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COSMIC MAGNETISM: AN LRP 2010 WHITE PAPER

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ABSTRACT

Magnetic fields are among the building blocks of the Universe and they pervade the cosmos. Yet we know less about magnetic fields than the other basic properties of cosmic plasmas. This is a consequence of the fact that we cannot see them directly. Instead must rely on indirect measurements such as the polarization of synchrotron radiation and Faraday Rotation of radio waves. This white paper highlights Canadian contributions to research in cosmic magnetism, from the 1970's through to the large surveys of polarization data being carried out under the CGPS, GMIMS, GALFACTS and the future projects of ASKAP and the SKA. These research activities represent an area of international excellence for Canadian research, and the theme of cosmic magnetism will play an important role in shaping our national contributions to some of the very largest international astrophysical initiatives over the coming decades.

1. INTRODUCTION

Magnetic fields are an essential component of the Universe. Spitzer 1978 lists the constituents of the interstellar medium (ISM) as atomic, molecular and ionized gas, dust, cosmic rays and magnetic fields. Many of these constituents, including magnetic fields, are components of the intergalactic medium as well. While most of the constituents produce some observable radiation, magnetic fields do not and thus cannot be observed directly. Yet without developing a complete understanding of magnetic fields, we cannot hope to understand the Universe itself.

We know cosmic magnetic fields span the range in intensity from a few μGauss in the disks of galaxies (lower for intergalactic regions) to milligauss in pulsar wind nebulae and molecular clouds, to 0.6 Gauss at the Earths surface, to tens and hundreds of Gauss in stellar interiors, to 10^8-10^{12} Gauss in typical pulsars and 10^{15} Gauss in magnetars. We also know that in addition to playing a significant role in pressure balance, magnetic fields play an essential role in star formation, by inhibiting gravitational collapse of interstellar clouds – primary star formation regions – and by removing prestellar angular momentum (Zweibel & Heiles 1997). Consequently, magnetic fields directly affect the distribution of stars. It is also believed that magnetic fields influence galaxy formation and evolution by causing large density fluctuations which result in structures within a galaxy (Kim et al. 1996). Magnetic fields and cosmic rays are also believed to contribute to the vertical support of the gas in the Galaxy (Boulares & Cox 1990). Furthermore, magnetic fields in the *intergalactic medium*, undoubtedly affect the distribution of galaxy formation. Yet despite their recognized significance, the origin and maintenance of magnetic fields are still open questions in astrophysics. When and how were the first fields generated? How did they evolve over cosmic time?

These and many related questions have propelled the radio astrophysics community to label cosmic magnetism one of the six key science drivers for the international Square Kilometer Array (SKA). In this paper we show that Canada has a strong record in research on cosmic magnetism, particularly in radio astronomy, and, through completed and ongoing projects, is strongly placed to contribute to research in this high-profile field.

2. TECHNIQUES FOR OBSERVING MAGNETIC FIELDS

Electrons moving at relativistic speeds in the presence of a magnetic field will accelerate through the Lorentz force and consequently generate linearly polarized synchrotron emission. Although this phenomenon can produce X-ray and optical wavelengths, it is the radio emission that has proven to be the main tool for study of cosmic magnetic fields in two key ways. First, synchrotron emission from a region with a uniform magnetic field is strongly polarised, up to a a theoretical limit of $\approx 70\%$ (Pacholczyk 1970), with the plane of polarisation perpendicular to the direction of $B_\perp$ in the plane of the sky. Polarisation of synchrotron emission therefore gives information on the magnetic field component perpendicular to the line of sight. Second, when a linearly polarised electromagnetic wave, such as that produced by synchrotron radiation, propagates through a region of free electrons permeated by a magnetic field, such as that of the interstellar medium, its plane of polarisation will rotate. This phenomenon is known as Faraday rotation (the measurable effect is called Rotation Measure or RM), and is dependent on the strength and orientation of the permeating magnetic field relative to the path length through the plasma, the electron density along the path, and the square of the emitted wavelength. Since different wavelengths will experience different amounts of rotation, it is preferable to observe over a wide range of wavelengths.

