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# Intermediate-mass Black Holes in the Universe: A Review of Formation Theories and Observational Constraints

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**Abstract**

This paper reviews the subject of intermediate-mass black holes (IMBHs) with masses between those of "stellar-mass" and "supermassive" black holes (BHs). The existence of IMBHs is a real possibility: they might plausibly have formed as remnants of the first generation of stars (Population III), as the result of dense star cluster evolution, or as part of the formation process of supermassive BHs. Their cosmic mass density could exceed that of supermassive BHs ($\Omega \approx 10^{-5.7}$) and observations do not even rule out that they may account for all of the baryonic dark matter in the Universe ($\Omega \approx 10^{-1.7}$). Unambiguous detections of individual IMBHs currently do not exist, but there are observational hints from studies of microlensing events, "ultra-luminous" X-ray sources, and centers of nearby galaxies and globular clusters. Gravitational wave experiments will soon provide another method to probe their existence. IMBHs have potential importance for several fields of astrophysics and are likely to grow as a focus of research attention.

## 1.1 Introduction

BHs were long considered a mathematical curiosity, but it is now clear that they are an important and indisputable part of the astronomical landscape (e.g., Begelman & Rees 1998). In particular, there is unambiguous evidence for "stellar-mass" BHs and "supermassive" BHs.

Stellar-mass BHs form in a reasonably well-understood manner through stellar evolution (Fryer 1999). A BH with a companion star might accrete matter from it to produce an X-ray binary (XRB). It is sometimes possible to determine the mass of the accreting object in an XRB from detailed modeling. Neutron stars cannot be more massive than 2–3$M_\odot$ and compact objects with larger masses are therefore assumed to be BHs. Some dozen such objects are know, mostly with masses in the range 5–15$M_\odot$ (Charles 2001). The fraction of stellar-mass BHs that manages to remain in a close binary throughout its evolution and is also currently accreting is very small, so most stellar-mass BHs exist singly and go unnoticed (§ 1.4.1). The Milky Way hosts $\sim 10^{7-9}$ stellar-mass BHs (Brown & Bethe 1994).

The paradigm that there are also supermassive BHs in the Universe is based on the existence of active galactic nuclei (AGNs) in the centers of some galaxies. Their properties can only be plausibly explained by assuming that a BH of $10^6$–$10^9 M_\odot$ acts as the central engine (Rees 1984). The proper motions of stars around our Galactic Center (Sgr A$^*$) provide direct evidence for this (Schödel et al. 2002; Ghez 2004). A variety of techniques now exist to detect and weigh supermassive BHs using stellar or gaseous kinematics (Kormendy & Gebhardt 2001). The BH mass is always of the order 0.1% of the galaxy bulge/spheroid mass. An even better correlation exists with the velocity dispersion, $M_{\bullet} \propto \sigma^4$ (Tremaine et al. 2002). The origin of these correlations, the triggers of AGN activity, and the exact formation mechanisms of supermassive BHs remain poorly understood (§ 1.2.3).

Stellar-mass and supermassive BHs can be studied because they (sometimes) exist in environments favorable for the production of observable signatures through accretion or gravitational influence. This need not to be true for all BHs in the Universe, which may therefore also exist in other mass ranges. BHs in the intermediate-mass range of, say, 15–$10^6 M_{\odot}$ (i.e, between the familiar classes of BHs), are of particular interest. Such IMBHs might plausibly have formed in different ways (§ 1.2). They have been suggested as an important component of the missing baryonic dark matter in the Universe (§ 1.3) and recent observational studies have provided hints of IMBHs in various environments (§ 1.4). It can be concluded that IMBHs are an important topic for additional research (§ 1.5).

## 1.2 Formation Theories

IMBHs may plausibly have formed as the remnants of Population III stars (§ 1.2.1), through dynamical processes in dense star clusters (§ 1.2.2), or as an essential ingredient or occasional by-product of the formation of supermassive BHs (§ 1.2.3). Primordial formation of IMBHs is unlikely (§ 1.2.4).

### *1.2.1 Formation from Population III Stellar Evolution*

The present-day stellar initial mass function (IMF) extends to $\sim 200 M_{\odot}$ (Larson 2003). Massive stars shed most of their mass through radiatively driven stellar winds. Above $\sim 100 M_{\odot}$ a nuclear pulsational instability sets in that generates additional mass loss. Evolutionary calculations indicate that massive stars leave compact remnants with masses below $\sim 15 M_{\odot}$, consistent with observations of X-ray binaries (Fryer & Kalogera 2001). The minimum initial mass for a star to become a stellar-mass BH (rather than a neutron star) is $\sim$ 20–25$M_{\odot}$ (Fryer 1999).

For the first generation of zero-metallicity stars in the Universe (Population III) the initial conditions and evolutionary path were quite different. There is now a growing body of evidence that suggests a top-heavy IMF in the early Universe (Schneider et al. 2002), although this issue continues to be debated. In the absence of metals, primordial molecular clouds cool through rotational-vibrational lines of $H_2$. Simulations of the collapse and fragmentation of such clouds (Abel, Bryan, & Norman 2000) suggest that the first generation of stars had typical masses of $\sim 100 M_{\odot}$, compared to the $\sim 1 M_{\odot}$ characteristic of stars at the present epoch. In addition, radiative mass losses are negligible at zero metallicity, and mass losses due to nuclear pulsational instability are greatly reduced (Fryer, Woosley, & Heger 2001).

