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Observations of Radio Pulsars

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Abstract. 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. Results of some recent surveys are here summarized, focusing mostly on those which aimed to increase the known sample of young pulsars and of millisecond pulsars. Basic concepts of follow-up timing observations are also presented and applied to the case of the recently discovered Double Pulsar system.

Key words. Pulsar: generality – Pulsar: individual (PSR J0737−3039A,PSR J0737−3039B) – Theory: General Relativity

1. Tuning pulsar surveys

Pulsars are relatively weak radio sources. Successful pulsar surveys therefore require a large radio telescope, low-noise receivers, a relatively wide bandwidth and long observation times. Pulsars have steep spectra, typically $S(\nu) \propto \nu^{-1.7}$, and low-frequency cut-off occurs usually below 200-300 MHz. So, in principle, we would better observe them at frequency around 400 MHz. However, pulsar signals suffer dispersion due to the presence of charged particles in the interstellar medium. The dispersion delay across a bandwidth of $\Delta\nu$ centered at a frequency ν is

$$\tau_{\rm DM} \simeq 8.30 \times 10^3 \, {\rm DM} \, \Delta\nu \, \nu^{-3} \quad {\rm s}, \qquad (1)$$

where the dispersion measure, DM, is in units of cm^{-3}pc and the frequencies are in MHz. To retain sensitivity, especially for short-period, high-dispersion pulsars, the observing bandwidth must be sub-divided into many channels. In most pulsar searches, this has been achieved using a filterbank system.

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The sensitivity of pulsar searches is also limited by the Galactic radio continuum background $\sim \nu^{-2.7}$ and by interstellar scattering, especially for low radio frequencies and at low Galactic latitudes. Interstellar scattering results in a one-sided broadening of the observed pulse profile with a frequency dependence $\sim \nu^{-4.4}$ (Rickett 1977) which cannot be removed by using narrow bandwidths.

Hence, the parameters chosen for any given pulsar survey are a compromise between different needs and each survey is optimized in spanning a subsection of the whole pulsar space parameters. In recent years, major surveys have been tuned on two classes of sources: young and energetic pulsars, and millisecond pulsars.

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 their supernova remnants (SNR). Traditionally, the material expelled during the supernova explosion produces the typical shell structure of many SNRs. A pulsar at the center 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 show often irregularities in their periods 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). 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 more rare 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 more rare in the observed sample. For these reasons deep searches of the Galactic disk at low latitudes are required in order to achieve a significant number of relatively young pulsars. Such surveys also significantly increase the total number of medium age pulsars in the sample, making available a large sample population, useful for statistical studies. In this context, the most successful experiment to date has been the Parkes 21cm Pulsar Multibeam Survey performed at the Parkes (Australia) 64m radiotelescope (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004; Faulkner et al. 2005). Recently completed, this survey has discovered more than 700 new pulsars, doubling the total sample, including about 25 young energetic pulsars, thus increasing by more than 200% the sample of young pulsars (Kramer et al. 2003). Many tens of pulsars have been also discovered searching with the same instrument at higher galactic latitudes (Edwards et al. 2001).

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 a 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 (Alpar et al. 1982). 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 during the last decade of the past century (Lyne et al. 1998) 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. Many millisecond pulsars in globular clusters have been discovered in the last five years 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 21cm multibeam receiver. This proved that both low frequency and high frequency observations can be useful in a search of the Globular Cluster system. Among many recent discoveries (D'Amico et al. 2001a; Possenti et al. 2003), there are peculiar objects, like that of a millisecond pulsar in a tiny binary system with a companion of planetary mass, or the first ever known example of a probably newly born millisecond pulsar with a binary companion close to the end of its evolution, PSR J1740-5340 in NGC6 397 (D'Amico et al. 2001b; Ferraro et al. 2001). The study of another Globular Cluster, NGC 6752, hosting 5 millisecond pulsars, has allowed 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 NGC 6752, it has been found (D'Amico et al. 2002) that the observed acceleration of three millisecond pulsars located in the cluster core indicates a light-to-mass ratio much higher that derived from optical observations, suggesting the presence of a high density of unseen dark remnants in the core. In addition, the discovery of more than 20 millisecond pulsars in a single globular cluster (47 Tucanae Camilo et al. 2000) allowed for the first time to measure the density of the ionized gas in a globular cluster (Freire et al. 2001). The very last burst of discoveries of millisecond pulsars in clusters has been triggered by a deep survey performed at the Green Bank radiotelescope at 1.4 GHz and 2.1 GHz. That has allowed to overcome the total number of 100 known sources (Jacoby 2003; Ransom et al. 2004; Freire et al. 2005) in 24 globulars. The most relevant result has been the detection of 21 new sources in Terzan 5 (Ransom et al. 2005), which is now the most populated cluster as far as pulsar content is concerned. Preliminary indications from timing of some of the binaries in this cluster suggest that it may host some of the most massive known neutron stars. Finally, the most eccentric ($e = 0.89$) binary pulsar to date (whose current companion has been probably acquired during a dynamical encounter in the globular cluster core) has been discovered at the Giant Meterwave Radio Telescope (India) in the cluster NGC 1851 (Freire et al. 2004).