Faraday rotation phenomena can be very complicated (Burn 1966; Sokoloff et al. 1998), especially if emission and Faraday rotation occur within the same volume. Rotation Measure Synthesis (Brentjens & de Bruyn 2005) is an new analysis technique that operates on wideband polarimetric data with many narrow frequency channels and delivers high sensitivity, capable of imaging different layers of a Faraday rotating medium, a process sometimes called Faraday Tomography. The wideband data required for input to RM Synthesis can be obtained with modern digital systems, usually based on FPGA chips.

Other techniques for measuring magnetic fields find application of narrower scope, but are still important. Dust grains tend to be elongated. Their emission at sub-mm

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wavelengths is polarised, and they polarise optical and infrared radiation that propagates through them by selective absorption. The optical measurements of Hiltner and Hall from the 1950s are now being joined by significant infrared observations (the GPIPS survey; Clemens 2009). The Zeeman effect is a magnetic-field dependent splitting of spectral lines. It is widely applied to measure magnetic fields in the denser parts of the ISM through molecular spectral lines (Crutcher 1973).

3. THE MAGNETIC FIELD OF THE MILKY WAY

Sixty years ago Fermi (1949) proposed that there must be a magnetic field in the Milky Way in order to generate and confine the observed high-energy cosmic rays. Today radio observations of external galaxies show us that spiral galaxies generally have well-organized large-scale fields that play crucial roles in the stability of their disks by contributing to the vertical support and the pressure of the ISM . They equally affect the outward flows of energy from stellar winds and supernova blasts, and play a pivotal role in returning matter and energy to the ISM. The preferred mechanism for generating magnetic fields in galaxies is the dynamo (Ruzmaikin et al. 1988) but many details of the theory are incomplete and there is no satisfactory match with presently available data. In part, this is due to an incomplete picture of what the magnetic field looks like *now*. Until we understand fully the present magnetic topology of the Galaxy, we cannot hope to understand how the field originally formed, nor how it is evolving.

4. MAGNETISM BEYOND THE MILKY WAY

The Milky Way is an ideal laboratory for the study of the role of magnetic fields in interstellar processes. However, we must extend these studies to extragalactic objects, galaxies of all types (spiral, irregular, starburst, and also active galaxies and clusters of galaxies) to obtain a full census of the astrophysical roles of magnetic fields. As in many areas of astronomy (e.g. stellar evolution), we must obtain sufficient statistics to develop an overarching model of magnetism in all types of galaxy systems.

Only a few Local Group galaxies have been studied with a sufficient number of polarized background sources to reveal the structure of their magnetic field. Magnetic field structure in more distant galaxies can be revealed only by polarisation of synchrotron emission, but this provides no information about magnetic field reversals[3]. Present day telescopes do not have the sensitivity to do polarimetric imaging of galaxies at arcsecond resolution or better, necessary to resolve galaxies at higher redshift.

International developments in radio astronomy will increase our capability to study magnetic fields in distant objects. The EVLA, LOFAR, ASKAP, MeerKAT, and the SKA will provide an increasing array of sensitive broadband wide-field radio telescopes with survey speeds that will allow deep surveys over tens of square degrees. Surveys with sub-microJy sensitivity may reveal a completely different polarized radio sky dominated by distant spiral galaxies that may remain unresolved, but be the dominant population of polarized radio sources (Stil et al. 2009).

[3] A magnetic reversal is a region of magnetic shear, where the field switches directions by roughly 180° across large (kpc) scales. The number and location of these is an essential constraint in dynamo theories.

5. EVOLUTION OF MAGNETISM OVER COSMIC TIME

While studying the extended populations of galaxies nearby will give us some sense of different evolutionary paths magnetic fields may take, it is the study of the magnetic fields in objects at high redshifts that promises to reveal the true history of magnetic field development. Radio galaxies and quasars powered by accretion on a massive central black hole can be observed at large distances, and are also polarised. Fitting both total-intensity source counts and polarized source counts with a cosmological model puts constraints on the evolution of magnetic fields in these objects (O'Sullivan et al. 2008). The deepest polarised source counts published to date are those of the DRAO ELAIS N1 deep field (Taylor et al. 2007; Grant et al. 2010). These deep images of the polarised sky reveal an increasing degree of polarisation for fainter radio sources, suggestive of more regular magnetic fields in faint radio sources than in bright radio sources.

