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Pulsars and collapsed objects

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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, from cosmology to stellar evolution, from globular cluster dynamics to the study of interstellar medium. This lecture aims to give a brief introduction to the theoretical and observational properties of pulsars. Classification and evolution of pulsars are dealt with first. Then the basic concepts driving the pulsar search experiments and the follow-up timing observations are presented. Finally it is reported on some of the most interesting scientific results obtained in the last decade using the pulsars as tools for the investigation, with particular emphasis for the case of the recently discovered first Double Pulsar system.

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Radio pulsars are rapidly rotating highly magnetized neutron stars radiating collimated beams of radio waves which we observe as pulses, once per rotation. Since some pulsars are highly stable clocks, they are unique tools for performing experiments in various fields of fundamental physics. In fact, 40 years after the original discovery, pulsar research shows a great vitality, setting the scene in many fields of science: from relativistic gravity to modern cosmology, from the physics of super-dense matter to the study of super-fluid and super-conducting materials, from plasma physics in ultra strong magnetic fields to stellar cluster dynamics, from the physics of the core collapse of massive stars to the properties of the interstellar medium.

In this lecture, I will give an introduction to the physical (§1), evolutionary (§2) and observational (§3) properties of the radio pulsars, reporting on some of the most recent results (§4) obtained studying this kind of radio sources. The perspectives in this field of radio astronomy are also finally dealt with in §5.

Further reading about this subject can be easily performed looking at the following excellent books, highly recommended for acquiring a more detailed knowledge of all the aspects of the pulsar research which have been only briefly touched (or sometimes simply neglected) in these notes: Manchester & Taylor 1977 [1], Lyne & Smith 2005 [2], Lorimer & Kramer 2005 [3].

1. Neutron stars & pulsars

Stars with typical initial mass ranging in the interval $5 \div 8\ \mathrm{M}_\odot \longrightarrow 20 \div 25\ \mathrm{M}_\odot$ [4] (the exact boundary values being still subject of scientific debate) end up their life with a gravitational collapse of their core. The dynamics of the event is not yet fully understood, but the current scenario (*Core collapse* model) suggests that the collapse originates a Type II supernova explosion, whose remnants are an expanding gaseous envelope (SuperNova Remnant: SNR) and a neutron star (NS). The latter being [5]:

$\longmapsto$ a ultra-compact object (mean density $<\rho> \gtrsim 10^{14}$ gcm^{-3}) of typical radius $R \sim 10^6$ cm,

$\longmapsto$ rotating at high spin rate (typical periods at the birth are supposed to be $P_{ini} \gtrsim 10^{-2}$ sec),

$\longmapsto$ having an high surface magnetic field B_S ($B_S \sim 10^{11}$ G$\longrightarrow 10^{14}$ G),

$\longmapsto$ and large spatial motion (median 3-dimensional speed of $\sim$ 400 km/sec)[6].

This kind of event is estimated to take place in a Galaxy similar to ours once every $\sim 50 \div 100$ yr. Another proposed [7] [8] avenue for the formation of a neutron stars is via the accretion of matter from a companion star onto a massive white dwarf, bringing it beyond the Chandrasekar limit (*Accretion induced collapse* model: AIC [9]).

Ultra high magnetic moments $\mu \sim B_S R^3$ and fast spinning rates allow the neutron stars to emit a large amount of energy in the form of accelerated particles and electromagnetic waves, typically along all the electromagnetic spectrum. Despite only a tiny fraction of the total energy flux is released in the radio band, it is possible to show that the observed radio emission must be coherent in nature. Moreover, it is beamed. The latter fact is crucial for the observation; in fact, combined with the misalignment of the rotation and the magnetic axes of the neutron star, implies that the radio emission appears pulsed (*light house* effect). All the neutron stars displaying this kind of

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pulsed radio emission are then called *radio pulsars* (or simply pulsars in this manuscript). The first object of this family has been discovered on 1967[10].

The details of the mechanism supporting the radio emission in the pulsars are still far from being satisfactorily understood and many models (see for example Melrose [11] for a review) have been proposed, suggesting various alternate processes and various sites for the acceleration of the particles. However, a common feature of most of the models seems to be the need of creating and sustaining a pair cascade [12]. In particular, in the original Ruderman & Sutherland's model [13] a gap of thickness h develops above the magnetic caps of the neutron star. A potential drop $\Delta V \sim (\Omega B_S h^2)/2c$ establishes along the gap, accelerating electrons up to a Lorentz factor $\gamma_{max} \lesssim (e\Delta V)/(m_e c^2)$. Moving in the neutron star magnetic field, these electrons emit curvature photons of frequency $\nu_{curv} \sim (c/r_{curv})\gamma_{max}^3$ where r_{curv} is the curvature radius of the magnetic field lines. The photons are able to pair create (thus sustaining the cascade) only if

$$\frac{\pi\hbar\nu_{curv}}{m_e c^2}\,\frac{B_\perp}{B_q} > \frac{1}{14} \tag{1.1}$$

with $B_q = 4.4\times10^{13}$ Gauss. The equation (1.1) translates into a relation between the surface magnetic field B_S and the angular velocity Ω of the neutron star. For a given value of B_S [14], only the neutron stars spinning with periods shorter than a predicted value $P_{death}(B_S)$ can radiate.

2. The $B_S - P$ diagram

The *surface magnetic field* versus *rotational period* (or the equivalent *magnetic moment* versus *rotational period*) diagram (abbreviated $B_S - P$ diagram, or $\mu - P$ diagram) offers a convenient graphic representation for classifying the pulsars and tracing their evolution. Thus in the following we will describe how it is built and where different classes of sources are located in it.

2.1 Filling the diagram

The $B_S - P$ diagram reports the rotational period and the surface magnetic field of all the pulsars for which these two values are known.

The pulsation period (along with the dispersion measure DM, see §3) is usually the first measured quantity when a new pulsar is detected. It corresponds to the rotational period P of the star, *i.e.* to the abscissa coordinate in the $B_S - P$ plane.

The measurement of B_S relies on the assumption that the rotational energy loss of the pulsar is due to the power emitted via magneto-dipole braking:

$$\frac{d}{dt}\left(\frac{1}{2}I\,\Omega^2\right) = -\frac{2}{3c^3}\,\mu^2\,\Omega^4 \tag{2.1}$$

where I is the moment of inertia of the neutron star and it has been implicitly assumed that the magnetic moment is perpendicular to the rotational axis of the star, that is $\mu \equiv \mu_\perp$. With a little algebra, from (2.1) one gets

$$\mu = \sqrt{\frac{3c^3}{8\pi^2}}\ \sqrt{I}\ \sqrt{P\dot{P}} = 3.2\times 10^{37}\ \sqrt{P\dot{P}}\ \text{Gauss cm}^3 \tag{2.2}$$

where the coefficient at the third member has been calculated assuming $I = 10^{45}$ gcm^2: this value satisfactorily approximates the moment of inertia calculated with different equations of state for a 1.4 $M_\odot$ neutron star. In order to obtain a reliable value for the period derivative a pulsar must be usually timed for about 1 yr. Once measured $\dot{P}$, the equation (2.2) allows us to determine μ. Adopting a specific value for the neutron star radius R (in turn dependent on the assumed mass and on the equation of state for the nuclear matter), one can also estimate the surface magnetic field intensity B_S using the relation $\mu \sim B_S R^3$. In *c.g.s Gaussian* units there are typically ~ 18 orders of magnitude between μ and B_S. However, due to the steep power in R, the determination of B_S is in principle more uncertain than that of μ.

