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ULTRALUMINOUS X-RAY SOURCES AS INTERMEDIATE-MASS BLACK HOLES FED BY TIDALLY CAPTURED STARS

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ABSTRACT

The nature of ultraluminous X-ray (ULX) sources is presently unknown. A possible explanation is that they are accreting intermediate-mass black holes (IBHs) that are fed by Roche lobe overflow from a tidally captured stellar companion. We show that a star can circularize around an IBH without being destroyed by tidal heating (in contrast to the case of $M_{\rm BH} > 10^6\ M_\odot$ massive black holes in galactic centers, where survival is unlikely). We find that the capture and circularization rate is $\sim 5 \times 10^{-8}$ yr^{-1}, almost independently of the cluster's relaxation time. We follow the luminosity evolution of the binary system during the main-sequence Roche lobe overflow phase and show it can maintain ULX source–like luminosities for greater than 10^7 yr. In particular, we show that the ULX source in the young cluster MGG-11 in starburst galaxy M82, which possibly harbors an IBH, is well explained by this mechanism, and we predict that $\gtrsim$10% of similar clusters with IBHs have a tidally captured circularized star. The cluster can evaporate on a timescale shorter than the lifetime of the binary. This raises the possibility of a ULX source that outlives its host cluster, or even lights up only after the cluster has evaporated, in agreement with observations of hostless ULX sources.

Subject headings: black hole physics — galaxies: star clusters — stellar dynamics — X-rays: binaries

1. INTRODUCTION

Black holes (BHs) have deep potential wells and can transform gravitational energy very efficiently to radiation. The energetic central engines of quasars are thought to host massive black holes (MBHs) of $M_{\rm BH} > 10^6\ M_\odot$. It is natural to extrapolate this idea and invoke an intermediate-mass black hole (IBH; $10^2 \lesssim M_{\rm BH}/M_\odot \lesssim 10^5$) to explain ultraluminous X-ray (ULX) sources, which are considerably brighter than a stellar mass object radiating at its Eddington luminosity. For example, Kaaret et al. (2001) have suggested that an IBH powers the ULX source in MGG-11 in starburst galaxy M82.

The origin of the gas that fuels the X-ray source is unclear, since almost all the gas in young clusters is rapidly blown away by the strong winds of massive stars. One possibility for providing the gas is the tidal disruption of a main-sequence (MS) star of mass M_* and radius R_* with periapse $r_p < r_t$, where $r_t = (M_{\rm BH}/M_*)^{1/3}R_*$ is the tidal radius. However, direct disruptions lead to a short flare ($t_{\rm flare} \lesssim 1$ yr; Rees 1988; Ulmer 1999; Ayal, Livio, & Piran 2000), which is incompatible with the ~20 yr observation period of the X-ray source. In this Letter, we investigate a more gradual process for feeding the IBH, namely, the tidal capture of an MS star and the subsequent Roche lobe overflow (RLOF).

2. TIDAL CAPTURE RATE

A BH in a cluster with velocity dispersion σ dominates the potential within its radius of influence $r_a = GM_{\rm BH}/\sigma^2$; inside r_a, orbits are approximately Keplerian, and stars are distributed according to a power law $n_* \propto r^{-\alpha}$, with $\alpha \approx 3/2$ (Bahcall & Wolf 1976; Baumgardt, Makino, & Portegies Zwart 2004). The cusp is truncated inside some radius $r_{\rm in}$, e.g., $r_{\rm in} \sim (M_{\rm BH}/M_*)R_*$, where the rate of destructive collisions exceeds the two-body relaxation rate (Frank & Rees 1976).

Stars can reach an orbit with periapse of order of the tidal radius by angular momentum diffusion. When the star passes at r_p, an energy $\Delta E_t(r_p)$ is invested in raising tides, causing the star to spiral in ($r_p < 3r_t$ is typically required for an appreciable effect). The evolution of a tidally heated star is not well understood. Two extreme models of "squeezars" (stars that are continually powered by tidal squeezing) were studied by Alexander & Morris (2003). "Hot squeezars" are heated only in their outer layers and radiate their excess energy efficiently; they hardly expand. "Cold squeezars" dissipate the tidal energy in their bulk and puff up to giant size.

