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Observing pulsars with the Sardinia Radio Telescope

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Abstract. After nearly 40 years since the original discovery the pulsars − rapidly rotating highly magnetized neutron stars − keep on having many exciting scientific applications, in fields ranging from ultra-dense matter physics to relativistic gravity, cosmology and stellar evolution. A striking example has been the confirmation of the existence of gravitational radiation, as predicted by Einstein's general theory of relativity. For 10 years, the Italian Pulsar group has been carrying out a series of successful pulsar experiments using the Parkes 64-m dish in Australia. The most exciting result has been the discovery of the J0737−3039 system, i.e. the most relativistic binary pulsar ever and the first system in which both the neutron stars emit detectable radio pulsations. In this scientific scenario, the Sardinia Radio Telescope may be exploited with two initial aims: (i) using known millisecond pulsars as laboratories for understanding gravity and gravitational waves; (ii) searching for further millisecond pulsars in the Galaxy and in the globular cluster systems.

1. Scientific framework

A neutron star is produced when nuclear reactions in the core of a massive star can no longer release the energy required to sustain it against gravitational collapse. In one of the most spectacular events in nature, the inner core collapses in a fraction of a second, while the outer layers are suddenly and explosively expelled in a supernova. What remains is an object slightly more massive than the Sun, but with a radius of only 10 km: in effect, a huge atomic nucleus. Because a neutron star spins and is highly magnetized, it radiates collimated beams of radio waves which we observe as pulses, lighthouse-like, once per rotation. After nearly 40 years since the original discovery, pulsar research has great vitality, making major contributions to fields ranging from ultra-dense matter physics to relativistic gravity, cosmology and stellar evolution.

In the last 10 years, the Italian Pulsar group has carried out a series of successful pulsar experiments using the Parkes 64-m dish in Australia. In 1996 a large-scale survey of the southern hemisphere at 430 MHz (Manchester et al. 1996; D'Amico et al. 1998) discovered more than 100 new pulsars, including 20 millisecond pulsars. More recently, using a new generation 1.4-GHz multi-beam receiver, the Italian group has been involved in an unprecedented boom of radio pulsar counting, doubling the number of known objects in the galactic field (D'Amico et al. 2001a; Manchester et al. 2001; Kramer et al. 2003). A deep search of the Globular Cluster (GC) system has found 12 millisecond pulsars in 6 GCs for which no associated pulsars were previously known, contributing a 25% to the number of clusters containing known pulsars (Possenti et al. 2003). A high latitude survey for millisecond pulsars has found many new interesting objects, including the first ever known double-pulsar (Burgay et al. 2003; Lyne et al. 2004). In fact, increasing the pulsar counting allows the discovery of many objects which are intrinsically rare in the population, but very interesting for their physical applications. The Italian group has identified several young energetic pulsars, relativistic binary systems, binary pulsars with a massive-star companion and millisecond pulsars in tiny orbits with a body of planetary mass. Future deep searches with similar equipment would eventually open up the possibility of detecting a pulsar orbiting a black hole.

1.1. Searching young pulsars

One interesting subject of pulsar research is the understanding of young (age less than 100,000 years) pulsars. Young pulsars are often associated with the supernova remnant (SNR). Traditionally, the material expelled during the supernova explosion produces the typical shell structure of many SNRs. A pulsar at the centre of a SNR, being a source of strong magnetic field and relativistic particle beams, might interact with the SNR leading to the observation of plerionic structures. The study of pulsar/SNR associations provides useful information on pulsar winds, on the physical process taking place in plerions, and on the interaction between plerionic and filamentary components. Young pulsars often show period irregularities and glitches which are very useful in the understanding of the interior structure of neutron stars. Young pulsars are also often detectable at high energies (X- and gamma-rays). It is believed that a substantial fraction of the unidentified Galactic gamma ray sources can be young pulsars. However, these objects are relatively rare in the population, and even rarer in the observed sample. They are intrinsically rare because they evolve relatively fast. Then, the density of young pulsars in the Galaxy is relatively low, and their distance is, on average, relatively high. Also, young pulsars tend to be found at low Galactic latitudes, close to their birth place. The observation of distant pulsars at low Galactic latitudes is limited by the dispersion and scattering of pulses in the interstellar medium, so young pulsars are even rarer in the observed sample. So, deep searches of the Galactic disk at low latitudes are required in order to reach a significant number of relatively young pulsars. Recent surveys significantly increased the total number of medium-age pulsars in the sample, making available a large sample population, useful for statistical studies. In the course of the Parkes 21-cm Multibeam Survey, completed recently, the Italian pulsar group and our international partners have discovered more than 700 new pulsars, so doubling the total sample, including about 25 young energetic pulsars (so, increasing by more than 200% the sample of young pulsars known).

