

# Advancing Astrophysics with the Square Kilometre Array

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**Robert Braun, Tyler L. Bourke, James A. Green, Evan F. Keane & Jeff Wagg**

*SKA Organisation, Jodrell Bank, UK*

*E-mail: [r.braun@skatelescope.org](mailto:r.braun@skatelescope.org)*

The Square Kilometre Array concept has grown from the answer to a simple question: What size radio telescope would it take to permit us to read the history of the Universe as written in the language of its most abundant constituent, Hydrogen? What has also become apparent, is that the same radio telescope that will answer fundamental questions about our cosmic origins and fate will permit a wealth of other discoveries to be made, in areas as diverse as the formation of planets similar to the Earth, detection of gravitational distortions of Space-Time, the origin of cosmic magnetic fields and understanding the formation and growth of Black Holes. In this paper we discuss a few of these headline science topics and refer the reader to the overview chapters within these proceedings for more details on the broad areas of anticipated impact, as well as the individual contributed chapters that focus on specific topics.

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## 1. Introduction

The Square Kilometre Array (SKA) concept is the result of answering the question: How large should the collecting area of a radio telescope be to enable the study of the history of the Universe via its most abundant constituent, Hydrogen? The answer is about one square kilometre. What's surprising about this answer is that it applies to such a wide range of cosmic time. An SKA-sized telescope is needed to:

1. See back to the Cosmic Dawn, when the very first stars formed in a Universe that was only 100 million years old,
2. Witness the epoch of galaxy formation at 1 billion years of age, as well as,
3. Understand the current epoch of accelerating expansion, 13.7 billion years after the Big Bang, driven by the mysterious force of Dark Energy.

This same telescope will permit a wealth of other discoveries to be made, in areas as diverse as the formation of Earth-like planets, the detection of gravitational distortions of Space-Time, the origin of cosmic magnetic fields, and the formation and growth of Black Holes. A selection of the most significant contributions anticipated within the eight different areas represented by the current SKA Science Working Groups are summarised in Figure 1. We consider just a few of these many areas briefly below, ordered by their relative distances, and refer the reader to the overview chapters within these proceedings referenced in Figure 1 for more details on the broad areas of anticipated impact, as well as the many individual contributed chapters that focus on an even more diverse set of specific topics. The current SKA Science programme builds on the strong foundations put in place previously in "Science with the Square Kilometre Array" edited by Carilli and Rawlings (2004), which builds in turn on the original compilation of the same name edited by Taylor and Braun (1999).

## 2. Planet Formation

Since the discovery of the first planetary body outside of the solar system in 1988 there have been almost 2000 planets discovered around more than 1000 stars. Planets have been found with the most diverse properties, ranging in size from half that of the Earth to about twice that of Jupiter and in density from half that of freshly fallen snow to twice that of lead. A particularly vexing problem facing planetary astronomers is understanding how the small pebbles in the disk surrounding a young star are able to stick together to form the boulders that ultimately coalesce into planets. At both smaller and larger sizes, the growth mechanisms are understood, but this key step in the planet formation process is still shrouded in mystery. The SKA will uniquely enable direct observation of this phase of planet assembly by observing at exactly those radio wavelengths that are matched to the size of coalescing particles, from cm-scales to metres, and it will do so with enough resolution to watch the assembly of planets in earth-like orbits about their parent stars.

	SKA1	SKA2
<b>The Cradle of Life &amp; Astrobiology</b> Hoare, M. et al. 2015 PoS(AASKA14)115	Proto-planetary disks; imaging snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10 <sup>4</sup> nearby stars.	Ultra-sensitive SETI: airport radar 10 <sup>5</sup> nearby star, TV ~10 stars.
<b>Strong-field Tests of Gravity with Pulsars and Black Holes</b> Kramer, M. & Stappers, B. 2015 PoS(AASKA14)036	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR- BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
<b>The Origin and Evolution of Cosmic Magnetism</b> Johnston-Hollitt, M. et al. 2015 PoS(AASKA14)092	The role of magnetism from sub- galactic to Cosmic Web scales, the RM-grid @ 300/deg <sup>2</sup> .	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg <sup>2</sup> .
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z ≈ 0.04.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13.
<b>Galaxy Evolution probed by Neutral Hydrogen</b> Staveley-Smith, L. & Oosterloo, T. 2015, PoS(AASKA14)167	Gas properties of 10 <sup>7</sup> galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid.	Gas properties of 10 <sup>9</sup> galaxies, <z> ≈ 1, evolution to z ≈ 5, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N <sub>H</sub> < 10 <sup>17</sup> at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N <sub>H</sub> < 10 <sup>17</sup> at 1 kpc.
<b>The Transient Radio Sky</b> Fender, R. et al. 2015 PoS(AASKA14)051	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.
<b>Galaxy Evolution probed in the Radio Continuum</b> Prandoni, I. & Seymour, N. 2015 PoS(AASKA14)067	Star formation rates (10 M <sub>⊙</sub> /yr to z ~ 4).	Star formation rates (10 M <sub>⊙</sub> /yr to z ~ 10).
	Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).	Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).
<b>Cosmology &amp; Dark Energy</b> Maartens, R. et al. 2015 PoS(AASKA14)016	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2× Euclid.	Primordial non-Gaussianity and the matter dipole: 10× Euclid.
<b>Cosmic Dawn and the Epoch of Reionization</b> Koopmans, L. et al. 2015 PoS(AASKA14)001	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages (z > 30).

