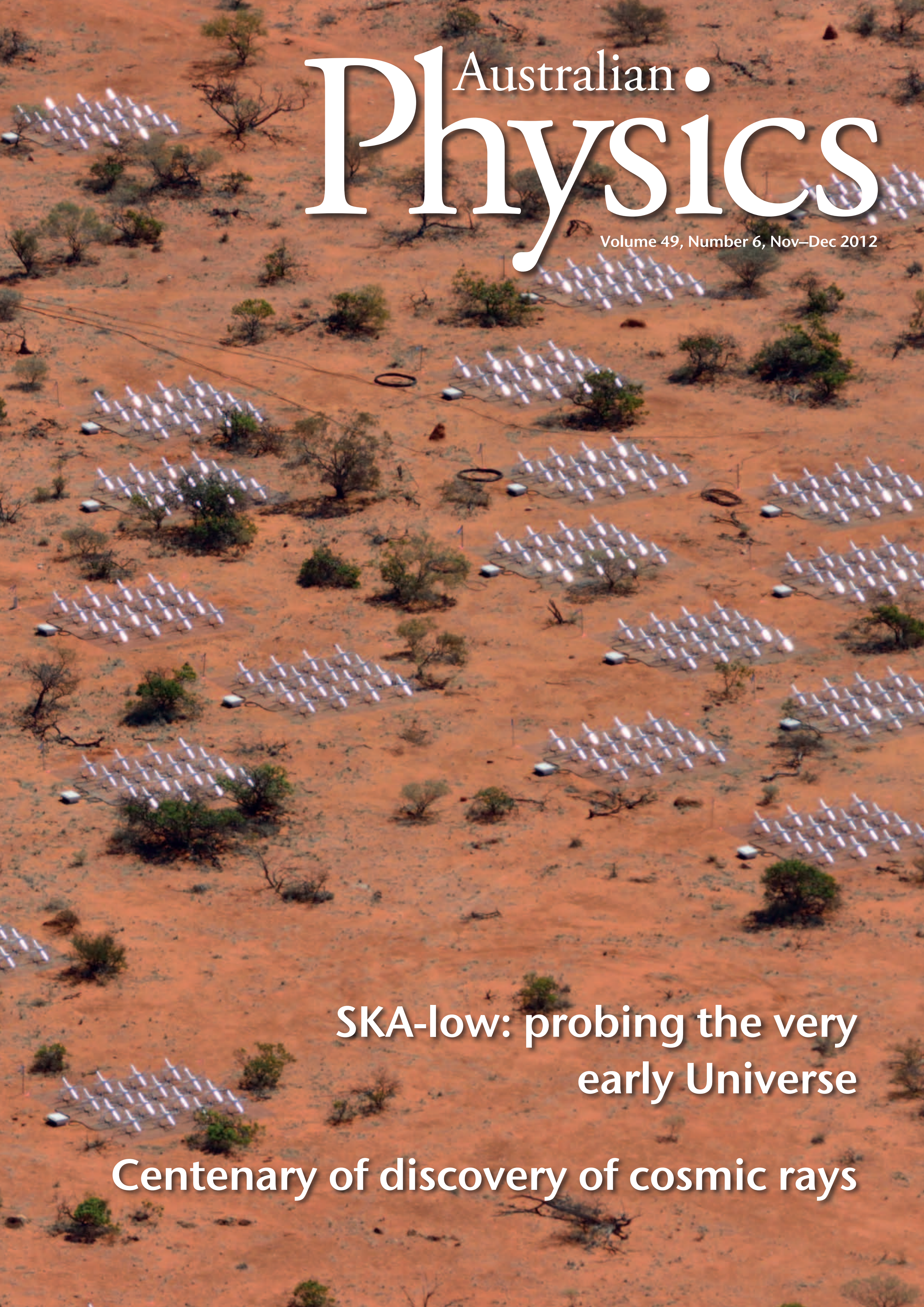

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SKA-low: probing the very early Universe
Centenary of discovery of cosmic rays

