

Intermediate Mass Black Holes

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1. Introduction

In 1915, Karl Schwarzschild was the first to use Einstein's newly-developed theory of general relativity to determine the gravitational field of a point mass. Such an object, which would later be termed a 'black hole', was widely thought to be little more than a theoretical curiosity until Robert Oppenheimer showed in 1939 that sufficiently massive stars could, in theory, experience a total core collapse. During this process, much of the mass of the star would be compressed to an infinitesimal point. Total core collapse is now known to be the final stage in the life cycle of stars with core masses of over $3M_{\odot}$, and can occur in one of two ways.

When a massive star is near the end of its life, it is undergoing fusion in shells around its degenerate core. Ash from these fusion processes 'rains' down onto the core, causing it to gain mass. Eventually, the mass of the core increases to the point that the electron degenerate pressure that supports it is no longer capable of preventing a collapse. The core of a star with a total mass of greater than $25M_{\odot}$ will have enough mass that not even neutron degenerate pressure will be able to prevent a total collapse into a black hole (Carroll and Ostlie 2007).

A stellar mass black hole can also form when a neutron star in a binary system strips material from its companion. As matter is accreted onto the neutron star, the mass of the neutron star increases until it surpasses the Tolman-Oppenheimer-Volkoff (TOV) Limit. The TOV limit imposes a maximum on the mass that can be supported by neutron degenerate pressure in a neutron star. Beyond this limit, a neutron star will undergo total core collapse.

In recent years, evidence has mounted for a second class of black hole, the so-called 'super-massive black holes' (SMBHs), which are believed to exist at the centers of many- if not most- galaxies. SMBHs range in mass from approximately 10^5M_{\odot} to 10^9M_{\odot} (Carroll and Ostlie 2007). It is not yet well understood how these objects form, but it is theorized that they are produced during collisions between galaxies, or in a series of collisions between black holes that have masses greater

than those of stellar mass black holes, but significantly less than those of SMBHs. These ‘intermediate mass black holes’ (IMBHs) are thought to range in mass from about $10^2 M_\odot$ to $10^3 M_\odot$, or possibly even upwards of $10^4 M_\odot$ (Carroll and Ostlie 2007).

Regardless of type, all black holes share similar properties. Each consists of a singularity- a point of infinite density and zero volume, but with finite mass- around which exists a region of such strong gravitational fields that not even light can escape the potential well. The boundary of this region is called the ‘event horizon’ and represents the radius beyond which light- and hence matter- can escape from the black hole. The presence of a singularity at the center creates strong gravitational tidal forces on objects near the event horizon, as well as a highly curved region of space-time. Indeed, space-time is said to have infinite curvature at the location of the singularity (Taylor and Wheeler 2000).

Due to the fact that light cannot escape from within the event horizon of a black hole, direct observation of these objects would be, of course, impossible, even if sufficient angular resolution could be attained. Instead, detection is achieved by searching for emission from regions outside the event horizon. As material falls into a black hole, it coalesces into a disk. As the material slowly spirals inward, gravitational potential energy is converted into heat, which is then radiated away. Additionally, charged particles in the disk can be accelerated by the strong magnetic fields of the black hole and ejected from the system in the form of relativistic jets emanating from the black hole’s magnetic north and south poles (figure 1). In the case of Intermediate Mass Black Holes, radiation emitted by the accretion disk may correspond to a class of objects known as ultraluminous x-ray sources (ULXs).

2. History

Until a few years ago, it was widely believed that black holes could be separated into two distinct categories: stellar mass and super-massive. In recent years, however, evidence for an intermediate class of objects has surfaced in the form of ultraluminous x-ray sources (ULXs) found

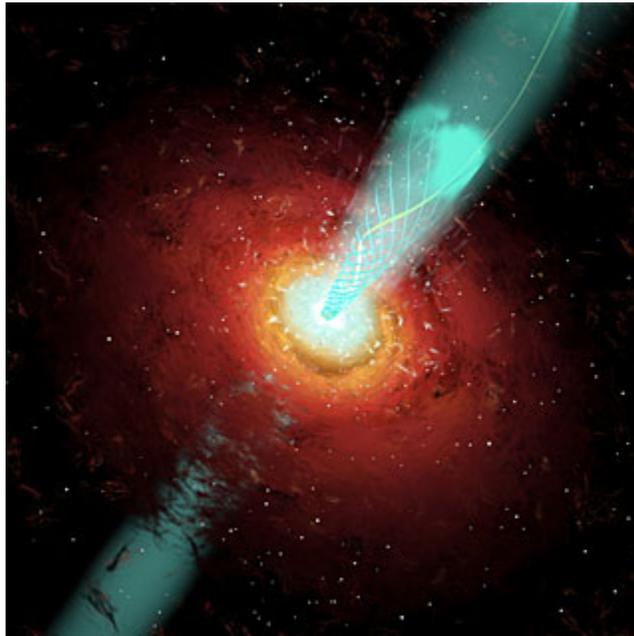


Fig. 1.— Shown here are the accretion disk and polar jets of a theorized black hole. Image credit: *Scientific American*