The evolution of massive Population III stars depends on the initial mass (Bond, Arnett, & Carr 1984; Heger & Woosley 2001). Stars below $140 M_{\odot}$ probably evolve into BHs in similar fashion as do stars of normal metallicity (Fryer 1999), although the remnant BHs will be more massive than today's stellar-mass BHs due to the more limited mass loss. Stars that are initially more massive than $\sim 140 M_{\odot}$ encounter the electron-positron pair-instability during oxygen burning. In the range $\sim$ 140–260$M_{\odot}$ this yields an explosion that leaves no remnant and is considerably more energetic than a normal supernova. Above $\sim 260 M_{\odot}$

there is direct collapse into a BH because nuclear burning is unable to halt the collapse and generate an explosion. The remnant mass exceeds half of the initial stellar mass, thus constituting an IMBH. Objects that are initially more massive than $\sim 10^5 M_\odot$ cannot have stable hydrogen burning to begin with, due to a post-Newtonian instability. As a result, such objects quickly collapse into a BH (Baumgarte & Shapiro 1999; Shibata & Shapiro 2002).

It is thus possible, and maybe even likely, that a population of IMBHs was produced from Population III stars. The size of this population was recently estimated by Madau & Rees (2001) and Schneider et al. (2002). Many details of these calculations are uncertain, but both papers find that a population could easily have been produced with a global mass density similar to that of the supermassive BHs in the Universe, and possibly more. The IMBHs would presumably have formed at redshifts $z \approx 10$–20 in peaks of the mass distribution.

### 1.2.2 Formation in Dense Star Clusters

Star clusters have long been suspected as possible sites for the formation of IMBHs. The self-gravity of a cluster gives it a negative heat capacity that makes it vulnerable to the so-called "gravothermal catastrophe": the core collapses on a timescale proportional to the two-body relaxation time (Binney & Tremaine 1987). The resulting high central density may lead to BH formation in various ways. The crucial issue is whether realistic initial conditions ever lead to densities that are high enough for this to occur, or whether core-collapse is halted and reversed at lower densities. This question has been addressed theoretically using semi-analytic arguments, Fokker-Planck calculations, and direct $N$-body codes.

Lee (1987) and Quinlan & Shapiro (1990) studied the importance of stellar mergers during core collapse. These can give rise to the runaway growth of a supermassive star, which at the end of its lifetime collapses to a BH (§ 1.2.1). These studies found that runaway merging occurs naturally in very dense clusters ($\rho > 10^6 M_\odot\,\mathrm{pc}^{-3}$) of many stars ($N > 10^7$). These initial conditions correspond to velocity dispersions of hundreds of km s$^{-1}$, and may be relevant for (early) galactic nuclei. This provides a scenario for the formation of an IMBH, which through accretion might subsequently grow to become a supermassive BH. By contrast, Quinlan & Shapiro (1987, 1989) and Lee (1993) studied the fate of a cluster of compact objects (neutron stars and stellar-mass BHs) instead of normal stars. In this situation they found, also for initial conditions appropriate for galactic nuclei, that the core collapses all the way to a relativistic state. When the redshift reaches values $z > 0.5$ (velocities in excess of $10^5$ km s$^{-1}$), a relativistic instability sets in that results in catastrophic collapse to a BH (Shapiro & Teukolsky 1985). However, this relativistic path to a BH may not be the most natural evolutionary scenario. Starting from a cluster of normal stars, runaway merging would likely produce a single IMBH before a cluster of compact objects could form (Quinlan & Shapiro 1990).

The aforementioned studies agreed that formation of an IMBH would not occur in star clusters with fewer than $10^6$–$10^7$ stars, such as globular clusters. In such clusters core collapse is halted by binary heating (Hut et al. 1992) before the densities become high enough for runaway stellar merging. Three-body interactions between "hard" binaries and single stars add energy to the cluster (at the expenses of the binaries, which become harder; Heggie 1975). The binaries form primarily through tidal capture. This process is much more efficient at the low velocity dispersions characteristic of globular clusters than at the higher velocity dispersions of galactic nuclei.

Although it has long been thought that core collapse in globular clusters is generically halted by binary heating, it was realized recently that this is not always true. Stars of different masses are not always able to reach energy equipartition (Spitzer 1969), and in fact, the Salpeter IMF is unstable in this sense (Vishniac 1978). This causes the heaviest stars to undergo core collapse more or less independently of the other cluster stars, on a timescale that is much less than the core collapse time for the cluster as a whole. Portegies Zwart & McMillan (2002) used $N$-body simulations to show that a runaway merger among these massive stars leads to the formation of an IMBH, provided that the core collapse proceeds faster than their main-sequence lifetime. This implies an initial half-mass relaxation time $< 25$ Myr. For a globular cluster that evolves in the Galactic tidal field the corresponding present-day half-mass relaxation time would have to be $< 10^8$ yr. It has been proposed that this scenario might be important for young compact star clusters, such as those often observed in star-forming galaxies (Ebisuzaki et al. 2001). Many of the Milky Way's globular clusters have half-mass relaxation times in the range $10^8$–$10^9$ yr, and some have half-mass relaxation times below $10^8$ yr (Harris 1996). So this scenario may well be relevant for Milky Way globular clusters as well, in particular because the physical conditions during their formation are only poorly understood.

A more unlikely route for the formation of IMBHs in globular clusters is through the repeated merging of compact objects, such as stellar-mass BHs (Lee 1995; Taniguchi et al. 2000; Mouri & Taniguchi 2002). Such objects get caught in binaries through dynamical effects. After hardening by interactions with single stars, they eventually merge after losing energy by gravitational radiation. However, the interactions that produce hardening also provide recoils that tend to eject the binaries from the cluster (Kulkarni, Hut, & McMillan 1993; Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000). This limits the scope for considerable growth through repeated merging, although in some situations four-body interactions may boost the probability (Miller & Hamilton 2002a). One way to avoid the recoil problem is to assume that there is a single BH somewhere in the cluster that starts out at $\sim 50 M_\odot$. After sinking to the cluster center through dynamical friction, the BH could slowly grow in mass through merging with stellar-mass BHs. The mass of the BH would be large enough to prevent ejection through recoil (Miller & Hamilton 2002b).