The path to the low frequency Square Kilometre Array in Australia

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The Square Kilometre Array (SKA) is a planned next-generation radio telescope to be constructed at two locations, in Western Australia and Southern Africa, utilising a range of antenna technologies to cover the radio frequency range required to satisfy its science goals. The SKA pushes the boundaries of physics and engineering on a number of fronts simultaneously and is thus a very ambitious project with innovation at its heart. In this article we consider the component of the SKA to be built in Western Australia in full scope, a survey telescope designed for very early Universe cosmology, operating at low radio frequencies. The path to the low frequency SKA in Australia involves precursor instrumentation, SKA pre-construction activities, and the deployment of the final instrument in two phases over approximately the next decade.

Science goals for the low frequency SKA

A significant component of the SKA (Hall et al. [1]) will operate at frequencies in the range 70 – 450 MHz, this portion of the telescope being referred to as SKA-low. The frequency range is driven by science goals that seek to use redshifted radiation from neutral hydrogen as a probe of conditions in the early and evolving Universe (Morales & Wyithe [2], Furlanetto, Oh & Briggs [3], Carilli et al. [4]).

The SKA-low focus on early Universe cosmology (summarised in Figure 1) will largely be via the study of the so-called dark ages of the Universe, the period after the Big Bang when the first stars and galaxies formed. The highly successful Wilkinson Microwave Anisotropy Probe (WMAP: http://map.gsfc.nasa.gov/) has extensively investigated the cosmic microwave background (CMB), the radiation leftover from the Big Bang. The CMB radiation originated from the time in the early Universe (approximately 300,000 years after the Big Bang) when baryonic matter and radiation decoupled, known as the Epoch of Recombination. Prior to the Epoch of Recombination, the Universe was fully ionised.

Once baryonic matter and radiation decoupled at the Epoch of Recombination, photons were free to propagate through the Universe and the baryonic matter (overwhelmingly hydrogen) was able to coalesce under the influence of gravity to form the first luminous structures, stars and galaxies. Over time, as these stars and galaxies produced ionising radiation, the remaining baryonic material that was not formed into stars and galaxies was progressively ionised. The transition from a Universe in which the baryonic material was neutral, to a Universe in which the baryonic material was largely ionised, is known as the Epoch of Reionisation (EoR) and is thought to have occurred within the first billion years after the Big Bang (the Universe is almost 14 billion years old). The most promising observational probe of the EoR is the radio wavelength signature from neutral hydrogen gas that was the fuel for the formation of the first stars and galaxies, the emission being heavily redshifted to low radio frequencies for an observer on the Earth.

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It is rather straightforward to make the statement that the EoR was a major phase in the evolution of the Universe, given evidence for the Big Bang and given the fully ionised state of the Intergalactic Medium in the Universe today. However, the details of the physics of the transition are likely to be complex and models for the EoR are currently a point of major debate. An enormous amount of interest in the EoR, both theoretical and experimental, exists within the physics and astrophysics community. As well as being a substantial part of the SKA science case, the search for the EoR signal features heavily in the motivations behind a new generation of low frequency radio telescopes: The Low Frequency Array, LOFAR (van Harlem et al. 2012, in preparation); the Murchison Widefield Array, MWA (Tingay et al. [5]); the Long Wavelength Array, LWA (Greenhill & Bernardi [6]) and the Precision Array to Probe the EoR, PAPER (Parsons et al. [7]). In the period 1997 – 2012, 240 papers with the phrase "Epoch of Reionisation" in the title have been published, garnering 4681 citations. Many of these papers are theoretical predictions of what the EoR signal will look like, with the first significant observational constraints at radio wavelengths being generated only very recently (e.g. Paciga et al. [8]).

