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MASSIVE BLACK HOLE BINARIES FROM COLLISIONAL RUNAWAYS

M. Atakan Gürkan,[1] John M. Fregeau, and Frederic A. Rasio
Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-2900;
fregeau@alum.mit.edu, rasio@northwestern.edu
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ABSTRACT

Recent theoretical work has solidified the viability of the collisional runaway scenario in young dense star clusters for the formation of very massive stars (VMSs), which may be precursors to intermediate-mass black holes (IMBHs). We present first results from a numerical study of the collisional runaway process in dense star clusters containing primordial binaries. Stellar collisions during binary scattering encounters provide an alternate channel for runaway growth, somewhat independent of direct collisions between single stars. We find that clusters with binary fractions $\gtrsim 10\%$ yield *two* VMSs via collisional runaways, presenting the exotic possibility of forming IMBH-IMBH binaries in star clusters. We discuss the implications for gravitational wave observations and the impact on cluster structure.

Subject headings: black hole physics — globular clusters: general — gravitational waves — methods: *n*-body simulations — stellar dynamics

Online material: color figures

1. INTRODUCTION

Observations hinting at the possible existence of intermediate-mass black holes (IMBHs) have mounted in recent years. Ultraluminous X-ray sources—point X-ray sources with inferred luminosities $\gtrsim 10^{39}$ ergs s^{-1}—may be explained by sub-Eddington accretion onto BHs more massive than the maximum mass of $\sim 10\ M_\odot$ expected via core collapse in main-sequence stars, although viable alternative explanations exist (Miller & Colbert 2004). Similarly, the cuspy core velocity dispersion profiles of the globular clusters M15 and G1 may also be explained by the dynamical influence of a central IMBH (van der Marel et al. 2002; Gerssen et al. 2002; Gebhardt et al. 2005), although theoretical work suggests that the observations of M15 may be equally well explained by a collection of compact stellar remnants in the cores of the clusters (Baumgardt et al. 2003).

At least three distinct IMBH formation mechanisms have been discussed in the literature. The first, and possibly simplest, is the core collapse of a massive Population III star (Madau & Rees 2001). The very low metallicity of Population III stars ($Z \lesssim 10^{-5}\ Z_\odot$) allows for much larger main-sequence stars to form, limits mass loss during stellar evolution, and increases the fraction of mass retained in the final BH (for stars more massive than $\sim 250\ M_\odot$; Fryer et al. 2001; Miller & Colbert 2004). The second is the successive merging of stellar mass BHs via dynamical interactions, which may occur in star clusters that do not reach deep core collapse before ~ 3 Myr, when the most massive cluster stars have become BHs (Kulkarni et al. 1993; Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000; Miller & Hamilton 2002; O'Leary et al. 2006). The process is relatively inefficient—in terms of the amount of mass added to the growing BH per BH ejected from the cluster—requiring BH seeds $\gtrsim 500\ M_\odot$ to create $10^3\ M_\odot$ IMBHs (Gültekin et al. 2004), even when aided by the Kozai mechanism (Miller & Hamilton 2002) or gravitational wave losses during close approaches (Gültekin et al. 2006). Introducing a mass spectrum for the BHs decreases the required seed mass, although growth is still rare (O'Leary et al. 2006). The third is the runaway merging of main-sequence stars via direct physical collisions to form a very massive star (VMS), which may then collapse to form an IMBH (Portegies Zwart et al. 1999; Ebisuzaki et al. 2001; Portegies Zwart & McMillan 2002; Gürkan et al. 2004). Recent work shows that runaway growth of a VMS occurs generically in clusters with deep core-collapse times shorter than ~ 3 Myr (Freitag et al. 2005a).

With the exception of one simulation (Portegies Zwart et al. 2004), all simulations of runaway collisional growth in clusters have ignored the effects of primordial binaries, which are known to exist in clusters in dynamically significant numbers (Hut et al. 1992). Indeed, some numerical results suggest that the primordial binary fraction (f_b) may have to be nearly 100% to explain the currently observed binary fractions in cluster cores (Ivanova et al. 2005). Primordial binaries are an important piece of the runaway collisional growth puzzle, since they introduce two effects that may strongly affect the process. On the one hand, binaries generate energy via dynamical scattering interactions in cluster cores, supporting the core against deep collapse and limiting the maximum stellar density attainable, and hence limiting the direct stellar collision rate (Heggie & Hut 2003). On the other hand, stellar collisions are much more likely in dynamical interactions of binaries, since the interactions are typically resonant (Bacon et al. 1996; Fregeau et al. 2004). Since these two effects of primordial binaries act in opposite senses with respect to the collision rate, it is not clear a priori how they affect the collisional runaway scenario.

