

LOFAR, LEAP and beyond: Using next generation telescopes for pulsar astrophysics

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Radio astronomy has benefited greatly from advances in technology and will continue to do so in the future. In fact, we are experiencing a revolution in the way radio astronomy is conducted as our instruments allow us now to directly “digitize” our photons. This has enormous consequences, since we can greatly benefit from the continuing advances in digital electronics, telecommunication and computing. The results are dramatic increase in observable bandwidths, FoVs, frequency coverage and collecting area. The global efforts will culminate in the construction of the SKA as the world’s largest and most powerful telescope. On the way projects like LOFAR, LEAP and others will revolutionize many areas of astrophysics and fundamental physics. Observations of pulsars will play a central role in these scientific endeavours. We briefly summarize here some recent scientific developments that help us in defining our expectations for the the new generation of radio telescopes for pulsar astrophysics.

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1. Introduction

Pulsar astrophysics has an impressive track record of making fundamental discoveries in a wide range of physics and astrophysics, covering the parameter space from the smallest scales (i.e. doing solid state physics under extreme conditions) to the largest scales (e.g. by exploring the nature of gravity). Apart from discovering the existence of neutron stars and their nature as gigantic quantum mechanical objects [1], further discoveries include, for instance, the first evidence for the existence of gravitational waves [2], the discovery of the first extrasolar planets [3] and the existence of very fast spinning objects challenging proposed equation-of-states [4]. Amazingly, in the 40+ years since the serendipitous discovery of pulsars, the rate of discovery has not slowed, driven by new technology and instruments that allows us to expand the accessible parameter space by improving the time and frequency resolution and observing bandwidth. However, the greatest leap in technological advance is yet to come with the new generation of radio telescopes. Facilities like LOFAR and the SKA will provide us with much larger collecting area, larger fractional bandwidth, larger fields-of-views and multi-beam capabilities. This combination will provide a massive increase in sensitivity combined with the opportunity to monitor many sources with excellent cadence. Based on current and past experience, we have very high expectations of what we are going to find. Indeed, we have every reason to believe that the previous amazing discoveries were just the prelude to what we will be able to do in the future. This contribution will try to glance into the future by providing some examples of excellent recent discoveries or developments and what can be expected when we will use the new facilities or re-use the existing ones in a novel fashion like in the LEAP project.

2. Finding new and exciting sources

Previous experience has proven that finding a large number of new pulsars will inevitably lead to the discovery of rare objects which push our understanding of their formation or which can be used as unique laboratories for fundamental physics. Currently, we know of about 2000 radio pulsars of which about half were discovered in a single survey, i.e. the Parkes Multibeam Survey for Pulsars [5]. The most recent jump in the discovery of the fast-spinning type of millisecond pulsars (MSPs) was achieved by performing radio searches in unidentified gamma-ray point sources as seen with the FERMI space-telescope [6]. A total of 19 MSPs were discovered so far, providing a “fast-track” method to identify these most useful sources. On-going surveys which employ high-sensitivity (like P-ALFA at the Arecibo telescope [7]) or high-time and -frequency resolution (like the HTRU survey with the Parkes and Effelsberg telescopes [8]) are finding interesting new pulsars. Indeed, the High-Time-Resolution Universe (HTRU) survey will provide an all-sky inventory of the variable sky, already discovering lots of new sources in a previously well-searched area. So far, the HTRU survey has already discovered about 40 slowly rotating pulsars and about 10 MSPs (including bright sources, eclipsing systems and planetary companions - stay tuned!). Perhaps, the most unexpected find of the HTRU survey so far was the first ever discovery of a magnetar in a blind radio survey [9]. The source PSR J1622–4950 has a 4.3-s period and with an inferred value of $B = 3 \times 10^{14}$ G, the highest magnetic field for any radio-discovered neutron star. Detections at X-rays show an X-ray luminosity that is a third of the spin-down luminosity, confirming that this

magnetar was discovered in an X-ray quiescent phase. Moreover there is no record of previous X-ray outbursts either. Yet, it shows all the radio properties of a radio-transient magnetar: strong variation in flux density and pulse shape, a flat spectrum and a very high degree of polarisation. Archival radio observations reveal that the source was radio active in the past, but that it was missed in previous observations.

