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Neutron star retention and millisecond pulsar production in globular clusters

Melvyn B. Davies[1]★ and Brad M. S. Hansen[2]
[1]*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2]*CITA, University of Toronto, 60 St. George Street, Toronto, ON, M5S 3H8, Canada*

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ABSTRACT
We investigate the conditions by which neutron star retention in globular clusters is favoured. We find that neutron stars formed in massive binaries are far more likely to be retained. Such binaries are likely to then evolve into contact before encountering other stars, possibly producing a single neutron star after a common envelope phase. A large fraction of the single neutron stars in globular clusters are then likely to exchange into binaries containing moderate-mass main-sequence stars, replacing the lower-mass components of the original systems. These binaries will become intermediate-mass X-ray binaries (IMXBs), once the moderate-mass star evolves off the main sequence, as mass is transferred on to the neutron star, possibly spinning it up in the process. Such systems may be responsible for the population of millisecond pulsars (MSPs) that has been observed in globular clusters. Additionally, the period of mass-transfer (and thus X-ray visibility) in the vast majority of such systems will have occurred 5–10 Gyr ago, thus explaining the observed relative paucity of X-ray binaries today, given the MSP population.

Key words: stars: evolution – stars: neutron – pulsars: general – globular clusters: general.

1 INTRODUCTION

Proper motion studies (Lyne, Anderson & Salter 1982; Harrison, Lyne & Anderson 1993) indicate that most pulsars possess significant space velocities. Although it has been suggested that these velocities are a result of binary disruption (Gott, Gunn & Ostriker 1970), the study of surviving binaries (Verbunt, Wijers & Burm 1990; Lai, Bildsten & Kaspi 1995; Kaspi et al. 1996) indicates that some pulsar 'kicks' must stem from the original supernova event. The magnitudes of such kicks are typically much larger than would be required to escape from a globular cluster. Thus we might expect only a small fraction of neutron stars to be retained in globular clusters (Drukier 1996). A number of observations of globular clusters indicate the presence of neutron stars today. According to the standard model, millisecond pulsars (MSPs) are produced in low-mass X-ray binaries (LMXBs) as the neutron star is spun up as it accretes material from its Roche-lobe-filled companion. However, observations of globular clusters suggest that the relative birth rates of MSPs and LMXBs is even more disparate in globular clusters than it is in the field, suggesting evolutionary paths with short X-ray visibility.

In this paper we shall show how the presence of a binary companion can retard the motion of a neutron star, enhancing the retention fraction relative to a population born from single stars. We also show how this binary population can lead to an alternative pathway to MSP formation that avoids an LMXB phase. In the crowded environments of globular clusters, a population of binaries will tend to collect the more massive stars as exchange encounters replace their low-mass components. These more massive main-sequence stars then evolve and transfer material on to the neutron stars, forming intermediate mass X-ray binaries (IMXBs). IMXBs are quite different from LMXBs and high-mass X-ray binaries (HMXBs). Their lifetimes will be somewhat shorter than LMXBs because of their more massive donor stars, although their masses are not sufficient to form neutron stars as is the case in HMXBs. In IMXBs, the neutron star may be spun up to millisecond periods if sufficient material (and angular momentum) is accreted. It is important to note that this epoch of mass transfer will have occurred *in the past* in most cases in globular clusters, as the main-sequence lifetimes of the mass donors in IMXBs are significantly smaller than the cluster ages. We would thus expect the current X-ray activity in clusters to be much less than that expected from the MSP population. All IMXBs will produce common envelope systems as the mass donors smother the neutron stars. Such common envelope systems are likely to produce tight neutron star–white dwarf binaries. The stars in such binaries will spiral together and come into contact in $\lesssim 10^{10}$ yr if the post-common-envelope phase separation of the white dwarf and neutron star $\lesssim 3\,R_{\odot}$. The neutron star may thus be spun up in this second phase of mass transfer, which will be relatively short-lived.

★E-mail: mbd@ast.cam.ac.uk (MBD)

We therefore consider the production of IMXBs in globular clusters. We begin by calculating the conditions necessary for neutron stars to be retained in globular clusters. As shown in Section 2, a large fraction of the neutron stars retained in globular clusters are likely to be in binaries. The subsequent evolution of such binaries in isolation is considered. In Section 3 we examine the evolution of these binaries in a crowded field where encounters with a third, single, star or another binary is possible. Such encounters may smother the neutron stars or eject them from the binaries but leave them within the cluster. In Section 4 we consider the subsequent encounters between single neutron stars and binaries in the cluster, in particular identifying possible pathways to MSP production via IMXBs. We apply our results to particular cluster models in Section 5 and summarize our findings in Section 6.

2 NEUTRON STAR RETENTION IN CLUSTERS

2.1 Kick velocities

Central to the issue of neutron star retention is the magnitude and distribution of the kick velocities neutron stars acquire at birth. Until recently, the best description was that of Paczynski (1990), whose distribution function was based on the proper motion measurements of Lyne et al. (1982). The gradual accumulation of better proper motions (Harrison et al. 1993) and revisions to the pulsar distance scale (Taylor & Cordes 1993) led to a dramatic increase in the claimed characteristic velocity (Lyne & Lorimer 1995). However, the observations are beset by several selection effects, and attempts to correct for this (Hansen & Phinney 1997) have reduced the characteristic velocity from the Lyne & Lorimer value, although reducing the low-velocity tail shown by the Paczynski distribution, which was the result of a biased contribution from old, slow and faint pulsars.[1] The current quality of the observations still allows some leeway in the choice of the distribution. The two functional forms chosen to indicate the allowed degree of variation are the following:

$$p(V_{\rm k}) = \sqrt{\frac{2}{\pi}}\frac{V_{\rm k}^2}{\sigma_v^3}\,{\rm e}^{-V_{\rm k}^2/2\sigma_v^2} \qquad (1)$$

with $\sigma_v = 190\,{\rm km\,s^{-1}}$, and

$$p(V_{\rm k}) = 0.8\delta(V_{\rm k} - 250\,{\rm km\,s^{-1}}) + 0.2\delta(V_{\rm k} - 1000\,{\rm km\,s^{-1}}). \qquad (2)$$

where equation (2) means that 80 per cent of the stars receive a kick velocity of $250\,{\rm km\,s^{-1}}$ whilst the remaining 20 per cent receive a kick of $1000\,{\rm km\,s^{-1}}$. Equation (1) fits the empirical distribution well over the entire range of observed velocities. The rather extreme nature of equation (2) and its comparison to (1) indicates that the distribution of high velocities ($>300\,{\rm km\,s^{-1}}$) is not strongly constrained (although the contribution to the overall number is <20 per cent) and that the low-velocity tail of (1) is only the maximum reasonable contribution; it could be smaller. This is the most important concern for globular cluster retention, because the escape velocities are $<100\,{\rm km\,s^{-1}}$. Cordes & Chernoff (1997) also find a paucity of low velocities, as do Portegies Zwart, Kouwenhoven & Reynolds (1997). Another concern is whether the velocities inferred from single pulsars are representative of the initial kicks, since many of the currently observed single pulsars could have been born in binaries. Fryer, Burrows & Benz (1998) find that a *kick* distribution like (1) is consistent with their field binary retention calculations (although they eventually favour even higher velocities because of a less detailed treatment of proper motion selection effects). We should note, however, that the low-velocity tail could increase if there is a significant population of slow, high-field pulsars that cross the death line in time-scales much shorter than 10^7 yr (thereby avoiding inclusion in the proper motion sample). The anomalously large magnetic fields of the Crab and Vela pulsars (both with velocities $\sim 100\,{\rm km\,s^{-1}}$) can be interpreted in this light, but we shall not do so here. Also, the combination of galactic dynamics and limited lifetimes may select against low-velocity pulsars in the proper motion surveys (Hansen, in preparation). We shall ignore this effect as well. In doing so, we adopt a conservative position regarding the number of low-velocity pulsars born in globular clusters. Increasing this fraction will only reinforce our conclusions in Sections 3 and 4.

