Kilometre Array

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Abstracts Book

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SKA
SQUARE KILOMETRE ARRAY

The Cosmic Dawn and Epoch of Reionisation with SKA

Leon Koopmans[1;*], and the EoR Working Group

[1] Kapteyn Astronomical Institute, University of Groningen, The Netherlands

[*] Presenter

E-mail contact: koopmans at astro.rug.nl

Concerted effort is currently ongoing to open up the Epoch of Reionization ($z \sim 15$-6) for studies with IR and radio telescopes. Whereas IR detections have been made of sources (Ly-α emitters, quasars and drop-outs) in this redshift regime, in relatively small fields of view, no direct detection of neutral hydrogen via the redshifted 21-cm line has yet been established. Such a direct detection is expected in the coming years with ongoing surveys and will open up the entire universe from $z \sim 6$-200 for astrophysical and cosmological studies, opening not only the EoR, but also its preceding Cosmic Dawn ($z \sim 40$-15) and possibly even the later phases of the Dark Ages ($z \sim 200$-40), leaving only the “Age of Ignorance” ($z \sim 1100$-200) inaccessible to astronomers. All currently ongoing experiments attempt statistical detections of the 21-cm signal during the EoR, with limited signal-tonoise. Direct imaging, except maybe on the largest (degree) scales at lower redshift, will remain out of reach. The Square Kilometre Array (SKA), however, will revolutionize the field, and allow direct imaging of neutral hydrogen from scales of arc-minutes to degrees over most of the redshift range $z \sim 6$-30. In this review I summarize the physics of 21-cm emission, the different phases the universe is thought to go through, the observables that SKA can probe. This is done within the framework of the current SKA1 baseline design and a nominal CD/EoR strawman survey, but possible modifications to it and also during SKA2 are discussed.

HI observables: fluctuations versus imaging

Garrelt Mellema[1,*], Hemant Shukla[2], Suman Majumdar[1], Kanan K. Datta[3] and Ilian T. Iliev[2]

[1] Dept. of Astronomy & Oskar Klein Centre, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden

[2] Astronomy Centre, Department of Physics & Astronomy, Pevensey II Building, University of Sussex, Falmer, Brighton BN1 9QH, UK

[3] National Centre For Radio Astrophysics, Post Bag 3, Ganeshkhind, Pune 411 007, India

[*] Presenter

E-mail contact: garrelt at astro.su.se

SKA Low will be the first low frequency radio telescope that will be sensitive enough to make images of the redshifted 21cm signal from the Cosmic Dawn and the Epoch of Reionization. In this talk I will address the question why tomographic imaging is a useful tool in addition to statistical measurements such as power spectra. I will also describe what will be possible in terms of resolution and noise levels with the different phases of SKA_Low and end with an overview of some of the scientific questions that can be answered using tomographic data.

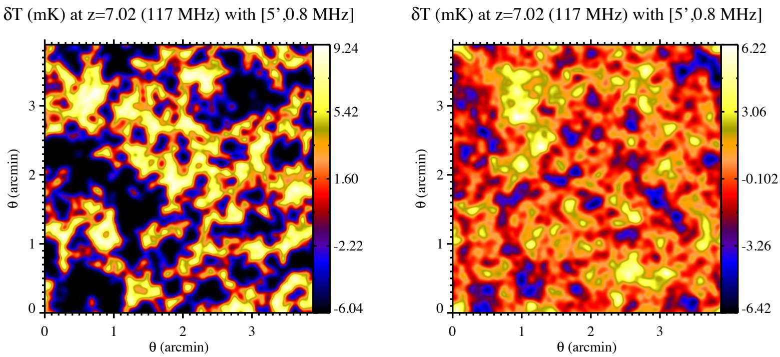


Figure 1: What is the connection between these two simulated images of the redshifted 21cm signal at z = 7.02? The answer will be in the talk.

Imaging HII Regions from Galaxies and Quasars During Reionizaion with SKA1-low

J. Stuart B. Wyithe*, Paul M. Geil and Hansik Kim

The University of Melbourne

* Presenter

E-mail contact: swyithe at unimelb.edu.au

Imaging the ionisation structure of the Inter-Galactic Medium (IGM) during reionization is a key goal for the SKA. The structure of cosmological HII regions is sensitive to the unknown galaxy formation physics that prevailed during reionization, and imaging of the scale and evolution in the ionisation structure will provide a direct measurement of different galaxy formation scenarios. For example, we show that the SKA1-low baseline design core will easily resolve HII regions expected from galaxy formation models which include strong feedback on low mass galaxy formation. However imaging the smaller HII regions predicted to result from galaxy formation models in the absence of SNe feedback will be more challenging and may require the greater sensitivity of SKA to study in detail.

Similarly, the redshifted 21cm observation of quasar HII regions will probe quasar physics as well as the evolution of the global HII fraction. In difference to galaxy HII regions which are driven by many sources over a long period of time, during their early phase quasar driven HII regions expand with a relativistic speed. Consequently, their measured sizes along and transverse to the line of sight should have different observed values due to relativistic time delay. A combined measurement of these sizes could therefore be used to directly constrain the neutral fraction of the surrounding intergalactic medium (IGM), as well as the quasar lifetime and ionising emission geometry.

Towards the end of reionization, the very large scales of quasar and galaxy driven HII regions seen in simulations mean that the light travel time can become comparable to the Hubble time. Thus, while HII regions can become arbitrarily large in a simulation at fixed proper time during the brief period of overlap at the end of reionization, the combined constraints of cosmic variance and light travel time imply that there is a maximum observed HII region size at the end of the overlap epoch. This maximum size is found to have a value of $\sim$ 100 Mpc. In addition to having baselines long enough to resolve HII regions, the field of view for SKA1-low reionization experiments should therefore cover at least several degrees in order to image the largest HI structures towards the end of reionization. The baseline design with 35 meter diameter stations have a single pointing field of view sufficient for this purpose.

Physics of reionization

Benot Semelin[1*] and Ilian Iliev[2]

[1] LERMA, Observatoire de Paris, UPMC, 77 av Denfert Rochereau, 75014 Paris, France

[2] Department of Physics Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK

[*] Presenter

E-mail contact: benoit.semelin at obspm.fr

The intensity of the 21 cm signal that will allow the SKA to probe the intergalactic medium at z>6 depends on a number of local quantities. The fundamental factor is obviously the presence of neutral hydrogen atoms able to emit 21 cm photons. Thus, understanding in details the physics of hydrogen ionization during this epoch is the first key to predicting and interpreting the future observations. While the local process of hydrogen ionization itself is well understood, it is determined by the local spectrum and intensity of ionizing radiations that are the result of complex, large scale radiative transfer processes.

We will first get an insight on the process of reinoization by estimating telling quantities such as the photons mean free path and the hydrogen recombination time in typical EoR environments. We will then reexamine the simple Stromgren sphere model in a cosmological setting and how it may be relevant for future observations.

Next we will review the current knowledge on the production of, absorption in and escape of ionizing radiations in primordial galaxies. Observations provide only indirect constraints at such high redshifts and simulations have only recently attacked this problem, yielding no clear answers yet. Along the source formation efficiency, the escape fraction of ionizing photon into the IGM is probably the biggest uncertainty in our currently knowledge of the EoR.

Once ionizing photons reach the IGM they create ionizing fronts (UV photons) or diffuse and fluctuating ionization field (X-ray). We will examine the physics of these two types of ionization and how they impact the 21 cm signal. Finally we will assess the current knowledge of the impact of dense, fast-recombining structures (mini-halos, Lyman Limit systems) on the global process of reionization.

Epoch of Reionization modelling and simulations for SKA

Ilian T. Iliev[1*], Mario G. Santos[2], Andrei Mesinger[3] and Suman Majumdar[4]

[1] Astronomy Centre, Department of Physics & Astronomy, Pevensey II Building, University of Sussex,Falmer, Brighton BN1 9QH, United Kingdom

[2] CENTRA, Instituto Superior Tecnico, Technical University of Lisbon, Lisbon, Portugal

[3] Scuola Normale Superiore, Pisa, Italy

[4] Department of Astronomy & Oskar Klein Centre, AlbaNova, Stockholm University, SE-106 91 Stockholm, Sweden

[*] Presenter

E-mail contact: I.T.Iliev at sussex.ac.uk

Abstract: Detailed modelling, both numerical or analytical, of the phenomena being studied plays important part in any large observational program. This is even more important for Epoch of Reionization studies, due to the current scarcity of direct observations. There is significant parameter space to be explored and a complex reionization physics to be understood for both proper planning of the observations and for reliable interpretation of the obtained data and its connection to the properties of the first galaxies and the progress and duration of the reionization process. We review the current state of the art in reionization modelling, progress achieved to date and challenges still to be overcome. We discuss the relevant scales of cosmic reionization, some of the physics involved (with references to other relevant chapters on this), all with particular focus on the SKA requirements in terms of survey size, resolution and sensitivity. Both the purely numerical and semi-analytical approaches are discussed, along with their relative merits and limitations. We also briefly estimate the computational and data storage requirements for such work and discuss outlook on the road to SKA phase 1 and beyond.

Constraining Cosmic Dawn and Epoch of Reionization Astrophysics with HI Data

Andrei Mesinger[1*], Andrea Ferrara[1], Ilian Iliev[2], Garrelt Mellema[3], Jonathan Pritchard[4], Mario G. Santos[5] (preliminary draft)

[1] Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy

[2] Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK

[3] Department of Astronomy and Oskar Klein Centre, Stockholm University, Albanova, SE-10691Stockholm, Sweden

[4] Department of Physics, Blackett Laboratory, Imperial College, London SW7 2AZ, UK

[5] CENTRA, Departamento de Fisica, Instituto Superior Tecnico, 1049-001 Lisboa, Portugal

[*] Presenter

E-mail contact: andrei.mesinger at sns.it

The Square Kilometre Array (SKA) will offer an unprecedented view onto the early Universe, using interferometric observations of the redshifted 21cm line. The 21cm line probes the thermal and ionization state of the cosmic gas, which is governed by the birth and evolution of the first structures in our Universe. Here we show how the evolution of the 21cm signal will allow us to study when the first generations of galaxies appeared, what were their properties, and what was the structure of the intergalactic medium.

Cosmology from EoR/Cosmic Dawn

Pritchard[1,*], Ichiki, Mesinger, Metcalf, Pourtsidou, Santos, on behalf of the Cosmology-SWG and EoR/CD-SWG

[1] Imperial College London

[*] Presenter

E-mail contact: j.pritchard@imperial.ac.uk

SKA Phase 1 will build upon early detections of the EoR by precursor instruments, such as MWA, PAPER, LOFAR, and HERA, to make the first high signal-to-noise measurements of fluctuations in the 21 cm brightness temperature from both reionization and the cosmic dawn. This will allow both imaging and statistical maps of the 21cm signal at redshifts $z = 6 - 30$ and constrain the underlying cosmology and evolution of the density field. This era includes nearly 60% of the (in principle) observable volume of the Universe and many more linear modes than the CMB, presenting an opportunity for SKA to usher in a new level of precision cosmology. This optimistic picture is complicated by the need to understand and remove the effect of astrophysics, so that systematics rather than statistics will limit constraints. This chapter will describe the cosmological, as opposed to astrophysical, information available to SKA Phase 1. Key areas for discussion include: cosmological parameters constraints using 21cm fluctuations as a tracer of the density field; lensing of the 21cm signal, constraints on heating via exotic physics such as decaying or annihilating dark matter; impact of fundamental physics such as non-Gaussianity or warm dark matter on the source population; and constraints on the bulk flows arising from the decoupling of baryons and photons at $z = 1000$. The chapter will explore the path to separating cosmology from 'gastrophysics', for example via velocity space distortions and separation in redshift. We will discuss new opportunities for extracting cosmology made possible by the sensitivity of SKA-1 and explore the advances achievable with SKA-2.

All-sky signals from recombination to reionization

Ravi Subrahmanyan[1*], N Udaya Shankar[1], Jonathan Pritchard[2] and Harish K Vedantham[3]

[1] Raman Research Institute, C V Raman Avenue, Sadashivanagar, Bangalore 560080, India

[2] Imperial College London, Astrophysics, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK

[3] Kapteyn Astronomical Institute, Landleven 12, 9747 AD Groningen, The Netherlands

[*] Presenter

E-mail contact: rsubrahm at rri.res.in

Cosmic evolution in the hydrogen content of the Universe through recombination and up to the end of reionization is expected to be revealed as subtle spectral features in the uniform extragalactic cosmic radio background. The redshift evolution in the excitation temperature of the 21-cm spin flip transition of neutral hydrogen appears as redshifted emission and absorption against the cosmic microwave background. The precise signature of the spectral trace is dependent on the spectral radiance, abundance and distribution of the first bound systems of stars and early galaxies, which govern the evolution in the spin-flip level populations. Redshifted 21 cm from these epochs when the spin temperature deviates from the temperature of the ambient relic cosmic microwave background results in an all-sky spectral structure in the 40–200 MHz range, almost wholly within the band of SKALow. Another spectral structure from gas evolution is redshifted recombination lines from epoch of recombination of hydrogen and helium; the weak all-sky spectral structure arising from this event is likely best detected at the upper end of the 350–3050 MHz band of SKA-mid. Total power spectra of SKA interferometer elements form the measurement set for these faint signals from recombination to reionization; the inter-element interferometer visibilities form a calibration set. The challenge is in precision polarimetric calibration of the element spectral response and solving for additives and unwanted confusing leakages of sky angular structure modes into spectral modes. Herein we discuss observing methods and design requirements that make possible these all-sky SKA measurements of the cosmic evolution in the baryons.

Signature of the First Galaxies in the High-Redshift 21-cm Observation

Kyungjin Ahn[1*], Andrei Mesinger[2], Marcelo A. Alvarez[3], and Xuelei Chen[4]

[1] Chosun University, 309 Pilmun-daero Dong-gu, Gwangju 501-759, Korea

[2] Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy

[3] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, 14th floor, Toronto, ON. M5S 3H8, Canada

[4] A429, National Astronomical Observatories, 20A Datun Road, Chaoyang District, Beijing, China, 100012

[*] Presenter

E-mail contact: kjahn at chosun.ac.kr

We briefly review the theory of the formation and evolution of the high-redshift astrophysical objects such as the First Stars and the early quasars, which is still under rapid and intensive development. Both imaging and power spectrum analysis of 21-cm signals constructed by these sources, either collectively or individually, seem promising with SKA, opening up the observational window for astrophysics (or cosmology) of the “Cosmic Dawn”. We present forecasts of a few representative 21-cm observations related to these early sources, in conjuction with recent developments in the theory of the First Star formation and the origins of temporal and spatial fluctuation, which can be both radiative (fluctuation in Lyα and X-ray background) and dynamical (fluctuation in density and heating).

Bulk Flows and the End of the Dark Ages

Umberto Maio[1*], Benedetta Ciardi[2], and Leon Koopmans[3]

[1] INAF – Osservatorio Astronomico di Trieste, via G. Tiepolo 11, Trieste, Italy; Marie Curie Fellow; Leibniz Institute for Astrophysics, An der Sternwarte 16, D-14482 Potsdam, Germany

[2] Max Planck Institute for Astrophysics, Karl-Schwarzshild-Straße 1, Garching, Germany

[3] Kapteyn Astronomical Institute, Landleven 12, Groeningen, The Netherlands

[*] Presenter

E-mail contact: maio at oats.inaf.it

The early Universe is a precious probe of the birth of primordial objects, first star formation events and consequent production of photons and heavy elements. Higher-order corrections to the cosmological linear perturbation theory predicts the formation of coherent supersonic gaseous streaming motions at decoupling time. These bulk flows impact the gas cooling process and determine a cascade effect on the whole baryon evolution. By analytical estimates and N-body hydrodynamical chemistry numerical simulations including atomic and molecular evolution, gas cooling, star formation, feedback effects and metal spreading for individual species from different stellar populations according to the proper yields and lifetimes, we discuss the role of these primordial bulk flows at the end of the dark ages and their detectable impacts during the first Gyr in view of the upcoming SKA mission. Early bulk flows can inhibit molecular gas cooling capabilities, suppressing star formation, metal spreading and the abundance of small primordial galaxies in the infant Universe. This can determine a delay in the re-ionization process and in the heating of neutral hydrogen making the observable HI signal during cosmic evolution patchier and noisier. The planned SKA mission will represent a major advance over existing instrumentations, since it will be able to probe the effects on HI 21-cm at $z \sim$ 6–20 and on molecular line emissions from first collapsing sites at $z \sim$ 20–30. Therefore, it will be optimal to address the effects of primordial streaming motions on early baryon evolution and to give constraints on structure formation in the first Gyr.

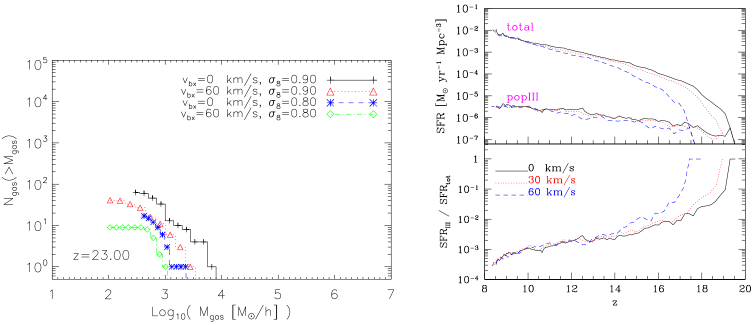


Figure 1: Right panel. Cumulative distributions of early gas clouds simulated in ~1Mpc-size boxes initialized with different σ_8 and bulk velocity shifts, v_{bx}. Left panel. Resulting cosmic star formation histories.

21cm Forest

Benedetta Ciardi[1], Susumu Inoue[2], Katherine J. Mack[3], Yidong Xu[4] and Gianni Bernardi[5,6*]

[1] Max Planck Institute for Astrophysics, Garching, Germany

[2] Institute for Cosmic Ray Research, University of Tokyo, Tokyo, Japan

[3] University of Melbourne, Melbourne, Australia

[4] National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

[5] SKA SA, Cape Town, South Africa

[6] Rhodes University, Grahamstown, South Africa

[*] Presenter

E-mail contact: ciardi at mpa-garching.mpg.de

An alternative to both the tomography technique and the power spectrum approach is to search for the 21cm forest, that is the 21cm absorption features against high-z radio loud sources caused by the intervening cold neutral intergalactic medum (IGM) and collapsed structures. Since the strongest absorption features arise from small scale structures, the 21cm forest can probe the HI density power spectrum on small scales not amenable to measurements by any other means. Also, it can be a unique probe of the heating process and the thermal history of the early universe, as the signal is strongly dependent on the IGM temperature. Here we show what SKA1-low could do in terms of detecting the 21cm forest in the redshift range $z \sim 7.5 – 15$.

Correlations and cross-correlations: kSZ, radio galaxies, and NIR background

Vibor Jelić[1,2,*], Benedetta Ciardi[3], Elizabeth Fernandez[1], and Hiroyuki Tashiro[4]

[1] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands

[2] ASTRON - the Netherlands Institute for Radio Astronomy, PO Box 2, 7990 AA Dwingeloo, the Netherlands

[3] Max-Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, D-85748 Garching beiMünchen, Germany

[4] Department of Physics and Astrophysics, Nagoya University, Furocho, Chikusaku, Nagoya, 464-8602 Japan

[*] Presenter

E-mail contact: vjelic at astro.rug.nl

The Universe's Cosmic Dawn (CD) and Epoch of Reionization (EoR) can be studied using a number of observational probes that provide complementary or corroborating information. Each of these probes suffers from its own systematic and statistical uncertainties. It is therefore useful to consider the mutual information that these data sets contain. In this talk we will discuss a potential of cross-correlations between the SKA cosmological 21 cm data with: (i) the kinetic Sunyaev-Zel'dovich (kSZ) effect in the CMB data; (ii) the galaxy surveys; and (iii) the near infrared backgrounds.

Synergy with CO/[CII]/Lyα Line Intensity Mapping

T.-C. Chang[1*],Y. Gong[2], M. Santos[3;4;5], J. Aguirre[6], J. Pritchard[7], on behalf of the EoR/CD-SWG

[1] Academia Sinica Institute of Astronomy and Astrophysics, 1 Roosevelt Rd, Section 4, Taipei, 10617, Taiwan

[2] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

[3] Physics Department, University of the Western Cape, Cape Town 7535, South Africa

[4] SKA SA, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa

[5] CENTRA, Instituto Superior T´ecnico, Universidade de Lisboa, Portugal

[6] Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA

[7] Imperial Center for Inference and Cosmology, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, United Kingdom

[*] Presenter

E-mail contact: tcchang at asiaa.sinica.edu.tw

This subchapter describes cross-correlation sciences and synergy with the SKA1-low 21-cm EoR surveys enabled by other programs, in particular promising line intensity mapping surveys of redshifted CO rotational lines, [CII] and Ly-α emissions during reionization are discussed. We briefly describe theoretical models of the three star-formation tracers at $z \sim 8$, and forecast their cross-power spectra measurements with the nominal 21cm EoR survey. We discuss how reionization parameters can be better extracted and constrained by the cross-power spectra.

Foreground Removal on Cosmic Dawn and Epoch of Reionization SKA Data

Emma Chapman[1,*], Filipe Abdalla[1], Gianni Bernardi[2], Jérôme Bobin[3], Anna Bonaldi[4], Fred Dulwich[5], Geraint Harker[1], Vibor Jelić[6], Benjamin Mort[5], Mario Santos[2], Jean-Luc Starck[3] and Saleem Zaroubi[7]

[1] Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT

[2] University of the Western Cape, Department of Physics, 7535 Belliville, Western Cape Province, Cape Town, South Africa

[3] Service d'Astrophysique (DAPNIA/SEDI-SAP), Centre Europeen d'Astronomie/Saclay, F-91191 Gif-sur-Yvette Cedex France

[4] Jodrell Bank Centre for Astrophysics School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK

[5] Oxford e-Research Centre, University of Oxford

[6] ASTRON, PO Box 2, NL-7990AA Dwingeloo, the Netherlands

[7] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700AV Groningen, the Netherlands

[*] Presenter

E-mail contact: Emma Chapman at eow@star.ucl.ac.uk

The exceptional expected sensitivity of the SKA will herald observations of unprecedented detail, both spectrally and spatially. For the measurement of the 21-cm radiation from the first ionizing sources, this new wealth of information is buried under Galactic and extragalactic foregrounds which are larger by several magnitudes. This problem has been addressed with the previous generation of radio telescopes and in this chapter we summarise the contributions to the field of foreground removal in the context of 21-cm high redshift measurements. We use a state-of-the-art simulation of the SKA Phase 1 observations complete with cosmological signal, foregrounds and frequency dependent instrumental effects to test both parametric and non-parametric foreground removal methods. We compare the recovered cosmological signal using several different statistics and explore one of the most exciting possibilities with the SKA - imaging of the ionized bubbles.

Cosmology with the SKA: overview

R. Maartens*, F. Abdalla, M. Jarvis, M. Santos, D. Bacon, S. Bridle, M. Brown, P. Bull, S. Camera, X. Chen, S. Colafrancesco, T. Kitching, H. Kloeckner, P. Patel, A. Raccanelli, D. Schwarz, K. Takahashi, J. Weller, L. Wolz, G. Zhao – on behalf of the SKA Cosmology Working Group

* Presenter

The SKA will be a cosmology machine with unprecedented power to probe the largest scales of the dark Universe. All-sky surveys in HI (intensity mapping and threshold) and in continuum can deliver constraints competitive with next-generation optical/ infrared experiments on key probes of dark energy, such as the Baryon Acoustic Oscillations and Redshift-Space Distortions. The SKA will also provide unprecedented constraints on key parameters such as the curvature of the Universe and primordial non-Gaussianity. With different systematics from the optical, the SKA provides a valuable consistency check of optical surveys, and cross-correlations with such surveys will further enhance precision cosmology. By also checking for consistency with features on large scales in the CMB, the SKA has the potential for discovery of new aspects of the Universe. SKA1 will pave the way for the billion galaxy survey and for revolutionary weak lensing surveys that will be delivered by SKA2.

Cosmology with HI intensity mapping surveys

Mario G. Santos[1;2;3;*] on behalf of the SKA Cosmology Science Working Group

[1] Department of Physics, University of Western Cape, Cape Town 7535, South Africa

[2] SKA SA, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa

[3] CENTRA, Instituto Superior Tecnico, Universidade de Lisboa, Portugal

[*] Presenter

E-mail contact: mgrsantos at uwc.ac.za

HI intensity mapping (IM) is a novel technique capable of mapping the large scale structure of the Universe in three dimensions and deliver exquisite constraints on cosmology by using HI as a biased tracer of the dark matter density field. This is achieved by measuring the intensity of the redshifted 21cm line over the sky and a range of redshifts without the requirement to resolve individual galaxies. By pinning down the baryon acoustic oscillation and redshift space distortion features in the matter power spectrum, thus determining the expansion and growth history of the Universe, HI IM surveys can provide powerful tests of dark energy models and modifications to General Relativity. They can also be used to probe physics on extremely large scales, where precise measurements of spatial curvature and primordial non-Gaussianity can be used to test inflation; and on small scales, by measuring the sum of neutrino masses.

In this talk I'll review the basic physics of the cosmological HI IM signal and discuss current measurements on its evolution. I'll then summarise the cosmological constraints that can be obtained with SKA1-Mid and SKA1-Sur for different frequency bands. Given the difficulty to detect large numbers of HI galaxies with SKA1 up to high z, an intensity mapping survey is seen as the best candidate to provide "game changing" cosmological constraints. SKA-Phase 1 can deliver HI intensity maps over a broad range of frequencies and a substantial fraction of the sky and put stringent constraints on key probes of dark energy, as well as key parameters such as the curvature of the Universe and primordial non-Gaussianity. In particular, I'll analyse the use of the single-dish (auto-correlation) mode to provide an all sky survey up to high redshifts ($z < 3$), with unprecedented volume, in combination with the interferometer data to calibrate the system and provide information on small scales. I'll then discuss the impact of foregrounds as well as various instrumental and survey design parameters on the achievable constraints.

Cosmology with HI galaxy surveys

Filipe Abdalla

Cosmology with Radio Continuum Surveys

Matt Jarvis[1,*], David Bacon, Michael Brown, Stefano Camera, Sergio Colafrancesco, Luis Ferramacho, Sam Lindsay, Sphesihle Makhatini, Prina Patel, Alvise Raccanelli, Mario Santos, Oleg Smirnov, Dominik Schwarz

[1] University of Oxford/University of the Western Cape

[*] Presenter

E-mail contact: matt.jarvis at astro.ox.ac.uk

The SKA will provide unique constraints on cosmology, large scale structure and General Relativity. The SKA will detect radio sources to the highest redshifts and the number density of radio sources at these high redshifts will exceed the density of galaxies detected in wide-field optical surveys, enbabling unique science. Furthermore, the precise knowledge of the synthesised beam in radio continuum surveys may provide a unique tool for weak lensing surveys. I will also highlight some of the synergies with other facilities, in particular for providing photometric redshift information. I will present an overview of these and other experiments that can be carried out with radio continuum surveys in the build-up to Phase 1 through to Phase 2.

