Formation Scenarios for Intermediate-Mass Black Holes

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Abstract. Black holes with hundreds to thousands of solar masses are more massive than can be formed from a single star in the current universe, yet the best candidates for these objects are not located in gas-rich environments where gradual accretion could build up the mass. Three main formation scenarios have been suggested in the literature: that intermediate-mass black holes are the remnants of the first, metal-poor, stars; that they result from direct collisions in young stellar clusters; or that they are produced by gradual interactions and mergers of compact objects in old dense clusters. We discuss each of these in turn and speculate on future observations that may help sharpen our understanding of the formation of intermediate-mass black holes.

INTRODUCTION

Black holes are solidly established to exist in the mass ranges $\sim 5 - 20 M_\odot$ in our Galaxy and others (stellar-mass black holes) and $\sim 10^{6-10} M_\odot$ in the centers of many galaxies (supermassive black holes). As discussed by Mushotzky and by van der Marel in these proceedings, there is now growing evidence for the existence of black holes in the mass range $10^{2-4} M_\odot$ (intermediate-mass black holes, or IMBH), especially in dense stellar clusters. Such objects would be strong sources of gravitational waves in a unique frequency range. The rates of merger events, as well as the information that could be gleaned from IMBH in binaries, depend on the mechanism by which the IMBHs were formed.

When considering how IMBH may be formed, one can adapt Shakespeare, as suggested by Keith Arnaud: "Some are born great, some achieve greatness, and some have greatness thrust upon 'em." Specifically, it may be that the objects we now see as IMBH were born with approximately their current mass, or it may be that through accretion or mergers, black holes with initially much smaller masses grow to their current size. We now consider each of these options briefly, then go into them in more detail in the following sections.

First, suppose that a black hole of mass $\sim 10^{2-4} M_\odot$ was born with that mass. We assume that the initial creation of a black hole is always through the collapse of the core of a massive star. Therefore, if a single star leaves behind an intermediate-mass black hole, the star itself obviously had to have at least as much mass as the remnant black hole. As stars with masses $M \gtrsim 200 M_\odot$ are thought not to form in the current universe (for qualitative arguments, see Larson & Starrfield 1971), black hole remnants with this mass are ruled out. Instead, the very early universe, where metallicities were probably small enough that cooling was minimal and pulsational instabilities were weak, might have

produced stars with the requisite mass (e.g., Abel et al. 1998; Bromm, Coppi, & Larson 1999; Bromm et al. 2001; Abel, Bryan, & Norman 2000; Fryer, Woosley, & Heger 2001; Schneider et al. 2002; Nakamura & Umemura 2002). These so-called Population III stars are therefore candidate progenitors for intermediate-mass black holes.

If instead IMBH were grown from a smaller seed, we can narrow down the ways in which it acquired mass. In general, acquisition of mass can take place by accretion or by mergers. Consider accretion. A black hole in the interstellar medium will gain mass by Bondi-Hoyle accretion of the medium. However, the rate of accretion is tiny, leading to growth timescales of (see, e.g., Miller & Hamilton 2002a)

$$M/\dot{M}_{\text{B}-\text{H}} \approx 10^{13} (M/10 M_\odot)^{-1} (\rho/10^{-24} \text{ g cm}^{-3})^{-1} (v/10^6 \text{ cm s}^{-1})^3 \text{ yr} . \qquad (1)$$

Here we assume that the interstellar medium has density ρ and thermal velocity v at infinity relative to the black hole. The shortest timescales would exist for cool, dense, molecular clouds, but even then the accreting matter is pre-heated by the accretion luminosity (e.g., Maloney, Hollenbach, & Tielens 1996; compare Blaes, Warren, & Madau 1995 for accretion onto neutron stars), and the timescale is still billions of years, much longer than either the lifetime of a molecular cloud or the time for a black hole to cross the cloud (see Miller & Hamilton 2002a). Therefore, accretion from the interstellar medium is insufficient unless gas is funneled to the hole, as may happen in the centers of galaxies via bar instabilities but not at the off-center locations of IMBH.

