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FORMATION OF SHORT-PERIOD BINARY PULSARS IN GLOBULAR CLUSTERS

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ABSTRACT

We present a new dynamical scenario for the formation of short-period binary millisecond pulsars in globular clusters. Our work is motivated by the recent observations of 20 radio pulsars in 47 Tuc. In a dense cluster such as 47 Tuc, most neutron stars acquire binary companions through exchange interactions with primordial binaries. The resulting systems have semimajor axes in the range ∼0.1–1 AU and neutron star companion masses ∼1–3 $M_\odot$. For many of these systems, we find that when the companion evolves off the main sequence and fills its Roche lobe, the subsequent mass transfer is dynamically unstable. This leads to a common envelope phase and the formation of short-period neutron star–white dwarf binaries. For a significant fraction of these binaries, the decay of the orbit due to gravitational radiation will be followed by a period of stable mass transfer driven by a combination of gravitational radiation and tidal heating of the companion. The properties of the resulting short-period binaries match well those of observed binary pulsars in 47 Tuc.

Subject headings: celestial mechanics, stellar dynamics — globular clusters: general — pulsars: general — stars: neutron

1. INTRODUCTION

Twenty millisecond radio pulsars have now been observed in the globular cluster 47 Tuc (Camilo et al. 2000; Freire et al. 2000). This is by far the largest sample of radio pulsars known in any globular cluster. Accurate timing solutions, including positions in the cluster, are known for 14 of the pulsars. These recent observations provide a unique opportunity to reexamine theoretically the formation and evolution of recycled pulsars in globular clusters.

The binary properties of the 47 Tuc pulsars are rather surprising. While seven pulsars are single, the majority are in short-period binaries. Most of the binaries (eight out of 13) have properties similar to those of the rare "eclipsing binary pulsars" seen in the Galactic disk population (see Nice 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 $m_2 \sin i \sim 0.01$–$0.1\ M_\odot$. The remaining five binaries have properties more similar to those of the bulk disk population, with nearly circular orbits, periods $P_b \sim 1$–3 days (near the short-period end of the distribution for binary millisecond pulsars in the disk), and companions of mass $m_2 \sin i \simeq 0.2\ M_\odot$.

The large inferred total population of recycled pulsars in 47 Tuc (∼10^3; see Camilo et al. 2000) and the high central density of the cluster ($\rho_c \sim 10^5$–$10^6\ M_\odot$ pc^{-3}; see De Marchi et al. 1996; Camilo et al. 2000) suggest that dynamical interactions must play a dominant role in the formation of these systems. However, the two dynamical formation scenarios traditionally invoked for the production of recycled pulsars in globular clusters clearly fail to explain the observed binary properties of the 47 Tuc pulsars.

Scenarios based on *tidal capture* of low-mass main-sequence (MS) stars by neutron stars (NSs) followed by accretion and recycling of the NSs 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, Taam, & McDermott 1990; Rasio & Shapiro 1991; Ray, Kembhavi, & Antia 1987). 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. Verbunt (1987) proposed that collisions between NSs and red giants might produce directly neutron star–white dwarf (NS-WD) binaries with ultrashort periods, but detailed hydrodynamic simulations later showed 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 10 years that globular clusters contain dynamically significant populations of *primordial binaries* (Hut et al. 1992a). Neutron stars can then 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 $P_b = 256$ days, in M53, which has the lowest central density, $\rho_c \sim 10^3\ M_\odot$ pc^{-3}, of any globular cluster with observed radio pulsars; see, e.g., Phinney 1996). 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 days. However, this scenario cannot explain the formation of recycled pulsars in binaries with periods shorter than ∼1 day. 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 ($v_e \simeq 60$ km s^{-1} for 47 Tuc).

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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 may very well 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 $t_{\rm rh}$. For a dense cluster like 47 Tuc, we expect $t_{\rm rh} \simeq 10^9$ yr, which is comparable to the MS lifetime of a $\simeq$2–3 $M_\odot$ star. If the majority of NSs acquired MS companions in the range of ∼1–3 $M_\odot$ (as we find), a drastically different evolution may follow. 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. The emerging binary will have a low-mass WD in a short-period, circular orbit around the NS. This simple idea is at the basis of the evolutionary scenario we explore quantitatively in § 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 NSs 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. FORMATION AND EVOLUTION OF SHORT-PERIOD BINARIES

We have carried out Monte Carlo simulations to test quantitatively a formation scenario based on the ideas outlined in § 1. The general framework follows that used in previous Monte Carlo studies of binary evolution and cluster dynamics (Di Stefano & Rappaport 1994; Hut, McMillan, & Romani 1992b; Joshi, Rasio, & Portegies Zwart 2000; Rappaport, Di Stefano, & Smith 1994, hereafter RDS). More details on our Monte Carlo method and dynamical simulations, as well as a systematic study of how the results depend on model parameters, will be presented in forthcoming papers (K. Joshi, E. D. Pfahl, S. Rappaport, & F. A. Rasio 2000, in preparation; E. D. Pfahl, K. J. Joshi, S. Rappaport, & F. A. Rasio 2000, in preparation). Here we simply outline the major steps in our simulations and present some representative results:

