Pulsars with the SKA

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Abstract. As for other areas in modern astronomy, the SKA will revolutionize the field of pulsar astrophysics. Not only will new science be possible by the shear number of pulsars discovered, but also by the unique timing precision achievable with the SKA. The combination of both will not simply mean a continuation of the successes already achieved by using pulsars as fundamental tools of physics but the SKA will provide a new quality of science.

1. Introduction

In the 35 years since the discovery of pulsars, these unique objects have been proven to be invaluable in the study of a wide variety of physical and astrophysical problems. Most notable are studies of gravitational physics, the interior of neutron stars, the structure of the Milky Way and stellar and binary evolution. Most, but not all, of these results have been obtained by pulsar timing. Other uses of pulsars depend on measuring their emission properties and/or the interaction of the radiation with an ambient medium. All such results will be measurable with the SKA to unprecedented precision. But pulsar astronomy will also benefit from the SKA simply because of the shear number of sources that will be discovered and studied. Searching for pulsars is a prime example where quantity results eventually in quality by discovering a large number of exotic objects that probe extreme physics. In the following I review the major aspects of the science case for pulsars which is also outlined in the report of the Radio Transient, Stellar End Products, and SETI working group. A more detailed account of the opportunities provided by the SKA will be presented in the forthcoming new SKA science case.

2. Science with the SKA

Studying the rotational behaviour and the propagation of the pulses in curved space-time is achieved by pulsar timing. In this mode of observing the arrival times of the pulses are measured with the highest possible precision. The timing precision can be expressed by the RMS of the residuals after fitting an appropriate spin-down model, which scales as

\[ \sigma \propto \frac{W}{\text{SNR}} \propto \frac{T_{\text{sys}}}{A_{\text{eff}}} \times \frac{1}{\sqrt{2} \Delta \nu \, t} \times \frac{W^{3/2}}{S_{\text{psr}}} ](1)\]
since the signal-to-noise ratio scales as $\text{SNR} \propto 1/\sqrt{W}$, roughly. The pulse width $W$ is measured in units of time, $T_{\text{sys}}$ is the system temperature on the sky, $A_{\text{eff}}$ the effective area of the telescope, $\Delta \nu$ the available observing bandwidth, $t$ the integration time, and $S_{\text{psr}}$ the flux density of the pulsar. The last term in the above expression is source dependent, favouring strong pulsars with narrow pulses (or narrow features that can be locked on in a template matching procedure). Obviously, pulsars with a small period (and hence $W$), so-called millisecond pulsars provide the highest timing precision.

The special property of the SKA will be its unique sensitivity, i.e. a $T_{\text{sys}}/A_{\text{eff}}$ about 10 times smaller than for Arecibo or 100 times smaller than for the Lovell telescope, Effelsberg or the GBT. Hence, for the same sources it should in principle be possible to achieve a timing accuracy with the SKA that is correspondingly better. Apart from the flux density of the pulsar to be timed, another limiting factor will be the possible presence of timing noise. This random-like variation in the pulsar’s spin-down properties has been studied for slowly-rotating pulsars, but is also now observed in some faster-rotating millisecond pulsars (e.g. Lange et al. 2001, Lommen 2001). This suggests that every pulsar may, when studied with sufficient precision, exhibit this phenomenon. However, newly developed techniques may help to circumvent this possible limitation (Hobbs et al. 2003), and further studies will show how common it will be observed for millisecond pulsars.

