

# Formation of Binary Pulsars in Globular Clusters

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**Abstract.** Close to 70 radio pulsars have now been discovered in 23 globular clusters, with a record 22 pulsars observed in 47 Tuc alone. Accurate timing solutions, including positions in the cluster, are known for many of the pulsars. These recent observations provide a unique opportunity to re-examine theoretically the formation and evolution of recycled pulsars in globular clusters. This brief review focuses on dynamical exchange interactions between neutron stars and primordial binaries, through which neutron stars can acquire intermediate-mass binary companions. The later evolution of these intermediate-mass binaries leads naturally to the two main types of binary millisecond pulsars observed in clusters.

## 1. Introduction

The properties of globular cluster pulsars (see articles by Lorimer et al. and Ransom et al. in this volume) are rather surprising. While some pulsars are single, the majority are in short-period binaries. Most of the binaries have properties similar to those of the rare “eclipsing binary pulsars” seen in the Galactic disk population (see Nice et al. 2000 for a review). These systems have extremely short orbital periods,  $P_b \sim 1 - 10$  hr, circular orbits, and very low-mass companions, with  $m_2 \simeq 0.03 M_\odot$ . The other, “normal” binaries have properties more similar to those of the disk population of binary millisecond pulsars, with nearly-circular orbits, periods  $P_b \sim 1$  d (near the short-period end of the distribution for binaries in the disk) and white-dwarf (WD) companions with  $m_2 \sin i \simeq 0.2 M_\odot$ .

The large inferred total population of millisecond pulsars in globular clusters (several hundred in 47 Tuc alone; see Camilo et al. 2000) and the very high stellar densities in many cluster cores ( $\rho_c \sim 10^4 - 10^6 M_\odot \text{pc}^{-3}$ ) suggest that dynamical interactions must play a dominant role in the formation of these systems. However, the dynamical formation scenarios traditionally invoked for the production of recycled pulsars in globular clusters have many problems.

Scenarios based on *tidal capture* of low-mass main-sequence (MS) stars by neutron stars (NS), followed by accretion and recycling of the NS during a stable mass-transfer phase, run into many difficulties. Serious problems have been pointed out about the tidal capture process itself (which, because of strong nonlinearities in the regime relevant to globular clusters, is far more likely to result in a merger than in the formation of a detached binary; see, e.g., Kumar

& Goodman 1996; McMillan et al. 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 et al. 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. Physical *collisions* between NS and red giants have also been invoked as a way of producing directly NS–WD binaries with ultra-short periods (e.g., Verbunt 1987), but detailed hydrodynamic simulations show that this does not occur (Rasio & Shapiro 1991).

The viability of tidal capture and two-body collision scenarios has become less relevant with the realization over the last decade 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  $\sim 10^{10}$  yr (Gao et al. 1991; McMillan & Hut 1994; Fregeau et al. 2003).

In dense clusters, retained NS can acquire binary companions through *exchange interactions* with these primordial binaries. Because of its large cross section, this process dominates over any kind of two-body interaction even for low primordial binary fractions (Heggie, Hut, & McMillan 1996; Leonard 1989; Sigurdsson & Phinney 1993). In contrast to tidal capture, exchange interactions with hard primordial binaries (with semimajor axes  $a \sim 0.1 - 1$  AU) can form naturally the wide binary millisecond pulsars seen in some low-density globular clusters (such as PSR B1310+18, with  $P_b = 256$  d, in M53, which has the lowest central density,  $\rho_c \sim 10^3 M_\odot \text{pc}^{-3}$ , of any globular cluster with observed radio pulsars). When the newly acquired MS companion, 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 NS–WD binaries have orbital periods in the range  $P_b \sim 1 - 10^3$  d. However, this scenario cannot explain the formation of recycled pulsars in binaries with periods shorter than  $\sim 1$  d. To obtain such short periods, the initial primordial binary must be extremely hard, with  $a \lesssim 0.01$  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.,  $v_e \simeq 60 \text{ km s}^{-1}$  for 47 Tuc).

One can get around this problem by considering more carefully the stability of mass transfer in NS–MS 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 NS and the most massive primordial binaries will undergo mass segregation and concentrate in the cluster core on a time scale comparable to the initial half-mass relaxation time  $t_{\text{rh}}$ . For typical dense globular clusters, we expect  $t_{\text{rh}} \sim 10^9$  yr, which is comparable to the MS lifetime of a  $\sim 2 - 3 M_\odot$  star. If the majority of NS in the cluster core acquire MS companions in the range of  $\sim 1 - 3 M_\odot$ , a very different evolution ensues. Indeed, in this case, when the MS star 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 common-envelope (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.