The only way to accrete mass quickly enough is via accretion from stars or mergers with stars or compact objects. However, since individual stars or stellar-mass compact objects are themselves much less massive than the eventual IMBH, many such mergers or accretion events are necessary. In the disk of a galaxy, encounters with stars are far too rare to account for the required change in mass. Only in a dense stellar cluster can there be multiple encounters as needed. The cluster could be a young stellar cluster, where interactions with massive main sequence stars dominate, or an old cluster such as a globular cluster, where interactions with compact remnants are most important.

In summary, the three ways currently considered to make IMBH are as remnants of individual Population III stars, as the result of stellar interactions in a young cluster, or as the result of interactions with compact objects in an old cluster. We now consider these possibilities in turn.

POPULATION III STARS

Stars that form in the current universe have masses limited by two effects. First, even if the Jeans mass of a molecular cloud is large, metal line cooling is efficient enough that as portions of the cloud contract they fragment into regions of mass $M \lesssim 100 M_\odot$. Second, although one might imagine that additional accretion could push the mass arbitrarily high, radiation forces and pulsational instabilities at $M \gtrsim 100 M_\odot$ are thought to exist that would expel matter faster than it could accrete (e.g., Larson & Starrfield 1971). In addition, even stars that do form with $M \sim 100 M_\odot$ are thought to leave behind black holes of much smaller masses, because of mass loss due to stellar winds (Fryer & Kalogera 2001).

All of these issues might be circumvented if the metallicity is sufficiently low, as it would be for stars formed in an environment of primordial composition. Cooling is then limited by rotational transitions of molecular hydrogen. It is therefore possible that many of the first stars formed at hundreds or even thousands of solar masses (e.g., Abel et al. 1998; Bromm, Coppi, & Larson 1999; Bromm et al. 2001; Abel, Bryan, & Norman 2000; Schneider et al. 2002; Nakamura & Umemura 2002). Moreover, given that both pulsational instabilities and wind losses are driven by radiation forces on metal lines, these may be insignificant for metal-free stars (Fryer, Woosley, & Heger 2001).

Even so, not all Population III stars will leave behind black holes of hundreds of solar masses. The fate of the first generation of stars has been explored by Nakamura & Umemura (2001) and others, and although there is still substantial uncertainty it is thought that the remnant depends on mass in a relatively straightforward way. If the initial mass is $10\,M_\odot \lesssim M_{\rm init} \lesssim 40\,M_\odot$, there is likely to be a standard core-collapse supernova that leaves behind a black hole with a mass $\sim 5 - 20\,M_\odot$. If $40\,M_\odot \lesssim M_{\rm init} \lesssim 100\,M_\odot$, it is believed that the energy transferred to the stellar envelope by the core collapse is insufficient to unbind the envelope, hence the mass of the resulting black hole is close to the mass of the original star. If $100\,M_\odot \lesssim M_{\rm init} \lesssim 250\,M_\odot$, however, another process enters. As discussed by many authors (e.g., Barkat, Rakavy, & Sack 1967; Bond, Arnett, & Carr 1984; Glatzel, El Eid, & Fricke 1985; Heger & Woosley 2002), at these masses the overburden of matter in the core is such that, in order to provide enough pressure, oxygen burns at a temperature $kT \gtrsim m_e c^2/3$. At such temperatures there is pair production. The pairs are nonrelativistic and therefore provide little pressure, hence the core has to contract further, raising the temperature and increasing the number of pairs. This process runs away and causes the fusion of $\sim 40\,M_\odot$ of oxygen within a short time, completely disrupting the star and leaving no remnant. Only when $M_{\rm init} \gtrsim 250\,M_\odot$ is the binding energy of the envelope enough to withstand the pair production instability, so a star of this mass again leaves behind a black hole with a mass close to that of the original star. Therefore, the abundance of IMBH from Population III stars depends entirely on the fraction of the first stars with initial masses more than $\approx 250\,M_\odot$.

