

COULD BLACK HOLE X-RAY BINARIES BE DETECTED IN GLOBULAR CLUSTERS?

V. KALOGERA,¹ A. R. KING,² AND F. A. RASIO¹

Received 2003 August 27; accepted 2003 December 15; published 2004 January 26

ABSTRACT

We consider the implications of the presence of an ~ 1 stellar-mass black hole (BH) at the center of a dense globular cluster. We show that BH X-ray binaries formed through exchange interactions are likely to have extremely low duty cycles (under about 10^{-3}), consistent with the absence of BH X-ray transients in Galactic globular clusters. In contrast, we find that BH X-ray binaries formed through tidal capture would be persistent, bright X-ray sources. Given the absence of any such source and the very high interaction rates, we conclude that tidal capture of a main-sequence star by a BH most likely leads to the complete disruption of the star.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — globular clusters: general — stellar dynamics

1. INTRODUCTION

Black hole X-ray binaries (BH XRBs) have been reliably identified as soft X-ray transients with dynamical mass measurements of the accreting compact objects (Lasota 2001). More than a dozen are known at present,³ the majority of them with low-mass donors (Kalogera 1999). Their transient behavior is currently understood in the context of a viscous disk instability that includes the effects of disk irradiation (Frank, King, & Raine 2002).

It has been noted for some time now that no BH XRB has ever been observed in a Galactic globular cluster (GC), even though large numbers of neutron star (NS) XRBs exist in GCs (e.g., Grindlay et al. 2001). Indeed, dynamical interactions in a dense star cluster can greatly enhance formation rates for close binaries with compact objects. This is well understood theoretically (Hut et al. 1992; Rasio, Pfahl, & Rappaport 2001; Sigurdsson & Phinney 1995) and well established observationally (Pooley et al. 2003). If BH XRB formation were similarly enhanced in GCs, some BH X-ray transients should have been detected in outburst by now. Instead, all soft X-ray transients and bright, persistent X-ray sources discovered in GCs have been shown to harbor NSs with the detection of Type I bursts (see Kuulkers 2003; Jonker et al. 2003; Wijnands, Homan, & Remillard 2002; Heinke et al. 2003; Rutledge et al. 2002; Deutsch, Margon, & Anderson 2000).

The absence of BH XRBs from GCs has been interpreted as evidence that BHs evolve differently in clusters (Kulkarni, Hut, & McMillan 1993; Sigurdsson & Hernquist 1993). Primordial BHs in GCs are thought to go through the Spitzer mass-segregation instability (Spitzer 1969; Watters, Joshi, & Rasio 2000), concentrating in a dense core and effectively decoupling from the rest of the cluster. Through dynamical interactions they form binaries with two possible outcomes: (1) either the central BH cluster completely evaporates (ejecting BHs through strong interactions), leaving behind at most ~ 1 BH (single or binary), or (2) successive mergers of binary BHs in the cluster, driven by gravitational radiation, form an $\sim 10^2$ – $10^3 M_\odot$ intermediate-mass BH (IMBH; Miller & Hamilton 2002). In the latter case one might expect this IMBH to become

visible as an ultraluminous X-ray source (ULX), if it is not ejected from the cluster by gravitational radiation recoil during the merger process (Redmount & Rees 1989; Favata, Hughes, & Holz 2003). While no such source has been observed in the old Galactic GCs, ULXs have been observed in younger extragalactic star clusters (Fabbiano & White 2003).

In this Letter, we explore the consequences of a single $\sim 10 M_\odot$ BH remaining in the dense GC core. We show that the absence of any detected BH X-ray transient in a Galactic GC does not necessarily rule out the presence of ~ 1 BH in every cluster.

2. DYNAMICAL FORMATION OF BH XRBs IN CLUSTERS

Black holes are formed from stars with initial masses $\geq 20 M_\odot$ that end their lives in ≤ 10 Myr. On this timescale it is unlikely that relaxation processes will have affected the cluster structure significantly (cf. Gürkan, Freitag, & Rasio 2003). We make the standard assumption that kicks from asymmetric explosions scale with mass (compared to NSs) and therefore are too low ($\leq 50 \text{ km s}^{-1}$) to eject many BHs from the cluster (in contrast to NSs, where one faces a serious “retention problem”; see, e.g., Pfahl, Rappaport, & Podsiadlowski 2002). After the evolution of massive stars down to $\sim 10 M_\odot$, BHs become the most massive objects in the cluster, and their subsequent dynamical evolution is driven by two-body relaxation and mass segregation.