Radio Weak Lensing with the Square Kilometre Array

M. L. Brown,[1,*] F. B. Abdalla,[2] D. J. Bacon,[3] S. Bridle,[1] S. Camera,[4] I. Harrison,[1] M. Jarvis,[5] B. Joachimi,[2] T. D. Kitching,[2] R. B. Metcalf,[6] L. Miller,[5] P. Patel,[7] A. Pourtsidou,[6] K. Takahashi,[8] and J. A. Zuntz[1]

[1] University of Manchester, UK

[2] University College London, UK

[3] University of Portsmouth, UK

[4] CENTRA-IST, Lisbon, Portugal

[5] Oxford Astrophysics, Oxford, UK

[6] Universitá di Bologna, Italy

[7] UWC, Cape Town, South Africa

[8] Kumamoto University, Japan

[*] Presenter

E-mail contact: m.l.brown at manchester.ac.uk

Over the last two decades, weak gravitational lensing has emerged as a key cosmological probe of the dark sector and of gravity. Lensing is a key science driver for current and forthcoming large surveys and telescopes, including the Kilo-Degree Survey, the Dark Energy Survey, the Large Synoptic Survey Telescope and Euclid. The SKA offers a unique approach to performing precision weak lensing. This is due to a number of compelling potential advantages of radio-based lensing measurements. In particular, large radio surveys offer: stable and deterministic point spread functions (beams), the ability to minimise systematic effects through radio-optical cross-correlations, the use of polarization and/or HI rotational velocity measurements to mitigate against intrinsic alignments, and the use of observations at multiple frequencies to eliminate "colour gradient" bias. The SKA has a unique ability to probe the very largest scales in the Universe. An ultrawide SKA-1 weak lensing survey with 2 years of on-sky observing, and covering 3π steradians, would provide highly competitive constraints on the evolution on the matter power spectrum in the purely linear regime. Alternatively, a two-year survey concentrated over a few thousand square degrees (e.g. the DES survey area) would probe the source galaxy population to higher redshift ($z > 1.2$) than typically reached by optical lensing surveys (e.g. DES median $z \sim 0.6$). The addition of this high redshift information would enhance studies of structure growth by adding additional high-redshift bins to a tomographic cosmic shear analysis. This would in turn result in improved constraints on dark energy parameters. Finally, an SKA-1 weak lensing survey will provide essential groundwork for SKA-2, which will take radio weak lensing to an entirely new level, potentially even exceeding the capabilities of any of the planned optical/IR surveys.

Measuring baryon acoustic oscillations in future SKA surveys

Philip Bull[1,*], Filipe Abdalla[2], Chris Blake[3], Stefano Camera[4], Pedro G. Ferreira[5], Manuela Magliocchetti[6], Alvise Raccanelli[7;8], Mario G. Santos[9;10;4], Dominik J. Schwarz[11], Keitaro Takahashi[12], Jochen Weller[13], and Gong-Bo Zhao[14;15]

On behalf of the SKA Cosmology Science Working Group

[1] Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo,Norway

[2] Dept. of Physics and Astronomy, University College London, UK

[3] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O.Box 218, Hawthorn, VIC 3122, Australia

[4] CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

[5] Astrophysics, University of Oxford, DWB, Keble Road, Oxford OX1 3RH, UK

[6] Osservatorio Astronomico di Trieste, Italy

[7] Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA

[8] California Institute of Technology, Pasadena CA 91125, USA

[9] Department of Physics, University of Western Cape, Cape Town 7535, South Africa

[10] SKA SA, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa

[11] Fakultät für Physik, Universität Bielefeld, Universitätstr. 25, Bielefeld, Germany

[12] University of Kumamoto, Japan

[13] Ludwigs-Maximilians University, Munich, Germany

[14] National Astronomy Observatories, Chinese Academy of Science, Beijing, 100012, P.R.China

[15] Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK

[*] Presenter

E-mail contact: p.j.bull at astro.uio.no

The imprint of baryon acoustic oscillations (BAOs) in large-scale structure can be used as a standard ruler for mapping out the cosmic expansion history, and hence for testing cosmological models. In this chapter we will briefly describe the scientific background of the BAO technique, and forecast the potential of the SKA Phase 1 and 2 telescopes to perform BAO surveys using both galaxy catalogues and intensity mapping, assessing their competitiveness with current and future optical galaxy surveys. In particular, intensity mapping should permit BAO measurements in the redshift range $z > 0.8$, adding extra constraining power for parameters such as the spatial curvature of the Universe.

Measuring redshift-space distortion with the SKA

Alvise Raccanelli[1,*],et al.
[1] Jet Propulsion Laboratory, USA
[*] Presenter
E-mail contact: alvise at caltech.edu

All-sky SKA surveys, in HI threshold and intensity mapping and in continuum, will probe the biggest volumes ever of large-scale structure in the Universe. This will allow a major advance in tackling two of the main questions in cosmology today - Are the fluctuations generated in the early Universe non-Gaussian? Does General Relativity hold on the largest scales? The best current constraints on primordial local non-Gaussianity are from the Planck CMB experiment, but future CMB experiments are unlikely to improve these results significantly. Surveys of the matter distribution are the new frontier for non-Gaussianity, and the SKA has the potential to deliver game-changing constraints, given the ultra-large scales that it probes. This expectation is supported by recent forecasts of the constraining power of different SKA surveys. Another advantage for SKA arises from the possibility of discriminating between different source types, allowing the use of the so-called multi-tracer technique to reduce cosmic variance and thus further increase the constraining capabilities on very large scales. Tests of General Relativity on cosmological scales can only be based on a combination of observations of the large-scale structure. Current constraints are weak, but with its huge volumes and multiple probes, the SKA should lead the next generation of tests. In addition, we can strengthen the current tests of dark energy and modified gravity models by including much larger scales, increasing the statistical power of the observations and improving constraints on any scale dependence of deviations from GR. Probing ultra-large scales includes a theoretical challenge that has only been recently recognized. On very large scales, relativistic effects on the galaxy over-density and the HI brightness temperature fluctuations also become important. They arise since we observe on the past lightcone and they can significantly change the predictions of the standard Newtonian approximation. In addition to the standard redshift-space distortions and the weak lensing magnification, there are Doppler, Sachs-Wolfe, integrated SW and time-delay contributions, which can become significant on horizon scales. It is therefore necessary to include these effects in predictions that will be tested against observations. The SKA has the potential to detect these relativistic effects, thus providing a clear signal of General Relativity - or an indication of its violation on the largest scales. Furthermore, the amplitude of the relativistic effects can be of the same order as primordial local non-Gaussianity that is consistent with Planck's constraints. We will discuss new techniques to improve constraints on primordial non-Gaussianity via a proper accounting of the relativistic effects.

Cosmology on the Largest Scales

S. Camera,[1,*] D. Bertacca,[2] S. Borgani,[3;4;5] P. Bull,[6] X. Chen,[7] C. Clarkson,[8] L. Ferramacho,[1] M. Kunz,[9;10] R. Maartens,[2;11] Y. Mao,[12] A. Raccanelli,[13;14] M.G. Santos,[1;2] P.R. Shapiro,[15] M. Viel[4;5] and Y. Xu[6]

[1] CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal

[2] Department of Physics, University of the Western Cape, Bellville 7535, South Africa

[3] Astronomy, Department of Physics, University of Trieste, via Tiepolo 11, 34131 Trieste, Italy

[4] INAF, Astronomical Observatory of Trieste, via Tiepolo 11, 34131 Trieste, Italy

[5] INFN, Sezione di Trieste, 34100 Trieste, Italy

[6] Institute of Theoretical Astrophysics, University of Oslo, P.O. 1029 Blindern, 0315 Oslo, Norway

[7] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

[8] ACGC, Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, Cape Town, South Africa

[9] Département de Physique Théorique and Center for Astroparticle Physics, Université de Genève, 24 quai Ansermet, CH 1211 Genève 4, Switzerland

[10] African Institute for Mathematical Sciences, 6 Melrose Road, Muizenberg 7945, South Africa

[11] Institute for Cosmology & Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK

[12] Institut d'Astrophysique de Paris, Institut Lagrange de Paris, CNRS, UPMC Univ Paris 06, UMR7095, 98 bis, boulevard Arago, F-75014, Paris, France

[13] Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA

[14] California Institute of Technology, Pasadena CA 91125, USA

[15] Department of Astronomy and Texas Cosmology Center, The University of Texas at Austin, 2515 Speedway C1400, Austin, Texas 78712, USA* Presenter

[*] Presenter

E-mail contact: stefano.camera at tecnico.ulisboa.pt

Surveys performed by the Square Kilometre Array (SKA) will probe the biggest volumes ever of the Universe's large-scale structure. In this context, we here review how the knowledge of the properties of cosmic structures on extremely large scale is one of the major strengths of SKA science. The growth of perturbations on ultra-large scales are well within the linear régime, and those scales are also unaffected by the poorly understood feedback of baryonic physics. Amongst the most interesting phenomena occurring on the largest cosmic scales are general relativistic corrections to cosmological observables. Such effects can significantly deviate from the standard, Newtonian prediction. Therefore, it is imperative to consider them fully in analyses and forecasts for the SKA. Moreover, it has been argued that modifications of the behaviour of gravity on cosmological distances—which can possibly explain the late-time accelerated expansion of the cosmos with need of neither a cosmological constant nor DE—may hide close to the horizon scale. Finally, it is also renown that most models of inflation predict slightly non-Gaussian initial conditions, whose effects on the clustering of galaxies and galaxy clusters are the strongest on ultra-large scales.

Topology of neutral hydrogen distribution with the Square Kilometer Array

Yougang Wang[1], Xin Wang[2], Xuelei Chen[1,*], Changbom Park[3], Renyue Cen[4], Juhan Kim[3], Khee-Gan Lee[4], Fengquan Wu[1], Yidong Xu[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China

[2] Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, USA

[3] School of Physics, Korean Institute for Adavanced Studies, Seoul, Korea

[4] Department of Astrophysical Science, Princeton University, Princeton, USA

[*] Presenter

E-mail contact: xuelei at cosmology.bao.ac.cn

Morphology of the complex HI gas distribution can be quantified by statistics like the Minkowski functionals, and can provide a way to statistically study the large scale structure in the HI maps both at low redshifts, and during the epoch of reionization (EoR). At low redshifts, the 21cm emission traces the underlying matter distribution. Topology of the HI gas distribution, as measured by the genus, could be used as a “standard ruler”. This enables the determination of distance-redshift relation and also the discrimination of various models of dark energy and of modified gravity. The topological analysis is also sensitive to certain primordial non-Gaussian features. Compared with two-point statistics, the topological statistics are more robust against the nonlinear gravitational evolution, bias, and redshift-space distortion. The HI intensity map observation naturally avoids the sparse sampling distortion, which is an important systematic in optical galaxy survey. The large cosmic volume accessible to SKA would provide unprecedented accuracy using such a measurement. During the EoR, topology can be a powerful and intuitive tool to distinguish among the different evolutionary stages of reionization, where the ionized regions make up a significant fraction of the volume. Furthermore, it can also discriminate among various reionization models. The genus curves evolve during cosmological reionization, and for different reionization scenarios, the topology of the HI gas distribution can be significantly different even if the global ionization fractions are the same. It can provide clear and intuitive diagnostics for how the reionization takes place, and indirectly probes the properties of radiation-sources. In this brief chapter we will describe the scientific background of the topology study, and forecast the potential of the SKA for measuring cosmological parameters and constraining structure formation mechanism through the study of topology of HI gas distribution.

Testing foundations of cosmology with SKA all-sky surveys

Dominik J. Schwarz,[a*] David Bacon,[b] Chris Blake,[c] Song Chen,[a] Chris Clarkson,[d] Dragan Huterer,[e] Martin Kunz,[f;g] Roy Maartens,[g;b] Alvise Raccanelli,[i;j] Matthias Rubart,[a] Jean-Luc Starckk

[1] Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany
[2] Institute of Cosmology and Gravitation, University of Portsmouth, Burnaby Road, Portsmouth PO1 3FX, United Kingdom
[3] Centre for Astrophysics & Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, VIC 3122, Australia
[4] Centre for Astrophysics, Cosmology & Gravitation and Department of Mathematics & Applied Mathematics, University of Cape Town, Cape Town 7701, South Africa
[5] Department of Physics, University of Michigan, 450 Church St, Ann Arbor, MI 48109-1040, USA
[6] Université de Genève, Département de Physique Théorique and CAP, 24 quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland
[7] African Institute for Mathematical Sciences, 6 Melrose Road, Muizenberg, 7945, South Africa
[8] Physics Department, University of the Western Cape, Cape Town 7535, South Africa
[9] Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA
[10] California Institute of Technology, Pasadena CA 91125, USA
[11] Laboratoire AIM, UMR CEA-CNRS-Paris, Irfu, SAp, CEA Saclay, 91191 GIF-SUR-YVETTECEDEX, France
[*] Presenter

E-mail contact: dschwarz at physik.uni-bielefeld.de

The Square Kilometre Array (SKA) will allow us to test fundamental assumptions of modern cosmology at redshifts of order unity and at an accuracy level matching and complementing observations of the cosmic microwave background (CMB). The cosmological principle, as inferred from cosmological inflation, states that the Universe is statistically isotropic and homogeneous. The SKA will probe an enormous number of independent modes when studying the large-scale structure of the Universe and will measure superhorizon sized modes at redshifts of order unity. We propose to use all-sky (3π) SKA continuum surveys to test statistical isotropy and to measure the cosmic dipole and other low-l multipole moments. All-sky SKA HI threshold surveys will additionally allow us to test the homogeneity of the Universe at superhorizon scales - a test that has never been performed so far.

Testing statistical isotropy and homogeneity will reveal many systematics of the SKA surveys and test the most fundamental assumptions of modern cosmology at the same time. The CMB dipole defines our reference frame and is assumed to be due to our peculiar motion. This kinetic dipole must also be present in radio observations and has been detected by means of the NVSS and WENSS, within large uncertainties. SKA will enable us to measure the radio dipole with high accuracy and to extract low-l multipole moments. At the largest angular scales, the cosmic microwave sky shows a suite of anomalous (unexpected) features, putting statistical isotropy in question. SKA surveys could test if these anomalies are related to secondary CMB effects, or if they are primordial and thus contain information on cosmological inflation.

This abstract has been coordinated within the SKA Cosmology SWG.

Cosmology with galaxy clusters in the SKA era

S. Colafrancesco [1], S. Borgani [2], J. Weller [3;*], B. Sartoris [2], P. Marchegiani [1], S.Emritte [1], C. Ferrari [4], K. Basu [5], S. Camera [6], F. Abdalla [7]

[1] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[2] INAF - Osservatorio Astronomico di Trieste, Trieste, Italy
[3] Universitäts-Sternwarte München, Ludwig-Maximilians-University Munich, München, Germany
[4] Observatoire de la Côte d'Azur, Nice, France
[5] University of Bonn, Bonn, Germany
[6] CENTRA - Centro Multidisciplinar de Astrofísica,Universidade de Lisboa, Portugal
[7] UCL, London, UK.
[*] Presenter

Galaxy clusters, the largest gravitationally bound structures in the Universe, are excellent cosmological probes used to determine the concordance model parameters, the equation of state of Dark Energy, the nature and distribution of Dark Matter, the impact of primordial magnetism on the evolution of large-scale structures, and even more fundamental probes of cosmic physics like, e.g., the fundamental properties of the photon. A highly efficient way to use clusters as cosmological probes is through the Sunyaev-Zel'dovich effect (SZE) that can be measured at radio frequencies (e.g., 10-25 GHz) where the SZE spectrum is almost independent of the relativistic corrections. Two important contributions can be provided by the SKA: 1) a wide exploration of the cluster number counts and power spectrum of their large-scale distribution by measuring the SZE for at least 10^6 clusters and groups out to $z \sim 2$ and beyond. Since the SZE emerges from the cluster radio halo steep spectrum at relatively high frequencies ($\gtrsim$ 10 GHz), this study is better suited with the SKA-1 Mid band 5 (4.6 -13.8) GHz, together with the complementary SKA-1 Mid bands 1 and 3 important to cover the transition between the synchrotron-dominated and the SZE-dominated part of the cluster spectrum. The possibility to have an extended frequency coverage of the SKA 2 (reaching 25 GHz) will allow to use both radio synchrotron and SZE observations of clusters to fully disentangle the radio halo phenomenon from the SZE used for cluster cosmology. 2) a new exploration of cluster number counts and redshift distribution by using the SZE produced by cluster electrons against the low-frequency CMB spectrum modified by a few dominant effects: the changes in the 21-cm background spectrum (resonant absorption of CMB intensity through spin-flip transition) at redshifts between 200 and 30, the onset of a Lyman-alpha radiation field produced by first sources at redshifts between 30 and 20, and gas heating (produced by soft X-ray photons from stars and quasars) during reionization at redshifts between 20 and 6. This 21cm-SZE retains information on both the high-z radiation field and on the nature of the electron population (thermal and/or non-thermal) inside clusters. The 21cm-SZE is optimally detectable in the range 0.01-1 GHz and the SKA-1 Mid Band 1 (350 -1050) MHz is crucially needed for cluster cosmology with the 21cm-SZE. The complementary detection of galaxy clusters directly from the integrated HI emission will add relevant synergy to this method. Further synergies with future X-ray, mm. and gravitational lensing surveys will enhance the role of SKA in exploiting the role of galaxy clusters a precision tools for cosmology.

Weak Lensing Simulations for the SKA

Prina Patel*, Filipe Abdalla, David Bacon, Michael Brown, Ian Harrison, Ian Heywood, Matt Jarvis, Sphesihle Makhathini, Lance Miller, Oleg Smirnov

* Presenter

E-mail contact: prina83 at gmail.com

Weak gravitational lensing has recently emerged as one of the key probes for the cosmological model. Weak lensing requires a large number density of objects and high precision imaging data for precision shape measurement. Data from the SKA will be have unprecedented sensitivity and resolution allowing this sort of measurement to be made at centimetre wavelengths. Measurements of individual galaxy shapes remains a key challenge to exploit this type of experiment. In this chapter we explore how well known galaxy shapes can be recovered using the current SKA-Mid Phase 1 configuration. We also explore what impact changing the antenna distribution has on shape recovery.

This chapter makes extensive use of MeqTrees based simulations to demonstrate the viability of weak gravitational lensing experiments at radio wavelengths with interferometer arrays such as the SKA. A suite of high resolution images containing realistic source morphology/shapes are simulated as SKA Phase 1 observations and then analysed using the the shapelet shape measurement technique. We explore how changing the antenna distribution affects the signal-to-noise ratio at the appropriate spatial scales, and the reliability with which we can recover the known, input shape distribution.

We also explore how the shapelet measurement technique fairs in real and Fourier space. Measurements of galaxy shapes in the uv plane would allow imaging steps to be bypassed and could provide less systematically effected shape measurements. Determination of a favoured technique will be important not only for the SKA but all pre-cursor instruments with which weak lensing measurements may be made.

This abstract has been coordinated within the SKA Cosmology SWG.

Foreground subtraction in Intensity Mapping

Laura Wolz[1;2;*], Filipe B. Abdalla[1], David Alonso[2], Chris Blake[3], Philip Bull[4], Tzu-Ching Chang[5] and Richard Shaw[6]

[1] Department of Physics and Astronomy, University College London, London WC1E 6BT, UK
[2] Astrophysics, University of Oxford, DWB, Keble Road, Oxford OX1 3RH, UK
[3] Centre for Astrophysics & Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, VIC 3122, Australia
[4] Institue of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway
[5] Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei, 10617 Taiwan
[6] Canadian Institute for Theoretical Astrophysics, 60 St. George Street, Toronto, ON M5S 3H8, Canada
[*] Presenter

E-mail contact: lwolz at star.ucl.ac.uk

Intensity Mapping of the neutral hydrogen (HI) line is an extremely promising and powerful probe to constrain cosmological parameters with an SKA1-survey. HI traces the large-scale matter distribution and is hence sensitive to cosmic growth regulated by Dark Energy for redshifts up to three. The HI emission maps, as seen by the SKA1 bands 1 and 2, require very low angular resolution which allows to observe a large fraction of the sky with few pointings.

The most challenging aspect of the data analysis is the subtraction of the very high foregrounds of our own Galaxy produced by synchrotron and free-free electron emission. The foregrounds can be up to five magnitudes higher than the HI signal and are particularly contaminating in the Galactic plane. The reliability of the cosmological results strongly depends on careful and thorough foreground subtraction.

Multiple approaches have been taken to remove the foregrounds from the HI signal. One group of methods separates the signals on the base of a-priori knowledge about the physical properties of the Galactic foregrounds such as their spectra or smoothness. This is accomplished by, for example, either subtracting the modeled spectra of the Galactic foreground components or by decomposing the data and removing the modes the foregrounds are particularly dominant in. A different route is chosen by non-parametric blind search methods. They separate the data into their individual components by applying statistical properties like independence or sparsity.

In the following, we present the state-of-art of foreground removal methods for Intensity Mapping and their ability to reliably extract the HI signal for an SKA1-survey. Furthermore, we demonstrate the expected level of foreground residuals and how they affect the cosmological results.

Real time cosmology - A direct measure of the expansion rate of the Universe

Hans-Rainer Klöckner[1;*], Danail Obreschkow[2], Carlos Martins[3], Alvise Raccanelli[4], David Champion[1], Alan Roy[1], Andrei Lobanov[1], Jan Wagner[1], Reinhard Keller[1]

[1] Max-Planck-Institut für Radioastronomie (MPIFR), Germany
[2] The University of Western Australia, ICRAR, Australia
[3] Centro de Astrofísica da Universidade do Porto, Portugal
[4] Caltech & JPL, USA
[*] Presenter

E-mail contact: hrk at mpifr-bonn.mpg.de

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 findings have 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 enables us to do the ultimate test in cosmology by directly measuring the expansion rate of the Universe via a rather simple experiment. This can be done by observing the neutral hydrogen (HI) signal of galaxies at different epochs. Due to the accelerated expansion of the Universe these signals will encounter a shift in redshift space and hence provide a real time measure of the cosmological expansion rate.

In order to measure such a change in redshift the current baseline design of the SKA need to be adjusted: providing an opportunity to increase the number of channels within sub-bands (strong requirement) and allowing for high system stability over 12 years with an accuracy of about 0.01 Hz (weaker requirement, which could be circumvent by pulsar observations).

The SKA allows for the ONLY model independent experiment that will measure the acceleration directly by observing HI galaxies up to redshift of 1. The E-ELT, with the CODEX-like experiment, instead will measure Lyman-alpha lines above redshifts of 2 and therefore will measure the deceleration, only.

Pulsar Science with the SKA – An Overview

Michael Kramer[1,2,*], Ben Stappers[2]

[1] Max-Planck-Institut für Radioastromomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Jodrell Bank Centre for Astrophysics, University of Manchester, Manchester M13 9PL, UK
[*] Presenter

E-mail contact: mkramer at mpifr.de

The Square-Kilometre-Array (SKA) represents the future of radio astronomy and will have a profound impact on a wide range of science. In particular, it will completely change the field of pulsar astronomy, providing not only a vast number of sources that can be studied but will also deliver an unprecedented sensitivity and timing precision for such studies. The result will be applications impossible with current technology, for example, in the field of gravitational physics. With the SKA we will study the nHz-gravitational wave sky, will probe the properties of gravitational waves and will also establish the properties of black holes. By enabling these Key Science goals, the SKA will also allow for a wide range of additonal science goals, addressing neutron stars, the structure of the Milky Way and many more. While these science areas will be presented in separate talks, this contribution gives an overview and puts them into context.

A Cosmic Census of Radio Pulsars

E. F. Keane[1,2,*], B. Bhattacharyya[3], M. Kramer[3,4], B. W. Stappers[3], S. D. Bates[5], M. Burgay[6], S.Chatterjee[7], D. J. Champion[4], R. P. Eatough[4], J. W. T. Hessels[8,9], G. Janssen[8], J. van Leeuwen[8,9], J. Margueron[10], M. Oertel[11], A. Possenti[6], S. Ransom[12], G. Theureau[13] & P. Torres Torne[4]

[1] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Australia
[2] ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO)
[3] School of Physics and Astronomy, The University of Manchester, UK
[4] Max-Planck Institute for Radio Astronomy, Bonn, Germany
[5] National Radio Astronomy Observatory, Green Bank, WV 24944, USA
[6] INAF-Osservatorio di Cagliari, loc Poggio dei Pini, strada 54, 09012, Capoterra, Italy
[7] Astronomy Department, Cornell University, Ithaca, NY 14853, USA
[8] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[9] Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands
[10] Institut de Physique Nucléaire de Lyon, CNRS, France
[11] Laboratoire Univers et Théories, Paris Observatory, France
[12] NRAO, Charlottesville, VA 22903, USA
[13] Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Centre National de la Recherche Scientifique, F-45071 Orléans, Cedex 2, France
[*] Presenter

E-mail contact: ekeane at swin.edu.au

The SKA will make ground breaking discoveries in pulsar science. The wide field-of-view, high sensitivity, multi-beaming and sub-arraying capabilities, coupled with advanced pulsar search backends, will result in the discovery of a large population of pulsars and new, high-quality data on select sources from the already known pulsar population. In this chapter we outline the surveys for new pulsars, as well as how we will perform the necessary follow-up timing observations of new discoveries. Pulsar surveys are essential to enable all of the SKA's headline pulsar science goals (tests of General Relativity with pulsar binary systems, investigating Black Hole Theorems with pulsar-black hole binaries, direct detection of gravitational waves in a pulsar timing array). Using SKA1-mid and SKA1-low at several different sky frequencies, we will survey the Milky Way to unprecedented depth, increasing the number of known pulsars by more than an order of magnitude. SKA Phase II will potentially enable us to find all of the Galactic radio-emitting pulsars beamed in our direction. This will give us a clear picture of the birth properties of pulsars and of the gravitational potential, magnetic field structure and interstellar matter content of the Galaxy. Our targeted searches will enable detection of the most exotic systems, such as the 1000 pulsars we infer to be closely orbiting Sgr A*, the supermassive black hole in the Galactic Centre. In addition to Galactic pulsars, the sensitivity of the SKA will be sufficient to detect pulsars from local group galaxies; we can use these sources as probes of the intergalactic medium. All of the discoveries will require regular (typically monthly, much more often for complex binary systems) re-observations for a few months in order to derive their spin characteristics and establish the particular science questions they can be used to address. To do this efficiently we will perform live searches, and use sub-arraying and dynamic scheduling to time pulsars as soon as they are discovered, while simultaneously continuing survey observations. The large projected number of discoveries suggests that we will uncover currently unknown rare systems that can be exploited to push the boundaries of our understanding of astrophysics and provide tools for testing physics, as has been done by the pulsar community in the past.

Understanding the Neutron Star Population

Thomas M. Tauris[1], Victoria M. Kaspi[2,*], René P. Breton[3], Adam T. Deller[4], Evan F. Keane[5], Michael Kramer[6], Duncan R. Lorimer[7], Maura A. McLaughlin[7], Andrea Possenti[8], Paul S. Ray[9], Ben W. Stappers[10], Patrick Weltevrede[10]

[1] AlfA, University of Bonn / Max-Planck Institute for Radio Astronomy, Bonn, Germany
[2] Department of Physics, McGill University,Montreal, Canada
[3] School of Physics and Astronomy, University of Southampton, UK
[4] The Netherlands Institute for Radio Astronomy (ASTRON), Dwingeloo, The Netherlands
[5] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Australia
[6] Max-Planck Institute for Radio Astronomy, Bonn, Germany
[7] Department of Physics and Astronomy, West Virginia University,Morgantown,WV, USA
[8] INAF-Osservatorio Astronomica di Cagliari, Italy
[9] Space Science Division, Naval Research Laboratory, Washington, DC, USA
[10] School of Physics and Astronomy, The University of Manchester, UK
[*] Presenter

E-mail contact: tauris at astro.uni-bonn.de or vkaspi at physics.mcgill.ca

Since their discovery in the late 1960's the population of known neutron stars has grown to ~2500. The last five decades of observations have yielded many surprises and demonstrated that the observational properties of neutron stars are remarkably diverse. The surveys that will be performed with SKA-low and SKA-mid will produce a further tenfold increase in the number of Galactic neutron stars known. Moreover, the SKA's broad spectral coverage, sub-arraying and multi-beaming capabilities will allow us to characterise these sources with unprecedented efficiency, in turn enabling a giant leap in the understanding of their properties. Here we outline our strategies for studying each of the growing number of diverse classes that are populating the 'neutron star zoo'. Some of the scientific questions that will be addressed by the much larger statistical samples and vastly improved timing efficiency provided by SKA Phase 1 include: (i) the spin period and spin-down rate distributions (and thus magnetic fields) at birth, and the associated information about the supernovae wherein they are formed; (ii) the radio pulsar–magnetar connection; (iii) the link between normal radio pulsars and intermittent pulsars and rotating radio transients (probing the emission of radio pulses); (iv) the slowest possible spin period for a radio pulsar (revealing the conditions at the pulsar death-line); (v) proper motions of pulsars (revealing supernova kick physics); (vi) the mass distribution of neutron stars; (vii) the fastest possible spin period for a recycled pulsar (constraining magnetosphere-accretion disc interactions, gravitational wave radiation and the equation-of-state); (viii) questions as to the origin of high eccentricity millisecond pulsars; (ix) the formation channels for recently identified triple systems; and finally (x) how isolated millisecond pulsars are formed. As well as this lengthy (but not exhaustive) scientific shopping list, we expect that SKA Phase 1, and in particular the full SKA Phase 2, will unveil exotic and heretofore unknown systems that will challenge our current knowledge and theories. The following discoveries would be possible with the SKA, and each in their own right would represent significant milestones in the astrophysics of compact objects: (i) sub-millisecond pulsars; (ii) neutron stars born as millisecond pulsars; (iii) neutron stars with masses below 1.1 or above 2.5 $M_\odot$; (iv) neutron star-black hole binaries; and (v) a triple system containing a pair of neutron stars.

