PROCEEDINGS OF SCIENCE

Pulsar Science with the SKA

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The SKA will be transformational for many areas of science, but in particular for the study of neutron stars and their usage as tools for fundamental physics in the form of radio pulsars. Since the last science case for the SKA, numerous and unexpected advances have been made broadening the science goals even further. With the design of SKA Phase 1 being finalised, it is time to confront the new knowledge in this field, with the prospects promised by this exciting new telescope. While technically challenging, we can build our expectations on recent discoveries and technical developments that have reinforced our previous science goals.

Advancing Astrophysics with the Square Kilometre Array
June 8-13, 2014
Giardini Naxos, Sicily, Italy

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PoS(AASKA14)036

1. Introduction

Pulsars are a physicist's dream come true. Their study combines a wide range of physics and astrophysics, from the fundamental laws of nature to the structure of the Milky Way. Pulsars, as compact objects of the most extreme matter, store a huge amount of rotational energy, making them massive flywheels and very stable rotators. With a radio beam fixed relative to the surface of this rotating object, which has a strange superfluid superconducting material inside a solid iron crust, it acts like a cosmic lighthouse. On long time-scales, the frequency stability of the lighthouse's beacon rivals atomic clocks on Earth and allows us to test the terrestrial time standards. If the pulsar has a companion, they fall together in the gravitational potential of the Galaxy. By studying the way in which they fall, we can test general relativity and alternative theories of gravity under strong-field conditions in a unique and elegant, simple and clean way by measuring the times-of-arrival (ToA) of the pulses on Earth. These ToAs and the pulse properties are modified by the interstellar medium, in turn allowing us to probe its properties. As we are always looking for even better laboratories, we stare at the sky with our radio telescopes to find new pulsars with ever better sensitivity and instrumentation. Once in a while, we discover something truly unexpected, such as the Fast Radio Bursts (FRB) from cosmological distances. With the Square Kilometre Array (SKA) and its sensitivity, we will not only be able to continue this research but we will take it to a new level. This overview chapter summarises the specialised chapters in the remainder of the book and puts them into perspective of what the community proposed in 2004 in the chapters by Kramer et al. (2004) and Cordes et al. (2004) in the SKA Science Book edited by Carilli & Rawlings (2004).

1.1 The discovery potential of the SKA

Almost all the science presented in the "pulsar chapters" in this book and summarised below was already proposed for the SKA in 2004. However that definitely does not mean that, in the intervening 10 years, this research field has stood still. The very opposite is true. If anything, the rate of discoveries has even increased, largely due to the employment of new instrumentation, providing unprecedented sensitivity and time resolution – all possible due to the recent ability to digitise and process large bandwidths with commodity computing equipment. Far exceeding all of this, the SKA will provide yet another gigantic leap in various areas of instrumentation, giving orders of magnitude improvement in sensitivity, FoV, survey speed and many more. In order to demonstrate this, we summarise the relevant discoveries in Figure 1. The left panel shows the cumulative increase in pulsar discoveries as a function of time, with a number of important discoveries in the last decade. In total, we know of more than 2300 normal pulsars and about 250 millisecond (recycled) pulsars, of which about 80% are in binaries. With the full SKA we can expect more than a 10-fold increase in each of these numbers, a large fraction of which can be already found with Phase I, as described in the census chapter by Keane et al. (2015). These numbers are even somewhat larger than predicted by Kramer et al. (2004) and Cordes et al. (2004) as our knowledge of the populations has increased dramatically. The right panel of Figure 1 puts the expected numbers in relation to the current ones, demonstrating that these new discoveries will lead clearly to excellent science, resulting from the subsequent (needed) follow-up and timing observations, as described in the accompanying chapters.