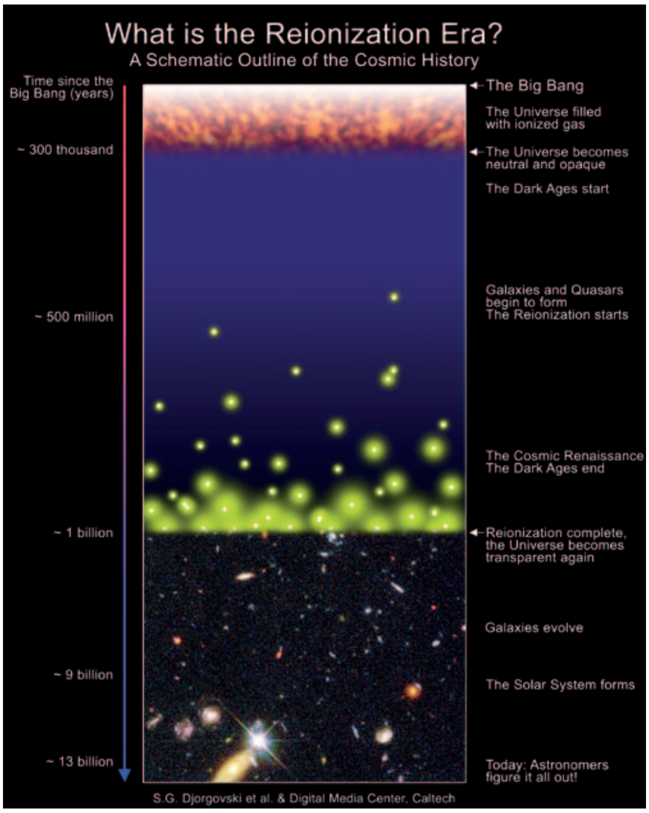

Figure 1: a schematic summary of the evolution of the early Universe (Credit: S.G. Djorgovski et al., Caltech).

This high level of interest is prompted by the fundamental physics that influences the evolution of the Universe at early times, including the role of enigmatic dark matter. Dark matter has been known to exist from the 1930s via astronomical observations but it is only recently that some understanding of its properties has started to emerge. As a significant component of matter in the early Universe, dark matter is likely to have had an influence on how the first stars and galaxies formed from neutral hydrogen during the EoR, as modeled recently by, for example, Visbal et al. [9].

The low frequency SKA concept

With its probing of fundamental physics, the low frequency component of the SKA is complementary to other large-scale physics experiments such as the Compact Muon Solenoid detector at the Large Hadron Collider and is of great interest to physicists and cosmologists. But how will SKA-low be implemented?

"Advances in technology mean that direct interface of SKA-low radio receivers to programmable digital signal processing engines, and general-purpose computers, is now feasible"

The low radio frequencies demanded by EoR investigations allow a departure from the dominant form of radio astronomy antenna technology used over the last 40 years, these earlier instruments being based on large steerable dishes and arrays of small dishes. Advances in technology mean that direct interface of SKA-low radio receivers to programmable digital signal processing engines, and general-purpose computers, is now feasible. This marriage of technologies gives a software-defined telescope of unprecedented capability and flexibility. In particular, the all-important forming of beams on the sky takes place in digital electronics rather than in parabolic dishes, allowing the use of simple, stationary antennas having a large natural field-of-view. One potential antenna type is shown in Figure 2 but a number of other types, some resembling the TV antennas which also operate in this frequency band, are being evaluated. With all the beamforming done electronically, there is no reason why many such operations cannot be done in parallel, allowing astronomers to "re-use" the telescope collecting area. Many beams, pointed at different areas of the sky, can be used to support simultaneous, independent science programs.

The simple nature of the SKA-low antennas means they are well suited to mass manufacture techniques and can be produced at low unit cost. Large arrays of these antennas can therefore be produced at modest cost, with the main functionality of the resulting telescope being defined by increasingly cost-effective ICT systems, allowing an evolution of SKA-low capability. Of course, supporting infrastructure, deployment and operations costs remain major engineering challenges.

The full SKA project is envisaged to proceed in a staged fashion, with two phases of construction. Phase 1 is intended to build 10% of the full SKA, with construction commencing in 2016. After Phase 1 is complete, Phase 2 will construct the remaining 90% of the SKA. SKA-low construction will be part of these phases, with Phase 1 SKA-low consisting of several hundred thousand low frequency antennas and Phase 2 consisting of several million.

