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Pulsars in Globular Clusters

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Abstract. More than 100 radio pulsars have been detected in 24 globular clusters. The largest observed samples are in Terzan 5 and 47 Tucanae, which together contain 45 pulsars. Accurate timing solutions, including positions in the cluster, are known for many of these pulsars. Here we provide an observational overview of some properties of pulsars in globular clusters, as well as properties of the globular clusters with detected pulsars. The many recent detections also provide a new opportunity to re-examine theoretically the formation and evolution of recycled pulsars in globular clusters. Our brief review considers the most important dynamical interaction and binary evolution processes: collisions, exchange interactions, mass transfer, and common-envelope phases.

1. Introduction

Following the discovery of the first millisecond pulsar (MSP) by Backer et al. (1982) and the wide acceptance of the "recycling" model, connecting low-mass X-ray binaries (LMXBs) to MSPs (Alpar et al. 1982), globular clusters (GCs) became a favorite place to search for MSPs. Indeed, GCs were known to contain surprisingly large numbers of LMXBs (Clark 1975), which should produce MSPs as their accreting neutron stars (NSs) are spun up and recycled into fast radio pulsars. After a flurry of activity, the first pulsar in a globular cluster (the single PSR B1821−24, with period $P = 3\,\mathrm{ms}$) was found in M28 by Lyne et al. (1987).

In the following 17 years much has been learned observationally and theoretically about the population of pulsars in GCs, and we provide here a brief review taking into account the latest detections. Note especially that, after the Aspen conference was held in January 2004, but before this review was completed (several months later), many more GC pulsars were discovered, including the 20 new MSPs detected in Ter 5 by Ransom et al. (2005). We have included these recent discoveries in our review (see Table 1) in order to provide an up-to-date summary.

For other reviews, somewhat dated but still excellent, see Kulkarni & Anderson (1996) and Phinney (1996), both written at a time when the total number of GC pulsars was only about 30!

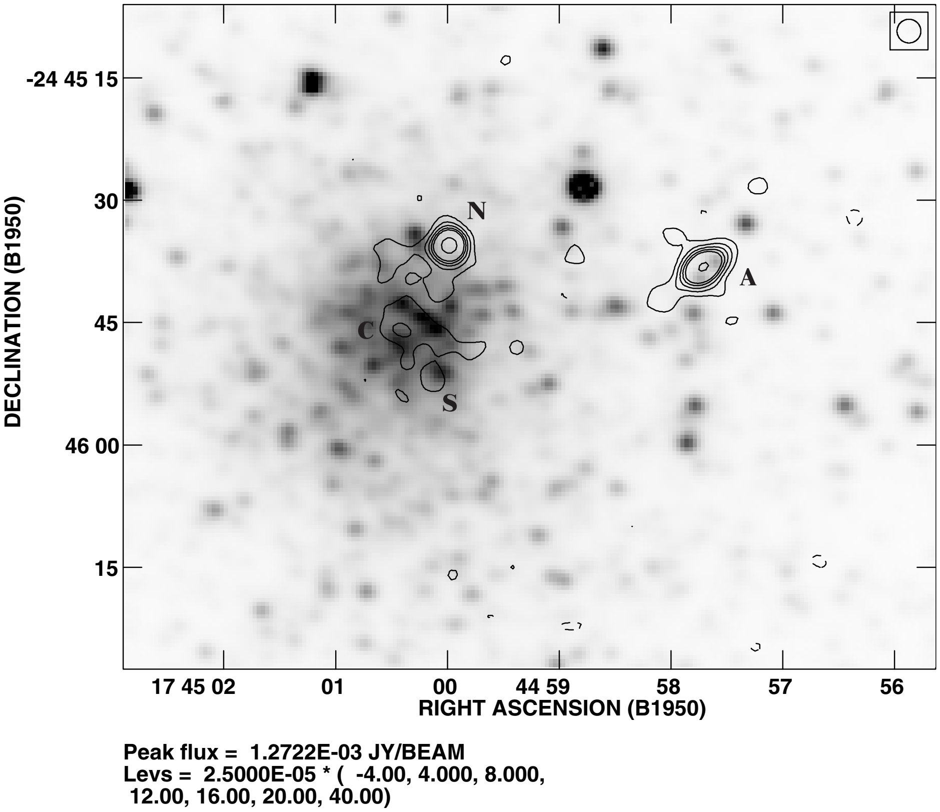

Figure 1. Terzan 5 imaged with the VLA at 20 cm wavelength (Fruchter & Goss 2000), overlaid on an optical I-band image. "A" marks the strong radio emission from PSR J1748–2446A (Ter 5 A), the first pulsar discovered in this globular cluster. Near the cluster core there is substantial diffuse emission with a steep spectrum, possibly originating from unidentified pulsars. The 20 new pulsars recently detected in Ter 5 by Ransom et al. (2005) presumably account for a significant portion of this emission.

2. Searches for Pulsars in Globular Clusters

2.1. Previous Searches

A powerful technique used to determine good GC targets for pulsation searches relies on imaging GCs to find those which contain steep spectrum, possibly polarized, radio sources — i.e., having the properties of pulsars (see Fig. 1). Alternatively, one can proceed straight to searching for pulsations from "all" globular clusters, starting with those that are closest to the Earth or have the smallest predicted dispersion measures (DMs). Once a first pulsar is discovered, the approximate DM for other pulsars in the same GC is known, simplifying considerably the search process. In this manner, about 30 pulsars had been found in 12 GCs by 1992.

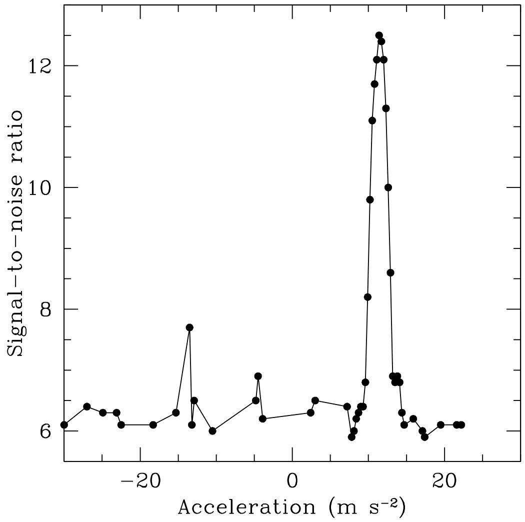

Figure 2. Signal-to-noise ratio vs. trial acceleration for the discovery of 47 Tuc R, a binary MSP with the shortest orbital period known for a pulsar, $P_b = 96$ min. This pulsar was discovered in 17 min sub-integrations at a frequency of 1.4 GHz with the Parkes telescope and would not have been detected without computationally onerous "acceleration searches" (Camilo et al. 2000). It has also only ever been detected on one day, showing the effect of interstellar scintillation on detectability for some pulsars.

Searches resumed in earnest in 1998, using a combination of upgraded/new telescopes, frequencies, spectrometers, and analysis techniques (particularly, widespread "acceleration searches"; see Fig. 2), and, by the end of 2004, about 100 pulsars were known in 24 GCs.

2.2. On-going Searches

Arecibo: Twenty-two GCs within 50 kpc are being searched at 1.4 GHz (see Hessels et al. 2004 and Ransom et al., in this volume).

GBT: Seven GCs were searched at 1.4 GHz by Jacoby et al. (2002), and about 13 more are being done at 1.4 and 2.0 GHz (Ransom et al. 2004, 2005; also in this volume; Hessels et al. 2004).

GMRT: About 10 GCs are being searched with ~ 2 hr integrations at 0.3 GHz (see Freire et al. 2004; also in this volume).

