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Pulsars and Millisecond Pulsars V: Observational Census of Globular Cluster and Field Pulsars

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Abstract

This fifth paper of a series on pulsars and millisecond pulsars (MSPs) looks at the observational side of the problem. We review the facilities that detect pulsars in different wavebands and the catalogues that collect their parameters, and we compare the pulsars of globular clusters (GCs) with those of the Galactic field (GF), using version 2.9.0 of the ATNF Pulsar Catalogue and the list of 372 GC pulsars in 46 clusters maintained by P. Freire. MSPs make up 94% of the GC pulsars and 15% of the GF pulsars, and GCs host 36% of the MSPs known in the Milky Way. Binary MSPs in GCs have shorter orbits than those in the GF, with median orbital periods of 1.1 and 4.8 days, and are more often eccentric, 16% against 5% with $e > 0.1$. The isolated fraction of GC MSPs is 86% in core-collapsed clusters and 42% in the others. The spin periods of the two populations differ only when the comparison is restricted to fully recycled MSPs, and 45% of the GC MSPs with a measured period derivative show a negative value, so that fields and ages derived from them are biased. We relate these results to the seven evolutionary scenarios of this series and to current simulations, and end with nine observational benchmarks for cluster models that follow pulsars.

Keywords: *Pulsars, Millisecond Pulsars, Globular Clusters, Galactic Field, Pulsar Catalogues, Pulsar Surveys, N-body simulations.*

1. Introduction

Radio pulsars are rotating, magnetised neutron stars (NSs). Millisecond pulsars (MSPs) are the subset whose rotation was accelerated to periods of a few milliseconds by matter and angular momentum transferred from a binary companion, a process known as recycling (Alpar et al., 1982, Bhattacharya & van den Heuvel, 1991, Radhakrishnan & Srinivasan, 1982). Shortly after the first MSPs were found in the Galactic disc, PSR B1821−24 was discovered in the globular cluster (GC) M28 (Lyne et al., 1987), and GCs have since become one of the richest hunting grounds for these objects. The reason is dynamical. In a dense core, an NS can capture a companion, exchange into an existing binary, have its orbit hardened by passing stars, or lose its companion altogether, so that binaries able to recycle an NS form far more often per unit stellar mass than in the Galactic field (GF) (Phinney, 1992, Sigurdsson & Phinney, 1995, Verbunt & Freire, 2014).

This paper belongs to a series on the formation and evolution of pulsars and MSPs. The first paper reviewed the observational progress and statistics of the known population and listed the main open questions (Rah et al., 2024). The second described the physical processes that change the spin and magnetic field of an NS and organised the possible histories into seven evolutionary scenarios (Rah et al., 2025a). The third followed compact objects in the direct N-body code NBODY6++GPU (Wang et al., 2015) and identified where a pulsar treatment can be attached (Rah et al., 2025b). An earlier study modelled the orbital and spin evolution of the double pulsar PSR J0737−3039 from birth to coalescence (Liu et al., 2021).

A pulsar model inside a cluster simulation is only useful if its output can be confronted with real pulsars, and the observational side has changed quickly. Lee et al. (2023) showed that MSPs in GCs and in the GF differ in several measurable properties. Such differences are expected because the two populations follow different evolutionary tracks: in the GF the binary that recycles an NS is nearly always the one in which it was born, while in a GC the same NS may change partners several times before it is spun up. Here we review

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the observing facilities and catalogues (Sect. 2), describe the sample and method (Sect. 3), compare the GC and GF populations (Sect. 4), summarise the observational signature of each scenario (Sect. 5) and the simulations that address them (Sect. 6), and close with benchmarks that a cluster simulation with pulsars should reproduce (Sect. 7).