1.2. Searching millisecond pulsars

A very interesting aspect of pulsar research is the understanding of millisecond pulsars. These are pulsars with spin periods of the order of few milliseconds and very low magnetic fields (typically 3-4 decades smaller than ”normal” pulsars). It is believed that millisecond pulsars are formed when a neutron star in a binary system with a low mass companion is spun-up as a result of mass accretion from the evolving companion. Clock stability in millisecond pulsars is observed to be very high, comparable to the best time-standard available on Earth, so they are useful for high precision timing. The Parkes low frequency survey carried out by our group has proved that millisecond pulsars, being old, can be abundant at high Galactic latitudes. This is the ideal location for a sensitive survey, because the sky background temperature is relatively low and dispersion and scattering are relatively negligible. Even more interesting are the millisecond pulsars found in Globular Clusters, because they provide constraints on the dynamical status of the host cluster, on the neutron star content of the cluster, and on the role of binaries in the dynamical evolution of clusters. In the course of various experiments at Parkes, using single-beam low frequency receivers (430 MHz and 650 MHz) or the central beam of the Parkes 21-cm multi-beam receiver, our group has discovered many more millisecond pulsars in globular clusters than any other group before. This proved that both low frequency and high frequency observations can be useful in a search of the Globular Cluster system. Among the most recent discoveries, there are peculiar objects, like for instance a millisecond pulsar in a tiny binary system with a companion of planetary mass, and the first ever known example of a newly born millisecond pulsar with a binary companion close to the end of its evolution, PSR J1740-5340 in NGC6397. The study of another Globular Cluster, NGC6752, hosting 5 millisecond pulsars, has allowed us to exploit their remarkable clock stability to put constraints on the dynamical status of the cluster and on the central light-to-mass ratio. In NGC6752, we have found that the observed acceleration of three millisecond pulsars located in the cluster core indicates a light-to-mass ratio much lower than that derived from optical observations, suggesting the presence of a high density of unseen dark remnants in the core. In addition, we have discovered more than 20 millisecond pulsars in a single Globular Cluster, 47 Tucanae.

1.3. Relativistic double neutron star binaries and the pulsar timing array

Binary systems relatively rare in the population but very interesting, are those containing a pulsar with a neutron star companion. In this case, the "clock" signal of the pulsar can be used to probe relativistic effects in the strong gravitational field of the companion. Using the Parkes radio telescope, we have discovered a highly relativistic double-neutron-star binary system with an orbital period of only 2.4 hours (Burgay et al. 2003) in which both of the neutron stars are observable as radio pulsars: the first-known double pulsar (Burgay et al. 2003; Lyne et al. 2004)! In this system, General Relativistic gravitational interactions are causing this system to evolve much faster than any previously known double-neutron-star system. We can predict that the two neutron stars will merge in about 85 million years. This, together with the relative proximity of this system to the Earth, implies an order of magnitude increase in the predicted merger rate for double-neutron-star systems in our Galaxy and in the rest of the Universe. Facilities presently being built in Europe, USA and Japan were commissioned with the expectation of detecting such events at most once every 20 years, but with this discovery the rate is increased up to one every few years. Above all, the availability of two pulsar clocks orbiting each other in such a highly relativistic system provides a unique test-bed for investigations of fundamental gravitational physics, including alternatives to Einstein's theory. In only a few months, we have already measured the relativistic effects which took years to measure with the original binary pulsar PSR B1913+16. In the next few years, we expect to measure new, previously untestable effects. Moreover, the radiation from each pulsar scans the local environment of the other, so that for the first time we are able to directly probe the magneto-ionic properties of pulsar magneto-spheres, studying extreme plasma physics that cannot be investigated in terrestrial laboratories.

It has been known for some time (Hellings & Downs 1983) that the clock stability of millisecond pulsars may in principle allow them to be used as gravitational wave detectors. On one hand, they may be used for detecting the deformation of the space-time along the line-of-sight between the pulsating source and the observer, produced by the passage of strong gravitational waves emitted by a specific source. On the other hand, they may even allow one to measure the stochastic background of gravitational waves resulting from the very early phases of the Universe's evolution. However, only recently the technology of receivers and data acquisition systems has reached the quality necessary for undertaking this kind of experiments, requiring a very high accuracy (typically better than 1 μsec) in the determination of the times of arrival of the pulsations. In order to remove any spurious contribution, the strategy is to regularly observe a set (i.e. an *array*) of some tens of stable millisecond pulsars evenly distributed in celestial coordinates and then combine the times of arrival (including the delays between the different observatories) in order to search for common trends. The best way for performing these observations is by simultaneously collecting data at two different frequencies, which allows one to remove any contributions to the times of arrival due to the dispersion of the radio signal in the interstellar medium. Some world-class single-dish radiotelescopes, such as the Parkes 64-m radiotelescope, the GBT 100-m dish and the Arecibo 300-m dish, have already been deeply involved in this project and the use of the SRT is strongly recommended also by the international pulsar community.

