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Formation of Compact Binaries in Globular Clusters

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Abstract. Globular clusters are overabundant per unit mass in neutron-star binaries, including low-mass X-ray binaries and radio pulsars. We report here on two complementary population synthesis studies which relate directly to the formation and evolution of neutron star binaries in globular clusters. In the first we consider an early population of massive stars, including those in binary systems, which produce the original population of neutron stars. We compute the probability of retention of these neutron stars, and quantitatively confirm the idea that the retention fraction for neutron stars born in binary systems is greatly enhanced over those born in isolated stars. However, with the currently fashionable natal kick velocities given to neutron stars, the retention fraction may well be insufficient to explain the current population of neutron star binaries. In the second study, we follow a large population of primordial binaries and neutron stars throughout the lifetime of a globular cluster whose properties may be similar to 47 Tuc. We directly compute all 3-body interactions among binary systems, neutron stars, and isolated field stars throughout the history of the cluster. The evolution of certain types of neutron star binaries is followed up to the current epoch. The numbers of close, recycled, binary radio pulsars are evaluated and compared with the results of radio observations. We find that for an initial population of some 10^6 primordial binaries and $\sim 10^4$ neutron stars, we can plausibly account for the large numbers of binary radio pulsars that are inferred to exist in clusters such as 47 Tuc.

1. Introduction

Globular clusters are known to contain a large variety of highly interesting systems containing neutron stars (NSs) and white dwarfs (WDs). These include binary millisecond pulsars, low-mass X-ray binaries, cooling WDs in binaries, CVs, and the enigmatic low-luminosity X-ray sources. Clusters are overabundant in these objects, per unit mass, due to the fact that numerous dynamical formation channels exist in clusters that are not available to stars born in the galactic disk. We describe here a comprehensive population synthesis study of the production and retention of compact objects in clusters and the binary systems containing these objects. Our study differs from others in that we follow an entire population of primordial binaries and NSs through the lifetime of their host cluster.

The study divides itself naturally into two parts. In the first part, we consider an early cluster population of massive stars, including those in binary systems, which produce the original population of NSs. We apply Monte Carlo methods, binary stellar evolution theory, and natal kicks to the NSs to calculate the retention probability for these NSs. We compute the NS retention fraction as a function of the rms kick speed and the central escape speed of the globular cluster.

In the second study, we follow a large population of primordial binaries and NSs throughout the lifetime of a globular cluster whose properties may be similar to 47 Tuc. Each of the NSs and primordial binaries is followed as it sinks toward the cluster core region as a result of dynamical friction. In or near the core, the binaries are allowed to undergo randomly chosen (according to the appropriate cross sections) collisions with field stars and NSs. We directly compute all relevant 3-body interactions among these systems throughout the history of the cluster. All of the binaries and $\sim 10^4$ NSs are followed, in parallel, as a function of time to the present epoch. The evolution of certain types of NS binaries are followed in detail up to the current epoch. The numbers of close, recycled, binary radio pulsars are evaluated and compared with the findings of radio observations. We conclude that for an initial population of some 10^6 primordial binaries and $\sim 10^4$ neutron stars, we can plausibly account for the large numbers of binary radio pulsars that are inferred to exist in clusters such as 47 Tuc. Companions to the NSs turn out to be white dwarfs, other NSs, and normal stars with lower than the turnoff mass. Other interesting binaries include combinations of He and CO WDs.

2. Retention of Globular Cluster Neutron Stars

A major question to be answered in the study of NS binaries in globular clusters is, "How are the NSs that are born in the cluster retained by the cluster?" The problem is that globular clusters have typical central escape speeds of a few 10's of km s^{-1}, and neutron stars are widely thought to be born with substantial "kick" velocities. A three-dimensional speed distribution for NSs in the galactic disk has been inferred from proper motion studies of about 100 radio pulsars (e.g., Lyne & Lorimer 1994). A number of authors (e.g., Hansen & Phinney 1997) have taken the natal kick speed distribution to be represented by a Maxwellian of the form $p(v) \propto v^2 e^{-v^2/2\sigma^2}$, where $\sigma \simeq 190$ km s^{-1}. A simple integration of this distribution from $v = 0$ to the typical escape speed of a globular cluster quickly demonstrates that only a very small fraction of neutron stars receiving such a kick could remain bound in the cluster ($\sim 0.1 - 1\%$ for a reasonable range of escape speeds). This is the essence of the NS "retention" problem.

It has been suggested by a number of authors, and demonstrated quantitatively (e.g., Drukier 1996; Davies & Hansen 1998), that if NSs are born in massive binaries, then there is a significant probability that the NS would remain in the binary, and that the recoil of the binary could be sufficiently small to allow it to remain bound in the cluster. In a study of a grid of models, Davies & Hansen (1998) found that somewhere between $\sim 4\%$ and $\sim 25\%$ of the NSs formed in massive binaries could be retained in a typical cluster, depending on the initial binary parameters. While these studies provided a useful verification of the potential role of massive binaries in retaining NSs in clusters, they did not involve a population study to determine a realistic net neutron star retention fraction. This is crucial, since the retention fractions found in the Davies & Hansen (1998) study span the range from providing the requisite number of NSs to leaving the problem essentially unsolved.

