Strong-Field Tests of Gravity Using Pulsars and Black Holes

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The sensitivity of the SKA enables a number of tests of theories of gravity. A Galactic Census of pulsars will discover most of the active pulsars in the Galaxy beamed toward us. In this census will almost certainly be pulsar-black hole binaries as well as pulsars orbiting the super-massive black hole in the Galactic centre. These systems are unique in their capability to probe the ultra-strong field limit of relativistic gravity. These measurements can be used to test the Cosmic Censorship Conjecture and the No-Hair theorem.

The large number of millisecond pulsars discovered with the SKA will also provide a dense array of precision clocks on the sky. These clocks will act as the multiple arms of a huge gravitational wave detector, which can be used to detect and measure the stochastic cosmological gravitational wave background that is expected from a number of sources.

1. Was Einstein Right?

In astrophysical experiments we are passive observers who must derive all information simply from photons (or particles or gravitons) received, in contrast to procedures in terrestrial laboratories where experimental set-up can be modified and environment can be controlled. As a result, terrestrial experiments are typically more precise and, most importantly, reproducible in any other laboratory on Earth. However, when probing the limits of our understanding of gravitational physics, we are interested in extreme conditions that are not encountered on Earth. In some cases, it is possible to perform the experiment from a space-based satellite observatory. Indeed, solar system tests provide a number of very stringent tests of Einstein's theory of general relativity (GR) (see [38]), and to date GR has passed all observational tests with flying colours.

Despite the success of GR, the fundamental question remains as to whether Einstein has the last word in our understanding of gravity or not — a question that was also included as one of eleven questions raised in *"Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century"* [3]. The likely answer to this question is that this is not the case, as physicists attempt to formulate a theory of quantum gravity. Quantum gravity would fuse the classical world of gravitation, currently best described by GR, with the intricacies of quantum mechanics. Quantum gravity would therefore account for all of the known interactions and particles of the physical world. Determining as to whether the as yet accurate theory of GR describes the gravitational interaction of the macroscopic world cor-

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rectly, would either justify the current approaches to use GR as the basis of quantum gravity or would imply that other alternative lines of investigations have to be followed during this enormous task.

There is a large parameter space that is not yet explored by the current experimental tests of GR. In particular, solar-system experiments made or proposed for the future are all made in the weak-field regime and hence will never be able to provide tests in the strong-field limit. Other tests involving the observations of X-ray line redshifts from neutron stars may explore some parts of this parameter space, but the interpretation of these results depends to some extent on the unknown equation-of-state [7]. Similarly, whilst it is in principle possible to utilize low-energy X-ray spectra or high frequency quasi-periodic oscillations to study relativistic effects around a spinning and accreting BH (e.g. [25]), the arguments still require certain plausible assumptions (e.g., the accretion disk reaches all the way down to the last stable orbit, etc.), and the precision with which the spin is determined is rather poor, even in systems where all the input parameters are comparably well known. In contrast, pulsars provide an accurate clock attached to a point-mass which can, in a binary orbit, allow us to perform high precision tests of gravitational theories. Hence, binary pulsars are and will remain the only way to test the predictions made by GR or competing theories of relativistic gravity in the strong-field limit. This is possible with a precision that is otherwise only achieved in terrestrial laboratories.

Ultra-sensitive pulsar observations with the SKA will open a new era in fundamental probing of gravitational physics. Figure 1 illustrates the as yet unexplored regions of the parameter space that can be filled with observations made with the SKA. Clearly, one should aim for discovering pulsars in compact orbits around a massive companion, i.e. a stellar or even massive black hole (BH), in order to probe the ultra-strong field limit. We discuss the potential for discovering such a pulsar-BH system in the next section. We will show that a pulsar orbiting a BH in a close orbit would be a high-precision laboratory not only for GR in general, but for BH physics in particular [27]. Being timed with the SKA, a PSR-BH system would be an amazing probe of relativistic gravity with a discriminating power that surpasses all of its present and foreseeable competitors [6].

Table 1
Frequency range and sensitivity limit of an SKA pulsar timing array (PTA) in comparison other means of detecting gravitational wave emission.