2. Timing concepts

When a new pulsar is discovered and confirmed, the only known parameters are its approximate position (within few arcminutes), rotational period P and dispersion measure DM, that gives a rough estimate of the pulsar's distance, once a model for the electrons' distribution in the Galaxy (Taylor & Cordes 1993) is assumed.

A follow-up observational campaign then has to start with the aim of better assessing new pulsars' positions and rotational parameters (P and $\dot{P}$). These quantities allow in turn to estimate the pulsar age and magnetic field and to cross-correlate its position with that of possibly related sources, such as X-ray,γ-ray objects, or supernova remnants. The regular monitoring ('timing') of new discoveries also allows to determine whether a pulsar is isolated or belongs to a binary system and, in the latter case, to derive orbital parameters.

Timing a pulsar means measuring and phase connecting the pulses times of arrival (TOAs). To do so, a standard profile (obtained summing in phase an adequate number – $\sim$ 1000 – of single pulses) is convolved with the integrated profiles of each observation: the topocentric TOA is then calculated adding at the starting time of the observation the fraction of period, τ, at which the χ^2 of the convolution is minimized. The measured times are then compared with TOAs predicted by a given pulsar model. The best fit positional, rotational and orbital parameters are then obtained minimizing the differences between measured and predicted times of arrivals (the timing residuals) with a multi-parametric fit.

The first step of a timing analysis is the transformation of the topocentric TOAs to the Solar System barycenter, in first approximation an inertial reference frame. If the pulsar is orbiting a companion star, the barycentric TOAs vary along the orbit anticipating when the pulsar is in front of the companion and delaying when it is behind it (orbital Doppler variations). Fitting for the orbital modulations, one can hence derive five keplerian parameters describing the binary system (Blandford & Teukolsky 1976): the orbital period P_b, the eccentricity e, the projection of the semi-major axis $x = a \sin i$, the periastron longitude ω and the epoch of periastron T_0. Combining these quantities one can derive the *mass function*:

$$f(M) = \frac{(M_c \sin i)^3}{(M_{NS} + M_c)^2} = \frac{4\pi^2 \, (a \sin i)^3}{G P_b^2} \qquad (2)$$

where M_c is the companion mass. Assuming a typical value for $M_{NS} = 1.4\ \mathrm{M}_\odot$ and an edge on orbit ($i = 90°$) we can obtain a lower limit for M_c.

When a pulsar is in a close orbit with a compact massive companion (producing a strong near gravitational field), further parameters – the so-called post-keplerian parameters – can be measured. In any given theory of relativistic gravity, the post-keplerian (PK) parameters can be written as function of the pulsar and companion masses and of the keplerian parameters. In the case of General Relativity (GR), the equations describing the PK parameters assume the form (Damour & Deruelle 1986; Taylor & Weisberg 1989; Damour & Taylor 1992):

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} (1-e^2)^{-1} \tag{3}$$

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2) \tag{4}$$

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi T_\odot}\right)^{-5/3} \frac{m_1\, m_2}{M^{1/3}}\, \mathcal{F}(e) \tag{5}$$

$$\mathcal{F}(e) = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1-e^2)^{-7/2}$$

$$r = T_\odot m_2 \tag{6}$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1} \tag{7}$$

where m_1 and m_2 are the two star masses, $M = m_1 + m_2$, $x = a \sin i$ and $T_\odot \equiv GM_\odot/c^3 = 4.925490947\,\mu$s. The parameter $\dot{\omega}$ measures the advance of the periastron, γ is a term taking into account gravitational redshift and time dilation, $\dot{P}_b$ is the so-called orbital decay and measures the rate at which the orbital period decreases due to losses of binding energy via gravitational radiation. Finally, r and $s \equiv \sin i$ are respectively the rate and the shape of the Shapiro delay, a parameter measuring the time delays of the signal caused by the space-time deformations around the companion star.