Did magnetic fields evolve gradually? Or did they grow abruptly with the galaxies? Questions like these will only be addressed when populations of galaxies far away in cosmic time can be thoroughly probed. While these questions are being asked now, it is likely answers will not come until the SKA or its prototypes come online.

6. SIGNIFICANT CANADIAN CONTRIBUTIONS

Canada has been a major contributor to the study of cosmic magnetism for several decades. Historically significant contributions include the first identification of a magnetic field reversal between the local arm and the Sagittarius arm (Simard-Normandin & Kronberg 1979), the first detection magnetic fields in high-redshift objects (Kronberg & Perry 1982), and the first detection of a magnetic field within a cluster of galaxies (Vallée et al. 1986). In the following sections we review current and future cosmic magnetism initiatives in which Canada is expected to play a significant role.

6.1. *Present and On-Going Initiatives*

The DRAO Synthesis Telescope has just completed the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003), producing a comprehensive database of high-fidelity and high-resolution images of the main constituents of the Galactic Interstellar Medium. Among those data products are polarization data at 1420 MHz ($\lambda = 21$ cm). The first revolutionary result from the CGPS polarization data is a large number of determinations of rotation measure (RM) for extragalactic sources seen through the Galactic disk (Brown et al. 2003a). With a RM density of 1 source per square degree, these data surpassed earlier efforts in the same region by a factor of twenty, allowing for more accurate probing of the disk field than had been previously possible (Brown & Taylor 2001; Brown et al. 2003b), and lead to similar work in the complementary Southern Galactic Plane Survey (Brown et al. 2007).

The RM studies of the Galactic plane surveys have inspired many similar efforts by groups around the world. This coincided with the definition of the major science goals for the SKA, and it is fair to say that the research that was done in Canada was responsible for placing Cosmic Magnetism in the pantheon of SKA objectives.

The latest significant Canadian result in this field has come from the realization that the NVSS, made with the

VLA in the 1990's, contained buried rotation measure information. Taylor et al. (2009) have reworked the NVSS data to obtain 37,543 RMs across the entire Northern sky. Although there are some unreliable RMs buried in this dataset (because of the way the data were taken), the sheer number of RMs makes this a valuable research resource.

A second data product from the CGPS is an unprecedented imaging of the diffuse polarized emission from the Galaxy, offering a new view of the ISM. The diffuse polarized emission comprises structures of large scale and fine structure. The CGPS dataset (Landecker et al. 2010) is the first large polarization survey to combine single-antenna data (from the DRAO 26-m Telescope and the Effelsberg 100-m Telescope) with the synthesis telescope data. Special techniques were developed at DRAO to make this combination possible. High-fidelity imaging of the diffuse polarized emission demands that corrections be made for instrumental polarization across the field of view of the synthesis telescope. Techniques were developed at DRAO to solve this difficult problem (Ng et al. 2005; Reid et al. 2008) and these will find application in the next generation of telescopes. The high quality polarization images produced by the DRAO Synthesis Telescope currently have no equal in the world, and are revealing exciting new structures unrelated to other ISM tracers.

Wolleben et al. (2006) used the DRAO 26-m Telescope to make a survey of polarized emission from the entire northern sky at 1420 MHz (angular resolution 36), surpassing the previous best data by an order of magnitude in sensitivity and two orders of magnitude in sky coverage. The intense interest in this dataset from astronomers working on Galactic science and on CMB foregrounds led to the initiation of the Global Magnet-Ionic Medium Survey (GMIMS; PI: M. Wolleben, DRAO). The goal of the project, outlined in Wolleben et al. (2009), is to map polarized emission from the entire sky in the Northern and Southern hemispheres, completely covering the frequency range 300 to 1800 MHz (λ 1 metre to 17 cm). This entails the development of wideband receiving systems and digital signal processing systems. The telescopes involved at present are the DRAO 26-m Telescope (the polarimetry system developed for this telescope is described in Wolleben et al. 2010), the Parkes 64-m Telescope and the Effelsberg 100-m Telescope. A low frequency feed and receiver (300 to 900 MHz) was built at DRAO for the Parkes 64-m Telescope and a copy is being installed on the Efflesberg 100-m Telescope. The GMIMS consortium comprises 13 scientists from 6 countries. The three Canadian involved are M. Wolleben and T.L. Landecker (DRAO) and A.R. Taylor (Calgary). GMIMS will apply Rotation Measure Synthesis to understanding the role of magnetic fields in the Milky Way. This first application of RM synthesis with a single-antenna telescope has demonstrated the power of RM synthesis. The sensitivity is very high since the entire bandwidth contributes to every image. RM synthesis is able to reveal structures that would otherwise be hidden as a result of depolarisation.