2. Observing facilities and pulsar catalogues

Radio. Nearly all GC pulsars were found at radio wavelengths, and the growth of the sample follows the arrival of new large telescopes. The 305 m Arecibo telescope timed pulsars in northern clusters such as M15, where a 110 ms pulsar shows a negative period derivative imposed by the cluster potential (Wolszczan et al., 1989). The 100 m Green Bank Telescope (GBT) found 21 MSPs in Terzan 5 in a single survey (Ransom et al., 2005) and soon after the fastest spinning pulsar known, at 716 Hz (Hessels et al., 2006); long-term timing there has mapped where the mass of the cluster is concentrated (Prager et al., 2017) and now spans 34 yr for the redback Terzan 5A (Rosenthal et al., 2025). The 64 m Parkes (Murriyang) telescope has measured proper motions, accelerations and jerks for the pulsars of 47 Tucanae (Freire et al., 2017) and found the first MSPs in ω Centauri (Dai et al., 2020). The upgraded Giant Metrewave Radio Telescope (uGMRT) timed the eccentric binary NGC 1851A (Ridolfi et al., 2019) and runs the GC GMRT Pulsar Search (Das et al., 2026). Among the most productive instruments of recent years are the Five hundred meter Aperture Spherical radio Telescope (FAST), whose first GC survey reported 24 pulsars in 15 clusters (Pan et al., 2021), and MeerKAT, whose TRAPUM (Transients and Pulsars with MeerKAT) programme found, among others, 13 new pulsars in NGC 1851 (Ridolfi et al., 2022) and ten in Terzan 5 (Padmanabh et al., 2024), and showed that PSR J0514−4002E orbits a compact object in the mass gap between NSs and black holes (Barr et al., 2024). The prospects with the Square Kilometre Array Observatory are discussed by Bagchi et al. (2025).

High energies, optical and gravitational waves. The link between accretion and recycling became direct when the Rossi X-ray Timing Explorer detected 2.49 ms pulsations from SAX J1808.4−3658, the first accreting millisecond X-ray pulsar (AMXP) (Wijnands & van der Klis, 1998). Chandra resolves the crowded GC cores and Zhao & Heinke (2022) compiled X-ray luminosities of 68 GC MSPs and upper limits for 107 more. The Fermi Large Area Telescope detects pulsed gamma rays from young pulsars and MSPs; its third pulsar catalogue (3PC) contains 294 pulsars (Smith et al., 2023). Combining such data, Lee et al. (2023) found that GC MSPs rotate more slowly, that their binaries show no correlation between orbital and spin period, and that their surface fields may be stronger, while the X-ray luminosity and hardness distributions are similar; they attribute the differences mainly to dynamical interactions, with a possible contribution from observational bias. The Hubble Space Telescope identifies companions and their cooling ages, as for the young white dwarf (WD) orbiting PSR J1835−3259B in NGC 6652 (Chen et al., 2023). Gravitational-wave (GW) detectors now see the end points of compact binaries with NSs, such as the two coalescences of an NS with a black hole (NSBH), GW200105 and GW200115 (Abbott et al., 2021).

Catalogues. The parameters of known pulsars are collected in the Australia Telescope National Facility (ATNF) Pulsar Catalogue (Manchester et al., 2005), maintained online in numbered versions with spin and binary parameters, associations, discovery year, and detections in other wavebands. GC pulsars are followed in more detail, and often earlier, in the list maintained by P. Freire[1], which also records discoveries announced before publication. Magnetars are collected in the McGill Magnetar Catalog (Olausen & Kaspi, 2014), gamma-ray pulsars in 3PC, X-ray MSPs in GCs by Zhao & Heinke (2022), and cluster parameters, including the core-collapse classification, in the catalogue of Harris (1996) (2010 edition).

3. Data and method

We use ATNF version 2.9.0 (4503 pulsars, retrieved on 29 October 2026) and the Freire list in its update of 11 October 2026. The GC sample consists of all 372 pulsars from that list, in 46 clusters, including 60 announced but not yet published; the list is more complete than the catalogue, which associates 272 pulsars with GCs. The GF sample consists of the ATNF pulsars with a measured spin period that are associated neither with a GC nor with the Magellanic Clouds, after removing PSR J1641+3627H, which the catalogue leaves unassociated but the Freire list places in M13; this leaves 4108 pulsars. Their 24 magnetars (type

[1] https://www3.mpifr-bonn.mpg.de/staff/pfreire/GCpsr.html

AXP in the catalogue) are shown in the figures but left out of the statistics, which therefore refer to 4084 GF pulsars. We call pulsars with $P < 30$ ms MSPs and the others normal pulsars. A GF pulsar is counted as binary when the catalogue gives an orbital period P_b and as isolated otherwise; for GC pulsars the status is taken from the Freire list, where 50 pulsars without a timing solution have unknown status. Minimum companion masses follow from the mass function for a pulsar mass of $1.35\,\mathrm{M}_\odot$ and an inclination of 90°.

