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FORMATION OF ULTRACOMPACT X-RAY BINARIES IN DENSE STAR CLUSTERS

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ABSTRACT

Bright, ultracompact X-ray binaries observed in dense star clusters, such as Galactic globular clusters, must have formed relatively recently, since their lifetimes as persistent bright sources are short (e.g., $\sim 10^8$ yr above 10^{36} ergs s^{-1} for a 1.4 $M_\odot$ neutron star accreting from a degenerate helium companion with an initial mass of $\sim 0.2\ M_\odot$). Therefore, we can use the present conditions in a cluster core to study possible dynamical formation processes for these sources. Here we show that direct physical collisions between neutron stars and red giants can provide a sufficient formation rate to explain the observed numbers of bright sources. These collisions produce tight, eccentric neutron star–white dwarf binaries that decay to contact by gravitational radiation on timescales $\sim 10^6$–10^{10} yr, usually shorter and often much shorter than the cluster age.

Subject headings: binaries: close — galaxies: star clusters — globular clusters: general — hydrodynamics — stellar dynamics — X-rays: binaries

1. INTRODUCTION

Ultracompact X-ray binaries (UCXBs) are persistent, bright X-ray sources ($L_X \sim 10^{36}$–10^{39} ergs s^{-1}) containing a neutron star (NS) accreting from a low-mass, degenerate companion in a very tight orbit of period $P \lesssim 1$ hr. UCXBs may well be dominant among the bright low-mass X-ray binaries (LMXBs) observed in old globular clusters (GCs), both Galactic (Deutsch et al. 2000; van der Sluys et al. 2005) and extragalactic (Bildsten & Deloye 2004). It was recognized 30 years ago that the total numbers of LMXBs observed in GCs clearly indicate a dynamical origin, with formation rates exceeding those in field populations by several orders of magnitude (Clark 1975). Indeed, the stellar encounter rate in a cluster core is an excellent predictor for the presence of a bright LMXB (Jordán et al. 2004).

The growing importance of UCXBs is clear from the role they have played recently in a number of different contexts. They may dominate the bright end of the X-ray luminosity function in elliptical galaxies (Bildsten & Deloye 2004). They pose a number of challenges to, and may allow us to test our fundamental physics of, stellar structure for low-mass degenerate or quasi-degenerate objects (Deloye & Bildsten 2003). They may also connect in a fundamental way to NS recycling, as suggested by the fact that three out of six accretion-powered millisecond X-ray pulsars known in our Galaxy are UCXBs (Chakrabarty 2004; Grebenev et al. 2004). Finally, UCXBs may well be the progenitors of the many eclipsing binary radio pulsars with very low mass companions observed in GCs (Rasio et al. 2000).

Several possible formation processes for UCXBs are possible. Exchange interactions between NSs and primordial binaries provide a natural way of forming possible progenitors of UCXBs (Rasio et al. 2000). This may well dominate the formation rate when integrated over the entire history of a cluster. However, it is unlikely to be significant for bright UCXBs observed *today*. This is because the progenitors must be intermediate-mass binaries, with the NS companion massive enough for the initial mass transfer (MT) to become dynamically unstable, leading to common-envelope (CE) evolution and significant orbital decay. Instead, all main-sequence stars remaining today in a GC have masses low enough to lead to *stable* MT (and orbits that expand during MT, leading to LMXBs with wide periods and nondegenerate donors). Alternatively, some binaries with stable MT could evolve to ultrashort periods by magnetic braking (Pylyser & Savonije 1988; Podsiadlowski et al. 2002). However, producing UCXBs through this type of evolution requires very careful tuning of initial conditions and is therefore very unlikely to explain most sources (van der Sluys et al. 2005).

Verbunt (1987) first proposed that a physical collision between an NS and a red giant (RG) could lead to UCXB formation. In his scenario, the collision was assumed to lead directly to a CE system in which the NS and RG core would quickly in-spiral. However, RG-NS collisions that occur now in old GCs (where RGs have low masses, close to m_{to}) do *not* lead to CE evolution. Instead, the RG envelope is promptly disrupted, leaving behind an eccentric NS–white dwarf (WD) binary, as shown by Rasio & Shapiro (1991) using three-dimensional hydrodynamic calculation. Nevertheless, if the postcollision NS-WD binaries can decay through gravitational wave emission all the way to contact, they can still become UCXBs (Davies et al. 1992).