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**Figure 1:** An overview of some of the key science applications of the Square Kilometre Array, both in its early deployment phase, SKA1, and as the fully scoped, SKA2. Scientific topics are ordered by their increasing distance from the Earth. Definitions of abbreviations are given in the references.

### 3. Gravitational Waves

When Einstein's General Theory of Relativity was published in 1915, it made some of the most surprising predictions about the nature of space and time; predictions that continue to be confirmed with increasing precision to this day. Although this might be considered reassuring, it actually is not, since the theory is known to be fundamentally incomplete, at least at quantum scales. When will this theory, which constitutes a fundamental building block of modern physics, finally break down and what lies beyond? One of the as yet unconfirmed predictions of the theory is that the rapid relative motion of very massive compact objects, such as are thought to exist at the centre of most galaxies today, will lead to a propagating Space-Time distortion of the Universe; a phenomenon termed Gravitational Waves. The only method yet proposed to measure long period Gravitational Waves makes use of our entire Galaxy as a detector. Rapidly spinning neutron stars with pairs of radio beams emanating from their poles known as millisecond pulsars serve as a system of high precision clocks. By accurately measuring the pulse arrival times from many of these clocks over the course of several years the SKA will create a Gravitational Wave Telescope. The first goal will be the detection of the general Gravitational Wave background due to sources from all directions and distances, but with higher precision it should become possible to identify individual sources of such waves and begin to conduct Gravitational Wave Astronomy for the first time. Just as important would be the absence of detection of such characteristic Space-Time distortions at all. Since current limits are already constraining our understanding of Gravity and massive Black Hole growth, a non-detection would signal the need for a new theory.

### 4. Cosmic Magnetism

Most of us only encounter magnetism in conjunction with a compass that aligns itself with the Earth's magnetic field. While this has undoubtedly proven useful for centuries to navigators sailing the seas, it may seem quite a subtle phenomenon with only limited relevance to humanity. On the contrary, the Earth's magnetic field plays a key role in sustaining life on the surface by deflecting highly energetic charged particles originating from the Sun and beyond, that would otherwise damage the DNA of many organisms. Similarly, we are beginning to understand that magnetic fields play an important role throughout the Universe on all scales yet studied. The energy contained in magnetic fields appears to be comparable to that due to the heat of the material constituents and it may well play a key role in regulating a whole range of processes, from the formation of planets and stars to both the accumulation and the dispersal of material on the scales of galaxies and clusters of galaxies. The challenge facing astrophysicists today is explaining how and when magnetic fields arose to achieve their current prominence. What is particularly puzzling is the strength of those fields on the largest scales. Current theories fall short of explaining the observed field strengths by factors of a million or more. The only way to solve this puzzle is with a much better sampling of our magnetic environment, so that the sources of magnetic enrichment become apparent as well as the timescales over which they operate. What the SKA will enable is the first three dimensional magnetic map of the Universe. This will be achieved by measuring the individual magnetic components toward extremely large samples of sources distributed in all directions on the sky and at

varying distances. In this way, we will form the first detailed magnetic map of our own Galaxy, as well as the much larger volume around us, reaching back in time to the birth of the first galaxies.

## 5. Galaxy Evolution

For most of human history it was believed that our Solar system, surrounded by its starry firmament, made up the entire Universe. It wasn't until 1734 that the suggestion was made that our Sun was just one of many stars which together make up our Galaxy, an Island Universe within an otherwise empty void. That belief was replaced in 1920 with the understanding that ours was but one of many galaxies, both larger and smaller in size. The recognition that galaxies and even the Universe itself were ephemeral objects that have a finite lifetime, with a distinct birth, life cycle and ultimate death subsequently emerged in the 1960s. And only within the last few years have we begun to appreciate just how closely the life cycle of an individual galaxy can be coupled to that of the Universe itself. The SKA will finally give us a front row seat to witness such galaxy evolution, as traced by the accumulation and utilisation of atomic Hydrogen – the ultimate galactic power source – throughout cosmic time. The major challenge that the SKA overcomes is that of raw sensitivity. Although Hydrogen is the most abundant element in the cosmos, it is only visible as a faint radio glow in the sky and that intrinsic faintness is exacerbated by large distances. As noted at the outset, it was the desire to study Hydrogen even in the distant, early Universe that originally motivated the concept of a radio telescope comprising one square kilometre of total collecting area. What will ultimately be achieved is the most complete galaxy census ever contemplated, reaching one billion individual galaxies and covering 12.5 billion years of cosmic history. This sample will provide the most precise determination of the properties of Dark Energy yet conceived. Even in its early deployment phase, the SKA will already provide samples of 10 million galaxies spanning 8 billion years of evolution, which will greatly advance our understanding of the galaxy life cycle.