[1]The analysis of Iben & Tutukov (1996) suffers from the same problem.

2.2 Binary retention

The effects of the supernova mass loss and kick velocities on a binary system has been studied by a number of authors (Flannery & van den Heuvel 1975; Sutantyo 1978; Wijers, van Paradijs & van den Heuvel 1992; Brandt & Podsiadlowski 1995; Kalogera 1996). Given the solid foundation in the literature, we simply quote the following results.

Given an initial (circular) binary with components of mass M_1, M_2 and separation d, the supernova transforms M_1 to $M_{\rm ns}$, produces a binary of separation d', and imparts a kick of magnitude $V_{\rm k}$ to the neutron star with components V_x, V_y and V_z. We assume the origin is at the position of M_1 before the explosion, the orbital separation vector lies along the x-axis and the orbital velocity vector along the y-axis. The resultant post-supernova parameters are

$$\frac{d'}{d} = \alpha = \beta\left[2\beta - V_x^2 - V_z^2 - (1+V_y)^2\right]^{-1}, \qquad (3)$$

$$1 - e^2 = \frac{1}{\alpha\beta}\left[V_z^2 + (1 + V_y^2)\right], \qquad (4)$$

$$V_{\rm bin} = \beta_1^2 + \beta_2^2\left[V_x^2 + V_z^2 + (1+V_y)^2\right] - 2\beta_1\beta_2(1+V_y), \qquad (5)$$

where $\beta = (M_{\rm ns} + M_2)/(M_1 + M_2)$, $\beta_1 = M_1/(M_1 + M_2)$, $\beta_2 = M_{\rm ns}/(M_{\rm ns} + M_2)$ and all velocities are normalized with respect to the pre-supernova orbital velocity $V_0 = [G(M_1 + M_2)/d]^{1/2}$. The velocity of an unbound neutron star is

$$V_{\rm ns} = 1 + \frac{V_{\rm bin} - 1}{\beta_2}. \qquad (6)$$

Setting all velocities equal to zero in equation (5) shows that there is still a minimum systematic binary velocity simply as a result of the mass loss from the system. The expression is relative to the orbital velocity, so that, given the companion masses and a cluster escape velocity, there is a minimum initial orbital separation or period such that the final system can possibly remain bound to the cluster. This is

$$d_{\rm min} = [\beta_1 - \beta_2]^2\frac{G(M_1 + M_2)}{V_{\rm esc}^2}, \beta > \frac{1}{2} \qquad (7)$$

$$d_{\rm min} = \left[\beta_1 - \sqrt{2\beta}\beta_2\right]^2\frac{G(M_1 + M_2)}{V_{\rm esc}^2}, \beta < \frac{1}{2} \qquad (8)$$

where the second condition applies in those cases where more than half the original mass is lost and therefore a minimum kick is required to maintain a bound system.

Our interests are in those scenarios in which the neutron star or binary has the smallest resultant velocity. Hence, we need to consider the effects characteristic of those systems with the deepest potential wells, i.e. the closest binary systems. Two effects need to be considered: the effect of the supernova shell impulse on the companion (which will work to unbind the binary), and the effect of stellar collisions (which may disrupt the companion and slow the neutron star). In the first case, the simulations of Fryxell & Arnett (1981) have shown that approximately half[2] of the shell linear momentum intercepted by the companion is channelled into an impulse (or kick) away from the site of supernova (i.e. along the x-axis in our coordinates). This impulse velocity is

$$V_{\rm imp} = \frac{1}{8}\left(\frac{R}{d}\right)^2 \frac{M_1 - M_{\rm ns}}{M_2}\left(\frac{2E_{\rm sn}/V_0^2}{M_1 - M_{\rm ns}}\right)^{1/2} \tag{9}$$

where R is the companion radius and $E_{\rm sn}$ is the total energy carried off by the supernova shell. For $d \sim 10\,{\rm R}_\odot$, $V_{\rm imp} \sim 0.01 - 0.03$ for the range of companion masses considered here, so that impulse velocities are not terribly important. A collision between the neutron star and its companion would certainly slow it down considerably (see for example Benz & Hills 1992), and this braking effect would help retain neutron stars in globular clusters. However, as will be shown in the following section, collisions between the two stars will occur only rarely, hence their influence on the retained neutron star population will be small.

2.3 Monte Carlo approach

In order to calculate the fraction of neutron stars likely to be retained in globular clusters, we performed a Monte Carlo analysis, considering circular binaries with various separations, d, and primary and secondary masses, M_1, M_2. For a given initial binary, we consider the outcome of a supernova for a number of neutron star kick velocities, the direction of the kick being chosen at random, and the magnitude of the velocity being drawn from equation (1). We use this form to determine what plausible results may be obtained given the constraints on the kick velocity distribution. Using the kick velocity distribution given by equation (2) results only in a small change in the fraction of neutron stars retained.

For each realization of the supernova, we compute whether the neutron star remains bound to the secondary. If it does, we also compute the properties of the binary, and the velocity of its centre-of-mass. If the binary is unbound, we compute the velocity of the neutron star (at infinity) allowing for the accelerating effects of the secondary. We may therefore calculate the fraction of neutron stars likely to be retained in a globular cluster by counting up the number of single neutron stars and binaries having speeds lower than some typical escape speed for a globular cluster.

In Fig. 1 we illustrate the fraction of neutron stars retained in a globular cluster, as a function of binary separation, d, and secondary mass, M_2. We consider two values for the primary mass, namely $M_1 = 3.5$ and $5.0\,{\rm M}_\odot$, and three values for the cluster escape speed, $V_{\rm esc} = 40$, 60, and $90\,{\rm km\,s^{-1}}$. Progenitors of type II supernovae have initial masses in excess of $\sim 8\,{\rm M}_\odot$. However, in the systems we consider here, the orbital separations are of order the size of giant star envelopes, so that we expect a period of mass transfer, or at least mass loss, to precede the supernova explosion. Material will either have been transferred to the secondary (which leads to more