2. OUTCOME OF COLLISIONS

Using the three-dimensional smoothed particle hydrodynamics (SPH) code StarCrash,[3] we have computed about 40 representative collisions between various RG stars and a 1.4 $M_\odot$ NS (J. C. Lombardi, K. L. Dooley, Z. F. Proulx, N. Ivanova, & F. A. Rasio 2005, in preparation). In our models, both the NS and the RG core are represented by point masses coupled to the gas by (softened) gravity only (Rasio & Shapiro 1991). Our initial RG models were calculated using the stellar evolution code described in detail in Podsiadlowski et al. (2002), Ivanova et al. (2003), and Kalogera et al. (2004). The models include stars on the subgiant branch (with total mass $M = 0.8\ M_\odot$, core mass $m_c = 0.10\ M_\odot$, and radius $R_{RG} = 1.6\ R_\odot$ and with $M = 0.9\ M_\odot$, $m_c = 0.12\ M_\odot$, and $R_{RG} = 2\ R_\odot$) and several models near the base of the RG branch. Our most evolved models have $M = 0.9\ M_\odot$, $m_c = 0.25\ M_\odot$, and $R_{RG} = 6.8\ R_\odot$. More evolved RGs contribute very little to the total collision rate (see § 3). The distance of closest

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[3] See http://www.astro.northwestern.edu/StarCrash.

approach for the initial collision varies from $r_p = 0.1R_{RG}$ (nearly head-on) to $r_p = 1.3R_{RG}$ (grazing).

In agreement with previous SPH calculations (Rasio & Shapiro 1991; Davies et al. 1992), we find that all collisions produce bound systems in which the RG core ends up in a high-eccentricity orbit around the NS. However, in contrast to those older studies, our new SPH calculations extend over much longer times (up to ∼500 successive pericenter passages), allowing us to determine accurately the final parameters of the orbit (J. C. Lombardi et al. 2005, in preparation). Typically ∼50% of the RG envelope is ejected to infinity, while most of the rest becomes bound to the NS. Only ∼0.1 $M_\odot$ remains bound to the RG core, which will eventually cool to a degenerate WD (cf. § 4). The material left bound to the NS will attempt to form an accretion disk as it cools. The fate of this material is rather uncertain. It could be accreted onto the NS and spin it up (in $\sim 10^6$ yr at the Eddington limit), or, more likely, it could be ejected if the energy released by accretion couples well to the gas. With an efficiency ϵ, the entire mass of gas could be ejected to infinity in as little as $\tau_{gas} \sim 500(\epsilon/0.1)^{-1}$ yr. This very short lifetime justifies our assumption that the parameters of the postcollision orbits determined by our SPH calculations are nearly final, i.e., that the orbital parameters are no longer affected by coupling of the orbit to the residual gas.

When we apply the Peters (1964) equations to these post-collision systems, we find that most of them in-spiral on rather short timescales (Fig. 1). Therefore, we assume for the rest of this Letter that *all* RG-NS collisions can produce UCXBs.