Our analysis is based on the following assumptions:

1. The stars are hot squeezars (in § 5, we discuss some consequences of relaxing this assumption).
2. As long as the eccentricity e is high,

$$1 - e = r_p/a < \xi_e \sim 0.1, \tag{1}$$

where a is the orbital semimajor axis, the stellar structure is not significantly affected by the tidal heating, and the tidal energy dissipated per orbit,

$$\Delta E_t(b) = \frac{GM_*^2}{R_*}\frac{T(b)}{b^6}, \tag{2}$$

is constant (Alexander & Morris 2003); here $b = r_p/r_t$, and $T(b)$ is the tidal coupling coefficient, which depends on the stellar structure and is a strongly decreasing function of b (e.g., Press & Teukolsky 1977). When the orbit decays to the point where $1 - e > \xi_e$, the tidal heating drops off until eventually the star circularizes at $a \gtrsim r_t$ and $\Delta E_t = 0$ (Hut 1980).

3. The star can survive as long as its tidal luminosity does

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not exceed, to within order unity, its Eddington luminosity $L_{\rm E} = 1.3 \times 10^{38}$ ergs s$^{-1} M_*/M_\odot$,

$$\Delta E_t/P < \xi_L L_{\rm E}, \tag{3}$$

where P is the orbital period and $\xi_L \approx 1$.

The tidal heating rate is highest when P is shortest, just before tidal heating shuts off when $a = br_t/\xi_e$ (eq. [1]). Therefore, the Eddington luminosity limit (eq. [3]) corresponds to a minimal periapse $b_{\rm min} r_t$ that a star can have and still circularize without being disrupted, which is given implicitly by

$$\Delta E_t(b_{\rm min}) = \xi_L L_{\rm E} \frac{2\pi}{\sqrt{GM_{\rm BH}}} \left(\frac{b_{\rm min} r_t}{\xi_e}\right)^{3/2}. \tag{4}$$

When $r_p < b_{\rm min} r_t$, the star is evaporated by its own tidally powered luminosity during in-spiral.

Stars within the "loss cone," a region in phase space where stars have periapse smaller than r_t (Frank & Rees 1976; Lightman & Shapiro 1977), are disrupted by the BH. Two-body scattering sustains a flow of stars in angular momentum space toward the loss cone. During in-spiral, two-body interactions change the periapse of the star. The time t_p over which the periapse of a star is changed by order unity owing to many small angle deflections is (Alexander & Hopman 2003)

$$t_p(b, a) = \frac{br_t}{a} t_r, \tag{5}$$

where t_r is the relaxation time. Note that t_r does not depend on the distance from the BH for $\alpha = 3/2$.

The in-spiral time is the time it takes until the semimajor axis of the star becomes formally zero; for a hot squeezar, it is (Alexander & Hopman 2003)

$$t_0(b, a) = \frac{2\pi M_* \sqrt{GM_{\rm BH} a}}{\Delta E_t(b)}. \tag{6}$$

If deflections increase the periapse, the dissipation becomes much less efficient, while if the periapse decreases, the star may cross r_t and be disrupted. Either way, it fails to circularize. Circularization can happen only if the in-spiral time t_0 is shorter than the timescale for deflections, t_p. The widest orbit $a_c(b)$ from which a star can still spiral in for periapse br_t is given by $t_0(b, a_c) = 3t_p(b, a_c)$ (Alexander & Hopman 2003, eq. [11] for $\alpha = 3/2$). It then follows from equation (4) that the maximal distance $a_{\rm max}$ from which a star can originate to reach the tidal radius without being destroyed is

$$a_{\rm max} = \left[\frac{3\Delta E_t(b_{\rm min}) b_{\rm min} r_t t_r}{2\pi M_* \sqrt{GM_{\rm BH}}}\right]^{2/3}. \tag{7}$$