As to February 2008, P and B_S have been determined for 1567 pulsars[1] in the Galactic field and for 18 sources in the Magellanic Clouds. Additional 70 pulsars have been discovered, but they have not a published measurement for $\dot{P}$ yet, and so cannot appear in Figure 1. Moreover, 137 pulsars[2] have been detected in globular clusters: they are not included in Figure 1 since the gravitational potential of the cluster can deeply affect the values of $\dot{P}$, in turn making the B_S-values extremely uncertain.

Besides the representative points for the 1567 objects discovered in the Galaxy (the 77 of them which are in binary systems appear surrounded by a circle in the Figure), four lines appear in Figure 1. They are:

- the DEATH LINE of Chen & Ruderman [14], drawn as the *lower solid line*. It divides the plane in two regions: in the upper part the radio emission is nominally allowed, whereas below the line it is nominally inhibited (see §1). This line roughly accounts for the dearth of pulsars in the right lower part of the diagram, the so-called *pulsar graveyard*. However the border in the $B_S - P$ diagram between the zone of the radio emitting and that of the radio quiet neutron stars is certainly not so sharp. An example is represented by the pulsar PSR J2144−3933 [15], having $P = 8.5$ sec and $B_S = 2.1\times 10^{12}$ G. Therefore, it is much better to refer to a DEATH VALLEY (bracketing the nominal death line), where the radio emission from a rotating neutron star progressively fades off. The region below this death valley should host many (the majority of) neutron stars, none of which is detectable in the radio-wave band.

- the HUBBLE LINE drawn as the *lower dotted line*. It marks where the characteristic age $\tau_c = P/(2\dot{P})$ of a pulsar is equal to the Hubble time $t_H = 10^{10}$ yr. Assuming (i) a magneto-dipole emission as in the equation (2.1), (ii) a constant magnetic moment for the star and (iii) a initial rotational period much shorter than the current period, the value of τ_c can be interpreted as the lifetime of the neutron star since the beginning of its radio-emission. Thus the Hubble line discriminates objects (those on the right of the line, having $\tau_c > t_H$) that certainly must violate one (or more) of the three hypotheses mentioned above.

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[1] http://www.atnf.csiro.au/research/pulsar/psrcat/

[2] http://www.naic.edu/ pfreire/GCpsr.html

- the YOUNG PULSAR LINE (drawn as the *upper dotted line*) is similar to the Hubble Line, despite it selects the pulsars younger than 10^5 yr (those on the left of the line, having $\tau_c < 10^5$ yr). There are now $\sim$ 85 known pulsars in this area, some of them still embedded in the remnant of the supernova event which gave them birth.
- the SPIN-UP LINE, drawn as the *upper solid line*. It concerns only the so-called *recycled pulsars* (see §2.3). Neutron stars with long rotational periods and low values of B_S (mostly located in the *pulsar graveyard*) can be spun up via the accretion of matter from a companion in a binary system. For each value of B_S and of the accretion rate $\dot{M}_{acc}$ the spin-up line defines the minimum period $P \propto B_S^{6/7}\dot{M}_{acc}^{-3/7}$ attainable during the spin up process. The line depicted in Figure is drawn for an accretion rate equal to the Eddington value.

2.2 Ordinary and recycled pulsars

Figure 1 shows that the known pulsars span almost 4 orders of magnitude in rotational period and more than 6 orders of magnitude in surface magnetic field. However the pulsars are not uniformly distributed in the plot and we can easily distinguish two main clusters of objects, which we could dub:

- **ordinary pulsars**, with high surface magnetic field and intermediate–long spin period;
- **recycled pulsars**, with low surface magnetic field and fast rotational rate.

The newly born pulsars belong to the former group, whose main features were listed in §1. In contrast, the observational properties of the population of the recycled pulsars can be summarized as follows:

- short periods $P \sim 1.4 \rightarrow 200$ ms (the upper bound being a conventional choice);
- surface magnetic fields in the range $10^{7.5} \rightarrow 10^{10.5}$ G (the upper bound being a conventional choice);
- high fraction of binarity ($\gtrsim$ 70%, in contrast with the $\lesssim$ 1% of the ordinary pulsars);
- mean 3-dimensional velocity of $\sim$ 100 km/sec, about four times slower than that of the ordinary pulsars;
- almost as many objects moving away from the galactic plane as toward [16], a clear signature for a dynamically old population (the bulk motion of the ordinary pulsars is most likely directed away from the galactic disk);
- large characteristic ages $\tau_c = P/(2\dot{P})$, with more than 10 objects showing τ_c which is nominally greater than the Hubble time $\sim 10^{10}$ yr;
- slightly less average radio luminosities with respect to the ordinary pulsar population [17];
- wider duty cycles (see §3) with respect to the ordinary pulsars (in average 21% versus 3% [17]);

