

## Eclipsing Binary Pulsars

Paulo C. C. Freire

*Arecibo Observatory, HC 3 Box 53995, Arecibo, PR 00612, USA*

**Abstract.** The first eclipsing binary pulsar, PSR B1957+20, was discovered in 1987. Since then, 13 other eclipsing low-mass binary pulsars have been found; 12 of these are in globular clusters. In this paper we list the known eclipsing binary pulsars and their properties, with special attention to the eclipsing systems in 47 Tuc. We find that there are two fundamentally different groups of eclipsing binary pulsars, separated by their companion masses. The less massive systems ( $M_c \sim 0.02 M_\odot$ ) are a product of predictable stellar evolution in binary pulsars. The systems with more massive companions ( $M_c \sim 0.2 M_\odot$ ) were formed by exchange encounters in globular clusters, and for that reason are exclusive to those environments. This class of systems can be used to learn about the neutron star recycling fraction in the globular clusters actively forming pulsars. We suggest that most of these binary systems are undetectable at radio wavelengths.

### 1. Introduction

The first eclipsing binary pulsar, PSR B1957+12, was discovered in 1987 (Fruchter, Stinebring, & Taylor 1987). Since its discovery, 13 other eclipsing binary pulsars with low-mass companions have been found, these are listed in Table 1, with relevant references. Of these systems, 12 are found in globular clusters (GCs). To these we add a list of binary systems with companion masses smaller than  $0.02 M_\odot$  that are, as we will see, intimately related to a subset of the eclipsing binary systems.

The systems that have been known longest are also the ones for which the pulsar has the highest flux density; it is therefore understandable that such systems have been discussed in great detail in a number of publications. A review of all these results is beyond the scope of this paper, mainly because of limitations in available space. We will concentrate instead on the general properties of the population of eclipsing binaries and infer some general trends. In Section 2., we concentrate specifically on the eclipsing binary pulsars in 47 Tuc; this is done for the sake of completeness, as most of the remaining eclipsing binary systems are discussed elsewhere in this volume.

In Table 1, we include mostly references that concentrate on the timing of the eclipsing pulsars. From these references, one concludes that for the 5 eclipsing binaries with a published timing baseline longer than 4 years (PSR B1957+20 and PSR J2051–0827, Terzan 5 A and 47 Tuc J and O) random variations of the orbital period have invariably been detected.

### 2. Four Eclipsing Binary Systems in 47 Tuc

Of the total of 22 millisecond pulsars (MSPs) in 47 Tuc observed at Parkes, 15 are members of binary systems. Of these, at least 4 are eclipsing: 47 Tuc J, O, R, W and possibly V. There are two other systems with very short orbital periods and very small companion masses that are analogous to 47 Tuc J, except for their even smaller mass functions and the non-detection of eclipses; these are 47 Tuc I and P. The systems with

Table 1. A set of eclipsing binary pulsars and related objects in GCs and in the Galactic disk. Those for which a timing solution is not known are followed by an asterisk; the names could change in the future when that solution is published. 47 Tuc W has a position determined by optical astrometry. Those that are known to eclipse are followed by an “e.” The minimum companion masses ( $m_c$ ) are calculated assuming a pulsar mass of  $1.4 M_\odot$ . References are: rh: Ransom, Hessels, in this volume; dn: David Nice, in this volume; st: Stappers, in this volume; po: Possenti, in this volume; 1: Camilo et al. 2000; 2: Possenti et al. 2003; 3: Lyne et al. 1993; 4: D’Amico et al. 2001, Ferraro et al. 2001; 5: Lyne et al. 2000, Nice et al. 2000; 6: Ransom et al. 2004; 7: Freire et al. 2003; 8: Chandler 2003; 9: D’Amico et al. 2001, Ransom et al. 2001; 10: Deich et al. 1993; 11: Fruchter, Stinebring, & Taylor 1988, Arzoumanian 1995; 12: Stappers et al. 1996, 1998