This fraction is still uncertain. Cooling is likely to be dominated by rotational transitions of molecular hydrogen. However, since H_2 is homopolar, its lowest-order rotational transition is quadrupolar, and occurs at a comparatively high temperature of $T = 510$ K. If HD is present in sufficient quantities, then its nonzero dipole moment and larger mass allows transitions at $T = 128$ K, which could lower the fragmentation mass by a factor of several (Nakamura & Umemura 2002). On the other hand, if there are extra sources of ionization present (e.g., an active galactic nucleus) then H_2 may be dissociated, leading to much higher temperatures and therefore, potentially, stars in the thousands of solar masses (e.g., Barkana & Loeb 2001; Mackey, Bromm, & Hernquist 2003). It is therefore not clear at this time how many stars with $M_{\rm init} \gtrsim 250\,M_\odot$ form in a given galaxy, although progress in this field has been rapid and consensus may be achieved in the next few years. It is also not clear where such objects would tend to form. In standard hierarchical assembly models, large dark matter halos are formed by the merger of many smaller halos, so one might expect that black holes from Population III stars (likely formed in high density halos) would congregate in the centers of large galaxies, and possibly merge. In this sense, it may be somewhat surprising that many ultraluminous

X-ray sources are found in globular clusters around the elliptical galaxy NGC 1399 (Angelini, Loewenstein, & Mushotzky 2001). However, there are abundant unknowns about the mass and spatial distribution of Population III remnants, so this is a viable model for IMBHs.

INTERACTIONS IN DENSE CLUSTERS

As discussed in the introduction, significant growth of a black hole requires residence in a dense stellar cluster if the black hole is not at the center of a galaxy. In addition, as shown by Mushotzky and by van der Marel in these proceedings, the best candidates for IMBH are observed to be in clusters currently, regardless of their origin. The dynamics of clusters are therefore essential to the understanding of intermediate-mass black holes, and especially to their potential as sources of gravitational radiation. Here we will first discuss general dynamical effects, then examine separately young and old clusters.

Dynamics of stellar clusters

Stellar clusters of the mass and density of globular clusters or young super star clusters (mass $\sim 10^{5-6} M_\odot$, number density $\sim 10^{5-6}$ pc^{-3} in the center) are wonderful testbeds for dynamics. This is because, unlike the central bulges of galaxies, stellar clusters have evolution timescales significantly less than their ages. The relevant timescale is the relaxation time (e.g., Binney & Tremaine 1987, pg. 190)

$$t_{\rm rel} \approx \left(\frac{N}{8 \ln N} \right) t_{\rm cross} \,, \tag{2}$$

where there are N stars in the cluster and the crossing time is $t_{\rm cross}$. For example, the relaxation time in the core of a globular is $t_{\rm rel} \sim 10^{7-9}$ yr, compared to its $\sim 10^{10}$ yr age.

In a cluster with components of a single mass, the tendency is for the core to contract while the outside of the cluster expands. In this as in many other ways, there are productive analogies with thermodynamics. For example, the contraction and expansion are driven by an increase in the total entropy of the cluster because the extra phase space available to the outer stars more than compensates for the decreased phase space in the core. When the contrast between central density and density at the edge reaches a critical value ~ 700, then single pointlike Newtonian objects undergo a rapid "core collapse" in which the central density formally becomes infinite in finite time (see Binney & Tremaine 1987, §8.2, for a discussion). Clearly, other physics will intervene, and the accepted primary physics is the interactions of primordial binaries, which we discuss below.