Gravitational wave astronomy with the SKA

G. H. Janssen[1,*], G. Hobbs[2], M. McLaughlin[3], and the SKA pulsar science working group

[1] ASTRON, Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands
[2] CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, New South Wales 1710, Australia
[3] Department of Physics, West Virginia University, Morgantown, WV 26506, USA
[*] Presenter

E-mail contact: janssen at astron.nl

On a time scale of years to decades, gravitational wave (GW) astronomy will become a reality. Ultra-low frequency (10^{-9} to 10^{-8} Hz) GWs are detectable through long-term, high precision pulsar timing observations of the most stable pulsars. Observatories worldwide are currently carrying out observing programs to detect such waves and their data sets are being shared as part of the International Pulsar Timing Array project. The most likely source of ultra-low frequency GWs detectable using pulsar observations will be a background formed from a large number of merging supermassive binary black holes. It is, however, also possible that individual sources could be detected through their continuous wave or burst emission. No GW signal has yet been detected, but stringent constraints are already being placed on models for galaxy evolution.

The SKA will be the ideal telescope to bring this research to fruition. In the chapter we will consider two scenarios:

For the first scenario we will assume the unlikely scenario in which GWs have still not been detected before the SKA commences observations. We will demonstrate how timing observations using the SKA-mid array will either be able to detect the waves or rule out most current predictions for their existence. We will describe the impact of the large number of millisecond pulsars to be discovered by the SKA; the expected physical properties of those pulsars (including phase jitter and timing noise); and the observing cadence, observation durations, and instrumentation required to reach the necessary sensitivity to GWs.

In the second scenario we will assume that an initial detection of GWs has already been made. We will demonstrate how SKA observations will be able to confirm the detection, identify the source(s) of the signal, search for anisotropies in the background, improve models of galaxy evolution, test theories of gravity, and characterize the early inspiral phase of a supermassive binary black hole binary. Using the GW information, pulsar distance measurements can be further refined to sub-pc accuracy, which will benefit future Galactic and stellar astronomical studies.

We will concentrate on a long-term timing program using the SKA-mid array and will consider the implications of any modifications to the current design. We will also describe the possible benefits from observations using the SKA-low array. The majority of this chapter will describe the detectability of ultra-low frequency GWs. We will also note the importance of using the SKA to search for rapidly-rotating neutron stars, which could lead to detectable audio-frequency GWs using groundbased detectors. Any such detection would provide new insight into the structure and dynamics of neutron stars.

Testing Gravity with Pulsars

Lijing Shao[1,*], Ingrid H. Stairs[2], John Antoniadis[3], Matthew Bailes[4], Marina Berezina[3], David J. Champion[3], Ismael Cognard[5,6], Adam T. Deller[7], Paulo C. C. Freire[3], Jason W. T. Hessels[7], Gemma H. Janssen[7], Michael Kramer[3,8], Jutta Kunz[9], Claus Lämmerzahl[10], Volker Perlick[10], Andrea Possenti[11], Scott Ransom[12], Ben W. Stappers[8], Willem van Straten[4], Gilles Theureau[5,6]

[1] School of Physics, Peking University, Beijing 100871, China
[2] Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[4] Centre for Astrophysics and Supercomputing and ARC Centre for All-Sky Astrophysics (CAASTRO), Swinburne University of Technology, PO Box 218 Hawthorn, VIC 3122, Australia
[5] LPC2E/CNRS - Université d'Orléans, 45071 Orléans, France
[6] Nançay/Paris Observatory, 18330 Nançay, France
[7] ASTRON, The Netherlands Institute for Radio Astronomy, 7990 AA Dwingeloo, The Netherlands
[8] Jodrell Bank Centre for Astrophysics, The University of Manchester, M13 9PL, United Kingdom
[9] University of Oldenburg, Department of Physics, 26111 Oldenburg, Germany
[10] University of Bremen, ZARM, 28359 Bremen, Germany
[11] INAF-Osservatorio Astronomico di Cagliari, Loc. Poggio dei Pini, 09012 Capoterra (CA), Italy
[12] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
[*] Presenter

E-mail contact: lshao at pku.edu.cn (LS); stairs@astro.ubc.ca (IHS)

The Square Kilometre Array (SKA) will enable a number of precision tests of strong-field gravity theories using pulsars. The Galactic census of pulsars will discover many more relativistic pulsar systems, including pulsar – black hole binaries which can be used to test the "cosmic censorship conjecture" and the "no-hair theorem". Also, the SKA's remarkable sensitivity will vastly improve the timing precision of millisecond pulsars allowing probes of proposed deviations from general relativity (GR). Aspects of gravitation to be explored include tests of equivalence principle, gravitational dipole radiation, extra field components of gravitation and spacetime symmetries.

Radio Pulsars in the Galactic Centre

R. P. Eatough[1,*], T. J. W. Lazio[2], S. Chatterjee[3], J. M. Cordes[3], P. B. Demorest[4], M. Kramer[1], K. J. Lee[5,1], K. Liu[6], S. M. Ransom[4] and N. Wex[1]

[1] Max-Planck-Institut für Radioastronomie, Bonn, 53121, Germany
[2] Jet Propulsion Laboratory, California Institute of Technology, M/S 138-308, 4800 Oak Grove Dr, Pasadena, CA 91109, USA
[3] Department of Astronomy and Space Sciences, Cornell University, Ithaca, NY 14853, USA
[4] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, Virginia 22903, USA
[5] Kavli institute for Astronomy and Astrophysics, Peking University, Beijing 100871, P. R. China
[6] Station de radioastronomie de Nançay, Observatoire de Paris, CNRS/INSU, Université d'Orléans, F-18330 Nançay, France
[*] Presenter

E-mail contact: reatough at mpifr-bonn.mpg.de

It is now well known that radio pulsars in relativistic binary systems are exceptional tools for the study of the curved spacetime around massive compact objects. The strictest tests of gravity, in strong field conditions, are expected to come from a pulsar orbiting a black hole. In this sense, a pulsar in a close orbit ($<$ 1 yr) around our nearest supermassive black hole candidate, Sgr A* (at a distance of $\simeq$ 8.3 kpc in the Galactic Centre - GC) would be the ideal tool to probe the spacetime properties of a supermassive black hole. The relativistic effects for pulsars orbiting Sgr A* are expected to be so large, that unlike previous tests of General Relativity and alternative gravity theories, made with relativistic binary pulsars in the Galactic plane, tests involving Sgr A* do not require either millisecond pulsars with extreme timing precision, or even recycled pulsars. While pulsars in short orbits will allow tests of the cosmic censorship conjecture and the no hair theorem in General Relativity, GC pulsars at larger radii would enable determination of the smoothly distributed mass enclosed within a pulsar's orbit by the Newtonian precession induced; this mass includes both stars and dark matter. Strong constraints on the stellar density can also be placed from two-body perturbations of pulsar orbits. In addition, pulsars are superb probes of the magnetized interstellar medium in this extreme environment. We consider the variety of potentiallymeasurable effects as an embarrassment of riches!

Several lines of argument suggest that not only is there a large neutron star population in the GC, but that many of these neutron stars should be active radio pulsars. The evidence includes the stellar cluster of mainly early-type stars around the central supermassive black hole, the estimated supernova rate within 100 pc of Sgr A*,Wolf-Rayet and othermassive stars (neutron star progenitors), a number of X-ray binary systems, a pulsar wind nebula and, over the last few years, the discovery of a small number of pulsars within 15′ of Sgr A* including the recent discovery of the magnetar, PSR J1745−2900, with a projected separation of less than half a light year. For the tests of gravity described above, pulsars even closer to Sgr A* are still needed. The sensitivity of SKA1 Mid, if equipped with the Band 4 or Band 5 (or both) receivers (observing frequencies that can mitigate the extreme interstellar scattering toward the GC) is such that it would be able to detect a substantial fraction of the currently known Galactic pulsar population, even if placed at the GC.

Pulsars in Globular Clusters with the SKA

J. W. T. Hessels[1,2,*], A. Possenti[3], M. Bailes[4], C. Bassa[1], P. Freire[5], D. Lorimer[6], R. Lynch[7], S. Ransom[8], and I. Stairs[9]

[1] ASTRON, the Netherlands Institute for Radio Astronomy
[2] University of Amsterdam
[3] INAF — Osservatorio Astronomico di Cagliari
[4] Swinburne University of Technology
[5] Max Planck Institute for Radio Astronomy
[6] West Virginia University
[7] McGill University
[8] National Radio Astronomy Observatory
[9] University of British Columbia
[*] Presenter

E-mail contact: hessels at astron.nl; possenti at oa-cagliari.inaf.it

Globular clusters are highly efficient pulsar factories. These pulsars can be used as precision probes of the clusters' structure, gas content, magnetic field, and formation history; they are also sometimes highly interesting in their own right because they probe exotic stellar evolution scenarios as well as the physics of dense matter, accretion, and gravity. Deep searches with SKA1-Mid and SKA1-Low will roughly double to triple the known population (currently 144 pulsars). Such searches will only require one to a few tied-array beams and can be done during early commissioning of the telescope, before an all-sky pulsar survey using hundreds to thousands of tied-array beams is feasible. With SKA2 it will be possible to observe all active radio pulsars within a large fraction of the Galactic globular clusters, an estimated population of 600 – 3700 observable pulsars (those beamed towards us). This rivals the total population that can be found in the Galactic field; fully characterizing it will provide the best-possible physical laboratories as well as a rich dynamical history of the Galactic globular cluster system.

Probing the neutron star interior and the Equation of State of cold dense matter with the SKA

AnnaWatts[1], Renxin Xu[2,*], Cristobal Espinoza[3], Nils Andersson[4], John Antoniadis[5], Danai Antonopoulou[1], Sarah Buchner[6], Shi Dai[2], Paul Demorest[7], Paolo Freire[5], Jason Hessels[1], Jérôme Margueron[8], Micaela Oertel[9], Alessandro Patruno[10], Andrea Possenti[11], Scott Ransom[7], and Ingrid Stairs[12]

[1] Astronomical Institute, University of Amsterdam, 1090GE Amsterdam, the Netherlands
[2] School of Physics, Peking University, Beijing 100871, China
[3] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
[4] Mathematical Sciences, University of Southampton, Southampton SO17 1BJ, UK
[5] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[6] HartRAO, PO Box 443, Krugersdorp, 1740, South Africa
[7] National Radio Astronomy Observatory, 520 Edgemont Rd., Charlottesville, VA 22903-2475, USA
[8] Observatoire de Paris, Université Paris Diderot, 5 place Jules Janssen, 92195 Meudon, France
[9] Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, F-69622 Villeurbanne Cedex, France
[10] Leiden Observatory, Leiden University, PO Box 9513, 2300RA Leiden, the Netherlands
[11] Osservatorio Astronomica di Cagliari, Loc. Poggio dei Pini, Strada 54, 09012 Capoterra, Italy
[12] Department of Physics and Astronomy, University of British Columbia, BC V6T 1Z1, Canada
[*] Presenter

E-mail contact: A.L.Watts@uva.nl

With an average density higher than the nuclear density, neutron stars (NSs) provide a unique test-ground for nuclear physics and quantum chromodynamics (QCD). Inside NSs, the density of matter progressively increases up to few-times the nuclear saturation density and the state of matter changes from ions embedded in a sea of electrons at surface, through superfluid/ superconducting neutron-rich matter in the inner crust, to an as yet-poorly constrained phase in the core. Determination of the fundamental interactions that govern matter at such extreme conditions is one of the major unsolved problems of modern physics, and – since it is impossible to replicate these conditions on Earth – a major scientific motivation for SKA. Currently the most stringent observational constraints on the properties of super-dense matter come from measurements of NS bulk properties: each model for the microscopic behaviour of matter predicts a specific density-pressure relation ('Equation of state'). This generates a unique mass-radius relation which predicts a characteristic radius for a large range of masses and a maximum mass above which NSs collapse to black holes. It also uniquely predicts other bulk quantities, like maximum spin frequency, moment of inertia, binding energy and composition.

The SKA, both in Phase I, and especially in Phase II will: 1) Provide many more precise NS mass measurements, due to the exquisite timing precision enabled by its raw sensitivity. High mass neutron star measurements are particularly important as they can exclude many NS interior models. 2) Allow the measurement of the NS moment of inertia in highly relativistic binaries such as the Double Pulsar and the triple pulsar. 3) Greatly increase the number of fast-spinning NSs, with the potential discovery of spin frequencies above those allowed by some NS interior models. 4) Improve our knowledge on new classes of binary pulsars such as black widows and redbacks (which may be massive as a class) through sensitive broad-band radio observations. 5) Improve our understanding of dense matter superfluidity and the state of matter in the interior through the study of pulsar glitches.

Understanding pulsar magnetospheres

Aris Karastergiou[1,*], Simon Johnston[2], and The Pulsar Community

[1] Oxford Astrophysics, Keble Road, Oxford OX1 3RH, UK
[2] CSIRO Astronomy & Space Science, Australia Telescope National Facility, P.O. Box 76, Epping, NSW 1710, Australia
[*] Presenter

E-mail contact: aris at astro.ox.ac.uk

By significantly increasing the population of known pulsars, and observing them with very high sensitivity, the SKA will provide the data to answer some of the key questions on pulsar magnetospheres and the radio emission mechanism. In this talk, we describe the current state of our understanding of pulsar magnetospheres from a number of different observational angles. These include current understanding of the 3D structure of the radio emission beam, how different classes of pulsars differ in their magnetospheric properties, the timescales of magnetospheric phenomena and the connections to high-precision pulsar timing. We will show how key advances in the SKA compared to current instruments will improve the models to interpret pulsar emission, understand the radio emission mechanism, and aid the experiments that rely on the use of pulsars as probes.

3D Tomography of Interstellar Magnetoionic Medium

JinLin Han[1,*], W. van Straten[2], C. Sobey[3], J. Lazio[4], J. Hessels, S. Chatterjee, J. Cordes, A. Deller, P. Demorest, B. Gaensler, H. Imai, A. Karastergiou, M. Keith, M. Kramer, J.-P. Macquart, K. Lee, A. Noutsos, D. Schnitzeler

[1] National Astronomical Observatories, Chinese Academy of Sciences, Jia 20 DaTun Road, Beijing 100012, China
[2] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia
[3] Max-Planck-Institut fur Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[4] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA91106, USA
[*] Presenter

E-mail contact: hjl at nao.cas.cn

A large number ($\sim 10^4$) of pulsars discovered by the SKA1 in the near half of the Milky Way will provide a unique chance to probe the 3-D structure of interstellar medium (ISM) in our Galaxy. Sensitive VLBI observations using the phased SKA1 Mid (and SKA1 Survey) will provide precise distances of a few thousands of pulsars. Pulsars with known distances are excellent probes for the 3D tomography of electron density distribution and the magnetic field structures. Because of their compact nature and short duration radio pulses, dispersion measures and scattering measures for the widely spreaded pulsars in our Galaxy, which can be observed via wide-band observations by SKA-low and SKA-mid, can be used to construct the averaged 3-D model for electron density. The wideband polarization observations can deduce the rotation measures of these pulsars, which can reveal the structure of magnetic fields both in the Galactic disk and the Galactic halo. The turbulent random components of the interstellar medium can be revealed through the variation of these observables and the dynamic spectrum of pulsar intensity due to high velocity of pulsars. High-signal-to-noise dynamic and secondary spectra of pulsar scintillations, observed with SKA1-low and SKA1-mid, which can be used to make speckle images of the interstellar medium, provide information on turbulence in the ISM on scales between $\sim 10^8$ and 10^{13} m, and allow us to probe pulsar emission regions on scales down to $\sim$10 km. With finally SKA2, the 3D tomography of interstellar magnetoionic medium of the whole Milky Way can be obtained.

Pulsar Wind Nebulae with the SKA

Joseph D. Gelfand[1,2,*], Rene Breton[3], C.-Y. Ng[4], Jason W. T. Hessels[5,6], Mallory S. E. Roberts[1], Andrea Possenti[7]

[1] NYU Abu Dhabi, PO Box 129188, Abu Dhabi, United Arab Emirates
[2] Center for Cosmology and Particle Physics, New York University, Meyer Hall of Physics, 4 Washington Place, New York, NY, 10003
[3] School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[4] Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong
[5] ASTRON, Postbus 2, 7900 AA Dwingeloo, The Netherlands
[6] University of Amsterdam
[7] INAF - Astronomical Observatory of Cagliari, via della Scienza 5 - 09047, Selargius, Italy
[*] Presenter

E-mail contact: jg168 at nyu.edu

The bulk of a neutron star's rotational energy is believed to power a magnetized outflow of highly relativisitic particles called a "pulsar wind." In turn, the expansion of the pulsar wind into the surrounding medium creates a pulsar wind nebula (PWN). Despite decades of study, many fundamental questions about this process remain unanswered: How is the rotational energy of the neutron star converted into the pulsar wind? How are particles which comprise the pulsar wind created inside the magnetosphere of the neutron star? How does the pulsar wind affect its environment? How are particles inside a PWN accelerated to the very high energies required to explain the observed TeV emission? Are PWNe the source of the recently discovered "anomalous" population of cosmic ray electrons and positrons? As described in this talk, SKA-1 and SKA-2, can play a critical role in answering these questions, which are needed to better understand the physics of neutron stars and the interstellar medium, and many others.

The Transient Universe with the Square Kilometre Array

Rob Fender[1,*], and the Transient Working Group

[1] Oxford University, United Kingdom
[*] Presenter

E-mail contact: rob.fender at astro.ox.ac.uk

In this talk I will outline the potential for exploring extreme astrophysics via radio observations of variable and transient phenomena. I will discuss the current state of the art in our understanding of such events, our best estimates of their rates, and the yield we expect for each component of the SKA. I will furthermore stress the importance of having a flexible and responsive telescope, capable of near-real-time commensal searches and rapid robotic response, in order to maximise the scientific return.

The Unknown Unknowns

Peter N. Wilkinson[1,*]

[1] University of Manchester, Jodrell Bank Centre for Astrophysics
[*] Presenter

E-mail contact: peter.wilkinson at manchester.ac.uk

As the design and operating concepts for the SKA1 system begin to emerge, as new scientists and engineers join the SKA project and as the pressures come on to maintain costs within a chosen envelope it is worth restating and updating the rationale for the "Exploration of the Unknown" (EoU) in which transient science is likely to play a leading role. EoU must remain an active element throughout the decision making process if the SKA is to realize its full potential and leave an astounding legacy for 21st century science. The thrust of this paper is, therefore, that the current community planning and implementing SKA1 should maintain faith with the scientists of the future by ensuring that the system as a whole is prepared for the EoU. This capability will come from a holistic vision of its:

- large data collecting power, from raw sensitivity and large field-of-view plus multiple beams some of which can be dedicated to specific tasks;
- freedom to take risks, from the use of independent beams plus new time allocation paradigms;
- "human bandwidth", maximised by commensal observing, multiple independent beam capability and an in-depth data archive coupled with a coordinated strategy for the use of international Virtual Observatories and the citizens of the world.

Many of the technical requirements are incorporated in present thinking. But the system is not yet built and there is no free lunch - the flexibility required for the EoU is likely to impose an additional cost burden and hence is vulnerable. What price is reasonable? I propose that we should be prepared to build up to 10 percent less collecting area for a given overall budget in order to enhance the ways in which this area can be utilized. The penalty may be up to 20 percent longer to carry out some projects but this is a graceful degradation and the upside is opening up "opportunity space". I believe that this is likely to prove a good bargain.

The SKA view of Gamma–ray Bursts

Davide Burlon[*,1,2], Giancarlo Ghirlanda[3], Tara Murphy[1,2], Ralph Wijers[5], Alexander van der Horst[5], Gabriele Ghisellini[3], Isabella Prandoni[4], Bryan Gaensler[1,2]

[1] Sydney Institute for Astronomy, The University of Sydney, NSW 2006, Australia,
[2] ARC Centre of Excellence for All-sky Astrophysics (CAASTRO),
[3] INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate (LC) - Italy,
[4] INAF – IRA, Via P. Gobetti 101, 40129 Bologna, Italy,
[5] Astronomical Institute Anton Pannekoek, Science Park 904, PO Box 94249, NL-1090 GE Amsterdam, the Netherlands
[*] Presenter

E-mail contact: davide.burlon at sydney.edu.au

We discuss how the SKA will advance the study of GRBs at radio frequencies starting from what we have learnt in the last ten years. To this aim we will present a range of predictions on (A) the detection rate of GRBs as pointed sources by the SKA and (B) on the detection rate of orphan GRB afterglows as transients by the SKA surveys. The main topics that we propose for the chapter are:

A) The GRB population whose jets are pointing to us. These are GRBs detectable in the gamma ray band by gamma–ray detectors. The unique ability of the SKA to observe the whole GRB population will add systematically the radio observations to multi wavelength data. This approach will secure the test of the standard afterglow model and allow the study of the possible early reverse shock component, the constrain of the microphysical shock parameters, the test of jet dynamics and the circumburst environment. The sensitivity of the SKA will allow us to observe the full population of GRBs provided that a gamma–ray instrument, possibly more sensitive than Swift, will be operational in the SKA era, providing the GRB localisation. Besides the SKA will allow to study the population of optically dark GRBs, and consequently the process of star formation in optically obscured regions.

A.1) GRB calorimetry. The SKA will allow us to study the transition to the non–relativistic regime in a systematic way. This, for the first time, will enable us to perform true GRB calorimetry. The relevance of the estimate of the kinetic energy budget of the GRB is twofold. If coupled with an independently-measured jet opening angle it will bring an estimate of the radiative efficiency. If the radiative efficiency is assumed to be constrained, it would bring a measure of the true (collimation corrected) energy budget. We will study how many and which GRBs will be accessible by SKA in the non-relativistic phase and the scientific clues they can provide on the general GRB studies (e.g. jet properties, radiative efficiency, adiabatic losses, etc...).

B) Revealing the orphan afterglow population. Most GRBs do not have their jets pointing towards us. As a result they are undetectable in the gamma ray band but can be detected as so called ”orphan afterglows (OA)”. Given the typical jet opening angles of GRBs, the population of OA should outnumber the pointing GRB population by two orders of magnitude. Current searches in the X-ray, optical or radio bands have not resulted in any OA detections. Estimates of their detection rate by the SKA survey depends on the main survey parameters (sensitivity, field of view, cadence etc.). Revealing this population for the first time would allow to obtain new clues on the GRB jet structure (uniform or structured).

SKA as a powerful hunter of jetted Tidal Disruption Events

Donnarumma I.[1,*], Fender R.[2], Komossa S.[3], Paragi Z.[4], Rossi E. M.[5], and Van Velzen S.[6]

[1] INAF-IAPS, via Fosso del Cavaliere 100, 00133, Rome, Italy
[2] Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[4] Joint Institute for VLBI in Europe, Postbus 2, NL-7990 AA Dwingeloo, the Netherlands
[5] Leiden Observatory, Leiden University
[*] Presenter

E-mail contact: immacolata.donnarumma at iaps.inaf.it emr at strw.leidenuniv.nl

Observational consequences of tidal disruption of stars (TDEs) by supermassive black holes (SMBHs) can enable us to discover quiescent SMBHs and constrain their mass function. Moreover, observing jetted TDEs (from previously non-active galaxies) provides us with a new means of studying the early phases of jet formation and evolution in an otherwise “pristine” environment. Only two jetted TDEs have been recently discovered in hard X-rays, and only one, Swift J1644, has a precise localization which further supports the TDE interpretation. These events alone are not sufficient to address those science issues, which require a substantial increase of the current sample. Despite the way they were discovered, the highest discovery potential for *jetted* TDEs is not held by current and up-coming X-ray instruments, which will yield only a few to a few tens events per year. In fact, the best strategy is to use the Square Kilometer Array to detect TDEs and trigger multi-wavelength follow-ups, yielding hundreds candidates per year, up to redshift of 3. Radio and X-ray synergy, however, can in principle constrain important quantities such as the the absolute rate of jetted TDEs, their jet power, bulk Lorentz factor, the black hole mass function, and perhaps discover intermediate massive black holes (IMBHs) with $< 10^5 M_\odot$. Finally, when comparing SKA results with information from optical surveys like LSST, one can more directly constrain the efficiency of jet production.

Time domain studies of Active Galactic Nuclei: intrinsic variability and propagation effects

Hayley Bignall[1], Steve Croft[2,*], Keith Bannister[3], Talvikki Hovatta[4,5], Jun Yi Koay[6], Joseph Lazio[7], Jean-Pierre Macquart[1], Anthony Readhead[4], Cormac Reynolds[1], and Mark Walker[8]

[1] ICRAR/Curtin University
[2] University of California, Berkeley
[3] CSIRO Astronomy and Space Science
[4] California Institute of Technology
[5] Aalto University, Metsähovi Radio Observatory
[6] DARK, Niels Bohr Institute, University of Copenhagen
[7] Jet Propulsion Laboratory, California Institute of Technology
[8] Manly Astrophysics
[*] Presenter

E-mail contact: h.bignall at curtin.edu.au, scroft at astro.berkeley.edu

Variability of radio-emitting active galactic nuclei can be used to probe both intrinsic variations arising from shocks, flares, and other changes in emission from regions surrounding the central supermassive black hole, as well as extrinsic variations due to scattering by structures in our own Galaxy. Current studies have necessarily been limited to either small numbers of objects monitored over long periods of time, or large numbers of objects but with poor time sampling. The dramatic increase in survey speed engendered by SKA will enable precision synoptic monitoring studies of hundreds of thousands of sources with a cadence of days. Statistics of variability, in particular concurrent observations at multiple radio frequencies and in other bands of the electromagnetic spectrum, will probe accretion physics over a wide range of AGN classes, luminosities, and orientations, as well as enabling a detailed understanding of the Galactic interstellar medium.

Fast Transients at Cosmological Distances

Jean-Pierre Macquart[1,*], Jason Hessels[2], R.P. Fender[3], Evan Keane[4], Keith Grainge[5], Shami Chatterjee[6], Duncan Lorimer[7], Laura Spitler[8], Matthew Bailes[4], Ramesh Bhat[1], Casey Law[9], Adam Deller[2], Ben Stappers[5], René Breton[10], Eran O. Ofek[11]

[1] ICRAR/Curtin Institute of Radio Astronomy, Bentley, WA 6845, Australia
[2] ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands/University of Amsterdam
[3] University of Oxford
[4] Swinburne University of Technology
[5] University of Manchester
[6] Cornell University
[7] West Virginia University
[8] Max Planck Institute for Radio Astronomy
[9] UC Berkeley
[10] University of Southampton
[11] Weizmann Institute of Science
[*] Presenter

E-mail contact: J.Macquart at curtin.edu.au

Impulsive radio bursts that are detectable across cosmological distances constitute extremely powerful probes of the ionized Inter-Galactic Medium (IGM), intergalactic magnetic fields, and the properties of space-time itself. Their dispersion measures (DMs) will enable us to detect the "missing" baryons in the low-redshift Universe and make the first measurements of the mean galaxy halo profile, a key parameter in models of galaxy formation and feedback. Impulsive bursts can be used as cosmic rulers at redshifts exceeding 2, and constrain the dark energy equation-of-state parameter, $w(z)$ at redshifts beyond those readily accessible by Type Ia SNe. Both of these goals are realisable with a sample of $\sim 10^4$ FRBs whose positions are localized to within one arcsecond, sufficient to obtain host galaxy redshifts via optical follow-up. It is also hypothesised that gravitational wave events may emit coherent emission at frequencies probed by SKA1-Low, and the localisation of such events at cosmological distances would enable their use as cosmological standard sirens.

To perform this science, such bursts must be localized to their specific host galaxies so that their redshifts may be obtained and compared against their dispersion measures, rotation measures, and scattering properties. The SKA can achieve this with a design that has a wide field-of-view, a substantial fraction of its collecting area in a compact configuration (80% within a 3 km radius), and a capacity to attach high-time-resolution instrumentation to its signal path.