Pulsar	GC, letter	P(ms)	$P_b$ (days)	$m_c$ ( $M_\odot$ )	Ref.
J0024–7204V*	47 Tuc V (e?)	4.81	$\sim 0.2$	$\sim 0.3$	1
J0024–7204W*	47 Tuc W (e)	2.35	0.133	0.127	1
J1701–3006B	M62 B (e)	3.59	0.145	0.124	2
B1718–19	NGC 6342A (e)	1004	0.258	0.117	3
J1740–5340	NGC 6397A (e)	3.65	1.354	0.188	4,po
J1748–2446A	Terzan 5A (e)	11.56	0.076	0.089	5,dn
J2140–2310A	M30 A (e)	11.02	0.174	0.101	6,rh
J0024–7204I	47 Tuc I	3.48	0.230	0.013	7
J0023–7203J	47 Tuc J (e)	2.10	0.121	0.021	7
J0024–7204O	47 Tuc O (e)	2.64	0.136	0.022	7
J0024–7204P*	47 Tuc P	3.64	0.147	0.018	1
J0024–7204R*	47 Tuc R (e)	3.48	0.066	0.026	1
J1518+0204C*	M5 C (e)	2.48	0.087	0.038	rh
J1701–3006E*	M62 E (e)	3.23	0.16	0.03	8
J1701–3006F*	M62 F	2.30	0.20	0.02	8
J1807–2459A*	NGC 6544 A	3.06	0.071	0.009	9
B1908+00*	NGC 6760 A	3.62	0.141	0.018	10,dn
J1953+1846A*	M71 A (e)	4.89	0.177	0.032	rh
B1957+20	(Galaxy) (e)	1.61	0.382	0.022	11,dn
J2051–0827	(Galaxy) (e)	4.51	0.099	0.027	12,st

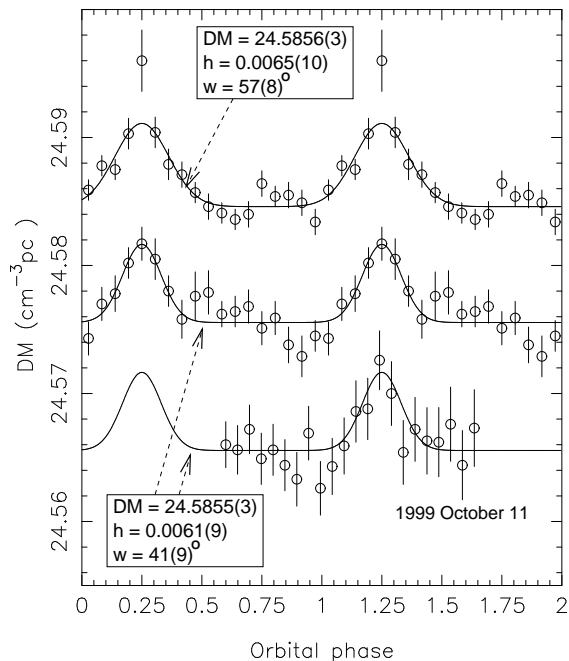


Figure 1. DM as a function of orbital phase ( $\phi = 0$  is the ascending node) for 47 Tuc J. The upper plot represents the values for DM obtained from 1998 January data at 660 MHz and 1400 MHz data obtained from 1998 June to 1999 August. The middle plot represents the measurements made with 1999–2002 high-resolution 1400 MHz data, displayed  $0.01 \text{ cm}^{-3} \text{ pc}$  below their measured values for clarity. The third plot represents the DMs obtained using only the data from the best observation (1999 October 11), displayed  $0.02 \text{ cm}^{-3} \text{ pc}$  below their measured values. The numbers indicate the parameters of the best fit for each data set (see text), which is depicted by the solid curves. From Freire et al. (2003).

known timing solutions (47 Tuc I, J and O) are analyzed in detail in Freire et al. (2003). The remaining systems (47 Tuc P, R, V and W) are briefly described in Camilo et al. (2000).

## 2.1. 47 Tuc J

This system has only been confirmed to eclipse at 430 MHz, at this frequency the pulsar is never detected near superior conjunction. The pulsar is detectable in some 660 MHz observations near superior conjunction, in others it is not. This could be due to occasional eclipses, but it could also be due to scintillation. At 1400 MHz no eclipses are ever detectable. In any case, it is clear that the DM of the pulsar varies with orbital phase, being measurably higher at superior conjunction. The extra electron column density at superior conjunction is  $\sim 1.7 \times 10^{16} \text{ cm}^{-2}$ , which is about 10 times smaller than the extra electron column density observed for PSR J2051–0827 at the same orbital phase (Stappers et al. 2001).