Before appealing to numerical methods, however, one can gain insight into the effects of primordial binaries by considering the coagulation equation (Lee 1993, 2000; Malyshkin & Goodman 2001)—a simplification of which is presented in Freitag et al. (2005b)—which describes the evolution of a spectrum of masses due to mergers. For growth to occur in a runaway fashion, the coagulation equation requires that the cross section for collisions with the runaway object scales sufficiently rapidly with its mass: $S_{\rm coll} \propto M^\eta$, with $\eta > 1$. For single-single star collisions in star clusters in which the central velocity dispersion is less than the escape speed from the surface of a typical star (so that the cross section is dominated by gravitational focusing), this corresponds to the constraint $R \propto M^\alpha$,

[1] Current address: Foundations Development, Sabancı University, 34956 Istanbul, Turkey; ato.gurkan@gmail.com.

with $\alpha > 0$, on the main-sequence mass-radius relationship, which is satisfied by main-sequence stars of any mass or metallicity. With some approximations, the coagulation equation analysis (Heggie 1975; Hut & Bahcall 1983; Sigurdsson & Phinney 1993; Gültekin et al. 2006) can be applied to collisions occurring in binary scattering interactions. From Figure 4 of Gültekin et al. (2006), the cross section for close approach distances of $r_{\min}$ in binary-single scattering encounters scales as $(S_{\rm coll}/\pi a^2)(v_\infty/v_c)^2 \propto (r_{\min}/a)^\gamma$, with $0.3 \lesssim \gamma \lesssim 1$, where a is the binary semimajor axis, v_∞ is the relative velocity between the binary and single star at infinity, and v_c is the critical velocity (see eq. [12] of Gültekin et al. 2006). Using the radius of the runaway star for $r_{\min}$, $R \propto M^\beta$ with $0.5 \lesssim \beta \lesssim 1$ for the scaling of the mass-radius relation, and assuming that the binding energy of the binary is roughly preserved during the encounter so that $a \propto M$, we find

$$S_{\rm coll} \propto M^{2+\gamma(\beta-1)}, \tag{1}$$

with $0.3 \lesssim \gamma \lesssim 1$ and $0.5 \lesssim \beta \lesssim 1$. The minimum of the exponent is ≈ 1.5. Thus, according to the coagulation equation, collisions induced in binary-single scattering interactions should yield runaway growth of a VMS. This result says nothing about the *rate* of growth of the runaway object. In other words, it is still not clear whether binary interactions will limit the cluster core density such that the runaway timescale is longer than the massive star main-sequence lifetime of ≈ 3 Myr, in which case the process would be halted.

Assuming that the cluster core density reached is high enough for the runaway to proceed, it would appear that a single binary is sufficient for a binary interaction–induced runaway to occur. This is, of course, not the case, since binary scattering interactions tend to destroy binaries. Thus, we expect that for sufficiently low f_b, the runaway will be primarily mediated by single-single collisions. For sufficiently large f_b, the runaway will be primarily mediated by binary-binary interactions (the analysis above assumes binary-single interactions—for binary-binary, the value of γ will be smaller, still allowing a runaway by eq. [1]). For intermediate f_b, it is possible that a binary interaction–induced runaway could proceed until the core binary population is sufficiently depleted that the cluster's core collapses. If the first runaway is far enough from the center of the cluster when the core collapses, it is possible that a second runaway will be formed during core collapse, mediated by single-single collisions. The exotic possibility of forming two VMSs in a cluster, and thus two IMBHs, is a tantalizing one, with implications for gravitational wave observations and cluster dynamics.

In this Letter we present first results from a study of the runaway collisional scenario for the formation of VMSs in young dense clusters with primordial binaries. We briefly describe our numerical method, present results showing the growth of two runaways, and discuss the implications.

2. NUMERICAL ANALYSIS

We use our Monte Carlo cluster code to simulate the evolution of young star clusters with primordial binaries (Joshi et al. 2000; Fregeau et al. 2003; Gürkan et al. 2004). This code uses the Hénon method for two-body relaxation and incorporates the Fewbody *N*-body integrator to perform dynamical scattering encounters of binaries. Stellar collisions are handled by assuming that stars whose surfaces touch merge with no mass loss, an assumption that has been shown to be valid for clusters with low velocity dispersion, such as globulars or young dense clusters (Freitag et al. 2005a, 2005b). Collisions are allowed to occur directly in single-single star encounters and during binary interactions (Fregeau et al. 2004).