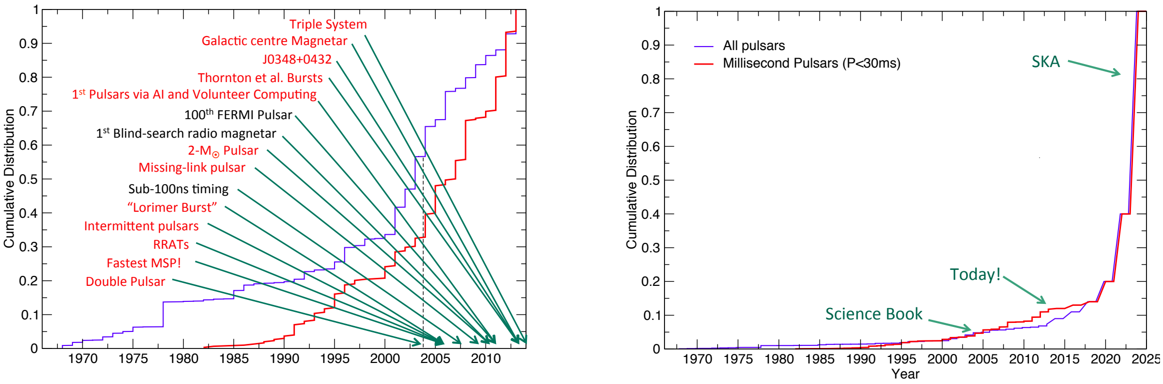

Figure 1: Pulsar-related discoveries as a function of time. The time of the first SKA Science Book is marked and some important (selected) discoveries since are marked. The right panel puts the current numbers into perspective with those expected for the SKA.

2. Science enabled by the discovery & study of pulsars and radio emitting neutron stars with the SKA

The pulsar key science described in the first SKA Science Book had a number of related components, which were summarised under the theme of "Testing Gravity". With pulsars being strongly self-gravitating bodies and precision clocks at the same time, timing observations of binary and isolated millisecond pulsars allow unprecedented strong-field experiments. These include testing general relativity and alternative theories of gravity using binary pulsars and (the yet to be discovered) pulsar-black hole systems as well as the direct detection of gravitational waves using a "Pulsar Timing Array" (PTA) experiment. Given the advances in recent years, prospects are now described in two separate chapters by Shao et al. (2015) and Janssen et al. (2015), respectively. In addition to those, we provide here a summary of the rich and varied science goals for the SKA described in the appropriate chapters:

Chapter 37 — Gravitational wave astronomy with the SKA — Janssen et al. (2015) A Pulsar Timing Array (PTA) is used as a cosmic gravitational wave (GW) detector. As described in the chapter by Janssen et al. (2015), Phase I essentially guarantees the direct detection of a GW signal. This may appear as a stochastic background from binary super-massive black holes in the process of early galaxy evolution, or it may be bright individual source(s) of this kind. Exotic phenomena like cosmic strings may also be expected to produce measurable GW signals, should they exist. The last ten years have seen a much better understanding of the source population, the detection procedures and the use of a PTA for fundamental physics (such as graviton properties, e.g. Lee et al. 2010) or single source localisation capabilities (e.g. Lee et al. 2011), all of which is described in the corresponding chapter.

Chapter 38 — Understanding pulsar magnetospheres with the SKA — Karastergiou et al. (2015) Considerable progress has been made with our understanding of the pulsar emission mechanism in the last decade. However, the wide bandwidth and exceptional sensitivity of the SKA will revolutionise our understanding of radio emission from all types of radio emitting neutron stars. Combined with the excellent high frequency data sets being accumulated by instruments like XMM, Chandra, FERMI, Magic, Veritas and HESS and new data from contemporaneous instruments like CTA, the data from SKA in Phase 1 will allow us to map the magnetosphere with unprecedented detail. With the SKA we will have an even greater range of radio frequencies available and sensitivity to study with more detail a greater number of sources. The high cadence of observing that should be afforded by the wide fields of view, sub-arraying capabilities, multi-beaming and commensal observing modes will revolutionise our understanding of the crucial relationship between the emission and spin properties of large samples of pulsars. The raw sensitivity of both MID and LOW will not only improve our understanding of the magnetospheric phenomena such as nulling and moding in a significantly increased sample of pulsars, it will also reveal in more detail how these manifest in millisecond pulsars. Both of these elements will be crucial in understanding the pulsar emission physics, but also for improving the use of pulsars as precision timing instruments. As we go from Phase 1 to SKA there will be significant improvements in the number of sources that can be studied, due to the large number of new sources and increased sensitivity, and even wider range of frequencies while the improved computing will enable even higher cadence.