Considering the separation between the pulsar and its companion for inclinations near  $90^\circ$ ,  $a = 1.14 R_\odot$ , and the length of the eclipse at 430 MHz, the radius of the eclipsing object must be larger than  $0.7 R_\odot$ . This implies an average electron density of  $\sim 10^3 \text{ cm}^{-3}$  near the companion. The Roche lobe for the companion is given by Eggleton (1983):

$$R_L = \frac{0.49 a q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}, \quad (1)$$

where  $q = m_c/m_p$  and  $a$  is the separation between the pulsar and the companion. The only source of uncertainty is the inclination of the system. For  $i = 90^\circ$ ,  $m_c = 0.0209 M_\odot$ ,  $q = 0.0155$ ,  $a = 1.14 R_\odot$  and  $R_L = 0.13 R_\odot$ . For  $i = 60^\circ$ ,  $m_c = 0.0241 M_\odot$ ,  $q = 0.0179$ ,  $a = 1.14 R_\odot$  and  $R_L = 0.14 R_\odot$ . Therefore, the Roche Lobe is much smaller than the diameter of the plasma cloud; the matter responsible for the increased DMs is not bound to the companion object. This is a clear indication that the companion is losing mass, it is behaving like a comet. The same is true for the other eclipsing systems discussed in this text.

For 47 Tuc J, we can measure significant orbital evolution:  $\dot{P}_b = (-0.52 \pm 0.13) \times 10^{-12}$  and  $\dot{x} = (-2.7 \pm 0.7) \times 10^{-14}$ . The  $\dot{P}_b$  is much smaller than what was measured for the two Galactic VLMBPs, but this could be due to the small timescale of the observations made to date.

## 2.2. 47 Tuc O

This pulsar is different from 47 Tuc J in the sense that it always displays sharp, well-defined eclipses at 1400 MHz (see Fig. 2). There are no good detections of this pulsar at 660 MHz, the reason for this lack of detections is unknown, the most likely explanation is that this pulsar has an unusually flat spectral index. The pulsar exhibits strong variability of its orbital parameters:  $\dot{P}_b = (9 \pm 1) \times 10^{-12}$ ,  $\ddot{P}_b = (24 \pm 8) \times 10^{-20} \text{ s}^{-1}$ , and  $|\dot{x}| < 1.8 \times 10^{-13}$ . This is comparable in timescale and amplitude with the variations observed for the Galactic eclipsing pulsars, PSR B1957+20 and PSR J2051–0827. It can therefore be said that 47 Tuc J and O are similar to the two eclipsing binaries in all their observational characteristics, which suggests a common origin to these systems.

## 2.3. 47 Tuc R

This is still the known binary pulsar with the shortest orbital period (96 minutes); the minimum companion mass is about  $0.03 M_\odot$ . When first announced in Camilo et al. (2000), only one orbit had been detected; in that orbit the pulsar signal was absent at superior conjunction in a way that is very characteristic of an eclipsing binary. Since then, the pulsar has been regularly detected in the high-resolution 20 cm data, which has allowed us to obtain orbital phase connection (see Figure 3). The pulsar has eclipsed near superior conjunction on all observations where it is detectable.

## 2.4. 47 Tuc W

This binary pulsar has an orbital period of 3.19 hours. Assuming for the pulsar a mass of  $1.35 M_\odot$ , the companion has a minimum mass of  $\sim 0.13 M_\odot$ , which is unusually large when compared to the previously known eclipsing binaries in 47 Tuc. At least in this respect this object is similar to the previously known Terzan 5 A binary system. The two radio eclipses in the single detection reported by Camilo et al. (2000) last for 35-40% of the orbital period. The companion has since been detected at optical wavelengths with the HST based on the coincidence of orbital periods (Edmonds et al. 2002); it is a normal main-sequence (MS) star. Since then the pulsar has been detected several times in the high-resolution Parkes 20 cm data (see Figure 4). The pulsar has eclipsed near superior conjunction on all observations when it is detectable.