Incoherent transient radio emission fromstellar-mass compact objects

Stéphane Corbel[1,*], JamesMiller-Jones[2], Rob Fender[3], Thomas Maccarone[4], Tim O'Brien[5], Zsolt Paragi[6], Michael Rupen[7] and Patrick Woudt[8]

[1] University Paris Diderot, France
[2] ICRAR, Curtin University, Australia
[3] Oxford University, UK,
[4] Texas Tech University, USA
[5] University of Manchester, UK
[6] JIVE, Netherlands
[7] NRAO, USA,
[8] Cape Town University, South Africa.
[*] Presenter

E-mail contact: stephane.corbel at cea.fr

The universal link between the processes of accretion and ejection leads to the formation of jets and outflows around accreting compact objects. Incoherent synchrotron emission from these outflows can be observed from a wide range of accreting binaries, including black holes, neutron stars and white dwarfs. Monitoring the evolution of the radio emission during their sporadic outbursts provides important insights into the launching of jets, and, when coupled with the behaviour of the source at shorter wavelengths, probes the underlying connection with the accretion process. Radio observations can also probe the impact of jets and outflows (including other explosive events such as magnetar giant flares) on the ambient medium, allowing us to quantify their kinetic feedback.

The high sensitivity of the SKA will open up new parameter space for the study of these extreme astrophysical processes, enabling the monitoring of accreting stellar-mass compact objects from their bright, Eddington-limited outburst states down to the lowest-luminosity quiescent levels, whose intrinsic faintness has to date precluded detailed studies. By enabling us to extend our existing investigations of black hole jets to the fainter jets from neutron star and white dwarf systems, the SKA will permit comparative studies to determine the role of the compact object in jet formation. Together with the high sensitivity, the wide field of view and multi-beaming capability of the SKA will enable the detection and monitoring of all bright flaring transients in the local Universe, including the radio counterparts of ultraluminous X-ray sources (ULXs; the bright, off-nuclear X-ray sources seen in external galaxies), improving our understanding of accretion and jet ejection at the highest rates, with important implications for the growth of the first quasars.

As synchrotron events peak earlier at higher frequencies, and with higher flux densities, such studies will be best enabled by SKA1-mid, in the higher-frequency bands 4 and 5. With the high sensitivity available from SKA1-mid, we will also be able to probe quiescent black holes undergoing Bondi-Hoyle accretion from the nearby environment, both stellar-mass black holes in the field and the putative population of intermediate black holes in globular clusters. This chapter will review the science goals outlined above, demonstrating the progress that will be made by the SKA in studying incoherent synchrotron emission from accreting compact objects, also including astrometric and imaging observations from a significant VLBI component in phase 1 (and eventually phase 2) of the SKA.

Early Phase Coverage of Extragalactic and Galactic X-ray Transients with SKA and Non-Stationary Accretion Regimes

Wenfei Yu*, Hui Zhang, Zhen Yan and Wenda Zhang

Shanghai Astronomical Observatory
Chinese Academy of Sciences
80 Nandan Road, Shanghai 200030, China
* Presenter

E-mail contact: wenfei at shao.ac.cn

SKAs large field of view and high sensitivity at low frequencies provides a complete coverage of the early rising phase of any extragalactic and Galactic transients which undergoes a flare or outburst due to an abrupt accretion of matter onto either supermassive (such as tidal disruption events, TDEs) or stellar mass black holes (black hole transients) when the emission is supposed to be jet-dominated, allowing SKA to be the first to make discoveries of these transients and to send out alerts for followup ground or space observations, which would revolutionize the way of monitoring of accreting black holes and neutron stars. On the other hand, due to extremely large rate-of-change in the mass accretion rate, the e-folding rise time scales during the rising phase of the TDE flares or transient outbursts are as short as a few days or less. Then SKA will be able to cover the entire dynamic range of the mass accretion rate as well as its rate-of-change. This will shape up our understanding of disk-jet coupling in accreting black holes of diverse masses in the extreme non-stationary accretion regimes, which is not accessible in other black hole systems.

Thermal in the Time Domain: Radio Emission from Novae and Symbiotic Stars

Michael Rupen

CCSNe in the local Universe with the SKA

Pérez-Torres, M.A.[*,1,2,3] A. Alberdi[1], R. J. Beswick[4], L. Wang[5], S. Ryder[6], P. Lundqvist[7], R. Herrero-Illana[1], C. Romero-Cañizales[8], J.M. Marcaide[9], T. Murphy[10], E. Ros[11], W. Tian[5]

[1] Instituto de Astrofísica de Andalucía (IAA-CSIC), E-18008 Granada, Spain
[2] Centro de Estudios de la Física del Cosmos de Aragón (CEFCA), E-44001 Teruel, Spain
[3] Departamento de Física Teorica, Facultad de Ciencias, Universidad de Zaragoza, E-50009, Spain
[4] Jodrell Bank Centre for Astrophysics/e-MERLIN, The University of Manchester, M13 9PL, UK
[5] National Astron. Observatory of China, Chinese Academy of Sciences, Beijing 100012, China
[6] Australian Astronomical Observatory, P.O. Box 915 North Ryde NSW 1670, Australia
[7] Stockholms Observatorium, Sweden
[8] Pontificia Universidad Católica de Chile, Chile
[9] Dept. de Astronomía, Universidad de Valencia Estudi General, Burjassot, Spain
[10] The University of Sydney, 44 Rosehill Street, NSW 2006, Australia
[11] Max Planck Institut fuer Radioastronomie, Auf dem Huegel, 69, D-53121 Bonn, Germany
[*] Presenter

E-mail contact: torres at iaa.es

Systematic searches of radio emission from core-collapse supernovae (CCSNe) are still lacking, and only targeted searches of radio emission from just some of the optically discovered CCSNe in the local universe have been carried out. And this in spite of optical searches missing a significant fraction of CCSNe, largely due to dust obscuration. Therefore, radio supernova searches are much more promising for yielding the complete, unobscured star-formation rates in the local universe. The future SKA yields the possibility of obtaining a free plate in this area of research by carrying out commensal, wide-field, blind transient survey observations. This could easily result in an essentially complete census of all CCSNe in the local universe, if the area covered by such a survey is large enough, and will result in an accurate determination of the true volumetric CCSN rate, which is poorly known. While both SKA1-sur and SKA1-mid could are good strategies, the best option is likely to be that of using SKA1-sur at a frequency of $\sim$1.7 GHz, taking advantage of its good angular resolution ($\sim$1.0″), large instantaneous field-of-view ($\sim$18 deg^2), and extremely good sensitivity ($\sim$ 3.7μJy/b)). At this frequency, SKA1-sur has a survey speed about 13 times that of SKA1-mid.

Investigations of supernovae and supernova remnants in the era of SKA

Lingzhi Wang[1,*], Xiaohong Cui[1], Hui Zhu[1], Miguel Pérez Torres[2], Wenwu Tian[1], and XiaofengWang[3]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2] Instituto de Astrofisica de Andalucia (IAA-CSIC), E-18008 Granada, Spain
[3] Department of Physics, Tsinghua University, Beijing 100084, China
[*] Presenter

E-mail contact: wanglingzhi at bao.ac.cn; tww at bao.ac.cn

Supernovae are extremely luminous and can outshine an entire galaxy within period of days. Two main physical mechanisms are used to explain supernova explosion: thermonuclear explosion of a white dwarf (Type Ia) and core collapse of a massive star (Type II and Type Ib/Ic). Type Ia supernovae are taken as distance indicator to discover the accelerating expansion of the Universe. Their progenitor system is still an embarrassment so far. Radio emission from the interaction between explosion front shock and its surrounding circumstellar medium (CSM) or interstellar medium (ISM) provides an important probe to see Ia SNe's last evolution stage. No radio emission was detected from Type Ia supernovae by current telescopes. SKA will hopefully detect radio emissions of Type Ia supernovae due to its much better sensitivity and resolution.

There is a 'supernovae rate problem' for the core collapse supernovae because the optically dim ones are missing due to intrinsically faint or due to dust obscuration. A number dust-enshrouded optically hidden supernovae will be discovered via SKA1-mid/survey, especially for those located in the innermost regions of host galaxies. Meanwhile, the detection of intrinsically dim ones will also benefit from SKA1. The detection rate will provide unique information about the current star formation rate and the initial mass function.

Supernova explosion triggers shock wave which expels and heats the surrounding CSM and ISM, so forms supernova remnant (SNR). It is expected that more SNRs will be discovered by the SKA.

This may decrease the great number discrepancy between the expected and observed. Several Supernova remnants have been confirmed to accelerate protons, main component of cosmic rays, to very high energy by their shocks. This brings us a hope to solve the cosmic ray origin's puzzle by combining the low frequency (SKA) and very high frequency (Cherenkov Telescope Array: CTA) bands' observations to SNRs.

Continuum Science with the SKA: An Overview

Isabella Prandoni[1,*], Nicholas Seymour[2]

[1] INAF - IRA, Via P. Gobetti 101, 40129 Bologna (Italy)
[2] CSIRO Astronomy & Space Science
[*] Presenter

E-mail contact: prandoni at ira.inaf.it

In this chapter we provide a general overview of the various science cases enabled by radio continuum surveys in the SKA era, highlighting the most relevant ones in the > 2020 scientific framework. We outline a number of general reference radio-continuum surveys for SKA1 that can in principle address such topics, and indicate potential scientific perspectives of SKA2 continuum surveys. Existing synergies and commensalities with surveys addressing other science areas (HI, magnetism, cosmology) are also briefly outlined. A comprehensive discussion of the most critical science requirements that we have identified for the SKA is presented, where we highlight what should be achieved by SKA1, to guarantee a major leap forwards with respect to the pre-SKA era, considering the science advances expected in the coming years with existing and upcoming telescopes (JVLA, LOFAR, MWA, eMERLIN, and two of the SKA precursors: ASKAP and MeerKAT). This chapter builds upon the work of the SKA Continuum Science Working Group, in consultation with a wider expert community. Each science topics is separately discussed in more detail in dedicated chapters.

Tracing star-formation activity over cosmic time with the SKA

Nick Seymour[1,*], Matt Jarvis[2], on behalf of the Continuum SWG

[1] CSIRO Astronomy & Space Science
[2] University of Oxford/University of the Western Cape
[*] Presenter

E-mail contact: nicholas.seymour at csiro.au

The radio continuum emission from star-forming galaxies provides an unbiased view of the total star formation rate in galaxies, free of dust obscuration. We present an overview of the measurements that will be possible in determining the star-formation history of the Universe with the SKA continuum surveys. We will also discuss the key multi-wavelength data that will be need for a complete picture of star-formation in the Universe.

The Astrophysics of Star Formation across Cosmic Time at $\gtrsim$10 GHz with the Square Kilometre Array

Eric J. Murphy[1], Mark T. Sargent[2,*], and the Continuum Science WorkingGroup

[1] IPAC, Caltech, MC 220-6, Pasadena CA, 91125, USA
[2] Astronomy Centre, Dept. of Physics & Astronomy, University of Sussex, Brighton BN1 9QH, UK
[*] Presenter

E-mail contact: emurphy at ipac.caltech.edu, Mark.Sargent at sussex.ac.uk

We highlight a number of science investigations that are enabled by the inclusion of Band 5 during SKA_1 science operations, while focusing on the astrophysics of star formation over cosmic time. For studying the detailed astrophysics of star formation at high-redshift, surveys at $\gtrsim$10 GHz have the distinct advantage over traditional $\sim$1.4 GHz surveys as they are able to yield higher angular resolution imaging while probing higher rest frame frequencies of galaxies with increasing redshift, where emission of star-forming galaxies becomes dominated by thermal (free-free) radiation. In doing so, surveys carried out at $\gtrsim$10 GHz provide a robust, dust-unbiased measurement of the rate of formation of massive stars by being highly sensitive to the number of ionizing photons that are produced. To access this powerful star formation rate diagnostic requires that Band 5 (4.6 – 13.8 GHz) be available during SKA_1. Furthermore, by being in the Faraday-thin regime, observations at $\gtrsim$10 GHz allow for a clear view of the intrinsic polarization properties for detailed exploration of the internal physics, magnetic fields, and thermal plasma environments of AGN cores. We additionally present a detailed science case for frequency coverage extending up to 30 GHz during SKA_2 operations, as this allows for highly diverse science while additionally providing contiguous frequency coverage between the SKA and ALMA. For instance, this spectral window opens up the possibility for investigations of the star formation law, which relates the star formation rate and gas surfaces densities in galaxies, by providing access to the low-J rotational lines of CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ for galaxies in the redshift range of z = 2.8 – 10.5. Such a capability will be highly synergistic with ALMA observations that map out the peak of the dust emission for galaxies in a similar redshift range. To enable this synergy, it is crucial that the dish design of the SKA be flexible enough to include the possibility of being fit with receivers operating up to 30 GHz.

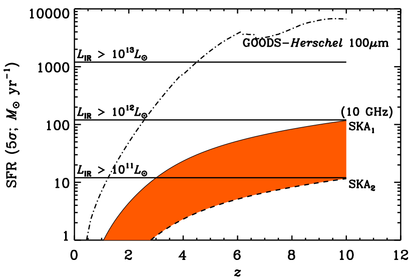


Figure 1: The expected 10 GHz selection function (5 σ) for unresolved star-forming galaxies after a 300 hr observations with SKA_1-MID and SKA_2-MID given in units of star formation rate. Even with SKA_1, surveys should be nearly 2 orders of magnitude more sensitive than the deepest space-based far-infrared survey data at $z \gtrsim 4$, providing the most sensitive observations to obscured star formation at high redshifts and thereby opening up a completely new observational parameter space.

SKA studies of nearby galaxies: star-formation, accretion processes and molecular gas across all environments

R. J. Beswick[1*], M. A. Perez-Torres[2], E. Brinks[3] S. Aalto[4], A. Alberdi[2], M. K. Argo[1], J. E. Conway[4], C. Dickinson[1] D. M. Fenech[5], M. D. Gray[1], H-R Klöckner[6], E. Murphy[7], T. W. B. Muxlow[1], A. M. S. Richards[1], E. Schinnerer[8]

[1] Jodrell Bank Centre for Astrophysics/e-MERLIN, The University of Manchester, M13 9PL, UK
[2] Instituto de Astrofisica de Andalucia (IAA-CSIC), E-18008 Granada, Spain
[3] Centre for Astrophysics Research, University of Hertfordshire, AL10 9AB, UK
[4] Onsala Space Observatory, SE-439 92, Onsala, Sweden
[5] Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK
[6] Max-Planck-Institut für Radioasronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[7] IPAC, Caltech, MC 220-6, Pasadena CA, 91125, USA
[8] Max-Planck-Institut für Astronomie, K¨onigstuhl 17, D-69117, Heidelberg, Germany
[*] Presenter

E-mail contact: Robert.Beswick at manchester.ac.uk

The SKA will be a transformational instrument in the study of our local Universe. In particular, via its high sensitivity (point sources and surface brightness) and the angular resolution and frequency ranges covered, the SKA will undertake a very wide range of astrophysical research in the field of nearby galaxies. In this chapter we present a range of key continuum and molecular line science projects that can be undertaken initially with SKA phase-1 and which will be significantly extended with SKA phase-2. In particular we will show that the SKA will significant impact on our understanding of star-formation within local galaxies of all types and within all environments, probe accretion physics on a wide range of mass scales, and provide a unique probe of the cold molecular gas that fuels this activity. With such observations of large samples of nearby galaxies the SKA will have a large impact on our global understanding of galaxy evolution as a whole, and provide a local benchmark for studies of galaxies at high redshift.

The Interplay between SF and AGN Activity and its role in Galaxy Evolution

Kim McAlpine*[1], Isabella Prandoni[2], Matt Jarvis[3], Nick Seymour[4], Paolo Padovani[5], Philip Best[6], Chris Simpson[7], Daria Guidetti[2], Eric Murphy[8], Min Huyhn[9], Mattia Vaccari[1], Sarah White[3], Rob Beswick[10], Jose AFonso[11], Manuela Magliocchetti[12] and Marco Bondi[2]

[1] University of the Western Cape, Robert Sobukwe Road, Bellville
[2] INAF - Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
[3] Oxford University, Astrophysics, Department of Physics, Keble Road, Oxford OX1 3RH
[4] CSIRO Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia
[5] ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching bei Mnchen, Germany
[6] Institute for Astronomy, University of Edinburgh, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ
[7] Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD
[8] California Institute of Technology, IPAC, MC 220-6, Pasadena, CA 91125, USA
[9] ICRAR - University of Western Australia, M468, 35 Stirling Hwy, Crawley WA 6009, Australia
[10] University of Manchester, Macclesfield, Cheshire, SK11 9DL
[11] Centre for Astronomy and Astrophysics, University of Lisbon, Tapada da Ajuda, 1349-018 Lisbon, Portugal
[12] INAF-IAPS, Via Fosso del Cavaliere 100, I-00133 Roma, Italy
* Presenter

E-mail contact: kim.mcalpine at gmail.com

It has become apparent that active galactic nuclei (AGN) may have a significant impact on the growth and evolution of their host galaxies and vice versa. The existence of tight correlations between the mass of the central super-massive black hole and the mass and velocity dispersion of the galaxy stellar bulge (e.g. Magorrian et al. 1998; Tremaine et al. 2002) is strongly suggestive of a link between star-formation and accretion activity. While theoretical models of galaxy evolution suggest that AGN 'feedback' is required in order to reproduce the size distribution and star-formation properties of observed galaxies in the universe (e.g. Bower et al. 2006; Croton et al. 2006). Yet a detailed understanding of the interplay between these processes is lacking.

Deep radio surveys provide a powerful, obscuration-independent tool for measuring both star formation and AGN activity in high-redshift galaxies. Multi-wavelength studies of deep radio fields show a composite population of star-forming galaxies and AGN (e.g. Prandoni et al. 2001; Afonso et al. 2006; Simpson et al. 2006; Padovani et al. 2009; Seymour et al. 2008; Smolcic et al. 2008), with the former dominating at the lowest flux densities (S<50–100 μJy). The sensitivity and resolution of the SKA will allow us to identify and separately trace the total star formation in the bulges of individual high-redshift galaxies, the related nuclear activity and any star formation occurring on larger scales within a disc. Thus providing a detailed picture of the apparently simultaneous development of stellar populations and black holes in the redshift range where both star-formation and AGN activity peak ($1 \lesssim z \lesssim 3$). In this chapter we will address the role of the SKA in studying the connection between AGN activity and galaxy evolution, and the most critical technical requirements for such of studies.

Radio Observations of Star Forming Galaxies

Claudia Mancuso[1,*], Andrea Lapi[1,2], Zhen-Yi Cai[3], Gianfranco De Zotti[1,4], Francesca Perrotta[1], Mattia Negrello[4], Luigi Danese[1]

[1] Astrophysics Sector, SISSA, Via Bonomea 265, I-34136 Trieste, Italy
[2] Dipartimento di Fisica, Università 'Tor Vergata', Via della Ricerca Scientifica 1, I-00133 Roma, Italy
[3] Center for Astrophysics, University of Science and Technology of China, Hefei, 230026, China
[4] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[*] Presenter

E-mail contact: cmancuso at sissa.it

We have combined determinations of the epoch-dependent star formation rate (SFR) function with relationship between SFR and radio (synchrotron and free-free) emission to work out detailed predictions for the counts of star-forming galaxies expected from the Square Kilometer Array (SKA) and its precursors. To this end we have exploited recent models fitting the far-infrared (FIR) to millimeter wave luminosity functions and ultraviolet (UV) luminosity functions up to high redshifts, and extended them to take into account additional UV data as well as estimates of Hα luminosity functions at different redshifts. The very deep 1.4 GHz counts were utilized to test the relationship between SFR and synchrotron emission, while that between the SFR and the free-free emission was tested against the 95 GHz South Pole Telescope (SPT) counts of dusty galaxies. In doing that we have found that the SPT counts of dusty galaxies are overestimated by a factor $\simeq 3$. The model was exploited to predict multi-frequency radio counts of star-forming galaxies down to nJy flux densities and redshift distributions for surveys planned with the SKA and its precursors. We show that the SKA will allow us to investigate the SFRs of galaxies down to tens of $M_\odot$/yr up to the highest redshifts, thus extending by up to two orders of magnitude the high-zz SFR functions derived from Herschel surveys. We also argue that 1.5–2% of faint galaxies that will be detected by the SKA are strongly lensed and compute the counts of those for which the SKA will detect at least two images.

AGN Activity over Cosmic Time

Vernesa Smolčić[1], Paolo Padovani[2], Jacinta Delhaize[1], Isabella Prandoni[3], Nicholas Seymour[4], Matt Jarvis[5], Jose Afonso[6], Manuela Magliocchetti[7], Minh Huynh[8], Mattia Vaccari[9]

[1] University of Zagreb, Croatia
[2] ESO
[3] IRA-INAF, Italy
[4] CSIRO/CASS, Australia
[5] Oxford University / University of the Western Cape
[6] Centre for Astronomy and Astrophysics - University of Lisbon
[7] IAPS/INAF
[8] ICRAR/UWA
[9] University of the Western Cape (RSA)
[*] Presenter

E-mail contact: vs at phy.hr

Galaxies are thought to evolve over time from an initial stage of blue star forming galaxies with spiralmorphology towards quiescent red galaxies with spheroidalmorphologies and the highest stellar masses. A galaxy evolves through interspersed episodes of intensive mass accretion onto the stellar body as well as the central massive BHs, creating a powerful AGN. This is consistent with the Λ-CDM paradigm, in which structure in the universe grows hierarchically in such a way that small structures evolve into larger ones. In this context, faint radio AGN ($L_{1.4GHz} < 10^{25}$ W/Hz) remain puzzling. They are found in red, passive galaxies, that would not be identified as AGN at any other wavelength, and they do not seem to fit into the Unified Model for AGN. They often reside at the bottom of the galaxy cluster/group potential wells, and their radio-bright outflows heat the intra-cluster/group gas and the hot gas halo of the host galaxy. This heating, deemed crucial in cosmological models of galaxy formation, is termed feedback, however both on group/cluster and galaxy scales it is still poorly understood. In the context of the most powerful AGN, Type 1 (broad line) AGN (quasars) experience the most intense SMBH (super-massive black hole) growth and are thought to possibly quench their galactic star formation by expelling the interstellar gas in quasar winds (so called 'quasar mode AGN feedback'). The existence of two physically distinct, radio-loud and radio-quiet quasar populations is a long debated issue that has far-reaching implications for astrophysical models, including unified models for AGN and the evolution of star formation. Although the quasar radio-loudness distribution has been carefully studied in many different quasar samples over the past decades, there is still no definite understanding or consensus. The bimodality could imply two physically distinct types of quasars (pointing to e.g. different SMBH accretion/spin mechanisms, physically different source of synchrotron emission) or be due to differing geometries.

In this talk the motivation for undertaking the Wide and Deep SKA surveys in the context of studying AGN activity across cosmic time will be summarized. With an rms of down to 2 μJy/beam at 1.4 GHz over 5,000 square degrees in 1year (Wide) and rms down to 200 nJy/beam over 30 square degrees in 2000 hours (Deep), they will directly detect faint radio-loud and radio-quiet AGN (down to a 1.4 GHz radio luminosity of about 2×10^{23} W/Hz at $z = 6$). For the first time, this will enable us to conduct detailed studies of the cosmic evolution of radio AGN activity to the cosmic dawn ($z \gtrsim 6$).

Unravelling the lifecycles of radio-loud AGN

Anna Kapińska[1,2,*] and Carole Jackson[3]

[1] ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO)
[2] ICRAR, The University of Western Australia, M468, 35 Stirling Hwy, Crawley 6009, Australia
[3] ICRAR, Curtin University, GPO Box U1987, Perth 6845, Australia
[*] Presenter

E-mail contact: anna.kapinska at uwa.edu.au; carole.jackson at curtin.edu.aui

The SKA will probe the entire extragalactic radio source population, detecting sources across the whole range in radio-AGN luminosity, at all redshifts and over a wide range of observing frequencies. The unprecedented sensitivity of the SKA coupled with its wide field of view capabilities will allow identification of objects of the same morphological type, e.g. classical FRI and FRII galaxies, disturbed morphologies, as well as weak radio-emitting AGN populations, whilst also revealing the evolution-age relationships, i.e. from the youngest CSS/GPS sources to giant and fading (dying), through to those with restarted activity. Critically, the wide frequency coverage of the SKA will permit analysis of same-epoch rest-frame radio properties, and the sample sensitivity and resolution must permit full cross-identification with multi-waveband data (including potentially SKA-deteced HI emission and absorption) further revealing insights into the physical processes driving the evolution of these populations.

In this chapter we discuss the best parameters for the proposed SKA continuum surveys for radio-loud AGN lifecycle studies. We also discuss how the known bias in the radio source populations' distributions can be explored to reduce, or perhaps even overcome, effects of cosmic variance.

Identifying the first generation of Radio Loud AGN in the Universe

Jose Afonso[1,2,*], Jordi Casanellas[3], Isabella Prandoni[4], Matt Jarvis[5], Manuela Magliocchetti[6] and Nick Seymour[7]

[1] Centre for Astronomy and Astrophysics of the University of Lisbon and Faculty of Sciences of the University of Lisbon, OAL, Tapada da Ajuda, 1349-018, Portugal
[3] Max Planck Institut fur Gravitationsphysik (Albert-Einstein-Institut), D-14476 Potsdam, Germany
[4] IRA-INAF, Via P. Gobetti 101, Bologna, Italy
[5] Astrophysics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK
[6] IAPS-INAF, Via Fosso del Cavaliere 100, 00133 Roma, Italy
[7] CSIRO Astronomy & Space Science, PO Box 76, Epping, NSW 1710, Australia
[*] Presenter

E-mail contact: jafonso at oal.ul.pt

One of the most challenging and exciting subjects in modern astrophysics is that of galaxy formation at the epoch of reionization. Of particular relevance for the SKA capabilities is the detection of the onset and earliest evolution of the AGN phenomenon in the Universe. Amongst the most luminous galaxies at any redshift and any wavelength, powerful radio AGN are relatively easy to find over the last 12 Gyr of Universe history. In particular, the last three decades of radio observations have been particularly effective in tracking much of what is currently known about AGN evolution. The study of the powerful sources revealed by large radio surveys has been fundamental to understand galaxy evolution, as an AGN is capable of completely determining the characteristics of its host galaxy and influencing even its extragalactic environment.

The existence of AGN has now been established well within the first Gyr of the Universe, through the observations of tens of QSOs up to the currently highest redshift of $z{\sim}7$, many of them exhibiting strong radio emission. Driven by these observations, theoretical work has shown that the rapid growth of a super-massive black hole up to a mass of $10^9 M_\odot$ as displayed by many of the detected sources, is indeed possible within just a few hundred Myr, depending on a still indeterminate initial black hole seed. These results imply that very high redshift ($z > 7$) radio loud sources are expected, but have so far escaped detection. By achieving a much higher sensitivity over very large survey areas, SKA (already from its phase 1) will be able to reach well into the epoch of formation of the earliest AGN. Besides the immediate interest for galaxy evolution, the successful detection of a bright radio loud AGN at very high redshifts would allow for the direct study of neutral hydrogen in the Epoch of Reionization, through observations of the HI 21cm forest against such a background source.

In order to understand how SKA and SKA1 observations can be optimised to reveal these earliest AGN, we have examined the effect of a hot CMB on the emission of powerful and young radio galaxies. By looking at the SKA1 capabilities we determine how the effects of "CMB-muting" of a radio loud source can be observationally minimised and how to identify the best highest-redshift radio candidates. Considering different predictions for the space density of radio loud AGN at such redshifts, we identify the survey characteristics necessary to optimize the detection and identification of the very first generation of radio loud AGN in the Universe.