The discovery of transient phenomena like the new radio magnetar underlines the need for repeated surveys of the whole sky. The new facilities like LOFAR and SKA with their large field-of-view will provide superb opportunities to undertake many such surveys in short time intervals. That is even already true for shallow surveys, for instance, with the Australian SKA Pathfinder (ASKAP) and the South-African MeerKAT. In any case, a combination of sensitivity and field-of-view will revolutionize our knowledge of the Galactic pulsar population. LOFAR will find the local population of neutron stars and will also be sensitive to those radio pulsars, which are too weak at the usual high search frequencies due to the generally steep pulsar flux density spectrum [10]. This local census will be complemented by the SKA and its Galactic census of pulsars, which will essentially include every pulsar that is beaming towards Earth. The 20,000 to 30,000 pulsars to be discovered should join the about 1000 MSPs, about 100 relativistic binaries and eventually the rare objects like pulsar-black hole systems [11, 12].

3. Monitoring, watching and triggering

The radio sky reveals variable and transient phenomena which are relevant for a huge range of (astro-)physical questions. We have already demonstrated above that repeated monitoring can reveal new, previously unseen objects which are important for population studies or the connections between radio and high-energy processes. Often radio observations can trigger searches and studies in other observational windows. Perhaps one of the most exciting such possibilities is the triggering of gravitational wave searches for neutron star oscillations after the detection of a pulsar glitch.

A pulsar glitch is a sudden increase in spin frequency of the neutron star caused by an internal reconfiguration of the star's interior structure (e.g. [13]). The relaxation of the glitch gives information about the super-fluid interior of the pulsar and enables us to do neutron star seismology. It is expected that such an event may also cause the neutron star to oscillate, which for certain vibration modes, should result in the emission of gravitational waves (e.g. [14]). Knowing the exact moment of the glitch through dense radio monitoring, gravitational wave data can be searched accordingly. The statistical information obtained from such radio monitoring with the new multi-beam capable telescopes will be used to study the glitch mechanism and to answer questions as to whether a possible bimodal distribution of the glitch sizes means that two different types of glitch processes are acting (e.g. [15]).

Radio monitoring with good cadence is also essential to study the recently discovered phenomenon that radio pulsars appear to be able to change the structure of current flow in the magnetosphere in an seemingly instantaneous way. This newly recognised class of "intermittent pulsars" [16], seem to be active for a period of time before switching off completely for a further period of time, where the change in observed radio output is correlated with a change in pulsar spin-down rate. In the case of PSR B1931+24, if the pulsar is emitting radio waves, the spin-down rate is about 50% larger than when the pulsar is off. This faster spin-down rate is caused by an extra torque that