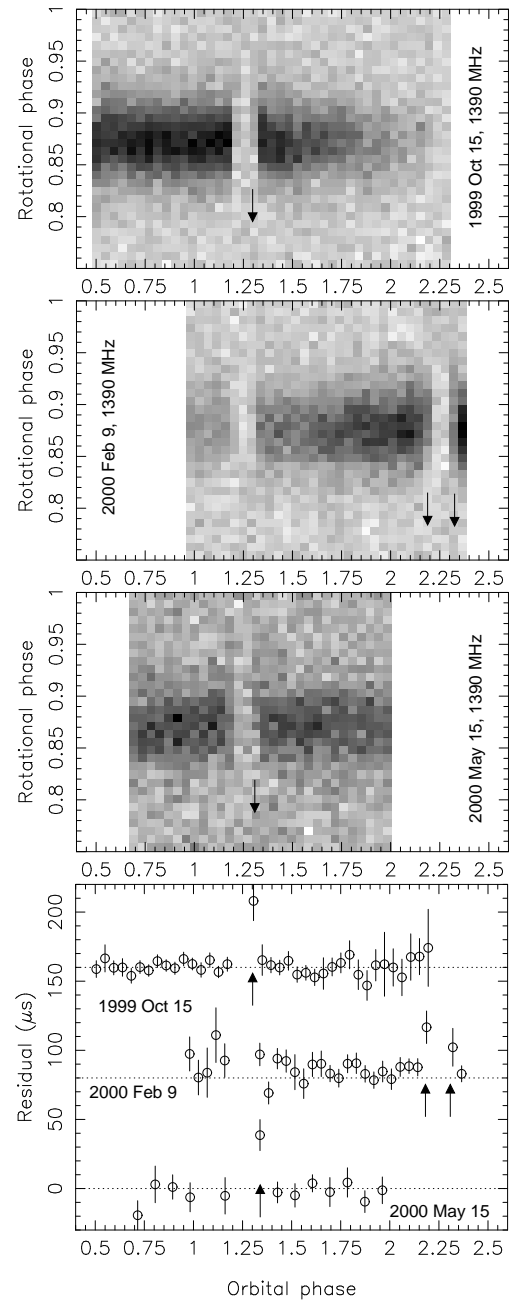


Figure 2. Top plots: Intensity as a function of orbital and rotational phases for three of the best observations of 47 Tuc O. The darkness is linearly proportional to the measured intensity. The residuals for the corresponding TOAs (used to obtain the best fit) are displayed at the bottom. Bottom plot: residuals for the same observations. From Freire et al. (2003).

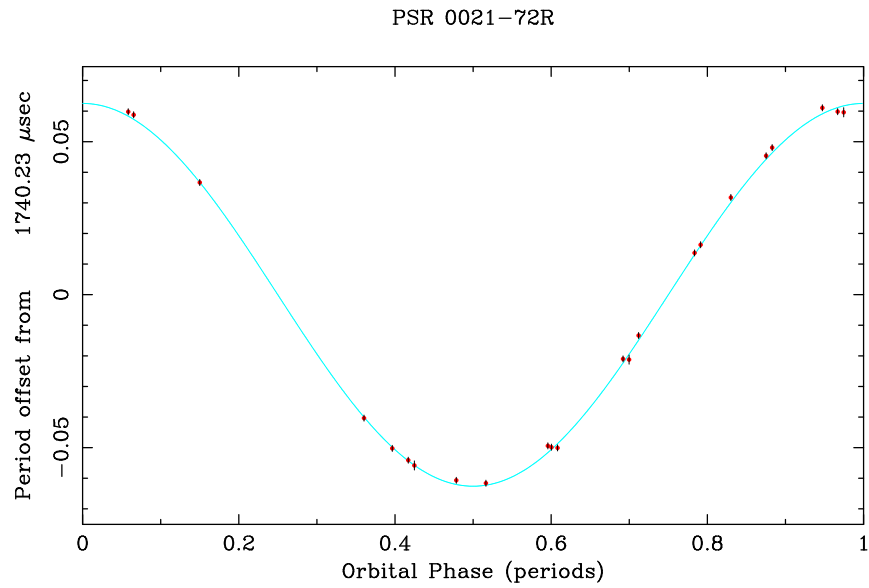


Figure 3. Orbital model for 47 Tuc R. The pulsar has now been detected on 5 different orbits at 1400 MHz. The eclipses never fail to happen.