In real multimass clusters, thermodynamic equilibrium would require that the temperature of all components be equal, which for a cluster implies that the average kinetic energy $\frac{1}{2} m_i \langle v_i \rangle^2$ is the same for all components i. In a gravitational field, smaller speed means that a star will sink, hence more massive objects congregate towards the center. In some situations, the more massive objects can decouple from the lighter stars, in a
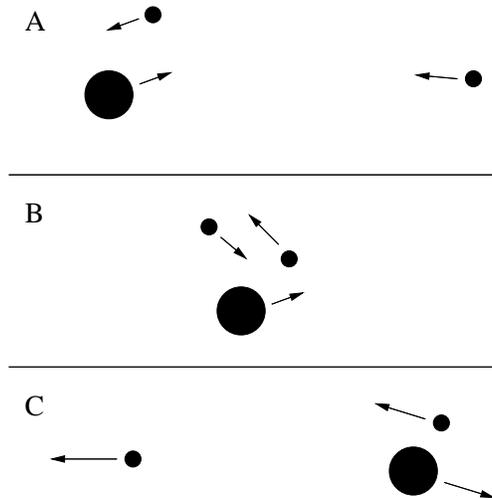
FIGURE 1. Typical interaction between binary and single star. In Panel A, the binary (at left) is approached by a single star from the right, which is initially unbound to the binary. We assume here that the system has negative total energy as measured in the barycentric frame. In a close encounter, as in Panel B, the interactions can be extremely complicated and last for hundreds of orbits or more. However, in a Newtonian point mass interaction without the possibility of dissipation, the system must eventually resolve itself into a binary and a single star, as in Panel C. For a hard binary, the likely result (as shown here) is that the binary has tightened, and that the binary consists of the two most massive of the three original star. The distribution of the fractional change in semimajor axis is independent of the original semimajor axis for very hard binaries, hence the recoil kick becomes larger for tighter binaries.

process called the Spitzer instability (Spitzer 1969). In any case, the centers of dense clusters are expected to be enriched in massive stars and binaries (e.g., Spitzer & Mathieu 1980), because on average binaries have more mass than single stars.

The interactions of binaries have a profound impact on the dynamics of dense clusters. The effective cross section of interaction of a binary is close to the area of the binary orbit, hence binaries are much more interactive than single stars. Over the course of many interactions, sufficiently wide binaries (called "soft") are widened more and more by interactions with single stars until they eventually are separated into single stars (a process called ionization). Soft binaries have little net effect on the cluster. However, sufficiently tight binaries (called "hard") tend to be tightened by interactions with single stars. The tendencies for soft binaries to soften and hard binaries to harden are called "Heggie's laws" (Heggie 1975) and have been explored numerically in many investigations. For many mass ranges (but not all; see Quinlan 1996), an approximate condition is that when in the three-body center of mass frame the total energy (kinetic plus potential) is positive, the binary is soft, but if the total energy is negative, the binary is hard. Some of the tendencies in binary-single interactions are depicted in Figure 1.

Hard binaries are extremely important in clusters. The hardening in an interaction produces recoil, hence binary-single interactions act as a heat source in the centers of clusters, which stabilizes the core against collapse for as long as the binaries can be tapped for energy (see Rasio, Fregeau, & Joshi 2001 for a recent investigation). Even if all stars are initially single, when the density becomes high enough ($\sim 10^{7-9}$ pc^{-3}

for central velocity dispersions $\sim 10-20$ km s^{-1}; Goodman & Hut 1993, Lee 1995) three initially mutually unbound stars can interact in such a way as to bind two of them together. In addition, non-pointlike stars (especially giants) can dissipate energy tidally, creating binaries during close passes of other stars. However, it is believed that the most important binaries are primordial, formed at the origin of the cluster (Goodman & Hut 1989). These provide significant heating when the binaries are hardened (because hardening is accompanied by recoil), at densities close to the observed 10^{5-6} pc^{-3}. This explains why some 20-40% of globulars are formally poised at the edge of core collapse (see Pryor & Meylan 1993 for data on globulars), despite this phase being very short-lived if all the stars are single. Over the long term, all the primordial binaries in a cluster will tighten enough that they no longer interact significantly and the cluster will collapse to much higher densities $\sim 10^{8}$ pc^{-3}, but this is likely to take much longer than the age of the universe (Rasio et al. 2001).