For initial conditions, we assume a $W_0 = 3$ King model density profile for the cluster, with no initial mass segregation. All stars are main-sequence stars with masses in the range $0.2 < M/M_\odot < 120$, distributed according to a Salpeter mass function. Simulations show that the primary condition required for a runaway is that the core-collapse time is shorter than the main-sequence lifetime for the most massive stars, ~ 3 Myr (Freitag et al. 2005a), and that for clusters of single stars with a wide mass spectrum, the core-collapse time is always $t_{\rm cc} \approx 0.15 t_{\rm rc}(0)$ [where $t_{\rm rc}(0)$ is the initial relaxation time in the core], independent of cluster mass, size, or density profile (Gürkan et al. 2004). This allows us to set the central density of the cluster such that the predicted core-collapse time is either less or greater than 3 Myr. We perform simulations with binary fractions[2] up to 0.2. The binary population is created from a cluster of single stars by adding secondary companions to randomly chosen cluster stars, with the secondary mass chosen uniformly in the binary mass ratio. The binary binding energy is distributed uniformly in the logarithm, truncated at high energy so that the binary members do not make contact at pericenter, and truncated at low energy so that the orbital speed of the lightest member in the binary is larger than the local stellar velocity dispersion (see Fregeau et al. 2006). The eccentricity is chosen according to a thermal distribution, truncated at large e so that the binary members do not make contact at pericenter. We use either $N = 5 \times 10^5$ or 10^6 total cluster objects, finding no difference in the runaway results between the two. We run all simulations until 3 Myr. Our criterion for a runaway is that its final mass is $\gtrsim 500\ M_\odot$. In our runs, the final masses of the VMSs are always at least twice this value.

Figure 1 shows the evolution of the cluster Lagrange radii and the mass of the (single) runaway as a function of time for a cluster with $t_{\rm cc} < 3$ Myr and $f_b = 0.05$. The evolution is typical for models with $f_b \lesssim 0.1$ and $t_{\rm cc} < 3$ Myr in that (1) the energy generated in binary interactions is not sufficient to postpone core collapse beyond 3 Myr and (2) there is a single runaway. In the model shown in Figure 1, the runaway grows to $\approx 2800\ M_\odot$ before the cluster begins to expand in response to the energy generated in collisions with the runaway.

We follow the membership of the collision products in binaries during the collisions and binary interactions. This allows us to produce merger trees to track the contributions to the formation of VMSs. Figure 2 shows the merger trees for the three most massive stars at the end of the simulation. There is clearly only one runaway for this model, and it grows primarily via direct, single-single collisions. Figure 3 shows the same as Figure 2 for the same model, but with $f_b = 0.1$. In this model, there are two VMSs at the end of the simulation. A binary interaction–induced collisional runaway begins at $t \approx 1.5$ Myr and proceeds to $\approx 1.3 \times 10^3\ M_\odot$. A direct collision–induced runaway begins at $t \approx 2.3$ Myr, yielding a second runaway, of mass $\approx 2.5 \times 10^3\ M_\odot$. The third most massive star at the end of the simulation has only grown to $\approx 400\ M_\odot$. The evolution is typical for models with $f_b \gtrsim 0.1$ and $t_{\rm cc} < 3$ Myr in that there are two runaways: one

[2] The binary fraction is defined such that f_b is the fraction of *objects* in the cluster that are binaries, with an object being either a binary or a single star.

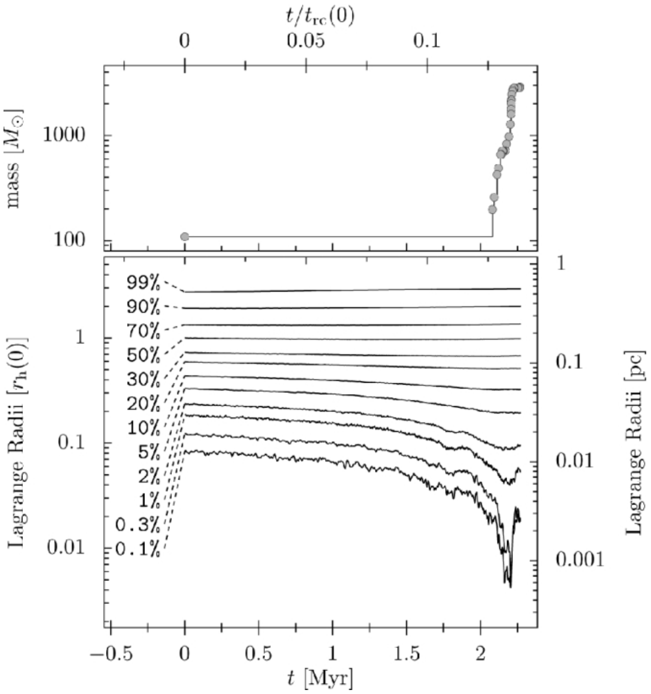

FIG. 1.—Evolution of the cluster Lagrange radii (*lower panel*) in units of the initial cluster half-mass radius (*left axis*) and in parsecs (*right axis*), and the mass of the (single) runaway for a cluster with 10^6 objects and $f_b = 0.05$. Time is shown both in megayears and in units of the central relaxation time. [*See the electronic edition of the Journal for a color version of this figure.*]