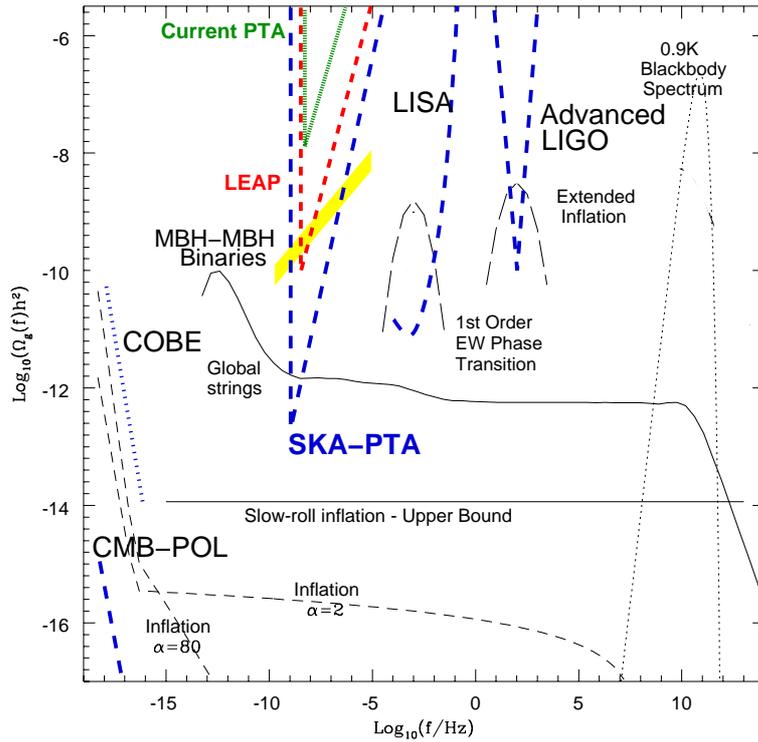


Figure 1: Summary of the potential cosmological sources of a stochastic gravitational wave (GW) background overlaid with bounds from COBE, current Pulsar Timing Array (PTA) experiments and the goals of CMB polarization experiments, LISA and Advanced LIGO. LEAP will improve on the current best PTA limits by more than two orders of magnitude, enabling the detection of a GW background caused by the merger of massive black holes (MBHs) in early galaxy formation. The amplitude depends on the MBH mass function and merger rate, so that uncertainty is indicated by the size of the shaded area. LEAP is the next logical step towards a PTA realized with the SKA which will improve on the current sensitivity by about four orders of magnitude.

is given by the electric current of the plasma that also creates the radio emission. If some or all of the plasma is absent, the radio emission is missing together with the additional torque component, so that the spin-down is slower. Very recently, Lyne et al. [17] realized that intermittent pulsars are actually the extreme form of a more common phenomenon, in which the restructuring of the plasma currents does not necessarily lead to a complete shutdown in the radio emission, but can be observed as changes between distinct pulse shapes. Lyne et al. showed that particular profiles are indeed correlated with specific values for the spin-down rates, confirming the previous picture. The times when the switch in the magnetospheric structure occurs are for some pulsars quasi-periodic but in general difficult to predict. The resulting change between typically two spin-down rates leads to seemingly random timing residuals that have been in the past classified as “timing noise”. The observations by Lyne et al. therefore simultaneously connect the phenomenon of timing noise to that of intermittent pulsars and that of “moding” and “nulling” (see e.g. [18]). An interesting aspect is the possibility of determining the exact times of the switch between magnetospheric changes by precisely measuring the pulse shapes with high-sensitivity, high-cadence monitoring with LOFAR

or the SKA. In this case, the changes in spin-down rate can be taken into account and the pulsar clock can be “corrected”. This would offer the opportunity to use not only the MSPs for timing experiments, but to utilize also the 20,000 to 30,000 normal pulsars that will be discovered in a Galactic census described above. Even though the precision will not be as high as for MSPs, the large number of pulsars may help to detect, for instance, gravitational waves.

4. Gravitational Wave detection

The observed orbital decay in binary pulsars detected via precision timing experiments so far offers the only evidence for the existence of gravitational wave (GW) emission. Intensive efforts are therefore on-going world-wide to make a direct detection of gravitational waves that pass over the Earth. Ground-based detectors like GEO600 or LIGO use massive mirrors, the relative distance of which are measured by a laser interferometer set-up, while the future space-based LISA detector uses formation flying of three test-masses that are housed in satellites. The change of the space-time metric around the Earth also influences the arrival times of pulsar signals measured at the telescope, so that high-precision MSP timing can also potentially directly detect GWs. Because pulsar timing requires the observations of a pulsar for a full Earth orbit before the relative position between pulsar, Solar System Barycentre and Earth can be precisely determined, only GWs with periods of more than a year can usually be detected. In order to determine possible uncertainties in the used atomic clocks, planetary ephemerides used, and also since GWs are expected to produce a characteristic quadrupole signature on the sky, several pulsars are needed to make a detection. The sensitivity of such a “Pulsar Timing Array” (PTA) increases with the number of pulsars and should be able to detect pulsars in the nHz regime, hence below the frequencies of LIGO (\sim kHz and higher) and LISA (\sim μ Hz) (see Fig. 1).