Parkes: In addition to 47 Tuc, with 22 pulsars known, 60 other GCs with predicted DM $\lesssim 300\,\mathrm{cm}^{-3}\,\mathrm{pc}$ are being searched with ~ 2 hr integrations at a frequency of 1.4 GHz, with work on 45 of these essentially complete (see Possenti et al., in this volume).

Collectively, these searches are proving to be very successful. However, as we survey here the properties of the pulsars, and the clusters they reside in, it is important to keep in mind that several selection effects are present:

1. Distance: we only detect the most luminous pulsars from many GCs.
2. DM/P and acceleration: it is more difficult to detect pulsars with larger DM and/or shorter periods, and particularly difficult to detect MSPs in very tight binaries.
3. Data processing: very significant amounts of computing (and people) power are required to analyze the data sets completely — e.g., years after being collected, 47 Tuc data are now being analyzed with greater sensitivity than previously done to pulsars having smaller P and P_b.
4. Propagation effects in the ISM: for some clusters it is necessary to observe often in order to detect weak pulsars on scintillation maxima. The same may be true for some pulsars that display eclipses. For some GCs, multi-path propagation (scattering) may prevent detection of short-period pulsars at relatively low observing frequencies ($\lesssim 1.5\,\mathrm{GHz}$).
5. Pulsar spectra: ideally, multiple observing frequencies should be used.

3. Properties of Pulsars in Globular Clusters

One hundred pulsars with reasonably well-measured parameters are known in 24 GCs as of this writing. Some important parameters of both the GCs and the pulsars are listed in Table 1. An updated table of GC pulsar parameters is maintained online by P. Freire at `http://www.naic.edu/~pfreire/GCpsr.html`.

3.1. Spin Period Distribution

As shown in Fig. 3 (left), the vast majority of pulsars in GCs are MSPs. There are only three slow ("young") pulsars in this set, although these may have a high birth rate (Lyne, Manchester & D'Amico 1996). As shown by the dashed-line histogram in the figure, the 47 Tuc pulsars have a very narrow distribution, and none is known at $P < 2\,\mathrm{ms}$, despite considerable sensitivity down to $P \lesssim 1\,\mathrm{ms}$. By contrast, the distribution of the pulsars known in Ter 5 (shaded histogram) is broader.

3.2. Binary Period Distribution

The binary period distribution for pulsars in GCs is shown in Fig. 3 (right). Fifty of the 100 pulsars known in GCs are represented here. Nine more are in binaries with periods yet to be determined, and it must be remembered that short-period binaries are selected against in pulsation searches. Still, it appears that the fraction of single pulsars in GCs ($\sim 40\%$ observed) is larger than the corresponding fraction of single MSPs in the Galactic disk ($\sim 20\%$).

There are evidently two main populations of pulsars distinguished by orbital period: those with periods of a few hours, and those with $P_b \sim 1$–$2\,\mathrm{d}$ with a tail extending to $\gtrsim 10\,\mathrm{d}$. Two pulsars with $P_b > 100\,\mathrm{d}$ stand out from this trend: PSR B1620−26, a triple system in M4 (e.g., Thorsett et al. 1999; Sigurdsson & Thorsett, in this volume), and PSR B1310+18 in M53 (see §6.3).

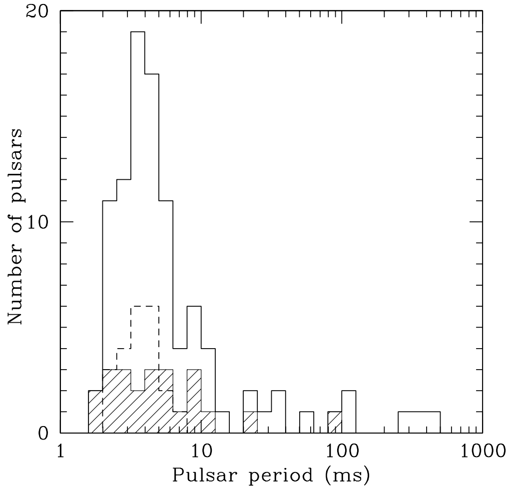

Figure 3. *Left:* Distribution of spin periods for pulsars known in globular clusters. The shaded area represents the 23 pulsars in Ter 5, while the 22 pulsars known in 47 Tuc are shown by the dashed-line histogram. *Right:* The distribution of orbital periods for 50 binary pulsars in globular clusters.

3.3. Pulsar Companions

The two groups selected by binary period correspond roughly to those pulsars, often eclipsing, that have $m_2 \sim 0.03\,M_\odot$ dwarf companions (the short-P_b systems), and those with $\sim 0.2\,M_\odot$ "He white dwarf" (WD) companions (see Fig. 4, left). In most cases these statements are drawn by analogy with the kinds of binary pulsar systems known in the Galactic disk, based on the measured mass function: in few cases do we actually detect the pulsar companions directly, for instance via optical emission. Also, by comparison with the situation in the disk, there is an apparent dearth of massive (CO) WDs among the GC pulsars; the recently discovered Ter 5 N (Ransom et al. 2005; Table 1) could be one such example. In addition to these groups, a very few pulsars have NS companions. Finally, importantly, some GC pulsars have companions with no analogue in the disk: systems that show eclipses and have $m_2 \gtrsim 0.1\,M_\odot$, which we designate here generically as "main sequence" (MS) companions.

In the case of 47 Tuc, the known pulsars are divided roughly into 1/3 isolated, 1/3 with $\sim 0.03\,M_\odot$ companions, 1/3 with $\sim 0.2\,M_\odot$ companions, and one with a $\sim 0.1\,M_\odot$ MS companion, 47 Tuc W (Edmonds et al. 2002).

Eclipses Fig. 4 (left) shows that most of the 14 eclipsing systems known in GCs have $2 \lesssim P_b \lesssim 6$ hr. Half of these have $\sim 0.03\,M_\odot$ companions like the "black widow" eclipsing binaries PSRs B1957+20 and J2051−0827 of the Galactic disk. Interestingly, five otherwise similar systems with $0.01 \lesssim m_{2\,\mathrm{min}} \lesssim 0.02\,M_\odot$ do *not* show eclipses, suggesting that they have companion masses similar to those of the eclipsing binaries, but are viewed in a more face-on geometry. Six other eclipsing binaries are unusual in that their companions are substantially more massive

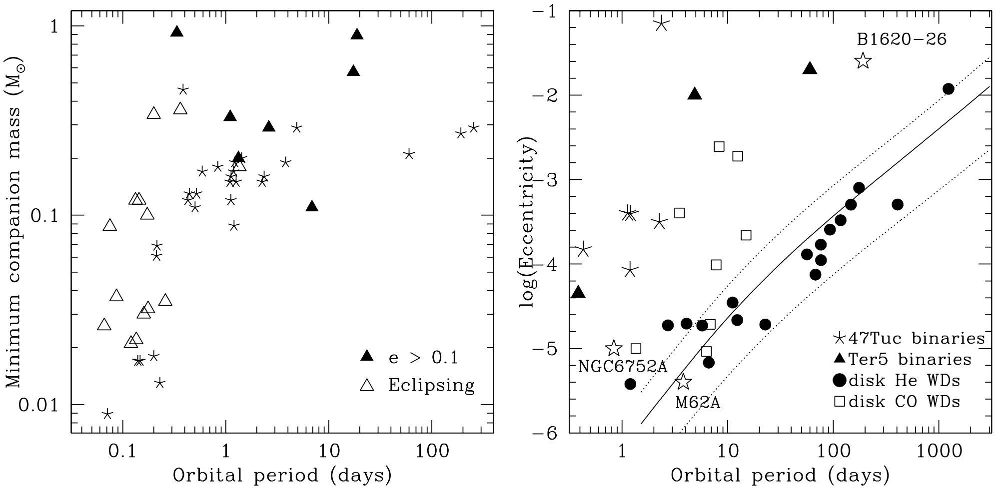

Figure 4. *Left:* Minimum companion mass (derived from the mass function assuming a pulsar mass of $1.35\,M_\odot$ and orbital inclination of $i = 90°$) vs. binary period for pulsars known in globular clusters. Pulsars that are known to eclipse or have eccentricities $e > 0.1$ are indicated. *Right:* Eccentricity vs. orbital period. Field pulsars with low-mass companions that are thought to have formed via stable mass transfer (denoted as having "He WD" companions) follow the prediction of the fluctuation–dissipation model of Phinney (1992), represented by the solid line and 95% confidence level dashed lines. Galactic disk pulsars with more massive CO WD companions do not follow this trend. Most GC pulsars with low-mass companions here (those in 47 Tuc, Ter 5 and M4) also do *not* follow those predictions: their eccentricities are unusually "large" (even when $e \sim 10^{-4}$). We note that the Ter 5 pulsars indicated here have more massive companions than those in 47 Tuc (see Table 1). It is also notable that two of the GC pulsars (in M62 and NGC 6752) *do* have extremely small eccentricities.