Within $r_{\rm in}$, the cusp flattens and relaxation is inefficient, so there are hardly any stars on eccentric orbits. Since $r_{\rm in}$ grows more rapidly with $M_{\rm BH}$ than $a_{\rm max}$, there exists a maximal BH mass $M_{\rm max}$, such that for $M_{\rm BH} > M_{\rm max}$, $a_{\rm max} < r_{\rm in}$, and tidal capture is strongly suppressed. Figure 1 shows $a_{\rm max}$ and $r_{\rm in}$ as a function

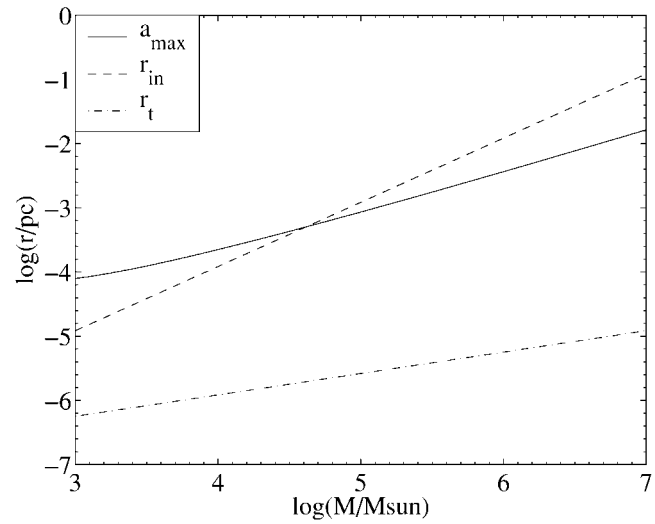

FIG. 1.—Dependence of $a_{\rm max}$ (*solid line*), $r_{\rm in}$ (*dashed line*), and r_t (*dash-dotted line*) on the mass of the BH, for a 10 $M_\odot$ star. Circularization is only possible provided that $a_{\rm max} > r_{\rm in}$.

of $M_{\rm BH}$; for the calculation of t_r, we assumed that the $M_{\rm BH}$-σ relation

$$M_{\rm BH} = 1.3 \times 10^8\ M_\odot \left(\frac{\sigma}{200\ {\rm km\ s^{-1}}}\right)^4 \tag{8}$$

(Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) can be extended to IBHs (see, e.g., Portegies Zwart & McMillan 2002). Circularization is only possible for $M_{\rm BH} < M_{\rm max} \approx 10^5\ M_\odot$.

The rate Γ at which stars diffuse into orbits that allow successful circularization is given by (eq. [9] in Syer & Ulmer 1999)

$$\Gamma = \frac{(a_{\rm max}/r_a)^{3-\alpha} N_a}{t_r \ln(2\sqrt{a_{\rm max}/b_{\rm min} r_t})} \qquad (a_{\rm max} > r_{\rm in}), \tag{9}$$

where the logarithmic term expresses the depletion of the stellar density near the loss cone; N_a is the number of stars within the radius of influence. The rate is essentially independent on M_* for a fixed stellar mass within r_a, and it decreases only logarithmically with t_r (see eqs. [7] and [9]): a larger t_r increases the volume of stars that contributes to Γ but decreases the rate at which stars enter the loss cone. The rate does not depend very sensitively on our assumptions: roughly, $\Gamma \propto \xi_L/\xi_e$.

3. ROCHE LOBE OVERFLOW ON THE MAIN SEQUENCE

Orbital angular momentum conservation implies that the circularization radius is $a_{\rm circ} = 2b_{\rm min} r_t$. Efficient in-spiral and successful circularization require $b_{\rm min} \sim 2$–2.5, so that $a_{\rm circ} \sim (4$–$5) r_t$. The onset of mass transfer through the Roche lobe occurs when the distance between the IBH and the star is $a_{\rm circ} \sim 2r_t$ (assuming $M_* = 10\ M_\odot$, $M_*/M_{\rm BH} \sim 0.01$; Eggleton 1983). This is roughly a factor of 2 smaller than the typical value of $a_{\rm circ}$. However, as it evolves on the MS, a 10 $M_\odot$ star expands by a factor of ~2.7 by the time it reaches the terminal-age MS (TAMS). This implies that RLOF occurs at some point on the MS and continues for a time $t_{\rm X}$, which is shorter than the MS lifetime $t_{\rm MS}$ (we assume here that the star expands significantly only after it has circularized). In the following