Detector	Approximate Frequency	Sensitivity $h_0^2\Omega_{gw}$
Advanced LIGO	~ 100 Hz	5×10^{-11}
LISA	$\sim$ mHz	10^{-12}
PTA	$\sim$ nHz	10^{-13}
COBE	$\sim 10^{-16}$ Hz	7×10^{-14}

Non-PTA reference: Maggiore (2000)

Previous pulsar tests have shown that GR's prediction for gravitational quadrupole radiation is correct to within the measurement uncertainties, which are currently better than 1% [41]. This particular test is performed by measuring the orbital decay of a pulsar orbit due to the emission of gravitational waves. Pulsars can also be used to directly *detect* gravitational radiation in contrast to the *indirect* measurements from orbital decay in binaries. What is predicted is a stochastic background spectrum of waves from energetic processes in the early Universe. Pulsars discovered and timed with the SKA act effectively as the endpoints of arms of a huge, cosmic gravitational wave detector. This "device" with the SKA at its heart promises to detect such a background, at frequencies that are below the band accessible even to LISA (see Table 1). We discuss the direct detection of gravitational waves in Section 3.

2. Strong-field Tests of Gravity

The strong-field limit of gravity is encountered when large velocities and large gravitational potentials of massive compact objects are involved. The effect of the latter can be estimated from the

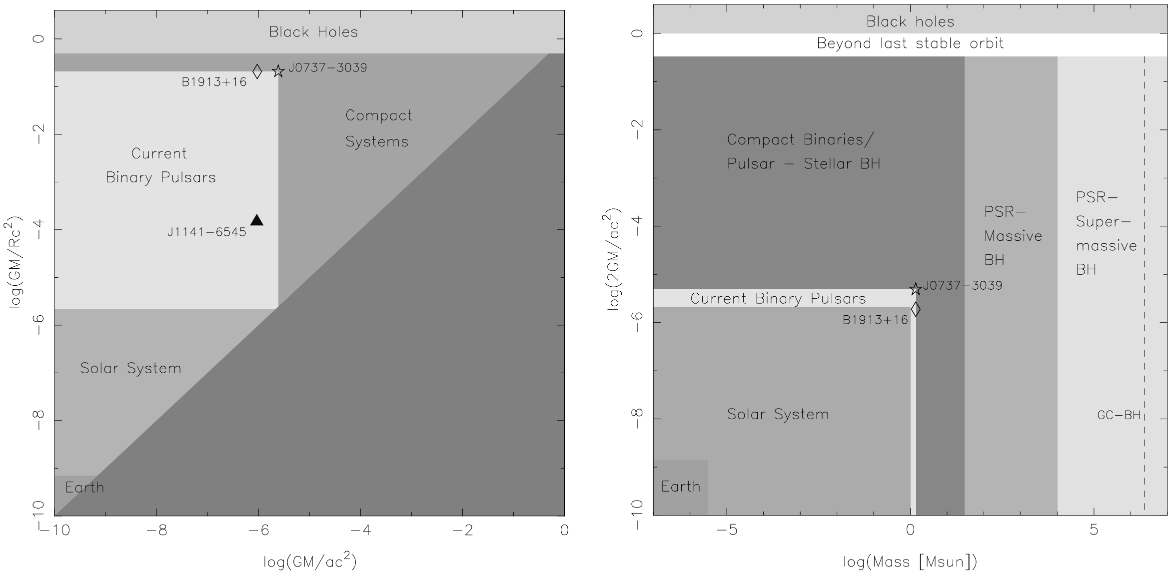

Figure 1. Parameter space of gravitational physics to be probed with pulsars and black holes. *(Left:)* Some theories of gravity predict effects that depend on the compactness of the gravitating body which is shown here (y-axis) as a function of orbital size and probed gravitational potential (x-axis). Note that the lower right half of the diagram is excluded as it implies an orbit smaller than the size of the body. *(Right:)* Orbital size in units of Schwarzschild radius as a function of gravitational mass.

body's gravitational self-energy, ϵ. For a mass M with radius R, ϵ can expressed in units of its rest-mass energy, i.e. $\epsilon = E_{\rm grav}/Mc^2 \sim -GM/Rc^2$, where G is the gravitational constant and c is the speed of light. In the solar system we find $\epsilon \sim -10^{-6}$ for the Sun and $\epsilon \sim -10^{-10}$ for the Earth. In contrast, for a NS, $\epsilon \sim -0.2$, whilst for a BH $\epsilon = -0.5$.