### *1.2.3 Relation to Supermassive Black Hole Formation*

The formation of supermassive BHs in the centers of galaxies is poorly understood, but there are many plausible scenarios (Begelman & Rees 1978; Rees 1984). Many scenarios are extensions of those discussed in the preceding sections, and involve IMBHs at some time in their evolution. It is therefore possible that supermassive BHs and IMBHs in the Universe are intimately linked. Also, not all BHs in galaxy centers may have had the opportunity to become supermassive, so some galaxies may have a central BH of intermediate mass.

Scenarios that evolve IMBHs into supermassive BHs usually invoke merging and/or accretion. Schneider et al. (2002) and Volonteri, Haardt, & Madau (2003) considered the case of IMBHs formed from Population III stars (§ 1.2.1). They envisaged that while galaxies are assembled hierarchically from smaller units, the IMBHs in these units sink to the center through dynamical friction. There they merge to form supermassive BHs. Haiman and Loeb (2001) found that this is a plausible scenario for building some $10^9 M_\odot$ BHs at very early times, as required observationally by the detection of bright quasars at redshifts as large as 6 (Fan et al. 2001). However, Islam, Taylor, & Silk (2003) argued that this scenario may not be able to account for all the mass observed today in supermassive BHs. Also, Hughes &

Blandford (2003) showed that supermassive BHs that grow through mergers generally have little spin, which makes it unlikely that such BHs could power radio jets. As an alternative to merging, a single intermediate-mass "seed" BH might have grown supermassive through accretion. The growth may happen quickly through collapse of a surrounding protogalaxy onto the BH (Adams, Graff, & Richstone 2001) or it may happen slowly by accretion of material shed by surrounding stars (Murphy, Cohn, & Durisen 1991). Feedback from the energy release near the center may limit both the growth of the BH (Haehnelt, Natarajan, & Rees 1998) and the growth of the galaxy (Silk & Rees 1998). Feedback from star formation may also limit the BH growth (Burkert & Silk 2001), while fresh gas supply provided during the merging of galactic subunits (Haehnelt & Kauffmann 2000; Kauffmann & Haehnelt 2000) may provide increased growth. These scenarios can reproduce observed correlations such as those between BH mass and bulge mass or bulge velocity dispersion (§ 1.1).

Not all scenarios for supermassive BH formation proceed through an IMBH stage. If a collapsing gas cloud can loose its angular momentum and avoid fragmentation into stars, it may collapse to a BH directly. Haehnelt & Rees (1993) sketched a route by which this may have occurred. Bromm & Loeb (2003) investigated this possibility quantitatively by studying the collapse of metal-free primordial clouds of $10^8 M_\odot$ using hydrodynamical simulations. To avoid fragmentation into stars, they assumed that the presence of $H_2$ (which would otherwise be responsible for cooling) is suppressed by an intergalactic UV background. With this assumption, condensations of $\sim 5 \times 10^6 M_\odot$ form that can collapse to a BH through the post-Newtonian instability (§ 1.2.1). It is unclear whether feedback from a growing BH may limit the attainable mass, so it is possible that the result would be an IMBH.

### *1.2.4 Primordial Formation*

BHs might have formed primordially in the early Universe. The mass of such BHs is generally of order the horizon mass at its formation time, $M \approx 10^5 (t/\mathrm{sec}) M_\odot$ (Barrow & Carr 1996), although smaller values are not impossible (Hawke & Stewart 2002). At the Planck time ($\sim 10^{-43}$sec) the horizon mass is the Planck mass ($\sim 10^{-38} M_\odot$) and at 1 sec it is $10^5 M_\odot$. Primorial BHs less massive than $\sim 10^{-18} M_\odot$ would by now have evaporated through the process of Hawking radiation. Primordial BHs around this mass would currently be evaporating, and the observed $\gamma$-ray background places useful limits on their existence (MacGibbon & Carr 1991). However, Hawking radiation becomes progressively less relevant for more massive BHs, and is negligible for the mass range of interest in the present context. So it places no useful observational limits on the existence of primordial BHs in the intermediate-mass regime, and our thinking must be guided by theoretical considerations.

One possible mechanism for primordial BH formation is through collapse of density fluctuations (Carr 1975; Carr & Lidsey 1993). However, in standard cold dark matter (CDM) cosmologies the early Universe is characterized by a very high degree of homogeneity and isotropy. The associated Gaussian density fluctuations are much too small to collapse to a BH (Begelman & Rees 1998). Another mechanism for the formation of primordial BHs does not require density fluctuations, but invokes collisions of bubbles of broken symmetry during phase transitions in the early Universe (Hawking, Moss & Stewart 1982; Rubin, Khlopov, & Sakharov 2000). For example, the quantum chromodynamic cosmic phase transition at $t = 10^{-5}$sec might have produced BHs of order $\sim 1 M_\odot$ (Jedamzik 1997). Primordial BHs could also have formed spontaneously through the collapse of cosmic strings (MacGibbon, Brandenburger & Wichowski 1998) or through inflationary reheating (Garcia-Bellido

& Linde 1998). Even if primordial BH formation is possible in these scenarios, it is by no means guaranteed. Also, these scenarios do not naturally lead to BHs in the intermediate-mass range. Afshordi, McDonald & Spergel (2003) recently addressed some cosmological implications of a potential large population of primoridial IMBHs. However, more conventional cosmological thinking suggests that such a population is not particularly likely.