A second important tendency in binary-single interactions is that the final binary is likely to consist of the two most massive of the three original stars (e.g., Sigurdsson & Phinney 1993). Therefore, objects such as an IMBH are probably commonly found in binaries, even if they were originally single. This has important implications for gravitational radiation, as we discuss later. The specific results of hardening depend on whether the most massive stars are on the main sequence (for young clusters) or are compact stellar remnants (for old clusters). We now discuss each of these.

Young stellar clusters

If a stellar cluster is less than a few tens of millions of years old, then the most massive stars are still on the main sequence. Their sizes are therefore significant, and collisions or mergers are possible. Ebisuzaki et al. (2001) and Portegies Zwart & McMillan (2002) have proposed that in a young cluster, core collapse may lead to multiple mergers of a single star with other stars, producing an extremely massive star that will leave behind a black hole of several hundred solar masses when the nuclear fuel of the star runs out.

The simulations backing this conclusion are not yet able to include the effects of binaries, because the binary orbital timescale is so much less than the relaxation time of the cluster. There are two expected effects from binaries that go in opposite directions. The first is the injection of heat mentioned above. This means that if there are many primordial binaries (as expected for massive stars based on observations of current star-forming regions; e.g., Elson et al. 1998), the central density of the cluster will not be as large as it would for single stars. By itself, this would decrease the collision rate significantly, and would therefore inhibit the growth of a large star by mergers. However, binary-single interactions are very complicated, meaning among other things that in such an encounter, two stars can pass very close to each other. For example, for three equal-mass stars the probability of some pair of stars passing within a distance εa or less of each other (where a is the original binary semimajor axis and $\varepsilon < 1$) is $\sim \varepsilon^{1/2}$ (Hut 1984; McMillan 1986; Sigurdsson & Phinney 1993). This tends to increase the collision rate.

It is not yet clear which of these effects is more important. It seems likely that the overall rate of collisions is increased by the presence of binaries. However, for growth

of a large star it is essential that the large star undergo many collisions. The probability of multiple collisions for a single star may be decreased significantly by the decrease in stellar number density produced by binaries, but this has to be investigated. In addition, although the mergers themselves are likely to occur with little mass loss (see Lai, Rasio, & Shapiro 1993; Rasio & Shapiro 1994, 1995), the question is whether the mergers can happen rapidly enough to offset mass loss by winds, pulsational instabilities, or stellar evolution.

Old stellar clusters

If a cluster is more than $\sim 10^8$ yr old, then the remaining main sequence stars have masses $\lesssim 10 M_\odot$ and are therefore less massive than stellar-mass black holes. If a cluster is more than a few billion years old, then the main sequence stars are less massive than $\sim 1.5 M_\odot$ neutron stars. Therefore, in old clusters the most massive objects are compact stellar remnants. These compact objects have negligible cross sections, hence direct collisions do not happen. However, if the binaries get tight enough, gravitational radiation may play a major role.