This simple idea has been explored quantitatively using Monte Carlo simulations of globular cluster dynamics (Rasio, Pfahl, & Rappaport 2000; Rappaport et al. 2001) and a brief summary of this work is presented in Sec. 2. A similar scenario, but starting from tidal capture binaries and applied to X-ray sources in globular clusters, was discussed by Bailyn & Grindlay (1987). The possibility of forming intermediate-mass binaries through exchange interactions was mentioned by Davies & Hansen (1998), who pointed out that NS retention in globular clusters may also require that the NS be born in massive binaries. Among eclipsing pulsars in the disk, at least one system (PSR J2050–0827) is likely to have had an intermediate-mass binary progenitor, given its very low transverse velocity (Stappers et al. 1998).

## 2. Results from Dynamical Simulations

Figure 1 shows typical results from our most recent numerical simulations for 47 Tuc (Rappaport et al. 2001). Given the many simplifying assumptions used in this work, the agreement with observations is quite encouraging. The parameters of observed systems were taken from Camilo et al. (2000) and Freire et al. (2001, 2003). We omitted 47 Tuc W, which is now known to have a MS companion (Edmonds et al. 2002). Such systems are the natural descendants of longer-period binaries (upper part of group c in Fig. 1), which are very likely to interact again in the dense cluster environment. These multiple interactions can produce both single recycled pulsars and binary pulsars with anomalous companions (like 47 Tuc W) and/or unusual positions in the cluster halo (as in NGC 6752; D’Amico et al. 2002).

The initial conditions for the simulations include MS stars and primordial binaries with standard initial mass functions and distributions of binary parameters, as well as a certain number of single NS, which are assumed to have been retained by the cluster (cf. Pfahl, Rappaport, & Podsiadlowski 2002). The total number of MS stars initially is  $\sim 10^6 - 10^7$  and the total number of NS is  $\sim 10^4$ .

Binaries and NS undergo mass segregation and enter the cluster core in a time  $t_s \sim 10(m_f/m_t)t_{\text{rh}}$ , for objects of mass  $m_t$  drifting through field stars of average mass  $m_f$  (see, e.g., Fregeau et al. 2000). For the simulation of Fig. 1 we assumed  $t_{\text{rh}} = 10^9$  yr. Binaries whose primaries evolve off the MS before entering the cluster core are removed from the simulation. From the numbers of binaries and NS in the core, we can compute the time for each binary to have a strong interaction with a NS. We can then decide on a list of actual interactions in each timestep using a Monte Carlo procedure. All 3-body interactions are computed by direct numerical integration. Disrupted and ejected binaries are removed from the simulation.

We then calculate the evolution of the newly formed NS–MS binaries. When the primary evolves off the MS, the orbit is assumed to circularize (conserving total angular momentum). We then test for the stability of mass transfer when the primary fills its Roche lobe. We find that typically about 50% of the systems enter a CE phase. The outcome of the CE phase is calculated using the standard treatment, with the efficiency parameter  $\alpha_{CE} = 0.5$  (Rappaport, Di Stefano, &