## 1.3 IMBHs: The Missing Baryonic Dark Matter?

There is now considerable evidence that the matter density of the Universe is $\Omega_{\rm m} \equiv \rho_{\rm m}/\rho_{\rm crit} \approx 0.3$, with an additional $\Omega_\Lambda \approx 0.7$ in a cosmological constant or "dark energy." Comparison of Big Bang nucleosynthesis calculations with the observed abundances of light elements yields the baryon density: $\Omega_{\rm b} = 0.041 \pm 0.004$ (this number scales as $H_0^{-2}$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ was assumed; Burles, Nollett, & Turner 2001). The non-zero value of $\Omega_{\rm m} - \Omega_{\rm b}$ indicates the presence of non-baryonic dark matter, with some form of CDM being the most popular candidate. However, this is probably not the only missing matter in the Universe. A detailed inventory of the visible baryonic matter adds up to a best guess of only $\Omega_{\rm v} = 0.021$ (Persic & Salucci 1992; Fukugita, Hogan, & Peebles 1998). Although this number can be stretched with various assumptions, it does appear that half of the baryons in the Universe are in some dark form.

Carr (1994) provided a general review of the candidates for, and constraints on, the baryonic dark matter. The hypothesis that it could be a population of IMBHs in the halos of galaxies (Lacey & Ostriker 1985) is of particular interest in the present context. Such a population is constrained observationally by the dynamical effects it would have on its environment (§ 1.3.1) and by its gravitational lensing properties (§ 1.3.2). Additional constraints exist if the IMBHs are assumed to have formed from Population III stars (§ 1.3.3).

### *1.3.1 Dynamical Constraints on IMBHs in Dark Halos*

The gravitational interactions that one would expect IMBHs to have with other objects provide important constraints on their possible contribution to the baryonic dark matter (Carr & Sakellariadou 1999). For example, IMBHs in dark halos would heat (increase the stellar velocity dispersion) of galaxy disks, the more so for larger BH masses. The observed velocity dispersions of stellar disks therefore limit the masses of BHs in galactic halos. If the Milky Way dark halo were composed entirely of BHs, then their mass would have to be less than $\sim 3 \times 10^6 M_\odot$ (Carr & Sakellariadou 1999). This limit becomes more stringent for small, dark matter dominated galaxies. Rix & Lake (1993) find an upper limit of $\sim 6 \times 10^3 M_\odot$ for the Local Group galaxy GR8, although this is open to debate (Tremaine & Ostriker 1999). Halo IMBHs also tend to disrupt stellar systems in galaxies, in particular globular clusters (Carr & Sakellariadou 1999). Klessen & Burkert (1995) found that this excludes the possibility that dark halos are made up entirely of BHs more massive than $\sim 5 \times 10^4 M_\odot$. If there are more massive BHs, they would have to make up a smaller fraction of the halo: no more than 2.5%–5% for BHs of $\sim 10^6 M_\odot$ (Murali, Arras, & Wasserman 2000). However, these constraints are quite uncertain because it is unknown what the properties of globular cluster systems were when they formed. It could even be that disruption of clusters by IMBHs may have played an essential role in the shaping of the present-day number and mass distribution of globular clusters (Ostriker, Binney, & Saha 1989).

IMBHs in a galactic halo sink to the center through dynamical friction. If they merge and accumulate there, then the observed masses of supermassive BHs in galaxy centers constrain the mass and number of halo IMBHs (Carr & Sakellariadou 1999). Xu & Ostriker (1994) modeled this in detail, taking into account the timescale for merging through emission of gravitational radiation and the possibility of slingshot ejection of BHs in three-body interactions. They found that unacceptable build-up of a central object occurs only for a halo made up of BHs more massive than $\sim 3 \times 10^6 M_\odot$. Consistent with this, Islam et al. (2003) found in a study of a cosmologically motivated population of IMBHs (remnants of Population III stars) that the build-up of central objects remains within observationally acceptable limits.

### *1.3.2 Lensing Constraints on IMBHs in Dark Halos*

Massive compact halo objects (MACHOs) can produce gravitational microlensing amplification of the intensity of background stars (Paczyński 1986). Several teams have monitored stars in the Large Magellanic Cloud (LMC) for a number of years to search for such signatures. For the specific case of the LMC, the average characteristic timescale for microlensing events is $\sim 130(M/M_\odot)^{1/2}$ days. Hence, MACHOs are progressively more difficult to detect for increasing masses. Still, Alcock et al. (2001) calculated that they should have been able detect $\sim 1$ event of multi-year duration toward the LMC if the Milky Way dark halo were made entirely of $100 M_\odot$ MACHOs. By contrast, no LMC events were detected with durations in excess of $\sim 130$ days. This rules out that the entire halo is made of MACHOs in the range $0.15$–$30 M_\odot$ (95% confidence), although contribution of a fraction below $\sim 25\%$ is allowed. Alcock et al. (2000) did detect many shorter duration events, from which it was concluded that $\sim 20\%$ of the Milky Way halo may be composed of compact objects with masses in the range $0.15$–$0.9 M_\odot$.

The possible contributions of compact objects to the dark halos of other (more distant) galaxies are constrained by various gravitational lensing effects as well. However, these do not yet place limits in the intermediate-mass regime that improve upon what is already known from Big Bang nucleosynthesis (Carr 1994).