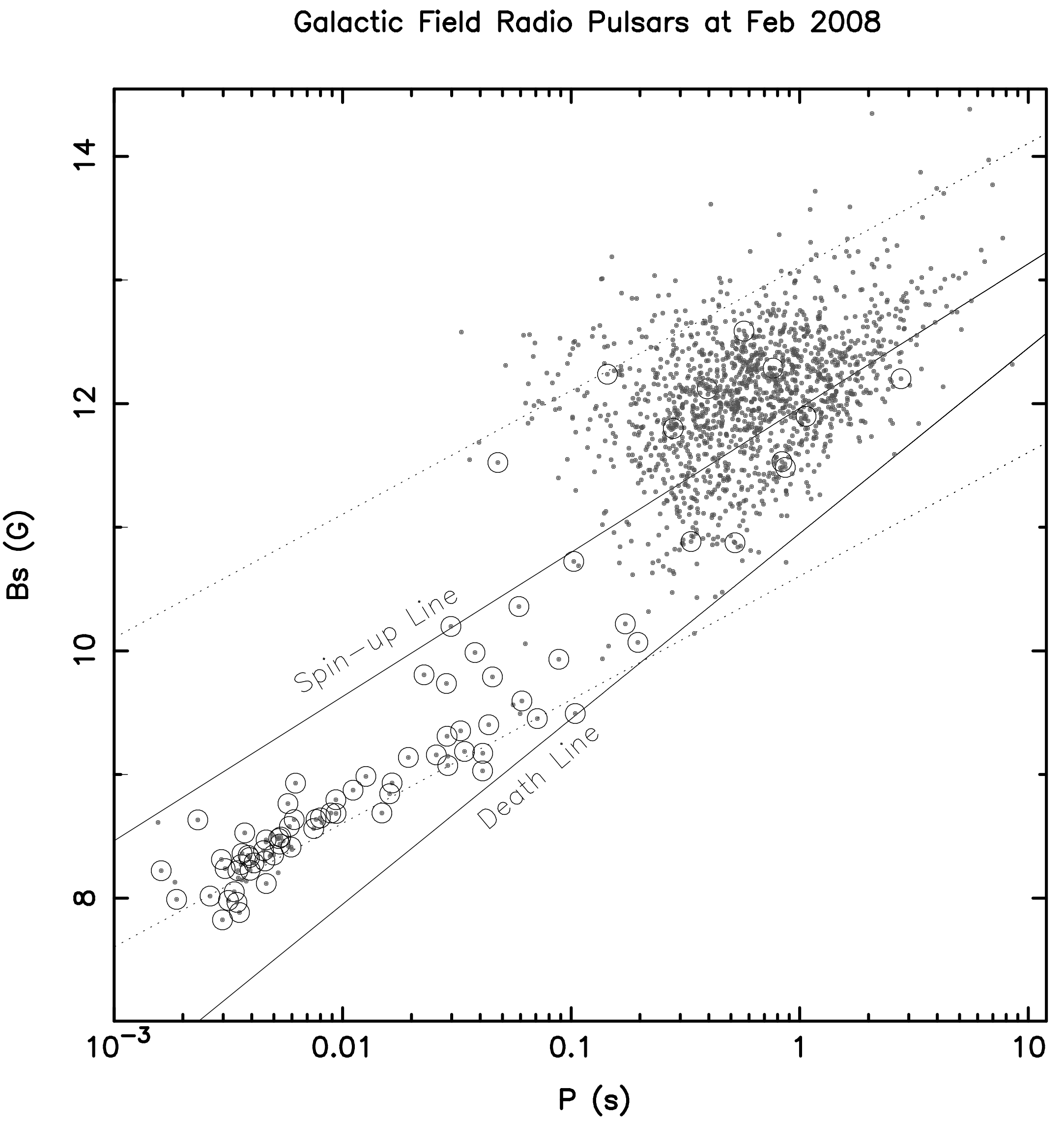

Figure 1: Surface magnetic field B_S versus rotational period P diagram updated at February 2008. It reports only the 1567 pulsars discovered in the Galactic field. The *lower solid line* represents the Chen & Ruderman's "death line" [14], below which the radio emission should be inhibited. The *upper solid line* is the "spin-up" line for Eddington accretion rate. The *lower dotted line* is the "Hubble line" whereas the *upper dotted line* is the line of constant pulsar age equal to 10^5 yrs.

- $\star$ mean spectral indexes identical to those of the normal population (-1.6 ± 0.1 versus -1.7 ± 0.1)[17];
- $\star$ higher degree of polarization and abnormal frequency development of the pulse profile with respect to the ordinary pulsars [18].

2.3 From ordinary to recycled pulsars: tracks in the $B_S - P$ plane

Given the observational facts summarized in §2.2 a question arises: which is (if any) the link between the two different classes of pulsars? The current answer is a paradigm known as *Recycling scenario*: **The recycled pulsars are old neutron stars spun up by the accretion of matter from a companion in a multiple stellar system.** Here we only sketch the general framework of the aforementioned scenario (see *e.g.* [19] or [20], or [21] for subtleties).

The model describes the bulk of the population of the known recycled pulsars as the final outcome of **binaries having a primary star of $M_{G,1} \gtrsim 8$ M$_\odot$ and a secondary star with mass in the range $M_{G,2} \lesssim 1-2$ M$_\odot$.** The evolution and expansion of the more massive star leads to a unstable mass loss from its outer layers, thus engulfing the binary system. As a consequence, the secondary lighter star is forced to spiral-in toward the center of mass of the system and eventually a compact binary is formed. It consists of the secondary star (whose gravitational mass $M_{G,2}$ is practically unchanged) and the Helium core of the swelled primary. The first part of this binary evolution ends up with the explosion of the He core as a supernova and the formation of a neutron star.

If the supernova event disrupts the system, the newly born neutron star (located somewhere in the upper left part of the $B_S - P$ plane) behaves as a young isolated pulsar. It spins down by magneto-dipole radiation, first moving through the region of the ordinary pulsars and then crossing (from left to right) the *death valley* in the $B_S - P$ plane. After that moment, the radio-emission would cease forever and the radio quiet neutron would travel in the *pulsar graveyard* along a path whose inclination (in the $B_S - P$ plane) is determined by the ratio between the rate of the magneto-dipole spin down and the rate of spontaneous decay (if any) of the surface magnetic field.

The history is completely different if the binary survives the supernova explosion. Due to the high mass of the He core ($M_{G,1}^{He} \gtrsim 2.2-4$ M$_\odot$ [22] [23]) the mass expelled from the system during the explosion could exceed half of the total pre-supernova mass of the binary. This circumstance should unbind the system, but detailed calculation [24] showed up that a suitable natal kick applied to the neutron star can indeed stabilize the binary. In particular we should be typically left with a neutron star of $M_{G,n} \sim 1.4$ M$_\odot$ orbiting a normal star of similar mass.

At the beginning (*ejector phase*), the neutron star could appear as a ordinary pulsar (unless the radio-waves being absorbed by the plasma wind from the companion), but later the matter from the secondary star can directly interact with the neutron star magnetic field, making the radio-emission impossible. First (*propeller phase*) the in-falling matter extracts angular momentum *from* the neutron star and thus the compact object moves toward far right in the $B_S - P$ plane. Conversely, when the rotational period typically reaches $100 \div 10000$ sec, the angular momentum of the plasma wind can be transferred *to* the neutron star (*wind accretion phase*), allowing a slight spin up of the compact object. During this very long phase (few billions years) a decreasing of the neutron star magnetic moment might occur (about two orders of magnitude from the original value).