GMIMS will also provide the absolute calibration of the polarized intensity scale for the Galactic Arecibo L-band Feed Array Continuum Transit Survey (GALFACTS; PI: A. R. Taylor, U. Calgary). GALFACTS is a polarisation survey with the Arecibo radio telescope that will have a sensitivity 80μJy, an angular resolution of 3 arcminutes, and thousands of spectral channels. A new multi-beam cleaning technique was developed in Calgary to make high-fidelity images of compact polarised sources and diffuse emission with the seven-beam Arecibo L-Band Feed Array (ALFA). GALFACTS will extend to 32% of the sky the kind of analysis that has so far been restricted to small deep fields. The many frequency channels and large bandwidth will open the possibility to study the wavelength-dependent polarisation in much more detail than any previous survey. It is expected GALFACTS will produce an RM catalogue of roughly 115,000 extragalactic sources. In addition, GALFACTS will image the Arecibo sky in diffuse emission, and will allow application of RM synthesis to two significant areas of the Galactic disk. Profitable studies of Galactic objects (SNRs. PWNs, HII regions, planetary nebulae) will all be possible.

6.2. *Future Initiatives*

Canada is a major participant in the Australian Square Kilometre Array Pathfinder (ASKAP; Johnston et al. 2007). This technology and science demonstrator for the much larger SKA, scheduled to be completed by 2020, will explore wide-field imaging (30 square degree instantaneous field of view) at bandwidth of 300 MHz divided into 16000 frequency channels. Apart from the engineering challenges for this new-generation radio telescope, SKA pathfinders such as ASKAP provide new challenges in terms of image calibration and processing. Canada is expected to play a leadership role in developing techniques for wide-field polarisation imaging and calibration for both SKA pathfinders (including ASKAP) and the SKA itself.

The polarization project POSSUM (Polarization Sky Survey of the Universes Magnetism) was selected as one of ten successful proposals from a pool of thirty eight to use use ASKAP in its first five years. This project is led by B.M. Gaensler (University of Sydney, Australia), A.R. Taylor (U. Calgary), and T.L. Landecker (DRAO). The consortium of 40 scientists engaged in POSSUM includes 8 Canadians. The success of POSSUM is heavily dependent on Canadian technical knowledge, developed through the CGPS and GALFACTS projects, and Canadian science experience at Calgary and DRAO.

POSSUM is expected to produce a catalogue of roughly 3 million RMs over 30,000 square degrees. This will be the highest source density of RMs ever determined, providing a much higher effective angular resolution for the study of the Galactic magnetic field, particularly the small-scale (turbulent) component. These sources will also permit studies of magnetic fields in external galaxies and galaxy clusters with unprecedented resolution, as well providing magnetic field strengths in objects at different redshifts. For all of these studies, the anticipated POSSUM RM source list will provide the statistics necessary to address the evolutionary questions of magnetic fields in galaxies.

7. CONCLUDING REMARKS

Cosmic magnetism is one of the six science drivers for the SKA. The SKA represents the international vision of radio astronomy for the future. Canada has demonstrated expertise on both the technical and scientific fronts defining the SKA, and we will undoubtedly continue to do so, provided we maintain our position as world leaders in radio astronomy. To do this, we must continue to be able to recruit and train HQP at home, through creative initiatives such as developing the DRAO into an international radio astronomy training facility.