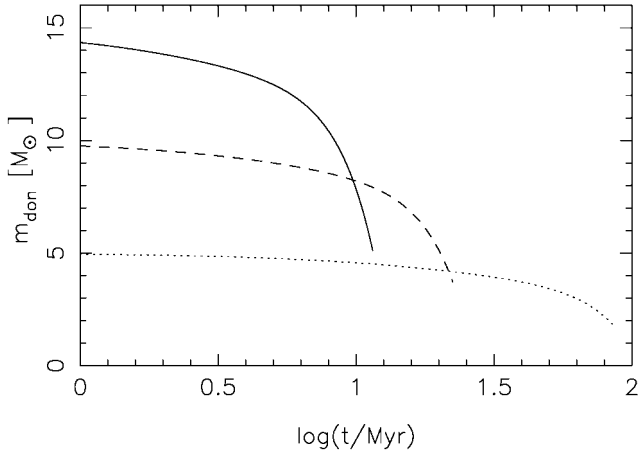

FIG. 2.—Mass evolution of the donor star, assuming Roche lobe contact at the zero-age MS to a 1400 $M_\odot$ IBH. The solid, dashed, and dotted lines are for a 15, 10, and 5 $M_\odot$ donor.

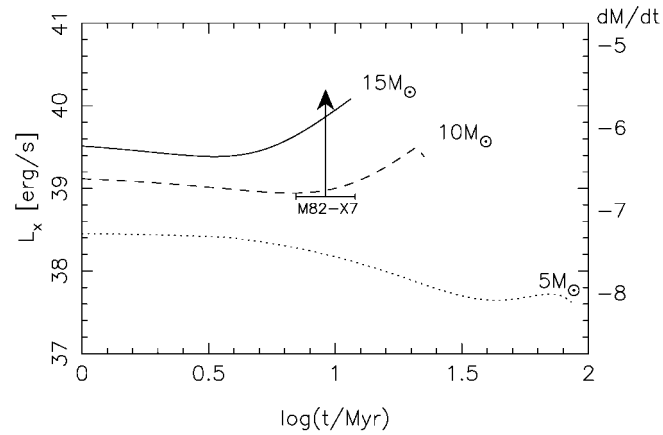

FIG. 3.—X-ray luminosity for a 1400 $M_\odot$ accreting IBH as a function of time. Line styles are the same as in Fig. 2. To the right side of the figure, we added $\dot{M}$ in logarithmic units of $M_\odot$ yr^{-1} for the regime where $\dot{M} > \dot{M}_{\rm crit}$. The radius of the star grows significantly toward the TAMS (where the lines for 15 and 10 $M_\odot$ donors rise). It is probably only near that point at which RLOF actually starts, so that the luminosity is higher than would be estimated from RLOF of a zero-age MS star. The 5 $M_\odot$ donor does not show this rise in $L_{\rm X}$ as $\dot{M} < \dot{M}_{\rm crit}$ after ~10 Myr. This also causes the drop of $L_{\rm X}$ for the 10 $M_\odot$ donor star at the end of its evolution. When $\dot{M} < \dot{M}_{\rm crit}$, the source becomes transient.

analysis, we assume for simplicity that RLOF holds over the entire MS. This does not affect our conclusions significantly since the observationally relevant phase of high X-ray luminosity occurs toward the TAMS. For massive MS stars, RLOF is preceded by a less luminous phase resulting from the accretion of strong stellar winds.

Mass transfer from an MS star to an IBH is driven by the thermal expansion of the donor and the loss of angular momentum from the binary system. Mass transfer then implies that the donor fills its Roche lobe ($R_* = R_{\rm RL}$) and continues to do so ($\dot{R}_* = \dot{R}_{\rm RL}$). We assume that as long as the Eddington limit is not exceeded, all the mass lost from the donor via the Roche lobe is accreted by the IBH ($\dot{M}_{\rm BH} = -\dot{M}_*$). Otherwise, the mass in excess of the Eddington limit is lost from the binary system.