The system undergoes another fundamental change when the secondary evolves off the main sequence and a heavy mass transfer sets in (*Roche-lobe overflow phase*): in fact it becomes a Low Mass X-ray Binary. Three mechanisms allows the mass exchange to keep on: for long orbital periods ($P_b \gtrsim 2$ days) the mass transfer is driven by the nuclear evolution of the secondary. For intermediate periods ($0.1 \lesssim P_b \lesssim 2$ days) the magnetic braking [25] basically dominates, whereas the gravitational radiation emission [26] sustains the mass transfer for extremely tight systems ($P_b \lesssim 2$ hours). Different values of the initial orbital periods $P_{b,i}$ and of the mass ratios $q_i = M_{G,2}/M_{G,n}$ lead to strongly different final systems. A complete classification is complex; as a general trend [27]:

- systems having $P_{b,i} \gtrsim 2$ days and $q_i < 5/6$ should terminate their evolution as long orbital period ($\gtrsim 50$ days) Low Mass Binary Pulsars (LMBPs) formed by a radio pulsar and a white dwarf in a circular orbit;
- systems having $P_{b,i} \gtrsim 2$ days and $q_i > 5/6$ should undergo a second spiral-in, thus ending up as a radio pulsar+white dwarf in a tight circular orbit ($\gtrsim 10$ hours);
- systems having $P_{b,i} \lesssim 0.5$ days should become near permanent faint Low Mass X-ray Binaries (LMXBs), formed by a radio quiet neutron star and a main sequence very light star;
- systems having $0.5 \lesssim P_{b,i} \lesssim 2$ days are much more sensitive to the interplay between q_i and $P_{b,i}$. They can end up as radio pulsar+white dwarf systems having either ultra short orbital periods (≤ 2 hours) or intermediate orbital periods ($1 \div 50$ days).

Besides the orbital evolution, the Roche Lobe Overflow phase implies a relevant spin-up of the neutron star. In most cases the compact object accretes matter and angular momentum from a keplerian disk, thus horizontally moving toward left in the $B_S - P$ plane. However this re-acceleration process cannot proceed unlimited. When the neutron star reaches the *spin-up line* (see Figure 1) it cannot spin up further unless its magnetic moment decays. Here it is evident the *tight connection between the rotational and the magnetic evolution of a recycled neutron star*: only if the surface magnetic field weakens down to $\sim 10^9$ G an accreting compact object can attain rotational periods shorter than 10 ms, typical of the so-called *fully recycled pulsars* (also known as *millisecond pulsars*). It is usually assumed that, once reached the spin-up line, a neutron star evolves sliding down it until the mass transfer from the secondary switches off.

In summary, according to scenario sketched above, **we are eventually left with a spun-up neutron star circularly orbiting a low mass white dwarf** ($M_{G,wd} \sim 0.1 \div 0.3$ M$_\odot$). Its position is often in the left lower corner of the $B_S - P$ plane. In particular, if it resides above the *death line*, **the neutron star can appear** (or re-appear) **as a rapidly pulsing radio pulsar**, slowly horizontally moving toward right in the diagram. Few tens of this systems are now known in the Galactic field. For special parameters of the system, the recycled pulsar could later ablate [28] or even evaporate the light companion [29], thus accounting also for the small subset of isolated fast spinning objects (for other mechanisms see e.g. [30]).

In this picture, the LMXBs are seen as the progenitors of the fully recycled pulsars. Indeed, such connection is not yet completely demonstrated. However, the discovery in 1998 of rapid (2.49 ms) coherent pulsations from a transient LMXB (SAXJ1808.4−3658 [31]) gave strong support to the model. Ten such systems are known to date in the X-ray sky[32].

The scenario reported above describes the formation of the *fully recycled* pulsars. Changing the initial parameters ($M_{G,1}$, $M_{G,2}$, orbital period) of the involved stars leads to other final states. For example, if both stars have initial masses larger than 8 M$_\odot$ also the secondary star can explode as a supernova. If the system is not disrupted, a double neutron star binary is formed. In principle three kinds of binary systems may be observed in this case: (i) the most likely possibility (7 such systems are known to date) is that of a *mildly recycled* pulsars (i.e. a pulsar spun up to few tens of millisecond and $B_S \sim 10^9 - 10^{10}$ G, it is the first born neutron star in the system) orbiting another (radio quiet) neutron star; alternatively (ii) we could see an *ordinary pulsar* (the second born neutron star in the system) orbiting another neutron star: given the significantly shorter lifetime of an ordinary radio pulsar (with respect to a recycled one) this possibility is much less likely than the previous (in fact only one known system is supposed to belong to this category); finally (iii) we could see both neutron stars active as radio pulsars, one being an *ordinary* pulsar, the other being a *mildly recycled* one: only one system of this type has been discovered so far.

Intermediate values of the initial masses $M_{G,1}$ and $M_{G,2}$ produce other kinds of binary pulsars, some of them *mildly recycled* and some others belonging to the *ordinary* family. A full description of the pathways for the binary pulsar formation is for example reported in [33].

An alternative hypothesis for the formation of *recycled* pulsars calls for the *Accretion Induced Collapse* of a white dwarf embedded in a binary system with a mass-losing companion [7]. The differences in the neutron star formation mechanism (with respect to the *Core Collapse* model) would account for the much shorter rotational periods and the lower surface magnetic fields of the *fully recycled* pulsars [9] with respect to the *ordinary* pulsars. However, many aspects of the AIC are still very unclear; in addition, the recent consideration of the so-called *r*-mode instabilities seems to indicate that the accretion induced collapse of a white dwarf cannot produce neutron stars rotating at periods shorter than ~ 10 ms [34].

A more appealing possibility [35] [36] is that a different kind of supernova explosion (i.e. electron capture supernova) may be sometimes responsible for the formation of the second born neutron star in a double neutron star binary: in fact, it could help explaining the low values of the orbital eccentricity and of the space velocity seen in some of these binaries.

3. Pulsar Observations

Pulsar observations naturally split in the two main categories of *search* and of *timing*. In this section it is given a brief summary of the methodologies and of the problems involved in these two aspects of the pulsar research.

3.1 The basic formulae

The relevant parameters of a pulsar search apparatus are the following:

- ν_{MHZ} = center observing radio frequency in MHz
- $\Delta\nu_{MHZ}$ = observing bandwidth in MHz
- $\delta\nu_{MHZ}$ = width of a single radio frequency channel in MHz
- T_{sky} = sky background temperature in K
- T_{sys} = system noise temperature in K
- G = antenna gain in K/Jy
- N_p = number of polarizations
- Δt = integration time of a single observation in seconds
- δt = sampling time in seconds

- β = parameter accounting for post-detection time constant and anti-aliasing filter; it is usually ~ 2

Indicating with σ_n the minimum signal-to-noise ratio for a *bona-fide* pulsar detection, the radiometer equation provides us with a formula for estimating the *minimum mean flux density* S_{min} *of a detectable pulsar* (see *i.e* [37] or [38]):

$$S_{min} \simeq \sigma_n \cdot \frac{T_{sys} + T_{sky}}{G\sqrt{N_p \Delta t \Delta\nu_{MHZ}}} \cdot \sqrt{\frac{W_e}{P - W_e}} \tag{3.1}$$

The fundamental relation (3.1) implies that the effectiveness in detecting pulsars depends not only on the experimental apparatus, but also on the shape of the received signals; namely on the relation between the pulse period P and its effective width W_e (both expressed in seconds). The more $W_e \longrightarrow P$, the higher S_{min} and so the worst the sensitivity.