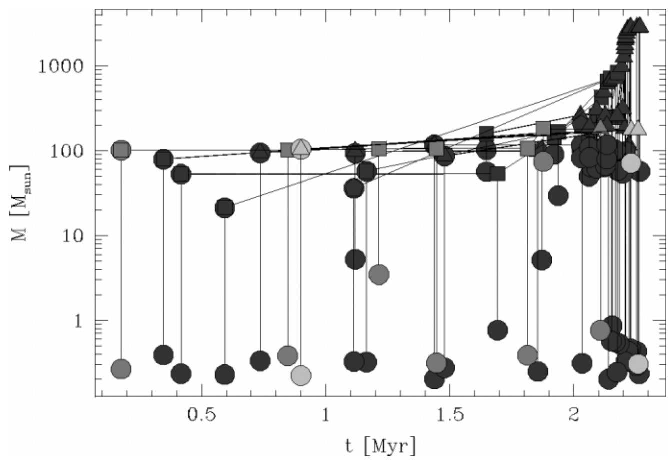

FIG. 2.—Merger trees for the three most massive stars at the end of the simulation for the model presented in Fig. 1. The dark gray symbols represent the most massive, intermediate gray the second most, and light gray the third most. For each collision with the massive star, a symbol is plotted at its mass at the time of the collision with lines drawn connecting to the symbols representing the stars participating in the merger. A triangle represents a single-single collision, a square a collision in a binary-single interaction, a pentagon a collision in a binary-binary interaction, and a circle a star that has not yet undergone a collision. As an example, the three intermediate gray points at $t \approx 0.2$ Myr represent a collision in a binary-single interaction of an $\approx 100\ M_\odot$ star with an $\approx 0.3\ M_\odot$ star, each having never undergone a collision previously. For this model, there is clearly just one VMS, created primarily in single-single collisions. [*See the electronic edition of the Journal for a color version of this figure.*]

via direct collisions and one via collisions in binary interactions.

Although we have not yet conducted a full parameter space survey, we have mapped a significant slice in f_b-$t_{rc}(0)$ space, from $f_b = 0.02$ to 0.2 and from $t_{cc}/(3\ \mathrm{Myr}) = 0.16$ to 28. Without exception, and independent of f_b, models with $t_{cc} = 0.15 t_{rc}(0) > 3$ Myr show no runaways (seven models), while those with $t_{cc} = 0.15 t_{rc}(0) < 3$ Myr show either one or two (10 models). This is in agreement with the results for clusters with no primordial binaries, presumably since binary fractions smaller than 20% are not sufficient to postpone core collapse beyond 3 Myr. Of the models that show runaways, those with $f_b < 0.1$ always yield only single runaways (four models), while those with $f_b \geq 0.1$ always yield double runaways (six models). No models ever produce more than two runaways. Due to the computational cost involved, we have not yet explored the $f_b > 0.2$ region of parameter space.

The numerical results presented here clearly agree with the analytical arguments made above on the runaway nature of binary interaction–induced collisions. Binary interaction–induced runaways occur on the outskirts or just outside the core (typically a few percent of a parsec for our models). This is a region where densities, in particular the binary densities, are high enough to start a runaway but the relaxation time is long enough that massive objects do not rapidly sink to the center. The rapid collapse near the center leads to an expansion of these regions, further increasing the relaxation time, and prevents a prompt merger of the VMSs.