($m_2 \gtrsim 0.1\,M_\odot$): Ter 5 A, 47 Tuc W, M62 B, M30 A, and in particular Ter 5 P and 47 Tuc V with $m_2 \gtrsim 0.3\,M_\odot$. One system is further unusual in having a larger orbital period: PSR J1740–5340 in NGC 6397, with $P_b = 1.3$ d, variable eclipses (D'Amico et al. 2001), a $\simeq 0.25\,M_\odot$ (Ferraro et al. 2003) "red straggler" companion showing ellipsoidal optical variations (Orosz & van Kerkwijk 2003), and possibly X-ray variability (Grindlay et al. 2002). See the article by Freire, in this volume, for more on eclipsing pulsars.

Eccentricities Fig. 4 (right) shows the orbital eccentricity of binary pulsars vs. their orbital period. It is clear by comparison with otherwise equivalent pulsars in the Galactic disk that even the "small" eccentricities of most GC binaries are unusually large — a clear sign of stellar interactions either during or post formation (§6). Surprisingly, the eccentricity of the binary M62 A, located near the core of a very dense GC, is extremely small (as is that of NGC 6752 A, which, in contrast, is located well outside the core of its parent GC).

Also in Fig. 4 (left) we indicate seven of the eight known GC pulsar systems having very large eccentricities, $e > 0.1$. These are: M15 C, a NS–NS system likely formed in a 3-body exchange and ejected out of the GC core (Prince et al. 1991; Phinney & Sigurdsson 1991); B1802−07 in NGC 6539 (Thorsett et al. 1993), with perhaps a He WD companion (formed through a collision with a red giant; see §6.2), or even a MS companion; B1516+02B in M5, about which not much is known (not even whether its companion is a WD or a NS; Anderson et al. 1997; see §6.3); J0514−4002 in NGC 1851, a 5 ms pulsar in a 19 d orbit of $e = 0.9$, with a massive companion whose nature is unclear (Freire et al. 2004; also in this volume); J1750−37 in NGC 6441, with a relatively large $P = 111\,\mathrm{ms}$ and $m_2 \gtrsim 0.5\,M_\odot$ (Possenti et al. 2001; also in this volume); and the recently discovered Ter 5 I ($P = 9\,\mathrm{ms}$) and Ter 5 J ($P = 80\,\mathrm{ms}$), each with $P_b \simeq 1\,\mathrm{d}$, $e \simeq 0.4$, and a total system mass of $\simeq 2.2\,M_\odot$, derived from the measured advance of periastron (Ransom et al. 2005; see also §6.2). In addition, M30 B has $e \gtrsim 0.5$ (Table 1).

3.4. Radial Distribution in Clusters

Fig. 5 shows the distribution of pulsar–GC center angular offset, in terms of the GC core radius r_c. The vast majority of pulsars are located at $0.2 < r/r_c < 5$. It should be noted that this is a snapshot in time and that some pulsars are located in eccentric orbits about their cluster centers (§6.3), although the bias of this effect for the population as a whole is likely small.

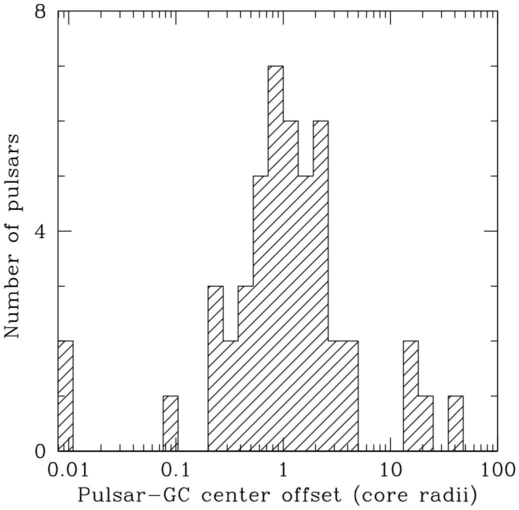

Figure 5. Histogram for 48 pulsar–globular cluster center angular offsets, in units of core radius r_c.

The four exceptions to this high degree of central concentration for the pulsars are: the "unusual" PSR J1740−5340 in NGC 6397; the NS–NS binary M15 C; and two otherwise normal MSPs (one isolated) in NGC 6752 (D'Amico et al. 2002).

We now comment on the case of PSR B1718−19, a very unusual eclipsing pulsar with $P = 1\,\mathrm{s}$, sometimes assumed to be associated with NGC 6342 (Lyne et al. 1993). The main argument against an association is that for this pulsar $r = 46\,r_c$. But, as can be seen from Fig. 5, this would no longer be a uniquely large offset. It is also curious that the metallicity of NGC 6342 is high, much like those of other GCs where slow pulsars are located. See also Bailes et al., in this volume.

4. Cluster Properties

4.1. What Globular Clusters Have Pulsars?

Fig. 6 (left) shows a scatter plot of metallicity vs. central density for 70 GCs (out of about 150 known in the Galaxy) that have been searched at *some* level (many of the searches are not yet complete, and the luminosity limits vary widely). It can be seen from the figure that pulsars are known in GCs with metallicities in a wide range and with $\rho_0 > 10^3\,L_\odot\,\mathrm{pc}^{-3}$.

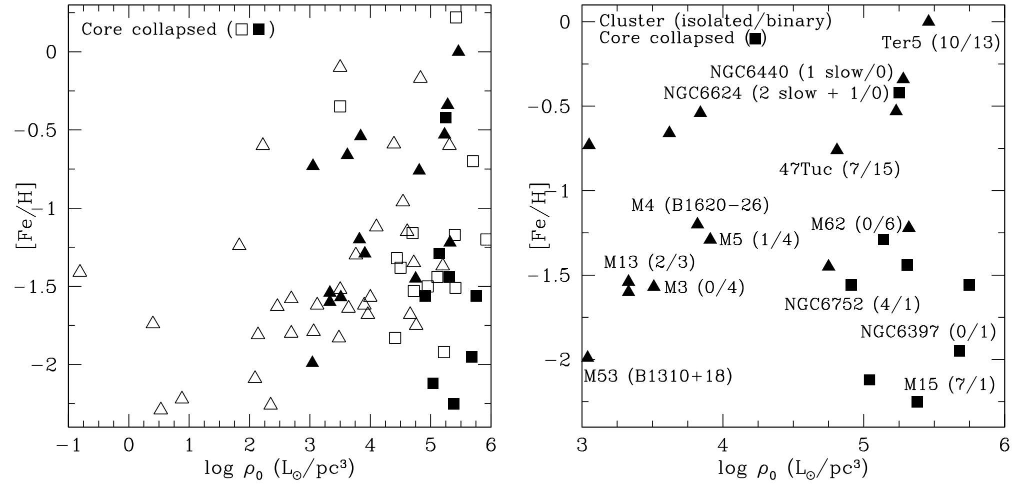

Figure 6. *Left:* Metallicity vs. central density for GCs searched at some level for pulsars. Core-collapsed clusters are indicated (squares), as are those where pulsars have been found (filled symbols). *Right:* A zoom-in on the left panel showing only those clusters having known pulsars. Some particular clusters are also named, with an indication of the number of isolated and binary pulsars known in each.