Observations show that the typical pulse profiles have a duty-cycle ($\sim W/P$) of $\lesssim 10\%$, where W is the intrinsic pulse width. Were the pulsar signal to propagate in vacuum, the effective width W_e would be close to the intrinsic pulse width and $W_e/(P - W_e) \lesssim 1/9$. For a suitable choice of the sampling time $\delta t \ll P$, the minimum flux S_{min} detectable by an assigned instrument would reach an asymptotic value almost independent on P.

The presence of the interstellar medium (ISM) deeply affects such an idealized scenario. It produces a broadening of the emitted signal, according to two main physical effects:

Dispersion

In traveling through the Galaxy, the radio-waves are dispersed in frequency by the ionized component (mainly electrons) of the interstellar medium (ISM). The dispersion causes a spread in the arrival times of the pulses at different radio frequencies. In particular, lower frequencies lag the higher ones, according to [39]:

$$t_{low} - t_{high} = \frac{8\pi^3 e^2}{m_e c} \left(\frac{1}{\nu_{low}} - \frac{1}{\nu_{high}} \right) DM \tag{3.2}$$

where m_e and e are the mass and the charge of the electron and DM is the so-called **Dispersion Measure**, defined as

$$DM = \int_0^d n_e dl \tag{3.3}$$

where n_e is the electron density which is encountered along the path joining the source (at distance d) and the receiver. Substituting ν_{low} and ν_{high} with the lower and upper frequencies of a channel of the detector, and introducing suitable units, from (3.2) we get the relation (3.4) accounting for the smearing of the pulse in a single channel (for which $\delta\nu_{MHZ} \ll \nu_{MHZ}$):

$$\delta t_{DM} = 8.3 \times 10^3 \; DM \; \frac{\delta\nu_{MHZ}}{\nu_{MHZ}^3} \tag{3.4}$$

where DM is expressed in pc/cm^3, δt_{DM} in seconds, $\delta\nu_{MHZ}$ and ν_{MHZ} in MHz.

Scattering

Local inhomogeneities of the electron density n_e in the ISM behave as center of scattering for the radio-waves emitted by a pulsar. Any detected pulse profile is the superposition of signals characterized by slightly different optical paths and therefore suffering a relative time shift. In particular the delay between a ray seen at a small angle θ and a direct ray (θ=0) from the same source is $t_\theta - t_0 \simeq d\theta^2/2c$ (d is the distance of the pulsar). Assuming a Gaussian distribution of density fluctuations in the ISM and the simple geometry of the thin screen model [40] one obtains the following scaling for the broadening of an impulsive signal:

$$\delta t_{scatt} \propto \frac{d^2}{\nu_{MHZ}^4} \tag{3.5}$$

More refined models [41] introduce a Kolmogorov turbulence spectrum for describing the density irregularities in the ISM. Such models predict a scaling law similar to (3.5); in particular $\delta t_{scatt} \propto \nu_{MHZ}^{-4.4}$

The effective pulse width W_e eventually results by the contributions of the intrinsic width W (expressed in seconds), of the propagation in the ISM and of the instrument time resolution:

$$W_e = \sqrt{W^2 + (\beta\delta t)^2 + (\delta t_{DM})^2 + (\delta t_{scatt})^2} \tag{3.6}$$

3.2 The choice of the parameters for the pulsar searches

Due to economical, technical and computational limits, any pulsar search experiment can probe only a selected volume of the pulsar parameter space. In the following, we describe how the interplay between different experimental parameters, together with the choice of their values, lead to the search of different pulsar populations.

OBSERVING BANDWIDTH VS FREQUENCY RESOLUTION

Pulsars are wide-band radio emitters, whose signals have been detected in an interval of frequencies varying from $\sim$ 10 MHz up to tens of GHz. So, in order to improve the sensitivity S_{min} of a pulsar search experiment (see equation (3.1)), one would like to adopt a very large value of the total bandwidth $\Delta\nu_{MHZ}$ of the receivers. Were the signal collected only in one channel, the dispersion in the ISM would smear the pulse (see equation 3.4 with $\delta\nu_{MHZ} = \Delta\nu_{MHZ}$) even for low values of DM. Therefore only a small galactic region around the Sun would be explored.

A good sensitivity for the detection of more distant pulsing sources can be recovered by splitting the signal into an adequate number of frequency channels $N_{\rm chan}$, thus reducing $\delta\nu_{MHZ} = \Delta\nu_{MHZ}/N_{\rm chan}$. This can be achieved using hardware devices (*i.e.* filterbanks[38]) or suitable software [42], but of course, the greater the number of channels, the larger the amount of data and the longer the time for its processing.

INTEGRATION TIME VS TIME RESOLUTION

The best options for minimizing S_{min} would be an extremely long integration time Δt and a very fast sampling rate $1/\delta t$, for selected values of the remaining parameters. The former permits the collection of a greater amount of energy from the source, the latter implies that the effective width W_e of the pulse increases of only a negligible amount (see equation (3.6)). As for the case of the two parameters “observing bandwidth” and “frequency resolution”, the current computational capabilities limit the choice of Δt and δt, whose ratio $\Delta t/\delta t$ gives the total number of samples which the algorithms for the periodicity search must deal with.

OBSERVING FREQUENCY VS “COVERED AREA”

The selection of the best observing frequency must take into account various factors, namely:

i _ *pulsar spectral shape* $\propto$ $\nu^{-\alpha}$ with average α typically $\sim 1.6-1.7$

ii _ *galactic background spectrum* $\propto$ $\nu^{-2.7}$;

iii _ *interstellar scattering* $\propto$ $\nu^{-4.4}$;

iv _ *interstellar dispersion* $\propto$ $\delta\nu\ \nu^{-3}$;

v _ *telescope beam* $\propto$ ν^{-1} .

In summary **high frequencies** (typical values $\sim$ 1400 MHz, $\lambda \sim$ 20 cm) are selected **for surveys in the galactic plane** or **for targeted searches of SuperNova Remnant cores**: they are much less sensitive to the interstellar scattering and need a moderate frequency resolution to remove dispersion. In particular *high frequency surveys* in the galactic plane [43] are ideal *for searching young pulsars* ($\lesssim 10^6$ yr), whose typical progenitors are massive stars born in the disk. Moreover, due to their strong magnetic fields, young pulsars evolve rapidly implying a low number density and a large average distance, thus favoring high observing frequencies. The **searches for millisecond pulsars in globular clusters** at DM $\gtrsim$ 100 pc cm^{-3} are another suitable target for high frequency experiments [44] [45], sometimes operating at a central frequency of 2 GHz [46]. In these stellar systems the bulk of the observed pulsar population underwent a phase of re-acceleration due to mass transfer in binaries; so we expect short rotational periods, whose detection requests the scattering smearing of the pulse to be kept negligible.