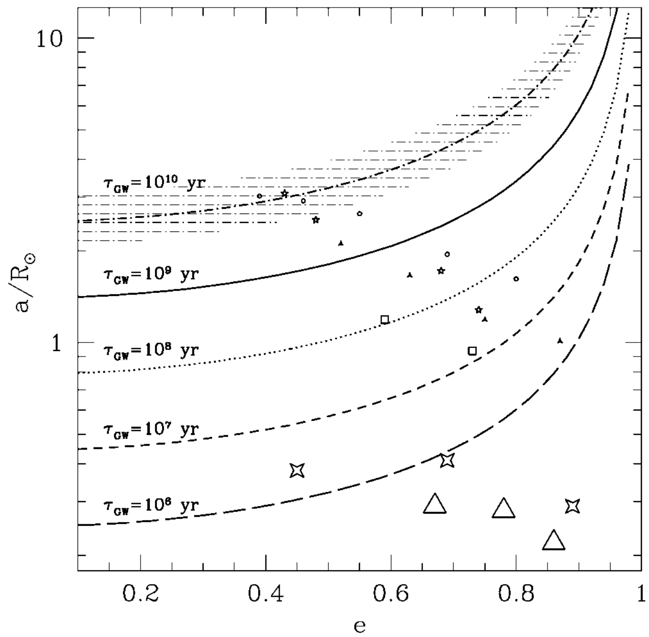

FIG. 1.—Dependence of the gravitational radiation merger time on post-collision semimajor axis a and eccentricity e for a binary consisting of a 1.4 $M_\odot$ NS and a 0.25 $M_\odot$ WD. The points with different symbols show the results of our SPH calculations for six different giant models (star symbols are for a 0.9 $M_\odot$ star; others are for a 0.8 $M_\odot$ star at different evolutionary stages, e.g., triangles represent a subgiant, and circles our most evolved RG model). The symbol area is proportional to the collision rate, according to eq. (4); i.e., symbols for less evolved RGs appear larger. The hatched area shows how the merger time (here for the line of constant merger time $\tau_{gw} = 10^{10}$ yr) changes when we vary slightly the binary parameters: the upper boundary corresponds to a 1.5 $M_\odot$ NS with a 0.45 $M_\odot$ WD, and the lower boundary corresponds to a 1.3 $M_\odot$ NS with a 0.15 $M_\odot$ WD.

3. COLLISION RATE

Consider an NS of mass m_{NS} in the core of a cluster containing N_* ordinary stars (here we neglect binaries; see § 4). If all these ordinary stars were turnoff stars of radius R_{to} and mass m_{to}, the collision rate for the NS would be

$$\mathcal{R}_{to} \equiv 2\pi G(m_{to} + m_{NS})N_* R_{to}\sigma^{-1}V_c^{-1}, \quad (1)$$

where σ is the relative velocity dispersion and V_c is the core volume. Here we assume that the collision cross section is dominated by gravitational focusing.

To compute the collision rate with RGs, we take into account that the number of RGs, dN_{RG}, within any small range of radii between R_{RG} and $R_{RG} + dR_{RG}$ is proportional to the time dt spent there by the star as it ascends the RG branch, $dN_{RG} = f_{RG}N_* dt/\tau$. Here f_{RG} is the fraction of stars with masses close enough to the turnoff mass to have become RGs, and τ is the total lifetime (from the zero-age main sequence to the end of the RG stage) of a turnoff star, only slightly larger than the cluster age. For a simple analytic estimate, we use the following approximate relation between age and radius (eq. [A9] of Kalogera & Webbink 1996):

$$R_{RG}(t) \simeq R_{ZAMS}\left(1 - \frac{t}{\tau}\right)^{-0.28}, \quad (2)$$

where we use $R_{ZAMS} \simeq 0.7R_{to}$. Next we replace dt by $dR_{RG}/(dR_{RG}/dt) = (R_{to}/R_{RG})^{4.6}\tau\, dR_{RG}/R_{to}$. The collision rate for an NS with RGs between R_{RG} and $R_{RG} + dR_{RG}$ is

$$d\mathcal{R} = 2.6\pi G(m_{to} + m_{NS})R_{RG}\sigma^{-1}V_c^{-1}\, dN_{RG}. \quad (3)$$