A number of PTA experiments are ongoing, namely in Australia, Europe and North America (see [19] for a summary). The currently derived upper limits on a stochastic GW background (e.g. [20, 21]) are very close to the theoretical expectation for a signal that originates from binary super-massive black holes expected from the hierarchical galaxy evolution model [22, 23]. It seems that “simply a bit of extra sensitivity is needed” to make a first detection. This is the motivation for the Large European Array for Pulsars (LEAP) project in Europe. It aims to phase-coherently connect Europe’s largest radio telescopes to form an Arecibo-sized dish that can observe a large number of MSPs with high sensitivity enabling high precision pulsar timing. LEAP is part of the European Pulsar Timing Array (EPTA) and also acts as a test-bed for SKA technology [21].

Demonstrating the power of PTA experiments, Champion et al. [24] recently used data of PTA observations to determine the mass of the Jovian system independently of the space-craft data obtained by fly-bys. Here, the idea is that an incorrectly known planet mass will result in an incorrect model of the location of the Solar System Barycentre (SSB) relative to the Earth. However, the SSB is the reference point for pulsar arrival time measurements, so that a mismatch between assumed and actual position would lead to a periodic signal in the pulsar data with the period being that of the planet with the ill-measured mass. This measurement technique is sensitive to a mass difference of two hundred thousand million million tonnes – just 0.003% of the mass of the Earth, and one ten-millionth of Jupiter’s mass.

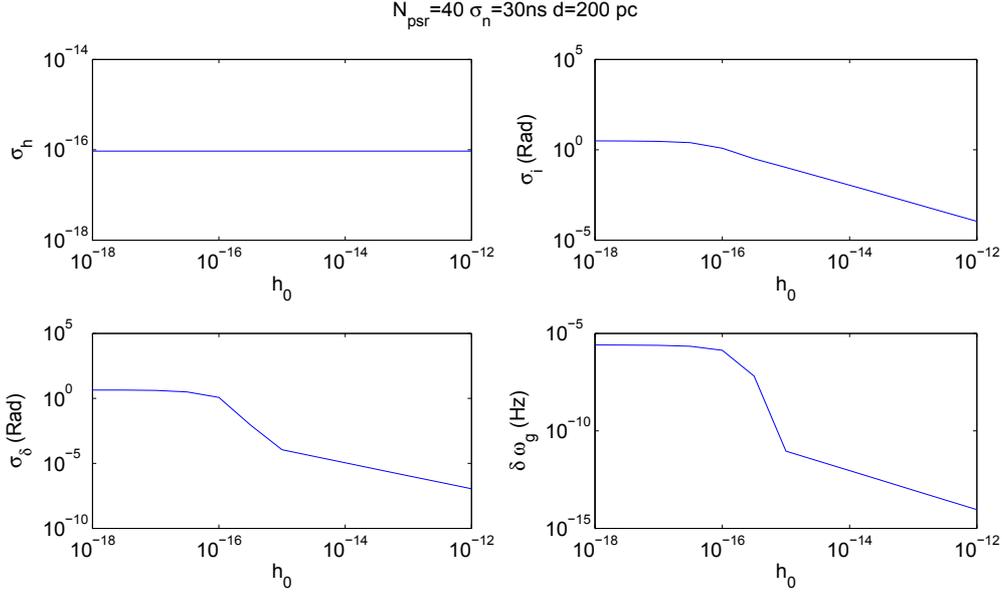


Figure 2: Results of computations for the detection of a single GW source with the help of a PTA consisting of 40 pulsars with an average timing precision of 300 ns at a typical distance of 200 pc [27]. *top left*) Error in measuring the characteristic strain amplitude of a single GW source for a variety of signal strengths. *top right*) corresponding error in orbital inclination measurement, *bottom left*) positional error on the sky and *bottom right*) error in determining the gravitational wave frequency. See Lee et al. for details.