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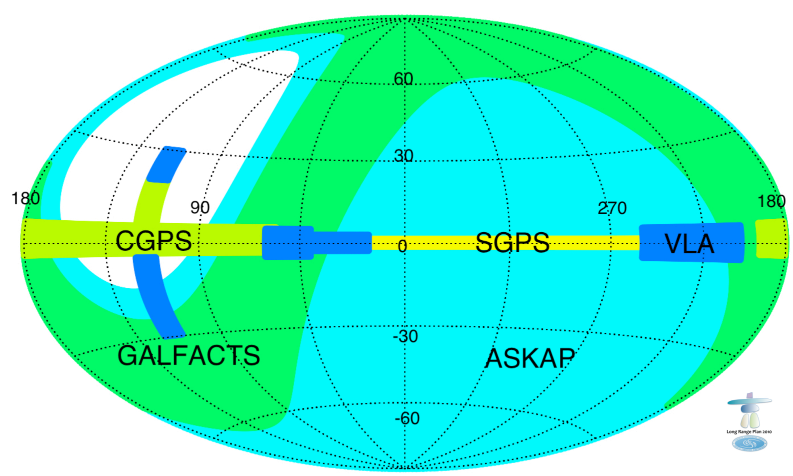

Fig. 1.— All sky view (in Galactic coordinates) of past, present, and future radio polarisation observation surveys with significant Canadian involvement. CGPS: Canadian Galactic Plane Survey (PI at UofC); SGPS: Southern Galactic Plane Survey (UofC participation); VLA: Very Large Array observations(Co-PI at UofC) ; GALFACTS: Galactic Arecibo L-band Feed Array Continuum Transit Survey (PI at UofC); ASKAP: Australian Square Kilometer Array Pathfinder (Canada is a formally recognized partner). The Global Magneto-Ionic Medium Survey (GMIMS: PI at NRC) will cover the entire sky.