Unlike general relativity, some alternative theories of gravity, such as tensor-scalar theories, predict effects that depend strongly on a body's gravitational self-energy. Such effects can be detected, for instance, when two objects of considerable different self-energies are moving in the same external gravitational potential or are in orbit about each other. These phenomena, related to possible violations of equivalence principles, can be probed in the weak-field limit of the solar system and in the strong-field regime by observing pulsar-white dwarf systems (e.g. [17,10]). Other tests can probe the existence of preferred reference frames or violation of the conservation of momentum [32].

The largest strong-field effects, however, are only encountered to date when studying pulsars in compact binary systems. Prime examples are Double-Neutron Star Systems (DNS) such as the famous PSR B1913+16 system [14] or the first-discovered double pulsar PSR J0737−3039 [4,23]. As described in more detail in the general description of the pulsar case (Cordes et al, this volume), pulsars enable high-precision tests of GR by probing a number of effects such as the possible violation of equivalence principles, conservation laws or gravitational wave damping. However, locating the position of the currently known binary pulsars in Figure 1 shows that these still do not probe those regions of the diagrams which are populated by ultra-compact systems, in particular those with a BH companion. These latter systems will almost certainly be discovered in a "Galactic Census" of pulsars with the SKA.

Through its sensitivity, sky and frequency coverage, the SKA will discover a very large fraction of the pulsars in the Galaxy, resulting in about 20,000 pulsars (see Cordes et al., this volume). This number represents essentially all active pulsars that are beamed toward Earth and includes the discovery of more than 1,000 millisecond pulsars (MSPs). This impressive yield effectively samples every possible outcome of the evolution of massive binary stars, thereby guaranteeing the discovery of systems that provide the best opportunity for testing fundamental physics.

The computer power available when the SKA comes on-line will enable us to do much more sophisticated acceleration searches than possible today. At the same time, the sensitivity of the SKA allows much shorter integration times, so that searches for compact binary pulsars will no longer be limited. Hence, the combination of SKA sensitivity and computing power means that the discovery rate for relativistic binaries is certain to increase beyond the number of compact binary systems that we can expect from a simple extrapolation of the present numbers. More detailed estimates come from binary evolution modelling (e.g. [2]), which imply that we should expect to find at least 100 compact *relativistic* binaries, providing almost certainly the first PSR-BH systems.

2.1. Pulsar-Black Hole Systems

As stars rotate, astrophysicists also expect BHs to rotate, giving rise to both a BH spin and quadrupole moment. The resulting gravitomagnetic field [34] gives rise to a relativistic frame-dragging in the BH vicinity, which causes the orbit of any test mass about the BH to precess if the orbit deviates from the equatorial plane [18]. The consequences for timing a pulsar around a BH have been studied in detail by Wex & Kopeikin (1999 [39]), who showed that the study of the orbital dynamics allows us to use the orbiting pulsar to probe the properties of the rotating BH.

The mass of the BH can be measured with very high accuracy as done for the DNS PSR B1913+16 [41] or the double pulsar [23]. The spin of the BH can also be determined very precisely using the nonlinear-in-time, secular changes in the observable quantities due to relativistic spin-orbit coupling. The anisotropic nature of the quadrupole moment of the external gravitational field will produce characteristic short-term periodicities due to classical spin-orbit coupling, every time the pulsar gets close to the oblate BH companion [37,39]. These short-term periodicities lead to a unique signature in the timing residuals that can be detected by regular SKA timing.

Therefore, with SKA observations, the mass, M, and both the dimensionless spin χ and quadrupole q,

$$\chi \equiv \frac{c}{G}\,\frac{S}{M^2} \qquad \text{and} \qquad q = \frac{c^4}{G^2}\,\frac{Q}{M^3} \tag{1}$$

of the BH can be determined, where S is the angular momentum and Q the quadrupole moment. These measured properties of a BH can be confronted with predictions of GR.

2.2. Cosmic Censorship Conjecture

In the theory of GR, the curvature of space-time diverges at the centre of a BH. The physical behaviour of this singularity is unknown. The Cosmic Censorship Conjecture was invoked by Penrose in 1969 (see e.g. [12]) to resolve the fundamental concern that if singularities could be seen from the rest of space-time, the resulting physics may be unpredictable. The Cosmic Censorship Conjecture proposes that singularities are always hidden within the event horizons of BHs, so that they cannot be seen by a distant observer. A singularity that is found not to be hidden but "naked" would contradict this Cosmic Censorship. In other words, the complete gravitational collapse of a body always results in a BH rather than a naked singularity (e.g. [36]).