Before we can time pulsars, we have to find them in the first place. The sensitivity of the SKA makes this a particularly exciting research area. The strawman-design of the SKA provides one with a sensitivity of $S_{\text{min}} \approx 1.4 \mu\text{Jy}$ in only 1 min integration time (assuming a detection threshold of $8\sigma$, a system temperature of $T_{\text{sys}} \approx 25\text{K}$, and a bandwidth of $\Delta \nu \approx 0.5\nu$). This corresponds to the luminosities listed in Table 1.

| Where                  | D (kpc) | L (mJy kpc$^2$) |
|------------------------|---------|-----------------|
| Galactic Centre        | 8.5     | 0.1             |
| Opposite Side of Galaxy| 24      | 0.8             |
| Magellanic Clouds      | 50–60   | 4.2             |
| M31                    | 690     | 660             |

At 1.4 GHz, the currently observed luminosities range from 0.01 mJy kpc$^2$ to 10,000 mJy kpc$^2$ with a (logarithmic) median of $\sim 25$ mJy kpc$^2$. Clearly, the luminosity limits achievable with the SKA at the low end will not only provide an essentially complete census of the Milky Way pulsars but reasonable integration times even allow the discovery (and study!) of pulsars in nearby galaxies. We will firstly consider the implications resulting from the large number of pulsars that will be discovered.
2.1. Studying the pulsar population

In seems possible that the largest part, if not all, of the Galactic radio pulsars beaming towards Earth will be discovered with the SKA, i.e. about 20,000 pulsar could be found. This Galactic Census of pulsars opens up new horizons in the study of a variety of subjects.

Pulsar as neutron stars. The observations of relativistic effects in binary pulsars allows the measurements of neutron stars masses. Most straightforward is the detection of a Shapiro time delay due to a companion for nearly edge-on orbits. Currently, the number of binary systems with such fortuitously aligned orbits is rather limited, but the combination of number of binary pulsars discovered and the sensitivity with the resulting timing precision will allow the measurement of many more neutron star masses. A manifold increase in the available statistics will allow to study the amount of matter accreted during a spin-up process and will also help in studying the neutron star equation-of-state.

The study of the latter will also benefit from the vastly improved statistics of observed pulse periods. Currently, the found periods range from 1.5 ms to 8.5 s. The discovery of even smaller rotational periods will provide significant insight in the properties and stiffness of the ultra-dense liquid interior of neutron stars. Even the case of a “null result”, that no period shorter than 1.5 ms will be found, will have consequence as it requires the existence of a limiting period not far away from the currently observed value. At the other extreme end, the discovery of very long period pulsars, isolated or in binary systems, will establish the connection of radio pulsars to magnetars, Soft-Gamma ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs), deciding as to whether these are distinct classes of neutron stars or simply different evolutionary stages or end products.

Pulsars as radio sources. Despite (or perhaps, ’because of’!) many intensive studies of the pulsar emission features occurring on timescales from nanoseconds to hours, weeks and months, the nature of the emission process is still unknown. One of the problems is the need to separate intrinsic effects from those caused by propagation. Moreover, it seems clear that solving the pulsar emission mechanism requires the observations of individual radio pulses. Only a limited number of pulsars is currently known that are luminous enough for such experiments. In particular, the needed multi-frequency observations are constrained by the relatively small number of pulsars that can be studied with sufficiently bright single pulses across a wide frequency range, and by the limited availability of large sensitive telescopes. The SKA will not only provide sufficient sensitivity at high frequencies (depending on design), increasing the sample of pulsars that can be studied to hundreds or more, but a combination of sub-arrays and/or multi-frequency feeds could perform these observations easily across a wide range of frequencies.

Many more very faint pulsars will be detected and the luminosity distribution of pulsars can finally be established. As we can expect from the recent discovery of faint neutron stars in deep searches (e.g. Camilo et al. 2002), many more neutron stars observed at high energies will have a detectable radio counterpart. Hence, the simultaneous availability of new gamma-ray telescopes like GLAST will mean that the relationship between the emission processes and
plasma particles involved at the far ends of the electromagnetic spectrum can be studied in great detail.

2.2. Pulsars as probes

Mapping the Galaxy. The emission of radio pulsars interacts with the ionized magnetized mediums it propagates through. The pulses become dispersed and scattered while the position angle of the linearly polarized emission component undergoes Faraday rotation depending on electron density and magnetic field. The currently best model for the electron density distribution in the Galaxy by Cordes & Lazio (2002) demonstrates impressively how information about dispersion and scattering measures for a large number of independent line-of-sights to pulsars located in different parts of the Milky Way can be used to establish an increasingly detailed knowledge. A Galactic Census of pulsars will provide so many lines-of-sight that, in particular with a combination of HI absorption measurements, distances, electron densities and scattering measures will be determined in such numbers that very detailed modelling becomes possible and a complete 3-D map of the Galaxy unfolds.