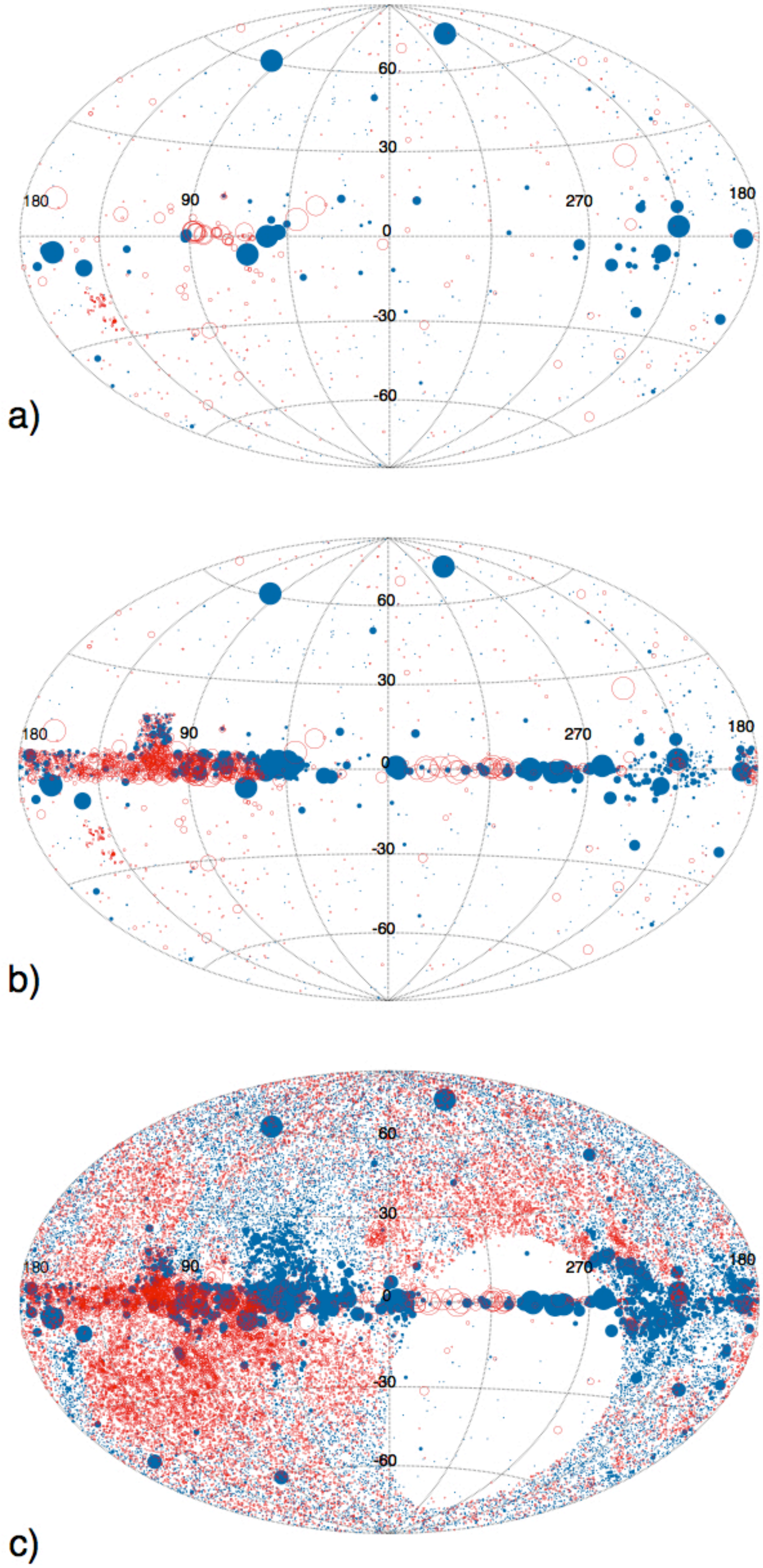

Fig. 2.— Rotation measures of extragalactic sources on an all-sky view. Filled-blue circles represent positive RMs; open-red circles represent negative RMs. Positive RMs indicate the average line-of-sight magnetic field is directed towards the observer, while negative RMs indicate the line-of-sight component is directed away. The size of the circles are scaled to RM magnitude (50 rad/m^2 < |RM| < 800 rad/m^2). Top panel: published data prior to CGPS (Broten et al. 1988; Oren & Wolfe 1995; Minter & Spangler 1996); Middle panel: data including the CGPS, SGPS and new VLA observations (Rae et al., in prep.; Brown et al. 2003a; Brown et al. 2007, Van Eck 2010, in prep.); Bottom panel: all data including the NVSS RMs (Taylor et al. 2009). Surveys of the future, including GALFACTS and ASKAP, are expected to increase the source densities in both the disk and halo by orders of magnitude.

FIG. 3.— The Dominion Radio Astrophysical Observatory (DRAO). Images highlight both the synthesis array telescope (the east-west array which includes the antennas on the tracks) and the 26 meter telescope (adjacent to the main building).

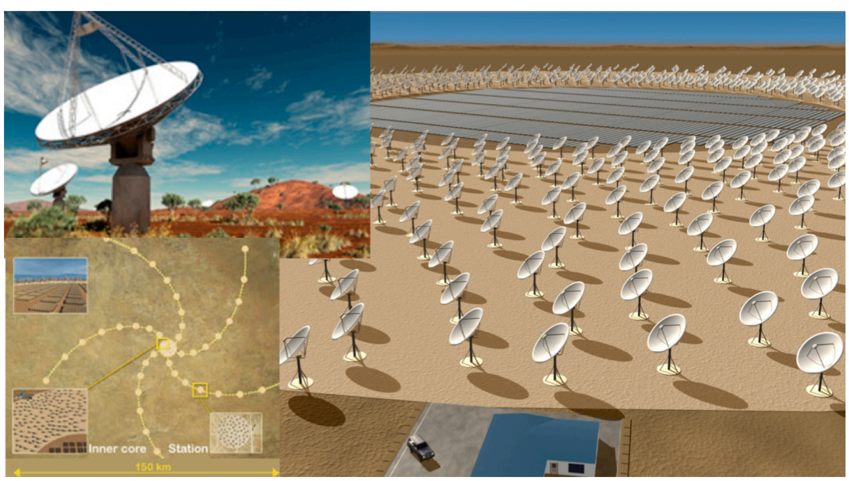

FIG. 4.— ASKAP and the SKA. Clockwise from upper left: Artists impression of ASKAP at the Murchison Radio-astronomy Observatory (Credit: Swinburne Astronomy Productions); Artist's conception of the core design and the SKA grand design (www.skatelescope.com).