About half the SKA-low antennas will be located in the central 10 km region, with the remainder being distributed in clumps, or stations, located out to perhaps 1000 km. Custom fibre networks for the core region and remote, radio-quiet power solutions are particularly challenging aspects for a project likely to be cost-capped at less than 300 million euro. Curtin University has been a driver of the sparse aperture array developments central to SKA-low and is leading the Murchison Widefield Array (MWA) project, described below. In a significant direct contribution by MWA, International Centre for Radio Astronomy Research (ICRAR)/Curtin and international colleagues are using MWA infrastructure in their deployment of the first SKA-low test antennas in WA in late 2012. The next few years will see a succession of increasingly capable verification systems in the Murchison, culminating in a 10,000 element array prior to the start of actual SKA-low Phase 1 construction.

Selecting the site for the low frequency SKA and the pre-construction phase

SKA-low is an ambitious undertaking in terms of the complexity and scale of the system. Furthermore, the telescope requires an extraordinary host site. At low radio frequencies, the electromagnetic spectrum is heavily polluted by human activities. In particular, FM radio between 87.5 and 108.0 MHz lies right in the region of interest for EoR signal detection. Some recent theoretical work places the region 50 – 100 MHz as a very important frequency range for the EoR (Visbal et al. [9]). Thus, a location that is remote from FM radio stations and other forms of low frequency transmitters is a strong requirement for the SKA-low site.

Four locations were originally in the running as potential sites for the SKA and, in 2006, a down-selection produced two candidates: Australia–New Zealand (centred on the Murchison region of Western Australia) and Southern Africa (centred on the Karoo region of the Northern Cape of South Africa). After six years of in-depth investigation and preparatory work by the international SKA community, on the 25th of May, 2012, the outcomes of the final site selection process were announced. The Board of the SKA Organisation, made up of the nations with a financial stake in the SKA Organisation, decided that the SKA would be split between the two candidate sites.

The full text of the SKA site decision announcement can be found at http://www.skatelescope.org/the-location/ and the full set of documentation used in the site selection process has been made public at http://www.skatelescope.org/the-location/site-documentation/

Briefly, in Phase 1, 190 dish antennas will be built in South Africa (extending the 64 dish South African MeerKat SKA precursor), 60 dish antennas will be built in Western Australia (extending CSIRO's 36 dish Australian SKA Pathfinder) and 50 SKA-low stations (a station consists of a clump of the simple antennas described above)