Here a collision is defined to be any encounter with a distance of closest approach less than $1.3R_{RG}$, consistent with our SPH results. Integrating this over R_{RG} from the base of the RG branch, defined by setting $R_{RG} \equiv bR_{to}$, to the maximum radius of an RG, $R_{max} \gg bR_{to}$, we find a total collision rate

$$\mathcal{R}_{UCXB} \simeq 0.51 f_{RG} b^{-2.6}\mathcal{R}_{to}. \quad (4)$$

Alternatively, note that we could also directly integrate equation (3) over time, without changing the variable from t to R_{RG}. Because the collision rate is linearly proportional to radius when gravitational focusing dominates, we can then write

$$\mathcal{R}_{UCXB} \simeq 2.6\pi G(m_{to} + m_{NS})N_* f_{RG}\bar{R}_{RG}\sigma^{-1}V_c^{-1}, \quad (5)$$

where $\bar{R}_{RG}$ is the time-average radius of the RG. Using equation (2), it is easy to show that equations (4) and (5) agree. Equation (5) has the advantage that any stellar evolution treatment can be used to determine $\bar{R}_{RG}$, including fitting formulae more detailed than equation (2) or numerical results from stellar evolution calculations.

The steep inverse dependence on b in equation (4) indicates that the collision rate is completely dominated by the smallest RGs: although the cross section increases (linearly) with radius, the faster stellar evolution at larger radii dominates, so that collisions are much more likely to happen when the star is just leaving the main sequence, i.e., on or close to the *subgiant* branch (Verbunt 1987). The corresponding core mass is also small, typically $m_c \simeq 0.1\ M_\odot$ for $m_{to} \simeq 0.8\ M_\odot$.

We now proceed to evaluate f_{RG}. This depends on the mass function of stars in the cluster core, which we expect to be very different from the initial mass function (IMF) because of mass segregation. Indeed, observations of cluster cores reveal flat or even slightly rising mass functions (e.g., Richer et al. 2004). Here we assume that the number of stars within dm is proportional to $m^{\alpha}\,dm$, with $\alpha > -1$, between a minimum $m_{\rm min}$ and a maximum $m_{\rm to} + \Delta m$. The spread Δm of masses along the RG branch is obtained from the mass dependence of the main-sequence lifetime $t_{\rm MS}$. Adopting the simple scaling $t_{\rm MS} = \tau(m_{\rm to}/m)^{3.6}$ (Hurley et al. 2000), we get $\Delta t_{\rm MS} = 3.6\tau(m_{\rm to}/m)^{3.6}\Delta m/m$. Setting $\Delta t_{\rm MS} = t_{\rm RG}$, the total time spent on the RG branch, and $m \simeq m_{\rm to}$, gives $\Delta m \simeq 0.28 m_{\rm to} t_{\rm RG}/\tau$.

To be consistent with our previous definition of an RG having a radius $\geq bR_{\rm to}$ and using again equation (2), we derive $t_{\rm RG}/\tau = 0.3b^{-3.6}$. We can now calculate $f_{\rm RG}$ directly from the IMF. Assuming $\Delta m \ll m_{\rm to}$, and $m_{\rm min} \ll m_{\rm to}$, we get

$$f_{\rm RG} = (\alpha + 1)\frac{\Delta m}{m_{\rm to}} \simeq 0.28(\alpha + 1)\frac{t_{\rm RG}}{\tau} = 0.08(\alpha + 1)b^{-3.6}. \tag{6}$$

Combining this with equation (4), we obtain the result

$$\mathcal{R}_{\rm UCXB} \simeq 0.04\,\frac{\alpha + 1}{b^{6.2}}\,\mathcal{R}_{\rm to}. \tag{7}$$

Assuming a steady state (justified given the short lifetimes $t_{\rm UCXB} \ll \tau$ of the bright UCXB phase), we can then estimate the number of UCXBs per 100 NSs at present in a cluster as

$$N_{100} \simeq 100\mathcal{R}_{\rm UCXB}t_{\rm UCXB}. \tag{8}$$

The lifetime $t_{\rm UCXB}$ depends on the minimum luminosity for a system to be classified as a UCXB. For our estimates, we adopt a minimum luminosity comparable with the observed minimum in our Galaxy, $L_{\rm X} \simeq 10^{36}$ ergs s^{-1}. The corresponding lifetime is $t_{\rm UCXB} \simeq 10^{8}$ yr (e.g., Rasio et al. 2000).