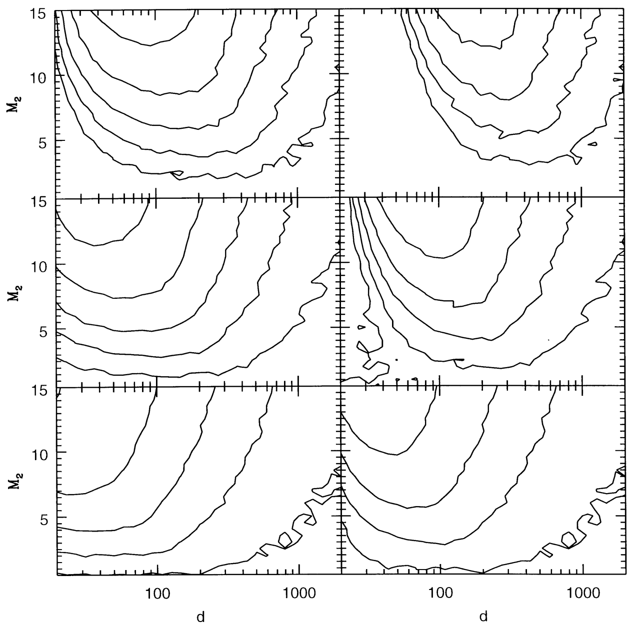

Figure 1. The fraction of neutron stars retained in a globular cluster as a function of binary separation, d, and secondary mass, M_2. Both are given in solar units. The primary mass, $M_1 = 3.5\,{\rm M}_\odot$ in the three plots on the left; for those on the right, $M_1 = 5.0\,{\rm M}_\odot$. The top, middle, and lowest row of plots use, respectively, a cluster escape speed, $V_{\rm esc} = 40$, 60, and $90\,{\rm km\,s^{-1}}$. The contours are logarithmic, at intervals of a factor of two in fraction of neutron stars retained (i.e. $f_{\rm ret} = 0.01$, 0.02, 0.04, etc.). Retention fraction increases with increasing M_2 in all cases. The lowest contour levels are 0.01, when $V_{\rm esc} = 40\,{\rm km\,s^{-1}}$, and $V_{\rm esc} = 60\,{\rm km\,s^{-1}}$. In the lowest two plots, the contours begin at $f_{\rm ret} = 0.04$.

massive secondaries and thereby aids retention), or lost completely, leaving the helium-burning core of the original primary (see Bhattacharya & van den Heuvel 1991 for a thorough discussion of the stellar evolution pathways available to binary systems with neutron stars).

From Fig. 1 we see that the fraction of neutron stars retained is a strong function of secondary mass and binary separation. The typical initial separation of the binaries that are retained is a strong function of the cluster escape speed. In the top panel (with $V_{\rm esc} = 40\,{\rm km\,s^{-1}}$), the high-mass, small-separation systems are lost, because the systematic velocities eject them from the cluster (it should be noted that the fraction of systems ejected would be even larger for lower values of escape speed). The absence of retained neutron stars for low-mass, small-separation systems in the upper-right panel is expected from inspection of equations (7) and (8). In the lower panels (larger cluster escape speeds) they are retained. Wider binaries tend to have lower systematic velocities, though they are more easily broken up. Hence the preferentially retained systems have initial separations $d \sim 100\,{\rm R}_\odot$ for low escape speeds, whilst $d \sim 10\,{\rm R}_\odot$ for larger escape speeds. The fraction retained is larger for the smaller value of M_1. The fraction retained also increases significantly for the larger values of escape speed, especially for lower values of M_2. For $M_2 \gtrsim 10\,{\rm M}_\odot$ we see that $\gtrsim$10 per cent of neutron stars will be retained. For $M_2 \sim 1\,{\rm M}_\odot$, this fraction is much lower than 1 per cent. Hence we conclude that, providing that a reasonable fraction of the initial binaries contained massive secondaries at the time of the supernova explosion ($M_2 \gtrsim 10\,{\rm M}_\odot$), then this population will dominate amongst those retained in globular clusters. In subsequent sections, we will consider the evolution of binaries with a range of secondary masses.

[2] The rest goes into ablation of some of the companion surface material. Only a few per cent of the mass is lost for even the closest binaries we consider.

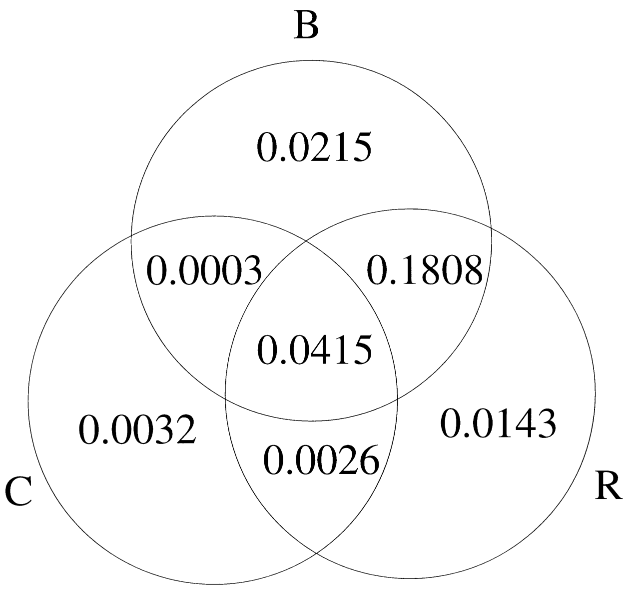

Figure 2. Venn Diagram showing the relative frequency of various outcomes of a supernovae occurring in a binary with primary mass, $M_1 = 3.5\,M_\odot$, and secondary mass, $M_2 = 10\,M_\odot$, and separation, $d = 80\,R_\odot$. The three circles labelled B, C, and R are, respectively, for events that leave binaries intact, systems in which the two stars collide, and those that will be retained in a globular cluster with an escape speed, $V_{esc} = 60\,km\,s^{-1}$. The values given are normalized such that the total (including the area exterior to all three circles) sums to unity.

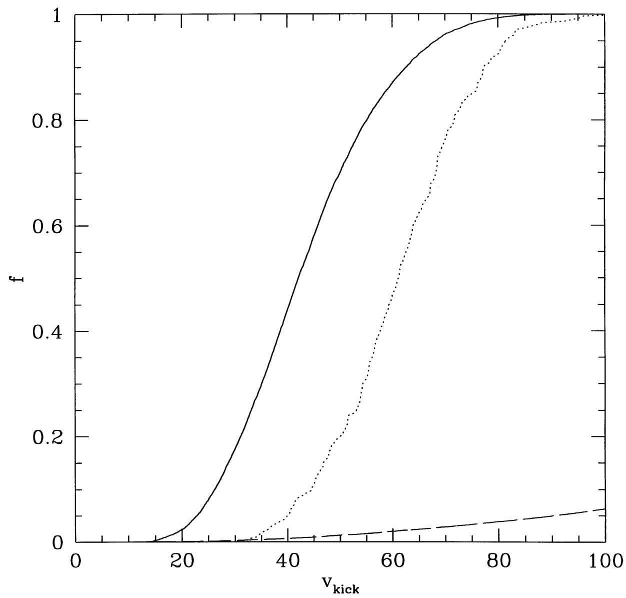

Figure 3. The velocity distribution for unbound neutron stars (dashed line), merged objects (dotted line) and intact binaries (solid line) from an initial binary with primary mass, $M_1 = 3.5\,M_\odot$, and secondary mass, $M_2 = 10\,M_\odot$, and separation d drawn from the range $50 - 200\,R_\odot$.