in other galaxies. These (unresolved) sources have fluxes greater than about $10^{39} \text{ erg s}^{-1}$ (Miller and Hamilton 2001), and exhibit luminosity variations on timescales of as little as 10^4 s . (Matsumoto et. al. 2001). Such short timescales suggest the presence of small, compact objects because light must be able to traverse the diameter of the object quickly enough to allow for the entire object to fluctuate in intensity as a whole. Additionally, such high luminosities require the mass of the source to be greater than $10^3 M_{\odot}$ (Miller and Hamilton 2001). Since it is believed that even the largest of stars cannot yield a black hole of greater than about $15 M_{\odot}$ due to the loss of their outer layers in supernova explosions- as well as in long-term mass loss due to the instability of stars with masses of $\sim 120 M_{\odot}$ and larger- ULXs cannot be explained away as solar mass black holes.

3. Formation

It is not well understood how IMBHs form. Two possible methods for their formation are through the collapse of population III stars- the first generation of stars to form in the early universe (Van Der Marel 2003)- and from collisions of massive stars or black holes in the interiors of star clusters.

The zero metallicity of the giant molecular clouds from which population III stars formed allowed for efficient cooling through emission of photons corresponding to rotational-vibrational lines of the H_2 molecule. More efficient cooling would have made it possible for protostars to accrete material more efficiently, leading to average stellar masses of approximately $100M_\odot$, rather than the $1M_\odot$ that is seen today (Van Der Marel 2003). In addition, the nuclear pulsations seen today in high mass stars would have been greatly reduced, leading to much less loss of mass over the star’s lifetime (Fryer, Woosley, and Heger 2001). Population III stars that had masses of less than $140M_\odot$ would most likely have formed stellar mass black holes in the usual way (Fryer 1999), and those with masses ranging from $\sim 140M_\odot - 260M_\odot$ would have experienced electron-positron pair instability during oxygen burning, and, consequently, would have exploded with such violence that no remnant would have been left behind (Van Der Marel 2003). Any population III stars of $\sim 260M_\odot$ or larger could have formed black holes with masses in the correct range to be classified as IMBHs.

The cores of large star clusters could also be responsible for the production of IMBHs, assuming the densities within these regions are sufficiently high (Van Der Marel 2003). The gravitational collapse of a star cluster’s core could trigger runaway growth of massive stars, which would then form stellar mass black holes at the ends of their lives. These stellar mass black holes could then merge to form intermediate mass black holes (Van Der Marel 2003). A second method of formation, proposed by Miller and Hamilton (2001), involves the slow (on the Hubble timescale) growth of massive stellar objects through occasional collisions with other stars.

4. IMBHs in Star Clusters

A cluster of stars will have a half-mass relaxation time (the time it takes for the system to reach equilibrium) of

$$t_{rlx} = \left(\frac{R_c^3}{GM_c} \right)^{1/2} \frac{N_c}{8 \ln \Lambda_c} \quad (1)$$

where G is the gravitational constant, M_c is the mass of the cluster, N_c is the number of stars in the cluster, R_c is the characteristic (half mass) radius of the cluster, and $\ln \Lambda_c \approx 10$ is the Coulomb Logarithm (Portegies Zwart and McMillan 2002). Assuming an isolated star cluster composed of stars of identical mass, this corresponds to a core collapse time of $t_{cc} \simeq 15t_{rlx}$ (Cohn 1980). Using a more realistic stellar mass distribution function, the collapse time decreases dramatically to $t_{cc} \simeq .19 \pm .08t_{rlx}$ (Portegies Zwart et. al. 1999). As the core of the cluster collapses, the most massive stars migrate inward toward the center. Assuming that the collapse time is less than the Main-Sequence lifetime of the stars, the number density of massive stars at the center of the cluster will reach the levels necessary for a collision runaway to form. A collision runaway is a star that experiences consecutive collisions with many others, causing it to grow rapidly in mass. As it grows, its collision cross-section increases, as does the strength of its gravitational field, making it even more likely to experience collisions. A collision runaway could reach masses of up to $200M_\odot$ before experiencing a supernova explosion. It is not known how much of the star would survive the explosion, but the resulting black hole would likely still be one of the most massive objects in the cluster, allowing it to continue its runaway growth (Ebisuzaki et. al. 2001). Because a star is less likely to escape from the star cluster with each progressive collision that it experiences, most of the collisions within the core of a star cluster are likely to involve the same star. Assuming a core collapse time $t_{cc} = 0.22t_{rlx}$ the maximum mass that can be gained is