We utilize Monte Carlo techniques to choose the initial parameters for some large number (e.g., 10^6) of primordial binaries (see, e.g., Rappaport, Di Stefano, & Smith 1994; Soker & Rappaport 2000). The primary mass is chosen from an assumed initial mass function (IMF) (see, e.g., Miller & Scalo 1979; Kroupa, Tout, & Gilmore 1993). For this part of the study, we consider only primaries sufficiently massive (i.e., $\gtrsim 8\,M_\odot$) to form NSs. We adopt a distribution of mass ratios for primordial binaries, $p(q)$, which is approximately flat (see, e.g., Duquennoy & Mayor 1991). The initial orbital period, P_{orb}, is chosen from a function which is constant in $\log P_{orb}$ (see, e.g., Duquennoy & Mayor 1991; Abt & Levy 1985). The orbital eccentricity is chosen from a uniform distribution. At the onset of mass transfer we simply assume that the orbit circularizes and that orbital angular momentum is conserved in the process.

Once the parameters of a primordial binary have been set, the subsequent evolution of the primary and the effects of mass transfer and loss are followed according to a set of prescriptions (see, e.g., Podsiadlowski, Joss, & Hsu 1992). Wherever possible, these prescriptions are derived from stellar evolution calculations with a Henyey-type code (Kippenhahn, Weigert, & Hofmeister 1967). Once the primary evolves, there are a number of possible outcomes, depending on whether mass transfer takes place while the primary is still on or near the main sequence (Case A), after the core is hydrogen exhausted (Case B), or after the core is helium exhausted (Case C); there is also the possibility that the orbit is sufficiently wide that no mass transfer takes place. For the case where mass transfer from the primary to the secondary takes place, the transfer may be either stable or dynamically unstable, depending on the mass ratio of the two stars and the evolutionary state of the primary.

For stable mass transfer a prescription is needed for the fraction, $(1-\beta)$, of transferred mass that is ejected from the binary system and the specific angular momentum, α, that is carried away with the ejected matter (see Podsiadlowski, Joss, & Hsu 1992). The value of β is rather uncertain and may essentially be taken to be a free parameter of the problem. At present we take a fixed value of $\alpha = 1.5$, which is close to the value expected for matter ejected from the L2 point. For β we somewhat arbitrarily take a fixed value of 0.7.

If the mass transfer is dynamically unstable, we assume that a common envelope (CE) phase is initiated and that the secondary spirals in toward the core of the primary as a result of drag forces. We adopt the standard approach of assuming that some fraction, $\alpha_{CE} \sim 1$, of the initial orbital binding energy is deposited into the CE as frictional luminosity (see, e.g., Meyer & Meyer-Hofmeister 1979; Sandquist, Taam, & Burkert 2000). For the envelope binding energy we use the recent calculations of Dewi & Tauris (2000) and Han, Podsiadlowski &

Eggleton (1995; who also consider the ionization energy in the envelope). If sufficient energy is available so as to unbind the envelope, what remains is a compact binary consisting of the secondary, which we assume is unaltered in the spiral-in process, and the helium-rich core of the primary. If the CE is not ejected, then drag forces will perpetuate the spiral-in until the two stars merge.

At the end of this first part of the evolution the result may be a stellar merger, a He star in orbit with a companion, or a wide binary whose evolution is essentially that of two single stars. Whichever the case, the primary evolves to core collapse, followed by a supernova explosion. At this point we choose a natal kick speed from some distribution (e.g., a Maxwellian) and a random direction for the kick. The post-supernova orbit is computed, and if the NS escapes the binary, its speed relative to that of the pre-supernova binary is computed, while if the NS remains bound in the binary, the recoil of the binary is computed. In either case it can be established whether the NS (either single or in a binary) is retained in the cluster. At the present time we simply use a fixed escape speed from the cluster, i.e., we do not consider the location of the binary within the cluster or the velocity of the binary prior to the supernova.

After this process is repeated for $\sim 10^5$ primordial binaries, we simply count the fraction of NSs retained by the cluster, whether single or in binary systems. As the binaries containing NSs continue to evolve, it is likely that the NS will ultimately be engulfed in the envelope of the companion once mass transfer commences (i.e., following a brief interval as a high-mass or intermediate-mass X-ray binary). In many cases, especially for the shorter orbital period systems where the companion is not too evolved when mass transfer occurs, this will lead to a complete spiral in and the possible formation of a Thorne-Żytkow object (Thorne & Żytkow 1977). The final fate of these objects is the subject of considerable debate (Podsiadlowski, Cannon, & Rees 1995). The envelope of the Thorne-Żytkow object may ultimately be dispersed, leaving a NS, or the NS may undergo hypercritical accretion and collapse into a black hole (Chevalier 1993; Bethe & Brown 1998). Since a second common-envelope phase may constitute a significant path for retaining NSs, the calculations we are performing could shed important light on the answer to this question.

Some preliminary results from our retention study are given in Figure 1. The plot shows the fraction of NSs retained in a cluster as a function of the escape speed from the cluster. The thick curves are for systems born in binary systems while the thin curves are for NSs born from single stars. The sequence of three line styles labeled 50, 100, and 200 km s^{-1} corresponds to the value of σ used in the Maxwellian kick speed distribution. Note that for NSs formed from single stars and kick speeds characterized by $\sigma = 200$ km s^{-1}, the retention fraction is very small (i.e., $\lesssim 2\%$) which is insufficient to explain the numbers of NSs that are inferred to be in globular clusters (Kulkarni, Narayan, & Romani 1990; Davies & Hansen 1998; Camilo et al. 2000). The formation of NSs in binary systems, with $\sigma = 200$ km s^{-1}, significantly increases the retention fraction to $\lesssim 8\%$, but even this probably falls short of the required efficiency.