Since BHs are expected to be distributed throughout the cluster initially, their mass segregation timescale is proportional to the initial half-mass relaxation time of the whole cluster, $\tau_{r,h}^{\text{cl}}$, and inversely proportional to the BH mass M_{BH} ,

$$\tau_{\text{seg}}^{\text{BH}} \approx \frac{\langle m \rangle}{M_{\text{BH}}} \tau_{r,h}^{\text{cl}}, \quad (1)$$

where $\langle m \rangle$ is the average stellar mass in the cluster (Fregeau et al. 2002). Typical values for Galactic GCs are $\tau_{r,h}^{\text{cl}} \sim 10^9$ yr and $\langle m \rangle \leq 1 M_\odot$, so that a population of $\sim 10 M_\odot$ BHs is expected to decouple dynamically in $\leq 10^8$ yr.

¹ Department of Physics and Astronomy, Northwestern University, 2131 Tech Drive, Evanston, IL 60208; vicky@northwestern.edu, rasio@northwestern.edu.

² Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK; ark@astro.le.ac.uk.

³ Data available online from I. A. Orosz at <http://mintaka.sdsu.edu/faculty/orosz/web>.

The subsequent evolution of the BH subcluster is dominated by BH-BH interactions on their *own* relaxation time:

$$\tau_r^{\text{BH}} \sim 10^6 \text{ yr} \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right)^3 \times \left(\frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-1} \left(\frac{\rho_c}{10^5 M_{\odot} \text{ pc}^3} \right)^{-1}, \quad (2)$$

where σ is the three-dimensional velocity dispersion of BHs, and ρ_c is the mass density of the BH subcluster (see eqs. [8]–[71] in Binney & Tremaine 1987, hereafter BT). Here $\sigma \sim 10 \text{ km s}^{-1}$ is set by the depth of the GC potential, but ρ_c is rather uncertain. Since decoupling occurs when the BH density becomes comparable to the density of the background stars, we adopt a value comparable to the central density of typical precollapse GCs today (Fregeau et al. 2003).

BHs are initially ejected out to the GC halo (from which point they sink back to the core on a short timescale of $\sim 0.1 \tau_{r,h}^{\text{cl}}$, because of dynamical friction); but, as the BH subcluster collapse proceeds and binaries harden on τ_r^{BH} , very soon they are ejected out of the GC altogether. We can estimate an upper limit to the timescale for complete evaporation by using the classical result for exponential evaporation in systems of equal point masses: $\tau_{\text{ev}} \approx 300 \tau_r$ (see eqs. [8]–[79] in BT). Therefore, the time for all BHs to evaporate and only ~ 1 to remain in the cluster is

$$t_{\text{ev}}^{\text{BH}} \lesssim 2 \times 10^9 \text{ yr} \ln \left(\frac{N_{\text{BH}}}{10^3} \right), \quad (3)$$

where N_{BH} is the initial number of BHs in the GC. In reality, evaporation is a more complex process driven mainly by inelastic collisions of binary BHs, possibly affected by gravitational radiation, and the time for complete evaporation is likely to be substantially smaller than the above classical estimate (Portegies Zwart & McMillan 2000). Here, we conservatively adopt $t_{\text{ev}}^{\text{BH}} \sim 10^9 \text{ yr}$. Since this timescale is comparable to the typical relaxation time $\tau_{r,h}^{\text{cl}}$ of the whole cluster, we expect that at the end of the evaporation process, the density of normal stars in the cluster will have started increasing through gravothermal contraction, and the remaining ~ 1 BH at the center of the cluster will be interacting significantly with normal stars. There are two interaction processes through which a BH can acquire a normal stellar companion: exchange interactions of the BH with primordial binaries (Heggie, Hut, & McMillan 1996; Sigurdsson & Phinney 1995) and tidal captures (TCs) of main-sequence (MS) stars by the BH (Fabian, Pringle, & Rees 1975; Press & Teukolsky 1977; Lee & Ostriker 1986).