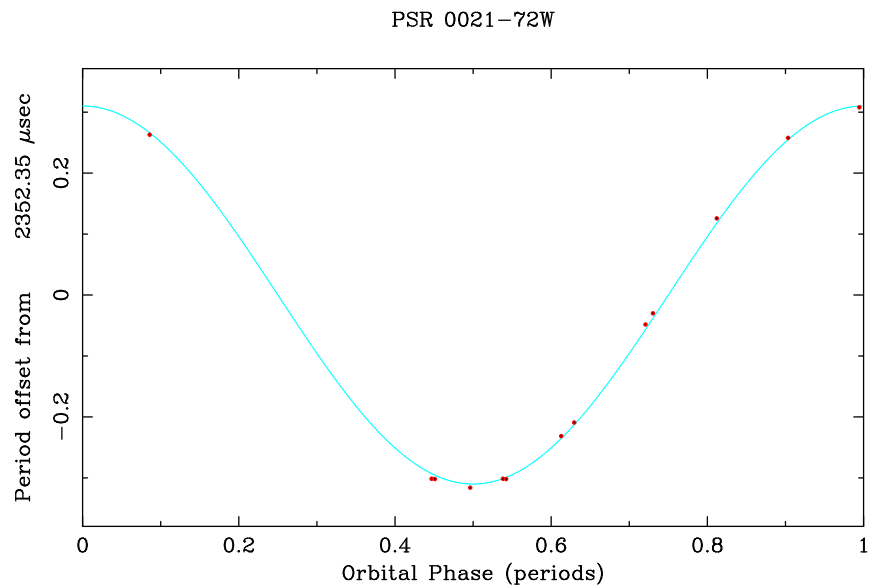


Figure 4. Orbital model for 47 Tuc W. The pulsar has now been detected on 4 different orbits at 1400 MHz. The eclipses last for about 40% of the whole orbit, and never fail to happen.

## 2.5. Short-period binaries with small-mass companions

For 47 Tuc I, the pulsar with the (apparently) lightest companion in 47 Tuc, the 1400-MHz TOAs are well described by a circular orbit, no eclipses are observed for superior conjunction. The number and quality of the TOAs at superior conjunction is the same as at other orbital phases. 47 Tuc P is similar in many respects to PSR B1908+00 in NGC 6760 (Deich et al. 1993; see also David Nice’s paper, these proceedings); during their detections (all at 1400 MHz, of which there is only one for 47 Tuc P) none of these pulsars displayed eclipses.

## 3. Discussion

In Figure 5, we can see that these eclipsing binary systems are divided in two main categories. The first set, consisting of a total of 8 objects, has mass functions below  $3 \times 10^{-5} M_{\odot}$ . These belong to a class of objects that we will henceforth call very low-mass binary pulsars (VLMBPs), also known as “black-widow” binaries. We will use the VLMBP designation regardless of the presence of eclipses. The second class of eclipsing binaries has mass functions above  $3 \times 10^{-4} M_{\odot}$ , they will henceforth be called eclipsing low-mass binary pulsars (ELMBPs). A third class of eclipsing binary pulsars has high-mass MS companions; they have a single known representative, PSR B1259–63. This system is discussed by Johnston et al., in this volume.

### 3.1. Very Low-Mass Binary Pulsars

*Formation* The clear separation in terms of mass function between the LMBPs and the VLMBPs strongly suggests that these binaries form a population that is distinct in its evolutionary history. This is expected from simulations of binary evolution in the GC 47 Tuc (Rasio, Pfahl, & Rappaport 2000), which have suggested that these objects were once normal MSP-WD binaries that underwent further recycling because of orbital decay due to the emission of gravitational waves. Such a scenario is consistent with the observed rotational periods of these objects. PSR B1957+20 has a rotational period of 1.6 ms, the second shortest known. The recently discovered PSR J1953+1846A, in M71, has the longest rotational period of this class, at 4.9 ms. Most of the remaining rotational periods range between 2 and 3 ms. It is therefore fair to say that, as a class, the pulsars in VLMBPs are the most heavily recycled neutron stars known, which supports the idea of more than one prolonged and intense accretion episode.

This formation process should also be active in the Galaxy, as it results from normal stellar evolution. The fact that we find two objects in the disk of the Galaxy (PSR B1957+20 and PSR J2051–0827) similar in all distinguishing features (eclipses and orbital variability) to the VLMBPs in clusters supports this idea. It is likely, however, that exchange encounters in GCs were involved in the formation of the progenitor binary systems; this is necessary to explain the large numbers of these systems in GCs.