Before we proceed to consider the subsequent evolution of the retained systems, we will first look in more detail at the outcomes of the supernovae on one set of values of M_1 and V_{esc}. For purposes of illustration here we use $M_1 = 3.5\,M_\odot$ and $V_{esc} = 60\,km\,s^{-1}$. We consider three properties of each realization of the initial binary undergoing a supernova. It can either remain intact or be broken up. The system can remain in a globular cluster, or not. Also the two stars may undergo a physical collision. The various combinations of these three properties yield eight distinct outcomes for each binary. The relative frequencies of these various outcomes is illustrated in a Venn diagram in Fig. 2, for $M_1 = 3.5\,M_\odot$, $M_2 = 10\,M_\odot$, $d = 80\,R_\odot$ and $V_{esc} = 60\,km\,s^{-1}$. In this figure, the numbers given are normalized such that they sum to unity. From this figure we see that ~75 per cent of the initial binaries are broken up, with the neutron star being ejected from the globular cluster. The next most frequent outcome is where the two stars remain in a binary which will stay in the cluster. Unbound (i.e. single stars resulting from a disrupted binary) neutron stars are rarely retained and even fewer born from single stars remain; thus most neutron stars found in clusters immediately after the phase of supernovae will be contained within binaries, *provided* that more than ~5 per cent of neutron stars were created in moderately massive binaries. This seems likely, as any massive stars formed in binaries will still be in them when they explode as supernovae, as the encounter time-scale to break up all but the widest of binaries exceeds the short lifetime of a massive star. We also note that, of the binaries retained in clusters, ~20 per cent will be sufficiently eccentric that the neutron star and secondary will collide at periastron forming a single merged object.

To illustrate the dependence of neutron star retention on cluster escape speed, the velocity distributions of intact binaries, merged objects, and unbound neutron stars are shown in Fig. 3, for $M_1 = 3.5\,M_\odot$, $M_2 = 10\,M_\odot$, and $50 \le d \le 200\,R_\odot$. We see that almost all intact binaries will be retained in clusters where $V_{esc} \gtrsim 75\,km\,s^{-1}$. The merged objects tend to possess larger velocities, only half being retained when $V_{esc} = 60\,km\,s^{-1}$. The unbound neutron stars have much larger velocities, and only a few per cent will be retained in any cluster. Truly single neutron stars are retained less than 0.5 per cent of the time.

2.4 Likely retained population

We now consider the properties of the binaries retained intact in a typical cluster. In all the initial binaries we use here $M_1 = 3.5\,M_\odot$, and we consider $50\,R_\odot \le d \le 200\,R_\odot$ as above. We consider binaries having secondaries of four different masses, namely 1.25, 2.5, 5 and $10\,M_\odot$. The number of realizations (out of a total of 50 000 for each set of parameters considered) that lead to retained neutron stars (taking $V_{esc} = 40\,km\,s^{-1}$), either as single stars, in merged objects, or within binaries is listed in Table 1 for the various secondary masses. It is clear from this table that a much larger fraction of the neutron stars will be retained if they are to be found initially in binaries with more massive secondaries.

We consider next the subsequent evolution of the retained binaries as it would occur in the field, or in a sufficiently low-density cluster where the time-scale for encounters with other stars is prohibitively large. The semimajor axes, d, and eccentricities, e, of the binaries retained in the above analysis with $M_2 = 10\,M_\odot$ are

Table 1. Number of neutron stars retained from a population of 50 000 binaries for a range of secondary masses, taking $V_{esc} = 40\,km\,s^{-1}$.

Secondary mass, M_2	$1.25\,M_\odot$	$2.5\,M_\odot$	$5\,M_\odot$	$10\,M_\odot$
unbound neutron stars	163	165	183	254
mergers	0	0	0	15
mergers from binaries	0	0	14	279
binaries	171	346	1135	4386
total	334	511	1332	4934

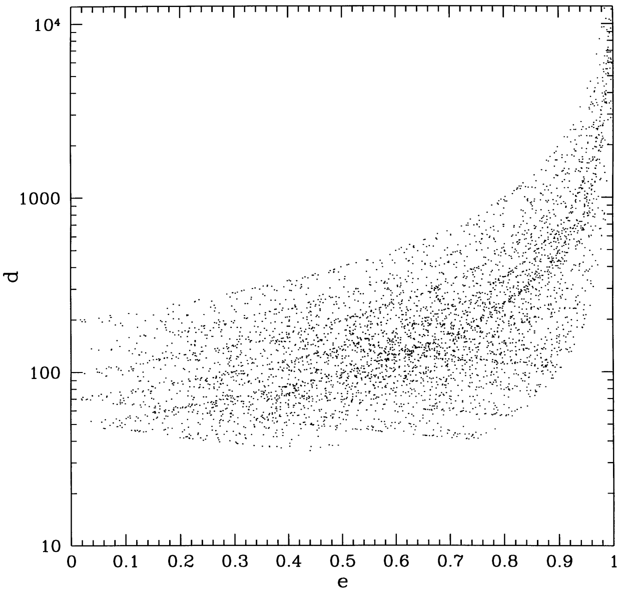

Figure 4. The semimajor axes, d, and eccentricities, e, of the binaries retained in a globular cluster having $V_{esc} = 40\,km\,s^{-1}$. The initial binaries contained a secondary of mass $10\,M_{\odot}$.

shown in Fig. 4. We note that the binaries have a large spread in eccentricity (recall that the initial binaries were all circular). There is also a large spread in semimajor axes, although most systems have $d \sim 100-300\,R_{\odot}$.

The time-scale for the secondary to evolve up the giant branch is, of course, dependent on its mass. We expect the systems where $M_2 = 10\,M_{\odot}$ to evolve in a time $\sim 10^7$ yr. Such systems may appear as Be systems or high-mass X-ray binaries (HMXBs).

For binaries of separation $\sim 100\,R_{\odot}$ such as we have here, the giant will overflow its Roche lobe either on the red giant branch or, for the wider systems, on the AGB (although these may be preceded by a short period of wind-fed mass transfer). The mass transfer for strongly convective envelopes is dynamically unstable, leading to the formation of a common envelope (Paczynski 1976) and an in-spiral of the two stellar remnants. The final state of this system is uncertain. The complete merger of the neutron star and secondary core is possible, although several field binaries consisting of neutron star and white dwarf in close (1–10 d) orbits are thought to result from this process. Similarly, a double neutron star binary could form if the spiral-in occurs with the secondary on the AGB, although the kick from the second supernova is likely to remove the binary from the cluster. Since a compact binary will behave as a single entity in the following encounter calculations, these differences will not affect our results directly, although they will influence the interpretation in terms of the spin properties of the remnants. Alternatively, the accretion of too much material on to the neutron star could result in collapse to a black hole.

Table 1 suggests that neutron stars formed in binaries containing massive secondaries are more likely to be retained in globular clusters (by a factor of ~ 20). Thus if a reasonable fraction of neutron stars were formed in massive binaries, the majority of neutron stars found in globular clusters today will have once been in an HMXB. This will also be true of neutron stars retained in binaries in the field. Indeed, the birth rates of HMXBs and Be systems are much higher than that of LMXBs.

Systems containing a main-sequence star of mass $M_{ms} < 0.66 M_{ns}$ will form low-mass X-ray binaries (LMXBs) once the secondary fills its Roche lobe. The fate of the binaries with slightly more massive secondaries (i.e. $M_{ms} \sim M_{ns}$) is less clear. A short period of mass transfer is likely if the secondary fills its Roche lobe close to the main-sequence. Such a phase may last $\sim 10^7$ yr. Her X-1 is an example of such a system (in this case, $M_2 = 2.35\,M_{\odot}$). Such systems may offer a solution to the birth-rate problem of millisecond pulsars, as the phase of mass transfer, and thus visibility as an X-ray bright object, is much shorter than that in an LMXB, whilst enough material might be accreted on to the neutron star to speed it up to millisecond periods. Alternatively, the subsequent in-spiral of the neutron star–white dwarf binary produced via a common envelope phase may lead to a second period of mass transfer (producing an object like 4U1820-30) which may spin up the neutron star to millisecond periods. Such *intermediate-mass X-ray binaries* (referred to hereafter as IMXBs) are unlikely to be produced in large quantities from the initial binary population as systems containing relatively low-mass main-sequence stars are unlikely to remain bound once the supernova occurs. Those that do are likely to have high kick velocities which would eject them from a globular cluster. For example, evolutionary models for Her X-1 predict that it received a kick velocity of $\sim 100\,km\,s^{-1}$ when the neutron star was formed (Verbunt et al. 1990). We therefore conclude that IMXBs produced directly from the primordial binary population are relatively rare and therefore are unlikely to be the source of the MSP population found in globular clusters.