On the contrary, **low frequencies** ($\sim$ 400 MHz, $\lambda \sim$ 70 cm) are preferred **for all-sky surveys**: they take advantage from the wider telescope beams (thus reducing the needed number of pointings) and the steep pulsar spectra. Thus, *low frequency surveys* [38] represent the best option *for investigating the low-luminosity tail of the pulsars in the neighborhood of the Sun*, where a population of relatively old objects prevails.

3.3 Pulsar search concepts

In general pulsars are weak radio sources and this certainly holds true for the vast majority of those which have not been discovered yet. Here the word “weak” means that their single pulses are well below the typical noise resulting from the contribution of the sky and that of the detector system, antenna plus back-end. This in turn implies that the researchers must often exploit the periodic nature of the pulsar signal in order to recognize that amid the noise. In this aim, various kind of techniques have been applied, working either in the Fourier domain or in the time domain.

The most commonly used procedure involves first the de-dispersion of the collected time-series (one for each frequency channel of the back-end) with the formation of a single time-series characterized by a given value of the dispersion measure DM. When a pulsar has not been discovered yet, the value of the DM is obviously unknown, and then the de-dispersion must be repeated for a large number of trial DMs: the number and the spacing of the DMs is calculated according to the parameters of the back-end used for the search and the direction in the sky where the radio telescope points to.

Each de-dispersed time-series is first transformed using a Fast Fourier Transform, and the values in the spectral bins interpolated for preserving the power to a signal falling just between two adjacent spectral bins. Then the low frequency noise is removed from the spectrum, typically using a running median over contiguous small chunks of the spectrum. Finally the resulting power spectra are searched for significant peaks above a spectral signal-to-noise $(S/N)_{\rm spec}$ threshold. In the aim of increasing the sensitivity to narrow pulses – whose power is typically distributed over many harmonic components – the process is often repeated for spectra obtained by summing 2, 4, 8, 16 and 32 harmonics. Therefore, at the end of this process, a very large number of pulsar "candidates" (each characterized by a given value of the spin period $P_{\rm cand}$, of the dispersion measure $\rm DM_{cand}$, of the spectral signal-to-noise $(S/N)_{\rm spec}$, and of the harmonic folding at which the candidate appears) are produced for any given observation.

These candidates are usually sorted in decreasing $(S/N)_{\rm spec}$, and possibly grouped together, if e.g. there appear similar candidate periods at similar values of DMs. In the next step, the time-domain data (de-dispersed at the candidate $\rm DM_{cand}$) of the candidates at the top of the sorted list (the number of which depends on the computational capabilities) are folded in sub-integrations, using a constant period equal to the candidate period $P_{\rm cand}$. All the resulting sub-integration arrays are then searched for any linear shift in pulse phase, corresponding to a correction in the candidate period. The final pulse profiles (one for each produced sub-integration array) resulting from this linear shift search are sorted again, this time according to the signal-to-noise $(S/N)_{\rm prof}$ of the profile. The profiles with the largest values of $(S/N)_{\rm prof}$ are finally displayed for visual inspection, with the resulting plots reporting all the significant parameters of the search.

The additional information in the output plots are very important for helping in a first discrimination of the putative "real" pulsar candidates, which are usually outnumbered by fake signals, mostly due to cosmic or terrestrial radio interferences. As a matter of fact, despite the use of high threshold values for $(S/N)_{\rm prof}$ (often at least 9 or 10), the combination of the effect of the interferences with that of the purely statistical probability of finding a spurious signal, requires that any reliable candidate pulsar signal is confirmed by an additional observation before announcing a new discovery.

The last two steps of the classical Fourier domain pulsar search suggest an alternate way for searching pulsars, i.e. folding the de-dispersed time-series at any plausible value of the period with a Fast Folding algorithm, and then searching for the resulting pulse profiles having the highest values of $(S/N)_{\rm prof}$. As such, the search would be computationally prohibitive, but it may be performed if the range of the searched values of P is suitably narrowed. In particular this time domain technique proves to be very efficient in finding pulsars with rotational period longer than about 2 seconds, whereas Fourier domain searches are usually better for faster spinning sources.

It has been recently discovered a class of rotating neutron stars emitting strong single radio pulses [47]: they have been dubbed Rotating Radio Transients (RRATs). Their relation with the bulk of the population of the radio pulsars in not assessed yet: however, it is interesting to point

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out that the technique used for discovering them (the so called Single-Pulse search) may be useful for discovering radio pulsars whose periodic pulsating signal is very faint (e.g. due to their large distance), but that, every now and then, emit strong enough (=giant) single pulses. The Single-Pulse search (see e.g. [47]) aims to recognize isolated dispersed pulses in a time-series: in order to do that, it searches in all the de-dispersed time-series for events whose amplitude goes beyond several standard deviations from the mean of the amplitudes of the given time-series. Then it compares the times of occurrence of these events in the time-series built for various values of the DM. The most promising events are stored and similar events (i.e. a single radio burst occurring at the same value of the DM) are searched both in the same or in subsequent observations.

What discussed above applies to isolated pulsars or to pulsars in very large binaries, the orbital period of which is much longer than the typical duration of the observation. Discovering a binary pulsar in a close binary is usually much more difficult: in fact, as soon as the observation lasts a sizable fraction of orbital period, the apparent period of the pulsating signal significantly drifts during the observation. This means that the power spreads in many Fourier spectral bins and the spectral signal-to-noise of each of them may easily go below the threshold for the candidate to be retained in the search analysis.

Various techniques have been proposed for minimizing the effects of the aforementioned Doppler distortion of the period of repetition of the collected signal. These procedures basically split in the classes of the coherent searches and of the incoherent searches. A typical coherent search in the time domain is based on the re-sampling of each de-dispersed time-series according to a set of trial values of the line-of-sight acceleration of the source with respect to the observer [48]. The acceleration is assumed to be constant along the observation and the re-sampling procedure compensates for the effect of the acceleration experienced by the source in a small section of its orbit. The method is efficient but computationally expensive. A similar method (less demanding in term of computational power) can be applied in the Fourier domain [49].

Most incoherent searches operate in the frequency domain: they usually split the observation in many segments, the Fourier spectrum of any of them being separately calculated. The idea is that the Doppler drift of the signal is small in these short segments. Moreover, the size of each spectral bin (being inversely dependent on the duration of the observation) is larger for these spectra than for the spectrum of the total observation. So, each spectral bin can preserve a power similar to that released by a supposedly isolated pulsar. According to a first method (the so-called Stack search, see e.g. [50]), these series of spectra are then summed together applying a set of trial linear frequency drifts, in order to compensate for the effect of a constant acceleration undergone by the source. Alternatively, the array of these spectra can be searched (Dynamic spectrum search, see e.g. [51]) for sinusoidal or even more complex trends, accounting for the not linear changing of the apparent pulse period along the orbit. The so-called Phase modulation search is another incoherent search in the Fourier domain [52]: in principle it should represent the best approach for detecting pulsars with orbital period smaller than the duration of the observation. So far no pulsar has been discovered with this promising technique, though. An incoherent search in the time domain can also be performed will running the last stage of the standard search technique [45]: instead of searching only for a linear drift in the sub-integration array, it is possible to search also for a parabolic correction, which is the signature of a (constant) pulsar acceleration due to the orbital motion.