The birth, life and death of radio galaxies

Martin J. Hardcastle[1]
[1] School of Physics, Astronomy and Mathematics, University of Hertfordshire
E-mail contact: m.j.hardcastle at herts.ac.uk

Radio-loud AGN will be the dominant bright source population detected with the SKA at all wavelengths, and the high resolution that it will provide even in wide-area surveys will mean that, for the first time sensitive, high-resolution, multi-frequency total intensity and polarization imaging of large samples of powerful radio-loud AGN will become available. Coupled with all-sky optical surveys for identification and redshift measurements, this will enable studies of all phases of their evolution, from their birth at small physical sizes and low radio luminosities, though the peak of their synchrotron luminosity on physical sizes of tens to hundreds of kpc, to their post-jet existence as radio relics. The focus will move from studies of individual objects or small samples to the physics of the population as a whole. Among other key points, we emphasise that our developing understanding of the dynamics and the spectral/polarization evolution of radio-loud AGN means that it will be possible, with the combination of radio observations provided by the SKA, to make relatively accurate estimates of the kinetic luminosity function of the AGN and their environmental properties from radio observations alone. The new science enabled by SKA is likely to be very important for our understanding of the radio-loud AGN population (which currently lags significantly behind that of radio-quiet objects) and for models of galaxy formation and evolution that rely on feedback processes from radio-loud objects.

The physics of the radio emission in the quiet side of the AGN population

M. Orienti[1,*], F. D'Ammando[2,1], M. Girolett[i1], G. Giovannini[2], F. Panessa[3]

[1] INAF –IRA, Bologna, Italy
[2] University of Bologna, Department of Physics and Astronomy, Bologna, Italy
[3] INAF – IAPS, Roma, Italy
[*] Presenter

E-mail contact: orienti at ira.inaf.it

Super massive black holes (SMBH) are thought to be ubiquitously hosted in massive galaxies. They may be either quiescent, like the case of SgrA* in our Galaxy, or active, and they are at the basis of the phenomenon known as Active Galactic Nucleus (AGN). In this case they manifest their presence by releasing a huge amount of energy overwhelming the star-related contribution of the entire host galaxy. Despite targets of many multiwavelength campaigns, the main physical processes at work in AGN are still under debate. In particular the origin of the radio emission and the mechanisms involved are among the open questions in astrophysics. The radio-loud AGN population and their radio emission is linked to the presence of bipolar outflows of relativistic jets. However, the large majority of the AGN population do not form relativistic jets. This does not mean that they are radiosilent objects. On the contrary, these systems are characterized by radio luminosity up to 10^{23} W/Hz at 1.4 GHz, challenging our knowledge on the physical processes at the basis of the radio emission in radio-quiet objects. The main mechanisms proposed so far are synchrotron radiation from mildly relativistic mini-jets, thermal cyclo-synchrotron emission by low-efficient accretion flow (like ADAF or ADIOS), or thermal free-free emission from the X-ray heated corona or wind. The difficulty in understanding the main mechanism involved is related to the weakness of these objects, which precludes the study of non-local radio-quiet AGN. Multifrequency, high-sensitivity polarimetric radio observations are, thus, crucial to constrain the nature of the power engine, and they may help in distinguishing between the contribution from star formation and AGN activity. The advent of the Square Kilometer Array (SKA), with its sub-arcsecond resolution and the unprecedented sensitivity will allow us to investigate these processes in radio-quiet AGN, even at high redshift for the first time. Both the polarization and the spectral index information will help us in disentangling between non-thermal and thermal origin of the radio emission. The jump in sensitivity of a few order of magnitudes at the (sub-)μJy level will enable us to detect radio emission from a large number of radio-quiet AGN, providing a fundamental step in our understanding of their cosmological evolution.

Strong Gravitational Lensing with the SKA

J. P. McKean[1,2,*], N. Jackson[3], S. Vegetti[4], M. Rybak[4], L. V. E. Koopmans[2], S. Serjeant[5], C. D. Fassnacht[6], P. J. Marshall[7], R. B. Metcalf[8], and M. Pandey-Pommier[9]

[1] Netherlands Institute for Radio Astronomy (ASTRON), P.O. Box 2, 7990 AA Dwingeloo, The Netherlands
[2] Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands
[3] Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Turing Building, Oxford Road, Manchester M13 9PL, United Kingdom
[4] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, D-85740 Garching, Germany
[5] Department of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, United Kingdom
[6] Department of Physics, University of California Davis, 1 Shields Avenue, Davis, CA 95616, USA
[7] Kavli Institute for Particle Astrophysics and Cosmology, P.O. Box 20450, MS29, Stanford, CA 94309, USA
[8] Alma Mater Studiorum Universit di Bologna, via Ranzani 1, 40127 Bologna, Italy
[9] Universit Lyon 1, Observatoire de Lyon, 9 avenue Charles Andr, 69230, Saint-Genis Laval, France
[*] Presenter

E-mail contact: mckean at astron.nl

Strong gravitational lenses provide an important tool to measure masses in the distant Universe, thus testing models for galaxy formation and dark matter; to investigate structure at the Epoch of Reionization; and to measure the Hubble constant and possibly w as a function of redshift. However, the limiting factor in all of these studies has been the currently small samples ($\sim 10^2$). The era of the SKA will transform our understanding of the Universe with gravitational lensing, particularly at radio wavelengths where the number of known gravitational lenses will increase to $\sim 10^4$. Here we discuss the technical requirements, expected outcomes and main scientific goals of a large area, subarcsecond angular resolution survey for strong gravitational lensing with the SKA phases 1 and 2. We first review past searches for gravitational lenses at radio wavelengths (e.g. MG, JVAS, CLASS), placing them in context with current surveys at radio and other wavelengths, before discussing the expectations (and synergies) that are envisaged with the next generation of large synoptic facilities (e.g. Eculid, LSST). We present calculations for the expected number of gravitationally lensed radio sources that can potentially be found, using the best estimates for the parent population luminosity function, together with imaging simulations to determine what fraction will be identifiable given various angular resolution (0.3–2 arcsec), frequency (1–3 GHz) and sensitivity (2–10 μJy beam^{-1} rms) constraints. We discuss methods for modelling large samples of gravitational lenses, which is important for both confirming the lensing nature of the candidates and for using the sample for scientific studies. Finally, we discuss the unique scientific questions that can addressed with the sample of radio-loud gravitational lenses that will be found with the SKA phases 1 and 2.

The SKA Mid-frequency All-sky Continuum Survey

Ray Norris[1,*], David Bacon[2], Kaustuv Basu[3], Ettore Carretti[1], Bryan Gaensler[4], Ian Heywood[1], Naomi McClure-Griffiths[1], Isabella Prandoni[5], Larry Rudnick[6], Mario Santos[7], Nick Seymour[1]

[1] CSIRO Astronomy & Space Science, PO Box 76, Epping, NSW 1710, Australia,
[2] Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, UK
[3] University of Bonn, Bonn, Germany
[4] Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
[5] INAF-IRA, Via P. Gobetti 101, 40129 Bologna, Italy
[6] Department of Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455, USA
[7] CENTRA, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[*] Presenter

E-mail contact: Ray.Norris at csiro.au

We show that, in addition to the specific SKA science goals, there is a strong case for conducting an all-sky SKA continuum survey which does not fit neatly into conventional science cases. Specifically, the SKA All-Sky continuum Survey is likely to achieve transformational science in two specific respects (a) Discovering the unexpected, (b)Transforming radio-astronomy from niche to mainstream by providing radio data on most galaxies found in optical surveys.

The greatest scientific discoveries of most major telescopes (e.g. HST) are not in the science goals written to justify the construction of the telescope. This need not be a random and haphazard process, but instead the telescope can be designed to maximise the likely scientific productivity of the telescope from discovering the unexpected, in addition to achieving the specific science goals. SKA1 will open up a large area of virgin parameter space, and should plan for unexpected discoveries. We cannot rely on serendipity, because of the large data volumes, and the complexity of the instrument, but should plan to systematically mine the data for the unexpected.

Photometric redshifts and SED fitting of spectral energy distributions have traditionally used only optical- infrared data, primarily because previous radio surveys were not sufficiently sensitive to detect most galaxies. Instead they were dominated by radio-loud AGN, and only the nearest star-forming galaxies were detected, The sensitivity of the SKA all-sky survey will mean that almost every galaxy found in optical and infrared surveys will have measured radio photometry (together with spectral shape and polarisation in many cases), which will become an indispensable part of every fitted SED or photo-z measurement. Surveying the entire sky will transform radio-astronomy from a niche science to an important part of the armoury of every astronomer.

In addition, we show that specific science areas greatly benefit from an all-sky survey:
Cosmology
Large-scale structure and cluster science
Understanding galaxy evolution
The Magnetic Sky
Nearby Galaxies
The variable and transient sky

Cluster Radio Halos at the crossroads between astrophysics and cosmology in the SKA era

R. Cassano[1,*], G. Bernardi[2], G. Brunetti[1], M. Brüggen[3], T. Clarke[4], D. Dallacasa[5,1], K. Dolag[6], S. Ettori[7], S. Giacintucci[8], C. Giocoli[5], M. Gitti[5,1], M. Johnston-Hollitt[9], R. Kale[1], M. Markevitch[10], R. Norris[11], M. Pandey-Pommier[12], G. Pratt[13], H. Röttgering[14], T. Venturi[1]

[1] INAF-Istituto di Radioastronomia, Italy
[2] SKA Africa, Rhodes University, South Africa
[3] University of Hamburg, Germany
[4] Naval Research Laboratory, US
[5] Bologna University, DIFA, Italy
[6] Universitäts-Sternwarte München, Germany
[7] INAF- Osservatorio Astronomico di Bologna, Italy
[8] University of Maryland, US
[9] Victoria University of Wellington, Australia
[10] NASA/GSFC, US
[11] CSIRO Astronomy & Space Science, Australia
[12] Centre de Recherche Astrophysique de Lyon, Observatoire de Lyon, France
[13] CEA Saclay - IRFU, France
[14] Leiden Observatory, Universiteit Leiden, The Netherlands
[*] Presenter

E-mail contact: rcassano at ira.inaf.it

Giant Radio Halos (RHs) are diffuse, Mpc-sized, synchrotron radio sources with steep radio spectra that are observed in the central regions of a fraction of galaxy clusters. RHs are always found in merging clusters, suggesting that they prove the dissipation of gravitational energy during the hierarchical mergers that leads to the formation of clusters themselves. The current leading scenario for the origin of giant RHs is based on the hypothesis that turbulence generated during mergers re-accelerates pre-existing electrons in the intra-cluster-medium (ICM) to the energies necessary to produce the observed radio emission. On the other hand, more relaxed clusters could host diffuse radio sources, called "off state" halos, fainter than classical RHs, and produced by secondary particles due to inelastic collisions between relativistic and thermal protons in the ICM. In this Chapter we will use Monte Carlo simulations, that combine turbulent-acceleration physics and the generation of secondaries in the ICM, to calculate the occurrence of RHs in the Universe, their spectral properties and connection with thermodynamical properties and mass of the hosting clusters at different cosmic epochs. Predictions for SKA1 surveys are presented at low (100-300 MHz) and mid (1-2 GHz) frequencies assuming the expected sensitivities and spatial resolutions of SKA1. SKA1 will step into an unexplored territory allowing us to study the formation and evolution of RH in a totally new range of cluster masses (down to $\sim 10^{14} M_\odot$) and redshift (up to ~ 1). Based on our study SKA1 observations will allow firm tests of the current theoretical hypothesis, in particular we show that the combination of SKA1 low and survey will allow the discovery of $\sim$ 500 ultra-steep-spectrum halos and to detect for the very first time "off state" halos. We expect that at least $\sim$ 1500 giant RHs will be discovered by SKA1-low surveys up to $z \sim 0.6$. SKA1 surveys will be highly competitive with present and future SZ-surveys in the detection of high-redshift massive objects.

Non-thermal emission from galaxy clusters: feasibility study with SKA1

Chiara Ferrari[1,*], Arwa Dabbech[1], Oleg Smirnov[2,3], Sphesihle Makhathini[2], Jonathan S. Kenyon[2], Matteo Murgia[4], Federica Govoni[4], David Mary[1], Eric Slezak[1], Franco Vazza[5], Annalisa Bonafede[5], Marcus Brüggen5, Melanie Johnston-Hollitt[6], Siamak Dehghan[6], Luigina Feretti[7], Gabriele Giovannini[7,8], Valentina Vacca[9], Michael Wise[10], Myriam Gitti[7,8], Monique Arnaud[11], Gabriel Pratt[11], Kristian Zarb Adami[12,13] and Sergio Colafrancesco[14]

[1] Laboratoire Lagrange, UMR 7293, Universit´e de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, 06300 Nice (FR)
[2] Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown, 6140
[3] SKA South Africa, 3rd Floor, The Park, Park Road, Pinelands, 7405 (ZA)
[4] INAF - Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047 Selargius (IT)
[5] Universität Hamburg, Hamburger Sternwarte, Gojenbergsweg 112, D-21029, Hamburg (DE)
[6] School of Chemical & Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington, 6140 (NZ)
[7] INAF – Istituto di Radioastronomia, Via Gobetti 101, I–40129 Bologna (IT)
[8] Dipartimento di Fisica e Astronomia, Università di Bologna, Via Ranzani 1, I–40127 Bologna (IT)
[9] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85748 Garching (DE)
[10] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo (NL)
[11] Laboratoire AIM, IRFU/Service d'Astrophysique – CEA F–91191 Gif-sur-Yvette Cedex (FR)
[12] Physics Department, University of Malta, Msida, MSD 2080 (MT)
[13] Physics Department, University of Oxford, Oxford, OX1 3RH (UK)
[14] School of Physics, University of the Witwatersrand, Private Bag 3, 2050-Johannesburg (ZA)
[*] Presenter

E-mail contact: chiara.ferrari at oca.eu

Galaxy clusters are known to host a variety of diffuse and extended radio sources: tailed radio galaxies whose shape is modelled by the interaction with the intra-cluster medium (ICM); radio bubbles filling cavities in the ICM distribution and rising buoyantly through the thermal gas; diffuse giant radio sources ("halos" and "relics") revealing the presence of relativistic electrons and magnetic fields in the intra-cluster volume. It is currently the subject of an active debate how the non-thermal components that we observe at radio wavelengths affect the evolutionary physics of galaxy clusters.

In this work we start our SKA1 feasibility study of the "radio cluster zoo" through simulations of a typical radio-loud cluster, hosting several bright tailed radio galaxies and a diffuse radio halo. Realistic simulations of SKA1 observations are obtained through the MeqTrees software. A new deconvolution algorithm, based on sparse representations and optimised for the detection of faint diffuse astronomical sources, is tested and compared to the classical CLEAN method.

The SKA view of cool-core clusters: evolution of radio mini-halos and AGN feedback

Myriam Gitti[1,2,*], Paolo Tozzi[3], Gianfranco Brunetti[2], Rossella Cassano[2], Stefano Ettori[4], Daniele Dallacasa[1,2], Luigina Feretti[2], Chiara Ferrari[5], Simona Giacintucci[6,7], Gabriele Giovannini[1,2], and Tiziana Venturi[2]

[1] Dipartimento di Fisica e Astronomia - Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy
[2] INAF - Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
[3] INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
[4] INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
[5] Laboratoire Lagrange, UMR 7293, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte dAzur, 06300 Nice (FR)
[6] Department of Astronomy, University of Maryland, College Park, MD 20742, USA
[7] Joint Space-Science Institute, University of Maryland, College Park, MD, 20742-2421, USA
[*] Presenter

E-mail contact: myriam.gitti at unibo.it

Radio observations of galaxy clusters provide a wealth of information which is crucial to assess not only the dynamical state of the clusters, but also the presence of feedback processes and their effects on the thermodynamical state of the intra-cluster medium (ICM). In about 70% of the population of relaxed, cool-core galaxy clusters, the brightest cluster galaxy (BCG) is radio loud, showing relativistic radio jets interacting with the surrounding ICM. In recent years such interactions have been unambiguously shown thanks to spectacular images where radio emission is observed to fill the cavities in the X-ray-emitting ICM. This phenomenon is widespread and is critical to understand the physics of the inner regions of galaxy clusters and the properties of the central BCG. In a number of cases, the radio-loud BCGs are surrounded by radio mini-halos, diffuse radio emission on scales comparable to that of the cooling region. Mini-halos are not directly connected with radio bubbles but the emission is on larger scales and is truly generated from the ICM. Large mini-halo samples are necessary to establish their origin and connection with the clusters thermal properties and dynamics, also in the light of future X-ray characterization of the cluster cores with, e.g., ATHENA-XIFU. In this talk we will show that surveys with the SKA Phase 1 in the 1-2 GHz band with resolution of $\sim$ 8 arcsec at confusion limit will be able to detect all the expected faint ($P_{\rm mh} \sim 10^{23}$WHz^{-1}) mini-halos at redshift $z < 0.6$. We further anticipate that with the SKA Phase 2 it will be possible to perform the complete radio follow-up of the current X-ray samples of strong cool core clusters and to follow the evolution of non-thermal emission and AGN feedback in every cool-core cluster up to redshift $z \sim 1.7$ (the highest-z where virialized clusters are currently detected) and even beyond, thus providing a complete picture of the feedback phenomenon and its role in shaping the large scale structure of the Universe.

Revealing the Mysteries of the Magnetised Universe with the Square Kilometre Array

Melanie Johnston-Hollitt*[1] and the SKA Cosmic Magnetism Working Group

[1] School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington, 6140, New Zealand

* Presenter

E-mail contact: Melanie.Johnston-Hollitt at vuw.ac.nz

Cosmic Magnetism is one of the key science projects to be undertaken on the SKA. The wealth of magnetism science to be gleaned from the SKA is both impressive and unique and will position the SKA to deliver significant scientific results not just for radio astronomy but for the entire astronomical community. In this talk we will present an overview of magnetism science to be conducted on the SKA and, in particular, discuss the results from the planned allsky polarimetric survey which has been a planned mainstay for SKA cosmic magnetism science for over a decade. The resultant rotation measure grid which will be obtained from this survey continues to provide a compelling observational goal to understand both the polarised sources themselves, and as a means to statistically probe numerous important extended sources including the Milky Way, Magellanic clouds, clusters of galaxies, the lobes of giant radio galaxies and perhaps even the elusive warm hot intergalactic medium. Using these data we will address a host of outstanding questions such as:

- What is the mechanism to generate and sustain magnetic fields in the Milky Way, Magellanic clouds and other nearby galaxies?
- How do magnetic fields manifest in HII regions, supernova remnants, planetary nebulae and high velocity clouds in the Milky Way?
- Over what scales and at what strengths are magnetic fields generated in galaxy clusters and how does this correlate with cluster dynamical state?
- What is the large-scale structure of the magnetised Universe and can we statistically detect the magnetic fields in the cosmic web?
- Finally, how do magnetic fields in galaxies and clusters evolve over cosmic time?

The SKA Cosmic Magnetism Working Group and wider magnetism communities have recently consolidated the science case for cosmic magnetism and in this presentation we will highlight the most ambitious and interesting magnetism science that the SKA will deliver.

Measuring Magnetism in the Milky Way with the SKA

Marijke Haverkorn[1,2], Takuya Akahori[3], Ettore Carretti[4], Katia Ferrière[5], Peter Frick[6], Bryan Gaensler[3,7], George Heald[8], Melanie Johnston-Hollitt[9], David Jones[1], Tom Landecker[10], Sui Ann Mao[11,*], Aris Noutsos[11], Niels Oppermann[12], Wolfgang Reich[11], Timothy Robishaw[10], Anna Scaife[13], Dominic Schnitzeler[11], Rodion Stepanov[6,14], Xiaohui Sun[3], and Russ Taylor[15,16], on behalf of the SKA Cosmic Magnetism Working Group

[1] Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands.
[2] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[3] Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
[4] CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia
[5] IRAP, Université de Toulouse, CNRS, 9 avenue du Colonel Roche, BP 44346, 31028 Toulouse Cedex 4, France.
[6] Institute of Continuous Media Mechanics, Korolyov str. 1, 614013 Perm, Russia
[7] ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO)
[8] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[9] School of Chemical & Physical Sciences, Victoria University of Wellington Box 600, Wellington, New Zealand
[10] National Research Council Canada, Herzberg Astronomy and Astrophysics Programs, Dominion Radio Astrophysical Observatory, PO Box 248, Penticton, BC V2A 6J9, Canada
[11] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[12] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto ON, M5S 3H8, Canada
[13] School of Physics & Astronomy, University of Southampton, Southampton, SO17 1BJ, UK
[14] Perm National Research Polytechnic University, Komsomolskii Av. 29, 614990 Perm, Russia
[15] Department of Astronomy, University of Cape Town, Cape Town, South Africa
[16] Department of Physics, University of the Western Cape, Cape Town, South Africa
[*] Presenter

E-mail contact: m.haverkorn at astro.ru.nl

I will review our current knowledge of the magnetic fields in the Milky Way and present how the SKA will unravel the detailed 3D structure and configuration of the magnetic fields in our Galaxy. The large-scale disk field appears to follow the spiral arms, exhibiting one large-scale reversal in the inner Galaxy. In the halo, the magnetic field also seems to have large-scale structures. The symmetry of the large-scale field is crucial for determining the correct dynamo model. Making use of the dense RM grid of extragalactic sources, RMs of pulsars with reliable distance estimates and spectro-polarimetric observations of the diffuse synchrotron emission provided by the SKA, we will be able to: model the MilkyWay disk and halo magnetic fields accurately, investigate magnetic fields in the Galactic Center, characterize interstellar magnetized turbulence and determine magnetic fields in discrete objects such as supernova remnants, HII regions, planetary nebulae and jets of YSOs.

Measuring Magnetic Fields Near and Far via the Zeeman Effect

Timothy Robishaw[1,*], James A. Green[2], Tyler Bourke[2], Sandra Etoka[3], Vincent Fish[4], Malcolm Gray[5], Hiroshi Imai[6], Busaba Kramer[7], James McBride[8], Emmanual Momjian[9], A. M. S. Richards[5], Anuj Sarma[10], Gabriele Surcis[11], Wouter Vlemmings[12], and Albert Zijlstra[5]

[1] National Research Council Canada, Herzberg Astronomy and Astrophysics Programs, Dominion Radio Astrophysical Observatory, PO Box 248, Penticton, BC V2A 6J9, Canada
[2] SKA Organization, Jodrell Bank Observatory, Lower Withington, Macclesfield, SK11 9DL, UK
[3] Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg, Germany
[4] Massachusetts Institute of Technology, Haystack Observatory, Route 40, Westford, MA 01886 USA
[5] Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, University of Manchester, M13 9PL, UK
[6] Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan
[7] Max Planck Institute for Radio Astronomy, Auf dem H¨ugel 69, 53121-Bonn, Germany
[8] Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
[9] National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801, USA
[10] Physics Department, DePaul University, 2219 N. Kenmore Ave., Byrne Hall 211, Chicago, IL 60614, USA
[11] Joint Institute for VLBI in Europe, Postbus 2, 79990 AA Dwingeloo, The Netherlands
[12] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden
[*] Presenter

E-mail contact: tim.robishaw at nrc-cnrc.gc.ca

The measurement of Zeeman splitting in spectral lines – both in emission and absorption – can provide direct estimates of the magnetic field strength and direction in atomic and molecular clouds, both in our own Milky Way and in distant galaxies. The SKA will employ this method to probe magnetic fields in the warm and cold neutral components of the interstellar medium, providing a complement to the extensive SKA Faraday studies being planned to probe magnetic fields in the ionized component.

The usefulness of the Zeeman effect as an astrophysical tool is limited by the sensitivity of a telescope and the telescope's instrumental contribution to the measurement of circular polarization. The collecting area of the SKA will address the first limitation and open new windows in the study of Zeeman splitting. We discuss the possibility of detecting magnetic fields via Zeeman splitting in: molecular clouds and star-forming regions in the Milky Way; HI and OH absorption lines in Galactic clouds towards background continuum sources; diffuse Galactic 21-cm HI structures; OH masers in the Milky Way and nearby galaxies; OH and H_2O megamasers in distant starburst galaxies; and damped Lyman-α absorber systems. We will briefly discuss some of the instrumental concerns that will affect circular polarization measurements with the SKA.

Structure, dynamical impact and origin ofmagnetic fields in nearby galaxies

Rainer Beck[1,*], Dominik Bomans[2], Sergio Colafrancesco[3], Ralf-Jürgen Dettmar[2], Katia Ferrière[4], Andrew Fletcher[5], George Heald[6], Volker Heesen[7], Cathy Horellou[8], Marita Krause[1], Yu-Qing Lou[9], Sui Ann Mao[1], Eva Schinnerer[10], Dmitry Sokoloff[11], Jeroen Stil[12], and Fatemeh Tabatabaei[10]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Astron. Inst. der Ruhr-Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany
[3] School of Physics, University of the Witwatersrand, South Africa
[4] IRAP, Univ. de Toulouse, CNRS, 9 avenue du Colonel Roche, 31028 Toulouse Cedex 4, France
[5] School of Mathematics & Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
[6] ASTRON, Postbus 2, 7990 AA Dwingeloo, the Netherlands
[7] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[8] Dept. of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, 439 92 Onsala, Sweden
[9] Dept. of Physics and Tsinghua Center for Astrophysics, Tsinghua Univ., Beijing, 100084, China
[10] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[11] Moscow State University,Moscow, 119991, Russia
[12] The University of Calgary, Calgary, AB T2N 1N4, Canada
[*] Presenter, On behalf of the SKA Cosmic Magnetism Working Group

E-mail contact: rbeck at mpifr-bonn.mpg.de

Magnetic fields are an important ingredient of the interstellar medium. Mapping the small-scale structure of interstellar magnetic fields (including field reversals) in many nearby galaxies is crucial to understand the coupling between cold gas and magnetic fields and how gas motions are affected. Measuring the power spectra of turbulent magnetic fields will enlighten the origin and role of turbulent fields. Magnetic fields govern the transport of the relativistic cosmic rays, relevant to the ignition, ejection and regulation of galactic outflows and winds, which in turn are pivotal in shaping the structure of halo magnetic fields. The mean-field galactic dynamo theory is able to make predictions for directly observable and derivable properties of galacticmagnetic fields, so that different dynamomodels can be tested against observations. The galaxy survey with SKA1 that we propose will allow us to identify the saturation mechanism for the galactic dynamo, important for astrophysical magnetohydrodynamics in general and for galaxy evolution models. The amplification of small-scale fields by turbulence has been investigated so far only in simulations, while compelling evidence of such fields is still lacking. Polarisation observations in the very nearest galaxies at high frequencies and with high spatial resolution hold the key here.

Magnetic Field Tomography in Nearby Galaxies

George Heald[1,2,*], Rainer Beck[3], Erwin de Blok[1,4,2], Ralf-Jürgen Dettmar[5], Andrew Fletcher[6], Bryan Gaensler[7], Marijke Haverkorn[8,9], Volker Heesen[10], Cathy Horellou[11], Marita Krause[3], Sui Ann Mao[3], Niels Oppermann[12], Anna Scaife[10], Dmitry Sokoloff[13], Jeroen Stil[14], Fatemeh Tabatabaei[15], Keitaro Takahashi[16], Russ Taylor[14,4], and Anna Williams[17]

[1] ASTRON, Postbus 2, 7990 AA Dwingeloo, the Netherlands
[2] Kapteyn Astronomical Institute, PO Box 800, 9700 AV Groningen, the Netherlands
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[4] University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
[5] Ruhr-Universität Bochum, Universitaetsstrasse 150, 44780, Bochum, Germany
[6] School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[7] The University of Sydney, Sydney, NSW 2006, Australia
[8] Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
[9] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[10] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[11] Chalmers University of Technology, Onsala Space Observatory, 43992, Onsala, Sweden
[12] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto ON, M5S 3H8, Canada
[13] Department of Physics, Moscow University, 119992 Moscow, Russia
[14] The University of Calgary, Calgary, AB T2N 1N4, Canada
[15] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[16] Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
[17] Department of Astronomy, University of Wisconsin-Madison, Madison, WI, USA
[*] Presenter, On behalf of the SKA Cosmic Magnetism Working Group

E-mail contact: heald at astron.nl

With SKA1, the 3D structure of galactic magnetic fields and the connection to star formation will be revealed. Magnetic fields play an important role in shaping the structure and evolution of the interstellar medium (ISM) of galaxies, but the details of this relationship remain unclear. A highly sensitive probe of the internal structure of the magnetoionized ISM is the partial depolarization of synchrotron radiation from inside the volume. Different configurations of magnetic field and ionized gas within the resolution element of the telescope lead to changes in the observed, highly frequency-dependent polarization degree. The results of spectro-polarimetric observations are tied to physical structure in the ISM through comparison with detailed modeling, supplemented with the use of new analysis techniques that are being actively developed and studied within the community such as Rotation Measure Synthesis. The SKA will enable this field to come into its own and begin the study of the detailed ISM structure in a sample of nearby galaxies, thanks to its extraordinary wideband capabilities coupled with the combination of excellent surface brightness sensitivity and angular resolution.