However, the spin evolution of the globular cluster neutron stars is also affected by three body exchanges in the dense cores, as we shall now demonstrate. This can happen in two ways. The first occurs when the retained binary interacts with another star before the secondary has evolved significantly. The second occurs when the final binary evolution endstate (be it a single star or a close binary) interacts with a primordial binary.

3 ENCOUNTERS BETWEEN RETAINED BINARIES AND SINGLE STARS

In this section we consider encounters between retained binaries and single stars (the first of the two possibilities mentioned above). We obtain an estimate of the time-scale for such encounters using the expression (Davies 1995)

$$\tau_{enc} \sim 10^{11} \frac{V_{10}}{n_5} \frac{1}{R_{min}} \frac{1}{M_1 + M_2 + M_3}\,\text{yr}, \tag{10}$$

where R_{min} is the minimum distance, $\sim d$, the semimajor axis of the binary, and $M_1 + M_2 + M_3$ is the sum of the masses of the three stars (all in solar units). n_5 is the number density of stars, n_0, in units of $10^5\,pc^{-3}$. Stars of one solar mass have velocity dispersion V_{10} in units of $10\,km\,s^{-1}$. We plot the cumulative distribution of τ_{enc} in Fig. 5, assuming a number density of 10^4 star pc^{-3} and using an IMF by Kroupa, Tout & Gilmore (1993) (it should be noted that the IMF derived by Kroupa was for stars in the solar neighbourhood). All three sets of binaries have comparable median encounter time-scales, $\tau_{enc} \sim 10^9$ yr.

Given the discussion in the earlier section it is clear that if most of the binaries have secondaries of mass $M_2 \sim 10\,M_{\odot}$, and they are retained somewhat uniformly within the cluster (recalling that even the systems retained in clusters receive significant kicks at birth), or perhaps even initially concentrated in the outer parts, where certainly $n_0 \lesssim 10^4\,pc^{-3}$, the main role of the secondary is to keep the neutron star in a cluster. The neutron star is likely to be single or perhaps in a compact binary with a white dwarf (or have been

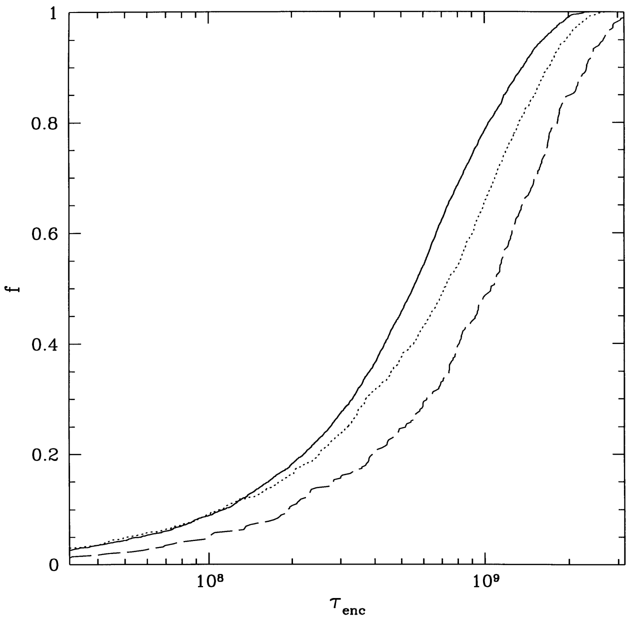

Figure 5. The cumulative distribution of encounter times for the binaries retained in a globular cluster having $V_{esc} = 40\,km\,s^{-1}$. Initial binaries having secondary masses of 2.5 (dashed line), 5 (dotted line), and $10\,M_{\odot}$ (solid line).

smothered by the core of its companion within a common envelope) by the time it encounters another star.

For lower mass secondaries the situation is less clear, especially if $n_0 \gg 10^4$ pc^{-3}. Following the method employed by Davies (1995) and Davies & Benz (1995), we performed a series of Monte Carlo simulations considering encounters between the retained binaries obtained in the previous section and a population of single stars derived from a Kroupa IMF. As the encounter time-scales illustrated in Fig. 5 are much longer than the lifetimes of very massive stars (i.e. $M \gtrsim 5\,M_{\odot}$), we consider here the evolution of only those binaries containing a 2.5-$M_{\odot}$ star. The evolution of systems containing less-massive stars will be similar, although the retention rates of such systems in globular clusters is likely to be low for the reasons discussed in the previous section. In the field these binaries will evolve into systems similar to Her X-1, and may produce MSPs by passing through a relatively brief phase of mass transfer (as an IMXB), as was discussed earlier. Thus any neutron stars contained in such binaries are potential MSPs if they can remain in their original binary until its companion evolves off the main sequence. In Table 2 we list the relative frequency of a number of possible outcomes for 5000 such binaries injected into a population of single stars (for different number densities). The number of neutron stars contained in the original binaries when the companions evolve, n_{orig}, is a strong function of the number density of the stellar cluster. For $n \lesssim 10^4$ star pc^{-3}, more than 80 per cent of such systems will reach the phase of mass transfer. For higher densities, more massive main-sequence stars will exchange into the binaries, often removing the less-massive neutron stars. In a small number of cases, the 2.5-$M_{\odot}$ main-sequence star will be replaced by a field main-sequence star (n_{imxb}). More often the evolution of the binary is terminated when the neutron star is smothered by a main-sequence star during an encounter (n_{sns}). Smothered neutron stars have also been seen in simulations of encounters between single neutron stars and main-sequence stars (Davies, Benz & Hills 1992) where the main-sequence star becomes utterly disrupted to produce a thick disc around the neutron star. The subsequent evolution of such a system is uncertain, but enough material may accrete on to the neutron star to produce an MSP.

Table 2. Outcome of neutron stars retained in 5000 binaries, containing $2.5\,M_{\odot}$ main-sequence companions, as a function of stellar number density *n*. n_{sns} is the number of smothered neutron stars produced. n_{imxb} is the number of intermediate-mass X-ray binaries produced via exchange encounters, and n_{orig} is the number of neutron stars contained in the original binaries when the companions evolve.

n	n_{sns}	n_{imxb}	n_{orig}
10 000	606	219	4175
30 000	1199	295	3506
100 000	2085	271	2644

If any of the neutron stars retained in clusters are initially contained in binaries with lower-mass main-sequence stars (i.e. $M_{ms} \lesssim 1\,M_{\odot}$), it seems likely that encounters with more-massive field stars will lead to exchange encounters where the more-massive field star replaces the less-massive component of the binary. In other words an IMXB will be produced.