1. We begin with a population of primordial MS binaries and single NSs, distributed as a constant fraction of the mass density in the cluster. Primary masses m_1 are selected using the P. Eggleton (2000, in preparation) Monte Carlo representation of the Miller & Scalo (1979) initial mass function (see eq. [1] of RDS). The secondary mass is chosen so that the probability distribution for the binary mass ratio $q = m_2/m_1$ is $p(q) \propto q^{1/4}$ (Abt & Levy 1978). Initial binary orbital periods are distributed uniformly in log P over the interval $\sim 10^{-1}$ to 10^8 days. Eccentricities are generated from a thermal distribution, $p(e_i) = 2e_i$. All NSs have mass $m_{\rm NS} = 1.4\ M_\odot$. For definiteness, we start with 5×10^6 binaries and 10^4 NSs in a cluster containing a total of 10^7 stars. These numbers affect only the overall normalization of our results.

2. Binaries and NSs undergo mass segregation and enter the cluster core in a time t_s, distributed according to $p(t_s) = (1/t_{\rm sc}) \exp{(-t_s/t_{\rm sc})}$, where the characteristic time $t_{\rm sc} \simeq 10(m_f/m_t)t_{\rm rh}$ for objects of mass m_t drifting through field stars of average mass m_f. This simple analytic law fits very well the results of detailed dynamical simulations of mass segregation (J. M. Fregeau, K. J. Joshi, & F. A. Rasio 2000, in preparation). We fix $t_{\rm rh} = 10^9$ yr in this Letter. Binaries whose primaries evolve off the MS before entering the cluster core are removed from the simulation.

3. We assume a fixed core density $n_c = 10^5\ {\rm pc}^{-3}$, core radius $r_c = 0.5$ pc, and three-dimensional velocity dispersion $v_c = 15$ km s^{-1} (meant to be average values over the evolution of the cluster). The fraction of the core density in single NSs increases slowly as NSs drift into the core, and it reaches a maximum of about 5% of the core density at $\sim 4 \times 10^9$ yr before exchange interactions begin to deplete their population significantly. From the numbers of binaries and NSs in the core, we compute the time for each binary to have a strong interaction. Here a strong interaction is defined to have a distance of closest approach less than $a_i(1 + e_i)$, where a_i and e_i are the initial binary semimajor axis and eccentricity. Soft binaries, with binding energies less than $m_f v_c^2/2$, are assumed to be disrupted by the interaction. Very hard binaries will have recoil velocities $v_{\rm rec} > v_e = 60$ km s^{-1} and will be ejected from the cluster. Here we approximate the results of scattering experiments by taking $v_{\rm rec} \simeq 0.1 v_b$, where v_b is the binary orbital velocity. Disrupted and ejected binaries, as well as those whose primaries evolve off the MS before interacting, are removed from the simulation.

4. Of the binaries that survive their first strong interaction, half are assumed to form a new NS-MS binary through exchange (most of the rest will experience a direct stellar collision and merger, and we do not follow their evolution). For simplicity, we assume that the less massive member of the original binary is always ejected in the exchange interaction (cf. Heggie et al. 1996). We approximate the results of scattering experiments by taking the final semimajor axis $a_f \simeq a_i$ and by generating a final eccentricity from a thermal distribution.

5. We now 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 (using eq. [33] of Rappaport, Verbunt, & Joss 1983, with $\xi_{\rm ad}$ adapted from new, unpublished results of P. Podsiadlowski; see also Kalogera & Webbink 1996). We find that, with the parameters adopted above, about half of the systems enter a CE phase. The outcome of the CE phase is calculated using the standard treatment, with the efficiency parameter $\alpha_{\rm CE} = 0.5$ (defined as in eq. [2] of RDS). The WD (core) mass is calculated from the progenitor mass and Roche lobe radius as in RDS.