$$m_r \simeq m_{seed} + 4 \times 10^{-3} f_c N_c \langle m \rangle \ln \Lambda_c \left[\ln \left(\frac{t_{disr}}{t_{cc}} \right) + \frac{t_{cc}}{t_{disr}} - 1 \right] \quad (2)$$

where m_{seed} is the mass of the original star from which the collision runaway started, f_c is the

fraction of binary star systems that produce a collision, t_{disr} is the cluster’s disruption time, and $\langle m \rangle$ is the average mass of the stars in the cluster. Star clusters with a core collapse time $t_{cc} \leq 2.5 \times 10^6 \text{years}$ should be able to form a collision runaway at their centers that would form a black hole with a mass of up to 1% of that of the entire cluster (Portegies Zwart and McMillan 2002).

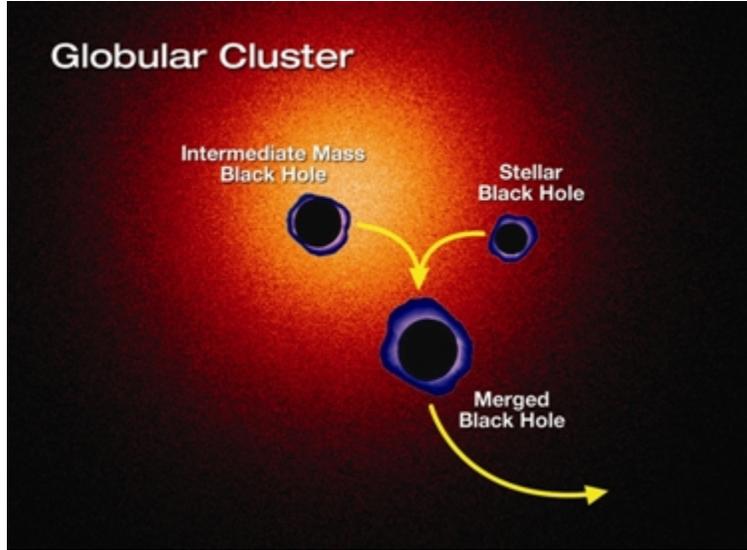


Fig. 2.— As the core of a star cluster collapses, the most massive objects within the cluster will migrate toward the center, collide, and then merge with one another. The result is a collision runaway that can eventually consume upwards of 1% of the total initial mass of the cluster. Image credit: *Nature*

Dynamical friction will cause globular star clusters to sink inward toward the center of their host galaxies. Eventually, they will be disrupted by the chaotic environment characteristic of a galaxy’s core regions and dissipate, depositing in the process any intermediate mass black holes that may have formed within them (Ebisuzaki et. al. 2001). The deposited IMBHs would then pair off into binary systems, which would emit gravitational radiation until they merged. Eventually, a single, super-massive black hole would be left at the center of the galaxy.

5. IMBHs in Galactic Nuclei

It has now been known for the better part of a decade that the mass of a galaxy’s bulge is very closely related to the mass of the super-massive black hole that can be found within. The current accepted value for the ratio of SMBH mass to galactic bulge mass is 0.1% (Merritt and Ferrarese 2000). There is also a strikingly close correlation between the mass M of a galaxy’s SMBH and the rms velocity σ of its galactic bulge. This relationship is known as the M- σ Relation. By extending the M- σ Relation to sufficiently low rms velocities- and hence, to sufficiently low galactic bulge masses- it can be inferred that galaxies with low mass galactic bulges should contain black holes that are in the correct mass range to be classified as IMBHs (Greene, Ho, and Barth 2004).