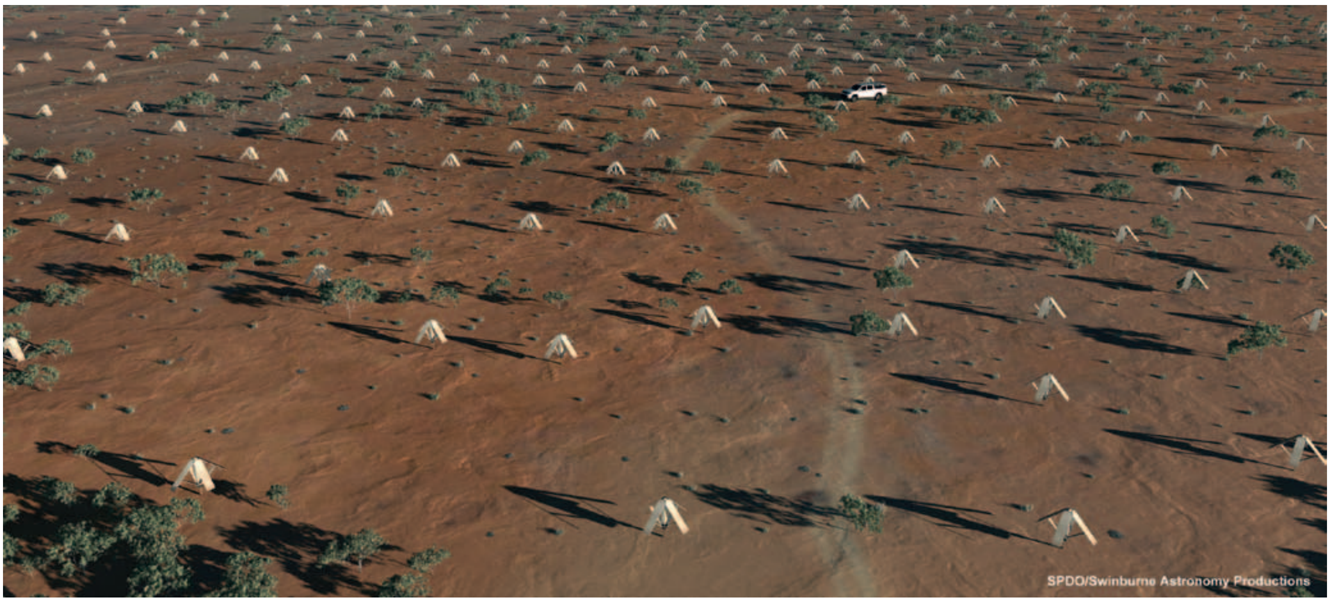

Figure 2: possible SKA-low antennas, featured as part of the SKA reference design (Credit: SPDO/Swinburne Astronomy Productions)

would be built in Western Australia.

In Phase 2, a further 3000 dishes will be built in South Africa, along with 250 stations of mid-frequency aperture arrays. In Western Australia, a further 250 stations of SKA-low antennas will be built.

Thus, the Western Australian site has been endorsed to host the entire SKA-low, in recognition of the superb conditions for low frequency radio astronomy that are a consequence of its remote location.

The long-awaited site decision is behind us and the SKA project now enters the pre-construction phase. With SKA technologies mapped to sites, this final stage of the design process will focus on producing tender-ready specifications for construction. Pre-construction will take place between 2012 and 2016, with significant involvement of Australian research institutions and companies in many of the design and prototyping activities.

The Murchison Widefield Array (MWA), the SKA low frequency precursor

A major portion of the international SKA program in the lead-up to the site decision and the pre-construction phase has focussed on several SKA precursor projects. An SKA precursor is defined as a science and technology pathfinder telescope located on one of the two SKA sites. The precursors are used to test various technologies and techniques, and to provide early insights in SKA key science programs.

Three precursor telescopes are under development. Two dish-based instruments are being built, CSIRO's Australian SKA Pathfinder (ASKAP: Johnston et al. [10]) and the South African MeerKAT array (http://public.ska.ac.za/meerkat). Both of these precursors will operate at frequencies higher than 450 MHz.

A single low frequency SKA precursor is under development, the Murchison Widefield Array (MWA: Tingay et al. [5]). The MWA is funded by 13 institutions in four countries (Australia, the USA, India, and New Zealand) and is in the final stages of construction and commissioning at CSIRO's Murchison Radio-astronomy Observatory (MRO), alongside ASKAP. Curtin University leads the MWA consortium.

As outlined earlier, low frequency radio telescopes can make use of inexpensive antennas and this is the case for the MWA, with 2048 individual dual-polarisation dipole antennas operating between 80 and 300 MHz, and grouped into 128 "tiles" (each equivalent to a mini SKA station). These 128 tiles (see front cover image) are distributed over an area 3 km in diameter, giving an angular resolution of a few arcminutes over an extremely large field of view, thousands of square degrees in extent. The full technical description of the MWA is given in Tingay et al. [5].

"The MWA is fulfilling its obligation as an SKA precursor, exploring novel solutions for antennas, signal processing, imaging and calibration that will be highly relevant during the SKA pre-construction phase."

While the MWA antennas are simple, complexity in the system is pushed into the electronics and, in particular, the back-end signal processing. The antennas send the received analogue signals to receiver packages built by Small to Medium Enterprise industry partner, Poseidon Scientific Instruments in Fremantle, WA. From the receivers, digital data streams enter a correlator and real-time imaging and calibration system based on Field Programmable Gate Arrays and an IBM iDataPlex Graphical Processor Unit compute cluster. All of the complex signal processing and imaging calculations are implemented on this essentially commodity platform running custom algorithms. Finally, processed data are transmitted over a 800 km high speed network that terminates at the new $80m iVEC Pawsey Supercomputing Centre in Perth, where a 15 PB archive will be the portal through which scientists access MWA data.