4 ENCOUNTERS BETWEEN SINGLE NEUTRON STARS AND PRIMORDIAL BINARIES

The previous sections have demonstrated how the population of neutron stars in a dense globular cluster is dominated by objects which have undergone some kind of interaction with their companions, whether it is a common-envelope-induced in-spiral (and perhaps merger) or a direct smothering collision with a main-sequence star. This occurs on time-scales significantly shorter than the cluster age. Thus, despite their binary origin (which was necessary to keep them in the cluster), rapid stellar evolution seems likely to yield a population of single neutron stars which will then encounter other single stars and binaries. We therefore next consider encounters between single neutron stars and binaries.

We inject a population of binaries into a static core of single stars (the effects of higher densities and mass segregation means that the core drives these processes). In order to more clearly discern the effects of the initial separation of the binaries, in each simulation, we only considered binaries of a single initial separation rather than a continuum of values. The single star population was drawn from the Kroupa IMF. The components of the binaries were drawn from the same IMF, with the additional constraints that $0.5\,M_{\odot} < M_1 < 2.0\,M_{\odot}$ and $0.1\,M_{\odot} < M_2 < M_1$. A larger upper limit for M_1 could have been taken (as main-sequence stars up to $\sim 8\,M_{\odot}$ exist when the neutron stars are formed). However, as the IMF favours lower-mass stars, the number of very massive stars is relatively small, and this, coupled with their shorter lifetimes, makes them unimportant as potential mass donors for the neutron-star population.

The cores of globular clusters are likely to contain a large fraction of massive stars compared to the rest of the cluster owing to the effects of mass segregation. In particular the core may (eventually) contain a large fraction of the retained neutron stars. The neutron

Table 3. Number of smothered neutron stars ($n_{\rm sns}$) and IMXBs ($n_{\rm imxb}$) produced in 15 Gyr as a function of stellar number density n. The number of systems produced between 14 and 15 Gyr is also given ($n^{\dagger}_{\rm sns}$ and $n^{\dagger}_{\rm imxb}$).

n	$n_{\rm sns}$	$n^{\dagger}_{\rm sns}$	$n_{\rm imxb}$	$n^{\dagger}_{\rm imxb}$
3000	258	12	156	4
10 000	795	27	245	1
30 000	1234	7	259	0
100 000	1504	0	162	0

star population was therefore boosted so that it made up 10 per cent of the population of single stars. In all cases, we assume the core has a volume of 1 pc^3. We also make the simplifying assumption that the number density of stars in the cluster core does not evolve in time. Although this will not be the case, the trends we present in this section will also hold for an evolving core, the production rates of interesting objects being some average of the rates obtained for the different number densities.

In a Monte Carlo fashion, we determine the encounters for each binary, evolving it through exchange and fly-by encounters and allowing for mergers, until the binary is broken up, or the time exceeds the allowed maximum of 20 Gyr. We also finish evolving the binary once a smothered neutron star is produced, or when a companion to a neutron star would start evolving off the main-sequence and transfer material on to the neutron star (the so-called IMXBs, as discussed in the previous two sections). As we are concerned only with the retention of neutron stars and the subsequent production of MSPs in this paper, we do not consider the production of other binaries such as CVs (see instead Davies [1997]), or other products of mergers such as blue stragglers (see for example Sandquist, Bolte & Hernquist 1997, and references contained therein).

We begin by considering the effects of stellar number density on the production rates of SNSs and IMXBs. We injected 5000 binaries (all with separations, $d = 300\,{\rm R}_{\odot}$) into core populations of various densities at a time of 1 Gyr. The number of SNSs and IMXBs produced in the first 15 Gyr is given in Table 3 ($n_{\rm sns}$ and $n_{\rm imxb}$). We also list the number of systems produced between 14 and 15 Gyr ($n^{\dagger}_{\rm sns}$ and $n^{\dagger}_{\rm imxb}$). If the mass-transfer time-scale is 1 Gyr, and the current age of the globular cluster is 15 Gyr, then these additional quantities give us the number of systems that will be active today. This is an extremely conservative upper limit; the mass-transfer time-scale is likely to be somewhat shorter. We note from Table 3 that the number of active IMXBs is smaller than the total number of systems produced over 15 Gyr by a ratio that far exceeds that expected if the systems are produced at a constant rate. In other words, we see that they are produced at a higher rate at early times. This is illustrated in Fig. 6, where we plot the total number of IMXBs produced as a function of time. For stellar number densities $\gtrsim 10^4$ star pc^{-3}, we see that the vast majority of IMXBs have been produced by a time of 13 Gyr, the subsequent production rate being extremely small. In this case, the time-scale for a neutron star to exchange into a binary is shorter than the lifetime of moderate mass stars ($1\,{\rm M}_{\odot} < M < 2\,{\rm M}_{\odot}$). Neutron stars therefore replace the secondaries of many binaries and are ready to receive material from the moderate-mass primaries from these systems once they evolve off the main sequence. Because the donor stars in the vast majority of these systems have masses $\gtrsim 1\,{\rm M}_{\odot}$, the onset of mass transfer will occur at a time, $t \lesssim 10$ Gyr, and be complete by today, possibly leaving a millisecond pulsar. This route therefore offers an attractive possible solution to the millisecond pulsar birthrate problem. In Fig. 7 we plot the total number of smothered neutron stars produced as a function of time for various stellar number densities. For lower number densities, we see that such systems are produced at a steady rate over time. For higher densities, however, we note that the vast majority of systems have been produced significantly earlier than a time of 15 Gyr.

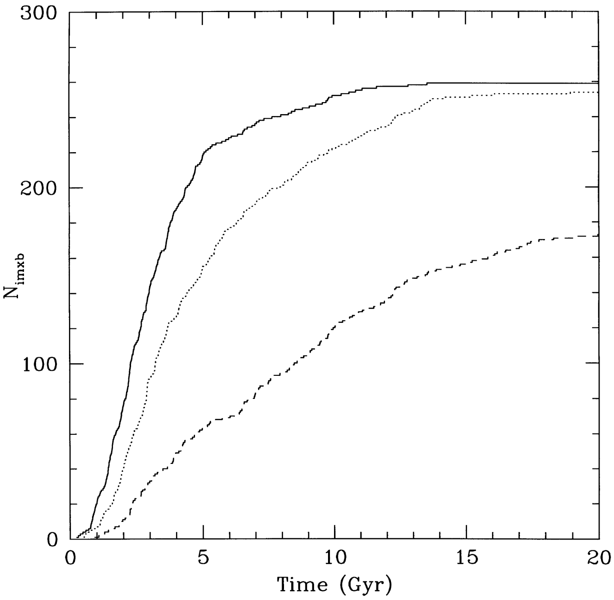

Figure 6. The total number of intermediate-mass X-ray binaries (IMXBs) produced as a function of time in a cluster core of stellar number density of 3000 (dashed line), 10^4 (dotted line), and 3×10^4 star pc^{-3} (solid line).