The expansion of the donor on the MS is calculated using fits from Eggleton, Tout, & Fitchett (1989) to detailed stellar evolution calculations. We assume that the evolution of the donor was not affected by mass loss. Variations in the Roche radius of the donor can be computed from the redistribution of mass and angular momentum in the binary system. The radius of the Roche lobe is estimated with the fitting formula from Eggleton (1983).

We stop following the binary evolution at the TAMS; the simple model for calculating the amount of mass transfer may be inappropriate for the post-MS evolution of the donor, as the star then rapidly expands. However, at the end of the MS the donor still has a considerable envelope and the star ascends the giant branch. The post-MS evolution is likely to result in a short ($t_{\rm PMS} < 0.1 t_{\rm MS}$) phase in which the luminosity increases by more than an order of magnitude.

In Figure 2, we plot the mass of the donor as a function of time. It is assumed here that there is Roche lobe contact directly after circularization. As discussed, this actually only happens when the star has evolved toward a later stage of the MS phase, which is when the mass loss in the plot starts to drop more rapidly.

We estimate the X-ray luminosity during mass transfer with the model discussed by Körding, Falcke, & Markoff (2002). They argue that the X-ray luminosity is generated by an accretion disk. The binary is in the hard state if $\dot{M} > \dot{M}_{\rm crit}$, in which case $L_{\rm X} = \epsilon \dot{M} c^2$. At lower accretion rates, $L_{\rm X} = \epsilon \dot{M} c^2 \dot{M}/\dot{M}_{\rm crit}$, in which case the X-ray source becomes transient (i.e., short outbursts, separated by long states of quiescence; Kalogera et al. 2004). For $\dot{M}_{\rm crit}$, we adopt the equation derived by Dubus et al. (1999, see eq. [32]) and assume $\epsilon = 0.1$. These choices are comparable to $\dot{M}_{\rm crit} \sim 10^{-7}$ $M_\odot$ yr^{-1} of Körding et al. (2002). The resulting X-ray luminosity is presented in Figure 3. Note that lower mass donor binaries ($M_* \lesssim 5$ $M_\odot$) live longer, are less luminous, and tend to show transient behavior, where high-mass donor binaries are more luminous, shorter lived, steady sources.

4. CLUSTER MGG-11

We apply our analysis to the young dense star cluster MGG-11 in the irregular galaxy M82, at a distance of ~4 Mpc. This cluster contains the variable X-ray source M82-X7 with $L_{\rm X} = (0.8–160) \times 10^{39}$ ergs s^{-1} (Watson, Stanger, & Griffiths 1984; Matsumoto & Tsuru 1999; Kaaret et al. 2001). The velocity dispersion in the cluster is accurately measured, $\sigma = 11.4 \pm 0.8$ km s^{-1} (McGrady, Gilbert, & Graham 2003). We assume that this cluster contains an IBH, which is also the engine for the X-ray source. If this IBH obeys the $M_{\rm BH}$-σ relation (8), its mass is $M_{\rm BH} = 1.4 \times 10^3$ $M_\odot$, which is consistent with the recent calculations of Portegies Zwart et al. (2004), who show that an IBH could have formed dynamically in MGG-11 by a runaway merger of MS stars. Within its radius of influence $r_a = 0.05$ pc, the number of stars is $N_a = 2M_{\rm BH}/M_*$ (Merritt 2004) and $t_r \sim 10^5$–10^6 yr.

The age of the cluster is $t_{\rm cl} = 7$–12 Myr, corresponding to a turnoff mass of 17–25 $M_\odot$ (Eggleton et al. 1989). The mean stellar mass of the cluster at birth is $\langle M_* \rangle = 3$ $M_\odot$, but as a result of mass segregation the average mass within r_a is much higher. The direct N-body calculations of Portegies Zwart et al. (2004) show that at an age of 7 Myr, the mean mass of the single stars in the core of MGG-11 is $\langle M_* \rangle = 8 \pm 3$ $M_\odot$. For simplicity, we assume within r_a a single mass population of stars with $M_* = 10$ $M_\odot$ and radius $R_* = 5.4$ $R_\odot$ (Gorda & Svechnikov 1998). The results of Figure 3 show that an MS donor of mass $M_* \gtrsim 10$ $M_\odot$ can account for the luminosity of the ULX source in MGG-11.