The MWA is fulfilling its obligation as an SKA precursor, exploring novel solutions for antennas, signal processing, imaging and calibration that will be highly relevant during the SKA pre-construction phase. In addition, the MWA will be the first of the SKA precursors to be completed (in late 2012) and will be the first to deal with the massive data challenge. A team at ICRAR (a joint venture between Curtin University and The University of Western Australia), is implementing the 15 PB archive and MWA data interface for users, one of the first steps toward dealing with the much bigger challenge posed by the SKA itself.

And a significant factor is the fact that the MWA has been implemented at the site chosen for SKA-low, ensuring that we are learning the right lessons in exactly the environment in which SKA-low will be built. The background knowledge gained will be very valuable for the international team being constituted for SKA-low preconstruction. The experience will extend even to the use of the data path to the Pawsey Centre and the use of the computing environment at Pawsey that will eventually be used to support the SKA.

The MWA will not simply be a technology demonstrator for SKA-low, but intends to make significant advances in areas of science that will inform the SKA-low science case and design parameters. The search for the first hint of the EoR signal is a significant part of the MWA science case, as are surveys of our own Galaxy and other galaxies, searches for transient and variable phenomena at radio wavelengths, and detailed investigations of the Sun, and the Sun – Earth connection. Many of these areas of scientific investigation with the MWA mirror areas of SKA science. A full description of the MWA science case will appear in Bowman et al. (2012, PASA submitted).

An example of some early MWA science is shown in Figure 3, an image of the plane of our own Galaxy produced by Hurley-Walker et al. (2012, in preparation). Made with a 32 tile MWA prototype that has since been de-commissioned to accommodate construction of the final 128 tile array, Figure 3 shows a great range of detail associated with supernova remnants in the disk of the Galaxy and complicated structures that extend well away from the plane, emitting non-thermal synchrotron emission. While beautiful, and rich in the physics that drives our own Galaxy, this emission masks the EoR signals that the MWA also seeks, the EoR emission being factors of ~10^4–10^5 weaker than the levels shown in Figure 3.

Detection of the EoR is an extraordinarily demanding experiment that will reach its full power with SKA-low. However, the MWA precursor (and other instruments such as LOFAR and PAPER) will make the first important steps on this path, blazing a trail to early Universe cosmology and giving an insight into fundamental physics. These steps will start to be taken in the first half of 2013, when the MWA becomes fully operational for science.

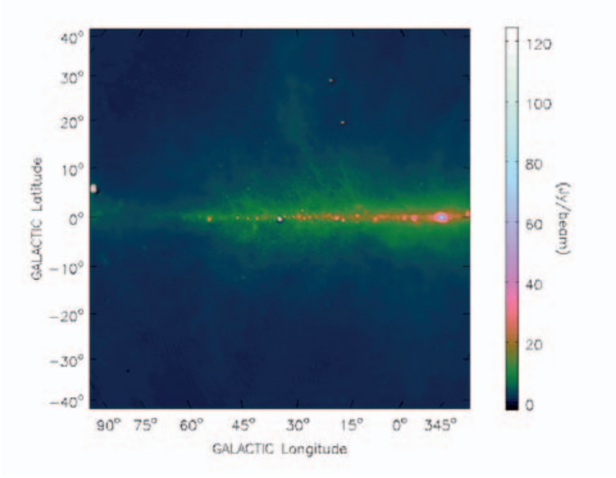

Figure 3: an early MWA image of our Galaxy, showing a range of structures (image credit: Dr Natasha Hurley-Walker).

Acknowledgements

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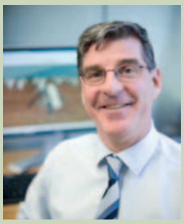

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