If LEAP or other experiments do not detect GWs in the next few years, a first detection is virtually guaranteed with the more sensitive Phase I of the SKA. But the science that can eventually be done with the full SKA goes far beyond simple GW detection – a whole realm of astronomy and fundamental physics studies will become possible. For instance, it will be possible to study the properties of the graviton, namely its spin (i.e. polarisation properties of GWs) and its mass (note that in general relativity the graviton is massless) [25, 26]. This is achieved by measuring the degree of correlation in the arrival time variation of pairs of pulsars separated by a certain angle on the sky. A positive correlation is expected for pulsars in the same direction or 180 deg apart on the sky, while pulsars separated by 90 deg should be anti-correlated. The exact shape of this correlation curve obviously depends on the GW polarisation properties [25] but also on the mass of the graviton [26]. The latter becomes clear when we consider that a non-zero mass leads to a dispersion relation and a cut-off frequency $\omega_{\text{cut}} = m_g c^2 / \hbar$, below which a propagation is not possible anymore, affecting the degree of correlation possible between two pulsars. With a 90% probability, massless gravitons can be distinguished from gravitons heavier than 3×10^{-22} eV (Compton wavelength $\lambda_g = 4.1 \times 10^{12}$ km), if bi-weekly observation of 60 pulsars are performed for 5 years with pulsar RMS timing accuracy of 100 ns. If 60 pulsars are observed for 10 years with the same accuracy, the detectable graviton mass is reduced to 5×10^{-23} eV ($\lambda_g = 2.5 \times 10^{13}$ km) [26].

In addition to detecting a *background* of GW emission, the probability of detecting a *single* GW source increases from a few percent now to well above 95% with the full SKA. We can, for instance, expect to find the signal of a single super-massive black hole binary. Considering

the case when the orbit is effectively not evolving over the observing span, we can show that, by using information provided by the “pulsar term” (i.e. the retarded effect of the GW acting on the pulsar’s surrounding space time), we can achieve a rather astounding source localization. For a GW with an amplitude exceeding 10^{-16} and PTA observations of 40 pulsars with weekly timing to 30 ns, precision one can measure the GW source position to an accuracy of better than ~ 1 arcmin (Fig. 2, [27]). With such an error circle, an identification of the GW source in the electromagnetic spectrum should be easily feasible. We note that in order to achieve such a result, a precise distance measurement to the pulsars is needed, which in turn can then be improved further during the fitting process that determines the orbital parameters of the GW source. Fortunately, the SKA will be a superb telescope to do astrometry with pulsars.

5. Astrometry

Astrometric parameters can be determined in two ways for pulsars. Firstly, using the telescope array as an imaging interferometer, the pulsar can be treated as point source while boosting the signal-to-noise ratio by gating the correlator to use only signals during the few percent duty cycle when the pulsar is actually visible. With images spread over a period of time, it will be possible to measure parallaxes for nearly 10,000 pulsars with an accuracy of 20% or less [28]. Secondly, pulsar timing can also be used for a precise determination of the position, proper motion and parallax as all these parameters affect the arrival time of the pulsars at our telescope on Earth. Here, MSPs with their higher timing precision can be used more readily. Distances are retrieved via a “timing parallax” which essentially measures the variation in arrival time at different positions of the Earth is orbit due to the curvature of the incoming wavefront. In contrast to an imaging parallax, the sensitivity is highest for low ecliptic latitudes and lowest for the ecliptic pole. Figure 3 shows this dependence of the parallax precision on ecliptic latitude. Interestingly, it is still possible to measure a parallax with finite precision at the ecliptic pole, in contrast to first expectations. The origin of this is the small eccentricity of the Earth orbit which allows us to still detect a variation of the arrival time at different times of the year [28]. We expect that we can measure distances of 20 kpc with a precision better than 20% for about 300 MSPs, while for some sources distances of 20 to 40 kpc can be measured to 10% or better.

A third method allows us to infer a distance to a binary MSP if we see a relativistic decay of the orbit. The observed value for the orbital period derivative will be altered from the intrinsic value by a contribution arising from secular acceleration. As this depends on distance, a comparison of the observed value with the one expected from general relativity, allows us to determine the distance [29]. In most cases however, we need to apply the reverse method, i.e. we need to know the distance in order to derive the intrinsic orbital decay rate, so that tests for theories of gravity can be performed.