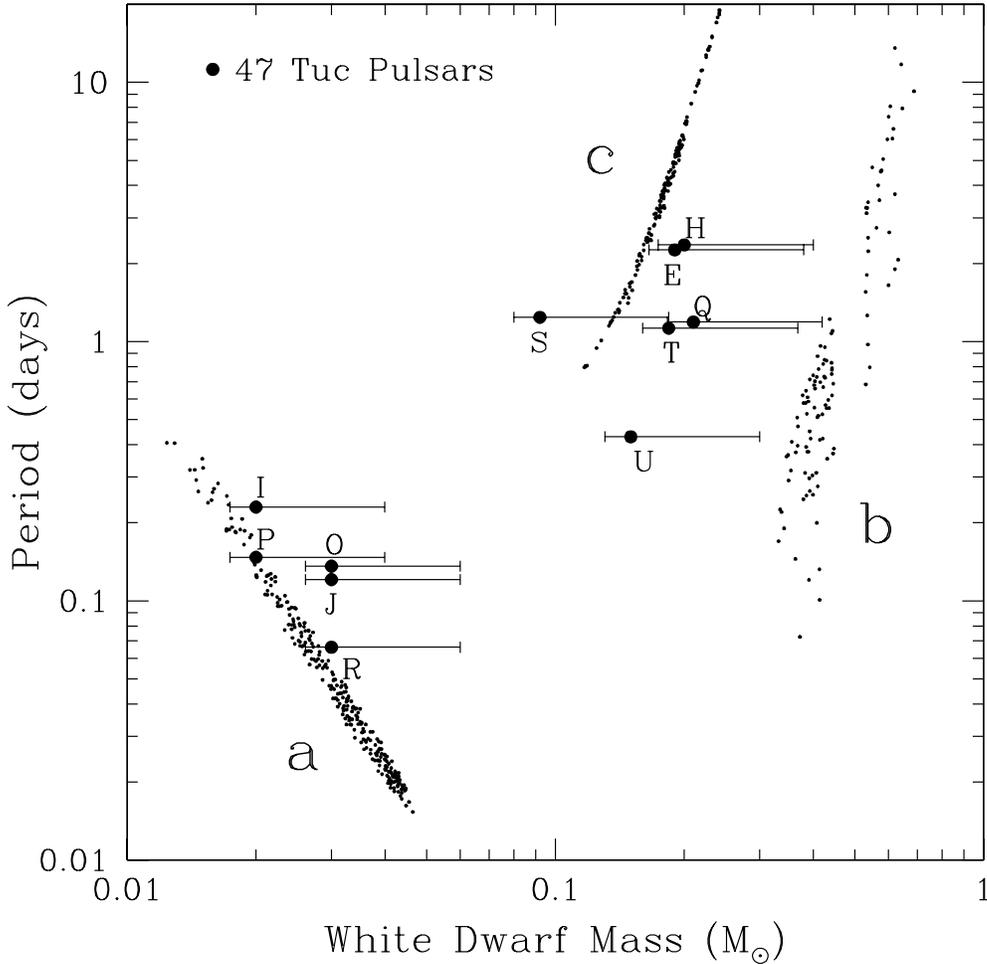


Figure 1. Typical results of a dynamical simulation for binary millisecond pulsar formation in 47 Tuc. Each small dot represents a binary system produced in the simulation, while the filled circles show the parameters of the observed binary pulsars in 47 Tuc. There are 3 separate groups of simulated binaries. Systems in the diagonal band on the left (a) come from post-exchange binaries that decayed via gravitational radiation to very short orbital periods ( $\sim$  mins), then evolved with mass transfer back up to longer periods. The sparse group on the right (b) contains post-exchange NS-WD binaries that had insufficient time to decay to Roche-lobe contact. The NS in this group are not thought to be recycled since they cannot have accreted much mass during the rapid CE phase. Finally, the systems lying in the thin diagonal band toward longer periods (c) are post-exchange binaries in which the mass transfer from the giant or subgiant to the NS would be stable. These have not been evolved through the mass transfer phase; the mass plotted is simply that of the He core of the donor star when mass transfer commences. There are many more systems in this category that have longer periods but lie off the graph.

Smith 1994). A significant fraction of these NS–WD binaries will undergo further evolution driven by gravitational radiation. For orbital periods  $\lesssim 8$  hr, the companion will be filling its Roche lobe in less than  $\sim 10^{10}$  yr and a second phase of mass transfer will occur. For WD masses  $\lesssim 0.4 M_{\odot}$  the mass transfer is stable and the evolution can be calculated semi-analytically. Our calculations for this phase also incorporate a simple treatment of the tidal heating of the companion (Applegate & Shaham 1994; Rasio et al. 2000). We track the accretion rate and spin-up of the NS during the mass-transfer phase and we terminate the evolution when the NS spin period reaches a randomly chosen value in the range 2 – 5 ms (at which point the radio pulsar emission is assumed to turn on and stop the accretion flow).

This simple scenario provides a natural way of explaining the large number and observed properties of short-period binary pulsars in a dense globular cluster such as 47 Tuc (Fig. 1). Although quantitatively the predicted properties of the final binary population depend on our parametrization of several uncertain processes (such as CE evolution and tidal heating), the overall qualitative picture is remarkably robust. Indeed, quite independent of the details of the various assumptions and choices of parameters, exchange interactions *inevitably* form a large population of NS–MS binaries that will go through a CE phase. The only way for a globular cluster to avoid forming such a population would be to start with a very low primordial binary fraction, a very small number of retained NS, or to have a very long relaxation time  $t_{\text{rh}} \gtrsim 10^{10}$  yr, such that all MS stars with masses  $\gtrsim 1 M_{\odot}$  evolve before the rate of exchange interactions becomes significant. A large fraction of the post-CE NS–WD binaries cannot avoid further evolution driven by gravitational wave emission, with the companion ultimately reduced to a very low mass  $m_2 \sim 10^{-2} M_{\odot}$ .

Pulsars in wider binaries with  $P_b \sim 1$  d and WD companions must have evolved from the group of systems with stable mass transfer from a  $\sim 1 M_{\odot}$  subgiant to a NS, which have orbital periods at the start of mass transfer in the range  $\simeq 1 - 5$  d (lower end of group c in Fig. 1). Conventional evolutionary scenarios suggest that systems where the donor has a well-developed degenerate core should inevitably evolve to longer orbital periods. However, many of the systems in group c of Fig. 1 have not yet developed such cores, and their final fate is uncertain. We also note that many binary pulsars in the Galactic disk population, which are supposed to fit this evolutionary scenario involving stable mass transfer from a low-mass giant to the NS, have orbital periods shorter than 5 d, with some  $< 1$  d. Even the most sophisticated binary evolution models currently available cannot explain these systems (see Podsiadlowski, in this volume).

The results illustrated in Fig. 1 also predict the existence of a large number of binary pulsars with companion masses  $m_2 \simeq 0.03 - 0.05 M_{\odot}$  and orbital periods as short as  $\sim 15$  min that may have so far escaped detection (lower end of group a in Fig. 1). Future observations using more sophisticated acceleration-search techniques or shorter integration times may be able to detect them.

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