The delay between the creation of an XRB progenitor and the birth of the XRB (when mass transfer is initiated through Roche-lobe overflow) can be neglected if the BH companion is already somewhat evolved, i.e., its mass is comparable to the MS turnoff (TO) mass. This is likely to be the case for several reasons: (1) the GC center is dominated by the most massive stars because of mass segregation; (2) exchange interactions have a much higher probability of ejecting the least massive object, so that the most massive star typically remains as a companion to the BH; and (3) the TC cross section is larger for more massive MS stars.

The characteristic timescale for the BH to acquire a binary companion is equal to the collision time with its “target” binary or single star. We assume that the collision cross section is

dominated by gravitational focusing, which is likely the case in all GC cores (§ 8.4 in BT). We also assume that $M_{\text{BH}} \gg \langle m \rangle$, and we average the collision rate over a Maxwellian velocity distribution with three-dimensional dispersion σ for the targets. For exchange interactions with primordial binaries, the collision time is then

$$\tau_{\text{ex}} \approx 3 \times 10^8 \text{ yr} \left(\frac{f_b}{0.1} \right)^{-1} \left(\frac{n}{10^5 \text{ pc}^{-3}} \right)^{-1} \times \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right) \left(\frac{A}{1 \text{ AU}} \right)^{-1} \left(\frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-1}, \quad (4)$$

where f_b is the binary fraction in the cluster core, with stellar density n , and A is the maximum distance of closest approach for an exchange to occur, comparable to the binary semimajor axis (Heggie et al. 1996).

For tidal captures of single stars, the collision time is

$$\tau_{\text{TC}} \approx 10^9 \text{ yr} \left(\frac{n}{10^5 \text{ pc}^{-3}} \right)^{-1} \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right) \times \left(\frac{r_{\text{TC}}}{5 R_{\odot}} \right)^{-1} \left(\frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-1}, \quad (5)$$

where r_{TC} is the *maximum* closest-approach distance for the capture to occur. For a $10 M_{\odot}$ BH and a $\lesssim 1 M_{\odot}$ MS star, we estimate $r_{\text{TC}} \lesssim 5 R_{\odot}$ by extrapolating the results of Lee & Ostriker (1986). Note that the final fate of TC binaries is very uncertain. Previously discussed TC scenarios involving NSs or white dwarfs have run into many difficulties. Problems have been pointed out with the TC process itself, which, because of strong nonlinearities in the regime relevant to GCs, is far more likely to result in a merger than in the formation of a long-lived binary (Kumar & Goodman 1996; McMillan, Taam, & McDermott 1990; Rasio & Shapiro 1991). Moreover, the basic predictions of these TC scenarios are at odds with many observations of binaries and recycled pulsars in GCs (Bailyn 1995; Shara et al. 1996). For BHs, which are even more massive and produce an even stronger tidal perturbation, it is likely that TC does not lead to BH XRBs. Nevertheless, we take it into account for completeness. TC events with red giants (RGs) can lead to BHs with low-mass degenerate cores as companions on a timescale comparable to TC with MS stars (the lower fraction of RG among single stars [under about 10%] is compensated by a larger r_{TC} [above about 10]). Such low-mass companions would be easily replaced by MS stars in a subsequent interaction and would lead to wide binaries similar to those produced by exchange interactions.

We now turn to the evaluation of these interaction timescales (eqs. [4] and [5]) for typical dense GCs. It is useful to consider three representative cases for cluster properties.