While the issue of whether the Cosmic Censor Conjecture is correct remains an unresolved key issue in the theory of gravitational collapse, we can test this conjecture by measuring the spin of a rotating BH: In GR we expect $\chi \leq 1$. If, however, SKA observations uncover a massive, compact object with $\chi > 1$ two important conclusions may be drawn. Either we finally probe a region where GR is wrong, or we have discovered a collapsed object where the event horizon has vanished and where the singularity is exposed to the outside world. The discovered object would not be a BH as described by GR but would represent an unacceptable naked singularity and hence a violation of the Cosmic Censorship Conjecture [13]. In this case, the Kerr metric would fail to be strongly asymptotically predictable, and thus would not describe a BH [36].

The observational parameters that need to be determined to measure BH spins are, at least, two Post-Keplerian parameters (see Cordes et al., this volume, for details) and the contributions of relativistic spin-orbit coupling to the first and second time derivatives of the projected semi-major axis, $\dot{x}_{\rm SO}$ and $\ddot{x}_{\rm SO}$, and the longitude of periastron, $\dot{\omega}_{\rm SO}$ and $\ddot{\omega}_{\rm SO}$. These contributions are likely to be small and whilst their determination is possible with the SKA, the currently available timing precision would almost certainly prevent such a measurement even if a PSR-BH system were discovered today [39]. With the timing precision affordable with the SKA, however, we can test the validity of the Cosmic Censorship Conjecture, which the physical relevance of BHs depends on in large measure.

2.3. "No-hair" Theorem

One may expect a complicated relationship between the spin of the BH, χ, and its quadrupole moment, q. However, for a rotating Kerr BH in GR, both properties share a simple, fundamental relationship [33,35],

$$q = -\chi^2. \qquad (2)$$

This equation reflects the "no-hair" theorem of GR which implies that the external gravitational field of an astrophysical (uncharged) BH is fully determined by its mass and spin (e.g. [31]). Therefore, by determining q and χ from timing measurements with the SKA, we can confront this fundamental prediction of GR for the very first time.

The secular changes caused by classical spin-orbit coupling due to the BH quadrupole moment are typically three orders of magnitude smaller than the changes caused by the spin-invoked relativistic spin-orbit coupling [39]. However, short-term periodic effects occurring every orbit lead to a unique signature in the timing residuals that can be used to extract the quadrupole moment. The duration ($\sim$ closest encounter of PSR and BH) and amplitude ($\sim$ few ns to μs) of these periodic signatures depend on the mass of the BH and the compactness and orientation of the orbit, all of which can be determined accurately by regular timing observations. The detection clearly requires the sensitivity and timing precision affordable with the SKA and would benefit greatly from SKA multi-beaming capabilities that allows for a very dense spacing of timing observations.

2.4. Experimental Strategy

About a hundred normal pulsar - stellar BH systems may be expected in the Galactic field from population studies (e.g. [2]). However, the best prospects for studying BH properties and GR in the strong-field limit would be given by the discovery of a PSR-BH system with MSP companion since these pulsars provide the best timing precision. In standard evolutionary scenarios, however, the BH would evolve first, hence preventing mass accretion to the pulsar and its spin-up to small periods (e.g. [2]). Nevertheless, in regions of high stellar density, exchange interactions can lead to compact binary systems that would otherwise not be formed (e.g. [29]), including those of MSP-BH systems. Prime survey targets would therefore be the innermost regions of our Galaxy and Globular Clusters. Discovering pulsars in the Galactic Centre requires high observing frequencies of up to 15 GHz in order to combat the effects of interstellar scattering [5].

Finding pulsars in orbits around massive or super-massive BHs would allow us to apply the same techniques for determining their properties as for the stellar counterpart [39]. Massive black holes ($\sim 10^4 M_\odot$) are expected to reside in the centre of some globular clusters, while we can also probe the super-massive BH in the centre of our Galaxy with a mass $\sim 3 \times 10^6 M_\odot$[30]. Since the spin and quadrupole moment of a BH scale with its mass squared and mass cubed, respectively, relativistic effects are much easier to measure for massive and super-massive BHs. In these cases, the discovery of an orbiting MSP is still desirable but not necessarily required. With a complete SKA census of the Galactic pulsar population, we can therefore probe and measure the properties of BHs on a wide range of mass scales.