Chapter 39 - Understanding the Neutron Star Population with the SKA - Tauris et al. (2015) The census will give a complete overview of the Galactic neutron star population. Not only has the number of neutron stars increased significantly in the last 10 years, but also new types of neutron stars have been discovered, such as Intermittent Pulsars (Kramer et al. 2006) or RRATs (McLaughlin et al. 2006), and unexpected types of binary systems. Also, some magnetars are now detected at radio frequencies, and it is therefore essential that we revisit the birth channels and properties of neutron stars and their evolution. The ingredients needed to understand the complex “zoo” of neutron stars and their inter-relationships is summarised in the chapter by Tauris et al. (2015).

Chapter 40 - A Cosmic Census of Radio Pulsars with the SKA - Keane et al. (2015) To transform and facilitate all of the science discussed here and in this book, it is essential to discover the largest possible fraction of the entire Galactic radio-emitting neutron star population. This is possible with the SKA. Moreover, this population, in itself, will provide an unparalleled opportunity to study the population as a whole and all that can tell us about the star formation and dynamical history of the Milky Way. This chapter presents a comprehensive analysis of the survey approaches and expected yields. We refer here only to selected highlights, noting that in the sample of radio emitting neutron stars we include RRATs and magnetars. In Phase 1 of the SKA, our simulations show that an optimised combination of pulsar search capabilities using both LOW and Bands 1 & 2 of MID can survey the entire sky visible from the SKA sites in a reasonable amount of observing time. Such a survey, with the rebaselined configurations of MID and LOW, would result in a yield of at least 7500 normal pulsars and 1200 millisecond pulsars. This assumes similar integration times on MID and LOW, if there were more time available on LOW a doubling of the integration time could be used to increase this yield by as much as 30%. Full SKA simulations have shown that a combination of a LOW, MID and an Aperture Array instrument working at below a GHz, could increase the total number of radio emitting neutron stars known in the Galaxy to more than 45,000 including more than 5,000 millisecond pulsars. In the majority of the regions of the Galaxy this would constitute the entire radio emitting neutron star population. In the Galactic centre a deep dedicated survey with Band 5 of the first phase of SKA will be sensitive to normal and millisecond pulsars, with the high frequency mitigating the deleterious effects of the interstellar medium (ISM) and the collecting area compensating for the steep pulsar spectra. With more than 1,000 pulsars predicted to be located with in the central parsec, in Phase 1 we can expect to detect dozens of pulsars in this region of the sky, and the later addition to the SKA of bands 3 & 4 combined with overall improved collecting area, will discover the vast majority of this predicted population.

Chapter 41 - Three-dimensional Tomography of the Galactic and Extragalactic Magnetoionic Medium with the SKA - Han et al. (2015) Another spin-off from the pulsar surveys will be the significant increase in the number of lines-of-sight through the Galaxy where we will be able to measure both the magnetic field properties and the electron column density, see this chapter for a full discussion. In Phase 1 there will already be an order of magnitude increase in the number of sources and the combination of LOW and MID will allow both near and distant sources, including some deep in the centre of the Galaxy, to be studied. The wide bandwidths, high frequency resolution and large number of sources will provide the accurate rotation measures and dispersions measure to generate a 3D tomographic view of the magneto-ionic properties of the Galaxy. With the full SKA revealing almost the entire radio pulsar population in the Galaxy it will allow one to probe the far side and also study the finer detail. Already in Phase 1 we will be able to find pulsars outside of our Galaxy and so study the fields inside those galaxies and also in the intervening medium. However the real renaissance in this area will come with the exceptional sensitivity of the SKA.