Only when the value of the mean Maxwellian kick speed is reduced by a factor of > 2 below the conventionally accepted value does the retention efficiency via binaries increase to the point where a healthy population of NSs can be retained. One immediate, albeit tentative, conclusion is that there is an apparent

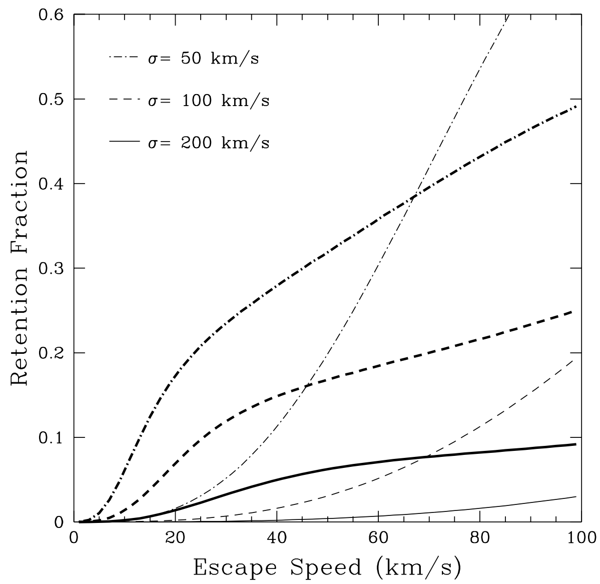

Figure 1. Retention of NSs in globular clusters. Heavy curves are for NSs born in binary systems; light curves represent NSs formed from single stars. The rms kick speed used in the Maxwellian distribution is denoted by σ.

need for a significant low-speed component to the kick distribution. Thus, it seems difficult to reconcile the apparent numbers of NSs in clusters, with the conventionally adopted natal kick speed distribution for NSs (Lyne & Lorimer 1994; Hansen & Phinney 1997; Cordes & Chernoff 1998).

3. Formation of Binaries With Neutron Stars

As mentioned above, the overabundance of NS binaries in globular clusters per unit mass, compared to that in the galactic plane, has led to the general conclusion that these objects are not formed directly from primordial binaries, but rather are the result of NS captures of a companion star. There are a number of scenarios that have been discussed over the years in which NSs can capture a companion star, in particular, low- and intermediate-mass stars which are the preferred companions for forming sources referred to as "LMXBs" and recycled pulsars. These include: (i) tidal capture of single field stars (Fabian, Pringle, & Rees 1975) and (ii) exchange collisions between primordial binaries and NSs (Hut, Murphy, & Verbunt 1991; Sigurdsson & Phinney 1993).

Tidal capture of a main-sequence or giant star by a NS has been invoked to explain the formation of close binaries in globular clusters (see, e.g., Di Stefano & Rappaport 1992). However, there are a number of problems with this scenario including possible catastrophic dynamical effects encountered during the initial capture and subsequent few orbits (Rasio & Shapiro 1991), as well as potentially catastrophic tidal heating during the subsequent circularization process (Ray, Kembhavi, & Antia 1987; Podsiadlowski 1996). However, the tidal heating may not present such a problem for the capture of more massive stars early in the cluster's history (Podsiadlowski 2000).

In the remainder of this paper we concentrate on the formation of NS binaries via NS-binary interactions.

Binary-Neutron Star Encounters Our population synthesis code for NS binaries in globular clusters includes a 3-body integrator with which we explicitly follow all relevant binary-single star encounters over the history of the globular cluster. From the total cross section for a "strong" 3-body encounter we choose via Monte Carlo methods whether there is, or is not, a scattering event for each binary in each time step. (A "strong" encounter is one in which the distance of closest approach is equal to $\lesssim 3$ times the apastron separation of the binary.) If there is a strong encounter, then we choose whether the incident single star is a NS or a field star. If the latter, the mass and type of object (either a normal star or a WD) are chosen from the stellar mass function at that epoch. Finally, the incident configuration and impact parameter for the scattering event are chosen.

A typical population synthesis run, which follows 10^6 binaries and 10^4 NSs, takes 2 days on a Sun Ultra 5 workstation; this includes following $\sim 2 \times 10^6$ scattering events.

During some binary-single star encounters, especially for those incident binaries with shorter orbital periods (e.g., $\lesssim$ a few days), and for those which develop into long-lasting resonant scattering events, there is an enhanced probability for two of the stars to come quite close together. In this case, "close" is defined as leading to a significant tidal interaction, or even mass transfer. At the present time, we merely keep track of these occurrences and eliminate systems where a NS would come close enough to one of the other stars to drive mass transfer. From our preliminary studies we have found that for the great *majority* of the scattering events we follow, there are no tidal or mass-transfer encounters between any of the stars; however, a non-negligible fraction of scattering events do show close interactions, and these should provide some interesting cases to study in the future. The reason for the relatively small number of close encounters lies in the fact that most of the 3-body collisions we follow involve systems with orbital periods $\gtrsim 10$ days, with some up to 100's of days.