For a positive period derivative $\dot{P}$ we compute the surface dipole field and the characteristic age,

$$B \simeq 3.2 \times 10^{19} \left(P\dot{P}\right)^{1/2}\ \mathrm{G}, \qquad \tau_\mathrm{c} = \frac{P}{2\dot{P}}, \tag{1}$$

with P in seconds (Lorimer & Kramer, 2004), and as the boundary of radio emission, we adopt the death line $B/P^2 = 0.17 \times 10^{12}\,\mathrm{G\,s^{-2}}$ (Bhattacharya & van den Heuvel, 1991), which is $\dot{P}_\mathrm{death} = 2.8 \times 10^{-17} P^3$. In a GC the measured $\dot{P}$ also contains the line-of-sight acceleration a_ℓ in the cluster potential and the Shklovskii term of a pulsar with proper motion μ at a distance d (Phinney, 1992),

$$\left(\frac{\dot{P}}{P}\right)_\mathrm{obs} = \left(\frac{\dot{P}}{P}\right)_\mathrm{int} + \frac{a_\ell}{c} + \frac{\mu^2 d}{c}. \tag{2}$$

For MSPs the acceleration term is often comparable to or larger than the intrinsic one, and even the 110 ms pulsar in M15 has a negative $\dot{P}$ (Wolszczan et al., 1989); conversely, the accelerations are used to probe the cluster potential (Freire et al., 2017, Prager et al., 2017). The ATNF value corrected for the Shklovskii term does not remove the cluster acceleration, so we use observed values in both samples. We therefore compare P, P_b, the eccentricity e, the minimum companion mass, and the binary fraction directly, and treat B and τ_c of GC pulsars as apparent values. Distributions are compared with the two-sample Kolmogorov–Smirnov (KS) test, and the P_b–P relation with Spearman's rank coefficient ρ. All numbers below were computed from the catalogue files with a single script.

4. The census revisited

Growth and composition. Paper I presented statistics of the known GC and GF pulsars (Rah et al., 2024); here we update them. Of the 4476 ATNF pulsars with a discovery year, 1957 (44%) were published in 2016 or later (Fig. 1a). In GCs the growth is faster: 181 of the 312 published GC pulsars appeared in 2016 or later, and 60 more await publication. Terzan 5 (49 pulsars), 47 Tucanae (42), NGC 6517 (21) and ω Centauri (19) hold 35% of the population. MSPs make up 348 of the 372 GC pulsars (94%) but only 612 of the 4084 GF pulsars (15%), so that GCs host 348 of the 960 MSPs known in the Milky Way (36%). Table 1 compares the four groups.

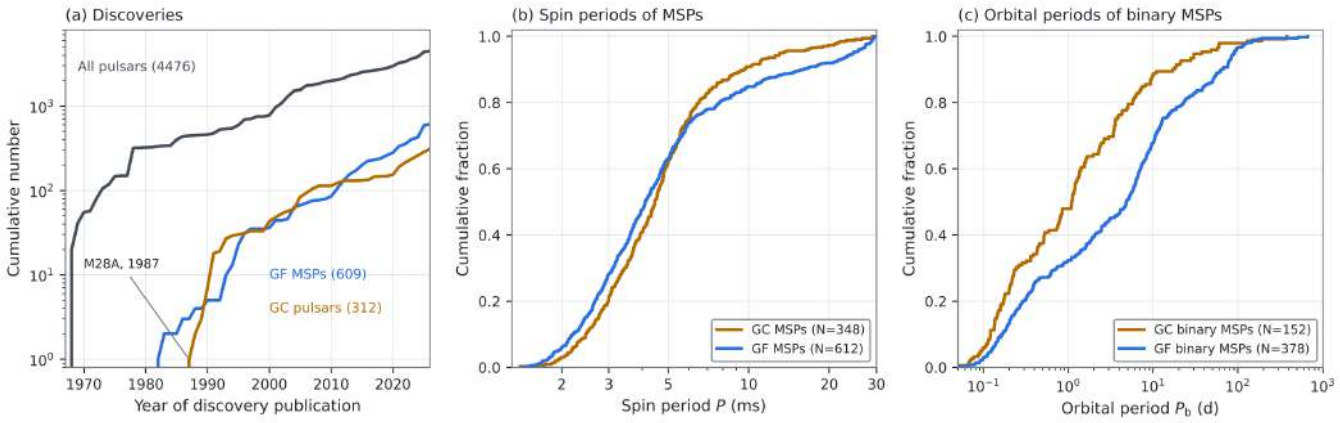


Figure 1: Census of GC and GF pulsars. (a) Cumulative number of pulsars by year of discovery publication: all pulsars in ATNF 2.9.0, GF MSPs, and GC pulsars from the Freire list, dated by the first reference given there (the 60 unpublished GC pulsars are not included). (b) Cumulative distributions of the spin period of GC and GF MSPs. (c) Cumulative distributions of the orbital period of binary MSPs.