Globular clusters. The study of millisecond pulsars in globular clusters has been rejuvenated in the last few years by a much increased number of discovered pulsars, adding also to the list of clusters with known pulsar content (e.g. D’Amico et al. 2001). The example of 47 Tucanae with more than 20 millisecond pulsars has provided already a good example for the kind of science that becomes possible by having the chance to study many more pulsars in this or similar clusters (Freire et al. 2003): It will be possible to use these pulsars to probe the clusters’ gravitational potential, their evolutionary stage, the stellar interaction and the intracluster medium. We already achieve “sub-milliarcsecond per year” precision in proper motion measurements and we start to see the relative motion of the pulsars in the cluster. However, with the current sensitivity and precision, further progress will be slow and it will need another 10 years or so to break the 0.01 mas/yr boundary. With an SKA we can achieve a proper motion measurement for 47TUC J, the brightest MSP in 47Tuc, of sub-µas/yr precision in about 2 years of weekly observations. This will also yield the distance of this 5-kpc cluster due to parallax measurements to better than 2%. This is a precision which even future astrometry missions like GAIA will not be able to surpass.

2.3. Gravitational Physics

One of the most exciting motivations to find lots of new pulsars is the prospect of finding some very exciting and exotic systems. The available computer power will enable us to do much more sophisticated searches than possible today, and the sensitivity allows much shorter integration times, so that searches for fast accelerated pulsars will not be limited anymore. Hence, the discovery rate for relativistic binaries is certain to increase. But even in the worst case scenario, with a detection rate remaining unchanged, we should expect at least hundred relativistic binaries, or so, that provide exciting test ground for gravitational physics. We should find more planetary systems, we may find (over-determined!) double pulsar systems and perhaps even exotic or strange stars. Studying regions
of high stellar density with an increased probability of stellar interactions, such as globular clusters and the Galactic centre (which is particularly interesting due to its conditions favouring more massive stars) should provide us with “the holy grail” of a pulsar-stellar black hole system, or even with a millisecond pulsar orbiting a black hole. For the first time it would be possible to probe the properties of a black hole predicted by Einstein’s theory of gravity.

Properties of black holes The current best candidates for a stellar black holes are provided by dynamical mass estimates in X-ray binaries. While it seems accepted that any unseen companion with a mass exceeding $\sim 3M_\odot$ is a likely black hole candidate, the mass limit is somewhat uncertain due to possible effects of rotation or even the speculated existence of Boson- or even Q-stars for which no reliable mass estimate exists. A realistic black hole should also rotate, which allows us for a black hole of mass $M$ to define a (dimension less) spin, $\chi = cS/GM^2$, and quadrupole moment, $q = c^4Q/G^2M^3$, whereas $S$ is the angular moment and $Q$ is the quadrupole moment. In GR we have $\chi \leq 1$ for Kerr-black holes, while $\chi > 1$ indicates a naked singularity. In fact, a measurement of both $\chi$ and $q$ can be used to identify the nature of the unseen companion, e.g. for a Kerr-BH we find $q \leq -10\chi^2$, while for a neutron star, $q = -\chi^2$. A rotating boson star may yield $q = -C\chi^2$ with $2.0 \leq C \leq 12.1$ (Wex & Kopeikin 1999).