Chapter 42 - Testing Gravity with Pulsars in the SKA Era - Shao et al. (2015) New discoveries also lead to new exotic laboratories for fundamental physics, in particular for the study of gravity. Discoveries in recent years have continued to confirm this impression. The unique Double Pulsar system was found unexpectedly (Burgay et al. 2003; Lyne et al. 2004), providing unique and, so far, the best tests of general relativity for strongly-self gravitating bodies (Kramer et al. 2006); the most massive neutron star in a relativistic binary was found and probes a previously untested regime for alternative theories of gravity (Antoniadis et al. 2013); and the SKA observations of a unique discovered triple system (Ransom et al. 2014) promises to enable tests of the Strong Equivalence Principle that will surpass solar system limits.

We expect that among the discoveries are also pulsar-black hole systems. Using pulsars as test masses, we can probe the properties of black holes and measure the mass and the spin, χ. This will lead to precision tests of the "Cosmic Censorship Conjecture", which states that every astrophysical black hole should have an event horizon (cf. Liu et al. 2014). In order to test also the "no-hair" theorem, stating that all black hole properties are uniquely described by the mass and spin (and charge) of the black hole, we would need to also measure the quadrupole moment, Q, of the black hole, which should be identical to the value predicted by the measured combination of mass and spin.

Chapter 43 - Probing the neutron star interior and the Equation of State of cold dense matter with the SKA - Watts et al. (2015) Finding a large population of neutron stars will also yield the extreme objects. The SKA surveys will yield the fastest spinning pulsars, perhaps even sub-ms pulsars should they exist, the most massive pulsars and also of high interest, the lightest neutron stars. All this information will be used to study the equation-of-state (EOS) of super-dense matter. With neutron stars consisting of the densest matter in the observable Universe, we cannot

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create the corresponding conditions in terrestrial laboratories, so that pulsar observations, including those of glitches, moment-of-inertia measurements, provide a unique insight into the EOS(s?), as discussed in detailed in the chapter by Watts et al. Combining this insight with X-ray observations will also be extremely valuable as discussed further below.

Chapter 45 - Observing Radio Pulsars in the Galactic Centre with the Square Kilometre Array - Eatough et al. (2015) Measuring the quadrupole moment Q, and hence testing the "no-hair" theorem, for stellar mass black holes is difficult, even with the SKA. It will be much easier using a pulsar in orbit about the super-massive black hole in the centre of our Milky Way. The recipe for how to extract this science using observations of relativistic effects such as frame-dragging was first presented by Wex et al. (1999). This was further studied (Kramer et al. 2004; Liu et al. 2012) and is discussed in much detail in the corresponding chapter by Eatough et al. (2015). The SKA prospects of measuring the mass of SGR A* to a precision of $1M_\odot$ (!), its spin χ to 0.1% or better and the quadrupole moment Q to about 1%, even with a normal pulsar orbiting SGR A* is exciting and unprecedented.

Chapter 46 - Pulsar Wind Nebulae in the SKA era - Gelfand et al. As well as making a great step forward in studying pulsars and their environments using their properties in the time domain, the SKA can also make enormous strides by studying the environments of pulsars through imaging. This chapter discusses how the bulk of the rotational energy of pulsars is radiated away in the pulsar wind and the only way to study it is through its interaction with the surrounding interstellar medium or with a binary companion and/or its wind. The SKA, using both the MID and LOW elements, in Phase 1 will already unveil dozens of new pulsar wind nebulae providing vital new insight in to the composition of the wind and the acceleration of leptons up to PeV energies. These interactions will also reveal important details of the ISM, the companion star composition and their winds. When combined with the existing and upcoming data from instruments such as HESS, Veritas, Magic and Fermi and that from instruments such as CTA, this will revolutionise our understanding of pulsar winds and their environments.