2. The role of SRT in pulsar research

In this scientific scenario, the capabilities of the SRT can be exploited with two initial aims.

(i) Understanding gravity and gravitational waves. This can be done on one hand, with the search and follow-up of highly relativistic binary systems, similar to (or even more extreme than) the double-pulsar; on the other hand, with the timing of millisecond pulsars on the long term. In particular the participation of the SRT at the *timing array* project would significantly improve the quality of the collected data, while including the new radiotelescope in the small circle of the 3-4 most qualified instruments of the world.

(ii) Search for and modeling of millisecond pulsars in the Galaxy and in the Globular Cluster system. In fact discovering more millisecond pulsars will allow one to address many interesting (astro-)physical issues, ranging from the neutron star Equation of State (Cook et al. 1994), to the binary evolution (with emphasis on the eclipsing millisecond pulsars, Nice et al. 2000; D'Amico et al. 2001b), to the population statistics of this kind of sources (Lyne et al. 1998). When detected in Globular Clusters, millisecond pulsars will disclose the possibility of studying the GC-potential well (D'Amico et al. 2002), the dynamical interaction in the GC-core (Colpi et al. 2002), the neutron star retention (Rappaport et al. 2001) and the gas content in a GC (Freire et al. 2001).

3. The equipment of the SRT for pulsar research

Two key-factors allowed the burst of pulsar discoveries that occurred during the past 5 years: the adoption of *multi-beam systems* and the availability of *large computing power*. The next steps ahead in pulsar instrumentation at world-class radiotelescopes are now the use of *ultra-wide bandwidths* and *dual-frequency receivers*. Given the aforementioned scientific framework and accounting for the pulsar projects ongoing at other major radiotelescopes, the Italian pulsar group believes that a development plan for a competitive pulsar research activity with the SRT on a short-medium term should be based on systems operating at three frequencies (two of which simultaneous) and exploiting the maximum available bandwidth compatible with technical requirements. In particular:

SYSTEM 1: 325-MHz (LOW FREQUENCY) OBSERVATIONS: The Radio Frequency Interference (RFI) environment at the SRT site indicates that the 325-MHz band is relatively free of interferences (much better than the 408-MHz band) and that a relatively large clean bandwidth is available. Depending on the dynamic range and robustness of the receiver system, a bandwidth up to 80 or even 100 MHz could be exploited. A 325-MHz low-noise cooled receiver system would be ideal in order to undertake large-scale surveys at high galactic latitude. Such a survey would probe the population of millisecond pulsars with unprecedented sensitivity in $\sim$ 100 days of observation. The system should ideally be equipped with a digital programmable filter-bank capable of re-arranging its total bandwidth (up to 1 GHz per polarization) and the number of channels (up to 2048 per polarization) according to the receiver in use. For observations at 325 MHz the basic set up would be 2048 channels with 50 kHz width each. The same receiver, equipped with a coherent de-dispersing system (like those developed at CalTech and Swinburne), can also provide excellent performance in high precision timing observations.

SYSTEM 2: 1.3–1.8-GHz (INTERMEDIATE FREQUENCY) OBSERVATIONS: As a short-term plan for a 21-cm pulsar system, we propose to build a high resolution de-dispersing system (an analogical 2×1024×0.50-MHz filter-bank or a flexible digital filter-bank) to be used with the 1.3–1.8-GHz receiver already planned. Such a system can be very well suited for a deep search of the GC system (requiring some tens of days of observations) and other selected targets (for instance SNRs), and can be used for regular timing observations of non-millisecond pulsars. The outstanding results obtained at Parkes at 21 cm, strongly suggest that this is a prime frequency for pulsar search. However, the key-feature of the success of the 21-cm Parkes experiments was the availability of a 13-element multi-beam receiver. The slightly shorter focal ratio of the SRT ($f/0.34$) compared to that of Parkes ($f/0.4$) constrains a multi-beam receiver to probably no more than 7 beams: for covering a given sky area, the typical integration time would then probably be reduced by a factor of 2 compared to that adopted in the Parkes survey (35 min). Thus, in order to keep the same sensitivity, a bandwidth twice as large as the Parkes' one (288 MHz) should be considered. The 1300–1800 MHz frequency interval is nominally relatively interference-free in Sardinia, but the lower end of the band is very close to the frequency of a civil aviation radar system. This is the typical situation that needs to be checked with a systematic RFI campaign, rather than a single shot, as the effective impact of these spurious effects might strongly depend on azimuth, and on the time of the day. Furthermore, we are now convinced that a state-of-the art 21-cm pulsar system should be equipped with a much higher frequency resolution than adopted at Parkes (3 MHz), which strongly limited the discovery of millisecond pulsars. With a double band per beam and a much larger number of frequency channels in the de-dispersing system, such a system would require the development of a major back-end. In summary a careful analysis of the effective RFI environment and a comparative evaluation of the scientific interest of other groups should be considered here before taking a decision about a 21-cm multi-beam receiver.