3. Gravitational Wave Background

The SKA will discover a dense array of MSPs distributed across the sky. Being timed to very high precision (<100 ns), they act as multiple arms of a cosmic gravitational wave (GW) detector. Each pulsar and the Earth can be considered as free masses whose positions respond to changes in the space-time metric. A passing gravitational wave perturbs the metric and hence affects the pulse travel time and the measured arrival time at Earth [8,11,28]. If the uncertainty in the pulse arrival time is σ and the total observing time is T, then the "detector" is sensitive to a dimensionless strain (or metric perturbation) of

$$h_c(f) \simeq \frac{\sigma}{T\sqrt{N_f}} \propto \frac{\sigma_f}{T^{1.5}} \tag{3}$$

where $h_c(f)$ describes the characteristic amplitude of the GW background per unit logarithmic interval of frequency, σ_f is the square-root of the power spectral density $h(f)$, and N_f the number of normal points per period of a GW at frequency f. With observing times of a few years, pulsars are sensitive to GWs frequencies of $f > 1/T$, hence in the ∼nHz range. The effect of GWs as a pseudo-perturbation of the index of refraction in ordinary 3-space can be viewed as the independent modification of the position of pulsars. At the same time, the other endpoint of the "detector arm", the Earth, is modified in a manner that is the same for all sources being timed, leaving a signal in the correlated timing residuals of all pulsars which form a so-called "Pulsar Timing Array" (PTA).

3.1. Pulsar Timing Array (PTA)

The measurement precision and accuracy of the pulsar clock is not sufficient to detect the gravitational radiation of stellar-mass binaries by means of a PTA. In contrast, super-massive black hole binaries in nearby galaxies with orbital periods of a few years would produce periodicities in pulsar arrival times of the order of 10 ns to 1 μs, which may be detectable with SKA timing [28,22]. Whilst the short lifetime of such massive binaries reduces the chances of observing such systems, the SKA can nevertheless detect the signal of a stochastic background of GW emission produced by a large number of unresolved independent and uncorrelated events.

A stochastic gravitational wave background should arise from a variety of sources. Cosmological sources include inflation, string cosmology, cosmic strings and phase transitions (e.g. [1,24]). We can write the intensity of this GW background as

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\log f} \tag{4}$$

where $\rho_{\rm gw}$ is the energy density of the stochastic background and ρ_c is the present value of the critical energy density for closure of the Universe,

$$\rho_c = \frac{3H_0^2}{8\pi G} \tag{5}$$

with $H_0 \equiv h_0 \times 100$ km s^{-1} Mpc^{-1} as the Hubble constant (e.g. [21,20]).

The frequency range covered by the PTA (∼nHz) complements the much higher frequencies accessible to Advanced LIGO (∼100Hz) and LISA (∼mHz), and the extremely low frequencies probed by studies of the Cosmic Microwave Background and its polarization (see Table 1). For the cosmological sources a spectrum $h_0^2\Omega_{\rm gw}(f)$ ∼const. is usually expected (see Fig. 2). With $h_0^2\Omega_{\rm gw} \propto h_c^2 f^2$, this translates into a characteristic strain spectrum of $h_c(f) \propto f^{-1}$. The amplitude of the GW background from inflation can already be constrained by COBE measurements with a safe upper bound of $h_0^2\Omega{\rm gw}^{\rm inflation} \lesssim 10^{-14}$. This signal appears to be too low to be observable with any GW detector [24].

In contrast, a much stronger GW signal is produced in string cosmology by the amplification of vacuum fluctuations. Cosmic strings are topological defects existing in grand unified theories. If they vibrate, they create a GW background that lies in the sensitivity range of both LISA and the PTA. Local defects would convert larger fractions of energy into GWs, potentially producing stronger signals that would be even easier to detect. However, the limits provided by current MSP timing already exclude the existence of local strings to a significant level [19]. The best current MSP timing limit is based on a single pulsar, PSR B1855+09 [21],

$$h_0^2\Omega\mathrm{gw}^{\mathrm{string}} < 4 \times 10^{-9} \qquad (6)$$

improving over the previously best limit [16] by more than one order of magnitude.

