Pulsar science with the SKA

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Abstract

The unprecedented sensitivity and large field of view of SKA will be of paramount importance for pulsar science, and for many related research fields. In particular, beside the obvious discovery of many more pulsars (even those with very low luminosity), and the extremely accurate timing analysis of the current pulsar population, SKA will allow to use pulsars to measure or put strong constraints on gravitational waves, Galactic magnetism, planet masses, general relativity and nuclear physics.

1 Introduction

Pulsars are the most common observational manifestation of neutron stars, which are considered *ideal laboratories* to study matter under extreme conditions of gravity, density, and magnetic fields, not reachable in terrestrial facilities. They are very compact objects with the mass of the Sun in a $\sim$10 km radius. Their rotational periods can span a very wide range between about 1.5 ms–1000 s, and their magnetic fields are in the $10^6 - 10^{15}$ G range [5]. They are possibly the only environment in the Universe where such extreme conditions can be reached simultaneously, and tested. The recent past has seen substantial advances in our understanding of the astrophysics of compact stars, thanks to the availability of new telescopes and space observatories. The launch of a new generation of satellites (e.g., *Chandra, XMM-Newton, Swift, Integral, Agile, Fermi*) has allowed us to collect unprecedented data on the high-energy emission (X-ray and gamma-ray) of compact stars. This data, together with ground-based astronomical observations at different wavelengths (mainly radio and optical) has significantly advanced our understanding of neutron stars, yielding more accurate measurements of their physical properties, as well as adding new classes of objects to the ones already known. Among the many examples, it is worth highlighting the accurate mass measurements and probe of general relativity in binary systems consisting of two pulsars and the increasing numbers of magnetars [7], relatively young neutron stars with extremely high magnetic fields which power their emission. The accurate measurements via radio observations of neutron stars with masses around two solar masses has set important constraints on the nuclear equation of state, ruling out some theoretical models.

In addition, new ambitious projects, such as the gravitational-wave detectors *Advanced LIGO* and *Advanced Virgo* are being completed, and even more ambitious projects, such as the X-ray mission *Athena* are planned in the near future, and others as *LOFT* (Large Observatory for X-ray Timing) are in an advanced design study. In the radio domain, LOFAR (the LOw Frequency ARray) is already taking exciting new data, while SKA (the Square Kilometer Array) will provide us with an unprecedented wealth of information about pulsars. The combined input of all these instruments will be crucial for our understanding of neutron stars and some aspects of fundamental physics, and SKA will play a leading role.

2 Pulsar science with the SKA

2.1 Pulsar surveys

The SKA sensitivity will allow to increase the number of currently known pulsars by about an order of magnitude [9]. In particular, simulations predict that $\sim$ 30000 new pulsars will be discovered in the first few years of operations, comprising also pulsars hosted in other Galaxies. Furthermore, about 3000 new recycled millisecond pulsars will be discovered, which are key systems for many of the studies mentioned in the following sections (as 2.2, 2.5 and 2.6). Using SKA for monitoring of pulsars will allow a precision in the pulse arrival time determination of the brightest pulsars a factor of 100 better than currently achievable, that will set pulsars as the best tool for the absolute *Time* calibrations.

2.2 Pulsars as a test of General Relativity

Millisecond pulsars in binary systems are important tests for General Relativity. In fact, when a pulsar is orbiting in a close system with another compact object with a very short orbital period, can lead to a strong space-time deformation that results in several relativistic effects. Timing the orbital parameters in double neutron star systems can provide stringent constraints on the theory of gravity in the strong field limit. In the point-mass approximation, the masses of the objects are the only two free parameters. Thus, measuring three or more relativistic corrections to the orbit (the so-called post-Keplerian parameters, e.g. periastron precession, Shapiro delay ...) overdetermines the systems and therefore provides a test of the theory of gravity. As an example, current monitoring of the Double Pulsar [1] has constrained the prediction of the General Relativity with an accuracy of 0.05 % [4]. SKA will greatly enlarge the number of relativistic binaries, as well as improving the timing analysis of known relativistic systems enabling the measurement of second order relativistic effects.