Spin periods. The spin distributions of GC and GF MSPs are close (Fig. 1b), and the KS test does not separate them ($D = 0.08$, $p = 0.10$). The slower spins reported by Lee et al. (2023) appear for fully recycled pulsars: for $P < 10$ ms the medians are 4.26 and 3.71 ms ($p = 3 \times 10^{-3}$). The GF has a larger

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Table 1: GC pulsars (Freire list, 11 Oct 2026) and GF pulsars (ATNF 2.9.0, magnetars excluded). GF pulsars without an orbital period are counted as isolated; isolated fractions are over pulsars of known status and eccentric fractions over binaries with a measured e. Fields use positive observed $\dot{P}$ only and are apparent values for GC pulsars.

	GC MSPs	GF MSPs	GC normal	GF normal
Number	348	612	24	3472
Isolated / binary / unknown	147 / 152 / 49	234 / 378 / 0	14 / 9 / 1	3395 / 77 / 0
Isolated fraction	0.49	0.38	0.61	0.98
Median P (ms)	4.45	4.11	108	634
Shortest P (ms)	1.396 (Terzan 5ad)	1.414 (J0952−0607)	30.5	30.1
Median P_b (d)	1.10	4.83	10.9	18.8
Longest P_b (d)	378	669	466	17000
$e > 0.1$	24 of 152 (16%)	12 of 252 (5%)	5 of 9	25 of 67
Median minimum M_c ($\mathrm{M}_\odot$)	0.15	0.19	0.38	0.79
$\dot{P} > 0$ / $\dot{P} \leq 0$	109 / 89	355 / 4	18 / 1	2390 / 4
Median B for $\dot{P} > 0$ (G)	6.2×10^8	2.2×10^8	5.8×10^{10}	1.1×10^{12}

tail of mildly recycled pulsars with $10 \leq P < 30$ ms, 15% of its MSPs against 9% in GCs, and this tail decides the result. The fastest pulsars of the two environments rotate at almost the same rate, Terzan 5ad at 1.396 ms (Hessels et al., 2006) and PSR J0952−0607 at 1.414 ms (Bassa et al., 2017).

Orbits. Binary MSPs in GCs have much shorter orbits (Fig. 1c; $D = 0.30$, $p = 4 \times 10^{-9}$), and eccentric orbits are three times more common. In contrast with Lee et al. (2023), the present sample shows a positive correlation between P_b and P for GC binary MSPs ($\rho = 0.32$, $p = 7 \times 10^{-5}$, 152 systems), of similar strength to that of the GF ($\rho = 0.28$, $p = 3 \times 10^{-8}$, 378 systems). The correlation in GCs remains when the sample is limited to $P < 20$ ms, the MSP definition of Lee et al. (2023) ($\rho = 0.29$, $p = 4 \times 10^{-4}$, 148 systems), to minimum companion masses below $0.45\,\mathrm{M}_\odot$ ($\rho = 0.30$) or to orbits with $e \leq 0.1$ ($\rho = 0.29$), each with $p \leq 1.1 \times 10^{-3}$, so it does not depend on the sample definition.