Cosmic Magnetism with the SKA1 Deep Field

Russ Taylor[1,2,*], Ivan Agudo[3], Takuya Akahori[4], Rainer Beck[5], Bryan Gaensler[6], George Heald[7], Melanie Johnston-Hollitt[8], Marita Krause[5], Mathieu Langer[9], Larry Rudnick[10], Dongsu Ryu[11], Anna Scaife[12], Dominik Schleicher[13], Jeroen Stil[14]

[1] Department of Astronomy, University of Cape Town, South Africa
[2] Department of Physics, University of the Western Cape, Cape Town, South Africa
[3] Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands
[4] Sydney Institute for Astronomy, The University of Sydney, Australia
[5] Max-Planck-Institut für Radioastronomie, Bonn, Germany
[6] ARC Centre for Excellence for All-sky Astrophysics, University of Sydney, Australia
[7] ASTRON, Dwingeloo, The Netherlands
[8] Victoria University of Wellington, Wellington, New Zealand
[9] Institute d'Astrophysique Spatiale, Université Paris-Sud, France
[10] Minnesota Institute for Astrophysics, University of Minnesota, USA
[11] Department of Physics, School of Natural Sciences, UNIST, Ulsan, Korea
[12] School of Physics and Astronomy, University of Southhampton, UK
[13] Institut für Astrophysik Göttingen, Göttingen, Germany
[14] Department of Physics and Astronomy, University of Calgary, Canada
[*] Presenter

E-mail contact: russ at ast.uct.ac.za

WiDeep surveys with the SKA1 mid-band array offers for the first time the opportunity to systematically explore the polarization properties of the microJy source population. Our knowledge of the polarized sky approaching these levels is still very limited. In total intensity the population will be dominated by star forming and normal galaxies to intermediate redshifts, and low-luminosity AGN to high redshift. The polarized emission from these objects is a powerful probe of their intrinsic magnetic fields and of their magnetic environments. For redshift of order 1 and above the broad bandwidth of the mid-bands span the Faraday thick and thin regime allowing study of the intrinsic polarization properties of these objects as well as depolarization from embedded and foreground plasmas. The deep field polarization images will provide Rotation Measures data with very high solid angle density, allowing detection and sensitive statistical analysis of the angular variation on critical arc-minute scales of Faraday Rotation from magnetic fields associated with cosmic Large Scale Structure.

Stacking for Cosmic Magnetism

Jeroen M. Stil[1,*], Ben W. Keller[2]

[1] Department of Physics & Astronomy, The University of Calgary
[2] Department of Physics & Astronomy, MacMaster University
[*] Presenter

E-mail contact: jstil at ucalgary.ca

Stacking polarized radio emission in SKA surveys provides statistical data on large samples that is not accessible otherwise due to limitations set by a combination of sensitivity, source statistics in a narrow survey, and frequency averaging. For samples selected by redshift, stacked in a narrow frequency range, the large bandwidth of the SKA allows investigation of the degree of polarization in the restframe of the sample, which is critical for magnetic field science that relies on evolution of the degree of polarization. Polarization is a special case for stacking because one obvious source of targets is the Stokes I source catalog of the same survey. Applications of stacking polarization include but are not limited to the degree of polarization down to the detection limit in total intensity, investigating depolarization and magnetic fields as a function of cosmic time, and magnetic field properties in objects with a low radio luminosity such as dwarf and low-surfacebrightness galaxies. Stacking Stokes parameters Q and U for a sample selected by a predictor of polarization angle (structure, optical polarization angle, etc.) allows one to investigate potential correlations of observable parameters with polarization angle in a class of sources, as a function of wavelength. More than proving the existence of a faint signal, stacking related samples divided by an observable parameter such as spectral index, infrared or optical classification, extends cosmic magnetism science to applications not previously considered. We also point out the potential use of stacking in validating the direction-dependent polarization calibration of a survey. While stacking is flexible in terms of survey definition, we discuss optimal survey parameters for a few select science experiments. While the computational footprint of stacking is modest, we emphasize it as an application that requires enduring, flexible and global access to SKA data.

Relativistic Jets in Active Galactic Nuclei.

Iván Agudo[a,*], Markus Böttcher[b], Heino Falcke[c], Markos Georganopoulos[d], Gabriele Ghisellini[e], Gabriele Giovanini[f], Marcello Giroletti[g], Leonid Gurvits[a], Jose L. Gómez[h], Robert Laing[i], Matthew Lister[j], Jose-María Martí[k], Eileen Meyer[l], Yosuke Mizuno[m], Shane O'Sullivan[n], Paolo Padovani[i], Zsolt Paragi[a], Manel Perucho[k], Dominik Schleicher[o], Lukasz Stawarz[p], Nektarios Vlahakis[q], and John Wardle[r]

[a]JIVE, [b]North-West Univ., [c]Univ. Nijmegen, [d]Univ. Maryland, [e]Univ. Brera, [f]Univ. Bologna, [g]IRAINAF, [h]IAA-CSIC, iESO, [j]Univ. Purdue, [k]Univ. Valencia, [l]STSCI, [m]Nat. Tsing-Hua Univ., [n]Univ. Sydney, [o]Göttingen Univ., [p]ISAS-JAXA, [q]Univ. Athens, [r]Brandeis Univ.,
[*] Presenter

E-mail contact: agudo at jive.nl

Relativistic jets in active galactic nuclei (AGN) are among the most powerful astrophysical objects discovered to date. Indeed, AGN relativistic jet studies have been considered a prominent science case for SKA, and were included in several different chapters of the previous SKA Science Book (Carilli & Rawlings 2004). Most of the fundamental questions about the physics of relativistic jets still remain unanswered, and await high sensitivity radio instruments such as SKA to solve them. These questions will be addressed by analysis of the massive data sets arising from all-sky and deep, total flux and polarimetric, surveys involving SKA. From the onset, wide-field very-long-baseline-interferometric survey observations involving SKA will serve as a unique tool for distinguishing between extragalactic relativistic jets and star forming galaxies via brightness temperature measurements. Subsequent follow-up SKA studies of relativistic jets at different resolutions will allow us, for the first time: i) imaging of a large number of jets throughout cosmic time, back to the epoch of re-ionization; ii) robust relativistic-jet composition studies through unparalleled circular polarization sensitivity/purity; iii) an understanding of the radio-loud/radio-quiet dichotomy in extragalactic AGN jets via imaging of thousands of radio weak Seyferts and LINERs; iv) a characterization of the three-dimensional distributions of flow parameters such as velocity, proper emissivity, and magnetic field structure (through total flux and polarization imaging), that lead to estimates of key physical quantities such as mass and energy fluxes and entrainment rates; v) a probe the magnetoionic environments of the jets (perhaps including their confining fields) through deep full Stokes (and Faraday rotation measure) imaging at all scales along and across a large number of objects; and vi) an understanding of the interplay between the jet and the ambient medium through mapping of faint structures and motions within the lobes of giant AGN jets. SKA1 will enable such studies for large samples of nearby jets; SKA VLBI will provide the sensitivity for pc-scale imaging and SKA2 (with resolution < 0.05 arcsec and 10 nJy/beam sensitivity) will allow us to resolve and model the most powerful kpc-scale jets for the first time.

Broadband Polarimetry with the Square Kilometre Array: A Unique Astrophysical Probe

B. M. Gaensler[1,2,*], Ivan Agudo[3], Takuya Akahori[1], Julie Banfield[4], Rainer Beck[5], Ettore Carretti[4], Jamie Farnes[1,2], Marijke Haverkorn[6], George Heald[7], David Jones[6], Thomas Landecker[8], Sui AnnMao[5], Ray Norris[4,2] Shane O'Sullivan[1,2], Lawrence Rudnick[9], Dominic Schnitzeler[5], Nicholas Seymour[4], Xiaohui Sun[1]

[1] Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW2006, Australia
[2] ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)
[3] JIVE, The Netherlands
[4] CSIRO Astronomy and Space Science, Australia
[5] MPIfR, Germany
[6] Radboud University Nijmegen, The Netherlands
[7] ASTRON, The Netherlands
[8] DRAO, Canada
[9] The University of Minnesota, USA
[*] Presenter

E-mail contact: bryan.gaensler@sydney.edu.au

Radio polarimetry and Faraday rotation are highly sensitive probes of astrophysical magnetic fields. Accordingly, a well-established key science project for the Square Kilometre Array (SKA) is the "rotation measure grid", with which we can study magnetic fields in a diverse range of foreground objects. However, to understand additional physics such as the properties of the polarised sources themselves, we now realise that the rotation measure grid needs to include or be complemented by observations of tens of thousands of polarised radio galaxies over very broad bandwidths: just as it is impossible to properly image a complex source with limited u-v coverage, we can only meaningfully understand the magneto-ionic properties of polarised sources if we have excellent coverage in λ^2-space. We here propose a set of broadband polarimetry surveys with SKA Phase 1 and SKA Phase 2, which will provide a singular set of scientific insights on the ways in which galaxies and their environments have evolved over cosmic time.

Unravelling the origin of large-scale magnetic fields in galaxy clusters and beyond through Faraday Rotation Measures

Annalisa Bonafede, Hamburg University - Hamburg Observatory, Franco Vazza, Marcus Brüggen, Takuya Akahori, Ettore Carretti, Sergio Colafrancesco, Luigina Feretti, Chiara Ferrari, Gabriele Giovannini, Federica Govoni, Melanie Johnston-Hollitt, Matteo Murgia, Lawrence Rudnick, Anna Scaife, Valentina Vacca

E-mail contact: annalisa.bonafede at hs.uni-hamburg.de

Magnetic fields are ubiquitous in the Universe but their origin is unknown. On large scales, magnetic fields are the hardest to explain because the usually invoked dynamo mechanism does not have the time to amplify the field on the largest scales starting from a weak initial seed. In addition, the magnetic fields in galaxy clusters are poorly constrained from an observational point of view, and it is unclear whether they are formed from primordial seeds - amplified during the process of structure formation - or are formed from magnetic fields injected by AGN or galactic outflows.

The presence of magnetic field in galaxy clusters can be probed by diffuse radio emissions associated with clusters and Faraday rotation measures of embedded and background polarised sources. In the last decade, there have been revolutionary improvements in modelling the magnetic field in galaxy clusters based partly on observations and partly on numerical simulations. Recent studies have given us important clues to elucidate the evolution history of the magnetic fields in galaxy clusters. However, because of the limits of current instruments, further improvements will be hard to achieve. A primary limiting factor is the sensitivity of present facilities, that limits the feasibility of such studies to a few nearby clusters where a sufficient number of background and embedded polarised sources can be detected. A secondary limiting factor is the small field of view of view of the instruments, which require multiple pointings and, hence, an enormous observing time to survey the entire cluster. Thanks to its sensitivity and large field of view, SKA-1 will overcome these limitations, and will be the instrument to unravel the origin and evolution of large-scale magnetic fields in the universe. To predict the SKA-1 capabilities in studying the properties of magnetic fields in the intra-custer medium, we use a numerical code to simulate different cluster magnetic field configurations in model clusters that follow analytical descriptions or are taken from cosmological simulations (Vazza et al. 2012). Considering the polarised source density counts predicted by Rudnick and Owen (2014) for the SKA-1 we have produced mock Rotation Measure images of sources in and behind the simulated clusters. According to our predictions, SKA-1 will be able to trace the magnetic field properties in galaxy clusters as a function of the cluster mass, covering all dynamical states of a cluster. In addition, using cosmological simulations to model the gas density, we can compute the rotation measure also through shock-waves. SKA-1 observations of embedded and background polarised sources in and behind galaxy clusters will provides us with powerful new datasets aimed at addressing the following questions:

1) What are characteristic properties of the magnetic field in galaxy clusters?

2) How does the magnetic field change with mass, dynamical state, and cosmic time?

3) How the IGMF connects to the cosmic web?

In this Chapter, we introduce strategies to study the magnetic field in galaxy clusters through Rotation Measure observations of embedded and background polarised sources. We will demonstrate SKA1 capabilities to conduct a detailed study of the magnetic field in a sample of galaxy clusters.

Clustermagnetic fields through the study of polarized radio halos.

Federica Govoni[1,*], Matteo Murgia[1], Hao Xu[2], Hui Li[3], Michael Norman[2], Feretti Luigina[4], Gabriele Giovannini[4], Valentina Vacca[5], Gianni Bernardi[6], Annalisa Bonafede[7], Gianfranco Brunetti[4], Ettore Carretti[8], Sergio Colafrancesco[9], Julius Donnert[4], Chiara Ferrari[10], Myriam Gitti[11], Luigi Iapichino[12], Melanie Johnston-Hollitt[13], Roberto Pizzo[14], and Lawrence Rudnick[15]

[1] INAF - Osservatorio Astronomico di Cagliari, Italy
[2] University of California at San Diego, CA, USA
[3] LANL Los Alamos, NM, USA
[4] INAF - Istituto di Radioastronomia Bologna, Italy
[5] MPA, Garching, Germany
[6] SKA SA, South Africa
[7] University of Hamburg, Germany
[8] CSIRO, Australia
[9] University of the Witwatersrand, South Africa
[10] Observatoire de Nice, France
[11] Universitá degli Studi di Bologna, Italy
[12] Zentrum fur Astronomie der Universitat Heidelberg, Institut fur Theoretische Astrophysik, Germany
[13] Victoria University of Wellington, NZ
[14] ASTRON, The Netherland
[15] Minnesota Institute for Astrophysics, USA
[*] Presenter, On behalf of the SKA Cosmic Magnetism Working Group

E-mail contact: fgovoni at oa-cagliari.inaf.it

Galaxy clusters - the largest known magnetized structures in the Universe - are unique laboratories to investigate turbulent fluid motions and large scale magnetic fields. Synchrotron radio halos at the center of merging galaxy clusters provide the most spectacular and direct evidence of the presence of relativistic particles and magnetic fields associated with the intra-cluster medium. The study of polarized emission from radio halos is extremely important to constrain the properties of intra-cluster magnetic fields and the physics of the acceleration and transport of the relativistic particles. However, detecting this polarized signal is a very hard task with the current radio facilities. We use cosmological magnetohydrodynamical simulations to predict the expected total intensity and polarized surface brightness of radio halos at 1.4 GHz. We compare these expectations with the sensitivity and the resolution reachable with the SKA1 to explore the potential to investigate intra-cluster magnetic fields through the detection of polarized emission from radio halos in the surveys planned with SKA1.

Filaments of the radio cosmic web: opportunities and challenges for the SKA

F. Vazza[1,2], C. Ferrari[3], A.Bonafede[1], M. Brüggen[1], C. Gheller[3], S. Brown[4]

[1] University of Hamburg, Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany
[2] INAF/Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
[3] CSCS, Via Trevano 131, CH-6900 Lugano, Switzerland
[4] Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242,USA

The detection of the diffuse gas component of the cosmic web is still elusive. We discuss the chance of detecting the cosmic web in radio, studying the detectability of the synchrotron emission originated by relativistic electrons accelerated within filaments of the cosmic web. Filaments should host strong stationary shocks, whose efficiency in acelerating cosmic ray electrons should be high. Our simulations suggest that the detection of the brightest parts of large (¿10 Mpc) filaments of the cosmic web should be detectable with long exposures with SKA-LOW, provided that the large-scale magnetic fields store at least a few percent of the thermal gas energy, which is on the high-end of what dynamo amplification from cosmological seed field can produce (as suggested by MHD cosmological simulations, including ours). Using some of the most well resolved cosmological simulations for this scientific case, we simulated the observation of such emission patterns as a function of redshift and observational strategies (e.g. 2 years survey, long pointed exposure, tapering of the data in the UV plane etc) and investigated the chances of detection with SKA LOW, MID and SUR. Our conclusion is that while SKA MID and SUR are not suited for this science case (owing to the missing baselines and the consequent lack of signal from the large-scale brightness fluctuations associated with the filaments), SKA LOW should offer the chance of a detection, provided that a large enough volume up to z=0.1 is surveyed. Even a modest increase in the planned sensitivity (i.e. by a factor 2-3, which should be reached in Phase 2 of the SKA) would lead to a dramatic increase in the detectability of the full extent of filaments. The design forseen for the the SKA LOW in Phase 1 should still be able to pinpoint the brightest emission pattern from filaments, while the confusion noise should hamper the chance of detecting the largest scale components of the radio emission on the full extend of filaments.

Statistical methods for the analysis of rotation measure grids in large scale structures.

Vacca V.[1,*], Ensslin T.[1], Oppermann N.[2], Junklewitz H.[3], Selig M.[1], Greiner M.[1], Jasche J.[4], Reinecke M.[1], Carretti E.[5], Feretti L.[6], Ferrari C.[7], Giovannini G.[6,8], Govoni F.[9], Horellou C.[10], Ideguchi S.[11], Johnston-Hollitt M.[12], Murgia M.[9], Paladino R.[6,8], Pizzo R. F.[13], Scaife A.[14]

[1] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany
[2] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto ON, M5S 3H8, Canada
[3] Argelander-Institut für Astronomie, Auf dem Hügel 71, 52121 Bonn, Germany
[4] CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis, boulevard Arago, F-75014 Paris, France
[5] CSIRO Astronomy and Space Science PO Box 276. Parkes 2870
[6] INAF-Istituto di Radioastronomia, Via P.Gobetti 101, 40129 Bologna, Italy
[7] Laboratoire Lagrange, UMR 7293, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte dAzur, 06300 Nice, France
[8] Dipartimento di Fisica e Astronomia, Universit di Bologna, via Ranzani 1, 40127, Bologna, Italy
[9] INAF-Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047, Selargius (CA), Italy
[10] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden
[11] Kumamoto University, 2-39-1 Kurokami, Kumamoto
[12] School of Chemical & Physical Sciences, Victoria University ofWellington, PO Box 600,Wellington 6014, New Zealand
[13] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[14] University of Southampton Highfield, Southampton SO17 1BJ, U.K.
[*] Presenter

E-mail contact: vvacca at mpa-garching.mpg.de

Magnetic fields are ubiquitous in the Universe and play a key role in several phenomena. Despite their importance, magnetic field formation and evolution are still open problems. To better understand the origin and properties of cosmological magnetic fields, a detailed knowledge of magnetic fields in the large-scale structure of the Universe (galaxy clusters, filaments) is fundamental.

Magnetic field studies can be performed by applying a variety of techniques, among which rotation measure observations are a powerful tool. The amount of Faraday rotation measured from radio observations is the result of the contribution from different environments: our Galaxy, voids, sheets, galaxy clusters, filaments and the source itself. To disentangle these different contributions is essential in order to study magnetic fields in large-scale structures, and consequently infer information on cosmic magnetism. However, this is a non-trivial task demanding a statistical approach.

During this talk we present a new statistical approach to separate the different extragalactic contributions. This approach will allow to study magnetic fields on large scales with the rotation measure grid data that are going to be obtained with SKA.

Unveiling the nature of Dark Matter with the SKA

S. Colafrancesco[1;*], M. Regis[2], H. Zechlin[2], P. Marchegiani[1], G. Beck[1], R. Beck[3], A. Lobanov[3], D. Horns[4]

[1] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[2] Dipartimento di Fisica, Università degli Studi di Torino and INFN-Sezione di Torino, Italy
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany; 4 DESY, Hamburg, Germany
* Presenter

Dark Matter (DM) is a fundamental ingredient of our Universe and of structure formation, and yet its nature is elusive to astrophysical probes. Information on the nature and physical properties of the WIMP (neutralino) DM (the leading candidate for a cosmologically relevant DM) can be obtained by studying the astrophysical signals of their annihilation/decay. Among the various electromagnetic signals, secondary electrons produced by neutralino annihilation generate synchrotron emission in the magnetized atmosphere of galaxy clusters and galaxies which could be observed as a diffuse radio emission (halo or haze) centered on the DM halo. Observations of cluster radio emission could be very effective in constraining the neutralino mass, composition and annihilation cross-section, but dwarf spheroidal galaxies are the optimal candidate for DM radio detection because they are the darkest (having mass-to-light ratios $M/L \gtrsim$1000, no other diffuse emission components and no strong star formation) and closest objects in the universe. We propose here a deep search for DM radio emission with SKA in local dwarf galaxies and galaxy clusters (with offset DM-baryonic distribution like e.g. the Bullet cluster). For the case of a typical dwarf galaxy, like e.g. Draco, the constraints on a typical DM model obtainable with SKA-1 mid will be at least a factor $\sim 10^3$ more constraining than the limits obtained by Fermi-LAT in the gamma-rays. These limits scale with the value of the B field, so a strategy for the magnetic field estimate in dwarf galaxies or galaxy clusters is necessary. In this framework the SKA-1 mid will be also able to set a reliable estimate of the magnetic field in the dwarf galaxy region by using both deep and wide-field Faraday Rotation measurements of background radio sources and polarization measurements. The SKA-1 mid Band 1 (350 -1050 MHz) and Band 5 (4.6 -13.8 GHz) are important to probe the DM-induced synchrotron spectral curvature at low-frequency (sensitive to DM composition) and at high frequency (sensitive to DM mass). These bands will also allow for an optimal description of the magnetic field through FR measures and polarization. The possibility to have an extended frequency coverage of the SKA in its Phase-2 reaching 25 GHz will allow to use both radio synchrotron observations and Inverse Compton observations of the same DM-produced secondary electrons to fully disentangle the magnetic field vs. electron degeneracy present in the synchrotron radio emission and thus determine at the same time both the magnetic field and the DM particle properties contributing to the diffuse radio emission in a DM halo.

SKA and the Cradle of Life

Melvin Hoare[1,*] and the Cradle of Life team

[1] School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK
[*] Presenter
E-mail contact: m.g.hoare at leeds.ac.uk

We present an overview of the capabilities of the SKA in the areas relating to the formation and characterisation of planets and the origins and potential detection of life. The capabilities of the Phase 1 of the SKA in terms of the studies of grain growth in proto-planetary disks and the detection of pre-biotic molecules in disks and pre-stellar cores will be summarized and set in the context of other facilities. Sensitive cm-wave studies are the only way to fill the large gap in our understanding of the early growth of grains through the cm-size regime. SKA1-mids 200 km baselines provide the resolution to probe these processes inside the snow line of the nearest systems. The unrivalled collecting area of SKA1-mid will also enable very deep searches for the very building blocks of life such as amino acids in regions close to where planets are forming. Both of these key science objectives on our origins will highlight the need for high frequency receivers to be deployed on SKA1-mid. At the other extreme of the frequency range the SKA can make a unique contribution to characterising exo-planets. Low-frequency bursts of electron cyclotron maser emission should arise when the winds from solar-like stars interact with the magnetic fields of planets in a similar way to the decametric emission from Jupiter. SKA1-Low should detect this emission for the first time at stellar distances which will provide the first insights into exo-planet magnetic fields, star-planet plasma interactions and the habitability of the planets. With the preponderance of planets now known the various searches for life on other systems are now on a firmer footing. It is therefore timely that the sensitivity of the SKA across the whole frequency range is such that it can detect the levels of leakage radiation from nearby exo-planets if the levels were similar to those on the Earth. Hence, the prospects for the study of the emergence of intelligent life will take a major step forward with SKA1. Our review will look at the synergies between these topics and their targeting strategies. We will also look forward to the anticipated discoveries in this field with Phase 2 of the SKA. The need for SKA1 to address these fundamental questions on the origins of mankind that so fire the imagination of the general public and stakeholders will play a key role in securing the funding necessary for the SKA as a whole.

Protoplanetary disks and the dawn of planets with SKA

L. Testi[1;2*] A. Boley[3], T. Bourke[4], J.R. Brucato[1], P. Caselli[5], C. Chandler[6], M. Hoare[7], A. Isella[8], I. Jimenez-Serra[2], J. Lazio[9], M.E. Palumbo[10], L. Perez[6], L. Podio[1], A. Remijan[6], J. Tarter[11], D.J. Wilner[12]

[1] INAF-OA Arcetri, Italy
[2] ESO, Germany
[3] University of British Columbia, Canada
[4] SKA Organisation, UK
[5] MPE, Germany
[6] NRAO, USA
[7] University of Leeds, UK
[8] Caltech, USA
[9] JPL, USA
[10] INAF-OA Catania, Italy
[11] SETI Institute, USA
[12] CfA, USA

E-mail contact: ltesti ateso.org

Protoplanetary disks form as a consequence of the collapse of rotating cloud cores during the star formation process. At early stages, disks allow material to loose angular momentum and accrete onto the central protostar. At later stages, when the central object is revealed as a pre-main-sequence star, planetary systems form in the disk midplane. Infrared and millimeter surveys show that circumstellar dust is dissipated on a timescale of few Myrs, so that growth to planetesimals must proceed very fast, as also inferred from meteoritic evidence in our own Solar System. During this epoch of disk dissipation, the physics and chemistry of disks is dominated by interplay of accretion flow, stellar processes, and planets in formation. These processes will shape the outcome of the planet formation process both in terms of the planetary systems demographics, including fraction of habitable planets, and in terms of the chemical complexity of the material delivered to the planetary atmospheres.

The SKA will enable unique observations for constraining the physics of planet formation and disk dissipation mechanisms. Studies of disks in the frequency range below 15 GHz have been severely hampered by the limited sensitivity of existing radio facilities. The upgraded VLA is providing tantalizing results that show the potential of SKA. We will discuss detailed sensitivity limits, frequency ranges, and spectral resolution requirements for SKA-1 and its future extensions, as well as observational strategies and constraints for important new experiments in this field. We will also present illustrative projects that harness the power of the SKA combined with ALMA, JWST and ELTs.

I will discuss three aspects related to the continuum emission from disks: (1) the growth of dust grains towards planetesimals, which can be constrained only with access to centimeter-wave emission from large dust grains and pebbles, (2) the emission of photoevaporative and disk winds, which regulate angular momentum transport in disks and the origin of outflows, and (3) the impact of energetic stellar flares on disk chemistry and processing of both solid and gaseous material.

For spectral lines, emission from complex and pre-biotic molecules are potentially detectable in protoplanetary disks at the high end of SKA-1 frequency range. Given the cold conditions of disk midplanes, organics can be locked into the icy mantles of dust grains and remain undetected. However, cosmic rays can desorb ice in in heavily shielded regions, as recent Herschel measurements of water in cores and protoplanetary disks suggest. This process would allow for the release of organic molecules in the gas phase.

Radio Jets in Young Stellar Objects

Guillem Anglada[1,*], Luis F. Rodríguez[2], and Carlos Carrasco-González[2]

[1] Instituto de Astrofísica de Andalucía, CSIC, Glorieta de la Astronomía s/n, E-18008 Granada, Spain
[2] Centro de Radioastronomía y Astrofísica, UNAM, Apartado Postal 72-3 (Xangari), 58089 Morelia, Michoacán, Mexico
[*] Presenter

E-mail contact: guillem at iaa.es

Jets and outflows are ubiquitous in the process of formation of stars since accretion is intimately associated with outflow. Free-free radio continuum emission in the centimeter domain is associated with these jets. The emission is weak, and sensitive telescopes are required to detect it.

One of the key problems in the study of outflows is to determine how they are accelerated and collimated. Observations in the cm range are most useful to trace the base of the ionized jets, close to the young central object and its accretion disk, where optical or near-IR imaging is difficulted by the high extinction present. Radio recombination lines in jets (in combination with proper motions) should provide their 3D kinematics at very small scale (near their origin). SKA will be crucial to perform this kind of observations.

Thermal jets are associated with both low and high mass protostars. The ionizing mechanism of these radio jets appears to be related to shocks in the associated outflows, as suggested by the observed correlation between the centimeter luminosity and the outflow momentum rate. From this correlation and that with the bolometric luminosity of the driving star it will be possible to discriminate with SKA between unresolved HII regions and jets, and to infer physical properties of the embedded objects.

Some jets associated with young stellar objects (YSOs) show indications of non-thermal emission (negative spectral indices) in part of their lobes. Linearly polarized synchrotron emission has been found in the jet of HH 80-81, allowing to measure the direction and intensity of the jet magnetic field, a clue ingredient to determine the collimation and ejection mechanisms. As only a fraction of the emission is polarized, very sensitive observations such as those that will be feasible with SKA are required to perform these studies.