A word on sensitivity puts Fig. 6 (left) into perspective: at Parkes, in all seven GCs with recent pulsar discoveries, the luminosity at 1400 MHz of the *brightest* pulsar in the GC is within a factor of two of $L_{1400} \approx 12\,\mathrm{mJy\,kpc}^2$. On the other hand, quite often the luminosity *limit* for various Parkes searches is $\gtrsim 10\,\mathrm{mJy\,kpc}^2$. Clearly, non-detection of a pulsar at these luminosity levels need not engender even the thought that pulsars do not exist in such GCs! Searches using the GBT or Arecibo can be more sensitive, as exemplified by the recent discovery with the GBT at a frequency of 2.0 GHz of 20 pulsars in Ter 5 (Ransom et al. 2005; see also Table 1), a cluster previously extensively searched at Parkes.

4.2. Clusters with Pulsars

Fig. 6 (right) shows a scatter plot of the metallicity vs. central density for GCs in which pulsars are known. Although the statistics are poor (and nearly half of all pulsars known reside in either Ter 5 or 47 Tuc), some tentative statements can be made:

- Long orbital period pulsars reside predominantly in low-density GCs.
- Pulsars with large r/r_c are located in high-density GCs.
- Pulsars with "MS" companions are located in high-density GCs.
- Slow pulsars are located in high-metallicity, high-density GCs.
- The binary fraction of pulsars known in a GC does not show any obvious pattern in the ρ_0–[Fe/H] plane.
- LMXBs reside predominantly in very dense GCs, but the pulsars appear more evenly distributed. A key question is *what kind* of LMXBs are progenitors of GC MSPs (see §6).

5. Applications of Pulsars in Globular Clusters

5.1. 47 Tucanae

Radial Distribution All 17 of the 47 Tuc pulsars with a precisely known position are located within $1\overset{\prime}{.}2$ of the center of the cluster, even though the area of the Parkes telescope beam that discovered them is about 100 times larger. The deprojected spatial density is $n_p(r) \propto r^{-2}$, with none at $r \gtrsim 3\,r_c$ (Freire et al. 2001a). While the slope of the density profile is consistent with thermal equilibrium (assuming a dominant stellar species of mass $\sim 1.5\,M_\odot$), the sharp "edge" in the radial extent may not be (Rasio 2000, but see also Heinke et al. 2005). In M15, by contrast, $n_p(r) \propto r^{-3}$, suggesting a dominant species with lower mass $\sim 0.9\,M_\odot$ WDs, possibly resulting from a flat IMF (Phinney 1993; Kulkarni & Anderson 1996).

Intracluster Gas and Accelerations Pulsars located on the "far side" of the GC from our point of view are accelerated toward us/the center of the GC and if this (negative) line-of-sight acceleration a_l/c is greater than the intrinsic (positive) $\dot{P}/P$ of a pulsar, the observed $\dot{P} < 0$. In 47 Tuc we see evidence that the pulsars with $\dot{P} < 0$ also have slightly greater DMs. The most straightforward interpretation of this is that at least the central regions of the GC are permeated by a tenuous plasma: $n_e = (0.067 \pm 0.015)\,\mathrm{cm}^{-3}$. Assuming one proton for every free electron, the mass of this gas is $\sim 0.1\,M_\odot$ within 2.5 pc of the center (Freire et al. 2001b). This is much less than the $\sim 100\,M_\odot$ expected to accumulate in $\sim 10^{7-8}$ yr between passages of the GC through the Galactic disk, and perhaps the pulsars themselves expel most of this gas (Spergel 1991).

Also, a bound placed on a_l for a given pulsar leads to a bound on surface mass density. Together with optical isophotes we can then obtain a bound on mass-to-light ratios. For instance, $M/L(r < 12'') > 1.4\,M_\odot/L_\odot$ in 47 Tuc (Freire et al. 2003).

Luminosity Function and Population It is not straightforward to determine the luminosity function for the pulsars in 47 Tuc because of their large-amplitude scintillations. Nevertheless, with careful averaging of many observations for the stronger pulsars, and with the assumption that on average scintillation affects all pulsars equally, Camilo et al. (2000) obtained an estimate for the average flux density of 14 pulsars. This leads to a luminosity function $d\log N = -d\log L$ (e.g., McConnell et al. 2004). *Assuming* that the minimum luminosity for 47 Tuc MSPs is $L_{1400} \lesssim 0.1\,\mathrm{mJy\,kpc^2}$, as in the disk of the Galaxy, *and* that the luminosity function maintains its form to these low levels, there should be 10 times as many pulsars in the range 0.1–1 $\mathrm{mJy\,kpc^2}$ as there are at 1–10 $\mathrm{mJy\,kpc^2}$ (about 20). This is the source (Camilo et al. 2000) of the oft-quoted estimate for ~ 200 pulsars in 47 Tuc (and does not even take into account a possible undercount due to beaming effects).

However, recent radio and X-ray results seem at variance with such a large population of pulsars. McConnell et al. (2004) tried to detect unresolved radio emission from a large number of very weak pulsars at the center of 47 Tuc (cf. Fig. 1 for Ter 5). Using their limits and the luminosity function inferred for the higher-luminosity objects they conclude that not many more pulsars could exist, perhaps a grand total of 30. From recent *Chandra* observations, Heinke et al. (2005) estimate that no more than 60 pulsars likely exist in 47 Tuc, regardless of radio beaming fractions. Both these very different arguments would suggest, if correct, that we will not detect many more radio pulsars in 47 Tuc than the 22 known at present. Considering the selection effects inherent in the radio searches, however, we suggest that this question has yet to be resolved with more sensitive searches. In the meantime, it seems fair to suppose that there are "only" 30–60 pulsars in 47 Tuc.

5.2. Populations in Other Clusters

Seven GCs are now known to have five or more pulsars. The populations of those in 47 Tuc, M5, M13, M62, and NGC 6752 appear uniform in that they have narrow period distributions, $2 \lesssim P \lesssim 10\,\mathrm{ms}$, while those in Ter 5 and M15 display a much broader range of P (Table 1). For the newly identified large population of pulsars in Ter 5 (Ransom et al. 2005), the luminosity distribution appears consistent with that of 47 Tuc (whether most of the diffuse radio flux shown in Fig. 1 can be accounted for by these pulsars remains to be determined). In any case, as noted before, many surveys have a luminosity limit $L_{1400} \gtrsim 10\,\mathrm{mJy\,kpc^2}$, while the maximum luminosity for pulsars in 18 GCs is $\sim 10\,\mathrm{mJy\,kpc^2}$ (the exceptions are the much brighter PSRs B1310+18, B1745–20, B1820–30A, B1821–24, and Ter 5 A). It seems, therefore, that in many cases at radio wavelengths we are still only probing the tip of the iceberg. For comparison, the total number of pulsars present in the Galactic GC system may range from ~ 1000 (e.g., Heinke et al. 2005) to ~ 10000 (e.g., Kulkarni & Anderson 1996)

Chandra observations provide a very useful complementary picture to the radio band (e.g., Grindlay et al. 2001, 2002; Grindlay, in this volume), especially of those clusters with a small neutral hydrogen absorbing column (since many pulsars are relatively soft X-ray sources). It is now possible to discern in *Chandra* images what must be substantial populations of neutron stars in some clusters (e.g., Pooley et al. 2003) even before we have detected them via pulsations.