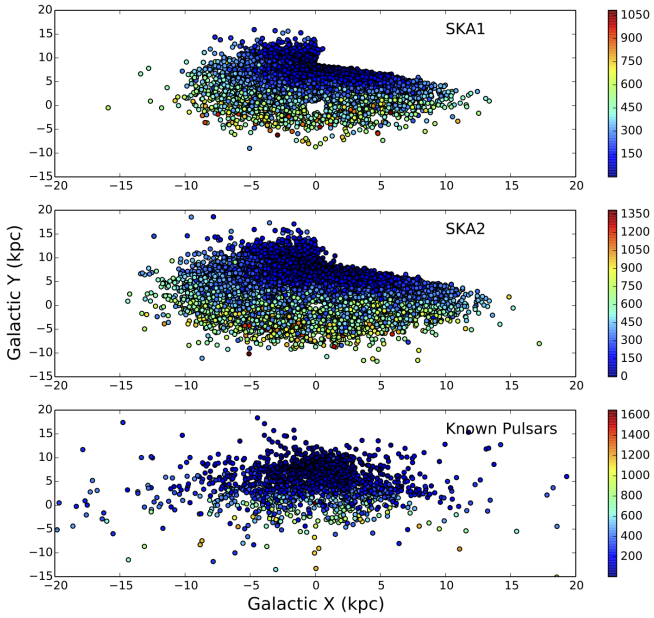

Figure 1: Distribution in Galactic coordinates of pulsars expected to be found with the SKA, compared to the known pulsar distribution. The color coding indicates the approximate range of dispersion measures of the simulated pulsars [3].

2.3 Pulsars as probe of ISM and Galactic magnetism

Pulsars are efficiently used to measure the warm ionized medium in the Milky Way, using Faraday rotation measures, dispersion and scattering by the interstellar medium (ISM) of the radio pulse arrival. SKA observations will enable to construct, via pulsar observations, the most detailed map of the Galactic ionized interstellar medium. This detailed map will shed light on the turbulent interstellar medium, but will also improve considerably our knowledge on the pulsar distances, and of the Galactic magnetic field.

2.4 Pulsars as a tool to measure Planet Masses

The unprecedented accuracy that pulsar timing will reach with SKA will enable an extremely accurate measure of our Solar System planets, taking advantage of pulsars as one of the most precise clocks. In particular, we can measure the delay in pulsar arrival times due to the motion of all planets with respect to the Earth. Modeling in the pulsar arrival times the residuals due to the planet motions will enable to measure the planet masses very accurately, with uncertainties comparable to dedicated space missions as Cassini or Galileo [2].

2.5 Pulsars to detect Gravitation Waves

The passage of a gravitational wave can alter the space-time metric. This alteration is expected to produce a very subtle signature in the arrival time of pulsars. The Pulsar Timing Array (PTA) project is currently monitoring several pulsars ($\sim$ bi-weekly since years) to reach an extremely accurate timing solution to be sensible to these tiny signatures. A gravitational wave due to a coalescing supermassive black-hole binary is expected to be detected by SKA thanks to the very high sensitivity and accuracy of the SKA pulsar monitoring [8].

2.6 Pulsars to constrain Nuclear Physics

Beating the present records of maximum observed mass and spin frequency of a neutron star will further constrain the equation of state of dense matter. Because of their history of accretion, recycled millisecond pulsars in binary systems are the most promising systems to search for very massive or fast rotating pulsars. With SKA, about 3000 of such systems will be discovered, increasing by a factor of ten the current sample. On the other hand, the improvement in the timing solutions for the known systems will allow to measure at least two relativistic effects for many systems, hence allowing for more mass measurements, and improving the precision of the existing measurements. Even in the case that no period shorter than 1.5 ms is found, this would require a theoretical explanation, probably connected to hydrodynamical instabilities and associated to the emission of gravitational waves.

In the other end of the spectrum, increasing the number of observed isolated radio-pulsars with long periods (several seconds, or longer), will also help discriminating between different models of the long-term magnetic field evolution and constraining the neutron star crust composition [6].

3 Conclusions

SKA will certainly lead a revolution in the field of pulsar astrophysics. It will increase significantly the number of pulsars observed in our galaxy, and allow the detection of many pulsars in the closest galaxies. It also allows to detect giant pulses from pulsars as distant as the Virgo cluster. Among the about 30 thousands new pulsars that will be discovered, we expect about 3 thousand millisecond pulsars, among which the most rapidly rotating and most massive neutron stars are expected to appear, placing new constraints on fundamental physics (the nuclear interaction and the equation of state of dense matter). We may also be witnessing the discovery of the, up to now elusive, first neutron star / black hole binary system, as well as detected gravitational waves via pulsar timing. In addition, the structure of the Milky Way and its magnetic field will also be studied in far more detail than at present, all thanks to the extraordinary sensitivity and large field of view of the SKA.

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