

Frontiers: Intermediate-Mass Black Holes

For our final lecture we will concentrate on one of my specialties: intermediate-mass black holes (IMBHs). These are black holes in the $10^{2-4} M_{\odot}$ mass range, and their existence has not been established with certainty. However, strong circumstantial evidence exists, and their formation and evolution have exciting contact with many frontier areas of astrophysics. For an extensive recent review on these objects, see Miller & Colbert 2004, *International Journal of Modern Physics D*, 13, 1.

Evidence for IMBH

To put the evidence for IMBHs into context, let us consider why we are confident that stellar-mass and supermassive black holes exist. In both cases, it comes down to a dynamical measurement of mass. For stellar-mass black holes, there are a small but growing number of cases in which (1) we see some X-ray source in our galaxy, (2) a normal star is seen in the area that is associated with that source (but not the cause of it), (3) motion of the companion gives a mass function, and (4) the net implication is that the source of the X-rays has to be more than 3 solar masses, hence is not a neutron star. We then conclude we have a black hole (or potentially something much more exotic).

For supermassive black holes, observations of our Galactic center over the past ~ 15 years have shown that a lot of stars are orbiting around something that is very massive and quite concentrated. Again, it's either a black hole or something a whole lot weirder.

For putative black holes in the $10^{2-4} M_{\odot}$ range, it's tougher. Candidates are few and far between. The ones we think are accreting a lot of mass in binaries are Mpc away instead of kpc, so detecting a companion is much more challenging than for the local stellar-mass black hole binaries. In addition, because IMBHs are much lower-mass than supermassive black holes, their "radius of influence", inside of which the IMBH dominates the potential, is far smaller than for an SMBH, so following the motions of stars is not easy at all, especially at great distance.

We are therefore reduced to circumstantial evidence in most cases, although there are claims that stellar motions in or the overall photometric properties of Galactic globular clusters support the existence of a few thousand solar mass black hole in the center. Hubble or Keck monitoring of such motions may ultimately lead to much better evidence for IMBHs. The difficulty is that there are few bright stars in globulars (since most have just evolved away), so one must typically rely on the rare red giants for good measurements. We'll see what happens.

In the meantime, most of the attention has focused on a class of X-ray emitters called Ultraluminous X-ray sources, or ULXs. The "Ultra" part means that if these sources are emitting more or less isotropically then their overall luminosity is at least a few times

10^{39} erg s⁻¹. **Ask class:** what is special about this value? It is the Eddington luminosity for a 10 – 20 M_{\odot} object. Since various models of stellar evolution suggest that solitary stars in the current universe don't evolve into black holes more massive than about 20 M_{\odot} , luminosities beyond the associated Eddington luminosity could suggest a qualitatively different origin for these objects. **Ask class:** given that we know of stars of masses $> 100 M_{\odot}$, why might a much smaller mass be the current limit? The idea is that with current metallicities, the high luminosity of high-mass stars implies huge mass losses to winds and pulsations, leaving a much less massive remnant.

If we want to be more careful, we can limit ourselves to the 10-20 objects with “isotropic luminosities” greater than about 10^{40} erg s⁻¹, to ensure that we are well beyond the best guess at a stellar-mass black hole mass limit. Here when I say “isotropic luminosity” I mean the flux times $4\pi d^2$, where d is the distance to the object. It is important to phrase it this way because as we'll see, there has been a lot of discussion of the possibility that these sources are beamed towards us, which would mean the true luminosity is a lot lower.

Now, just having a high luminosity doesn't have to imply that we have a high-mass black hole. For example, maybe there are just a bunch of unresolved sources together, with none of them individually exceeding 10^{38} erg s⁻¹. Or, perhaps these are supernova remnants, which can get to a very high luminosity. **Ask class:** how might we rule out such explanations? A powerful constraint comes from variability. ULXs are often seen to change in flux by a factor of nearly 10 over a few months. This can't happen with multiple sources (how would they know to go up and down together?), and also does not happen in this way for supernova remnants. One can also look at the multiwavelength spectrum, and find that the radio emission from ULXs is much weaker than you would expect if in fact these were SN remnants.