Due to the possibility of a large fraction of primordial binaries in globular clusters (Hut et al. 1992), binary-binary interactions may also be important in the production of NS-binaries and in the partial depletion of the binary population. We plan to incorporate binary-binary interactions in the future. For the present study, however, all of our results are based on only binary-single star encounters.

3.1. Stellar Evolution Within Systems Containing Neutron Stars

Any given primordial binary may undergo a complicated series of exchange interactions (possibly also an ionizing interaction which terminates that particular binary), one or more of which may leave a NS in the binary. If, at some point in the history of that binary, before the current epoch, the companion to the NS evolves to the point of filling its critical potential lobe at periastron passage, the subsequent mass transfer evolution must be followed in order to ascertain whether an interesting binary, e.g., a LMXB or recycled radio pulsar, is formed.

The onset of mass transfer divides into two distinct branches: dynamically unstable and dynamically stable. In the former case a CE ensues and the NS spirals in toward the core of the donor star. The net result is likely to be the formation of a very close binary pair consisting of a NS and WD with an orbital period of a fraction of a day. [This assumes, of course, that the NS does not accrete sufficient material to collapse into a black hole during the spiral-in process (Chevalier 1993; Bethe & Brown 1998).] If the post-CE orbital period is sufficiently short (typically < 6 hours for a WD-NS pair) gravitational radiation losses may bring the binary to a semi-detached state, with the WD filling its Roche lobe, by the current epoch. The subsequent evolution will be dynamically unstable if the mass of the WD exceeds $\sim 0.4\ M_\odot$. Otherwise the mass transfer will be quite rapid, but nonetheless stable. We discuss below this type of short-lived X-ray source as possible progenitors of the very short orbital period binary radio pulsars discovered in 47 Tuc.

The other distinct possibility is that the initial mass transfer from the normal donor star to the NS will be *stable*. At the present time we do not attempt to follow the evolution of binary systems leading to stable transfer. We merely store the properties of such binaries at the onset of mass transfer.

To determine mass transfer stability from a main-sequence, subgiant, or giant star onto a NS, we combine a number of results to produce an analytic expression for the "adiabatic" stellar index, ξ_{ad}, of such a star, i.e., the logarithmic derivative of radius with respect to mass of the donor star in the absence of any heat input to the star. In particular, we used results from Hjellming (1990; see also Kalogera & Webbink 1996), as well as from our own stellar models with constant mass loss rates, as inputs to deriving such an expression. In our formulation ξ_{ad} is a function of the instantaneous mass of the donor, its original mass, and its evolutionary state (e.g., core mass or composition). We also ensured that in certain well-known limiting cases, e.g., for a fully convective star, ξ_{ad} goes to the correct limit (e.g., $\xi_{ad} = -1/3$).

Evolution of the Common-Envelope Products If the result of the initial mass transfer onto the NS is unstable, leading to a CE phase and the production of a WD-NS binary (as discussed above), the subsequent evolution of such a system can be quite interesting and may well explain some of the LMXBs and short period recycled radio pulsars in globular clusters (see the evolutionary schematic in Fig. 2). For a detached WD-NS binary the orbital decay timescale via the emission of gravitational radiation is given by $\tau_{GR} = 3 \times 10^7 (P_{orb}/\mathrm{hr})^{8/3} (\mu/M_\odot)^{-1} (M_{tot}/M_\odot)^{-2/3}$ yr, where μ and M_{tot} are the system reduced mass and total mass, respectively. So, for typical WD masses of $0.2 - 0.4\,M_\odot$, systems with $P_{orb} \lesssim 6$ hrs have a reasonable probability of becoming semi-detached (i.e., the WD fills its Roche lobe) between the formation of the binary and the current epoch. Once the WD starts to transfer matter to the NS it will be driven at very high rates by gravitational radiation losses (far in excess of the Eddington limit), and therefore mass will be ejected from the system (i.e., $\beta \simeq 0$). The condition for stability is that the quantity $D = 5/6 + \xi_{ad}/2 - (q+3)/[3q(1+q)] > 0$ (Rappaport, Verbunt, & Joss 1983), where ξ_{ad} is the adiabatic stellar index of the WD (see the above discussion), and $q \equiv M_{ns}/M_{wd}$. In turn, $\xi_{ad} \simeq (-1/3)[1 + m^{4/3}]/[1 - m^{4/3}]$ where $m \equiv M_{wd}/1.4\ M_\odot$ (see, e.g., Rappaport et al. 1987). If we combine these two expressions, we find that essentially all He WDs will transfer mass to a NS companion stably, while CO WDs will not.

For a WD-NS binary undergoing dynamically unstable mass transfer, the result will be a massive disk formed around the NS. The outcome of this is

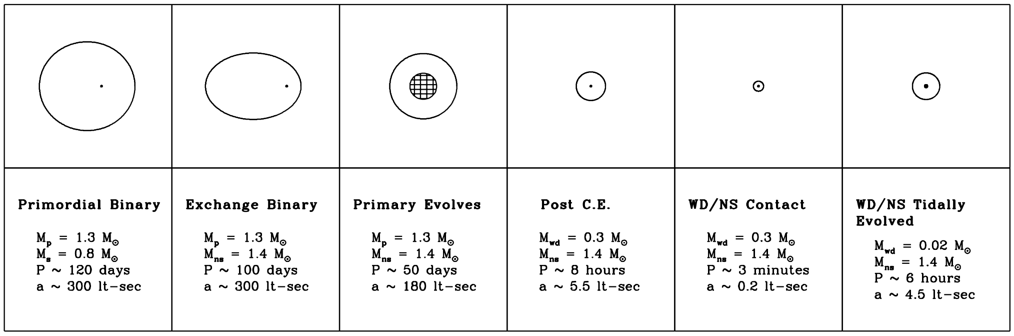

Figure 2. Schematic evolution of a highly compactWD-NS binary.

greatly uncertain, but it may be a spun up NS or black hole. We simply record these events but do not attempt to compute what the end product might be.