In addition to this truly cosmological stochastic GW background, a contribution is also expected from astrophysical processes, in particular from the coalescence of massive BH binaries during early galaxy evolution [28,15]. While LISA may detect individual mergers of the more massive BH binaries, these sources also form a stochastic background. The spectrum of this "foreground" contribution follows $h_c(f) \propto f^{-2/3}$ or $h_0^2\Omega_{\mathrm{gw}}(f) \propto f^{+2/3}$ [26]. Whilst the exact amplitude of this signal depends on the mass function of the massive BHs and their merger rate [15] (see shaded area in Fig. 2), massive BH binaries are the among primary sources expected for the background in the frequency range detectable with LISA and the PTA [15,40,9]: the nHz frequency background is thought to be dominated by BH binaries at redshifts $z \lesssim 2$ whilst more than half of the massive BHs detectable at mHz are likely to originate at redshifts $z \gtrsim 7$. A complementary detection of this background and a measurement of its amplitude from nHz to mHz with LISA and the PTA would allow to discriminate between this foreground signal from the cosmological sources and would provide unique information about the physics and history of BH growth in galaxies.

3.2. Experimental Strategy

The sensitivity of the PTA scales according to

$$h_0^2\Omega_{\mathrm{gw}} \propto \mathrm{RMS}^2 f^4 \qquad (7)$$

producing a wedge-like sensitivity curve as shown in Fig. 2 (e.g. [15]). For timing precision that is only limited by radiometer noise, the RMS is expected to scale with the collecting area of the observing telescope. In reality, the precision is also affected by pulse phase jitter, propagation effects in the interstellar medium and gain and polarization calibration (see pulsar science for details). While we discuss the resulting technical requirements such as multi-frequency capabilities

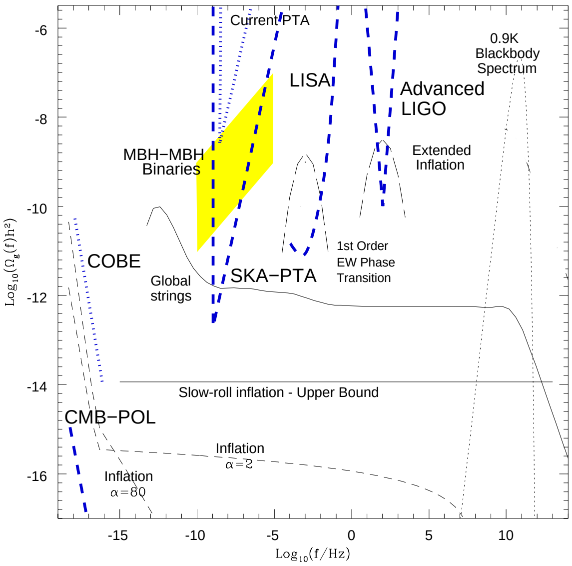

Figure 2. Summary of the potential cosmological sources of a stochastic gravitational background, including inflationary models, first-oder phase transitions and cosmic strings and a primordial 0.9K black-body graviton spectrum as presented Battye & Shellard (1996). We also overlay bounds from COBE, from current millisecond pulsar timing and the goals from CMB polarization, LISA and Advanced LIGO (see e.g. Maggiore 2000). The PTA provided by the SKA will improve on the current MSP limit by about four orders of magnitudes. The gray area indicates the spectrum of an additional astrophysical background caused by the merger of massive black holes (MBHs) in early galaxy formation (e.g. Rajagopal & Romani 1995, Jaffe & Backer 2003). For this background, $\Omega_{gw} \propto f^{2/3}$, whilst its amplitude depends on the MBH mass function and merger rate. The uncertainty is indicated by the size of the shaded area.

and polarization purity in §4, the effects of phase-jitter mean that not all MSPs will be suitable to be included in the PTA. Their precision and the application of correction schemes will need to be determined on a case by case basis. However, extrapolating from the experience with the best performing MSPs today, we can expect the SKA to improve on the current limit on $h_0^2\Omega_{\rm gw}$ by a factor 10^2-10^3! We gain an additional factor $1/\sqrt{N_{\rm PSR}}$ from a correlation of many pulsars, where $N_{\rm PSR}$ is the number of timed pulsars in the PTA. While a minimum of seven pulsars is required for calibration and cross-correlation purposes [11], ideally, a much larger $N_{\rm PSR}$ should be included and a very large fraction of the sky should be covered by the PTA in order to identify large-scale spatial correlations. In summary, with the SKA sensitivity and a large number of MSPs to be discovered and timed in the PTA, the SKA will provide a huge leap in sensitivity of many orders of magnitude.