5.3. Other Applications

Pulsars allow for a variety of other applications that we cannot discuss in any detail in this short review. Here we mention briefly some of these applications.

Constraining GC Dynamics This has been discussed extensively by Phinney (1992, 1993), but there are many more recent examples. For instance, the M/L in the NGC 6752 core is very high (D'Amico et al. 2002), while that for M62 is "normal" — and an apparent dearth of isolated MSPs in the latter (0 out of 6 total) may hint at the dynamical state of the GC (Possenti et al. 2003). See also the discussion by Lommen et al., in this volume, of the possibility of detecting black hole binaries in GCs through MSP timing.

Other interesting applications should become possible in the near future by measuring (or obtaining useful limits on) proper motions of some pulsars with respect to their GC centers (e.g., Freire et al. 2001a).

Constraining Pulsar Parameters Knowing, from GC properties, the maximum expected acceleration at a cluster center, $a_{l\,\mathrm{max}}$ (Phinney 1993), one can often obtain a useful limit on the intrinsic $\dot{P}_{\mathrm{int}}$ of a pulsar, $(\dot{P}/P)_{\mathrm{int}} < |a_{l\,\mathrm{max}}/c| + (\dot{P}/P)_{\mathrm{obs}}$, and hence on characteristic age $\tau_c = P/2\dot{P}$ and inferred surface dipole magnetic field strength $B \propto (P\dot{P})^{1/2}$. For example, all four of M13's pulsars have $\tau_c \gtrsim 1\,\mathrm{Gyr}$ and $B \lesssim 10^9\,\mathrm{G}$ (Ransom et al., in this volume), and similarly for many of 47 Tuc's pulsars (e.g., Freire et al. 2001a).

Physical Conditions of Pulsars and Companions Through the study of eclipses (e.g., D'Amico et al. 2001), X-ray observations of the pulsars (and possibly of some companions; e.g., Grindlay et al. 2002; Bassa et al. 2004; Grindlay, in this volume), and optical observations of the companions (with five systems now clearly detected; e.g., Edmonds et al. 2001, 2002; Sabbi et al. 2003; Sigurdsson et al. 2003; Bassa et al. 2003; van Kerkwijk et al., in this volume), it is possible to begin characterizing the physical conditions of the pulsars and of their companions. For example, the detection of the WD companion to PSR B1620−26 by *HST* has led to an estimate of the age of the system, with important consequences for the origin of the more distant, planetary companion (Sigurdsson et al. 2003; Sigurdsson & Thorsett, in this volume).

6. Formation and Evolution Processes

6.1. Dynamical Formation Processes

The properties of GC pulsars are quite different from those of the field population. There is a greater proportion of single pulsars in clusters, and the majority of the binaries have very short periods compared to field binary pulsars. Many of these binaries have properties similar to those of the rare eclipsing "black widow" pulsars seen in the Galactic disk population (see the review by Freire, in this volume). These systems have extremely short orbital periods, $P_b \sim 1$–$10\,\mathrm{hr}$, circular orbits, and very low-mass companions, with $m_2 \simeq 0.01$–$0.04\,M_\odot$. Many of the other, "normal" binaries have properties more similar to those of the disk population of low-mass binary pulsars (LMBPs), with nearly-circular orbits, periods $P_b \sim 1$–$2\,\mathrm{d}$ (near the short-period end of the distribution for such binaries in the disk) and WD companions with $m_2 \sin i \simeq 0.2\,M_\odot$ (see Figs. 3 and 4).

The large inferred total population of MSPs in GCs (~ 50 in 47 Tuc alone; see §5.1) and the very high stellar densities in many cluster cores ($\rho_c \sim 10^4$–$10^6\,M_\odot\,\mathrm{pc}^{-3}$) suggest that dynamical interactions must play a dominant role in the formation of these systems. A similar conclusion is reached by considering LMXBs in clusters, which are the likely progenitors of binary MSPs. It was recognized almost 30 years ago that the total number of LMXBs observed in GCs indicates clearly a dynamical origin, with formation rates exceeding those in field populations by several orders of magnitude (Clark 1975). Indeed, the stellar encounter rate in a cluster core is an excellent predictor for the presence of a bright LMXB (Pooley et al. 2003; Jordán et al. 2004).

The types of dynamical interactions involving NSs in GCs can be divided into two categories: *two-body interactions*, which include close tidal encounters and physical collisions, and interactions involving more than two objects, i.e., where at least one is a binary. A particularly important type is an *exchange interaction*, where one of the two binary components is replaced by another star. The other star could be a single NS, which can therefore acquire a binary companion through this process. Alternatively, a previously formed binary MSP, or a binary containing a non-recycled NS, could interact with another star or binary. This can lead to a new companion for a MSP, or for a non-recycled NS, or could release a MSP from a binary, creating a single MSP.

6.2. Two-body Interactions

Tidal Captures Older scenarios based on the formation of binaries by *tidal capture* of low-mass MS stars by NSs (Fabian, Pringle & Rees 1975), followed by accretion and recycling of the NS during a stable mass-transfer phase, have run into many difficulties. First, the formation of a long-lived binary following tidal capture is very unlikely. This is because nonlinearities in the regime relevant to globular clusters lead to significant energy dissipation in the MS star on a timescale shorter than the orbital period after capture, resulting in the rapid expansion of the star and a merger, rather than the formation of a detached binary (Kumar & Goodman 1996; McMillan, Taam & McDermott 1990; Rasio & Shapiro 1991). Moreover, the basic predictions of tidal capture scenarios are at odds with many observations of binaries and pulsars in clusters (Bailyn 1995; Johnston, Kulkarni & Phinney 1992; Shara et al. 1996). It is likely that "tidal-capture binaries" are either never formed, or contribute negligibly to the production of recycled pulsars (see Ivanova et al., in this volume).

The viability of tidal capture scenarios has become less relevant with the realization in the 1990s that globular clusters contain dynamically significant populations of *primordial binaries* (Hut et al. 1992). Dynamical interactions involving hard primordial binaries are now thought to provide the dominant energy production mechanism that allows many globular clusters to remain in thermal equilibrium and avoid core collapse over very long timescales ($\gtrsim 10^{10}$ yr; Gao et al. 1991; McMillan & Hut 1994; Fregeau et al. 2003).

Stellar Collisions Physical *collisions* between stars (including mergers from tidal captures) must be occurring often in dense GC cores. This is particularly true in the presence of primordial binaries, which act as catalysts for collisions (Bacon, Sigurdsson & Davies 1996; Fregeau et al. 2004). The products of collisions between MS stars are directly observable in the form of *blue stragglers*. These are objects that appear as MS stars above the turnoff point in the color–magnitude diagram of a cluster. All observations suggest that they must be formed through mergers of lower-mass MS stars. Some blue straggler masses have been measured directly, confirming that they are more massive than a turnoff star (Shara, Saffer & Livio 1997; Sepinsky et al. 2002). Many observations of radial profiles of blue stragglers also confirm that they are more massive than other stars (and therefore more centrally concentrated, as expected from mass segregation; see, e.g., Guhathakurta et al. 1998; Heinke et al. 2003).

Collisions involving a NS have been studied using 3-D hydrodynamic simulations (Rasio & Shapiro 1991; Davies, Benz & Hills 1992). For a collision with a MS star, the outcome is the complete destruction of the star, and the formation of a thick, rapidly rotating envelope around the NS. The lifetime of this envelope is highly uncertain, and it is not clear that the NS is able to accrete enough material to be recycled to a MSP. If it is, then this is a possible formation process for single MSPs that does not involve the disruption of a binary (Krolik, Meiksin & Joss 1984). In particular, it might explain the large numbers of single, mildly recycled MSPs in clusters with extremely high central densities, such as M15.