## 6. The Bursting Sky

Changes in the night sky have traditionally been viewed with a mixture of awe and concern in previous millennia. But for at least the past 100 years such events have instead proven to be valuable tools in recognising our place in the cosmos. First via distance estimates of variable stars that established the distinction between our Galaxy and other external galaxies, and since 1990 in allowing the deduction of an accelerating expansion of the Universe via distance estimates of Supernovae in very distant galaxies. The insights provided by such time variable phenomena show no signs of diminishing returns on an investment in their study. One such class of source is the Gamma-Ray Bursts; first witnessed in the 1960s by satellites designed to detect nuclear weapon detonations on the Earth, these events are now believed to originate in the supernovae of particularly massive stars in the distant Universe. The very high brightness of these events allows them to be seen to very great distances, and this provides an opportunity, at least temporarily, to detect any translucent material along the sightline. What may well be a similar phenomenon, the Fast Radio Bursts, was first discovered in 2007 and only established as a population in 2013. While we are still awaiting the first identification of a long-lived counterpart or galaxy host for the Fast Radio Burst phenomenon, it is quite possible that they reside in extremely distant galaxies.

What makes this plausible is that the radio waves reaching us from these sources have traversed a very substantial amount of ionised plasma, comparable to that seen between the Earth and the very centre of our Galaxy; despite the fact that these events are seen in entirely different directions where our Galaxy's plasma content is minimal. The intervening plasma results in a time delay for lower radio frequencies to reach us compared to the higher radio frequencies of about one second. The length of this time delay provides an accurate measurement of exactly how much plasma there is along the sightline. The SKA will enable us to associate thousands of individual bursts with the objects that host them, allowing us to map out the Universe's plasma content and how it evolves with time in a way that was never previously possible. This is particularly important since we believe that about 70% of all normal matter in the Universe today is in the form of such plasma, but we only have direct measurements of about 10%. The study of Fast Radio Bursts with the SKA will open a completely new window on the cosmos.

## 7. Forming Stars through Cosmic Time

The realisation that stars like our Sun have a finite lifetime emerged in the early 1900s. This was followed by the comforting conjecture that the Universe was essentially in a “steady state” with a constant rate of stars ageing and being replaced. What instead became apparent in the late 1990's is that the rate at which stars are formed has varied dramatically with time. That rate has increased from a low level in the early Universe to a major peak at some 3 billion years of age, followed by a continuous decline to the rather low rates that apply today. In very broad terms this pattern can be explained by the changing balance between two competing forces of Nature, gravitational attraction which dominates in the first few billion years and Dark Energy driven repulsion which dominates today. While gravity dominated, large quantities of Hydrogen were pulled together from the environments of the early galaxies to fuel a spectacular epoch of star-forming fireworks. Since Dark Energy has become dominant it is increasingly difficult to pull together any additional fuel to sustain future generations of stars. While the quantity of such fuel is still extensive, with only about 25% having been consumed, it has become essentially inaccessible. Although the basic pattern of growth and decline of star formation with time has been established, there are still many unanswered questions. We have evidence that the basic mode of star formation was fundamentally different in the early Universe, often occurring within intense concentrations of “super star clusters” that have few, if any, counterparts today. When and where did this mode first arise and how and why did it come to disappear again? The SKA will play a key role in answering these questions, since it's likely that such events are so deeply enshrouded by material that they can only be seen at radio frequencies that can penetrate the shroud. The SKA will ultimately allow detections of such Super Star Clusters back to when the Universe was only 0.5 billion years old and resolved images of such structures to be made back to 1 billion years of age. Even in its first deployment phase the SKA will permit detection back to 1.5 billion years and imaging back to 6 billion years of age.