### *1.3.3 Constraints on IMBHs Formed from Population III Stars*

The cosmic density of IMBHs that have formed from Population III stars (§ 1.2.1) is limited by additional constraints (Carr 1994). Stars with initial masses below $260 M_\odot$ expel much of their metals at the end of their lifetime, enriching the interstellar medium (ISM). The fact that the enrichment must have been less than the lowest metallicities observed in Population I stars ($Z \approx 10^{-3}$) limits the cosmic mass density $\Omega$ in such Population III stars to no more than $10^{-4}$. The cosmic density of stars more massive than $260 M_\odot$ (and their IMBH remnants) is not constrained by metallicity considerations because they do not end their life in a supernova explosion. However, they might shed helium before their ultimate collapse. This places some constraints on their potential contribution to $\Omega$, but these are no more stringent than what is already known from Big Bang nucleosynthesis. Objects more massive than $10^5 M_\odot$ shed neither metals nor helium because they collapse to a BH without reaching stable hydrogen burning.

All Population III stars below $10^5 M_\odot$ shine brightly during their main-sequence phase. Their numbers are therefore constrained by observations of the extragalactic background light, particularly in the infrared. The constraints depend on the formation redshift and on whether or not allowance is made for possible reprocessing by dust. Depending on the exact assumptions, a cosmic density of Population III stars sufficient to explain all the baryonic dark matter may just barely be consistent with the available extragalactic background light data (Carr 1994; Schneider et al. 2002). There are also limits from the accretion that one would expect onto a cosmologically important population of BHs, but these do not place strong constraints in the intermediate-mass range (Ipser & Price 1977; Carr 1994).

## 1.4 Searches for Individual IMBHs

IMBHs may contribute as much as $\Omega \approx 0.02$ to the cosmic baryon budget (§ 1.3). However, even if they existed in far smaller numbers, they would be of great importance for astrophysics. For comparison, the cosmic mass density of supermassive BHs in galaxy centers is only $10^{-5.7}$ (Yu & Tremaine 2002). Cosmologically motivated scenarios of Population III evolution easily predict densities that rival or exceed this (Madau & Rees 2001; Schneider et al. 2002). Hence, it is important to search for evidence of individual IMBHs. Such IMBHs may exist in the main luminous bodies of galaxies, where they could reveal themselves through their microlensing properties (§ 1.4.1), or through accretion-powered X-ray emission (§ 1.4.2). Alternatively, they could exist in the centers of galaxies (§ 1.4.3) or globular star clusters (§ 1.4.4). In the near future it may be possible to search for gravitational-wave signatures of IMBHs (§ 1.4.5).

### *1.4.1 Bulge Microlensing*

Compact objects can be detected through microlensing. The Einstein ring crossing time scales as $M^{1/2}$ and long-duration events are therefore of particular interest. No long-duration events were detected toward the LMC (§ 1.3.2) but the situation is different for the Galactic bulge: $\sim 10\%$ of the few hundred detected events have timescales exceeding $\sim 140$ days (Bennett et al. 2002).

The lensing timescale depends not only on the lens mass, but also on the unknown transverse velocity of the lens and the ratio of lens and source distances. The latter quantities can be constrained statistically from the fact that they are drawn from the known phase-space distribution function of the Galaxy. When many events are modeled as a statistical ensemble this yields an estimate of the mass distribution of the lenses (Han & Gould 1996). Additional information is needed to constrain the masses of individual lenses. This is often possible for long-duration events from the "microlensing parallax" effect, which produces a signature in the light curve due to the fact that the Earth moves around the Sun as the event progresses. Modeling yields the transverse velocity of the lens as projected to the solar position. Bennett et al. (2002) identified six events with sufficiently accurate parallax data to yield an estimate of the lens mass. The largest masses are $6^{+10}_{-3} M_{\odot}$ (MACHO-96-BLG-5) and $6^{+7}_{-3} M_{\odot}$ (MACHO-98-BLG-6). The observational limits on the lens brightness make these events excellent candidates for stellar-mass BHs, the first tentative detections outside of XRBs. The long-duration event MACHO-99-BLG-22/OGLE-1999-BUL-32 is even more interesting (Agol et al. 2002; Mao et al. 2002). The lens-mass likelihood function is bimodal, with maximum likelihood at mass $130^{+42}_{-114} M_{\odot}$ and with a secondary peak of lower likelihood at $4.0^{+1.5}_{-1.8} M_{\odot}$ (Bennett et al. 2004). So this lens could be an IMBH.

The bulge microlensing events suggest that stellar-mass BHs may contribute more than 1% of the Milky Way mass (Bennett et al. 2002, 2004), more than is traditionally believed (Brown & Bethe 1994; Fryer 1999). An important caveat in the analysis is that the dynamics of the lenses is assumed to follow that of the known stars. This would be violated if BHs are born with large kick velocities, as are neutron stars. There is conflicting observational evidence on this issue (Nelemans, Tauris, & van den Heuvel 1999; Mirabel et al. 2002).

### 1.4.2 Ultra-luminous X-ray Sources

The Eddington luminosity for an accreting compact object of mass $M$ is $1.3 \times 10^{38}\,(M/M_\odot)$ erg s$^{-1}$. This is $\sim 2 \times 10^{38}$ erg s$^{-1}$ for a neutron star and $(0.4\text{–}2) \times 10^{39}$ erg s$^{-1}$ for a stellar-mass BH. Surprisingly, X-ray observations with *Einstein* (Fabbiano 1989), *ROSAT* (Colbert & Mushotzky 1999; Roberts & Warwick 2000; Colbert & Ptak 2002) and *Chandra* have shown that more luminous sources appear to exist in $\sim 30\%$ of nearby galaxies. If the emission of these sources is assumed to be isotropic, then the observed fluxes indicate X-ray luminosities $2 \times 10^{39} \leq L_X \leq 10^{41}$ erg s$^{-1}$. These sources are generally referred to as ultra-luminous X-ray sources (ULXs); their isotropic luminosities are less that those of bright Seyfert galaxies ($10^{42}$–$10^{44}$ erg s$^{-1}$), so they are also sometimes referred to as "intermediate-luminosity X-ray objects."