Collisions with Red Giants In contrast to NS–MS collisions, collisions of NSs with red giant (RG) stars *always lead to the formation of a binary* (Rasio & Shapiro 1991). This is because the RG core always survives and ends up in a high-eccentricity orbit around the NS. Typically $\sim 30\%$ of the RG envelope is ejected to infinity, while most of the rest becomes bound to the NS. Only about $\sim 0.1\,M_\odot$ remains bound to the RG core, which will eventually cool to a degenerate WD. The material left bound to the NS will attempt to form an accretion disk as it cools. The fate of this material is again highly uncertain. It could be accreted onto the NS and spin it up to millisecond periods (in $\sim 10^6$ yr at the Eddington limit), or it could be ejected, if the energy released by accretion couples well to the gas. With an efficiency ϵ, the entire mass of gas could be ejected to infinity in as little as $\tau_{\rm gas} \sim 10^4\,(\epsilon/0.01)^{-1}$ yr. This short lifetime suggests that (1) the orbit may well remain eccentric (in the absence of an extended gaseous envelope, no tidal circularization is possible); (2) the NS would only get mildly recycled.

Thus RG–NS collisions appear to provide a natural formation process for eccentric LMBPs with WD companions around mildly recycled pulsars, such as NGC 6539 A or Ter 5 J (Rasio & Shapiro 1991; Thorsett et al. 1993; Ransom et al. 2005). Systems with higher-mass companions, fast MSPs, and very high eccentricities, such as NGC 1851 A (Freire et al. 2004; also in this volume), are more likely the result of exchange interactions (§6.3), i.e., the presently observed companion was likely acquired later and is not the donor from which the NS was recycled. A circularized binary MSP can also be perturbed to a higher eccentricity by a passing star in a flyby (§6.3).

Note that the eccentric LMBPs found in clusters must all be formed through dynamical processes, as there is no primordial binary evolution channel that can produce an eccentric binary with a recycled pulsar and a low-mass companion (cf. article by Kalogera et al., in this volume: the eccentric binaries considered there all contain a *young* pulsar).

Ultracompact Binaries from Collisions The RG–NS collisions may also play an important role in the formation of *ultracompact X-ray binaries* (UCXBs) in clusters. These are persistent, bright LMXBs ($L_x \sim 10^{36}$–$10^{39}\,\mathrm{erg\,s^{-1}}$) where the NS is accreting from a low-mass, degenerate companion in a very tight orbit of period $P_b \lesssim 1\,\mathrm{hr}$. UCXBs may well be dominant among the bright LMXBs observed in old globular clusters, both Galactic (Deutsch, Margon & Anderson 2000; van der Sluys, Verbunt & Pols 2004) and extragalactic (Bildsten & Deloye 2004). They must connect in a fundamental way to NS recycling, as suggested by the fact that three out of five accretion-powered millisecond X-ray pulsars known in our Galaxy are UCXBs (Chakrabarty, in this volume). In addition, UCXBs may well be the progenitors of the many black-widow MSPs with very low-mass companions observed in GCs (Rasio, Pfahl & Rappaport 2000 and §6.3 below).

Several possible dynamical formation processes for UCXBs have been discussed in the literature. Exchange interactions between NSs and primordial binaries provide a natural way of forming possible progenitors of UCXBs (Davies & Hansen 1998; Rasio et al. 2000; §6.3). This may well dominate the formation rate when integrated over the entire GC dynamical history. However, it is unlikely to be significant for bright UCXBs observed *today* in clusters. This is because the progenitors must be intermediate-mass binaries, with the NS companion massive enough for the initial mass transfer to become dynamically unstable, leading to common-envelope (CE) evolution and significant orbital decay. Instead, all MS stars remaining today in an old GC (with masses below the turn-off mass $m_{\rm to} \simeq 0.8\,M_\odot$) have masses low enough to lead to *stable* mass transfer (and orbits that expand during mass transfer, leading to LMXBs with wide periods and non-degenerate donors). Alternatively, some binaries with stable mass transfer could evolve to ultra-short periods under the influence of magnetic braking (Pylyser & Savonije 1988; Podsiadlowski, Rappaport & Pfahl 2002). However, producing UCXBs through this type of evolution requires very careful tuning of initial conditions, and it is therefore very unlikely to explain most sources in GCs (van der Sluys et al. 2004).

Verbunt (1987) first proposed that RG–NS collisions could lead to UCXB formation. In the original scenario, the collision was assumed to lead directly to a CE system in which the NS and RG core would quickly inspiral. However, RG–NS collisions that occur now in old globular clusters (where RGs have low masses, close to $m_{\rm to}$) do *not* lead to CE evolution. Instead, as noted above, the RG envelope is promptly disrupted, leaving behind an eccentric NS–WD binary (Rasio & Shapiro 1991). Nevertheless, if the post-collision NS–WD binaries can retain their high eccentricities, then many of these systems could decay through gravitational-wave emission all the way to contact and still become UCXBs (Davies et al. 1992; Ivanova et al. 2005).

6.3. Interactions with Binaries

Binary Flybys As noted in §3.3, the eccentricity of a binary can be perturbed significantly during a close flyby of another object in the cluster. Secular perturbations of the eccentricity scale as a power-law in the distance of closest approach, and can therefore be significant even in fairly distant interactions (Heggie & Rasio 1996). In contrast, semi-major axis (energy) perturbations decay *exponentially* with distance of closest approach (Heggie 1975). Since the intrinsic eccentricities of tidally circularized binary MSPs can be extremely small (down to $\lesssim 10^{-6}$ for Galactic disk binaries; see right panel of Fig. 4), the currently measured eccentricities of LMBPs in clusters provide a sensitive record of past dynamical interactions (Phinney 1992; Rasio & Heggie 1995).

However, inducing a significant eccentricity (say $e > 0.1$) in an initially circular binary requires a very close flyby, because there is no perturbation to the eccentricity of an initially circular orbit to lowest order in secular perturbations (Heggie & Rasio 1996). As a consequence, the most likely result from a flyby is a nonzero but small eccentricity ($e \lesssim 0.1$) for an otherwise usual LMBP with a reasonably wide orbit ($P_b \gtrsim 1\,\mathrm{d}$). For example, the ~ 0.1 eccentricity of M5 B ($P_b \simeq 7\,\mathrm{d}$) is entirely consistent with having been induced by close interactions with passing stars in the cluster (Rasio & Heggie 1995). It is likely that many binaries with $e \sim 10^{-5}$–10^{-1} appearing well above the theoretical eccentricity–period relation in Fig. 4 (right) have been similarly perturbed through flybys.

Exchange Interactions Single NSs retained in a dense GC can easily acquire binary companions through *exchange interactions* with primordial binaries. Because of its large cross section, this process tends to dominate over two-body interactions, at least for sufficiently high binary fractions (Heggie, Hut & McMillan 1996; Leonard 1989; Sigurdsson & Phinney 1993).

In contrast to tidal capture, exchange interactions with hard primordial binaries (with semi-major axes $a \sim 0.1$–$1\,\mathrm{AU}$) can form naturally the wide LMBPs seen in some low-density globular clusters (such as PSR B1310+18, with $P_b = 256\,\mathrm{d}$, in M53, which has the lowest central density, $\rho_c \sim 10^3\,M_\odot\,\mathrm{pc}^{-3}$, of any globular cluster with detected radio pulsars; see right panel of Fig. 6). When the newly acquired companion star, of mass $\lesssim 1\,M_\odot$, evolves up the giant branch, the orbit circularizes and a period of *stable* mass transfer begins, during which the NS is recycled (see, e.g., Rappaport et al. 1995). The resulting MSP–WD binaries have orbital periods in the range $P_b \sim 1$–$10^3\,\mathrm{d}$ (see Willems & Kolb, in this volume). Very wide binaries formed in this way will interact again easily, possibly releasing the NS as a single MSP.