## 8. Cosmology and Dark Energy

Its remarkable how the Universe seems to have an endless capacity to surprise those who study it. One of the biggest surprises to emerge in the past century was that normal matter, of the kind

described in the periodic table of the elements, is only a minor constituent of our Universe and is outweighed more than five to one by some form of invisible Dark Matter. We see evidence for such Dark Matter, in the form of excess gravitational attraction, on all scales between about 300 light years and 300 million light years. The gravitational attraction of Dark Matter has played a crucial role in shaping the Universe we inhabit, locally overcoming the general expansion imparted by the Big Bang and pulling together enough normal matter to allow stars and galaxies to form. But even Dark Matter is now dwarfed by the three times larger effects of Dark Energy. Dark Energy is in many respects the antithesis of Dark Matter, exerting a repulsive rather than attractive force that seems to grow in proportion to the volume of the Universe. During the first 3 billion years following the Big Bang it was Dark Matter that reigned supreme, but since that time, Dark Energy has taken over the dominant role. Establishing the true nature of these Universe-shaping quantities is a key motivation for cosmologists today. Since neither of these constituents was anticipated by current theories, we are still desperately in need of enhancing our observational constraints to inform a more fundamental physical theory. When confronted with such unexpected phenomena it is usual to begin with the simplest possible description of the effect, captured by a single parameter that does not change with cosmic time. This is the current state of affairs for our understanding of the Dark Energy phenomenon. As more extensive observations become available, it becomes possible to extend this practical description of the Universe with both a larger number of parameters and allowing for the possibility that they may change with time. Once such a higher level description becomes sufficiently detailed, it should finally be possible to derive a new physical theory that both explains Dark Energy and makes new predictions about other phenomena. It is anticipated that the SKA will fundamentally advance our understanding of Dark Energy by allowing for as many as ten parameters to describe both the nature and time evolution of this mysterious phenomenon. This is in contrast to other facilities operating on the same timescale that are only anticipated to permit three parameters to be meaningfully constrained. Even in its early deployment phase, the SKA should already permit as many as five Dark Energy parameters to be derived, making major progress toward the goal of enabling precision cosmology.

## 9. Cosmic Dawn and the Epoch of Re-ionisation

Many of us have become familiar with images, of ever increasing resolution and sensitivity, of the Cosmic Microwave Background; the surface surrounding us that represents the boundary of the visible Universe at only 380,000 years of age and a temperature of 3000 degrees Kelvin. Imprinted on that surface are the small density enhancements that will grow to become galaxies and clusters of galaxies as well as the small density decrements that will evolve to become large empty voids. However, the next 700 million years of evolution, before the birth of the most distant galaxies yet identified, are still shrouded in mystery. It's thought that the Universe's normal matter, which at the time still consists of about 92% Hydrogen, 8% Helium and only rare traces of heavier elements, quietly cools down to temperatures below 100 K. This period is known as the Dark Ages and it lasts until the first stars begin to provide localised heating at about 100 million years of age. This heralds the onset of Cosmic Dawn, characterised by the first signs of temperature contrast between heated and unheated regions, even though essentially all of the Hydrogen is still relatively cold and neutral. The next major era is termed the Epoch of Reionisation lasting from about 370

to 800 million years of age. The heat sources have now become so intense and well distributed that Hydrogen is heated to more than 1000 K, becomes fully ionised and eventually the individual ionised bubbles grow to the point of completely overlapping one another. What the SKA will uniquely enable is measurement of a complete time sequence of images from the onset of Cosmic Dawn to the end of Reionisation using the faint radio light coming directly from the Hydrogen itself. The resulting movie of the Universe's first 700 million years will answer a multitude of questions. When exactly did the first stars form? Were individual stars, large stellar clusters or even early black holes the most important source of heating and ionisation of the Universe? How exactly did the process unfold; was there a single progression from dark to light or were there multiple fits and starts with different heating populations dominating at different times? This vital chapter in the history of the Universe was written long ago, but is now waiting to be read.

## 10. The SKA Observatory

The SKA Observatory that will make these and a wide range of other discoveries possible will be deployed in two phases; an early deployment phase termed SKA1 of 10 – 20% of the complete system, followed by the fully scoped SKA2. The detailed design of SKA1 is currently underway, building on the preliminary design work toward the original Baseline Design (Dewdney et al., 2013). The scope of the SKA1 deployment has been adjusted in the first quarter of 2015 to match the budget established by the SKA Board of Directors. The updated Baseline Design, the Top Level Science Requirements and the associated System Level Requirements can be found in Cornwell et al. (2015), Braun et al. (2015) and Turner et al. (2015) respectively. The rescope has meant some reduction in the early science capabilities of the Observatory with respect to that envisaged in the original design. Fortunately, the updated SKA1 design preserves a transformational enhancement of capabilities over today's state-of-the-art across the full range of radio frequencies being targeted. The entire suite of high priority scientific objectives identified for the SKA1 still remains viable, albeit with some adjustments of approach. Although the extremely wide-field capabilities that had been planned for the SKA1-Survey facility are not part of the initial deployment, the enabling technology of Phased Array Feeds will be a high priority component of an accelerated research and development program, funded from the SKA1 construction budget, to enable scientific deployment within the SKA at the earliest possible opportunity.

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