Kulkarni, Hut, & McMillan (1993) and Sigurdsson & Hernquist (1993) have examined whether gradual tightening of a black hole binary in a cluster could lead to mergers in the cluster due to gravitational radiation. The issue is that the change in binding energy of a binary in an interaction is proportional to the original binding energy (Heggie 1975), therefore the recoil kicks become stronger as the binary tightens. Kulkarni, Hut, & McMillan (1993) and Sigurdsson & Hernquist (1993) found that for interactions of a single $10 M_\odot$ black hole with a binary $10 M_\odot - 10 M_\odot$ black hole, the recoil speed exceeds the ~ 50 km s^{-1} escape velocity from the core of a globular (Webbink 1985) before the binary becomes tight enough to merge by gravitational interaction. This may mean that globulars are the engines for many mergers, but that the mergers themselves happen well outside globulars (Portegies Zwart & McMillan 2002). On the other hand, Miller & Hamilton (2002a) showed that if one of the black holes in the binary has an initial mass $M \gtrsim 50 M_\odot$, its inertia keeps it in the cluster and therefore it can undergo repeated mergers and, in principle, grow to $M \sim 10^3 M_\odot$ or more. In addition, binary-binary interactions might produce hierarchical triples in which the inner binary undergoes large eccentricity oscillations via the Kozai mechanism, such that the inner binary can merge without any dynamical recoil (Miller & Hamilton 2002b). The rates of such interactions, and the efficiency with which a black hole can grow, need to be investigated more thoroughly to determine the viability of this mechanism.

IMPLICATIONS FOR GRAVITATIONAL RADIATION

The rates and properties of gravitational waves from intermediate-mass black holes depend on many unknowns, including the number density of IMBH in the universe, the types of interactions they undergo, and their formation process. Their number density may be addressed by future X-ray and optical data (see the contributions by Mushotzky

and van der Marel in these proceedings). For example, observations in the next few years may clarify the fraction of globular clusters that harbor IMBH, and the mass distribution of those black holes.

The formation process is also important. In the Population III and young cluster scenarios, the initial mass of the black hole is several hundred solar masses. These high masses mean that the frequency of gravitational waves from IMBH in binaries would be at most a few Hertz, which is too low for detectability from the ground. However, the longer-term inspiral of, e.g., a stellar-mass black hole into an IMBH in a cluster could be detected with space-based instruments such as LISA. If IMBH are common in globulars, then there may be tens of globulars around the Milky Way with IMBH binaries that have frequencies in the 10^{-4} Hz $\lesssim f_{\rm GW} \lesssim 1$ Hz range of LISA (Miller 2002). These are persistent sources, and therefore the signal to noise will be increased by continued observation. However, the majority of those will have frequencies $f_{\rm GW} < 10^{-3}$ Hz, hence they will suffer confusion with the unresolved white dwarf binary background. A more promising source is globulars in the Virgo cluster of galaxies. Although Virgo is $\sim 10^3$ times more distant than Galactic globulars, it has several hundred times more globulars than our Galaxy, with the result that a few IMBH binaries are likely to be detectable in a few years with LISA (Miller 2002). The frequencies of detectable IMBH binaries in VIRGO will be $f_{\rm GW} \gtrsim 10^{-3}$ Hz, and therefore relatively free of contamination.

If instead IMBH form in old clusters, their initial masses are likely to be tens of solar masses (Miller & Hamilton 2002a). These masses imply gravitational wave frequencies in merger and ringdown of a few tens of Hertz, which is within reach of ground-based instruments. As many as tens of events per year could be detected with Advanced LIGO (Miller 2002). The LISA rate would also be enhanced slightly, because this scenario involves several mergers before becoming indistinguishable from pictures in which the initial mass is high.

In either case, although by the time the binaries enter the bandpasses of ground-based instruments they will be nearly circular (Wen 2002), in the LISA band the binaries are likely to have large eccentricities. This is because three-body interactions will continue until the gravitational radiation timescale is less than the time to the next encounter. The strong dependence of merger timescale on eccentricity (Peters 1964),

$$\tau_{\rm GW} \approx 3 \times 10^8 (M_\odot^3/\mu M^2)(a/R_\odot)^4 (1-e^2)^{7/2} \text{ yr} \tag{3}$$

for a total binary mass M and reduced mass μ, means that if a binary is pushed to high eccentricity it is more likely to merge. This produces a significant selection effect towards high eccentricities, and means that the initial eccentricity of a binary on its final inspiral is usually $e \gtrsim 0.9$ (Gultekin, Miller, & Hamilton, these proceedings). Therefore, effects such as pericenter precession will be detectable in the LISA signals. For IMBH binaries in the VIRGO cluster, one expects to see orbital decay as well (in addition, possibly, to Lense-Thirring precession), which gives enough information to solve for the distance to Virgo using just gravitational radiation (Miller 2002).