*Non-Eclipsing VLMBPs* The VLMBPs with the lowest mass functions do not display eclipses, despite having orbital periods similar to those of the eclipsing VLMBPs. A correlation between small mass function and the lack of eclipses can only be understood if the mass distribution is narrower than what is indicated in Table 1 and the inclination is the main factor determining the observed mass function for these objects: at high inclinations, the system is seen edge-on, eclipses can be seen and the minimum companion mass is near 0.03 to 0.04  $M_{\odot}$ . At lower inclinations, no eclipses can be seen, as we are looking at the system nearly face-on; the mass function is lower by a  $(\sin i)^3$  factor. Being the same sort of object, VLMBPs with no eclipses should exhibit the same kind of orbital variability as those with eclipses. Table 1 shows that, with the exception

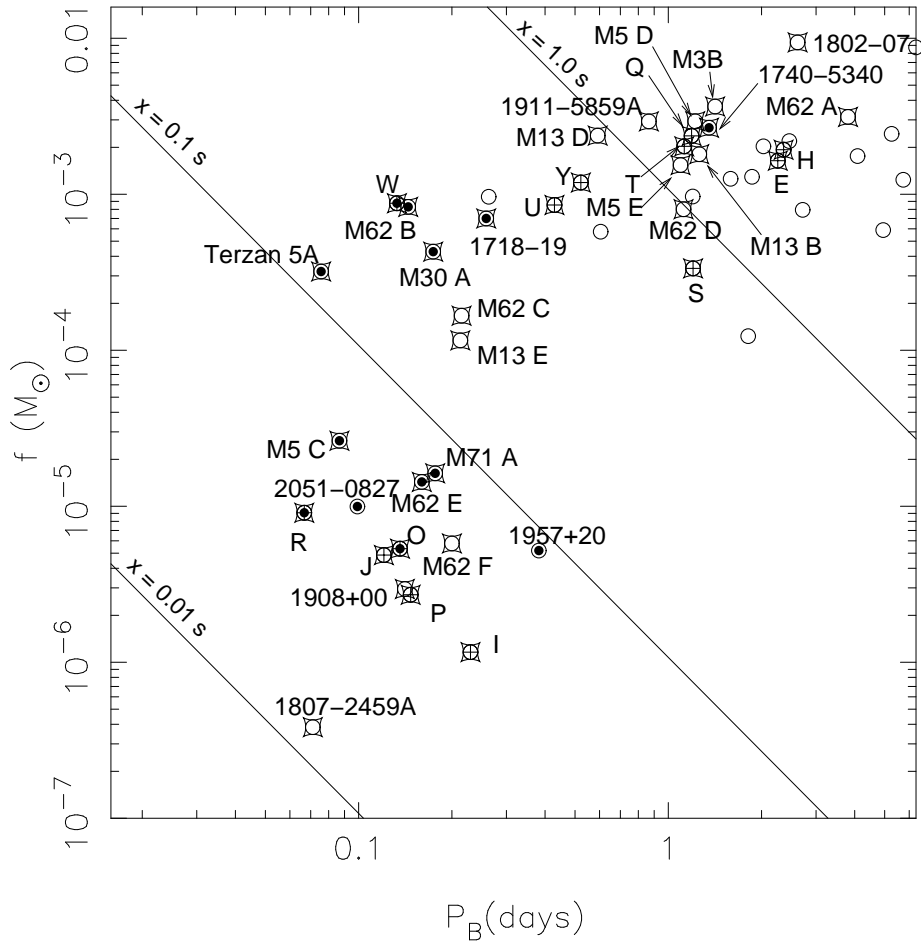


Figure 5. Mass function plotted against orbital period for all the binary pulsars known (circles) within the given range of orbital period and mass function. Those binaries in GCs are indicated inside 4-pointed stars and named; we highlight those in 47 Tuc with a “+” and name them only by their letters. A black dot inside the symbol indicates a binary pulsar that eclipses at 1400 MHz; the two eclipsing Galactic binaries are also named. Binaries with  $f < 3 \times 10^{-5} M_{\odot}$  (VLMBPs) have companions with masses of  $0.01\text{--}0.04 M_{\odot}$ , and generally present shorter orbital periods than the LMBPs ( $f > 10^{-4} M_{\odot}$ ). About two thirds of the VLMBPs display eclipses. The inclined lines indicate constant projected semi-major axis  $x$ .



of 47 Tuc I, none of these systems has published timing solutions. The timing precision for 47 Tuc I is quite low; even if it had the same amount of variability seen in the other systems, the variations of orbital period would not be detectable.

It is possible that the above interpretation of the role of the orbital inclination is incorrect and that companions with a minimum mass of  $\sim 0.01 M_{\odot}$  are fundamentally different in nature than those with  $\sim 0.03 M_{\odot}$ , being for some reason incapable of producing any sizable atmospheres. We find such an explanation unlikely, as the less massive companions must have lower surface gravities and escape velocities; it should be easier, using the same energy input from the pulsar, to create an extended atmosphere around such objects.