Finally, we note the apparent disagreement between our results and those of Portegies Zwart et al. (2004), who performed two direct *N*-body integrations of models of the cluster MGG 11 with $f_b = 0.1$ and found only single runaways. Our results predict that whenever $f_b \gtrsim 0.1$, and the cluster central relaxation time is short enough so that a runaway is expected in a corresponding cluster with only single stars, a double runaway should result. The models of Portegies Zwart et al. (2004) are extremely centrally concentrated, with $W_0 = 12$, while our models all use $W_0 = 3$. From the discussion above, it is clear that if the density profile is sufficiently steep, the binary interaction–induced runaway will take place close enough to the center so that it will seed the subsequent direct collision–induced runaway, yielding just one runaway. In addition, the condition $f_b \gtrsim 0.1$ for double runaways is only approximate. Since the models of Portegies

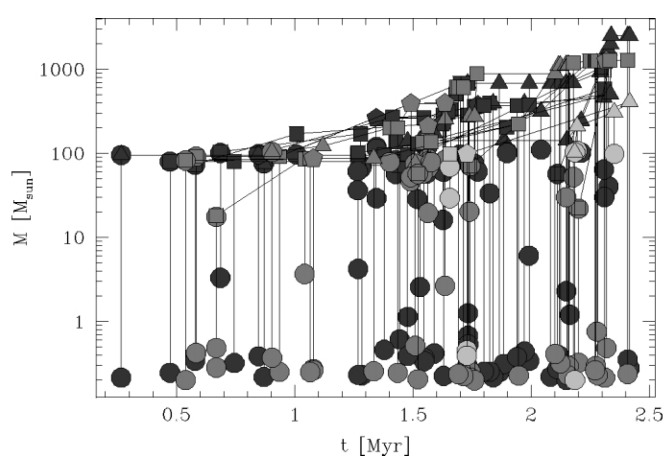

FIG. 3.—Same as Fig. 2 for the same model, but with $f_b = 0.1$. A binary interaction–induced collisional runaway begins at $t \approx 1.5$ Myr and proceeds to $\approx 1.3 \times 10^3\ M_\odot$. A direct collision–induced runaway begins at $t \approx 2.3$ Myr, yielding a second runaway, of mass $\approx 2.5 \times 10^3\ M_\odot$. The third most massive star at the end of the simulation has only grown to $\approx 400\ M_\odot$. [*See the electronic edition of the Journal for a color version of this figure.*]

Zwart et al. (2004) are right on this boundary, it is possible that a small difference in the initial conditions has prevented a double runaway in their models.

3. DISCUSSION

Although the process is somewhat uncertain, it is likely that the VMSs formed in young clusters via collisional runaways will undergo core collapse and become IMBHs on a timescale of ∼1 Myr (Freitag et al. 2005a). Our results show no evidence of the VMSs merging prior to becoming IMBHs. After their separate formation, the two IMBHs will quickly exchange into a common binary via dynamical interactions. The IMBH-IMBH binary will then shrink via dynamical friction due to the cluster stars, to the point at which the stellar mass enclosed in the binary is comparable to the binary mass. This occurs on a timescale $\sim t_r\langle m\rangle/M_{\rm IMBH}$, where t_r is the local relaxation time and $\langle m\rangle$ is the local average stellar mass. Since $\langle m\rangle/M_{\rm IMBH} \lesssim 10^{-2}$, this timescale is likely to be $\lesssim$10 Myr. The binary will then shrink via dynamical encounters with cluster stars, the rate of which is governed by loss-cone physics. The timescale for the binary to shrink to the point at which it merges quickly via gravitational radiation energy loss is likely to be $\lesssim$1 Gyr (Yu & Tremaine 2003; Miller 2005).

Although IMBH-IMBH binaries do not merge in the *Laser Interferometer Space Antenna* (*LISA*) band—the gravitational wave frequency at merger is ∼1 Hz—they do represent bright sources that take at least $\sim 10^6$ yr to cross the *LISA* band. Their inspiral (chirp) signals should be easily detectable by *LISA* out to a few tens of megaparsecs. Thus, the number of detectable IMBH binary sources may be quite large, since most clusters are probably born with $f_b \gtrsim 0.1$, and any cluster with mass $\gtrsim 10^6\ M_\odot$ and central relaxation time $\lesssim$20 Myr will lead to a double runaway.

Significant core rotation (with a rotational speed comparable to the local velocity dispersion) is observed in the clusters M15, ω Cen, 47 Tuc, and G1 (e.g., van der Marel et al. 2002; Gebhardt et al. 2005). This rotation suggests the presence of a core angular momentum source, such as an IMBH binary (Mapelli et al. 2005). Similarly, observations of a millisecond pulsar in the halo of NGC 6752, and two others in the core with high negative spin derivatives, hint at the existence of an IMBH binary in the core (Colpi et al. 2003). Since the IMBH-IMBH binaries formed via collisional runaways will merge within ∼1 Gyr after formation, any angular momentum imparted to the cluster by the IMBH-IMBH binary will quickly diffuse out of the core on a core relaxation time. An alternate mechanism must be at work in creating the core rotation seen in some present-day globular clusters.

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