Jets are common in many kinds of astrophysical scenarios. Characterizing radio jets in YSOs, where thermal emission allows to determine their physical conditions in a reliable way, would be also useful in understanding acceleration and collimation mechanisms in all kinds of astrophysical jets.

Complex OrganicMolecules in Protostellar Environments

C. Codella[1], L. Podio[1,*], F. Fontani[1], I. Jiménez-Serra[2], P. Caselli[3], C. Ceccarelli[4], M. E. Palumbo[5], A. López-Sepulcre[4], M.T. Beltrán[1], B. Lefloch[4], J. R. Brucato[1], S. Viti6, L. Testi[2]

[1] INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[2] ESO, Karl Schwarzschild srt. 2, 85748 Garching, Germany
[3] MPE, Giessenbachstr. 1, 85748 Garching, Germany
[4] IPAG, UMR 5274, UJF-Grenoble 1/CNRS-INSU, 38041 Grenoble, France
[5] INAF, Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123 Catania, Italy
[6] UCL, Gower Street, WC1E 6B London, UK
[*] Presenter

E-mail contact: codella at arcetri.astro.it

Molecular complexity builds up at each step of the Sun-like star formation process, starting from simple molecules and ending up in large polyatomic species. Complex organic molecules (COMs; such as methyl formate, $HCOOCH_3$, dymethyl ether, CH_3OCH_3, formamide, N_2CHO, or glycoaldehyde, $HCOCH_2OH$) are formed in all the components of the star formation recipe (e.g. pre-stellar cores, hot-corinos, circumstellar disks, shocks induced by fast jets), due to ice grain mantle sublimation or sputtering as well as gas-phase reactions. Understanding the formation routes is likely the only way to predict the ultimate molecular complexity reached in the ISM, as the detection of large molecules is increasingly more difficult with the increase of the number of atoms constituting them. In this talk we will focus on the chemistry of both cold prestellar cores and hot and shocked regions. We will review results and open questions provided by mm to far-infrared spectral surveys, and we will show the need of carrying on the observations of COMs at lower frequencies, where SKA will operate. We will also emphasize the importance of the experimental studies performed by our team, which are investigating the chemical effects induced by ionising radiation bombarding relevant ices.

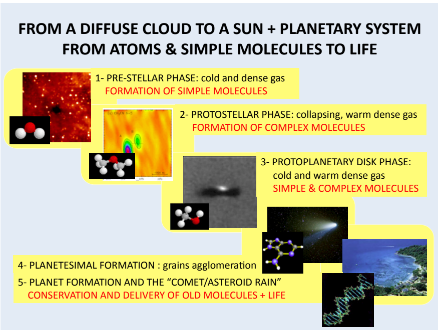


Figure 1: Star formation and chemical complexity (from Caselli & Ceccarelli 2012).

Maser astrometry with VLBI and the SKA

James A Green[1;*], Huib Jan van Langevelde[2;3], Andreas Brunthaler[4], Hiroshi Imai[5], Simon Ellingsen[6], Wouter Vlemmings[7], Mark Reid[8], and Anita Richards[9]

[1] SKA Organisation, Jodrell Bank Observatory, Lower Withington, Macclesfield, SK11 9DL, UK
[2] Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo the Netherlands
[3] Sterrewacht Leiden, Leiden University, Postbus 9513, 2300 RA Leiden, the Netherlands
[4] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[5] Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan
[6] School of Mathematics and Physics, University of Tasmania, Private Bag 37, Hobart, Tasmania 7001, Australia
[7] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, 439 92, Onsala, Sweden
[8] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[9] Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK
[*] Presenter

E-mail contact: j.green at skatelescope.org

We discuss the unique opportunities for maser astrometry with the inclusion of the Square Kilometre Array (SKA) in Very Long Baseline Interferometry (VLBI) networks. The first phase of the SKA will enable observations of hydroxyl and methanol masers, and the second phase may allow water maser observations. The fantastic sensitivity of the SKA will enable large-scale surveys and, through collaboration, will turn any VLBI network into a fast astrometry device. Both evolved stars and high mass star formation regions will be accessible throughout the (Southern) Galaxy, completing our understanding of the content, dynamics and history of the Milky Way; as well as throughout the Local Group galaxies, providing new insight into their dynamics and evolution.

Magnetospheric Radio Emissions from Exoplanets

Philippe Zarka[1,*], T. Joseph W. Lazio[2], and Gregg Hallinan[3] on behalf of the Astrobiology Science Working Group

[1] LESIA, CNRS – Observatoire de Paris, 92190 Meudon, France

[2] Jet Propulsion Lab., California Institute of Technology, M/S 138-308, Pasadena, CA 91109, USA

[3] California Institute of Technology, Pasadena, CA 91109, USA

[*] Presenter

E-mail contact: philippe.zarka at obspm.fr, Joseph.Lazio at jpl.nasa.gov, gh at astro.caltech.edu

Planetary-scale magnetic fields are a window to a planet's interior and provide shielding of the planet's atmosphere and surface for life. The Earth, Mercury, Ganymede, and the giant planets of the solar system all contain internal dynamo currents that generate planetary-scale magnetic fields. These currents arise from differential rotation, convection, compositional dynamics, or a combination of these in objects' interiors. When coupled to energetic (keV) electrons, such as those produced by solar wind-magnetosphere interaction (compression or magnetic reconnection), magnetosphereionosphere or magnetosphere-satellite coupling, the polar regions of a planetary magnetic field are the place of intense, coherent, circularly polarized cyclotron radio emissions. These emissions – that may be as intense as solar ones – are produced by all magnetized planets in the solar system in the MHz range, except for Jupiter where emission reaches 40 MHz. Detection of similar emissions from exoplanets will provide a means of constraining the thermal state, composition, and dynamics of their interior – very difficult to determine by other means – as well as an improved understanding of the entire planetary dynamo process.

Detailed knowledge of magnetospheric emissions from solar system planets and the discovery of exoplanets have motivated both theoretical and observational work on magnetospheric emissions from exoplanets. Scaling laws and theoretical frameworks were built and extrapolated to obtain orderof-magnitude predictions of frequencies and flux densities of exoplanetary radio emissions. The present stage of the theory suggests that radio detection of exoplanets will develop the new field of comparative exo-magnetospheric physics, but also permit to measure exoplanetary parameters such as rotation or orbit inclination. Observational searches started even before the confirmed discovery of the first exoplanet.

This chapter reviews the scientific return of the detection of exoplanetary magnetospheric radio emissions, the current status of observational searches, and discusses the future promise in the context of SKA, especially SKA1-Low. To the extent that solar system planets are a fair sample of the range of magnetic field strengths that planets can produce, the current lower frequency limit of SKA1-Low (50 MHz) implies that the telescope will likely detect Jovian-mass planets. With the currently planned sensitivity of SKA1-Low, we estimate that a Jupiter-like planet could be detected to about 10 pc. Within this volume there are ~200 known stars, and ~35 currently known exoplanets, but this number should increase substantially with coming space missions dedicated to transits and powerful groundbased (VLT) instruments. The accessible volume will be much increased if scaling laws derived in our solar system can be reliably extrapolated to exoplanetary systems, permitting to measure lower mass planets' dynamos and magnetospheres.

Searching for Extraterrestrial Intelligence with the Square Kilometre Array

Andrew Siemion[1,2,3,*], James Benford, Jin Chengjin, Jayanth Chennamangalam, Jim Cordes, Heino Falcke, Mike Garrett, Simon Garrington, Leonid Gurvits, Melvin Hoare, Eric Korpela, Joseph Lazio, David Messerschmitt, Ian S. Morrison, Tim O'Brien, Zsolt Paragi, Alan Penny, Andrew P. V. Siemion, Laura Spitler, Jill Tarter, Dan Werthimer

[1] ASTRON, Netherlands

[2] Radboud University Nijmegen, Netherlands

[3] University of California, Berkeley, United States

[*] Presenter

E-mail contact: siemion at astron.nl

In the coming years, the vast collecting area of the Square Kilometre Array (SKA), harnessed by sensitive receivers, flexible digital electronics and increased computational capacity, could permit the most sensitive and exhaustive search for technologically-produced radio emission from advanced extraterrestrial intelligence (SETI) ever performed. While it is difficult to predict the specific properties of electromagnetic emission from extraterrestrial technologies, basic assumptions of intentionality or communication of information imply particular detectable features that constrain the search space, e.g. signal features that impart distinguishability over the astrophysical background or non-Gaussian statistical properties. Traditionally, radio SETI has focused on narrow-band sinusoids, but it is clear that other types of signals possess merit as well.

SETI searches with the SKA1 facilities will build from an active base of theoretical and experimental work being done in the field with existing large-scale facilities, but the combination of raw sensitivity, flexible electronics and increased computational capacity will enable orders-of-magnitude improvement in the speed, depth and breadth of previous SETI experiments. We will detail several conceivable SETI experimental programs on SKA1-low and SKA1-mid, including commensal, primary-user, targeted and survey programs, and will project the enhancements to them possible with SKA Phase 2. We will discuss target selection criteria for these programs, and in the case of commensal observing, how the varied use cases of other primary observers can be used to full advantage for SETI. There are a range of targets that warrant exploration, including nearby stars, lines of sight with high stellar density and preferential alignments with other stellar and planetary systems. We will also discuss how the SKA digital backends could enable, or potentially prohibit, various aspects of these programs, including discussion of the necessity for quality interference excision and the utility of real-time processing and sensitivity to diverse signal types. Searches for life beyond Earth, especially searches for intelligent life, have a remarkable ability to spark the imagination of the public, and this component of the SKA science case will offer ample opportunity for outreach and public engagement.

The impact of SKA on Galactic Radioastronomy: continuum observations

G. Umana[1,*], et al.

[1] INAF Osservatorio Astrofisico di Catania, Catania, Italy

[*] Presenter

E-mail contact: Grazia.Umana at oact.inaf.it

The SKA will be a state of the art radiotelescope optimized for both large area surveys as well as for deep pointed observations. In this paper we analyze the impact that the SKA will have on Galactic studies, starting from the immense legacy value of the all-sky survey proposed by the continuum SWG but also presenting some areas of Galactic Science that particularly benefit from SKA observations both surveys and pointed. The planned all-sky survey will be characterized by unique spatial resolution, sensitivity and survey speed at 1-2 GHz, providing us with a wide-field atlas of the Galactic continuum emission. Synergies with existing, current and planned radio Galactic Plane surveys will be discussed as well as the importance of combining the radio data with the wealth of ready available multi-wavelengths Galactic Plane surveys.
SKA will give the opportunity to create a sensitive catalog of discrete Galactic radio sources, most of them representing the interaction of stars at various stages of their evolution with the environment: complete census of all stage of HII regions evolution; complete census of late stages of stellar evolution such as PNe and SNRs; detection of stellar winds, thermal jets, Symbiotic systems, Chemically Peculiar and dMe stars, active binary systems in both flaring and quiescent states. Coherent emission events as Cyclotron Maser due to particle acceleration and interaction with exoplanets can be detected. Pointed, deep observations will allow new insights into the physics of the coronae and plasma processes in active stellar systems and single stars, enabling the detection of flaring activity in larger stellar population for a better comprehension of the mechanism of energy release in the atmospheres of stars with different mass and age.

OH masers in the MilkyWay and Local Group galaxies

Sandra Etoka[1,*], Dieter Engels[1], and Hiroshi Imai[2]

[1] Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany

[2] Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan

[*] Presenter

E-mail contact: sandra.etoka at googlemail.com

Intense line emission of OH masers is a perfect tracer of regions where new stars are born as well as of evolved giant and supergiant stars, shedding large amounts of processed matter into the interstellar medium. The study of this maser emission has many applications, including the determination of magnetic field strength, the study of stellar kinematics and astrometry. Deep surveys at 18 cm with the SKA, where the maser lines from the ground-state of the OH molecule arise, are expected to discover several thousand new sites of maser emission throughout the Galaxy and the Magellanic Clouds.

The ionised, radical and molecular MilkyWay: spectroscopic surveys with the SKA

Mark Thompson[1,*], Henrik Beuther[2], Steven Longmore[3], Adam Ginsburg[4], Clive Dickinson[5], Anthony Remijan[6] and Karl Menten[7]

[1] Centre for Astrophysics Research, School of Physics Astronomy & Mathematics, University of Hertfordshire, College Lane, Hatfield, AL10 9AB, UK
[2] Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heildelberg, Germany
[3] Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, Liverpool L3 5RF, UK
[4] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei Munchen, Germany
[5] Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[6] National Radio Astronomy Observatory, Charlottesville, VA 22903, USA
[7] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany
[*] Presenter

E-mail contact: m.a.thompson at herts.ac.uk

The bandwith, sensitivity and sheer survey speed of the SKA offers a unique potential for deep spectroscopic surveys of the Milky Way. In this chapter we describe the impact on our understanding of the Milky Way that can be achieved by SKA1 & SKA2 surveys of radio recombination lines (RRLs), hydride radicals and molecular absorption and emission lines.

Neutral Hydrogen and Galaxy Evolution

J.M. van der Hulst[1,*], S.-L Blyth[2], and M.A.W. Verheijen[1]

[1] Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700AV Groningen, The Netherlands

[2] Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, Republic of South Africa

E-mail contact: vdhulst at astro.rug.nl

There are still many unanswered questions revolving around exactly how galaxies formed and how they evolve over time. One prominent puzzle is the large discrepancy between the rapid decline in the star formation density between $z = 2$ and $z = 0$ and the much slower decline in HI density. To understand galaxy evolution, in particular the role of HI consumption, accretion and removal, it is crucial to explore HI in the universe out to beyond a redshift of $z \sim 2$.

The Square Kilometre Array will enable us to probe the HI content of galaxies for hundreds of thousands of galaxies in a large variety of environments: Phase-1 will reach $z \sim 1$ while Phase-2 will extend this to a redshift of $z \sim 3$, well beyond the epoch when the star formation density in the universe started dropping dramatically. HI will provide key information about how galaxies get their gas and about the balance between gas accretion and gas removal processes. Simulations are now implementing the details of these processes in order to arrive at the right stellar mass function at $z = 0$ and observations of the HI of hundreds of thousands of galaxies out to $z \sim 3$ will provide a crucial test of the physics implemented in the simulations.

Connecting the Baryons: Multiwavelength Data for HI Surveys

Martin Meyer[1;*], Aaron Robotham[1], Simon Driver[1], Danail Obreschkow[1], Lister Staveley-Smith[1], Martin Zwaan[2]

[1] International Centre for Radio Astronomy Research
[2] European Southern Observatory
* Presenter

E-mail contact: martin.meyer at icrar.org

The science achievable with SKA HI surveys will be greatly increased through the combination of HI data with that at other wavelengths. These multiwavelength datasets will enable studies to move beyond an understanding of HI gas in isolation to instead understand HI as an integral part of the highly complex baryonic processes that drive galaxy evolution.

As they evolve, galaxies experience a host of environmental and feedback influences, many of which can radically impact their gas content. Important processes include: accretion (hot and cold mode, mergers), depletion (star formation, galactic winds, AGN), phase changes (ionised/atomic/molecular) and environmental effects (ram pressure stripping, tidal effects, strangulation). Governing all of these to various extents is the underlying dark matter distribution. In turn, the result of these processes can significantly alter the baryonic states in which material is finally observed (stellar populations, dust, chemistry) and its morphology (galaxy type, bulge/disk ratio, bars, warps, radial profile). To fully understand the evolution of HI and the role it plays in galactic evolution requires the ability to quantify each of these separate processes, and hence to coordinate SKA HI surveys with extensive multi-band photometric and spectroscopic campaigns. In addition, multiwavelength data is essential for statistical methods of HI analysis such as HI stacking and intensity mapping cross-correlations.

In this chapter, we summarise the major advances of multiwavelength survey programs and capabilities that have occurred since the last SKA science review, along with plans for upcoming facilities (eg. LSST, Euclid, SPICA, ALMA, CCAT and 4MOST). We discuss the key science that will be enabled by combining data from these programs with tiered HI surveys on SKA1-SURVEY, SKA1- MID, and ultimately the full SKA.

The Intergalactic Medium and the CosmicWeb

A. Popping[1;*], M. Meyer[1], L. Staveley-Smith[1], D. Obreschkow[1], G.I. Jozsa[2], D.J. Pisano[3] and G. Heald[4]

[1] International Centre for Radio Astronomy Research (ICRAR), The University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia.
[2] SKA South Africa, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa.
[3] Department of Physics and Astronomy,West Virginia University, P.O. Box 6315, Morgantown, WV 26506, USA
[4] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[*] Presenter

E-mail contact: attila.popping at icrar.org

The interaction of galaxies with their environment, the Inter Galactic Medium (IGM), is a very important aspect of galaxy formation. One of the most fundamental, but unanswered questions in the evolution of galaxies is how gas around galaxies is distributed and how it enters the galaxies to support star formation. We have several lines of evidence that the observed evolution of star formation requires gas accretion from the IGM at all times and on all cosmic scales. Until today this gas has been largely unaccounted for and the outstanding question is where this gas resides and what the physical mechanisms of accretion are. The gas is expected to be embedded in an extended CosmicWeb. Large scale filaments of gas are well supported by simulations that have made significant progress in recent years to not only model the large scale structure of the Cosmic Web, but also concentrate on the neutral gas component. The simulations have been increasingly successful in predicting the HI densities in outer disks of galaxies and filaments in the IGM. At high redshift low column density HI clouds are visible as intervening structures in Lyman-alpha absorption lines of QSO spectra. At low redshifts observations have been pushing the limits of existing telescopes, to image the extended environment of galaxies at very low column densities and to detect gas filaments connecting the galaxies.

To truly make significant progress in understanding the distribution of HI in the IGM, column densities of $N_{HI} \sim 10^{18}$ cm^{-2} and below have to be probed over large areas on the sky at arcminute resolution. These are the densities at which the faintest large structures have been found, however all with single dish telescopes that lack the resolution to resolve these structures and investigate any kinematics. Existing interferometers lack the collecting power or short baselines to achieve brightness sensitivities below $N_{HI} \sim 10^{19}$ cm^{-2}. The SKA will for the first time break these barriers and enable making observations an order of magnitude deeper than current interferometers and with an order of magnitude better resolution than single-dish telescopes.

The IGM contains a large fraction of the Universal baryon budget and is key aspect in galaxy formation. This chapter will focus on recent observational results and progress in simulations of the cosmic web. We will motivate the new insights in cosmology and galaxy evolution that the SKA will bring and we will assess the detectability of the IGM at low column densities with SKA-1 and SKA-2.

Galaxy Formation & Dark Matter Modelling in the Era of the Square Kilometre Array

Chris Power[1†], Claudia Lagos[2‡], Carlton Baugh[3], Daniel Cunnama[4], Jian Fu[5], Hansik Kim[6], Cedric Lacey[3], Danail Obreschkow[1], Bo Qin[5], Jie Wang[5], Yougang Wang[5] & Ming Zhu[5]

[1] International Centre for Radio Astronomy Research,The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.
[2] European Southern Observatory,Karl-Schwarzschild-Str. 2, 85748 Garching bei M¨unchen, Germany.
[3] Institute for Computational Cosmology, Durham University, Science Laboratories, South Road, Durham DH1 3LE, United Kingdom.
[4] Department of Physics, University of Western Cape, Bellville 7535, Republic of South Africa.
[5] National Astronomical Observatories, 20A Datun Road, Chaoyang District, Beijing 100012, China PR.
[6] School of Physics, The University of Melbourne, Parville, Vic 3010, Australia.
[*] Presenter

E-mail contact: †chris.power at icrar.org, ‡clagos at eso.org

Theoretical galaxy formation models are an established and powerful tool for interpreting the astrophysical significance of galaxy surveys. These models have been utilised with great success by optical surveys such as 2dFGRS and SDSS, but their application to radio surveys of cold gas in galaxies has been limited. In this chapter we describe how the models have evolved over the last 5 years and explain why this evolution is required if the models are to be applied to cold gas surveys of the kind that will be carried out with the SKA. By linking explicitly a galaxys star formation rate to its molecular hydrogen mass and not its cold gas mass, as was assumed previously, the latest models can naturally reproduce many of the observed global atomic and molecular hydrogen properties of galaxies. We review some of the key results of the latest models and highlight areas where further development of the models is necessary. We also discuss how model predictions can be most accurately compared with observational data, the challenge of creating synthetic galaxy surveys in the SKA era, and how the SKA can used to test models of dark matter.

The SKA as a Doorway to Angular Momentum

D. Obreschkow[1;*], M. Meyer[1], A. Popping[1], P. Quinn[1], and L. Staveley-Smith[1]

[1] International Centre for Radio Astronomy Research (ICRAR).

[*] Presenter

E-mail contact: danail.obreschkow at icrar.org

Angular momentum is one of the most fundamental physical quantities governing galactic evolution. However, the enormous potential of angular momentum science is only just becoming accessible to astronomers, thanks to a dramatic increase in kinematic observations and the emergence of the first kinematically converged simulations of evolving galaxies. The SKA has a unique opportunity to become the world-leading facility for angular momentum studies, given its unprecedented power to measure the resolved and/or global H I kinematics in large, well-characterised galaxy samples. Those measurements will allow (1) a very robust determination of the two-dimensional distribution of galaxies in the (M, j)-plane, (2) the largest, systematic measurement of the relationship between M, j, and tertiary galaxy properties (morphology, gas fraction, depletion time), and (3) the most accurate measurement of the large-scale distribution and environmental dependence of angular momentum. The reason why the SKA is such an important machine for angular momentum studies is that H I extends to the far outskirts of the galactic disks, where most of the angular momentum is hidden. In fact, kinematic H I maps from 21cm interferometry, combined with optical images, allow the specific angular momentum j of disks to be measured within 5% uncertainty – the most accurate measurements to-date. In particular, H I maps outperform optical IFS maps, since the latter are generally limited to smaller radii. Furthermore, j can also be estimated at ~40% accuracy from spatially unresolved H I emission lines combined with spatially resolved optical images.

To predict the capabilities of the SKA1, as specified in the System Baseline Design (March 2013), we adopt the reference survey scenarios considered at the H I Science AssessmentWorkshop (September 2013). Our sensitivity estimations build on a telescope simulation (courtesy to Attila Popping), assuming observations at a declination of -30°. The respective RMS noise levels per beam for an 8h integration with 10kms^{-1} channels are 0.08 mJy (SKA1-MID) and 0.2 mJy (SKA1-Survey), approximately constant ($\sim$ 50% variations) across the ranges of frequency and beam size relevant to this analysis. To estimate the number of detections expected within these telescope specifications, we use a 100 deg^2 mock cone drawn from the S^3-SAX simulation, truncated radially to redshifts below z = 1.2, the distance limit for H I set by the 650 MHz lower limit of SKA1-Survey band 2.

The numerical analysis reveals that the SKA Phase 1 will, in a 2yr wide-field survey, increase the number of high quality (>300 pixels) kinematic H I maps by 2–3 orders of magnitude, enabling precision measurements of the stellar and baryonic j in at least 30,000 galaxies. Our analysis has shown that to reach this goal, a 100% realisation of SKA1-Survey is pivotal. A 50% SKA1 yields 1–2 orders of magnitude less kinematic maps. We find that the number of spatially unresolved, but well-defined (S/N≥5 per channel) H I emission lines with sufficient optical counterparts (m_R <20 and R_e >1") for approximate stellar mass and inclination measurements is of order $2{\cdot}10^6$ (SKA1-Survey, 2yr widefield survey), respectively half that number in a 50% SKA1 scenario. The mock galaxy catalogs used for this analysis are documented and made available at **http://ict.icrar.org/store/staff/do/s3sax.**

Cool Outflows and HI absorbers

Raffaella Morganti[1,2*], Elaine Sadler[3] on behalf of the HI SWG Members

[1] ASTRON, the Netherlands Institute for Radio Astronomy, PO Box 2, 7990AA Dwingeloo, The Netherlands

[2] Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

[3] University of Sydney/CAASTRO School of Physics A28, University of Sydney, NSW 2006, Australia

[*] Presenter

E-mail contact: morganti at astron.nl

HI 21-cm absorption spectroscopy provides a unique probe of the cold neutral gas in normal and active galaxies from redshift $z > 6$ to the present day. There are two headline science drivers for extragalactic HI absorption studies:

Galaxy evolution: Observations of intervening 21cm HI absorption along the line of sight to background radio sources provide unique information about the neutral gas content of galaxies at redshifts far beyond those probed by HI emission-line surveys, yielding information on the kinematics, mass and size of the gas reservoirs in these distant galaxies. The SKA's high sensitivity, broad frequency coverage and wide field of view will allow many thousands of HI absorption lines to be detected out to high redshift, providing information on the evolution of neutral atomic gas which complements future ALMA studies of molecular gas in galaxies at the same cosmic epoch and provides essential observational constraints for galaxy evolution models.

Active galaxies and AGN feedback: The science case for HI absorption studies of AGN has become stronger in recent years, mainly through the discovery that fast AGN-driven HI outflows are now also detected in molecular gas. This has confirmed the picture that most of the gas in AGN-driven outflows is cold, due to rapid cooling of the gas after the interaction with the jet or its cocoon. The combination with ALMA observations, the higher sensitivity of SKA1 and SKA, but in particular the possibility to detect absorption over a much larger range of redshifts ($z = 0$ to $z > 3$), makes this science very compelling.

We describe the status of HI absorption studies, the plans for pathfinders/precursors, the expected breakthroughs which will be possible with SKA1, and some limitations set by the current design.

The Cool Interstellar Medium in Galaxies

W.J.G. de Blok[1;2;3;*], F. Fraternali[4;3], G.H. Heald[1;3], E.A. Adams[1], A. Bosma[5] and B.S. Koribalski[6]

[1] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, the Netherlands
[2] Astrophysics, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
[3] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands
[4] Department of Physics and Astronomy, University of Bologna, via Berti Pichat 6/2, I-40127 Bologna, Italy
[5] Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France
[6] Australia Telescope National Facility, CSIRO Astronomy & Space Science, P.O. Box 76, Epping, NSW 1710, Australia
[*] Presenter

E-mail contact: blok at astron.nl

The transformation of gas into stars is one of the most important processes in galaxy evolution. Understanding the conditions that determine the efficiency of this process, and the associated physics, is the goal of many observational and theoretical studies. They also form important input into numerical computer models of galaxy formation and evolution.

A complete understanding requires knowledge of these processes over a large range in scales: from galaxy-sized scales where gas is transported from outside the galaxy into the disk to parsec scales where individual stars are formed. The recent completion of ALMA is now, for the first time, enabling high-resolution studies of the star-forming ISM in other galaxies over a large range of spatial scales and in a range of environments. The SKA will provide a similar, revolutionary step forward in the study of the neutral, atomic ISM. High-resolution observations of the neutral ISM will provide crucial information on the physics leading to star formation, the effects star formation in turn has on the ISM in the form of feedback processes, and the importance of various cold and warm phases in regulating star formation and with that galaxy evolution.

Similarly, the exquisite surface density sensitivity of SKA at larger spatial scales will enable deep observations of the low-column density neutral hydrogen surrounding galaxies, and will enable a more complete overview and understanding of gas accretion processes that are though to supply galaxies with their gas.

In this chapter we will give on overview of the types of observations and results that the various SKA phases will allow us to obtain. We particularly highlight the great advances that can be made using both the high-resolution as well as low-column density observations that can be obtained with the SKA.