### 3.2. Eclipsing Low-Mass Binary Pulsars

There are 6 known ELMBPs. Optical identifications of the companions were made for three systems: PSR J0024–7204W in 47 Tuc (Edmonds et al, 2002), PSR B1718–19 in NGC 6349 (van Kerkwijk et al. 2000) and PSR J1740–5340 in NGC 6397 (Ferraro et al. 2001). See also the articles by Grindlay and by Possenti et al., in this volume. In all cases the companion happens to be a low-mass MS star. It is therefore reasonable to conclude that this is also the case for the three remaining systems, PSR J1748–2446A in Terzan 5, PSR J1701–3006B in M62, and PSR J2140–2310A in M30. In fact, there is a tentative optical identification of the companion of PSR J2140–2310A with a faint, red MS star (Ransom et al. 2004). Interestingly, not one of the non-eclipsing low-mass binary pulsars (henceforth LMBPs) was found to have a MS star as a companion. In all cases for which we have an optical identification (PSR J0024–7203U in 47 Tuc, Edmonds et al. 2001; PSR J1911–5859A in NGC 6752, Bassa et al., in this volume; and PSR B1620–26 in M4, Sigurdsson et al. 2003, and in this volume) the companion turns out to be a low-mass white dwarf (WD), presumably the remnant of the star from which the MSP has accreted and got recycled. LMBPs and ELMBPs are therefore very different kinds of objects.

*Formation* The nature of ELMBPs suggests that these objects were formed through exchange encounters. These only have a reasonable probability of happening in GCs, therefore ELMBPs should only occur in GCs, as observed. This is not the case with LMBPs and VLMBPs, which are also observed in the Galaxy and are therefore the result of normal stellar evolution in binary systems.

In an exchange encounter, when an isolated star or a component of a binary system comes within less than 4 times the separation between the components of a binary system, this is normally followed by strong, unpredictable gravitational interactions. The end result tends to be the formation of a new binary system containing the two most massive objects, and the ejection of the lighter star(s), with a resulting recoil of the newly formed binary system. The tighter the system, the more violent this recoil will be.

Originally, GCs had many massive, blue MS stars. These reached the end of their lives very early in the cluster life, with a large number of supernova explosions. These formed many energetic, young pulsars, these slowed down and died on a timescale much shorter than the age of the cluster. Many remained bound to the cluster, and roam it today as dead neutron stars. Occasionally, exchange encounters place one of these neutron stars into orbit with a MS star; then the evolution of the MS star might lead it to fill its Roche lobe, leading to accretion onto the neutron star. Such systems are observed in the Galactic disk and in GCs as low-mass X-ray binaries, but are far more abundant per unit mass in GCs; in the Galactic disk these systems can only form from primordial binary systems. After accretion stops, these systems become MSP – WD binary pulsars (LMBP), which are also over-abundant in GCs. They can then undergo further exchange encounters.

It happens sometimes in GCs that the neutron star placed in orbit around a MS star through an exchange encounter is a previously recycled pulsar, in some cases a former member of a LMBP (channel I), in others a previously isolated pulsar that intruded into a primordial MS binary system (channel II). These are the systems we observe as ELMBPs. They are very similar to the systems that give origin to LMXBs, but it is not clear that such will be their fate: pulsar wind pressure might prevent accretion onto the neutron star. For a system like PSR B1718–19, with a mildly recycled pulsar with a characteristic age of only a few million years, this will not be a problem after pulsar emission ceases, which should happen in a relatively small amount of time. Such a system is therefore a prime candidate to become an LMXB in less than a Gyr.

*Position Relative to the Center of the Cluster* It is interesting to remark that two of the ELMBPs are found to be at considerable distances from the centers of their GCs. Such are the cases of PSR J1718–19 and PSR J1740–5340. This is suggestive of exchange encounters; we are probably witnessing the effects of stellar recoil. After evolving for a few more hundred Myr, two-body encounters with other stars will gradually reduce the kinetic energy of the system and bring it closer to the center of the GC, as observed for the remaining 4 ELMBPs and most of the other pulsars in GCs. For a system like PSR J1718–19, the characteristic age of the pulsar is smaller than the time it will take for the system to settle at the GC’s core, and it is probable that when that happens this object will no longer be observable as a radio pulsar. Conversely, it is unlikely that one can observe a system like PSR J1718–19 near the center of a GC.