4. Technical Requirements

The key observations required to achieve the outlined science goals are

- a complete Galactic census of pulsars
- an ultra-deep census of Galactic globular clusters
- a sensitive search for pulsars in the Galactic Centre region at high frequencies (~ 15 GHz)
- intensive observations of all PSR-BH candidates in the Galactic field and in particular in globular clusters
- intensive observation of all pulsars discovered in the Galactic Centre
- VLBI observations of all PSR-BH candidates to determine precise distances
- frequent ($\lesssim$ weekly) observations of a large number of MSPs to determine the best performing clocks to form the PTA
- continuous timing observations of all PTA pulsars

whereas it is essential that all non-search (i.e. timing) observations are performed (quasi-) simultaneously over wide range of frequencies in order to achieve best precision by removing effects of the frequency-dependent “interstellar weather”.

It is important to emphasise that the technical requirements for search and timing observations are significantly different and that *both* modes of observations have to be enabled to guarantee the success of this key science programme. The technical implications are described in detail in the general description of the pulsar case (Cordes et al., this volume) and are summarized here for completeness. The requirements are

Configuration: a dense core with a significant fraction of the total SKA area to be used in blind surveys; about 10% of the SKA's collecting area should be distributed over trans-/intercontinental baselines to achieve 1 mas resolution at 5 GHz.

Field-of-View: large FOV of *at least* 1-deg^2 at 1.4 GHz that needs to be fully sampled for the blind survey and with $\sim 50-100$ beams/deg^2 for timing. The result should be large instantaneous sky coverage with a large number of independently steerable beams using full SKA sensitivity.

Frequency range: frequency coverage from 500 MHz to 15 GHz to detect weak, steep-spectrum sources but also pulsars at the Galactic Centre which are invisible due to scattering below frequencies of 9-15 GHz. Coverage should be simultaneous to allow for simultaneous multi-frequency observations.

Bandwidth: wide bandwidth for large sensitivity with adequate channelization for de-dispersion.

Time-resolution: fast temporal sampling ($<1\mu$s) for high precision timing, less fast sampling ($\sim 50\mu$s) is required for search observations and sampling of the full FOV.

Correlator: flexibility of the correlator/beam-former to provide required sampling.

Polarization: full-Stokes capability with net purity of −40dB to enable high precision timing.

5. Conclusions

The SKA will make some significant experimental contributions to the quest of developing quantum gravity. It will enable us to precisely test gravity on macroscopic scales in regions of a parameter space that are not accessible by any other means. It also allows us to directly search for a gravitational wave background at a sensitivity limit that is several orders of magnitude better than previous limits currently achievable with pulsar timing or gravitational wave detectors. This is possible since a Galactic Census of pulsars with the SKA will unlock a large number of exotic pulsar binary systems and will produce a dense array of MSPs. Being timed to very high precision, the MSPs act as multiple arms of a cosmic GW detector. This "device", with the SKA at its heart, will be sensitive to GWs at frequencies of nHz. Thereby complementing the much higher frequencies accessible to Advanced LIGO (∼100Hz) and LISA (∼mHz), the SKA is crucial in answering the question about the existence, nature and composition of a GW background expected from a variety of sources, such as coalescence of massive black hole binaries during galaxy evolution and the evolution and decay of cosmic strings as predicted in grand unified theories.

High precision timing observations of pulsars orbiting a stellar or (super-)massive BHs – only possible in the radio band and with the SKA – will provide unprecedented probes of relativistic gravity with a discriminating power that surpasses all its present and foreseeable competitors. The experiments will provide extreme limits on the most general deviations from GR to a level a thousand times tighter than present solar-system limits and at least an order of magnitude better than expected from any future satellite mission. Most importantly, SKA observations will finally address the fundamental question of whether GR can describe nature in the ultra-strong field limit, in particular BHs. For a wide range of BH masses, one can determine their mass, spin and quadrupole moment to test their description in Einstein's theory and to confront the Cosmic Censorship Conjecture and the No-hair-theorem for the first time – obviously a major achievement in the history of physics!

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