6. 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 semianalytically using standard methods and assumptions (e.g., Li et al. 1980; Rappaport et al. 1987). 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). Results for a typical system are illustrated in Figure 1 and for the entire population in Figure 2. In its simplest version, the calculation assumes that the NS companion remains degenerate during the

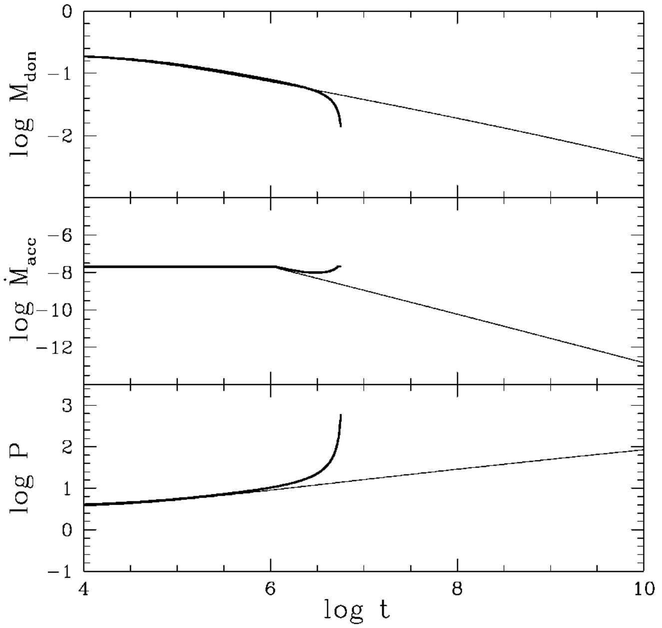

FIG. 1.—Evolution of one representative NS-WD binary driven by gravitational radiation only (*thin lines*) and by a combination of gravitational radiation and tidal heating (*thick lines*). Here time t is in years, the orbital period P is in minutes, the mass accretion rate $\dot{M}_{\rm acc}$ (onto the NS) is in $M_\odot$ yr^{-1}, and the companion (donor) mass $M_{\rm don}$ is in $M_\odot$.

entire evolution. In an effort to better match the observed properties of the 47 Tuc binaries, we have also considered a modified evolution in which the companion becomes tidally heated and nondegenerate (but still modeled as a simple $n = 3/2$ polytrope), as appears to be the case in many eclipsing binary pulsars (Applegate & Shaham 1994; Nice 2000). We adopt a synchronization time $t_{\rm syn} = 6 \times 10^4$ yr and a (magnetically driven) asynchronism $\Delta = |\Omega_s - \Omega_b|/\Omega_b = 0.3$, in agreement with the values suggested by Applegate & Shaham (1994) for PSR B1957+20. Note, however, that in our scenario the companion is initially degenerate, while Applegate & Shaham (1994) start with a low-mass MS companion.

3. DISCUSSION

Our scenario provides a natural way of explaining the large number and observed properties of short-period binary pulsars in 47 Tuc. 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. We find that, quite independent of the details of our 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 NSs, or to have a very long relaxation time $t_{\rm rh} \gtrsim 10^{10}$ 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 driven to a very low mass $m_2 \sim 10^{-2}\ M_\odot$.

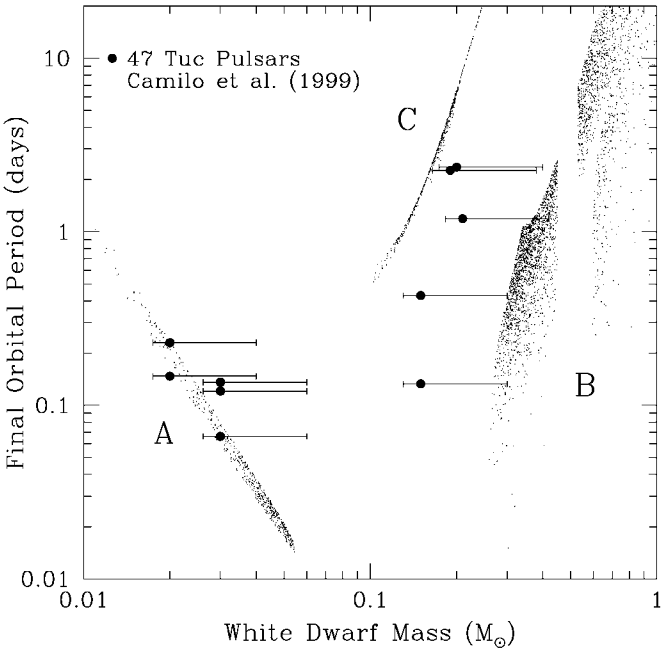

FIG. 2.—Results of our initial population synthesis study for binary millisecond pulsars in 47 Tuc. Each small dot represents a binary system in our simulation, while the circles are the 10 binary pulsars in 47 Tuc with well-measured orbits (the error bars extend from the minimum companion mass to the 90% probability level for random inclinations). There are three principal groups of simulated binaries. Systems in the diagonal band on the left (A) are binaries that decayed via gravitational radiation to very short orbital periods (~minutes), then evolved with mass transfer back up to longer periods under the influence of both gravitational radiation and tidal heating. The large group labeled B on the right contains NS-WD binaries that had insufficient time to decay to Roche lobe contact via the emission of gravitational radiation. The NSs in this group are not likely to be recycled since they may not have accreted much mass during the CE phase. Finally, the systems lying in the thin diagonal band toward longer periods (C) are those 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. The numbers in the three groups are $N_A \sim 1000$, $N_B \sim 2400$, and $N_C \sim 3500$.