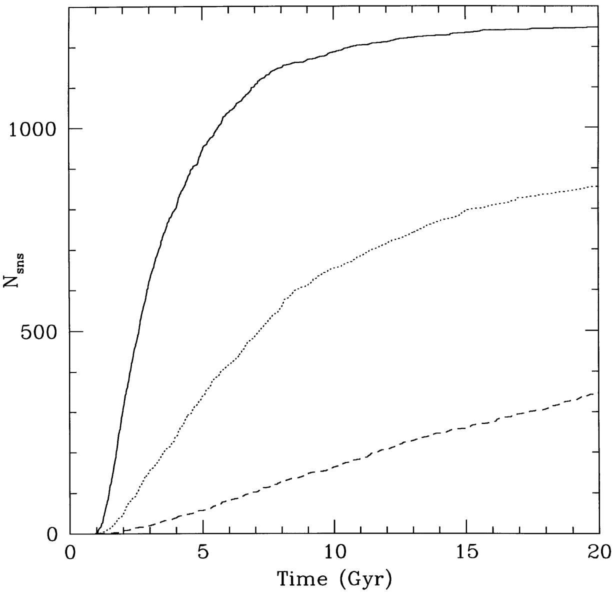

Figure 7. The total number of smothered neutron stars (SNSs) produced as a function of time in a cluster core of stellar number density of 3000 (dashed line), 10^4 (dotted line), and 3×10^4 star pc^{-3} (solid line).

We next consider the effects of varying the time at which the binaries are injected into the core of single stars. In a globular

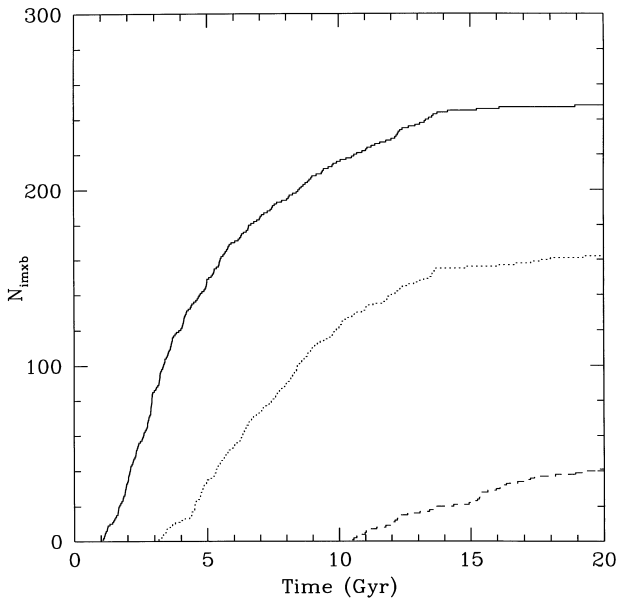

Figure 8. The total number of intermediate-mass X-ray binaries (IMXBs) produced as a function of time when binaries are injected into the core at a time of 1 (solid line), 3 (dotted line) and 10 Gyr (dashed line).

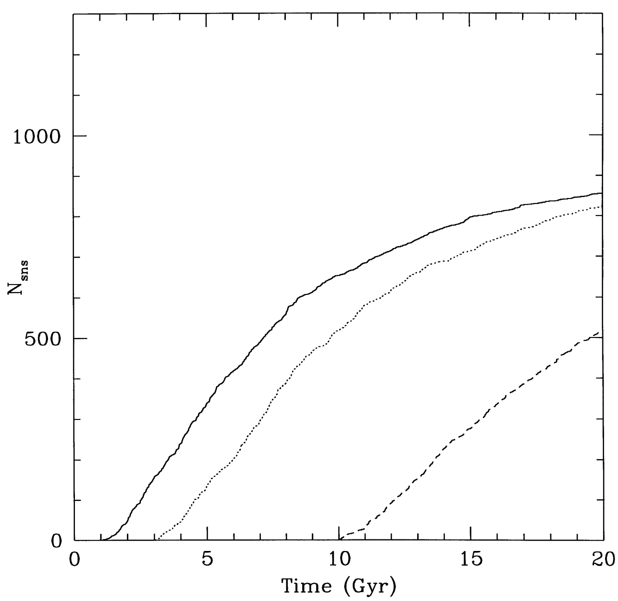

Figure 9. The total number of smothered neutron stars (SNSs) produced as a function of time when binaries are injected into the core at a time of 1 (solid line), 3 (dotted line), and 10 Gyr (dashed line).

cluster, massive stars will sink into the core on a time-scale similar to the half-mass relaxation time-scale (Bonnell & Davies 1997). Those initially found in the outer regions of the cluster halo will take even longer to sink into the core. We repeat the procedure discussed above, for the same binaries, but injecting them at 3 and 10 Gyr as well as at 1 Gyr, as used above, and illustrated in Figs 8 and 9. In all three simulations, we take the stellar number density, $n = 10^4$ star pc^{-3}. The numbers of SNSs and IMXBs produced are listed in Table 4 together with the number produced at a time between 14 and 15 Gyr. As before, the total number of systems produced is much larger than that produced recently. However, the rate of production

Table 4. Number of smothered neutron stars ($n_{\rm sns}$) and IMXBs ($n_{\rm imxb}$) produced in 15 Gyr as a function of time of injection into the cluster core, $t_{\rm inj}$. The number of systems produced between 14 and 15 Gyr is also given ($n^{\dagger}_{\rm sns}$ and $n^{\dagger}_{\rm imxb}$).

$t_{\rm inj}$	$n_{\rm sns}$	$n^{\dagger}_{\rm sns}$	$n_{\rm imxb}$	$n^{\dagger}_{\rm imxb}$
1	795	27	245	1
3	712	25	155	0
10	275	49	22	2

of both SNSs and IMXBs is approximately constant when the binaries are injected at 10 Gyr. We therefore conclude that in order to have produced a large number of SNSs and IMXBs in the past, compared to the current rate, we require that the neutron stars and primordial binaries that fuel such production sink into the cluster core on a time-scale $\lesssim$5 Gyr. In other words, the hypothesis that the MSPs are produced via IMXBs will only be viable if mass segregation can act to bring a large fraction of the retained neutron stars and massive primordial binaries into the cluster core in $\lesssim$5 Gyr. The time-scale for half the neutron stars to sink will be $\sim\tau_{\rm rh}$, the half-mass relaxation time, which is $\sim 1-10$ Gyr for most globular clusters today (Pryor & Meylan 1993). Thus we conclude that a large fraction of the retained neutron stars and heavy binaries will have sunk into the cores of most clusters on sufficiently short time-scales to produce a significant IMXB population.

Finally we investigate the effects of varying the separations of the initial binaries. Thus far we have only considered binaries having initial separations $d = 300\,{\rm R}_{\odot}$. In reality the binaries will have a range of separations. Wide binaries ($d \gg 1000\,{\rm R}_{\odot}$) are likely to be broken up by encounters with single stars. Smaller binaries will be less likely to encounter other stars, and thus less likely to produce either SNSs or IMXBs. We consider binaries with separations $d = 100$, 300 and $1000\,{\rm R}_{\odot}$. In all cases, the number density of the cluster, $n = 10^4$ star pc^{-3}, and the binaries are inserted into the core at a time, $t_{\rm inj} = 1$ Gyr. The number of SNSs and IMXBs produced are given in Table 5. From this table, we note that SNSs are produced at an approximately constant rate when the binary separations, $d = 100\,{\rm R}_{\odot}$. For all three values of d, the IMXB production rate decreases rapidly with time. The total number of systems produced increases with d, but only slowly. A given binary simply has to be large enough such that the time-scale for a neutron star to replace the secondary is shorter than the evolutionary time-scale of the primary.