*Rotational Period Distribution* While VLMBPs have a very narrow range of rotational periods, ELMBPs have a very wide distribution of rotational periods. 47 Tuc W has a rotational period of 2.35 ms, while PSR B1718–19 has a rotational period of 1.004 s, the largest rotational period for any known pulsar in a GC. The other rotational periods are 11.6, 11.0, 3.59 and 3.65 ms. This is, again, consistent with the idea of these systems forming through exchange encounters; the present orbital companion and orbital parameters have little relation to the recycling history of the pulsar.

*The Significance of 47 Tuc V* A perplexing feature in Fig. 5 is that, despite their fundamentally different nature, the ELMBPs have the same mass functions as the LMBPs, implying in both cases companion masses of 0.1 to  $0.2 M_{\odot}$ . Such a uniform number is probably not unimaginable for LMBPs, as the stellar evolution process they went through is similar for all systems. However, if ELMBPs were formed in exchange encounters, then the MS stars in their orbits should have the same mass distribution as the MS stars in the parent cluster.

A possible hint to the solution of this problem is the existence of 47 Tuc V, described in Camilo et al. (2000). This pulsar has a rotational period of 4.81 ms. *Assuming* that the orbit is circular, the orbital period is about 5 hours and the companion mass is about  $0.3 M_{\odot}$ . If this model is correct, the pulsar was only observed near inferior conjunction. Even at this orbital phase, the pulsar emission is sharply interrupted and re-started, with timescales of about 5 minutes. This suggests a relatively large MS companion, and the presence of orbiting clouds of material that occult the pulsar even at inferior conjunction. The mere existence of this system and its phenomenology strongly suggest that: (i) Pulsars with MS companions heavier than  $0.3 M_{\odot}$  exist; and (ii) such systems are likely, because of the large size of the star, to be “shrouded” by material from the star. Therefore, the lack of observations of systems with MS companions more massive than  $0.2 M_{\odot}$  might at least in part be due to an adverse selection effect. This shrouding effect should not be so severe for pulsars in wider binary systems. It should be possible to detect pulsars with, say,  $0.7 M_{\odot}$  MS companions if the orbital periods are of the order of a few days, but a detection is probably unlikely if the orbital period is of the order of a few hours. It is possible that pulsars in very tight orbits with relatively massive

MS stars might in their future undergo a common envelope phase, forming something similar to a LMBP or VLMBP.

*Fraction of Recycled Neutron Stars in GCs* Of a total of 80 known pulsars in GCs, the 6 known ELMBPs are the result of exchange encounters that placed the pulsar in orbit around a MS star, i.e., pulsars that became part of a system that could evolve towards a LMXB and later into a LMBP if the pulsar had been a dead neutron star initially. We can think of these 80 pulsars as pre-existing probes of neutron star behavior. If 7.5% of these pulsars suffered an exchange encounter that puts them, for the second time, on a potential recycling path, we can suggest that the same happened to the unseen dead neutron stars, i.e., the *observable* pulsars in GCs (the total number of active pulsars that one would find assuming no limitations in sensitivity) are about 7.5% of the total neutron star population in GCs. This estimate does not take into account effects that would increase the percentage of recycled pulsars compared to this number:

- 7.5% is an under-estimate of the number of ELMBPs due to selection effects against the detection of this kind of objects, including the shrouding effect discussed in the previous paragraph.
- Single, dead neutron stars have been available for exchange interactions for a longer time than the recycled systems, which necessarily formed later.

It does not take into account effects that would diminish this percentage either:

- Dead, neutron stars are generally isolated, so they have no companion to exchange for an isolated MS star. To find a companion, they depend exclusively on the existence of primordial MS–MS binaries.

Making a better allowance for these selection effects and extending the samples through deeper surveys should allow us to derive a better fraction for neutron star recycling in GCs. However, such a number will always be to some extent cluster-dependent, as some are denser and therefore bound to have a higher recycling rate and produce more pulsars. The global figure of 7.5% relates mostly to the GCs actively forming pulsars.

#### 4. Conclusions

We have listed the set of observational properties that lead us to believe that VLMBPs, LMBPs and ELMBPs are different kinds of objects. The first two classes are likely products of stellar evolution in binary systems, and can therefore be observed in GCs as well as in the Galaxy. The second kind is likely the result of exchange encounters, such systems should only be observed in GCs. Many of them are unlikely to be undetectable, because of the effect of shrouding suggested by the existence of 47 Tuc V. The rate of occurrence of such systems in GCs can be used to estimate neutron star recycling for the GCs that produce more pulsars.

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