The first case corresponds to a fairly dense but non-core-collapsed cluster, such as 47 Tuc, with a central density $n \sim 10^5 \text{ pc}^{-3}$ (Freire et al. 2003). We adopt a binary fraction $f_b = 0.1$, typical of dense GCs with resolved cores (Albrow et al. 2001). Such a cluster is thought to support itself in a state of quasi-static equilibrium against gravothermal contraction by primordial binary “burning” (Fregeau et al. 2003). The binaries most likely to interact with a BH in the cluster core are the widest among the surviving (hard) systems, which have $A \sim 1 \text{ AU}$. Thus, we obtain $\tau_{\text{ex}} \sim 3 \times 10^8 \text{ yr}$. This short timescale implies that a BH will have had multiple exchange interactions

during the recent GC dynamical history and that it would be very unlikely for a BH not to have a binary companion in this kind of environment. For the same cluster parameters, the TC time is $\tau_{\text{TC}} \sim 10^9$ yr, implying that this process is less important than exchange interactions but could also have happened.

Next, we consider a more extreme environment typical of a “core-collapsed” cluster, such as NGC 6397, with a central density $n \sim 10^6$ pc $^{-3}$. Most binaries are expected to have been destroyed or ejected from the cluster, so we adopt $f_b = 0.01$ as a typical value, consistent with observations (Cool & Bolton 2002). Since the few surviving binaries will have been hardened considerably (Fregeau et al. 2003), we take $A \sim 0.1$ AU. We thus obtain $\tau_{\text{ex}} \sim 3 \times 10^9$ yr, while the TC time in this case is $\tau_{\text{TC}} \sim 10^8$ yr. Assuming that a star can survive TC by a BH, these results once again imply that it would be unlikely for the BH not to have a companion, but in this case TC would dominate over exchanges.

Finally, we consider an even denser cluster similar to M15, with a central density $n \sim 10^7$ pc $^{-3}$ (Dull et al. 1997). In this case no primordial binaries are expected to have survived in the cluster, so we assume $f_b = 0$ and that exchange interactions are unimportant (although wide binaries may still form through TC with RGs). The TC time becomes $\tau_{\text{TC}} \sim 10^7$ yr and implies an extremely high rate of tidal interactions.

3. X-RAY DUTY CYCLES

We estimate the duration of any mass-transfer phase as a fraction of the timescale for replacing the BH companion through dynamical interactions. We also consider whether X-ray emission is persistent or transient (within the viscous disk instability model). We are then able to estimate an effective X-ray “duty cycle” (DC). DC values close to unity imply a high probability of detecting a BH XRB, since DC = 1 would correspond to X-ray emission being “on” throughout its lifetime, even though the BH may go through several companions.

In all three cases of GC properties considered above, we find interaction timescales much shorter than typical GC ages ($\geq 10^{10}$ yr). Thus, recent companions are most important, and these will have masses comparable to the current TO mass $\approx 0.8 M_{\odot}$.

Post-exchange binaries are relatively wide, with separations $A_{\text{ex}} \sim 1\text{--}10$ AU (where A is defined in eq. [4]; they are also eccentric, but tidal circularization is very likely before the onset of mass transfer). This is simply from energy conservation, accounting for the higher BH mass, and is in agreement with the results of detailed scattering experiments (J. Fregeau 2003, private communication). Therefore, BH companions acquired through exchanges may not always encounter Roche lobe overflow. When they do, this will typically occur on the red giant branch (RGB). For GCs like 47 Tuc, where the typical post-exchange orbital separation is $\sim 1\text{--}10$ AU, the X-ray lifetime would be much shorter than the RGB lifetime, τ_{RGB} . In addition, the widest post-exchange binaries may well be destroyed by another interaction (removing the companion) before the onset of mass transfer. As an example, consider a binary with a $0.8 M_{\odot}$ TO star and a $10 M_{\odot}$ BH: the Roche lobe radius is $\approx 0.2 A_{\text{ex}}$, so that no mass transfer occurs if $A_{\text{ex}} > 2$ AU. For $A_{\text{ex}} = 1$ AU, the mass-transfer duration is only $\approx 10^7$ yr (for a metallicity $Z = 0.001$; Schaller et al. 1992).