For WD-NS systems with stable mass transfer, the binary evolution is straightforward to follow for the case where the WD remains degenerate. A sample evolution plot for a WD-NS binary is shown in Fig. 3 (thin solid curves). The initial mass of the WD is $0.2\,M_{\odot}$, but the evolution of all stable WD-NS binaries join together once the respective masses of the WDs have been reduced to a common value. Note that M_{wd} and $\dot{M}$ decrease rapidly at the start of mass transfer, then slow considerably as the evolution progresses. During the same time, the orbital period grows due to the fact that the donor star is less massive than the accretor, even though angular momentum is being extracted from the binary via gravitational radiation. The overall evolution time for the binary to expand back to a period of ~ 2 hrs is of the order of a Hubble time.

This basic evolutionary scenario appears promising to explain 5 of the binary radio pulsars in 47 Tuc with short orbital periods (Camilo et al. 2000) and very low-mass companions ($\sim 0.02\,M_{\odot}$), as well as 3 LMXBs in other globular clusters; however, the values of P_{orb} for some of these recycled pulsars range up to ~ 6 hr, which cannot be reached with mass transfer driven by gravitational radiation alone. We have therefore also considered the effects of tidal heating as an added source of internal energy to keep the WD "bloated" beyond its completely degenerate radius (Applegate & Shaham 1994). Inclusion of tidal heating is somewhat speculative and requires the assumption of an (unknown) mechanism for keeping the WD rotation asynchronous with the orbit, as well as a synchronization timescale (a measure of viscous damping) which is essentially a free parameter. We have used a simple polytrope to represent the WD in carrying out the tidal evolution calculations, and no surface cooling has been taken into account. For the purposes of this calculation, we have adopted a fixed *a*synchronization factor of 50% and a synchronization timescale of 6×10^4 yr (see Rasio, Pfahl, & Rappaport 2000).

The results of the tidal evolution calculations are shown in Figure 3 as the set of heavy curves. The tidal heating results in a rapidly accelerated evolution, and a larger orbital period is reached than can be attained with gravitational radiation alone. Not only are the longer periods important (to match the observations), but the X-ray phase is terminated more quickly. This bears on the question of how many LMXBs with short orbital periods should be found

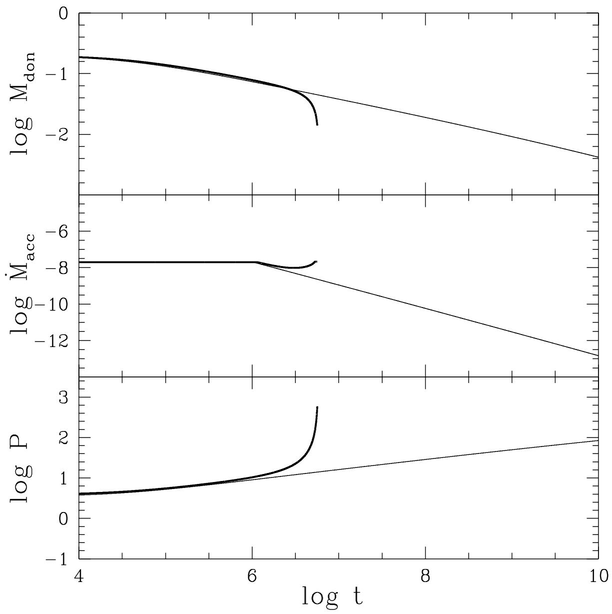

Figure 3. White dwarf-neutron star binary evolution. Solid curves are for the case of no tidal heating. Heavy curves include tidal heating; asynchronous rotation of the WD with the orbit is maintained artificially. The units for the three panels are $M_\odot$, $M_\odot\,\mathrm{yr}^{-1}$, and minutes, respectively.

in clusters at the current epoch. At present, only 4U1820-303 (P_{orb}=11 min; Stella et al. 1987), X1850-087 (P_{orb}=21 min; Homer et al. 1996), and X1832-330 (P_{orb}=44 min; Deutsch, Margon, & Anderson 2000 and references therein) may correspond to this type of system. This modest number is, in fact, more compatible with a short lived X-ray phase, than one without tidal heating.

We note that there is an alternative channel for forming compact NS binaries that does *not* involve a CE phase. From our binary evolution calculations, we find that if, at the start of mass transfer, the donor star is near the main sequence ($P_{orb} \lesssim 1$ day) and its mass is in the range of $\sim 1-3\ M_\odot$, then the mass transfer proceeds stably on a thermal timescale and the orbital period tends to shrink as magnetic braking removes angular momentum from the orbit, yielding periods as short as ~ 5 min. However, the relevance of this scenario for the formation of compact binaries in globular clusters is not yet clear since, at present, our simulations indicate that most binaries containing a NS commence mass transfer when $P_{orb} \gtrsim 10$ days.