We assume $(\xi_e, \xi_L) = (0.1, 0.5)$ and take the numerical values

for the function $T(b)$ for parabolic orbits from Alexander & Kumar (2001). With these parameters, we find a capture rate of $\Gamma = 5 \times 10^{-8}$ yr^{-1}. This implies that a fraction $\Gamma t_{\rm cl} t_{\rm X}/t_{\rm MS} =$ 30%–50% of clusters harboring an IBH has formed a tidal binary and may be observed during RLOF in the MS phase. A fraction $\Gamma t_{\rm cl} t_{\rm PMS}/t_{\rm MS} \sim 4\%$ of clusters with an IBH should be observed during the more luminous post-MS phase.

5. SUMMARY AND DISCUSSION

MS stars can spiral into an IBH as a result of tidal capture and circularize close to the tidal radius. This process is unique to IBHs, since stars cannot survive tidal in-spiral around an MBH in a galactic center. After circularization, the star expands on the MS until high-luminosity RLOF accretion starts toward the end of the MS phase. We analyzed RLOF during the MS phase in some detail and calculated the X-ray luminosity. Post-MS RLOF is harder to model, but the resulting luminosity is expected to be at least an order of magnitude brighter and about an order of magnitude shorter in duration. The X-ray luminosity is consistent with observed ULX sources, such as MGG-11.

MGG-11 is the only cluster out of hundreds in M82 with a ULX source. Possibly other clusters were not sufficiently dense to form IBHs (Matsushita et al. 2000; Portegies Zwart et al. 2004). If a fraction $f_{\rm BH}$ of the $N_{\rm cl}$ clusters in M82 harbors an IBH, the number of ULX sources is estimated by $N_{\rm X} = f_{\rm BH}\Gamma t_{\rm cl} t_{\rm X}/t_{\rm MS}$. Thus, $f_{\rm BH}$ has to be of the order of a few percent in order to account for one ULX source in M82.

In order to circularize, a star has to dissipate $\sim(M_{\rm BH}/M_*)^{2/3}$ times its binding energy. If a certain fraction δ of the energy is invested in bulk heating (for hot squeezars, $\delta = 0$ as assumed so far; for cold squeezars, $\delta = 1$), the star expands. An X-ray binary can form only if $\delta < (M_*/M_{\rm BH})^{2/3}$. Nevertheless, a shorter lived ULX source phase is still possible even if $\delta > (M_*/M_{\rm BH})^{2/3}$. When the star expands to a radius greater than bR_*, it loses a small amount of gas at each periapse passage. In this way, the star can feed the IBH for a period much longer than $t_{\rm flare}$. However, the process is limited by the two-body deflection timescale t_p, which is $\lesssim 10^3$ yr for a $10^3\ M_\odot$ IBH. This translates to a detection probability of only $\Gamma t_p \sim 5 \times 10^{-5}$, and so it is unlikely that the ULX source in MGG-11 originates in this type of process. For similar reasons, it is improbable to observe a very luminous tidally heated star (squeezar) during the final stages of its in-spiral into an IBH in a stellar cluster (this may be possible for squeezars near the MBH in the Galactic center, where the in-spiral time is longer and the capture rate higher; Alexander & Morris 2003).

The lifetime of the host cluster is limited by the galactic tidal field and can be as short as 100 Myr (Portegies Zwart et al. 2001). This is much shorter than the RLOF phase of a low-mass donor (e.g., ~1 Gyr for a 2 $M_\odot$ star). Thus, the X-ray lifetime of a low-luminosity binary can be much longer than the lifetime of the cluster. Quiescent orphaned IBHs can suddenly light up when their companion ascends the giant branch and starts to transfer mass to the IBH. Our scenario predicts the existence of hostless ULX sources, which are more likely to be transient and less luminous. Their exact fraction in the ULX source population cannot be reliably estimated at this time. However, it is interesting to note that three to 10 out of 14 of the ULX sources in the Antennae galaxies are coincident with a stellar cluster, while the others are not (Zezas et al. 2002).

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