A final intriguing possibility for IMBH gravitational waves is that some number of IMBH may merge with the central supermassive black hole of a given galaxy (Madau & Rees 2001). Such events, which are the merger of a $\sim 10^3 M_\odot$ black hole with a $\sim 10^{6-9} M_\odot$ black hole, have extremely high mass ratios and therefore can be treated

using test particle techniques (Hughes 2001). In addition, since IMBH have masses tens to hundreds of times those of stellar-mass black holes, the signal to noise of such a merger is much greater than that of a stellar-mass black hole with a supermassive black hole. An event such as this would therefore provide incredibly precise probes of the spacetime of a rotating supermassive black hole. The event rate is difficult to estimate, but if tens of IMBH fall into a typical supermassive black hole in a Hubble time then a few to tens of such events per year can be expected (Miller 2002).

IMPACT OF FUTURE OBSERVATIONS

Despite the many exciting implications of intermediate-mass black holes, we must keep in mind that at this point they are not conclusively established to exist. Unambiguous measurements of the mass are required. For the ultraluminous X-ray sources the only way to do this is to identify a stellar companion and do radial velocity measurements, a very difficult task for objects that distant. For IMBH candidates in globular clusters, however, there are hints of effects in current data that may lead to dramatic improvements in our understanding.

Observations of M15 (Gerssen et al. 2002) and possibly other globulars (K. Gebhardt, personal communication) suggest that the cores of these globulars are rotating rapidly. The evidence comes from radial velocity measurements of stars and fits of models to them, and may soon be supplemented by proper motion measurements (K. Gebhardt, personal communication). Taken at face value, the evidence suggests that in the cores the ratio of rotation speed to velocity dispersion is $v_{\mathrm{rot}}/\sigma \sim 1$. This is a surprising result. Simulations using n-body codes suggest that this rotation will be communicated outward, and that in a core relaxation time there will be little net rotation unless there is a supply of angular momentum in the core (e.g., Einsel & Spurzem 1999). Given that the core relaxation time is as short as $\sim 10^7$ yr in dense clusters such as M15, how can this angular momentum be supplied?

One possibility invokes an IMBH in a binary with a stellar-mass black hole (F. Rasio, personal communication). Such a binary has the required angular momentum, and can have the necessary rate (see Miller & Colbert 2003 for a more complete discussion). In addition, because after the binary hardens and merges the next binary would have an orbital plane at a random angle to the previous one, the position angle of rotation in the cluster is expected to wander as one measures farther from the center, consistent with observations (Gerssen et al. 2003). If the observational interpretation is confirmed, and if no other theoretical explanation is found, this has extremely exciting implications for gravitational wave generation. Not only would it confirm that IMBH exist, it would show that right now, IMBH in globulars are undergoing frequent coalescences with stellar-mass black holes, hence are strong sources of gravitational radiation with unique potential as astrophysical probes and testing grounds for predictions of general relativity.