However, this scenario cannot explain the formation of recycled pulsars in binaries with periods shorter than $\sim 1\,\mathrm{d}$. To obtain such short periods, the initial primordial binary must be extremely hard, with $a \lesssim 0.01\,\mathrm{AU}$, but then the recoil velocity of the system following the exchange interaction would almost certainly exceed the escape speed from the shallow cluster potential (e.g., $v_e \simeq 60\,\mathrm{km\,s}^{-1}$ for 47 Tuc).

Intermediate-Mass Binaries One can get around this problem by considering more carefully the stability of mass transfer in binaries formed through exchange interactions. While all MS stars in the cluster *today* have masses $\lesssim 1\,M_\odot$, the rate of exchange interactions should have peaked at a time when significantly more massive MS stars were still present. Indeed, the NSs and the most massive primordial binaries will undergo mass segregation and concentrate in the cluster core on a timescale comparable to the initial half-mass relaxation time t_{rh}. For typical dense globular clusters, we expect $t_{rh} \sim 10^9$ yr, which is comparable to the MS lifetime of a ~ 2–$3\,M_\odot$ star. The exchange interactions will then lead to the formation of *intermediate-mass binaries* (Davies & Hansen 1998). Among LMBPs in the Galactic disk, at least one system (PSR J2051−0827) is likely to have had an intermediate-mass binary progenitor, given its very low transverse velocity (Stappers et al. 1998).

If the majority of NSs in a cluster core acquired MS companions with masses up to $\sim 3\,M_\odot$, a very different type of evolution could result. Indeed, in this case, when the MS companion evolves and fills its Roche lobe, the mass transfer for many systems (depending on the mass ratio and evolutionary state of the donor star) is *dynamically unstable* and leads to a CE phase (see, e.g., Taam & Sandquist 2000). The emerging binary will have a low-mass WD in a short-period, circular orbit around the NS. Some of these tight NS–WD binaries will decay to contact through gravitational wave emission, forming UCXBs, and, ultimately, black-widow pulsars (Rasio et al. 2000).

Simple Monte Carlo simulations of this process can produce a variety of short-period binaries with properties that agree well with those of observed MSPs in 47 Tuc (Rasio 2003). The results also predict the existence of a large number of binary MSPs with companion masses $m_2 \simeq 0.03$–$0.05\,M_\odot$ and orbital periods as short as ~ 15 min (descendants of UCXBs) that may have so far escaped detection. Future observations using more sophisticated acceleration-search techniques or shorter integration times may be able to detect them.

Multiple Interactions Exchange interactions can also involve previously formed LMBPs. With the MSP liberated from the binary in which it was formed, this provides the simplest mechanism for producing single MSPs in clusters (and explaining their higher incidence in GCs than in the field). In addition, exchange interactions can lead to the replacement of the original MSP companion by a new, unexpected companion. The resulting orbit can be highly eccentric, and the system can be ejected from the cluster core so that, if the interaction was recent enough (compared to the relaxation time near the new orbit's apocenter), the system may now be observed with an unusually large offset from the center. The most exotic products might be NS–NS systems, such as M15 C (Phinney & Sigurdsson 1991), or MSP–black hole binaries (Sigurdsson 2003). More commonly, the new companion would be a MS star, explaining systems such as PSR J1740−5340 in the outskirts of NGC 6397. If this MS star later evolves and attempts (a second episode of) mass transfer onto the MSP, unusual binary evolution may ensue, with the MSP wind preventing accretion onto the NS, and all mass from the companion leaving the system (Nelson, in this volume). This type of evolution has been proposed as a way of forming some of the black-widow binaries (King, Davies & Beer 2003).

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Table 1. Parameters for 100 pulsars known in 24 globular clusters.

Pulsar	P (ms)	$\dot{P}$ (10^{-20})	r (r_c)	P_b (d)	x (s)	e	m_2 ($M_\odot$)	Ref
47 Tuc (r_c=0.40, r_h=2.79, c=2.03, ρ_0=4.81, t_c=7.96, t_h=9.48, [Fe/H]=–0.76, R=4.5)								
J0023−7204C	5.756	−4.98	3.02					1
J0024−7204D	5.357	−0.34	1.70					1
J0024−7205E	3.536	+9.85	1.62	2.256	1.981	0.000315	0.15	1
J0024−7204F	2.623	+6.45	0.47					1
J0024−7204G	4.040	−4.21	0.72					1
J0024−7204H	3.210	−0.18	1.92	2.357	2.152	0.07056	0.16	1
J0024−7204I	3.484	−4.58	0.72	0.229	0.038	< 0.0004	0.013	1
J0023−7203J	2.100	−0.97	2.50	0.120^e	0.040	< 0.00004	0.021	1
J0024−7204L	4.346	−12.2	0.35					1
J0023−7205M	3.676	−3.84	2.62					1
J0024−7204N	3.053	−2.18	1.22					1
J0024−7204O	2.643	+3.03	0.01	0.135^e	0.045	< 0.00016	0.022	1
P	3.643			0.147	0.038		0.017	2
J0024−7204Q	4.033	+3.40	2.45	1.189	1.462	0.00008	0.17	1
R	3.480			0.066^e	0.033		0.026	2
J0024−7204S	2.830	−12.0	0.47	1.201	0.766	0.00039	0.088	1
J0024−7204T	7.588	+29.3	0.85	1.126	1.338	0.0004	0.16	1
J0024−7203U	4.342	+9.52	2.35	0.429	0.526	0.00014	0.12	1
V	4.810			0.2^e	0.8		0.34	2
J0024−7204W	2.352		0.20	0.133^e	0.243		0.12	3
X	4.771			?				4
Y	2.196			0.521	0.671		0.13	4
NGC 1851 (r_c=0.06, r_h=0.52, c=2.32, ρ_0=5.32, t_c=6.98, t_h=8.85, [Fe/H]=–1.22, R=12.1)								
J0514−4002	4.990		1.72	18.785	36	0.88	0.89	5
M53 (r_c=0.36, r_h=1.11, c=1.78, ρ_0=3.05, t_c=8.76, t_h=9.66, [Fe/H]=–1.99, R=17.8)								
B1310+18	33.163			255	84	< 0.01	0.29	6
M3 (r_c=0.55, r_h=1.12, c=1.84, ρ_0=3.51, t_c=8.84, t_h=9.35, [Fe/H]=–1.57, R=10.4)								
A	2.545			?				7
B	2.389			1.42	1.9		0.20	7
C	2.166			?				7
D	5.443			?				7
M5 (r_c=0.42, r_h=2.11, c=1.83, ρ_0=3.91, t_c=8.26, t_h=9.53, [Fe/H]=–1.27, R=7.5)								
B1516+02A	5.553	+4.12	1.19					8
B1516+02B	7.946	−0.3	0.71	6.858	3.048	0.1378	0.11	8
C	2.484			0.087^e	0.057		0.037	7
D	2.988			1.22	1.6		0.19	7
E	3.182			1.10	1.2		0.15	7
M4 (r_c=0.83, r_h=3.65, c=1.59, ρ_0=3.82, t_c=7.57, t_h=8.82, [Fe/H]=–1.20, R=2.2)								
B1620−26	11.075	−5.46	0.92	191.442	64.809	0.025315	0.27	9
M13 (r_c=0.78, r_h=1.49, c=1.51, ρ_0=3.33, t_c=8.80, t_h=9.30, [Fe/H]=–1.54, R=7.7)								
B1639+36A	10.377	< 4.5						6
B1639+36B	3.528			1.259	1.38	< 0.001	0.15	10
C	3.722							7
D	3.118			0.591	0.92		0.17	7
E	2.487			0.213	0.17		0.061	7

Table 1. (continued).