In tighter systems with post-exchange separations $A_{\text{ex}} \sim 0.1\text{--}1$ AU (through interactions with very hard binaries in a denser GC like NGC 6397), TO stars could fill their Roche lobes soon after the interaction. A strict upper limit to the

duration of the mass transfer is then set by the RGB lifetime τ_{RGB} of the stellar companion to the BH. For a $0.8 M_{\odot}$ star, we have $\tau_{\text{RGB}} \lesssim 10^9$ yr. This is still shorter than the interaction timescale $\tau_{\text{ex}} \approx 3 \times 10^9$ yr estimated for a cluster like NGC 6397. Therefore, *for all clusters where exchanges are important* (or where post-exchange-like binaries are formed through TC with RGs), we find $\tau_{\text{MT}}/\tau_{\text{ex}} \ll 1$.

Next, we consider the disk stability in post-exchange mass-transfer binaries with orbital separations in the range $\sim 0.1\text{--}2$ AU (orbital periods $\sim 4\text{--}400$ days). It has been shown that such wide binaries with a mass ratio ~ 0.1 should be transient systems (King, Kolb, & Burderi 1996, 1997). Although theoretically it is difficult to estimate the transient duty cycles, observationally it appears that all systems with more than one outburst have duty cycles $f_x < 0.01$, and for wide binaries it may be even lower (Taam, King, & Ritter 2000). Such low duty cycles imply that the probability of detecting a wide BH XRB as an X-ray source (during an outburst) in a GC is vanishing. Even if we adopted an optimistic average value of $\tau_{\text{MT}}/\tau_{\text{ex}} = 0.1$ for all Galactic GCs, the overall duty cycle $\text{DC} = f_x \tau_{\text{MT}}/\tau_{\text{ex}} < 10^{-3}$ would be compatible with the absence of any detection in the ~ 100 Galactic GCs.

In contrast to post-exchange binaries, TC binaries are expected to form systems with very short orbital periods. Taking the typical closest-approach distance for TC to be $3 R_{\odot}$, we find the orbital period of the circularized binary to be ~ 10 hr. Such tight binaries would contain small accretion disks heated significantly by irradiation. For the low-mass ratios relevant to BH XRBs of interest here, it has been shown that the disks are stable throughout the mass-transfer phase (see, e.g., middle panel of Fig. 1 in King et al. 1996). Therefore, we would expect TC BH XRBs to be persistent X-ray sources. In these binaries, mass transfer is thought to be driven by magnetic braking initially, and gravitational radiation when the companion mass decreases below $\approx 0.3 M_{\odot}$. Typical X-ray lifetimes of such systems are estimated to be $\tau_x \sim (1\text{--}10) \times 10^9$ yr (Haswell et al. 2002). Based on this estimate and the timescales computed in § 3, we expect the effective X-ray duty cycle of such binaries to be DC ~ 1 . At face value this result would imply that in any dense GC containing at least one $\sim 10 M_{\odot}$ BH, a TC BH XRB should have been detected as a bright, persistent X-ray source. The absence of any such detection could be used to argue against the existence of any BHs in these clusters. However, a more reasonable conclusion is that although TC of MS stars by a BH can occur at very high rates in dense GC cores, no stable binary can form through this process.

4. DISCUSSION

We have examined the dynamical and mass-transfer evolution of BH XRBs that could possibly form in GCs if ~ 1 BH remains in each cluster after $\sim 10^9$ yr. For a wide range of cluster properties representative of dense Galactic GCs, we have found that (1) post-exchange BH XRBs should have extremely low X-ray duty cycles, but (2) BH XRBs formed through TC should be persistent bright X-ray sources. We concluded that TC cannot form long-lived XRBs and that our theoretical expectations for exchange interactions are then consistent with the absence of any detected BH XRB in Galactic GCs. Conversely, a future detection of a BH XRB at the center of a GC would imply that either wide binaries with low mass ratios can have disks with high X-ray duty cycles (if the period of the observed system were at least a few days) or that TC can in fact lead to long-lived BH XRBs (if the observed period were ~ 10 hr).