It is finally important to remark that none of the procedures listed above is *optimal*, i.e. none of them allows us to detect a binary pulsar with the same efficiency with which we could detect an isolated pulsar having the same P, DM and flux of the binary one. Adopting one or the other of those techniques is then the result of a compromise between the available computational capabilities and the volume in the space of the pulsar parameters that a researcher aims to explore.

3.4 Pulsar timing concepts

The possibility of using some neutron stars as probes for fundamental physics relies on their being precise cosmic clocks, a feature which is exploited by means of the procedure of timing described below. In this perspective, the best available sources are represented by the *mildly* or *fully recycled* pulsars: on one hand, their very short rotational period allows us to determine the Time of Arrival of the pulses (see later) with better accuracy than for most of the *ordinary* pulsars. On another side, their being relatively older neutron stars implies that they typically appear much more stable rotators than the *ordinary* pulsars.

When a new pulsar is discovered and confirmed the only known parameters are its approximate position (within few arc minutes), 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 [53] is assumed.

A follow-up observational campaign then have to start in the aim of better assessing new pulsars' positions and rotational parameters (P and $\dot{P}$). These quantities allow one 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 or γ-ray objects or supernova remnants. The regular monitoring ('timing') of new discoveries also allows one 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 – ~ 1000 – of single pulses) is convolved with the integrated profiles of each observation: the topocentric TOA is then calculated adding at the mid 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 [54]: 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*:

$$f(M) = \frac{(M_c \sin i)^3}{(M_{NS}+M_c)^2} = \frac{4\pi^2\,(a\sin i)^3}{GP_b^2} \tag{3.7}$$

where M_c is the companion mass. Assuming a typical value for $M_{NS} = 1.4\ \mathrm{M}_\odot$ and an edge on orbit ($i = 90^\circ$) 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 [55][56][57]:

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}\,(1-e^2)^{-1} \tag{3.8}$$

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2(m_1+2m_2) \tag{3.9}$$

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi T_\odot}\right)^{-5/3}\frac{m_1 m_2}{M^{1/3}}\,\mathscr{F}(e) \tag{3.10}$$

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

$$r = T_\odot m_2 \tag{3.11}$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1} \tag{3.12}$$

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.

4. Some recent results from pulsar search and timing

As a illustration of the large number of scientific applications of the study of the pulsars, in this section it will be given a summary of some of the best results emerged from the investigation of three categories of pulsars during the last decade: namely, the young pulsars, the recycled pulsars contained in a globular cluster and the pulsars included in relativistic binaries.

4.1 Young pulsars

Young pulsars (age less than 100,000 years) are often associated with their supernova remnant (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. Moreover, young pulsars show often 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). In particular, 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 radio telescope (e.g. [43][58][59]). Recently completed, this survey have discovered more than 700 new pulsars, doubling the total sample, including about 45 young energetic pulsars, thus increasing significantly the sample of young pulsars [58]. Many tens of pulsars have been also discovered searching with the same instrument higher galactic latitudes [60].

4.2 Recycled pulsars in globular cluster

Globular clusters are a fertile environment for the formation of recycled pulsars: besides evolution from a primordial system, exchange interactions in the ultra-dense core of the cluster favor the formation of various types of binary systems suitable for spinning up the neutron stars they host [61]. Because of this, about 60% of all known fully recycled pulsars are in globular clusters. Unfortunately, the pulsars located in these stellar systems are elusive sources since they are often distant and in close binary systems. Their large distances make their flux density typically very small and their signals strongly distorted by propagation through the dispersive interstellar medium. In addition, they frequently are members of close binary systems, causing large changes in the apparent spin period and sometimes periodic eclipsing of the radio signal.

Despite all these difficulties many millisecond pulsars in globular clusters have been discovered in last 7 years in the course of various experiments at Parkes, in particular using the central beam of the Parkes 21cm multibeam receiver. Among many recent discoveries [44][62], 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 probably newly born (or re-born) millisecond pulsar with a binary companion close to the end of its evolution, PSR J1740−5340 in NGC6397 [63][64]. This binary system promises to be the best laboratory to date for studying both the effects of the matter released by the companion onto the radio signal from the pulsar (in fact the radio signal is eclipsed for about 40% of the orbit) and the effects of the pulsar energetic flux onto the companion.

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 mass-to-light ratio. In NGC6752, it has been found [65] that the observed acceleration of three millisecond pulsars located in the cluster core indicates a mass-to-light 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 [66]) led for the first time to measure the density of the ionized gas in a globular [67].

The very last burst of discoveries of millisecond pulsars in clusters has been triggered by a deep survey performed at the Green Bank radio telescope at 1.4 GHz and at 2.1 GHz. That has led to reach the total number of 137 known sources in 25 globulars. The most relevant result has been the detection of 32 new sources in Terzan 5 [46], which is now the most populated cluster as far as pulsar content. In particular it contains the most rapidly rotating recycled pulsar known so far, PSR J1748$-$2446ad [68], spinning at 716 Hz (corresponding to a rotational period $P = 1.396$ ms).

Preliminary indications from the timing of some of the binary pulsars discovered in other clusters suggest that they may be associated with some of the most massive known neutron stars: i.e. PSR J1748$-$2021B in the cluster NGC 6440 shows [69] a most likely mass 2.74 ± 0.21 $M_{\odot}$. If the latter result would be confirmed, it would put significant constrain to the Equation of State (EoS) for the nuclear matter, excluding all the so called *soft*-EoSs.

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 [70].

4.3 J0737$-$3039 system: the unique 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 [71][72] 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 J0737$-$3039A and PSR J0737$-$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 [71] 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 [71]. 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 [73].

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 3.8 to 3.12 (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 [74] and B1534+12 [75], timing observations yielded the measurement of three PK parameters in $\sim$ 20 years [56], and all five PK parameters in $\sim$ 10 years [76] respectively. This comparison gives an idea of the possibilities that J0737−3039 system opens in this field. It is worth noting, for instance, that using only the information given by pulsar A and in about two years of follow-up observations, 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 0.05% level [77]. This can be compared with the 0.2% agreement resulting from the measurement of the orbital decay in PSR B1913+16 [78], 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 us 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

$$R \equiv \frac{a_B}{a_A} = \frac{M_A}{M_B} \tag{4.1}$$

is largely independent on the adopted theory of gravity. In fact, equation 4.1 is valid for all 'fully conservative' theories [79] and in particular for all Lagrangian-based theories [57]. 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 2 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 [80]. Aberration and higher order corrections to eccentricity may also become measurable relatively soon [77].