2.1. The Double Pulsar

The binary systems containing a pulsar with a neutron star companion are relatively rare in the population but very interesting. In this case, the "clock" signal of the pulsar can be used to probe relativistic effects in the strong gravitational field of the companion. One of the major results in pulsar research during last twenty years has been the discovery (Burgay et al. 2003; Lyne et al. 2004) of a highly relativistic double-neutron-star binary system with an orbital period of only 2.4 hours in which both the neutron stars are observable as a radio pulsar, i.e. the first-known double-pulsar (PSR 0737−3039A and PSR 0737−3039B are the names of the two pulsars). This system is evolving much faster than any previously known double-neutron-star system. One can predict that the two neutron stars will merge in about 85 million years (Burgay et al. 2003) due to emission of gravitational waves. This, together with the relative proximity of this system to the Earth, implies about 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 (Burgay et al. 2003). Facilities presently being commissioned in Europe, in the USA and in Japan were designed 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 in the most favorable models (Kalogera et al. 2004).

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 theory. Since the only unknowns in the left hand side of eqs 3 to 7 (or their analogues in other relativistic gravity theories) are the masses of the two stars in the binary system, the measurement of two post-keplerian parameters yields the masses and the measurement of three or more PK-parameters over-determines the system. In other words, once the masses are obtained measuring any two PKs, their value can be placed in the equation of 3rd, 4th and 5th parameter and the values obtained can be compared with the measured ones, giving a self-consistency test of the theory on which the given equations are based.

Timing of PSR J0737−3039A over only $\sim$ 18 months led to the measurement of all 5 aforementioned post-keplerian parameters. For the two other pulsars belonging to a double neutron star system on which these kind of measurements have been successfully done, B1913+16 (Hulse & Taylor 1974) and B1534+12 (Wolszczan 1991), timing observations yielded the measurement of three PK parameters in ~ 20 years (Taylor & Weisberg 1989), and all five PK parameters in ~ 10 years (Stairs et al. 2002) respectively. This comparison gives an idea of the possibilities that the J0737−3039 system opens in this field. It is worth noting, for instance, that using only the information given by pulsar A and in less than two years of follow-up observations, the J0737−3039 system already tests GR with very high accuracy: the measured value of the shape of the Shapiro delay, s_{obs}, agrees with Einstein's predictions, s_{GR}, at about 0.1% level (Kramer et al. 2005). This can be compared with the 0.2% agreement resulting from the measurement of the orbital decay in PSR B1913+16 (Weisberg & Taylor 2003), although the two tests belong to different classes, since the latter checks the radiative predictions of GR, whereas the former involves only non-radiative timing parameters.

Having detected the pulsations also from the second neutron star in the binary system allows for the first time to perform even better and significant tests of relativistic gravity: the timing measurement of the projected semi-major axis of both pulsars, in fact, yields the measurement of the mass ratio R of the two neutron stars. This value gives a qualitatively different constraint to the masses of the stars, since the relation

$$R \equiv \frac{a_B}{a_A} = \frac{M_A}{M_B} \tag{8}$$

is largely independent on the adopted theory of gravity. In fact, equation 8 is valid for all 'fully conservative' theories Will (1992) and in particular for all Lagrangian-based theories Damour & Taylor (1992). Hence, for any given set of equations describing the post-keplerian parameters, the lines formed on the mass-mass diagram must cross on the line indicating the mass ratio. In Figure 1 all the constraints on the masses of PSR J0737−3039A and PSR J0737−3039B are plotted. Note that all the plotted strips (derived from applying the GR equations to the measured values of the PK parameters with their uncertainties) have a common – though tiny – area of overlap and this area lays on the mass ratio R line.

In the next few years, previously untestable (or barely detectable) effects are expected to become measurable. In GR, the proper reference frame of a freely falling object suffers a precession with respect to a distant observer, called geodetic precession. As a consequence, provided the pulsar spin axis is not aligned with the orbital angular momentum axis, the pulsar spin precesses about the total angular momentum, changing the relative orientation of the pulsars to one another and toward Earth. This effect first produces variations in the pulse shape due to changing cuts through the emission beam as the pulsar spin axes precess. With the orbital parameters of the double pulsar, GR predicts precession periods of only 75 yr for A and 71 yr for B, much shorter than for any other known binary and in fact this effect may already be detected (only after 18 months of observation) as a secular change in the orbital phases at which B is very bright (Burgay et al. 2005). Aberration and higher order corrections to eccentricity may also become measurable relatively soon (Kramer et al. 2005).

Another effect involves the prediction by GR that the neutron stars' spins affect their orbital motion via spin-orbit coupling. As it depends on the pulsars' moment of inertia, a potential measurement of this effect allows the moment of inertia of a neutron star to be determined for the first time (Damour & Schäfer 1988), thereby resulting in a strong constraint on the equation of state for nuclear matter.