ULXs do not generally reside in the centers of galaxies, so they are unrelated to low-level AGN activity. They are generally unresolved at the high spatial resolution ($\sim 0\overset{''}{.}5$) of *Chandra*. Combined with the fact that many show variability (Fabbiano et al. 2003), this rules out the hypothesis that ULXs are closely spaced aggregates of lower-luminosity sources. A detailed study of the "Antennae" galaxies (Zezas et al. 2002; Zezas & Fabbiano 2002) shows that the large majority do not have radio counterparts. Combined with the observed variability, this rules out that they are young supernovae. Hence, ULXs are believed to be powered by accretion onto a compact object. Bondi accretion from a dense ISM is insufficient to explain the observed luminosities (King et al. 2001), so the accretion is believed to be from a companion star in a binary system. This interpretation is supported by the variability seen in ULXs (in one case there is even evidence for periodicity; Liu et al. 2002) and the fact that some show transitions between hard and soft states (Kubota et al. 2001). These characteristics are commonly seen in Galactic XRBs.

If ULXs are emitting isotropically at the Eddington luminosity, then the accreting objects must be IMBHs with masses in the range $15\text{–}1000\,M_\odot$. Sub-Eddington accretion or partial emission outside the X-ray band would imply even higher masses. However, the mass cannot be more than $\sim 10^6\,M_\odot$, or else the BH would have sunk to the galaxy center through dynamical friction (§ 1.3.1; Kaaret et al. 2001). Either way, the IMBH interpretation of ULXs has several problems (King et al. 2001; Zezas & Fabbiano 2002). There is no known path of double-star evolution that produces a binary of the required characteristics (King et al. 2001). One would need to assume that the IMBH was born isolated, and subsequently acquired a binary companion through tidal capture in a dense environment. This predicts a one-to-one correspondence between ULXs and star clusters, which is not observed. In the Antennae, ULXs are often observed close to, but not coincident with, star clusters. This suggests a scenario in which ULXs are XRBs that have been ejected out of clusters through recoil (Portegies Zwart & McMillan 2000). This precludes an IMBH because the mass would be too large for the binary to be ejected (Miller & Hamilton 2002b).

An alternative to the IMBH interpretation is that ULXs are an unusual class of XRBs. One possibility is that radiation is emitted anisotropically, so that the luminosity is overestimated when assumed isotropic. Mild beaming (King et al. 2001) and a relativistic jet (Körding, Falcke, & Markoff 2002; Kaaret et al. 2003) have both been proposed. It is also possible that ULXs are in fact emitting at super-Eddington rates (Begelman 2002; Grimm, Gilfanov, & Sunyaev 2002). Observations show that ULXs are often associated with actively star-forming regions or galaxies. The brightest known source resides in the starburst galaxy M82 (Matsushita et al. 2000; Kaaret et al. 2001; Matsumoto et al. 2001), and the merging Antennae galaxy pair has the most known sources in a single system (18 above $10^{39}$ erg s$^{-1}$). The association with young stellar populations suggests that ULXs might be related to high-mass XRBs (where "high-mass" refers to the companion). Indeed, optical counterparts reported for ULXs suggest a young star cluster in one case (Goad et al. 2002) and a single O-star in another case (Liu, Bregman, & Seitzer 2002). However, ULXs have also been identified in elliptical galaxies (Colbert & Ptak 2002) and globular clusters (Angelini, Loewenstein, & Mushotzky 2001; Wu et al. 2002), which suggests an association with low-mass XRBs. So it may be that the ULX population encompasses different types of objects, possibly related to Milky Way sources like SS433 and microquasars (King 2002). Outbursts with luminosities similar to those of ULXs have indeed been reported for some Milky Way sources (Revnivtsev et al. 2001; Grimm et al. 2002).

X-ray luminosity functions provide additional information. In both the Antennae and the interacting pair NGC 4485/4490 (Roberts et al. 2002) the luminosity function has constant slope across the luminosity boundary that separates normal XRBs from ULXs. This is not expected if the two classes formed through different evolutionary paths, and hence does not support the IMBH interpretation. However, if normal XRBs and ULXs differ only in beaming fraction then one would also have expected a break in the luminosity function (Zezas & Fabbiano 2002).

The X-ray spectra of ULXs are important as well. Most tend to have hard spectra that are well fit by a so-called multi-color disk black-body model (Makishima et al. 2000). Others are equally well fit by a single power law (Foschini et al. 2002; Roberts et al. 2002). These results are consistent with an association with accreting binaries. The good fits of accretion disk models suggest that the bulk of the emission is not relativistically beamed (Zezas et al. 2002). The inner-disk temperature in the models is of the order of $kT$ = 1–2 keV. This is similar to values observed in Galactic microquasars, and is larger than what would naturally be expected for an IMBH (Makishima et al. 2000). On the other hand, Miller et al. (2003) recently found strong evidence for soft components in *XMM-Newton* spectra of the two ULXs in NGC 1313. These soft components are well fit with inner-disk temperatures of $\sim$ 150 eV. Temperature scales with mass as $T \propto M^{-1/4}$, so this was interpreted as spectroscopic evidence that at least in these ULXs the accreting object is an IMBH of $\sim 10^3 M_\odot$.