Galactic and Magellanic Evolution with the SKA

N. M. McClure-Griffiths[1;*], S. Stanimirović[2], J. M. Dickey[3], J. E. G. Peek[4], E. Vázquez-Semadeni[6], D. Li[3], M. E. Putman[5], M.-A. Mivilles-Deschênes7, J. Bland-Hawthorn[7]

[1] CSIRO Astronomy & Space Science, PO Box 76, Epping NSW 1710 Australia
[2] Department of Astronomy, University of Wisconsin, Madison, WI 53706, USA
[3] University of Tasmania, School of Maths and Physics, Private Bag 37, Hobart, TAS 7001, Australia
[4] Department of Astronomy, Columbia University, New York, NY 10027, USA
[5] Centro de Radioastronomía y Astrofísica, UNAM, Morelia, Mich., 58089 MEXICO
[6] National Astronomical Observatories of China, China
[7] CNRS - Institut d'Astrophysique Spatiale Université Paris-XI, Orsay, France
[8] Sydney Institute for Astrophysics, The University of Sydney, Australia
[*] Presenter

E-mail contact: naomi.mcclure-griffiths at csiro.au

As we strive to understand how galaxies evolve, we can apply our increased knowledge, and test our theories, in nearby systems that we can observe in much greater detail. Our own Galaxy, the Milky Way and Magellanic Clouds each provide unique windows into the evolution of galaxies, each with its own metallicity and star formation rate. They allow us to study with more detail than anywhere else in the Universe how galaxies acquire fresh gas to fuel their continuing star formation, how they circulate gas and how they turn warm, diffuse gas into molecular gas and ultimately, stars. The λ21-cm line of atomic hydrogen (H I) is an excellent tracer of the neutral interstellar medium in galaxies. H I is found in a variety of environments, from dense clouds to the diffuse galactic halo and shows structure with size scales from kilo parsecs to a few tens of Astronomical Units. With the SKA, working together with ALMA, we will be able to completely revolutionise our understanding of the evolution of gas in galaxies.

In this chapter we outline a number of areas where the SKA will utterly transform our understanding of the Milky Way, Magellanic Clouds and Magellanic System. Specifically we will measure the amount of mass in the cold neutral medium (CNM) as a function of Galactic position using a densely sampled grid of 21-cm absorption. We will understand how the warm and cold atomic gas interrelate and vary with position on all scales larger than molecular clouds. We will be able to understand the physical processes of gas accretion onto the Galaxy and Magellanic clouds, including the exchange of gas between the disk and halo through the galactic fountain, and loss of gas through a pressure-driven wind. Finally, by combining optical stellar dust tomography and segmented 21-cm line emission structures we will determine the 4D structure of the Galaxy's ISM. The understanding gained in the Milky Way and Magellanic Clouds will provide much of the physical underpinning for how large spirals and dwarf irregular galaxies evolve.

The Physics of the Cold Neutral Medium: Low-frequency Radio Recombination Lines with the Square Kilometre Array.

J. B. R. Oonk[1;2;*], L. K. Morabito[2], F. Salgado[2], C. Toribio[1], R. J. van Weeren[3], A. G. G. M. Tielens[2] and H. J. A. Röttgering[2]

[1] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, NL-7990 AA Dwingeloo, the Netherlands
[2] Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[*] Presenter

E-mail contact: oonk at astron.nl

The Square Kilometre Array (SKA) will transform our understanding of the role of the cold, atomic gas in galaxy evolution. The interstellar medium (ISM) is the repository of stellar ejecta and the birthsite of new stars and, hence, a key factor in the evolution of galaxies over cosmic time. Cold, diffuse HI clouds are a key component of the ISM, but so far this phase has eluded detailed studies, because the main tracer, the HI 21 cm line, does not constrain basic physical information of the gas (e.g., temperature, density) well.

With the SKA we can study this component of the ISM through low-frequency (<350 MHz) radio recombination lines (RRL) from carbon and hydrogen, which provide a unique, sensitive probe of the physical conditions in cold, HI clouds. The superb sensitivity, large field of view, frequency resolution and coverage of the SKA allows for efficient surveys of the sky, that will revolutionize the field of low-frequency recombination line studies. By observing these lines the SKA will determine the thermal balance, ionization rate and chemical enrichment of the cold, neutral medium (CNM) on unprecedented small scales in our own Galaxy and beyond. Furthermore, being sensitive only to the cold, atomic gas, observations of low-frequency RRL's with the SKA will disentangle the warm and cold constituents of the HI signal.

We propose to perform (i) a CRRL survey of the Galactic plane, deriving, for the first time, a comprehensive inventory of the low-density cold ISM in our Galaxy. This will allow us to quantify its role in the overall pressure, mass and energy balance of the interstellar medium and how it relates to the cycles star formation and death. (ii) Through a survey of extragalactic radio sources, the low density ISM will be probed over almost the entire history of the universe. This will provide important input on how the characteristics of this gas evolve with time.

Euclid & SKA Synergies

Thomas D. Kitching[1;*], David Bacon[2], Michael Brown[3], Phil Bull[4], Jason McEwen[1], Masamune Oguri[5], Keitaro Takahashi[6], Kinwah Wu[1], Daisuke Yamauchi[7]

[1] University College London, Department of Space and Climate Physics
[2] ICG, University of Portsmouth
[3] Department of Physics, University of Manchester
[4] University of Oslo, Institute for Theoretical Physics
[5] Graduate School of Science, University of Tokyo, Japan
[6] Graduate School of Science and Technology, Kumamoto University, Japan
[7] Research Center for the Early Universe, University of Tokyo, Japan
[*] Presenter

E-mail contact: t.kitching at ucl.ac.uk

Over the past few years two of the largest and highest fidelity experiments conceived have been approved for construction: Euclid is an ESA M-Class mission that will map three-quarters of the extra galactic sky with Hubble Space Telescope resolution optical and NIR imaging, and NIR spectroscopy, it has scientific aims to create a map of the dark Universe (and others) and to determine the nature of dark energy, the Square Kilometre Array (SKA) has similar scientific aims (and others) using radio wavelength observations. The two experiments are synergistic in several respects, both through the scientific objectives and through the control of systematic effects. SKA Phase-1 and Euclid will be commissioned on similar timescales offer exciting opportunity to exploit synergies between these facilities.

Multiple supermassive black hole systems: SKA's future leading role

Roger Deane[1;2;*], Gianni Bernardi[2;3;4], Mickaël Coriat[1;2], Sandor Frey[5], Ian Heywood[6], Matt Jarvis[7;8], Hans-Rainer Klöckner[9], Zsolt Paragi[10]

[1] University College London, Department of Space and Climate Physics
[2] ICG, University of Portsmouth
[3] Department of Physics, University of Manchester
[4] University of Oslo, Institute for Theoretical Physics
[5] Graduate School of Science, University of Tokyo, Japan
[6] Graduate School of Science and Technology, Kumamoto University, Japan
[7] Research Center for the Early Universe, University of Tokyo, Japan
[*] Presenter

E-mail contact: roger.deane at ast.uct.ac.za

To date there are poor observational constraints on multiple supermassive black hole (SMBH) systems with separations comparable to a SMBH gravitational sphere of influence (<<1 kpc). I will discuss how the SKA will make leading contributions towards understanding how multiple SMBH systems evolve; the resultant impact on their host galaxies; as well as the low-frequency gravitational waves they emit. The SKA is unique in this field in that it can constrain the evolution of these exotic systems using a number of different techniques, including (1) direct imaging of flat-spectrum sources; (2) inference of unresolved binary SMBHs from the large-scale radio-jet morphology; and (3) estimates of the sub-parsec population from detection of the low-frequency stochastic gravitational background, using a pulsar timing array. These methods can be used to probe a broad range in orbital separations of binary/multiple SMBHs and will enable the SKA to explore this observational frontier from different perspectives, which differentiates it from existing/planned electromagnetic and gravitational wave facilities.

The connection between radio and high energy emission in black hole powered systems.

M. Giroletti[1;*], M. Orienti[1], F. D'Ammando[1;2], F. Massaro[3], G. Tosti[4;5] on behalf of the Fermi-LAT collaboration, and R. Lico[1;2], G. Giovannini[1;2], I. Agudo[6], A. Alberdi[7], Pandey-Pommier[8], A. Wolter[9]

[1] INAF Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
[2] University of Bologna, Italy
[3] Yale University
[4] University of Perugia, Italy
[5] INFN Perugia, Italy
[6] Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands
[7] Instituto de Astrofísica de Andalucía (CSIC), Granada, Spain
[8] Observatoire de Lyon, France
[9] Osservatorio Astronomico di Brera, Italy
[*] Presenter

E-mail contact: giroletti at ira.inaf.it

Strong evidence exists for a highly significant correlation between the radio flux density and the high energy (E > 100 MeV) gamma-ray energy flux in blazars revealed by the Fermi Gamma-ray Space Telescope (Ackermann et al. 2011a, ApJ, 741, 30). However, there are central issues that need to be clarified in this field: what are the counterparts of the about 30% of gamma-ray sources that are as yet unidentified? Are they just blazars in disguise or they are something more exotic, possibly associated with dark matter? How would they fit in the radio-gamma ray connection studied so far? With their superb sensitivity, SKA1-mid and SKA1-survey will help to resolve all of these questions. Even more, while the radio-MeV/GeV connection has been firmly established, a radio-VHE (Very High Energy, E > 0.1 TeV) connection has been entirely elusive so far. The advent of CTA (Cherenkov Telescope Array) in the next few years and the expected CTA-SKA1 synergy will offer the chance to explore this connection, which is even more intriguing since it involves the opposite ends of the electromagnetic spectrum and the acceleration of particles up to the highest energies.

We are already preparing to address these questions by exploiting data from the various SKA pathfinders and precursors. We have obtained 18 cm European VLBI Network observations of E >10 GeV sources, with a detection rate of 83% (and higher than 50% for the unidentified sources). Moreover, we are cross correlating the Fermi catalogs with the MurchinsonWidefield Array commissioning survey: when faint gamma-ray sources are considered, pure positional coincidence is not significant enough for selecting counterparts and we need an additional physical criterion to pinpoint the right object. It can be the radio spectral index, variability, or polarization; timing studies can also reveal pulsars, which are often found from dedicated searches of unidentified gamma-ray sources. In all these areas, SKA will be the ideal instrument for investigating these characteristics in conjunction with CTA. In terms of physics, a proper classification of the unidentified gamma-ray sources and the study of the radio-gamma ray connection will be essential to constrain the processes at work in the vicinity of super massive black holes.

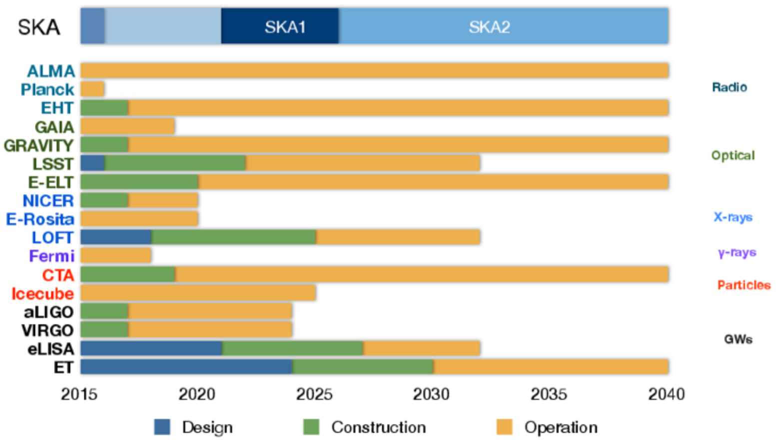
SKA and the next generation multi-wavelength observatories

J. Antoniadis[1], S. Bogdanov[2], L. Guillemot[3,4], M. Kramer[1], R. P. Mignani[5,6,7], A. Possenti[8,*], B. W. Stappers[9] and P. Torné Torres[1]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[3] Laboratoire de Physique et Chimie de l'Environnement, 45071 Orléans, France
[4] Station de radioastronomie de Nançay, Obs. Paris, CNRS/INSU, 18330 Nançay, France
[5] Mullard Space Science Laboratory, UCL, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
[6] INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via Bassini 15, 20133, Milano, Italy
[7] Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265, Zielona Góra, Poland
[8] INAF-Osservatorio Astronomico di Cagliari, via della Scienza 5, 09047 Selargius, Italy
[9] School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, UK
[*] Presenter

E-mail contact: jantoniadis at mpifr-bonn.mpg.de

The Square-Kilometer Array (SKA) is an integral part of the next-generation observatories that will survey the Universe across the electromagnetic spectrum, and beyond, revolutionizing our view of Fundamental Physics, Astrophysics and Cosmology. Owing to their extreme nature and clock-like characteristics, pulsars discovered and monitored by SKA will enable a broad range of scientific endeavor and play a key role in this quest. This chapter summarizes the Key Science Goals that will be achieved with coordinated efforts among SKA and other observatories, focusing on the anticipated benefits for pulsar astrophysics.



Timeline for observatories of interest for synergistic neutron star science with the SKA.

Synergy between the Large Synoptic Survey Telescope and the Square Kilometre Array

David Bacon[1;*], Sarah Bridle[2], Rob Fender[3], Zeljko Ivesic[4], Matt Jarvis[3], Michael Brown[2], Stefano Camera[2], Philip Bull[5], Filipe Abdalla[6], John McKean[7], Jeffrey Newman[8], Chris Blake[9], Chris Fassnacht[10], Neal Jackson[2], Bob Mann[11], Phil Marshall[12], Carole Mundell[13], Ue-Li Pen[14], Alvise Raccanelli[15], Martin Sahlen[3], Mario Santos[16], Michael Schneider[17], Stephen Smartt[18] and Tony Tyson[10]

[1] Institute of Cosmology and Gravitation, University of Portsmouth, Burnaby Road, Portsmouth P01 3FX, UK
[2] Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[3] University of Oxford, Department of Physics, Astrophysics, Keble Road, Oxford, OX1 3RH, UK
[4] Astronomy Department, University of Washington, Box 351580, Seattle WA 98195-1580
[5] Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway
[6] Department of Physics & Astronomy, University College London, Gower Place, London WC1E 6BT, UK
[7] Astronomy Group, ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
[8] University of Pittsburgh, Department of Physics and Astronomy, 310 Allen Hall, 3941 O' Hara St. Pittsburgh, PA 15260, USA
[9] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, Victoria 3122, Australia
[10] Department of Physics, University of California, One Shields Avenue, Davis, CA 95616, USA
[11] Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[12] Kavli Institute for Particle Astrophysics and Cosmology, P.O. Box 20450, MS29, Stanford, CA 94309, USA
[13] Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
[14] Canadian Institute for Theoretical Astrophysics, McLennan Laboratories, 60 St. George Street, Toronto, Ontario, Canada
[15] NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[16] Department of Physics, University of Western Cape, Cape Town 7535, South Africa
[17] Lawrence Livermore National Laboratory, P.O. Box 808 L-211, Livermore, CA 94551, USA
[18] Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland UK
[*] Presenter

E-mail contact: david.bacon at port.ac.uk

We overview the science benefits of combining information from the Square Kilometre Array (SKA) with that from the Large Synoptic Survey Telescope (LSST). We first summarise the capabilities and timeline of the LSST and overview its science goals. We then discuss the cosmology questions in common between the two projects and how they can be best addressed by combining the data from both telescopes. We describe how weak gravitational lensing and galaxy clustering studies with LSST and SKA can provide improved constraints on the causes of the cosmological acceleration. We summarise the benefits to galaxy evolution studies of combining deep optical multi-band imaging with radio observations. One of the most unique features of the LSST is its temporal cadence in the optical waveband, which can be very well matched in the radio by the SKA.

Delivering SKA Science

P.J.Quinn[1,*], T. Axelrod[2], I. Bird[3], R. Dodson[1], A. Szalay[4], A. Wicenec[1]

[1] International Centre for Radio Astronomy Research (ICRAR)
[2] LSST Project
[3] LHC Computing Grid Project, CERN
[4] Institute for Data Intensive Science, Johns Hopkins University
[*] Speaker

E-mail contact: peter.quinn at icrar.org

The SKA will be capable of producing a stream of science data products that are Exa-scale in terms of their storage and processing requirements. This Google-scale enterprise is attracting considerable international interest and excitement from within the industrial and academic communities. In this chapter we examine the data flow, storage and processing requirements of a number of key SKA survey science projects to be executed on the baseline SKA1 configuration. Based on a set of conservative assumptions about trends for HPC and storage costs, and the data flow process within the SKA Observatory, it is apparent that survey projects of the scale proposed will potentially drive construction and operations costs beyond the current anticipated SKA1 budget. This implies a sharing of the resources and costs to deliver SKA science between the community and what is contained within the SKA Observatory. A similar situation was apparent to the designers of the LHC more than 10 years ago. We propose that it is time for the SKA project and community to consider the effort and process needed to design and implement at distributed SKA science data system that leans on the lessons of other projects and looks to recent developments in Cloud technologies to ensure an affordable, effective and global achievement of SKA science goals.

Very Long Baseline Interferometry with the SKA

Zsolt Paragi[1,*] et al.

1 Joint Institute for VLBI in Europe, Postbus 2, 7990AA Dwingeloo, Netherlands

* Presenter

E-mail contact: zparagi at jive.nl

A high angular resolution capability has long been considered an essential part of the Square Kilometer Array (SKA) concept. SKA-VLBI will provide very sensitive, milliarcsecond resolution imaging that is important to study active galactic nuclei down to very low luminosities, to understand the detailed physics of jet formation and its coupling to the accretion process, and to understand the growth of the first generation of massive black holes in the Universe. It will also allow the detection $10^6\ M_\odot$ dark matter haloes from high resolution imaging of gravitationally lensed arcs to investigate galaxy formation scenarios and test models for dark energy from the measurement of geometric distances to nuclear water maser galaxies at high redshift. Ultra-precise astrometry at the microarcsecond level to determine distances and transverse velocities via the measurement of proper motion and parallax of Galactic objects will be possible out to a distance of tens of kpc. Achieving this for a large fraction of the radio pulsar population detected in the SKA Galactic pulsar census will enable a range of scientific goals, including: strong field tests of gravity, tomographic modelling of the large scale Galactic magnetic field and mapping the ionized interstellar plasma in the Galaxy, core-collapse physics and the physics of neutron stars. Accurate distance and proper motion measurements via relative astrometry are also envisaged for many other classes of compact radio source with emission in the SKA frequency range – for instance, masers, protostellar objects and accreting compact objects. For radio-emitting stars, in addition to the distance via parallax, the presence of a planetary companion can be sought via the reflex motion of the star.

In the talk the possible realizations of SKA-VLBI along with expected sensitivities and capabilities based on the SKA1 Baseline Design will be presented. Selected applications in the field of astrometry, VLBI surveys, and resolving explosive outflows will be shown as well.

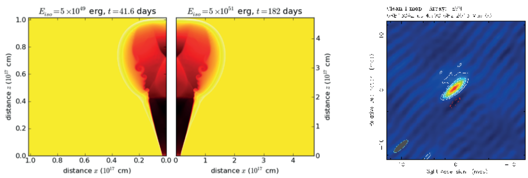


Figure 1: Left: 2D simulations of gamma-ray burst (GRB) jets. The scale invariance between relativistic jets of different energy allows easy reproduction of the jet dynamics. This provides a powerful method for fitting simulation results to observational data (van Eerten et al. 2012). With SKA-VLBI this will be possible for a large number of GRBs. Right: Early e-EVN detection of the highest luminence GRB for decades, GRB130427A.

The synergy between SKA and ALMA in studying the formation of stars and stellar clusters

Sergio Molinari

Synergies between SKA and ALMA: observations of Nearby Galaxies

Rosita Paladino[1;2*], Jan Brand[2], Emanuela Orrù[3], Viviana Casasola[2], Elisabetta Liuzzo[2], Marcella Massardi[2], Arturo Mignano[2]

[1] Università di Bologna (Italy)

[2] INAF-Istituto di Radioastronomia (Italy)

[3] ASTRON (The Netherlands)

[*] Presenter

E-mail contact: paladino at ira.inaf.it

The past decade has seen amazing advances in radioastronomy, which led to the construction of brand-new instruments such as LOFAR and ALMA, and the updating of existing ones, e.g. JVLA and e-MERLIN. The SKA will be the spearhead of this technological development and it will change the way astrophysical topics have been studied so far by opening up new frequency windows with unprecedented spatial resolution and sensitivity. The SKA location in the southern hemisphere makes it particularly suitable to complement ALMA, which is already giving exciting results both on the local and the more distant Universe.

Among the possible synergies between SKA and ALMA, we focus on the observations of nearby star forming galaxies and AGNs. Star formation processes in galaxies involve all the components of the interstellar medium, so the only way to have a complete picture of them is through multifrequency observations.

ALMA observes gas and dust emission, while the SKA will provide high resolution and sensitivity within an acceptable amount of observing time to trace both the free-free thermal component and the non-thermal synchrotron emission, and to separate their contribution locally in star forming galaxies.

The SKA will allow the extention of the kind of studies currently done on galactic H II regions to nearby spiral and irregular galaxies. The combination of SKA and ALMA will allow the global and local triggering of high-mass star formation to be established.

Furthermore, ALMA and SKA will allow the spatial distinction of the emission due to the AGN from that of the host galaxy. Constructing the continuum spectral energy distribution from centimeter to sub-millimeter wavelengths, will allow the investigation of the interaction between star formation and nuclear activity.

By the time the SKA will start observing, ALMA will have already imaged many nearby galaxies in the southern hemisphere, for which no low frequency data at comparably high spatial resolution will be available. The SKA will fill this gap, and have a profound impact on the studies of nearby galaxies, making valuable contributions to our understanding of star formation processes, and of the role of magnetic fields and cosmic rays in them.

Lunar detection of ultra-high-energy cosmic rays and neutrinos

J. Alvarez-Muñiz[1], J.D. Bray[2;*], S. Buitink[3], R.D. Dagkesamanskii[4], R.D. Ekers[5], H. Falcke[3;6], K.G. Gayley[7], T. Huege[8], C.W. James[9], M. Mevius[10], R.L. Mutel[7], R.J. Protheroe[11], O. Scholten[10], F.G. Schröder[8], R.E. Spencer[12], and S. ter Veen[3]

[1] Depto. de Física de Partículas & Instituto Galego de Física de Altas Enerxías, Univ. de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[2] School of Physics & Astronomy, Univ. of Southampton, SO17 1BJ, United Kingdom
[3] Dept. of Astrophysics/IMAPP, Radboud Univ. Nijmegen, 6500 GL Nijmegen, The Netherlands
[4] LPI, Russian Academy of Sciences, Moscow Region 142290, Russia
[5] CSIRO Astronomy & Space Science, NSW 2122, Australia
[6] Netherlands Institute for Radio Astronomy (ASTRON), 7990 AA Dwingeloo, The Netherlands
[7] Dept. of Physics & Astronomy, Univ. of Iowa, IA 52242, USA
[8] IKP, Karlsruhe Institut für Technologie, Postfach 3640, 76021 Karlsruhe, Germany
[9] ECAP, Univ. of Erlangen-Nuremberg, 91058 Erlangen, Germany
[10] KVI-CART, Univ. of Groningen, 9747 AA Groningen, The Netherlands
[11] School of Chemistry & Physics, Univ. of Adelaide, SA 5005, Australia
[12] School of Physics & Astronomy, Univ. of Manchester, M13 9PL, United Kingdom
[*] Presenter

E-mail contact: j.bray at soton.ac.uk

The origin of the most energetic particles in nature, the ultra-high-energy (UHE) cosmic rays, is still a mystery. Due to their extremely low flux, even the 3,000 km^2 Pierre Auger detector registers only about 30 cosmic rays per year with sufficiently high energy to be used for directional studies. A method to provide a vast increase in collecting area is to use the lunar technique, in which groundbased radio telescopes search for the nanosecond radio flashes produced when a cosmic ray interacts with the Moon's surface. The technique is also sensitive to the associated flux of UHE neutrinos, which are expected from cosmic ray interactions during production and propagation, and the detection of which can also be used to identify the UHE cosmic ray source(s). An additional flux of UHE neutrinos may also be produced in the decays of topological defects from the early Universe.

Observations with existing radio telescopes have shown that this technique is technically feasible, and established the required procedure: the radio signal should be searched for pulses in real time, compensating for ionospheric dispersion and filtering out local radio interference, and candidate events stored for later analysis. For the SKA, this requires the formation of multiple tied-array beams, with high time resolution, covering the Moon, with either SKA-low or SKA-mid. With its large collecting area and broad bandwidth, the SKA will be able to detect the known flux of UHE cosmic rays using the visible lunar surface – millions of square km – as the detector, providing sufficient detections of these extremely rare particles to solve the mystery of their origin.

Overview of Complementarity and Synergy with Other Wavelengths in Cosmology

Keitaro Takahashi[1;*], Michael L. Brown[2], Carlo Burigana[3], Carole A. Jackson[4], Matt Jarvis[5], Thomas D. Kitching[6], Jean-Paul Kneib[7], Masamune Oguri[8], Simon Prunet[9], Huanyuan Shan[7], Jean-Luc Starck[a], and Daisuke Yamauchi[b]

[1] Graduate School of Science and Technology, Kumamoto University, Japan
[2] Jodrell Bank Centre for Astrophysics, University of Manchester, Oxford Road, Manchester M139PL, UK
[3] INAF-IASF Bologna, Via Piero Gobetti 101, I-40129, Bologna, Italy Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Giuseppe Saragat 1, I-44100 Ferrara, Italy
[4] ICRAR, Curtin University, GPO Box U1987, Perth 6845, Australia
[5] Astrophysics Department, University of Oxford, UK
[6] Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK
[7] Ecole Polytechnique Fédérale de Lausanne, Laboratoire d'Astrophysique, Observatoire de Sauverny, CH-1290 Versoix, Switzerland
[8] Graduate School of Science, University of Tokyo, Japan
[9] Canada-France-Hawaii Telescope
[a] Laboratoire AIM, UMR CEA-CNRS-Paris 7, Irfu, SAp, CEA Saclay, F-91191 Gif sur Yvette cedex, France
[b] Research Center for the Early Universe, University of Tokyo, Japan
* Presenter

E-mail contact: keitaro@sci.kumamoto-u.ac.jp

The Square Kilometer Array (SKA) will perform continuum and HI all-sky surveys of unprecedented volume which contribute substantially to unravelling fundamental cosomological issues. In the same period, next-generation facilities of other wavelengths, such as Euclid, LSST and WFIRST (optical/IR), PRISM, PIXIE and LiteBird (CMB/CIB) and eROSITA (X-ray), will also be available and perform huge surveys.

In the context of cosmology, combining and cross-correlating multiple-wavelength data can not only break the degeneracy in parameter determination but also reduce the systematic errors. The latter is especially important because systematic errors, rather than statistical ones, will dominate the parameter errors in the era of huge surveys. Further, it has been suggested that even cosmic variance could be reduced by a method called multi-tracer, which is expected to be powerful to study primordial non-Gaussianity and galaxy bias.

In this chapter, we give an overview of complementarity and synergy between the SKA and other next-generation facilities. First we briefly describe each project and then discuss the expected benefit focusing on studies on dark energy and primordial non-Gaussianity through weak lensing, baryon acoustic oscillation, integrated Sachs-Wolfe effect, cluster number count and multi-tracer method.

Enabling the next generation of cm-wavelength studies of highredshift molecular gas with the SKA

Jeff Wagg[1,*], Chris Carilli[2,3], Elisabete Da Cunha[4], Fabian Walter[4], Manuel Aravena[5], Ian Heywood[6], Jacqueline Hodge[7], Eric Murphy[8], Dominik Riechers[9], Ran Wang[10]

[1] SKA Organisation, Lower Withington, UK
[2] NRAO, Socorro, USA
[3] Cavendish Astrophysics Group, Cambridge, UK
[4] MPIA, Heidelberg, Germany
[5] U. Diego Portales, Santiago, Chile
[6] CASS, Sydney, Australia
[7] NRAO, Charlottesville, USA
[8] IPAC, Caltech, Pasadena, USA
[9] Cornell University, Ithaca, USA
[10] KIAA, Peking, Beijing, China
* Presenter

E-mail contact: j.wagg at skatelescope.org

The square kilometre array will be a revolutionary instrument for the study of gas in the distant Universe. Phase 1 of the SKA will be among the first facilities with sufficient senstivity to detect and image atomic HI in individual galaxies at significant cosmological distances, complementing ongoing ALMA imaging of redshifted high-J CO line emission and far-infrared interstellar medium lines such as [CII] 157.7μm. At frequencies below ~50 GHz, observations of redshifted emission from low-J transitions of CO, HCN, HCO^+, HNC, H_2O and CS provide insight into the kinematics and mass budget of the cold, dense star-forming gas in galaxies. In advance of ALMA band 1 (35 to 52 GHz) deployment, the most sensitive facility for high-redshift studies of molecular gas operating below 50 GHz is the Karl G. Jansky Very Large Array (VLA). Here, we present an overview of the role that the SKA should play in molecular emission line studies during phase 1 and 2, with an emphasis on studies of the dense gas tracers directly probing regions of active star-formation.