If TC of an MS star by a BH does not form a binary, one may ask what, if any, might be the observable consequences of such an event? For a $\sim 10 M_{\odot}$ BH and typical GC velocity dispersions, we expect very little mass loss on a hydrodynamic timescale. Thus, if the MS star is disrupted, essentially all its mass will remain bound to the BH in a rapidly rotating torus (as in collisions with a NS; see Rasio & Shapiro 1991; Davies, Benz, & Hills 1992). On the hydrodynamic timescale of about a few hours, the gas will settle in hydrostatic equilibrium. On a much longer angular momentum transport timescale t_{visc} , accretion onto the BH will commence. Unless t_{visc} is extremely long ($\geq 10^6$ yr), the accretion rate $\dot{M} \sim 1 M_{\odot}/t_{\text{visc}}$ must be highly super-Eddington, and the mass will probably be ejected with speed $v \sim (M_{\text{Edd}}/\dot{M})c$ (King & Pounds 2003). For realistic t_{visc} , v easily exceeds the GC escape velocity, leading to the complete disruption of the MS star and ejection of the gas after a very brief X-ray phase (~ 100 yr, based on simple energetics for a BH accretion efficiency of ~ 0.1).

We have focused here on old GCs, like those found in our Galaxy, where the absence of BH XRBs is well established (cf. recent claims for BH XRBs in GCs of elliptical galaxies; Sarazin et al. 2003). In younger GCs, BH companions would be more massive, possibly leading to post-exchange binaries with persistent X-ray emission and high detection probability. Such conditions could explain the recent *Chandra* observations of large numbers of bright X-ray sources associated with young GCs and with X-ray luminosities above the Eddington limit for a NS (e.g., Maccarone, Kundu, & Zepf 2003).

We have not considered in detail a *binary* BH system that could be retained at the end of the BH evaporation phase (see Colpi, Mapelli, & Possenti 2003). We expect that interactions with normal stars will lead to rapid hardening of the binary. In principle, such a process can result either in a final BH merger or in the ejection of a tight BH binary through classical or relativistic recoil (hence, the absence of a BH XRB). It is easy to show that the merger timescale due to gravitational radiation (see eq. [5] in Kalogera et al. 2001) becomes shorter than the collision timescale (eq. [5]) long before the binary can reach sufficiently high recoil velocities ($\geq 50 \text{ km s}^{-1}$). The result would be a binary merger, and the estimates presented here would still apply.

Finally, we note that our results can be scaled to IMBHs ($\sim 10^3 M_{\odot}$). Post-exchange binaries would be extremely wide ($\geq 10\text{--}100$ AU for $A \geq 0.1$ AU), and strong hardening would be necessary for XRB formation. TC binaries would have circularized to periods of ~ 10 days, and if they exist, they would be transients with very low duty cycles (Kalogera et al. 2003).

We acknowledge support from the Aspen Center for Physics, where this work began. We thank K. Belczynski, J. Fregeau, T. Maccarone, and R. Taam for useful discussions. V. K. is partially supported by a Packard Fellowship, F. A. R. by NASA ATP grant NAG5-12044 and a *Chandra* Theory Grant, and A. R. K. by a Royal Society Wolfson Research Merit Award. A. R. K. also thanks the Theoretical Astrophysics Group at Northwestern University for visitors' support.