The present mass of a cluster M_t is always less than its initial mass $M_{t;\,0} = f_{\rm ML}^{-1}M_t$, where $f_{\rm ML}$ is the total mass loss fraction. About 40% of the initial mass is lost just through stellar winds and supernova explosions, so that $f_{\rm ML} < 0.6$. Without tidal mass loss (Joshi et al. 2001), and adopting a lower mass cutoff of 0.1 $M_{\odot}$ in the IMF of Kroupa (2002), we expect about 1 NS per 65 $M_{\odot}$ of mass at present (see also Ivanova et al. 2005b). About 5% of these NSs will be retained, depending on the escape velocity and the NS natal kick velocity distribution (Ivanova et al. 2005b). The corresponding *minimum* number of UCXBs expected (without any tidal mass loss) is then

$$N_{\rm min} \sim 8 \times 10^{-4} M_t \mathcal{R}_{\rm UCXB}t_{\rm UCXB}, \tag{9}$$

where M_t is in units of solar masses.

In Table 1, we show numerical results for several Galactic clusters: all clusters where a UCXB has been identified and 47 Tuc (which does *not* contain any bright LMXB). The probability of finding a bright UCXB in a cluster like 47 Tuc is only about 23%. NGC 6652 has poorly measured parameters (see Table 1 note), and our numbers for this cluster are necessarily uncertain. Two clusters, NGC 6624 and NGC 6712, are thought to have very eccentric orbits and to be on the verge of complete disruption in the Galactic tidal field (Richtler et al. 1994; Gnedin et al. 1999; Andreuzzi et al. 2001). This suggests that they may have had much higher mass and density in the past. Indeed, observations show that NGC 6712 has a strikingly unusual mass function for stars below the turnoff (Andreuzzi et al. 2001), and this can only be explained if the cluster has lost more than 99% of its initial mass (Takahashi & Portegies Zwart 2000).[4]

TABLE 1
UCXB Formation in Galactic Clusters

Cluster	$t_{\rm RG}/\tau$	$\bar{R}_{\rm RG}$ ($R_{\odot}$)	log ρ_0	σ (km s^{-1})	log M_t	N_{100}	$N_{\rm min}$
NGC 1851	0.071	6	5.7	10.4	6.0	0.11	0.85
NGC 6624	0.087	4.2	5.6	5.4	5.2	0.14	0.18
NGC 6652	0.076	5.4	4.8	5.9	5.4	0.02	0.05
NGC 6712	0.070	5.9	3.0	4.3	5.0	0.0005	0.0004
NGC 7078	0.034	7.1	6.2	12.0	6.1	0.16	1.62
Terzan 5	0.10	4.3	6.1	10.6	5.6	0.27	0.87
47 Tuc	0.081	4.9	5.1	11.5	6.1	0.23	0.23

Notes.—The RG lifetime fraction $t_{\rm RG}/\tau$ and the average RG radius $\bar{R}_{\rm RG}$ are calculated directly from our stellar evolution code and used in equation (6) (with $\alpha = 0$) and equation (5); ρ_0 is the cluster core density (in units of $M_{\odot}$ pc^{-3}), σ is the (one-dimensional) velocity dispersion, and M_t is the total cluster mass (in units of $M_{\odot}$). For Ter 5 and NGC 6652, log ρ_0 is based on the luminosity density from Djorgovski (1993) and an adopted mass-to-light ratio of 2. The value of log ρ_0 for NGC 6652 appears rather uncertain (see, e.g., Pryor & Meylan 1993; Djorgovski 1993). Values of log M_t for NGC 6652 and Ter 5 are from Gnedin et al. (2002; supplementary online data at http://www-int.stsci.edu/~ognedin/gc/vesc.dat); σ for Ter 5 is from Gnedin et al. (2002) and for NGC 6652 from Webbink (1985). Otherwise, log ρ_0, σ, and log M_t are from Pryor & Meylan (1993).