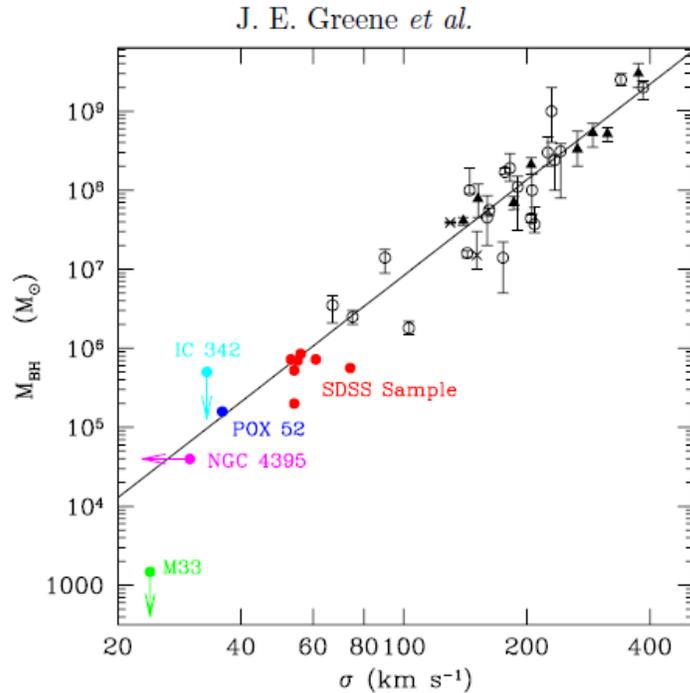


Fig. 3.— The rms velocity of a galaxy’s bulge can be used to determine the mass of its central black hole through use of the M- σ Relation. Values with error bars correspond to nearby galaxies for which stellar dynamics (open circles), gas dynamics (triangles) or maser dynamics (crosses) were able to provide the mass of the central black hole. The M- σ Relation can be used to infer the presence of IMBHs in galaxies with low mass bulges. Image credit: Green, Ho, and Barth (2004)

6. Observational Evidence and Candidate Objects

Most evidence for intermediate mass black holes comes in the form of ultraluminous x-ray sources (ULXs), which are unresolved sources of x-ray emission found outside of our galaxy. The Eddington Limit corresponds to the maximum luminosity that a radiating source can have and still maintain hydrostatic equilibrium. For an object of mass M ,

$$L_{Eddington} = \frac{4\pi Gc}{\bar{\kappa}} M \quad (3)$$

with $\bar{\kappa}$ corresponding to the star's average opacity, G to the gravitational constant, and c to the speed of light. For the accretion disk of a stellar mass black hole, $4 \times 10^{38} \text{erg s}^{-1} \leq L_{Eddington} \leq 2 \times 10^{39} \text{erg s}^{-1}$. A ULX exhibits a luminosity beyond that imposed on stellar mass black holes by the Eddington Limit. Such sources are found in about 30% of galaxies (Van Der Marel 2003). Because ULXs are not resolved by Chandra, which has an angular resolution of $0.5''$, a limit can be placed on their size. ULXs have also been observed to show variations in their luminosities, further constraining their maximum sizes and ruling out the possibility that they are simply collections of smaller luminous objects.

Supernovae have been proposed as possible sources of the high luminosities characteristic of ULXs. Most ULXs, however, do not exhibit the radio signature associated with supernovae. The lack of radio emission, combined with the observation of variability, makes it extremely unlikely that ULXs are simply young supernova remnants (Van Der Marel 2003).

Feng and Kaaret measured the luminosities of the ULXs that they observed to be greater than $2 \times 10^{39} \text{erg s}^{-1}$. Assuming that these objects are emitting isotropically at the Eddington Limit, they must have masses between $15M_{\odot}$ and 10^3M_{\odot} (Van Der Marel 2003). Of course, if these objects are black holes that have accretion disks radiating below the Eddington Limit, or if a portion of their radiation lies outside of the x-ray band, then that would imply larger masses. This would suggest that ULXs are good candidates for intermediate mass black holes, as long as ULXs do, in fact, emit isotropically. In the event that ULXs are determined to display anisotropic emission, then their luminosities may have been significantly overestimated, particularly if relativistic beaming is

involved.

There are problems with the theory that ULXs are intermediate mass black holes. Luminosity functions show no discontinuities in their slopes across the boundary between ULXs and x-ray binaries (XRBs), suggesting that these two classes of object may be one and the same. Though some ULXs have been found in elliptical galaxies and globular clusters, others have been discovered in younger, open clusters (Van Der Marel 2003), which should not be old enough to form IMBHs.

ULXs are most commonly found in starburst galaxies, followed by elliptical galaxies, and then spiral galaxies. They are often- but not always- associated with large star clusters. ASCA and CHANDRA have discovered a possible IMBH in the starburst galaxy M82 which appears to coincide with a young, compact star cluster (Ebisuzaki et. al. 2001). A pair of colliding spiral galaxies in the NGC 4038 Group (in the constellation Corvus) known as The Antennae contain significant numbers of ULXs, as does the elliptical galaxy NGC 1399. In NGC 1399, approximately 60% of the ULXs are associated with star clusters (Feng and Kaaret 2006).