Systems Undergoing Stable Mass Transfer For captured field stars undergoing *stable* mass transfer onto the neutron star, we would like to be able to follow this portion of the binary evolution in detail so that we can (i) classify the system at various epochs according to its properties as an X-ray source, and (ii) learn what sort of remnant recycled binary radio pulsar will remain at the current epoch. However, this would require following the evolution of a large number of systems with a Henyey-type stellar evolution code, which is very time consuming. This is clearly something that should be done in future studies.

3.2. Other Considerations for the Binary Population Synthesis Study

Time-Dependent Aspects of the Overall Cluster Evolution At least 80% of globular clusters in our Galaxy have well-resolved cores and are well-fitted by

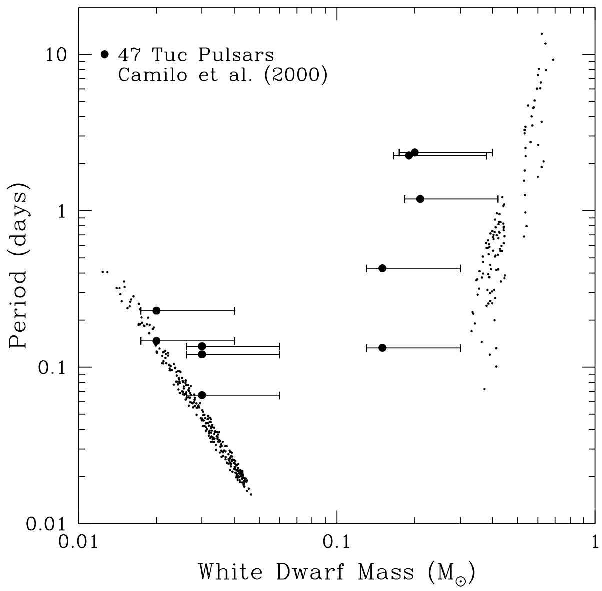

Figure 4. Orbital period vs. white dwarf mass for the end products of systems involving a low-mass WD and a NS.

standard King models (e.g., Djorgovski 1993). These clusters are thought to be supported against core collapse by the heating generated in their cores through dynamical interactions involving hard primordial binaries (Gao et al. 1991; Hut et al. 1992; McMillan & Hut 1994; Rasio 2000). During this "binary-burning" phase of cluster evolution, the core parameters remain nearly constant in time. In particular, the core radius and central density do not vary by more than a factor of ~ 2. This justifies our assumption of an approximately steady-state cluster density profile.

Sinking Times of Binaries and Neutron Stars At present, we assume that binaries and NSs undergo mass segregation and enter the cluster core in a time t_s, distributed according to $p(t_s) = (1/t_{sc})\exp(-t_s/t_{sc})$, where the characteristic time $t_{sc} \simeq 10(m/m_f)t_{rh}$ for objects of mass m drifting through field stars of average mass m_f (see, e.g., Fregeau, Joshi, & Rasio 2000). For the present study, we have simply adopted a fixed value for $t_{rh} = 10^9$ yr.

Temporal Evolution of the Field Star Population We assume that the background of single objects (normal stars and WDs) in the globular cluster core is completely confined to the core for the entire lifetime of the cluster. Thus, a star more massive than the cluster turnoff mass will shed its envelope to become a WD, and we assume that the WD remains in the core. Based on this *confinement* assumption we have derived an essentially analytic formula for the time-dependent mass function of field stars in the core, given the *initial* mass function of the stellar population. This includes a developing population of degenerate remnants.

3.3. Results From the Population Synthesis Study

Here we show some examples of the types of results that can be obtained with the approach we have adopted. The cluster parameters used to produce the

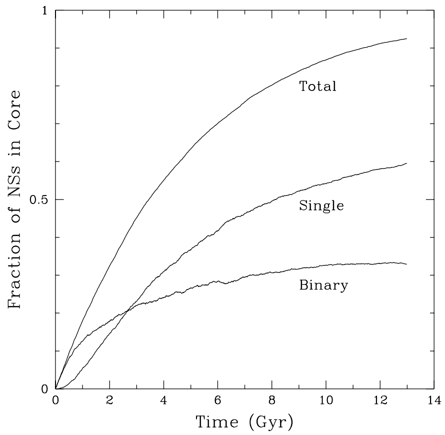

Figure 5. Fraction of the 10^4 NSs, both single and in binaries, in the core of the simulated globular cluster.

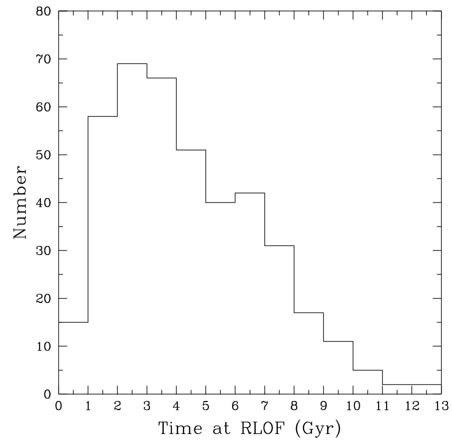

Figure 6. Time of first RLOF for systems becoming white dwarf-neutron star binaries.

following results were: 10^6 primordial binaries; 10^4 neutron stars, and a constant core density of 10^5 stars pc^{-3} (i.e., a possible representation of 47 Tuc).