A limitation of this preliminary study is that we do not take into account multiple interactions. The average collision time for a hard binary with component masses $m_1 = 1.4\ M_\odot$ and $m_2 = 0.1\ M_\odot$ and orbital period P_d days, in a cluster of density $n_5 10^5$ pc^{-3} and one-dimensional velocity dispersion $\sigma_{10}10$ km s^{-1}, is $t_{\rm coll} \simeq (10^{10}\ {\rm yr})\, n_5^{-1}\sigma_{10}P_d^{-2/3}$. Thus, in Figure 2, all binaries with periods $\gtrsim 1$ day will be affected by further interactions if they reside in the cluster core (consistent with the positions of the wider binary pulsars well outside the core of 47 Tuc; see Rasio 2000). For a small fraction of systems that undergo multiple interactions, the NS may acquire a new MS companion that will be evolving before the next interaction, thereby leading to essentially the same type of evolution already considered in § 2. Another small fraction may liberate the NS. This could be an important channel for forming single millisecond pulsars in globular clusters, although complete evaporation of a low-mass companion (as proposed for the disk population of single millisecond pulsars by Kluzniak et al. 1988) is another possibility. However, in most cases, multiple interactions will lead to the direct collision of the NS with a MS star, especially if the cluster core is dominated by binaries and resonant binary-binary encounters are frequent (Bacon, Sigurdsson, & Davies 1996). The outcome of such collisions is highly uncertain (see Fryer, Benz, & Herant 1996 for a recent discussion). Note that, if, as we suggest, recycled pulsars in short-period binaries have progenitors that went through a CE phase, then the NS must be able to survive inside the envelope of a low-mass giant without hypercritical accretion and subsequent collapse to a black hole. This is in agreement with the results of Fryer et al. (1996).

In addition to explaining the short-period binary millisecond pulsars in 47 Tuc, our scenario for the evolution of NS-WD binaries driven by gravitational radiation and tidal heating may be relevant to eclipsing binary pulsars in the disk population as well as to short-period X-ray binaries such as 4U 1820−30, 4U 1850−087, 4U 1626−67, 4U 1916−053, and SAX J1808−3658. In particular, 4U 1820−30 in the globular cluster NGC 6624, with an orbital period of ∼11 minutes, may be the prototypical NS-WD system observed during the short-lived, bright X-ray phase of its evolution (Rappaport et al. 1987). The stable, super-Eddington mass-transfer phase for these systems lasts typically $\sim 10^6$–10^7 yr (see Fig. 1). Since these recycled pulsars do not have long-lived X-ray binary progenitors, our scenario naturally avoids a "birthrate problem" (Kulkarni, Narayan, & Romani 1990).

While the properties of five "eclipsing binary pulsars" are clearly well explained by our scenario (group A in Fig. 2), the other group of five binaries in 47 Tuc with companion masses $\sim 0.2\ M_\odot$ lie distinctly toward smaller masses than the simulated systems in the left part of group B (with He WDs). We speculate that these pulsars may in fact 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 days (lower end of group C in Fig. 2). Conventional evolutionary scenarios suggest that systems in which the donor has a well-developed degenerate core should inevitably evolve to longer orbital periods. However, many of the systems in group C of Figure 2 have not yet developed such cores. Moreover, we note that of the 20 binary radio pulsars in the Galactic disk population that are supposed to fit this evolutionary scenario involving stable mass transfer from a low-mass giant to the NS, nine systems have orbital periods shorter than 5 days, with some less than 1 day (Rappaport et al. 1995). We suggest that detailed binary evolution calculations of these types of systems be undertaken.

Our results predict the existence of a large number of binary pulsars with companion masses $m_2 \sim 0.05\ M_\odot$ and orbital periods as short as ∼15 minutes that may have so far escaped detection (lower end of group A in Fig. 2). Future observations using more sophisticated acceleration search techniques or shorter integration times may be able to detect them (see Camilo et al. 2000). They should approximately follow a period–companion mass relation given by $P_b(\mathrm{days}) \simeq 10^{-5}(m_2/M_\odot)^{-2.5}$. We also find a large number of post-CE NS-WD binaries with periods $P_b \sim 1$–30 days and WD masses above 0.5 $M_\odot$ (CO WDs; right side of group B in Fig. 2). No such system has been definitely observed among the binary radio pulsars in 47 Tuc. One obvious reason may be that the NS was not recycled during the short CE phase, although we must point out that two systems of this type may have been observed in the Galactic disk population (PSR J2145−0750 and PSR B0655+64; see, e.g., Phinney & Kulkarni 1994).

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