Table 5. Number of smothered neutron stars ($n_{\rm sns}$) and IMXBs ($n_{\rm imxb}$) produced in 15 Gyr as a function of binary separation, d. The number of systems produced between 14 and 15 Gyr is also given ($n^{\dagger}_{\rm sns}$ and $n^{\dagger}_{\rm imxb}$).

d	$n_{\rm sns}$	$n^{\dagger}_{\rm sns}$	$n_{\rm imxb}$	$n^{\dagger}_{\rm imxb}$
100	419	27	161	3
300	795	27	245	1
1000	1214	11	357	0

5 DISCUSSION

From table 2 of Phinney (1996), we see that some 3000 recycled pulsars have been produced in globular clusters with central densities in excess of $3\times10^5\,M_\odot\,pc^{-3}$. These clusters in total contain a mass of $\sim10^7\,M_\odot$. Therefore $\sim5-10$ per cent of all neutron stars produced in these clusters have become recycled pulsars, assuming that all pulsars are made from neutron stars (as opposed to via accretion-induced collapse of white dwarfs). In less dense clusters, $\sim10^3$ recycled pulsars have been produced from a total stellar mass of $\sim3\times10^7\,M_\odot$, in other words ~1 per cent of neutron stars have become recycled pulsars. If we (optimistically) assume that 10 per cent of neutron stars are retained in all clusters, then at least half of this retained population must form MSPs in the most dense clusters. In those with lower central densities, this figure is closer to 10 per cent.

Our results indicate that, with current estimates of pulsar birth velocities, the majority of pulsars that remain in clusters were born in binaries with massive companions (assuming a binary fraction $\gtrsim5$ per cent). However, the short lifetime of massive stars means that the pulsar is either single or in a close binary before it encounters a third star. Thus, the interaction of pulsars with the main-sequence binaries in the cluster is largely unaffected by the pulsars' origins. The pulsars, being quite massive, tend to exchange into those binaries they encounter, resulting in either a smothered neutron star (SNS) or an intermediate-mass X-ray binary (IMXB). An important point about this population is that *the vast majority of such systems will have passed through the (X-ray visible) first phase of mass transfer 5–10 Gyr ago* and this may explain why the number of MSPs outnumbers the population of X-ray binaries today. Some IMXB may also evolve into a common envelope system in which the mass donor smothers the neutron star, either merging the system or creating a tight binary containing the neutron star and a low-mass white dwarf (i.e. the former core of the mass donor). If the binary is sufficiently close initially (separation $\lesssim3\,R_\odot$) it will spiral into contact in $\lesssim10^{10}$ yr and a second period of mass transfer will occur, again on a short time-scale, producing a system similar to 4U1820-30 (Bisnovatyi-Kogan 1989; Kluzniak, Czerny & Ray 1992; Ergma, Lundgren & Cordes 1997). The detailed post-common-envelope evolution of IMXBs will be discussed in detail in a subsequent paper.

If the first phase of mass transfer does indeed spin the neutron stars up to millisecond periods, it follows that most of the observed millisecond pulsars are old. Unfortunately the timing ages determined from spin parameters are notoriously unreliable for millisecond pulsars (see Hansen & Phinney 1998) and the spin-down rates for many are further contaminated by the ambient cluster accelerations (Phinney 1993). Also, the luminosity evolution of the millisecond pulsar population is not well constrained. The luminosities of normal pulsars decay on similar time-scales as the spin-down time. If the millisecond pulsars follow a similar trend, their luminosities will decay only on time-scales of several Gyr. Thus it is not possible to infer age information from the pulsar population directly.

The investigation of how our results affect the spin evolution of these pulsars is a complicated operation, involving several uncertainties related to the nature of the mass transfer in each of the different interaction possibilities (see Krolik, Meiksin & Joss 1984; Phinney 1996) and the cluster density. A detailed study will be presented in a subsequent paper. Nevertheless, several interesting consequences immediately present themselves. The fact the production of SNS is as fast as that of IMXB (and more numerous for the higher density environments) suggests that a significant fraction of SNS will be able to interact again with a second binary, so that some pulsars may undergo several spin-up/down episodes. A smothered neutron star, exchanged into an IMXB, should spin down by the propeller effect (Illarionov & Sunyaev 1975) quite rapidly and thereafter resemble an ordinary IMXB product.

Another interesting possibility results from the fact that close binaries, such as might be produced from the original common-envelope evolution, will behave like single stars when exchanging into binaries. Thus, we see that there is a strong possibility of such a binary being smothered by collision with a main-sequence star, which should drive such a system to coalescence. It is worth noting here that, although we haven't explicitly treated the possibility, a close double degenerate white dwarf binary will weigh $\sim1-2\,M_\odot$ and so will behave in a similar fashion. A smothering-induced merger of these two objects could well be an alternative pathway to collapse to form a neutron star. This has the attractive feature of inevitability. One of the primary objections to invoking accretion-induced collapse has been the lack of observed progenitor systems.

The saturation of SNS/IMXB production is the result of the exhaustion of the binary reservoir, i.e. once nearly all the binaries contain stars more massive than the average single star, the probabilities of exchange interactions decreases. However, the fact that the average binary is an IMXB, with a secondary lifetime significantly less than the age of the cluster, means that there will be a significant population of neutron stars with $\sim0.3-0.4\,M_\odot$ white dwarf companions. These are likely to have a wide range of separations, and the wider ones will again be vulnerable to exchange interactions with field stars. This suggests that one may obtain either smothered millisecond pulsars (which will probably spin down rapidly via the propeller mechanism) or perhaps even a binary containing a millisecond pulsar and an unevolved star! The latter would be an unambiguous signature of an exchange interaction.

The arresting of the core collapse has been variously attributed to three-body encounters, stellar mergers or central black holes (see Goodman 1988, Murphy 1993 and references therein). The scenario we describe here will influence both the primordial binary distribution and the pulsar distribution. The latter is important because the mass segregation influences the rate of core collapse. If a significant fraction of the pulsars are in binaries (as suggested by our results), then the mass segregation will become all the more important.

6 CONCLUSIONS

We have investigated the process by which neutron stars are retained in globular clusters and spun-up to millisecond periods. We conclude the following.

(1) Retention of a newly-formed neutron star in a globular cluster is greatly favoured if the neutron star remains bound to a massive companion. Given the current consensus on kick velocities, it is *extremely unlikely* that any neutron stars formed outside a binary will be retained in a globular cluster.

(2) The subsequent evolution of such massive binaries occurs on a time-scale typically much shorter than the time-scale required to encounter another star or binary. These systems will therefore follow evolutionary paths in globular clusters similar to those in the field, probably producing single neutron stars, or possibly tight binaries containing two compact objects.

(3) Any single neutron star produced by the evolutionary path described above that is retained in the core, or has time to sink into

the denser regions of a cluster, will have sufficient time to exchange into a binary containing a moderately massive ($\sim 1-3\,\mathrm{M}_{\odot}$) star before the latter evolves off the main sequence. Stellar evolution will then drive the binary into contact and a brief period of mass transfer; a system we labelled an intermediate mass X-ray binary (IMXB).

(4) Mass transfer in the IMXB phase may spin up the neutron star to millisecond periods. An important characteristic of such systems is that they all will have occurred in the past.

(5) The interactions between binaries and field stars give rise to a wealth of evolutionary pathways to spin up neutron stars. The fact that binary companions to pulsars will tend to be more massive on average than in the field will affect the spin-up histories. In particular, many pulsars may undergo more than one accretion episode, either as the result of exchange into another unevolved binary or as a result of the spiral-in of a compact secondary. In the latter case, the binary will resemble 4U1820-30.

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