System 1+2: The case for a dual-frequency receiver: The state-of-the-art for observations in the context of the pulsar timing is represented by dual-band receivers: in fact they provide the large frequency baseline ($\gtrsim 60\%$ of the upper frequency) and simultaneity necessary to measure with high accuracy the dispersion delay of most millisecond pulsars, and estimate with ultra-high precision (rms 0.1–1.0 μsec) any secular or transient effect affecting their pulse arrival times at infinite frequency. These receivers are also unrivalled instruments for studying the class of the so-called eclipsing pulsars (Nice et al. 2000), the emission of giant pulses (Cairns 2004) and the interstellar medium along the line-of-sight to a radio-pulsar (Bhat & Gupta 2002). Recent technology allows to minimize the loss of efficiency (few percent at worst) with respect to single-band receivers operating at the same frequencies and hence dual-band systems also optimize observation times and telescope scheduling: a given sensitivity in both the bands can be attained in a much shorter observation time than that required if observing at the two frequencies separately.

In particular the availability of a dual-frequency receiver for performing pulsar timing observations has become of paramount importance in recent years, within the framework of the international programme called Pulsar Timing Array, which there is a strong pressure for the SRT to be involved in. Other big radiotelescopes collaborating with this project have already been equipped (or are going to be equipped) with dual-band systems: at Parkes a 10-cm/50-cm receiver has recently been installed, whose performances are significantly better than those of the two receivers previously available at those frequencies (and comparable with the best single band receivers at 10 cm or 50 cm installed elsewhere). At GBT the construction of a dual 340-MHz/820-MHz feed capable of performing "simultaneous observations at both bands" has been highly recommended, being "extremely useful scientifically" (Report from the NRAO-GBT Pulsar Workshop of November 2004) and largely preferable over other kinds of dual-feed systems (Report from the NRAO-GBT Pulsar Workshop of November 2004).

In view of this, a natural configuration for SRT would be that of a 90-cm/21-cm receiver, which would allow unique investigations by itself but might in turn overlap with the Parkes (and future GBT) systems in term of frequency baseline, significantly improving the overall precision of the international Pulsar Timing Array. Of course this dual-band receiver would replace the two systems (System 1 & System 2) mentioned before.

System 3: 3-GHz (high frequency) observations: Relatively high frequency ($\sim$ 3 GHz) observations are also very useful to undertake a program of extremely high precision timing observations like those involving the measurements of relativistic effects in double neutron star systems. Moreover this frequency band is now revealing itself suitable for discovering millisecond pulsars in distant clusters (having a high dispersion measure) and for searching young pulsars (with spin rates of about 100 ms) in regions close to the galactic center, where scattering washes out the pulsating signal at 1.4 GHz. In order to compensate for the reduced intrinsic flux from the source, this frequency choice requires a rather large bandwidth ($\gtrsim$ 1 GHz). According to the RFI environment, a relatively clean bandwidth is available at the SRT site in the frequency interval 3–4 GHz. This is a bit higher than the typical centre frequency ($\sim$ 3 GHz) adopted for these applications, but still well-suited. The pulsar back-end necessary for these applications should be the same digital filter bank suitable for lower frequency observations. In this case the most common set-up will be that of 1024 channels, each 1 MHz wide. The decision of the focal location of such a receiver is a matter of compromise with other scientific interests. For pulsar applications, side-lobe suppression and spill-over are not of paramount importance, while the key parameter is the effective antenna gain; so concerning pulsar research, this receiver with mono-feed could be better accommodated in the primary focus. On the other hand, should the SRT Board decide for the construction of a BWG-focus receiver operating at a similar frequency, the Italian pulsar group could cope with that.

Further developments : A multi-beam 7-horn system operating in the Methanol band (6.6 GHz with 600 MHz bandwidth, T_{sys} of 40 Jy) has been installed at the Parkes radiotelescope and recently began a large-scale search for pulsars in the central region of the Galactic disk, where scattering hampers detection of young and rapidly rotating pulsars at 1.4 GHz. The availability of 7 beams permits one to perform $\sim$10-times longer pointings than with a single beam, partly compensating for the decrease in intrinsic flux with respect to observations at 1.4 GHz. Given the wide interest for this frequency band in the Italian radioastronomical community, we highlight the advantages (also for pulsar research) of installing a multi-beam system at this frequency rather than a single horn.

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