Chapter 47 - Pulsars in Globular Clusters with the SKA - Hessels et al. (2015) The sheer number of pulsars and radio emitting neutron stars in globular clusters make them ideal targets for the SKA, especially as the vast majority are best viewed from the Southern Hemisphere. As discussed in this chapter, the excellent sensitivity of both LOW and MID in Phase 1 will already more than triple the number of pulsars known in globular clusters, while the SKA will discover a sample of millisecond pulsars to rival the rest of the Galactic population. Not only does this provide the opportunity to find rare systems for some of the applications discussed above, it provides unique tools to probe the magneto-ionic properties of the clusters, the star formation and dynamical history of these important Galactic building blocks. In the vein of targeted searches both LOW and MID will be excellent instruments for searching for pulsars in sources that are likely to contain neutron stars, either through their high frequency emission, in particular Fermi unidentified sources, or their steep spectrum radio emission. The ability to frequently search these targets will also reveal more of the evolutionarily important transition sources, that mark the birth of radio millisecond pulsars. Already in Phase 1 we will be to find dozens more pulsars in the Magellanic clouds enabling us to sample the pulsar population in completely different environments to our own Galaxy and we will sample the top end of the luminosity function of any pulsars located in other nearby dwarf galaxies. By looking for giant pulse like emission, as exhibited by the Crab pulsar, the reach will extend well out into the local group galaxies in Phase 1. With the SKA we will not only sample a very large fraction of the pulsars in the Magellanic clouds but will be able to detect significant numbers of pulsars in many of the galaxies in the local group and giant pulse emitters out to the Virgo Cluster.

Chapter 157 - SKA and the next-generation multi-wavelength observatories - Antoniadis et al. (2015) We have already alluded to a few of the synergies between pulsar work with the SKA and other instruments. However there are many more, and these are detailed in this chapter on synergies. These include the synergy with new and next generation gravitational wave detectors where the discovery of an increased number of double-neutron star binaries will enhance our understanding of the binary merger rate, the discovery of thousands of more radio pulsars may unveil some that are sufficiently distorted to emit gravitational waves, provide timing ephemerides for all of these pulsars to search for gravitational waves. There is also the possibility of the PTAs uncovering burst sources of GWs that can be followed up with instruments like LSST, IXO/Athena, Astro-H and of course proposed binary supermassive black holes can be searched for in the PTA data. Combining the astrometric information on binary systems with optical studies of their companions with instruments like LSST, E-ELT and GAIA can provide new insight into the stellar evolution, Galactic dynamics and cooling properties and ages of the stars. Combined X-ray and radio searches can reveal new transition systems which can reveal more about the formation process of millisecond pulsars and studies at both wavelengths can provide important input into our understanding of the neutron star equation of state. In particular, we are looking forward to synergies with Advanced LIGO and other ground (or even space-based) detectors. One one hand, they complement the SKA tests in the strong-gravity regime in a nearly perfect way, while they also allow us to probe similar sources in different evolutionary stages and across the mass scale.

3. Where does the SKA fit?

3.1 The synergy between SKA LOW and MID

It is important to recognise that the combined value of SKA LOW and MID in both Phase 1 and Phase 2 is more than the sum of its parts. This is true for all of the pulsar science discussed in this book, except only for the study of the innermost regions of the Galaxy. The significant increase in computing power to allow the removal of dispersion in the ISM combined with the ultra-wide bandwidths of instruments like LOFAR, MWA and the LWA have highlighted the value of returning to the lowest few octaves of the radio spectrum visible from the Earth for both pulsar searching and detailed pulsar studies. The excellent sensitivity of LOW already in Phase 1 will make it the ideal instrument for performing pulsar searches off the plane, where it is likely to find at least half of the known pulsars beamed in our direction. On the other hand the higher frequencies of MID will allow us to reach deep into the Galactic plane and see through the ISM to find thousands of pulsars there. It is essential though, that for both instruments there are sufficient numbers of tied-array beams available to ensure a sufficiently rapid survey speed with sufficiently long integration times. This will be possible with a minimum of 500 tied-array beams available for LOW and about 1500 beams for MID in Phase 1.