4. DISCUSSION

For Galactic clusters, our estimates indicate that it is quite possible for all observed UCXBs to have been formed through RG-NS collisions (Table 1). For extragalactic clusters, we can crudely estimate the expected total number of UCXBs in a galaxy by integrating over the cluster mass function and assuming some average formation rate per NS in all clusters. As an example, consider the case of M87 (Jordán et al. 2004). We adopt a power-law cluster IMF with $\alpha = -2$ (Kravtsov & Gnedin 2005). With an average formation rate $\mathcal{R}_{\rm UCXB} \sim 2 \times 10^{-12}$ to 4×10^{-11} yr^{-1} per NS (assuming that M87 clusters have structural parameters distributed roughly like those of Galactic clusters) and $t_{\rm UCXB} \sim 10^{6}$ yr (corresponding to $L_{\rm X} > 10^{37}$ ergs s^{-1}, near the detectability limit for M87), we find that ~10–100 UCXBs are expected in the 1688 identified clusters, in rough agreement with the 58 detected LMXBs associated with these clusters.

In several galaxies, the probability of finding a bright LMXB in a cluster appears to correlate strongly with cluster metallicity (Kundu et al. 2002, 2003; Jordán et al. 2004). As there is no strong dependence of the RG-NS collision rate on metallicity, in our scenario, we have to interpret this trend as due to other factors, such as the metallicity dependence of the IMF, of the number of NSs formed in the cluster, or of the NS retention fraction. In other words, the metallicity dependence must appear through the number of NSs rather than through $\mathcal{R}_{\rm UCXB}$. This is difficult to verify, since there are no well-established theoretical or observational predictions on how the IMF and NS natal kicks change with metallicity. Alternatively, a strong metallicity dependence of $t_{\rm UCXB}$ is also possible, with higher metallicity sys-

[4] After significant mass loss, and depending on its initial density profile, the cluster could undergo strong gravothermal oscillations (Takahashi & Portegies Zwart 2000), so that a UCXB could also have formed when the core had a much higher density during a recent, brief episode of core collapse.

tems having longer lifetimes as bright sources (cf. Maccarone et al. 2004).

Our conclusions are fairly robust, independent of assumptions and in spite of some large theoretical uncertainties. We now examine a few of the most important ones. Binaries were neglected in our analysis. This implies that our estimated collision rate is a lower limit, as interactions involving binaries always *increase* this rate (Fregeau et al. 2004). However, the effects of binaries on collision rates in very dense clusters *today* are likely to be small because core binary fractions in these clusters are very small, typically a few percent at most. This is known observationally (Cool & Bolton 2002) and expected theoretically (Fregeau et al. 2003; Ivanova et al. 2005a). Another important assumption we made is that postcollision binaries do not circularize. As seen in Figure 1, high eccentricities are an important factor in keeping merger times short. However, one can also see directly from Figure 1 that, even if *all* binaries were able to circularize quickly (compared to the gravitational radiation merger time), a large fraction of postcollision systems would still merge in less than the cluster age. On the basis of the results of § 2 and the relation between postcollision semimajor axis and collision parameters derived from our SPH simulations, we estimate this fraction to be about 70%. Thus, even under the extreme assumption that all systems circularize, the rate of UCXB formation would still be within a factor of 2 of the total RG-NS collision rate. One possible further complication could come from the residual gas left bound to the RG core. All our collision calculations suggest that the mass left bound to the RG core is $\sim 0.1\ M_\odot$. Although there are many theoretical uncertainties, it is possible that this is sufficient to reconstitute an RG envelope (Castellani et al. 1994). In this case, the orbit would likely circularize, and *stable* MT from the reconstituted RG onto the NS would occur. However, the Roche lobe in the postcollision binary is smaller than the equilibrium radius of the RG, so that the MT proceeds on a thermal timescale and the corresponding bright LMXB phase lasts only $\sim 10^5$ yr, making detection unlikely. In addition, the total mass accreted by the NS will be only $\sim 10^{-3}\ M_\odot$, which is not sufficient to produce a recycled millisecond pulsar.

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Note added in proof.—Bildsten & Deloye (2004) pointed out that the observed break around 5×10^{38} ergs s^{-1} in the X-ray luminosity functions of elliptical galaxies could be explained naturally if all donors in UCXBs had initial masses clustered near $\sim 0.1\ M_\odot$. This is precisely what is predicted by our scenario.