Fundamental Physics with the SKA: Strong-Field Tests of Gravity Using Pulsars and Black Holes

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Abstract. The Square-Kilometre-Array (SKA) will be a radio telescope with a collecting area that will exceed that of existing telescopes by a factor of a hundred or so. This contribution summarises one of the key-science projects selected for the SKA.

The sensitivity of the SKA allows us to perform a Galactic Census of pulsars which will discover a large fraction of active pulsars beamed to us, including the long-sought for pulsar-black hole systems. These systems are unique in their capability to probe the ultra-strong field limit of relativistic gravity. By using pulsar timing we can determine the properties of stellar and massive black holes, thereby testing the Cosmic Censorship Conjecture and the No-Hair theorem. The large number of millisecond pulsars discovered with the SKA will also provide us with 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 Introduction

Solar system tests provide a number of very stringent tests of Einstein’s theory of general relativity (GR), and to date GR has passed all observational tests with flying colours. Nevertheless, the fundamental question remains as to whether Einstein has the last word in our understanding of gravity or not. Solar-system experiments are all made in the weak-field regime and will never be able to provide tests in the strong-field limit which is largely unexplored. Tests involving the observations of X-ray binaries may help, but the interpretation of these results depends to some extent on models which are known with only limited precision. In contrast, pulsars represent accurate clocks which can, in a binary orbit, allow us to perform high precision tests of gravitational theories. In the following we describe a key-science project developed for the SKA with a number of colleagues, namely Don Backer, Jim Cordes, Simon Johnston, Joe Lazio and Ben Stappers. Details can be found in [8,2].

2 Strong-field tests of gravity

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. 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. The sensitivity of the SKA allows much shorter integration times, so that searches for compact binary pulsars will no longer be limited. Among the discovered sources, pulsar-black hole (PSR-BH) systems are to be expected. 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.

2.1 Black Hole properties

As stars rotate, astrophysicists also expect BHs to rotate, giving rise to both a BH spin and quadrupole moment. The resulting gravito-magnetic field causes a relativistic frame-dragging in the BH vicinity, leading the orbit of any test mass about the BH to precess if the orbit deviates from the equatorial plane. The consequences for timing a pulsar around a BH have been studied in detail by Wex & Kopeikin (1999), who showed that the study of the orbital dynamics allows us to use the orbiting pulsar to probe the properties of the rotating BH. Not only can the mass of the BH be measured with very high accuracy, but the spin of the BH can also be determined 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. Therefore, the mass, $M$, and both the dimensionless spin $\chi$ and quadrupole $q$,

$$\chi \equiv \frac{c}{G} \frac{S}{M^2} \quad \text{and} \quad q \equiv \frac{c^4}{G^2} \frac{Q}{M^3}$$

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.

In GR, the curvature of space-time diverges at the centre of a BH, producing a singularity, which physical behaviour is unknown. The Cosmic Censorship Conjecture was invoked by Penrose in 1969 (see e.g. [8]) 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. [11]). 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.
One may expect a complicated relationship between the spin of the BH, $\chi$, and its quadrupole moment, $q$. However, for a rotating Kerr BH in GR, both properties share a simple, fundamental relationship \[ q = -\chi^2 \]. This equation reflects the “No-hair” theorem which implies that the external gravitational field of an astrophysical (uncharged) BH is fully determined by its mass and spin. Therefore, by determining $q$ and $\chi$ from timing measurements with the SKA, we can confront this fundamental prediction of GR for the very first time.

The best timing precision would be provided by a PSR-BH system with a MSP companion. Such systems do not evolve in standard scenarios, but they can be created in regions of high stellar density due to exchange interactions. Prime survey targets would therefore be the innermost regions of our Galaxy and Globular Clusters. 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 [13]. Since the spin and quadrupole moment of a BH scale with its mass squared and mass cubed, respectively, relativistic effects would be measured much easier.

2.2 Gravitational Wave Background

The SKA will discover a dense array of MSPs distributed across the sky. Being timed to very high precision (<100 ns), this “Pulsar Timing Array” (PTA) acts as 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 [14,15]. With observing...
times of a few years, pulsars are sensitive to GWs frequencies of $f > 1/T$, hence in the $\sim\text{nHz}$ range. Consequently, the SKA can detect the signal of a stochastic background of GW emission in a frequency range that is complementary to that covered by LISA and LIGO.

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

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

where $\rho_{\text{gw}}$ is the energy density of the stochastic background and $\rho_c$ is the present value of the critical energy density for closure of the Universe, $\rho_c = 3H_0^2/8\pi G$ with $H_0 = h_0 \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ as the Hubble constant. A contribution to the GW background is also expected from astrophysical processes, i.e. the coalescence of massive BH binaries during early galaxy evolution [9,7]. The amplitude of this signal depends on the mass function of the massive BHs and their merger rate [7]. Measuring the slope of the spectrum would allow us to discriminate between this foreground signal and the cosmological sources. The wedge-like sensitivity curve of the PTA is shown in Fig. 1. 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 other effects. Their limiting influence 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 $h_0^2\Omega_{\text{gw}}$ by a factor $\sim 10^4$!

References

1. R. A. Battye, E. P. S. Shellard, Class. Quant. Grav. 13 (1996) A239–A246
2. J. M. Cordes, M. Kramer, T. J. W. Lazio, et al.: ‘Pulsars as Tools for Fundamental Physics & Astrophysics’ in: C. Carilli, S. Rawlings (Eds.), New Astronomy Reviews, (2004)
3. T. Damour, G. Esposito-Farèse, Phys. Rev. D 58 (042001), 1–12 (1998)
4. S. Detweiler, ApJ 234 (1979) 1100–1104.
5. R. S. Foster, D. C. Backer, ApJ 361, 300 (1990)
6. S. W. Hawking, R. Penrose, Royal Soc. of London Proc. Ser. A 314, 529–548 (1970)
7. A. H. Jaffe, D. C. Backer, ApJ 583, 616–631 (2003)
8. M. Kramer, D. C. Backer, J. M. Cordes, et al.: Strong-Field Tests of Gravity Using Pulsars and Black Holes, in: C. Carilli, S. Rawlings (Eds.), New Astronomy Reviews (2004)
9. M. Rajagopal, R. W. Romani, ApJ 446, 543–549 (1995)
10. K. S. Thorne, R. H. Price, D. A. Macdonald, Black Holes: The Membrane Paradigm (Yale Univ. Press, New Haven 1986)
11. R. M. Wald, General relativity, (University of Chicago Press, Chicago 1984)
12. N. Wex, MNRAS 298, 997–1004 (1998)
13. N. Wex, S. Kopeikin, ApJ 513, 388–401 (1999)