REFERENCES

- Albrow, M. D., Gilliland, R. L., Brown, T. M., Edmonds, P. D., Guhathakurta, P., & Sarajedini, A. 2001, *ApJ*, 559, 1060
 Bailyn, C. D. 1995, *ARA&A*, 33, 133
 Binney, J., & Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton Univ. Press) (BT)
 Colpi, M., Mapelli, M., & Possenti, A. 2003, *ApJ*, 599, 1260
 Cool, A. M., & Bolton, A. S. 2002, in *ASP Conf. Ser. 263, Stellar Collisions, Mergers, and Their Consequences*, ed. M. Shara (San Francisco: ASP), 163
 Davies, M. B., Benz, W., & Hills, J. G. 1992, *ApJ*, 401, 246
 Deutsch, E. W., Margon, B., & Anderson, S. F. 2000, *ApJ*, 530, L21
 Dull, J. D., et al. 1997, *ApJ*, 481, 267
 Fabbiano, G., & White, N. 2003, in *Compact Stellar X-Ray Sources*, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0307077)
 Fabian, A. C., Pringle, J. E., & Rees, M. J. 1975, *MNRAS*, 172, P15
 Favata, F., Hughes, S., & Holz, D. 2003, *ApJ*, submitted
 Frank, J., King, A. R., & Raine, D. J. 2002, *Accretion Power in Astrophysics* (3rd ed.; Cambridge: Cambridge Univ. Press)
 Fregeau, J. M., Gürkan, M. A., Joshi, K. J., & Rasio, F. A. 2003, *ApJ*, 593, 772
 Fregeau, J. M., Joshi, K. J., Portegies Zwart, S. F., & Rasio, F. A. 2002, *ApJ*, 570, 171
 Freire, P. C., et al. 2003, *MNRAS*, 340, 1359
 Grindlay, J. E., et al. 2001, *Science*, 292, 2290
 Gürkan, M. A., Freitag, M., & Rasio, F. A. 2003, *ApJ*, in press (astro-ph/0308449)
 Haswell, C. A., Hynes, R. I., King, A. R., & Schenker, K. 2002, *MNRAS*, 332, 928
 HEGGIE, D. C., HUT, P., & McMILLAN, S. L. W. 1996, *ApJ*, 467, 359
 Heinke, C. O., et al. 2003, *ApJ*, 590, 809
 Hut, P., et al. 1992, *PASP*, 104, 981
 Jonker, P. G., et al. 2003, *MNRAS*, 341, 823
 Kalogera, V. 1999, *ApJ*, 521, 723
 Kalogera, V., Henninger, M., Ivanova, N., & King, A. R. 2004, *ApJ*, in press (astro-ph/0309035)
 Kalogera, V., Narayan, R., Spigel, D., & Taylor, J. H. 2001, *ApJ*, 556, 340
 King, A. R., Kolb, U., & Burderi, L. 1996, *ApJ*, 464, L127
 King, A. R., & Pounds, K. A. 2003, *MNRAS*, 345, 657
 King, A. R., et al. 1997, *ApJ*, 484, 844
 Kulkarni, S., Hut, P., & McMillan, S. 1993, *Nature*, 364, 421
 Kumar, P., & Goodman, J. 1996, *ApJ*, 466, 946
 Kuulkers, E. 2003, *A&A*, 399, 663
 Lasota, J.-P. 2001, *NewA Rev.*, 45, 449
 Lee, H. M., & Ostriker, J. P. 1986, *ApJ*, 310, 176
 Maccarone, T. J., Kundu, A., & Zepf, S. E. 2003, *ApJ*, 586, 814
 McMillan, S. L. W., Taam, R. E., & McDermott, P. N. 1990, *ApJ*, 354, 190
 Miller, M. C., & Hamilton, D. P. 2002, *MNRAS*, 330, 232
 Pfahl, E., Rappaport, S., & Podsiadlowski, P. 2002, *ApJ*, 573, 283
 Pooley, D., et al. 2003, *ApJ*, 591, L131
 Portegies Zwart, S., & McMillan, S. 2000, *ApJ*, 528, L17
 Press, W. H., & Teukolsky, S. A. 1977, *ApJ*, 213, 183
 Rasio, F. A., Pfahl, E., & Rappaport, S. A. 2001, *ApJ*, 532, L47
 Rasio, F. A., & Shapiro, S. L. 1991, *ApJ*, 377, 559
 Redmount, I. H., & Rees, M. J. 1989, *Comments Astrophys.*, 14, 165
 Rutledge, R., et al. 2002, *ApJ*, 578, 405
 Sarazin, C., et al. 2003, *ApJ*, 595, 743
 Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269
 Shara, M. M., Bergeron, L. E., Gilliland, R. L., Saha, A., & Petro, L. 1996, *ApJ*, 471, 804
 Sigurdsson, S., & Hernquist, L. 1993, *Nature*, 364, 423
 Sigurdsson, S., & Phinney, E. S. 1995, *ApJS*, 99, 609
 Spitzer, L., Jr. 1969, *ApJ*, 158, L139
 Taam, R. E., King, A. R., & Ritter, H. 2000, *ApJ*, 541, 329
 Watters, W. A., Joshi, K. A., & Rasio, F. A. 2000, *ApJ*, 539, 331
 Wijnands, R., Homan, J., & Remillard, R. 2002, *Astron. Telegram*, 101, 1