In Figure 4 we show the simulated population of NS-WD binaries at the current epoch in the $P_{orb} - M_{wd}$ plane (see Rasio, Pfahl, & Rappaport 2000). Note the "track" of systems to the lower left which have 20 min $\lesssim P_{orb} \lesssim$ 6 hr and WD companion masses in the range of 0.01–0.04 $M_\odot$. These have all been spun up by the accretion process to rotation periods shorter than 5 msec. This track lies suggestively near a group of 5 binary millisecond pulsars discovered in 47 Tuc (Camillo et al. 2000). The other prominent group of simulated systems lies toward somewhat longer orbital periods (2 hr $-$ 10 days) and $M_{wd} \sim 0.4\ M_\odot$. While these systems do lie in a part of parameter space near to 5 other binary msec pulsars found in 47 Tuc, the computed binaries have systematically larger companion masses and, moreover, should not have undergone any significant amount of accretion to spin up the pulsar (these are systems where the WD-NS binary never decayed sufficiently for mass transfer to commence).

The simulated systems shown in Fig. 4 represent only a portion of the types of interesting systems formed in the population synthesis, i.e., those that result from unstable mass transfer from the normal companion to the NS leading to a CE phase. Not shown are systems of double WDs and double NSs, and importantly, none of the systems where the mass transfer from the normal star to the NS is stable. In future studies we plan to follow all of the systems undergoing stable mass transfer either with a Henyey-type code or with a large grid of pre-prepared binary evolution models.

The code also produces a wealth of supplementary information, some of which we illustrate here. From the distribution of the number of scattering interactions that a binary system undergoes before either one of the stars commences Roche-lobe overflow (RLOF) or the current epoch is reached, we find

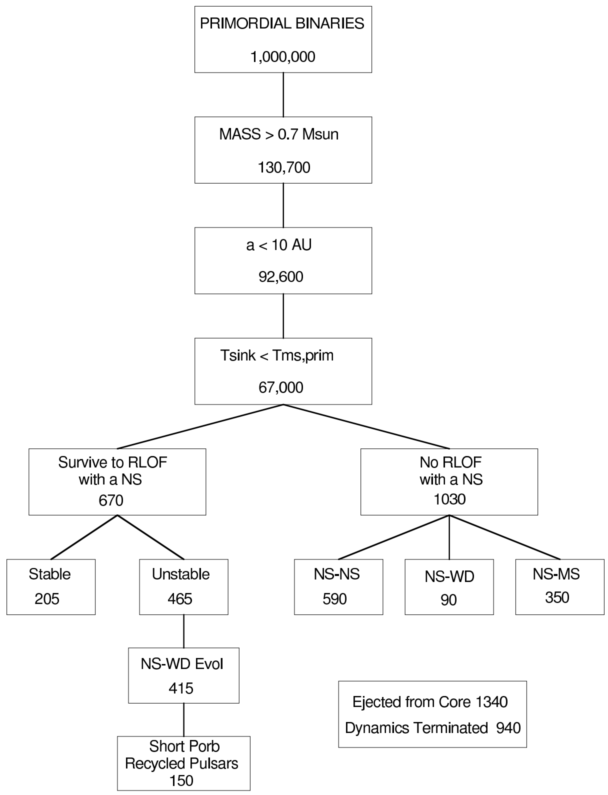

Figure 7. Numbers of surviving systems in the population synthesis study that contain neutron stars.

that the average number of interactions is ~ 25, while some binaries undergo more than 100 interactions. Fig. 5 shows the number of NSs (labeled “total”) as a function of time in the core of the cluster; the curves labeled “single” and “binary” are for isolated NSs vs. those in binaries. In Fig. 6 we show a histogram of the number of binaries (containing a NS) which commence mass transfer as a function of time. Note that this distribution peaks at ~ 3 Gyr and is rather low by the current epoch. Therefore, most of the incipient mass transfer systems were of intermediate mass and occurred relatively early in the history of the cluster (see also Davies & Hansen 1998). This type of result bears directly on the issue of the“birthrate problem” (Kulkarni, Narayan, & Romani 1990) since the progenitors of many of the recycled pulsars may have been intermediate-mass X-ray binaries (IMXBs) rather than LMXBs (Davies & Hansen 1998), were born long ago in the history of the cluster, and the X-ray phase of such systems may no longer be observed.

Finally, we show in Figure 7 a “flow” diagram which illustrates what happens to the 10^6 primordial binaries and 10^4 NSs that we started with in the particular run which generated the figures shown above. After the cuts requiring a minimum mass for the primary ($0.7\ M_{\odot}$), a maximum semimajor axis of 10 AU (such systems would be quickly ionized), and no RLOF before the primordial binary sinks to the core, there are 6.7×10^4 binaries remaining. Roughly 2000 binaries acquire a NS via exchange interactions; of these about 1/3 ultimately undergo RLOF from an evolving donor star. About 2/3 of the RLOF cases are unstable and produce WD-NS binaries, while the remainder undergo stable mass transfer. Of the systems which end up without RLOF onto the NS, there are substantial numbers with companion WDs (~ 100), NSs (~ 600; these are generally in wide orbits and are not recycled), and low-mass, unevolved main-sequence stars. A substantial number of binaries and NSs are also ejected from the core during dynamical encounters.