Finally, it is worth mentioning that the radiation from each of the two pulsars scans the local environment of the other. Therefore, the pulsar beams may become a unprecedented probe for investigating the magneto-ionic properties of pulsar magneto-spheres (Lyne et al. 2004), and for studying extreme states of plasma, that cannot be reproduced in terrestrial laboratories.

3. Future

Thanks to the extremely successful experiments performed at Parkes, culminated with the discovery of the Double Pulsar (Burgay

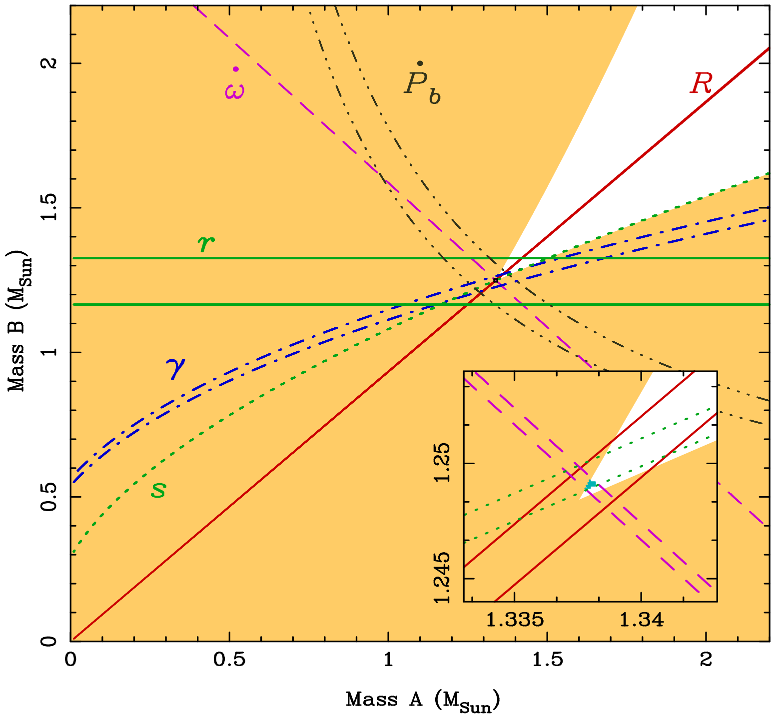

Fig. 1. 'Mass–mass' diagram showing the observational constraints on the masses of the neutron stars in the double pulsar system J0737−3039. The shaded regions are those that are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as given by the observed mass ratio and PK parameters shown here as predicted by general relativity. Inset is an enlarged view of the small square encompassing the intersection of these constraints. Courtesy M. Kramer.

et al. 2003; Lyne et al. 2004) a new era in pulsar research has been opened. Next years promise to be by far more exciting than past decades. The just started P-Alfa Survey at 20cm exploits the new multibeam receiver installed at the Arecibo (Puerto Rico) 300m dish and will allow to add perhaps $\sim$ 1000 entries in the catalog. It is very likely that at least about ten of them will be very intriguing relativistic systems. Two extensions of the pulsar surveys at 20cm are also running at Parkes (Australia): one looking towards the Perseus Arm region and the other deeply searching close to the galactic plane. Lower frequency surveys of the galactic field are ongoing at the Green Bank Telescope (GBT: USA) and at the Westerbork Synthesis Radiotelescope (WSRT: the Netherlands) and are planned at the Sardinia Radiotelescope (SRT: Italy) as soon as it is be completed. Globulars are still searched at Parkes, at Green Bank and at the Giant Meterwave Radio Telescope (GMRT) in India. This effort may finally lead to the next milestone in pulsar research, the discovery of a pulsar orbiting a black-hole.

On a longer time scale, a further revolution in pulsar science is expected with the construction of the Square Kilometer Array (SKA). It will be a radiotelescope with a collecting area about a factor a hundred larger than that of existing instruments. The sensitivity of SKA will permit to really perform a Galactic Census of pulsars, detecting almost all the radiopulsars whose beam sweeps our line-of-sight. In particular the large number of discovered millisecond pulsars will provide us with a very dense array of highly precise clocks in the sky, suitable for detecting the stochastic background of gravitational waves (Kramer et al. 2004). Timing of putative pulsars orbiting stellar and more massive black-holes will also allow to probe the ultra-strong field of relativistic gravity, thereby hopefully testing the No-Hair theorem and the Cosmic Censorship Conjecture (Kramer et al. 2004).

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