6. Tests of theories of gravity

Binary pulsars already provide the best tests of theories of gravity for strongly self-gravitating bodies [30]. In the future, with improved timing precision, we expect that these tests will even surpass the precision of the current best tests of general relativity in the weak-field regime of the

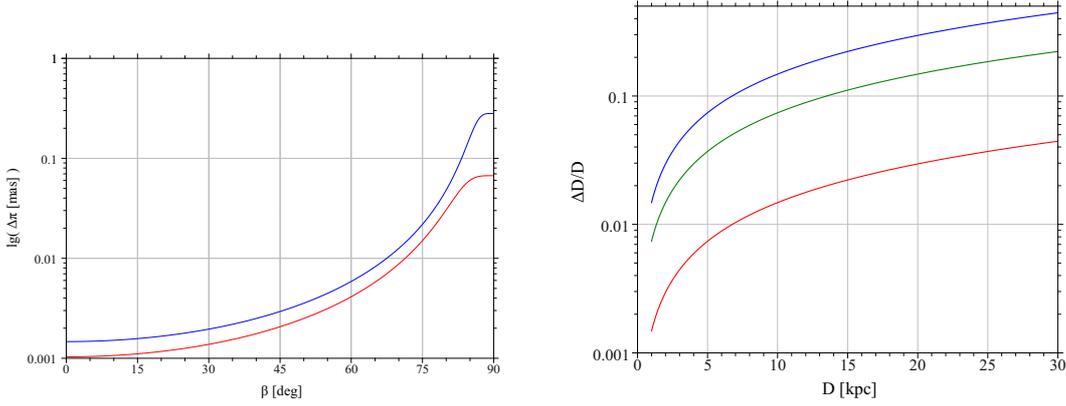


Figure 3: Precision of parallax measurements from weekly timing of MSP with the SKA. *left*) Error in the timing parallax as a function of ecliptic latitude. The top (blue) line assumes a time span of 5 years, the lower (red) one 10 yr of observations. Both assume a timing precision of 10 ns. *right*) fractional precision of distance measurements for three different timing precision values, 10 ns (red, bottom), 50 ns (green, middle) and 100ns (blue, top). See Smits et al. for details.

Solar System. In particular the continued observations of the Double Pulsar will derive important constraints for testing alternative theories of gravity and the validity of specific concepts in strong gravitational fields, such as the Lorentz-invariance [31]. Most importantly, however, with the SKA we will be able to probe the properties of black holes and compare those to the prediction of general relativity for Kerr black holes. With pulsars orbiting the super-massive black hole in the Galactic centre and the discovery of binary pulsars with stellar-mass black hole companions, we will be able to measure the mass, spin and quadrupole moment of the black holes. These measurement will allow us to test the *cosmic censorship conjecture* as well as the *no-hair theorem* [11]. The cosmic censorship conjecture states that every astrophysical black hole, which is expected to rotate, has an event horizon that prevents us from looking into the central singularity. However, the event horizon disappears for a given value of the black hole spin, so that we expect the measured spin to be below the maximum allowed value. The no-hair theorem makes the powerful statement that the black hole has lost all features of its progenitor object, and that all black hole properties are determined by only the mass and the spin (and possible charge). Therefore, if the no-hair theorem is valid, the expected quadrupole moment of the black hole can be unique determined from the mass and the spin. With a measurement of all three quantities, this theorem can be tested [11].

With the chance to perform these experiments with the super-massive black hole in the Galactic Centre, stellar black holes and, possibly, intermediate mass black holes in globular clusters, a whole black hole mass range can be studied. As already pointed out by Damour & Esposito-Farese [32], a pulsar - black hole system will be a superb probe of gravity.

7. Conclusions

These technological advances will provide pulsar observers new tools that will allow them to probe further into the unexplored regions of the physical parameter space. The new telescopes combine a huge increase in sensitivity with multi-beaming capability - a dream combination for

studies of pulsars and their exploitation as tools for fundamental physics. The possible science applications extend far beyond what has been, and can be, discussed here. A more complete review can be found in the SKA science case [33], we will however mention one other fascinating application in passing, as it connects to the science drivers of the large optical telescopes: with the SKA we will have the potential to find all the pulsars in the Galaxy with radio beams pointed in our direction. The timing precision in most cases should be sufficient to detect planets or minor bodies possibly orbiting the neutron stars. Hence, for the first time, we will not only get a census of radio emitting pulsars in the Galaxy but also a census for planetary-sized objects around neutrons stars. Using this statistical information we may finally have the chance to answer the question: Why pulsar planets are so rare? Whatever the answer to the formation process will be, it is clear that with the new generation of radio telescope the future of pulsar astrophysics is extremely bright.

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