Pulsar	P (ms)	$\dot{P}$ (10^{-20})	r (r_c)	P_b (d)	x (s)	e	m_2 ($M_\odot$)	Ref
M62 (r_c=0.18, r_h=1.23, c=1.70c, ρ_0=5.14, t_c=7.64, t_h=9.19, [Fe/H]=–1.29, R=6.9)								
J1701−3006A	5.241	−13.19	1.77	3.805	3.483	< 0.000004	0.19	11
J1701−3006B	3.593	−34.97	0.01	0.144^e	0.252	< 0.00007	0.12	11
J1701−3006C	3.806	−3.18	0.97	0.215	0.192	< 0.00006	0.069	11
D	3.418			1.12	0.98		0.12	12
E	3.234			0.16^e	0.07		0.030	12
F	2.295			0.20	0.05		0.018	12
NGC 6342 (r_c=0.05, r_h=0.88, c=2.50c, ρ_0=4.77, t_c=6.09, t_h=8.66, [Fe/H]=–0.65, R=8.6)								
B1718−19*	1004.03	+150000	46.0	0.258^e	0.352	< 0.005	0.11	13
NGC 6397 (r_c=0.05, r_h=2.33, c=2.50c, ρ_0=5.68, t_c=4.90, t_h=8.46, [Fe/H]=–1.95, R=2.3)								
J1740−5340	3.650	+16	18.3	1.354^e	1.652	< 0.0001	0.18	14
NGC 6440 (r_c=0.13, r_h=0.58, c=1.70, ρ_0=5.28, t_c=7.54, t_h=8.76, [Fe/H]=–0.34, R=8.4)								
B1745−20	288.602	+40000	0.76					15
Terzan 5 (r_c=0.18, r_h=0.83, c=1.87, ρ_0=5.06, t_c=8.16, t_h=8.97, [Fe/H]=0.00, R=10.3)								
J1748−2446A	11.563	−3.4	2.77	0.075^e	0.119	< 0.0012	0.087	16
J1748−2446C	8.436	−60	0.94					16
D	4.713							17
E	2.197			60.06	23.6	∼0.02	0.21	17
F	5.540							17
G	21.671							17
H	4.925							17
I	9.570			1.328	1.818	0.428	0.20	17
J	80.337			1.102	2.454	0.350	0.33	17
K	2.969							17
L	2.244							17
M	3.569			0.443	0.596		0.13	17
N	8.666			0.385	1.619	0.000045	0.46	17
O	1.676			0.259^e	0.112		0.035	17
P	1.728			0.362^e	1.272		0.36	17
Q	2.812			>1?				17
R	5.028							17
S	6.116							17
T	7.084							17
U	3.289			>1?				17
V	2.072			0.503	0.567		0.11	17
W	4.205			4.877	5.869	0.015	0.29	17
X	2.999			>1?				17
NGC 6441 (r_c=0.11, r_h=0.64, c=1.85, ρ_0=5.25, t_c=7.77, t_h=9.19, [Fe/H]=–0.53, R=11.7)								
J1750−37	111.609			17.3	24.4	0.71	0.57	18
NGC 6539 (r_c=0.54, r_h=1.67, c=1.60, ρ_0=3.62, t_c=8.60, t_h=9.37, [Fe/H]=–0.66, R=8.4)								
B1802−07	23.100	+47	0.46	2.616	3.920	0.212	0.29	19
NGC 6522 (r_c=0.05, r_h=1.04, c=2.50c, ρ_0=5.31, t_c=6.32, t_h=8.90, [Fe/H]=–1.44, R=7.8)								
J1803−30	7.101							18
NGC 6544 (r_c=0.05, r_h=1.77, c=1.63c, ρ_0=5.73, t_c=5.09, t_h=8.40, [Fe/H]=–1.56, R=2.7)								
A	3.059			0.071	0.012		0.0089	20
B	4.186			?				12

Table 1. (continued).

Pulsar	P (ms)	$\dot{P}$ (10^{-20})	r (r_c)	P_b (d)	x (s)	e	m_2 ($M_\odot$)	Ref
NGC 6624 (r_c=0.06, r_h=0.82, c=2.50c, ρ_0=5.25, t_c=6.61, t_h=8.73, [Fe/H]=–0.44, R=7.9)								
B1820−30A	5.440	+338	0.83					21
B1820−30B	378.596	+3150	3.83					21
C	405.9							12
M28 (r_c=0.24, r_h=1.56, c=1.67, ρ_0=4.73, t_c=7.58, t_h=9.04, [Fe/H]=–1.45, R=5.6)								
B1821−24	3.054	+161	0.09					22
NGC 6749 (r_c=0.77, r_h=1.10, c=0.83, ρ_0=3.33, t_c=8.90, t_h=8.79, [Fe/H]=–1.60, R=7.9)								
A	3.193							7
B	4.968							7
NGC 6752 (r_c=0.17, r_h=2.34, c=2.50c, ρ_0=4.91, t_c=6.83, t_h=9.01, [Fe/H]=–1.56, R=4.0)								
J1911−5958A	3.266	+0.30	37.5	0.837	1.206	< 0.00001	0.18	23
J1910−5959B	8.357	−79	0.58					23
J1911−6000C	5.277	+0.2	15.8					23
J1910−5959D	9.035	+96	1.11					23
J1910−5959E	4.571	−43	0.76					23
NGC 6760 (r_c=0.33, r_h=2.18, c=1.59, ρ_0=3.84, t_c=7.94, t_h=9.39, [Fe/H]=–0.52, R=7.4)								
J1911+0102A	3.618	−0.65	1.27	0.140	0.037	< 0.00013	0.017	24
J1911+0101B	5.384	−0.2	0.36					24
M71 (r_c=0.63, r_h=1.65, c=1.15, ρ_0=3.04, t_c=7.65, t_h=8.43, [Fe/H]=–0.73, R=4.0)								
A	4.888			0.176^e	0.078		0.032	7
M15 (r_c=0.07, r_h=1.06, c=2.50c, ρ_0=5.38, t_c=7.02, t_h=9.35, [Fe/H]=–2.26, R=10.3)								
B2127+11A	110.664	−2107	0.25					10
B2127+11B	56.133	+956	1.12					10
B2127+11C	30.529	+499	13.4	0.335	2.518	0.681	0.92	10
B2127+11D	4.802	−107	0.27					10
B2127+11E	4.651	+17	1.92					10
B2127+11F	4.027	+3	3.98					10
B2127+11G	37.660	+195	1.51					10
B2127+11H	6.743	+2	0.54					10
M30 (r_c=0.06, r_h=1.15, c=2.50c, ρ_0=5.04, t_c=6.38, t_h=8.95, [Fe/H]=–2.12, R=8.0)								
A	11.019	−5.18	1.11	0.173^e	0.234	< 0.00012	0.10	25
B	13.0			>0.8	> 0.1	> 0.52		25

Cluster parameters (Harris 1996): r_c (core radius in arcmin), r_h (half-mass radius in arcmin), $c = \log(r_t/r_c)$ (central concentration where r_t is tidal radius and a "c" denotes core-collapsed cluster), ρ_0 (log of central luminosity density in $L_\odot\,\mathrm{pc}^{-3}$), t_c (log of core relaxation time in yr), t_h (log of relaxation time at r_h in yr), [Fe/H] (metallicity), R (distance from Sun in kpc).

Pulsar parameters: P (period); where measured, observed period derivative ($\dot{P}$) and angular positional offset from GC center (r); for binaries: P_b (orbital period; binaries with uncertain P_b are indicated by "?"; ^{e} indicates radio eclipses), x (projected semi-major axis light travel time), e (eccentricity), m_2 (minimum companion mass assuming a pulsar mass $m_1 = 1.35\,M_\odot$).

* Membership in NGC 6342 for PSR B1718–19 is not certain (see §3.4).

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