### *1.4.3 Galaxy Centers*

Dynamical studies of galaxies indicate that they generally have central supermassive BHs and that the BH mass scales with the velocity dispersion of the host spheroid as $M_\bullet \propto \sigma^4$ (§ 1.1). This result is based on data for galaxies with Hubble types earlier than Sbc, $\sigma > 70$ km s$^{-1}$, and $M_\bullet > 2 \times 10^6 M_\odot$. It is unknown whether the same $M_\bullet$–$\sigma$ relation holds for later-type and/or dwarf galaxies. If so, then one would expect such galaxies to host IMBHs (owing to their less massive spheroids and correspondingly smaller velocity dispersions). However, no firm detections and mass measurements exist for such galaxies. In fact, it is not guaranteed that such galaxies have central BHs at all. This would provide a natural explanation for the scarcity of AGNs among late-type galaxies (Ho, Filippenko, & Sargent 1997; Ulvestad & Ho 2002). On the other hand, we do know that at least some late-type galaxies host AGNs. The most famous example is NGC 4395, a dwarf galaxy of type Sm, which has the nearest and lowest-luminosity Seyfert 1 nucleus yet found (Filippenko & Sargent 1989). The conventional explanation of Seyfert activity suggests that at least this galaxy must have a central BH. Filippenko & Ho (2003) argue that the BH mass lies in the range $10^4 - 10^5 M_\odot$, which puts it firmly in the intermediate-mass regime.

Dynamical measurements of BH masses in late-type and dwarf galaxies are complicated by the fact that such galaxies generally host a nuclear star cluster of mass $10^6$–$10^7 M_\odot$ (Böker et al. 2002). The cluster is often barely resolved at *Hubble Space Telescope (HST)* resolution so that its gravitational influence resembles that of a point mass. This masks the dynamical effect of any BH, unless the BH is at least as massive as the cluster. This is not expected in view of the $M_\bullet$–$\sigma$ relation, and is indeed generally ruled out by detailed modeling. Böker, van der Marel & Vacca (1999) inferred a BH mass upper limit of $5 \times 10^5 M_\odot$ for the nearby Scd spiral IC 342. Geha, Guhathakurta, & van der Marel (2002) inferred upper limits in the range $10^6$–$10^7 M_\odot$ for six dwarf elliptical galaxies in Virgo. The only way to obtain more stringent limits is to study galaxies in the Local Group, for which it is possible to obtain spectroscopic observations that resolve the central star cluster itself. This was done for M33 ($\sigma = 24$ km s$^{-1}$), with no resulting BH detection. Two independent groups analyzed the same *HST* spectra, and obtained upper limits of $1500 M_\odot$ (Gebhardt et al. 2001) and $3000 M_\odot$ (Merritt, Ferrarese, & Joseph 2001). This is a factor $\sim 10$ below the value predicted by extrapolation of the $M_\bullet$–$\sigma$ relation.

### 1.4.4 Globular Clusters

The existence of theoretical scenarios for IMBH formation in dense star clusters (§ 1.2.2) makes it natural to search for IMBHs in globular clusters. This search splits into two questions: does the mass-to-light ratio ($M/L$) increase toward the center in globular clusters? (§ 1.4.4.1); and can this be explained as a result of normal mass segregation, or must an IMBH be invoked? (§ 1.4.4.2).

#### 1.4.4.1 Centrally Peaked $M/L$ Profiles in Globular Clusters

The radial $M/L$ profile of globular clusters is constrained by the observed profile of the line-of-sight velocity dispersion $\sigma$ (through the equations of hydrostatic equilibrium). For distant clusters one can use integrated light techniques similar to those used for galaxy centers. Gebhardt, Rich, & Ho (2002) performed such a study for the globular cluster G1, the most massive cluster of M31. A constant $M/L$ model cannot fit their *HST* data, and they inferred the presence of $M_d = 2.0^{+1.4}_{-0.8} \times 10^4 M_\odot$ of dark material near the center. The corresponding "sphere of influence" $r_d = GM_d/\sigma^2$ is only $0''.035$, which is less than the *HST* FWHM. Nonetheless, it is plausible that $M_d = 2.0 \times 10^4 M_\odot$ can indeed be detected in G1: it is similar in distance and physical properties to the central star cluster of M33, for which *HST* data yielded an upper limit as small as 1500–$3000 M_\odot$ (§ 1.4.3).

For Milky Way globular clusters, velocity determinations of individual stars are better than integrated light techniques. The cluster M15 has been observed from the ground by many groups (most recently by Gebhardt et al. 2000) and has long been a focus of discussions on IMBHs in globular clusters (as reviewed by van der Marel 2001). A recent *HST* study (van der Marel et al. 2002) added important stars in the central few arcsec of the cluster, yielding a combined sample of $\sim 1800$ stars with known velocities. The inferred velocity dispersion increases radially inward and cannot be fit with a constant $M/L$ model. Gerssen et al. (2002) modeled the data and inferred the presence of $M_d = 3.2^{+2.2}_{-2.2} \times 10^3 M_\odot$ of dark material near the center.

There are $\sim 70$ pulsars known in globular clusters and some of these have a negative period derivative $\dot{P}$. These can be used to constrain the cluster mass distribution. Pulsars are expected to be spinning down intrinsically (positive $\dot{P}$), so negative $\dot{P}$ must be due to acceleration by the mean gravitational field. This places a lower limit on the mass enclosed inside the projected radius $R$ of the pulsar. In M15 there are two pulsars at $R \approx 1''$ (Phinney 1993) whose negative $\dot{P}$ values are consistent with the mass distribution implied by the stellar kinematics (Gerssen et al. 2002).