Candidate IMBHs have also been found within our own galaxy. The rms radial velocities of stars in the central region of the globular cluster M15 have been found to be approximately 14km/s . This would suggest the presence of a non-radiating, compact object with a mass of $3.9 \pm 2.2 \times 10^3 M_\odot$ (Gerssen et. al. 2002). Likewise, the velocities of stars in NGC 5139 (ω Centauri) suggest the presence of an IMBH (Noyola, Gebhart, and Bergmann 2008). Currently, ω Centauri is classified as a globular cluster, but it may also be the remnant core of an accreted dwarf galaxy. Noyola, Gerbhart, and Bergmann find that the velocity distribution of ω Centauri can be explained by the presence of a black hole with a mass between $3.0 \times 10^4 M_\odot$ and $4.75 \times 10^4 M_\odot$, which is in agreement with predictions made using the M - σ Relation.

7. Summary

Intermediate mass black holes are a class of object that, should they be proven to actually exist, would fill in the gap between the solar mass black holes which are created during the supernova explosion of a star with a mass of $\approx 25M_\odot$ or greater and the super-massive black holes of $10^5 M_\odot$

to $10^9 M_\odot$ that reside at the centers of many galaxies. One possible mechanism for the production of IMBHs is the core collapse of large star clusters. If the relaxation time of a cluster is less than the main sequence lifetime of its constituent stars, the proper conditions should arise for a collision runaway to form. Through a series of collisions between the most massive stars within the cluster, a compact object could form, and eventually accrete up to 1% of the cluster’s original mass.

While a star cluster is experiencing core collapse, it will also be migrating toward the center of the galaxy as it loses gravitational potential energy to friction with its surroundings. Eventually, the cluster will reach the central regions of its host galaxy, where it will be destroyed. Any intermediate mass black hole that managed to form within the cluster will continue to migrate inward until it interacts with one of the other IMBHs that has been deposited by some other in-falling star cluster. In this way, IMBHs will pair off into binary systems. Black holes in a binary system will continuously emit energy in the form of gravitational radiation, which will eventually cause them to merge. In this fashion, many intermediate mass black holes will form a single super-massive black hole at the very center of the galaxy. In the case of low mass galaxies, there may not be enough intermediate mass black holes deposited at the galactic center to act as ‘seeds’ for an SMBH to form. Instead, these galaxies will be left with an IMBH at their cores. The existence of IMBHs at the centers of low mass galaxies is predicted by the M - σ Relation. If ω Centauri is the core of a dwarf galaxy that was accreted by the Milky Way, then recent evidence of the presence of a compact object with a mass between $3.0 \times 10^4 M_\odot$ and $4.75 \times 10^4 M_\odot$ at its center will support this prediction.

Ultraluminous x-ray sources are often cited as evidence for IMBHs in other galaxies. A ULX is a compact, often variable, x-ray source with a mass between $15 M_\odot$ and $10^3 M_\odot$, assuming that they emit isotropically at sub-Eddington luminosities. ULXs are thought to be present in about 30% of galaxies. They are most common in starburst galaxies, though they do appear with slightly less frequency in both elliptical and spiral galaxies as well. Most, but not all, ULXs are associated with star clusters. They are found in globular clusters, which is to be expected if they are the product of a collision runaway in a large star cluster, but they have also been found in small open clusters that should not have had time to produce an intermediate mass black hole. An alternative explanation for ULXs is that they are x-ray binary systems. The fact that luminosity functions

show a smooth transition from x-ray binaries to ULXs seems to support that hypothesis. There is also the possibility that ULXs emit anisotropically, in which case their luminosities- and therefore, their masses- would be significantly less than in the isotropic case.

The M- σ Relation and the correlation between a galaxy's bulge and the mass of its central black hole imply the existence of a class of object with a mass between that of the most massive stellar mass black hole and the least massive super-massive black hole. ULXs appear to show the luminosities and small physical sizes that would be expected from an IMBH, but their similarities to x-ray binary systems make their exact nature somewhat uncertain. Observations of the velocities of stars near the centers of certain globular clusters seem to imply the presence of massive, compact objects at the cores of these clusters, providing additional evidence for IMBHs. Continued study of ULXs as well as globular clusters and dwarf galaxies is needed before the question of the existence of IMBHs can be answered one way or the other.

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