4. Summary

We have carried out two complementary population synthesis studies of the retention of neutron stars and the formation of neutron-star binaries in globular clusters. We have shown that with a "conventional" distribution of natal kick velocities, the fraction of neutron stars retained by a large globular cluster can be as high as 8% for neutron stars formed in primordial binary systems. However, this may be *in*sufficient to explain the large numbers of neutron stars being discovered in, and inferred for, clusters such as 47 Tuc. A significant component of neutron stars formed with substantially smaller (e.g., factors of $\sim 2-3$) kick speeds may be required in order to retain a sufficiently larger fraction of the neutron stars (e.g., $\gtrsim 20\%$).

In a second population synthesis study, we have followed some 10^6 primordial binaries and 10^4 neutron stars through the history of a globular cluster. We find that such an initial population can be adequate to account for the large measured and inferred population of close binary millisecond pulsars in some of the massive, centrally concentrated clusters. With the current version of the population synthesis code we also derive information on the numbers of NS-NS-, detached NS-WD-, and WD-WD-binaries. Future studies, with an extended version of the code, will allow us to compute in a more realistic way other branches of the binary stellar evolution which we do not follow at the present time.

References

Abt, H.A. & Levy, S.G. 1985, ApJS, 59, 229

Applegate, J., & Shaham, J. 1994, ApJ, 436, 312

Bethe, H., & Brown, G. 1998, ApJ, 506, 780

Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G., & Manchester, R. N. 2000, ApJ, 535, 975

Chevalier, R. 1993, ApJ, 411, L33

Cordes, J., & Chernoff, D. 1998, ApJ, 505, 315

Davies, M., & Hansen, B. 1998, MNRAS, 301, 15

Deutsch, E. W., Margon, B., Anderson, S. F. 2000, ApJ, 530, L21

Dewi, J., & Tauris, T. 2000, A&A, in press

Di Stefano, R., & Rappaport, S. 1992, ApJ, 396, 587

Djorgovski, S. 1993, in Structure and Dynamics of Globular Clusters, ASP Conf. Series Vol. 50, eds. S.G. Djorgovski & G. Meylan, 373

Drukier, G. 1996, MNRAS, 280, 498

Duquennoy, A. & Mayor, M. 1991, A&A, 248, 485

Fabian, A., Pringle, J., & Rees, M. 1975, MNRAS, 172,15

Fregeau, J., Joshi, K., & Rasio, F. 2000, in preparation

Gao, B., Goodman, J., Cohn, H., & Murphy, B. 1991, ApJ, 370, 567

Han, Z., Podsiadlowski, Ph., & Eggleton, P. P. 1995, MNRAS, 272, 800

Hansen, B., & Phinney, E. 1997, MNRAS, 291, 569

Hjellming, M. S. 1990, Ph.D. Thesis, University of Illinois at Urbana-Champaign

Homer, L. et al. 1996, MNRAS, 282, L37

Hut, P., Murphy, B., & Verbunt, F. 1991, A&A, 241, 137

Hut, P. et al. 1992, PASP, 104,981

Kalogera, V., & Webbink, R. F. 1996, ApJ, 458, 301

Kippenhahn, R., Weigert, A., & Hofmeister, E. 1967, in Methods of Computational Physics, Vol. 7, ed. B. Adler, S. Fernbach, & M. Rothenberg (New York: Academic), p. 129

Kroupa, P., Tout, C., & Gilmore, G. MNRAS, 262, 545

Kulkarni, S. R., Narayan, R., & Romani, R.W. 1990, ApJ, 356, 174

Lyne, A., & Lorimer, D. 1994, Nature, 369, 127

McMillan S.L.W., & Hut P. 1994, ApJ, 427, 793

Meyer, F., & Meyer-Hofmeister, E. 1979, A&A, 78, 167

Miller, G.E., & Scalo, J.M. 1979, ApJS, 41, 513

Podsiadlowski, Ph. 1996, MNRAS, 279, 1104

Podsiadlowski, Ph. 2000, in preparation.

Podsiadlowski, Ph., Joss, P., & Hsu, J. 1992, ApJ, 391, 246

Podsiadlowski, Ph., Cannon, R., & Rees, M. 1995, MNRAS, 274, 485

Rappaport, S., Nelson, L. A., Ma, C. P., Joss, P. C. 1987, ApJ, 322, 842

Rappaport, S., Di Stefano, R., & Smith, J. 1994, ApJ, 426, 692

Rappaport, S., Verbunt, F., & Joss 1983, ApJ, 275, 713

Rasio, F. A. 2000, in ASP Conference Series, Dynamics of Star Clusters and the Milky Way, Spurzem et al. (eds.)

Rasio, F., Pfahl, E., & Rappaport, S. 2000, ApJ, 532, L147

Rasio, F., & Shapiro, S. 1991, ApJ, 377, 559

Ray, A., Kembhavi, A. K., &Antia, H. M. 1987, A&A, 184, 164

Sandquist, E., Taam, R., & Burkert, A. 2000, ApJ, 533, 984

Sigurdsson, S., & Phinney, E. 1993, ApJ, 415, 631

Soker, N., & Rappaport, S. 2000, ApJ, 538, 241

Stella, L., White, N., & Priedhorsky, W. 1987, ApJ, 315, L49 88, 529

Thorne, K., & Żytkow, A. 1977, ApJ, 212, 832