D'Amico et al. (2002) recently reported two pulsars with negative $\dot{P}$ at $6''$ and $7''$ from the center of the cluster NGC 6752. These suggest a large enclosed mass and a considerable central increase in $M/L$. However, the inferred masses may be inconsistent with the stellar kinematics of this cluster (Gebhardt 2002, priv. comm.). NGC 6752 is interesting also because it hosts a pulsar at an unusually large distance from the cluster center. It has been suggested that this pulsar may have been kicked there through interaction with an IMBH in the cluster core (Colpi, Possenti, & Gualandris 2002; Colpi, Mapelli, & Possenti 2004).

#### *1.4.4.2 IMBH versus Mass Segregation*

A natural consequence of two-body relaxation in globular clusters is mass segregation. In an attempt to reach equipartition of energy, heavy stars and dark remnants sink to the center of the cluster, which causes a central increase in $M/L$. One must model the time evolution of the cluster in considerable detail to determine the theoretically predicted $M/L$ increase. M15 is one of the few clusters for which this has been done. The most recent and sophisticated Fokker-Planck models constructed for M15 are those of Dull et al. (1997). Gerssen et al. (2002) found that the $M/L$ profile published by Dull et al. (1997) did not contain enough dark remnants near the cluster center to fit their *HST* data, which suggested the presence of an IMBH. However, it was subsequently reported that the $M/L$ figure of Dull et al. (1997) contained an error in the labeling of the axes (Dull et al. 2003). A corrected data-model comparison shows that the Fokker-Planck models can provide a statistically acceptable fit to the *HST* data (Gerssen et al. 2003). Baumgardt et al. (2003a) performed direct $N$-body calculations and reached a similar conclusion.

Although models without an IMBH can fit the kinematical data for M15, this does not necessarily mean that such models are the correct interpretation. The dark remnants that segregate to the cluster center evolve from stars with initial masses $M \geq 3\,M_\odot$. The evolutionary end-products of such stars are only understood with limited accuracy (Fryer 1999; Claver et al. 2001), and the same is true for their IMF (especially at the low metallicities of globular clusters). Depending on the assumptions that are made on these issues, it is possible to create models that either do or do not fit the M15 data. Most of the neutron stars that form are expected to escape because of kicks received at birth (Pfahl, Rappaport, & Podsiadlowski 2002). The $M/L$ increase from mass segregation is therefore due mostly to white dwarfs with masses $> 1\,M_\odot$. Such white dwarfs have cooled for too long to be observable in globular clusters, which makes this prediction hard to test. Another caveat is that M15 is known to have considerable rotation near its center. This is not naturally explained by evolutionary models and may hold important new clues to the structure of M15 (Gebhardt et al. 2000). Hence, an IMBH of mass $\leq 2 \times 10^3\,M_\odot$ is certainly not ruled out in M15 (Gerssen et al. 2003; Baumgardt et al. 2003a).

There are no X-rays observed from the center of M15. Ho, Terashima, & Okajima (2003) find $L_X/L_{\rm Edd} \leq 4 \times 10^{-9}$. This does not imply that there cannot be an IMBH. In globular clusters there is only a limited gas supply available for accretion (Miller & Hamilton 2002b) and an advection-dominated accretion flow (Narayan, Mahadevan & Quataert 1998) can naturally lead to very low values of $L_X/L_{Edd}$. The galaxy M32, which has a well-established supermassive BH, has an upper limit $L_X/L_{Edd} < 10^{-7}$ (van der Marel et al. 1998).

Scaling of the Dull et al. (1997, 2003) M15 models to the mass, size and distance of G1 does not yield a sufficient concentration of dark remnants to fit its *HST* data (Gebhardt 2002, priv. comm.). Hence, G1 may well contain an IMBH in its center, as suggested by Gebhardt et al. (2002). If true, this need not necessarily be representative for globular clusters in general. G1 is unusually massive, and it has been suggested to be the nucleus of a disrupted dwarf galaxy (Meylan et al. 2001). Either way, a simple scaling of the Dull et al. models to the case of G1 is likely to be an oversimplification. Baumgardt et al. (2003b) performed $N$-body calculations and argued that the G1 data can be explained without an IMBH. However, the proper scaling of these calculations with $N \approx 7 \times 10^4$ particles to the case of G1 (with $N \approx 10^7$ stars) is uncertain. The same argument applies to the Baumgardt et al. (2003a) models for M15; improved modeling of both clusters remains highly desirable.

It is intriguing that the BH mass detections/upper limits suggested for G1 and M15 fall right on the $M_\bullet$–$\sigma$ relation for supermassive BHs. This leaves open the possibility that there may be some previously unrecognized connection between the formation and evolution of globular clusters, galaxies and central BHs.

### *1.4.5 Gravitational Waves*

In the near future, gravitational wave detection experiments such as LIGO and LISA will provide a new way to probe the possible existence of IMBHs. Binary systems of compact objects and mergers of supermassive BHs are already well known as possible sources of gravitational radiation. Miller (2002) recently emphasized that a population of IMBHs could also be observable, especially if they reside in dense stars clusters. With optimistic assumptions, LIGO could see the coalescence of a stellar-mass BH with an IMBH up to several tens of times per year.

## 1.5 Concluding Remarks

The main conclusion to emerge from this review is that the existence of IMBHs in the Universe is not merely a remote possibility. IMBHs have been predicted theoretically as a natural result of several realistic scenarios. In addition, it has been shown that IMBHs might plausibly explain a variety of recent observational findings. Much progress has been made in the last few years, but certainly, even more work remains to be done. None of the theoretical arguments for IMBH formation are unique. Many alternative theoretical scenarios exist that do not lead to IMBHs. Similarly, none of the observational suggestions for IMBHs are clear cut. Alternative interpretations of the data exist that invoke known classes of objects and many would argue that such conservative interpretations are more plausible. Either way, these issues can only be addressed and resolved with additional research. IMBHs are therefore likely to grow as a focus of research attention.

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