REFERENCES

1. Abel, T., Anninos, P., Norman, M. L., & Zhang, Y. 1998, ApJ, 508, 518
2. Abel, T., Bryan, G., & Norman, M. L. 2000, ApJ, 540, 39
3. Angelini, L., Loewenstein, M., & Mushotzky, R. F. 2001, ApJ, 557, L35
4. Barkana, R., & Loeb, A. 2001, Phys. Rep., 349, 125
5. Barkat, Z., Rakavy, G., & Sack, N. 1967, Phys. Rev. Lett., 18, 379
6. Binney, J., & Tremaine, S. 1987, Galactic dynamics (Princeton University Press, Princeton, NJ)
7. Blaes, O., Warren, O., & Madau, P. 1995, ApJ, 454, 370
8. Bond, J. R., Arnett, W. D., & Carr, B. J. 1984, ApJ, 280, 825
9. Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJ, 527, L5
10. Bromm, V., Ferrara, A., Coppi, P. S., & Larson, R. B. 2001, MNRAS, 328, 969
11. Ebisuzaki, T. et al. 2001, ApJ, 562, L19
12. Einsel, C., & Spurzem, R. 1999, MNRAS, 302, 81
13. Elson, R. A. W., Sigurdsson, S., Davies, M., Hurley, J., & Gilmore, G. 1998, MNRAS, 300, 857
14. Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548
15. Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372
16. Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C., & Pryor, C. 2002, AJ, 124, 3270
17. Glatzel, W., El Eid, M. F., & Fricke, K. J. 1985, A&A, 149, 413
18. Goodman, J., & Hut, P. 1989, Nature, 339, 40
19. Goodman, J., & Hut, P. 1993, ApJ, 403, 271
20. Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
21. Heggie, D. C. 1975, MNRAS, 173, 729
22. Hughes, S. A. 2001, Class. Quant. Grav., 18, 4067
23. Hut, P. 1984, ApJS, 55, 301
24. Kulkarni, S. R., Hut, P., & McMillan, S. L. W. 1993, Nature, 364, 421
25. Lai, D., Rasio, F. A., & Shapiro, S. L. 1993, ApJ, 412, 593
26. Larson, R. B., & Starrfield, S. 1971, A&A, 13, 190
27. Lee, H. M. 1995, MNRAS, 272, 605
28. Mackey, J., Bromm, V., & Hernquist, L. 2003, ApJ, 586, 1
29. Madau, P., & Rees, M. J. 2001, ApJ, 551, L27
30. Maloney, P. R., Hollenbach, D. J., & Tielens A. G. G. M., 1996, ApJ, 466, 561
31. McMillan, S. L. W. 1986, ApJ, 306, 552
32. Miller, M. C. 2002, ApJ, 581, 438
33. Miller, M. C., & Colbert, E. J. M. 2003, IJMPD, in preparation
34. Miller, M. C., & Hamilton, D. P. 2002a, MNRAS, 330, 232
35. Miller, M. C., & Hamilton, D. P. 2002b, ApJ, 576, 894
36. Nakamura, F., & Umemura, M. 2001, ApJ, 548, 19
37. Nakamura, F., & Umemura, M. 2002, ApJ, 569, 549
38. Peters, P. C. 1964, Phys. Rev. B, 136, 1224
39. Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899
40. Pryor, C., & Meylan, G. 1993, in Structure and Dynamics of Globular Clusters, eds. Djorgovski, S. G., and Meylan, G. (San Francisco: ASP), vol 50, p. 357
41. Quinlan, G. D. 1996, NewA, 1, 35
42. Rasio, F. A., Fregeau, J. M., & Joshi, K. J. 2001, astro-ph/0103001
43. Rasio, F. A., & Shapiro, S. L. 1994, ApJ, 432, 242
44. Rasio, F. A., & Shapiro, S. L. 1995, ApJ, 438, 887
45. Schneider, R., Ferrara, A., Natarajan, P., & Omukai, K. 2002, ApJ, 571, 30
46. Sigurdsson, S., & Hernquist L. 1993, Nature, 364, 423
47. Sigurdsson, S., & Phinney, E. S. 1993, ApJ, 415, 631
48. Spitzer, L. 1969, ApJ, 158, L139
49. Spitzer, L., & Mathieu, R. D. 1980, ApJ, 241, 618
50. Webbink, R. F. 1985, in Dynamics of Star Clusters, IAU Symposium 113, ed. J. Goodman & P. Hut (Dordrecht: Reidel), 541
51. Wen, L. 2002, ApJ, submitted (astro-ph/0211492)