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 may lead to a determination of the moment of inertia of a neutron star for the first time [81], thereby resulting in a strong constraint on the equation of state for nuclear matter.

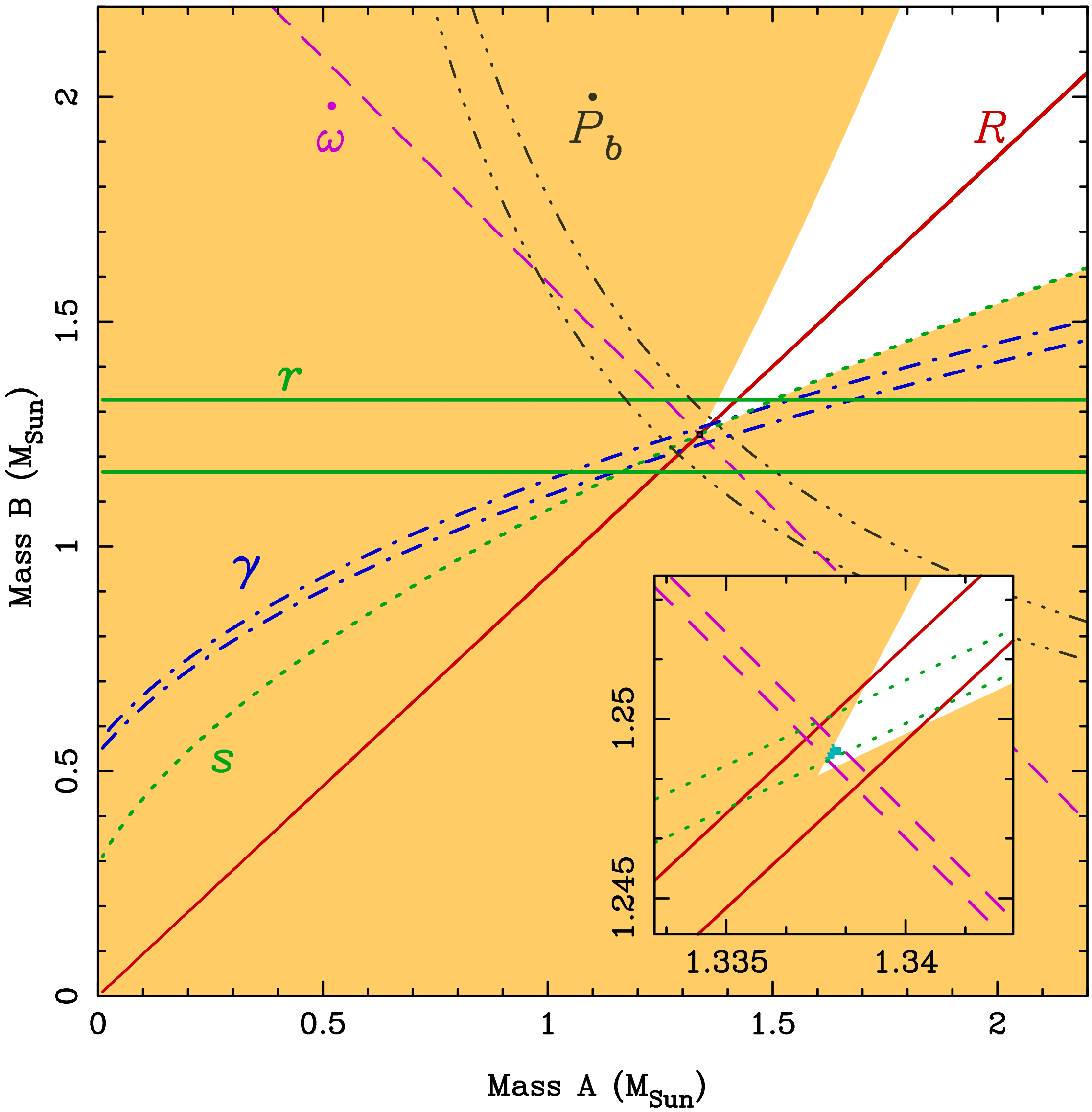

Figure 2: ‘Mass–mass’ diagram showing the observational constraints on the masses of the neutron stars in the double pulsar system J0737−3039. The shaded regions are those that are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted 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.

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 [72], and for studying extreme states of plasma, that cannot be reproduced in terrestrial laboratories.

5. The future

Thanks to the extremely successful experiments performed at Parkes, culminated with the discovery of the Double Pulsar [71][72] a new era in pulsar research has been opened. Next years promise to be by far more exciting than past decades. The ongoing P-Alfa Survey [82] at 20cm exploits the new multibeam receiver installed at the Arecibo (Puerto Rico) 300m dish and will allow the researchers to add perhaps $\sim$ 500 entries in the catalog. It is very likely that at least about ten of them will be very intriguing system. In fact, two very interesting binaries have been already discovered: PSR J1906+0746 is likely the only example of a double neutron star binary where the second born neutron star is visible as a radio pulsar [83]. Furthermore, more recently a fully recycled pulsar in a very eccentric orbit has been also discovered, being probably the first unambiguous example of a pulsar ejected from a globular cluster into the Galactic field.

Lower frequency surveys of the galactic field are ongoing at the Green Bank Telescope (GBT: USA) and at the Westerbork Synthesis Radio telescope (WSRT: the Netherlands) and are planned at the Sardinia Radio telescope (SRT: Italy) as soon as it will be completed. Globulars are still searched at Parkes, at Green Bank and at the Giant Meterwave Radio Telescope (GMRT) in India. The installation of a digital filter-bank for the 13 beam Parkes receiver at 1.4 GHz will largely reduce dispersion smearing with respect to the analog filter-banks used so far. This will open the possibility of finding distant recycled pulsars in the Galaxy (and among them many relativistic binaries), as well as fast transients at high time resolution. A series of surveys with the new backend is then expected to begin since late 2008. As a whole, these efforts 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 radio telescope with a collecting area about a factor a hundred larger than that of the existing fully steerable instruments. The sensitivity of SKA will permit to really perform a Galactic Census of pulsars, detecting almost all the radio pulsars (some tens of thousands) whose beam sweeps our line-of-sight. In particular the large expected number of discovered recycled pulsars (about a thousand in the Galactic field) will provide us with a very dense array of highly precise clocks in the sky, suitable for detecting the stochastic background of gravitational waves [84]. Timing of putative pulsars orbiting stellar and more massive black-holes will also allow us to probe the ultra-strong field of relativistic gravity, thereby hopefully testing the *No-Hair theorem* and the *Cosmic Censorship Conjecture* [85].

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