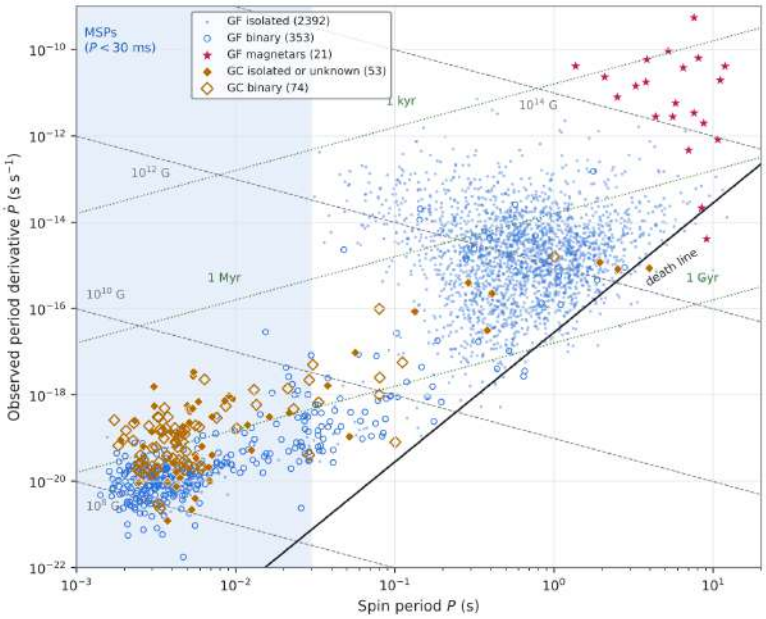


Figure 2: Observed P–$\dot{P}$ diagram of GC pulsars (Freire list) and GF pulsars (ATNF 2.9.0). Only positive $\dot{P}$ are shown; the 90 GC pulsars with $\dot{P} \leq 0$ are omitted, and 21 of the 24 magnetars are shown. Legend numbers give the pulsars shown. Dashed lines: constant B (Eq. 1); dotted lines: constant τ_c; solid line: death line; shaded band: $P < 30$ ms. GC values include the cluster acceleration (Eq. 2).

Isolated MSPs. The excess of isolated MSPs in GCs comes from the core-collapsed clusters of Harris (1996): in the ten such clusters that host pulsars, 44 of 51 MSPs (86%) are isolated, compared to 103 of 248 (42%) in the other 36. This is the dependence on the encounter rate per binary found by Verbunt & Freire (2014), now with a much larger sample.

Period derivatives. Of the 198 GC MSPs with a published $\dot{P}$, 89 (45%) have $\dot{P} \leq 0$, against 4 of 359 in the GF (Fig. 2), the most direct measure of how strongly the cluster potential shapes the observed values. The median apparent field of GC MSPs with $\dot{P} > 0$ is 2.9 times the GF median, in the direction of the indication of Lee et al. (2023), but with negative values discarded and an unknown acceleration term

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in the rest this ratio is biased and is not a measurement of intrinsic fields. Eight GC normal pulsars have apparent $B > 10^{11}$ G and τ_c between 10 and 190 Myr; seven are in the core-collapsed clusters NGC 6342, NGC 6624, M15 and. Terzan 1 and one is in NGC 6440. These are the apparently young pulsars discussed by Boyles et al. (2011) and Kremer et al. (2023).

5. Observational signatures of the seven scenarios

Table 2 lists the seven evolutionary scenarios of Paper II (Rah et al., 2025a), under the names used there, with the observations that test each of them most directly in GCs, the GF counterpart, and the population models that follow them. The scenario of a pulsar in a wide binary without Roche lobe overflow (RLOF) is constrained in GCs mainly by an absence: wide binaries are soft in a dense core and are disrupted by encounters (Sigurdsson & Phinney, 1995). In GCs, the isolated MSP after companion disruption and MSP formation via dynamical interactions leave the signatures that are rare in the GF: eccentric binary MSPs (Freire, 2009) and a high isolated fraction in clusters where encounters are frequent.

Table 2: The seven evolutionary scenarios of Paper II, named as in that paper, with their main signature in GCs, the GF counterpart, and the population models that follow them. Census values are from Sect. 4.