The ability of the SKA to have almost continuous frequency coverage from 50 MHz up to about 15 GHz with continuous up to 1.8 GHz in Phase 1, is of real value for studies of the pulsar

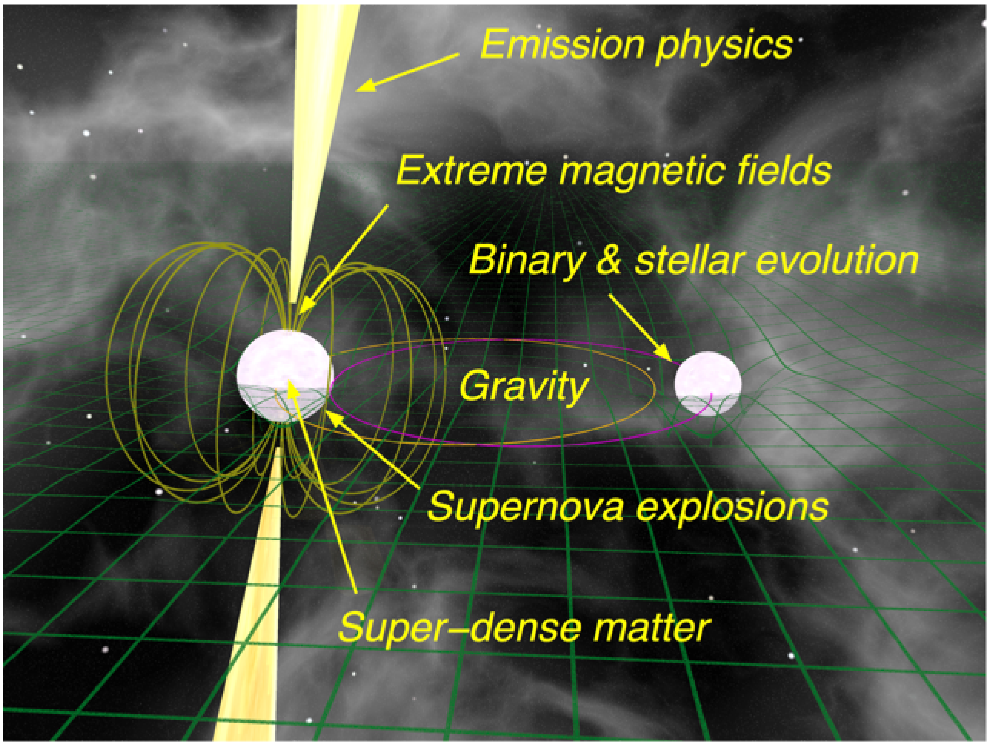

Figure 2: Artistic impression demonstrating the wide range of physics and astrophysics that finds its application when studying pulsars.

emission mechanism and magnetospheres, providing the ability to sufficiently sample the variations in emission properties as a function of frequency. The ability to correct for the influence of the ISM on high precision timing will be essential for all of the gravity studies and this is made possible through measuring the ISM weather through the continuous frequency bands. This is even more important if the highest frequency for pulsar timing in Phase 1 is around 1.8 GHz. Studies of the ISM and the Galactic distribution of electrons and the structure of the magnetic fields also value the combination of frequencies allowing measurements to be made nearby where the effects are best seen at LOW frequencies, and further away using the higher frequency bands. In the case of the pulsar wind nebulae the two instruments provide an ability to trace the energy deposition history and the physics of the pulsar wind.

3.2 Synergies with other SKA science goals

The pulsar surveys and associated observing and processing infrastructure naturally lead to a strong overlap with the fast transients goals (see Chapter 51). It is highly desirable therefore that the infrastructure, including the beamformer, be made available for searching for short duration radio bursts, be they from radio emitting neutron stars or from other radio transients, operate commensally, ideally with all other observations with both SKA MID and LOW, but certainly as frequently as possible. This will increase the yield for both the pulsar and radio emitting neutron star searches but also for the fast transients. As discussed in Chapter 41 and others, pulsars are very useful for the study of the ISM, providing full knowledge about the Milky Way, its constituents and its magnetic field structure. Synergies will also be present by comparing experimental results in gravity (via pulsars and cosmology) and the detailed characterisation of individual sources. In general, the aim should be to share discoveries with these communities as soon as possible to maximise the science return as rapidly as possible.