It has been suggested that frame dragging could be measured by pulsar timing to identify a black hole companion to a pulsar in an edge-on orbit (Laguna & Wolszczan 1997). Unfortunately this effect would be superposed on the usually stronger light-bending effect (Doroshenko & Kopeikin 1995) which would make the detection of the frame dragging effect difficult. Alternatively, the most promising way is to measure non-linear changes in the longitude of periastron, $\omega$, and the projected semi-major axis, $x$, caused by the gravitomagnetic field (Wex & Kopeikin 1999). Again, the precessional effects to be searched for will be superposed on other effects, but separating these effects on the way, will provide an exciting tour de force through tests of gravity in its own right. Competing effects for the observed change in $x$ are

$$\left(\frac{\dot{x}}{x}\right)_{\text{obs}} = \left(\frac{\dot{x}}{x}\right)_{\text{pre}} + \left(\frac{\dot{a}_p}{a_p}\right)_{gw} + \left(\frac{\dot{x}}{x}\right)_{pm} + \left(\frac{\dot{D}}{D}\right) + \left(\frac{d\epsilon_a}{dt}\right)$$

The first term is the one to be measured, the second term is due to the shrinkage of the orbit due to gravitational wave emission, the third term arises from a motion of the system relative to the observer, the fourth term is due to an acceleration in an external gravitational potential while the last term is due to geodetic precession. All but the first term have been studied in pulsars and binary systems already (e.g. Weisberg & Taylor 2003, van Straten et al. 2001, Kramer 1998), so that with the increased precision of the SKA we should be able to handle them even easier. Still, unless a millisecond pulsar in orbit around a black hole can be found, the task of measuring the black hole properties will even be a challenging for the SKA. But it is not impossible and it would be surely among the most remarkable discoveries that is likely to be made with the SKA.

Cosmological Gravitational Wave Background Monitoring a large sample of millisecond pulsars in a so-called Pulsar Timing Array (PTA) offers the means to
detect the stochastic gravitational wave background that is expected in various cosmological theories (e.g. Foster & Backer 1990). The PTA would be used to search for (correlated) structures in the timing residuals of MSPs distributed across the sky. It will be sensitive to long-wave gravitational signals and is therefore complementary to current ground-based gravitational wave detectors such as GEO600 or LIGO and even future detectors such as LIGO-II or LISA. With a rough estimate of about 1000 millisecond pulsars to be discovered, the SKA would not only provide the necessary dense PTA but also the means of achieving the necessary sub-mus timing precision that will be needed to extract the weak signal.

2.4. Extragalactic pulsars

We have already seen above that standard searches with the SKA should result in the discovery of pulsars in the most nearby galaxies, allowing to study the population of pulsars as seen from the distance and for different star formation histories. This search volume can be further expanded if we search for giant pulses rather than for periodic signals (e.g. McLaughlin 2001). We could possibly reach a distance of 5 Mpc or even 10 Mpc, and depending on the strength of the pulses, larger distances are not impossible. Even though the study (and timing!) of these far away pulsars would be virtually impossible, their giant pulses can still be used study the distribution of pulsars in galaxies of different types, and to investigate the ionized medium in the host galaxies and intergalactic space.

2.5. Value Added Science

The above is clearly only a fraction of the science that will be achievable with the SKA – and that only in the area of pulsar astrophysics! There is much more I should have added and which deserves much more attention. Examples are the interior of neutron stars, birth properties of pulsars, neutron star-supernova
associations, stellar, binary and planetary evolution, core collapse physics, astrometry, metrology, time keeping to name only a few.

3. Conclusions

Most of the science suggested here can be achieved with the proposed strawman design. Simulations studying the multi-beaming requirements for the pulsar case are underway, as the timing of about 20,000 pulsars is certainly a challenging task even for a multi-beaming telescope. Some long baseline capabilities are desirable for astrometric purposes (1 mas at 5 GHz). The required upper frequency limit is relatively modest but should be around 15 GHz which is necessary to penetrate the scattering screen towards the inner Galaxy. Additionally, pulsar science sets tough requirements for the correlator in terms of dump time (about 5\mu s for timing, 50\mu s for searching) and bandwidth that can be processed. Overall, the science case in its potential and diversity appears overwhelming, so that if there would not be a SKA anyway, there should be at least one to study pulsars.

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