Scenario (Paper II)	Signature in GCs	GF counterpart	Models
Isolated Pulsar Formation and Evolution	Apparently young slow pulsars (Boyles et al., 2011, Kremer et al., 2023); census: 8 with $B > 10^{11}$ G, 7 in core-collapsed GCs	Bulk of the normal pulsars; census: 98% isolated	(Song et al., 2025, Ye et al., 2019)
Isolated MSP After Companion Disruption	Isolated fraction rises with encounter rate per binary (Verbunt & Freire, 2014); census: 86% in core-collapsed, 42% in other GCs	Census: 38% of MSPs isolated	(Ye et al., 2024)
MSP Formation via Accretion in a Binary System	Redback Terzan 5A (Rosenthal et al., 2025); young WD companion of PSR J1835−3259B (Chen et al., 2023)	AMXP SAX J1808.4−3658 (Wijnands & van der Klis, 1998)	(Chattopadhyay et al., 2020, Song et al., 2025, Ye et al., 2019)
MSP Formation via Dynamical Interactions in Globular Clusters	Eccentric binary MSPs (Freire, 2009); census: median P_b 1.10 d, 16% with $e > 0.1$	Census: median P_b 4.83 d, 5% with $e > 0.1$	(Song et al., 2025, Ye et al., 2019, 2024)
Pulsar in a Wide Binary Without Roche Lobe Overflow	Very wide orbits absent; census: longest P_b 466 d (M71B)	PSR J0210+5845, $P_b = 17000$ d, main-sequence companion	Not followed separately
NS-NS Merger Leading to MSP or Black Hole	M15C (PSR B2127+11C), a DNS with measured masses, $P_b = 0.34$ d, $e = 0.68$ (Jacoby et al., 2006); NGC 1851A, a possible MSP + NS system (Ridolfi et al., 2019); census: 5 binaries with an NS companion in ATNF	25 in ATNF; double pulsar PSR J0737−3039 (Liu et al., 2021)	(Chattopadhyay et al., 2020)
NS-BH Merger and Removal	PSR J0514−4002E, mass-gap companion (Barr et al., 2024)	GW200105, GW200115 (Abbott et al., 2021); radio pulsars with BH companions predicted, none confirmed	(Chattopadhyay et al., 2021)

6. Current simulations of pulsars in clusters

Population models now follow the spin and magnetic field of each NS together with the dynamics of its host. With the Cluster Monte Carlo code (CMC), Ye et al. (2019) modelled MSPs in GCs together with their black hole populations, and Ye et al. (2024) followed the formation of single MSPs through dynamical interactions. Direct N-body models with NBODY6++GPU reach a million stars (Wang et al., 2015, 2016) with updated single and binary stellar evolution (Kamlah et al., 2022), and Song et al. (2025) added pulsar spin-down and spin-up by accretion to NBODY6++GPU and applied it to a model of M71. In the GF, population synthesis with the COMPAS code has predicted the radio and GW properties of DNSs (Chattopadhyay et al., 2020) and NSBH binaries, with 50 to 2000 pulsars with black hole companions expected in the Milky Way (Chattopadhyay et al., 2021). In this series, the seven scenarios of Paper II (Rah et al., 2025a) and the integration points of Paper III (Rah et al., 2025b) are being turned into a pulsar module for NBODY6++GPU, whose development version is public.[2] Whatever the method, a model has to produce a population that can be placed next to the catalogue as in Sect. 4.

[2] https://github.com/Maria-Rah/pulsar-subroutine-testing

7. Conclusions and observational benchmarks

More GC pulsars have been published in the last ten years than in the three decades before. The GC and GF populations differ clearly in their orbits, in the frequency of eccentric and isolated MSPs, and in the sign of the observed $\dot{P}$, while their spin periods differ only for fully recycled pulsars. We summarise the results as benchmarks for cluster simulations with pulsars (ATNF 2.9.0; Freire list of 11 October 2026):

1) MSP fraction: 94% of GC pulsars against 15% in the GF; GCs host 36% of the known Galactic MSPs.
2) Spin periods: medians 4.45 and 4.11 ms (GC, GF) for $P < 30$ ms, not distinguished by the KS test; 4.26 against 3.71 ms for $P < 10$ ms ($p = 3 \times 10^{-3}$).
3) Orbital periods of binary MSPs: medians 1.10 and 4.83 d; longest 378 and 669 d.
4) Eccentricity: $e > 0.1$ in 16% of GC binary MSPs against 5% in the GF.
5) Isolated MSPs: 49% in GCs, 86% in core-collapsed and 42% in other clusters, against 38% in the GF.
6) Companions: median minimum companion masses of 0.15 and 0.19 $M_\odot$; one mass-gap companion in a GC (Barr et al., 2024).
7) Apparently young pulsars: eight in GCs, seven of them in core-collapsed clusters.
8) Period derivatives: 45% of GC MSPs with a measured $\dot{P}$ have $\dot{P} \leq 0$, so model values must include the cluster acceleration before they are compared with observed $\dot{P}$, B or τ_c.
9) Orbit and spin: P_b and P of binary MSPs are positively correlated in both environments ($\rho = 0.32$ and 0.28 for $P < 30$ ms; 0.29 and 0.33 for $P < 20$ ms).

Benchmarks 1 to 6 and 9 use only P, P_b, e and the mass function, which are free of the acceleration problem and are the most robust targets. The next step in this series is to place the output of the NBODY6++GPU pulsar module next to these numbers.

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