3.3 Impact of the SKA

The impact of the pulsar science obtained with the SKA promises to be very significant. Pulsars are among the very few objects that are visible across the whole electromagnetic spectrum and through new, unexplored windows like gravitational wave astronomy. At the same time, the understanding requires the application of theories ranging from quantum mechanics and solid states physics to gravitation and extreme plasma physics. Consequently, the variety of expected results is guaranteed to be relevant for a global community of physicists and astronomers alike. Literally, we can expect that we can mark our understanding of neutron stars, gravity and the Milky Way itself in a time before and after the SKA came online.

Besides this massive scientific impact, the pulsar science with the SKA also has the potential to draw great attention and interest from the general public. Neutron stars and in particular the black holes studied with the pulsars always fascinate the public. The fact that we can visualize pusar data in a unique dynamic way — and make them even audible — will make it easy to advocate the SKA and its science in general.

3.4 Risk and challenges

The technological components of "non-imaging processing" are challenging. This involves the task of beamforming and, due to the high data rates, the required on-line search processing. Data can not be stored but have to be analysed in real time. Imperfect algorithms would require a repeat of the experiment or parts of it. This may be both expensive or even impossible. On the other hand, the discovery rate could be high, consequently.

There are also scientific risks that are more difficult to quantify, as we are conducting discovery science. The biggest risk here is probably the uncertainty in the number of suitable pulsar - black hole systems or of pulsars about Sgr A* to conduct the proposed key science. Nevertheless, we know that extreme binary systems can be found in globular cluster (see Chapter 47) or in the regions of high stellar density in the central Galaxy. Here, the discovery of a rare radio-loud magnetar Eatough et al. (2013) however gives confidence that the expections are warranted (see Chapter 45).

4. Technical requirements of non-imaging processing with the SKA

The key technical requirements of the SKA are beyond the scope of this chapter and so we refer the interested reader to the papers by Smits et al. (2009, 2011) as well as to the detailed technical design from both the Non-Imaging work in the Central Signal Processing and Science Data Processor consortia[1] and also in the associated Chapters in this book. However, we highlight here some of the key requirements on both SKA MID and LOW to achieve the pulsar science goals.

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[1] www.skatelescope.org

- It is essential that in Phase 1 of SKA MID and LOW that there be a sufficiently large number of beams (e.g. 1,500 and 500 respectively) to be able to survey the sky sufficiently rapidly and with sufficient sensitivity.
- When searching for the extreme binary systems that are key to the gravity studies it is not possible to trade integration time for sensitivity as the required processing capacity scales as the third power of the integration time. So maximum sensitivity possible in the core regions needs to be maintained.
- Sub-arraying and a significant number of beams capable of undertaking precision timing are required to be able to enable characterisation of the large numbers of pulsars that will be discovered, but also to enable the high cadence observing required to reveal the physics of neutron star interiors and magnetospheres.
- Commensal observing will allow for transformation changes to the observing cadence achievable on the largest possible sample of objects.
- It should be possible to combine as many of the elements as possible, when forming the smaller number of beams to be used for the timing experiments to maximise sensitivity.
- Having as complete as possible frequency coverage across the entire LOW range and the ability to subarray so that that different frequencies can be observed simultaneously will be highly valuable for the physics of the magnetosphere.
- A combination of pulsar timing on both the LOW and MID instruments is required in order to be able to fully characterise and correct for the contribution of the ISM in the high precision pulsar timing experiments.
- It will be necessary to be able to calibrate the polarisation purity of the array to at least -40 dB for high precision timing experiments.

5. Summary

The science summarized in this overview can only give a glimpse of the science promises given by the SKA. With Phase 1 of the telescope being defined, we can safely predict what will be possible. However, the most exciting results will be, of course, obtained by unpredicted, unexpected discoveries and results. We may not be able to imagine what awaits us, but even the "expected" results are strong motivation to make the SKA a reality.

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