What, then, are these objects? Three basic ideas have been put forth. One is that these are IMBHs emitting below their Eddington limit. A second is that these are stellar-mass black holes that are below their Eddington limit, but beamed towards us so that the flux is really high. The third is that these are stellar-mass black holes that are emitting nearly isotropically, but that manage to bypass the Eddington limit by a lot, as in a factor of at least tens and sometimes hundreds. One might also think of the possibility that these are supermassive black holes emitting very far below their Eddington limits. However, a typical selection criterion for a ULX is that it not be at the center of its host galaxy. An offset supermassive black hole would sink to the center within much less than a Hubble time, so lower masses are indicated. One also has to worry about background sources, so it is a good idea to choose ULXs that are not *too* far offset from the center of a candidate host galaxy or globular cluster.

The IMBH explanation works perfectly well with all observations if there is a way to produce them and feed them. We'll discuss that in the next section.

The other two explanations have the advantage of appealing to a known population (stellar-mass black holes), but the disadvantage of being in an unknown state, meaning that it is difficult to know what to expect in terms of a spectral or temporal signature. In fact, for many aspects of the observations (e.g., specific variations in the flux, and characteristics of the spectra), what we see is not at all what one would normally expect from beaming or super-Eddington emission. There is, in fact, no single ULX that has any definitive characteristic consistent with these explanations (at least at the simplest level), whereas there are of order 10 which have been observed enough that they show complete consistency with an IMBH explanation. This is why I favor IMBHs, but without dynamical mass measurements we will always have uncertainty.

With this in mind, let us consider ways to produce black holes in this mass range.

Formation of IMBHs

As mentioned above, solitary stars in the current universe probably can't evolve into IMBHs, because mass losses will drop them down to maybe $20 M_{\odot}$ or less. How, then, can we get to $10^{2-4} M_{\odot}$? The three main mechanisms that have been considered are (1) evolution of the earliest "Population III" stars, (2) runaway collisions of massive stars in young massive star clusters, and (3) collisionless three-body interactions and mergers. We will consider these in turn.

The Big Bang produced hydrogen and helium, and trace amounts of lithium and beryllium, but nothing else (the lack of stable nuclei at 5 and 8 atomic mass units prevented much more). Since stellar processes are required to generate heavier elements, this means that the very first generation of stars had essentially zero metallicity, which as a reminder means to astronomers no elements heavier than helium. The very first star in the universe might have been born at redshift $z \sim 70$ (in a very high- σ dark matter halo), but people typically talk in terms of $z \sim 20 - 30$.

These so-called Pop III stars might therefore have had different properties than the stars that followed. To see this, consider first the formation of stars. Consider a gas cloud of density ρ and temperature T , and think about larger and larger spherical masses M within that cloud. The (negative) gravitational energy scales as $E_{\text{grav}} \propto -M^2/r$, where $r \propto (M/\rho)^{1/3} \propto M^{1/3}$, so $E_{\text{grav}} \propto M^{5/3}$. The (positive) thermal energy scales as $E_{\text{th}} \propto NkT \propto M$, where $N \propto M/m_p$ is the number of molecules. Therefore, small masses are unbound whereas large masses are bound and can collapse (you can also show this with a perturbation analysis and dispersion relation). The mass at which the cloud can collapse is the Jeans mass, and is about $M_J = 2 M_{\odot} (T/1 \text{ K})^{3/2} (n/1 \text{ cm}^{-3})^{-1/2}$.

If a cloud does start to collapse, adiabatic heating would increase its temperature. For a nonrelativistic ideal gas with $P \propto \rho^{5/3}$, then $T \propto P/\rho \propto \rho^{2/3}$, so given that $n \propto \rho$ we have $M_J \propto \rho \times \rho^{-1/2} \propto \rho^{1/2}$. Therefore, a cloud that started to collapse would be halted if there

were no cooling, showing that cooling is essential to further collapse and formation of stars.

With metals (as in the current universe), there are lots of ways for cooling to proceed. That leads to low temperatures, and hence low Jeans mass. Therefore, even though molecular clouds can start off at millions of solar masses, the stars we get are tenths of a solar mass to tens of solar masses. In the H and He only universe, He doesn't contribute much, leaving it to H and its molecules (mainly H₂, with a tiny amount of HD). Cooling is thus less efficient, so temperature and hence masses are higher. Detailed calculations suggest that the masses can possibly be hundreds of solar masses at stellar birth.

Once formed, mass losses are also less significant, because stellar winds and pulsations are primarily driven by metal line opacities. This implies that the stars can keep almost their entire mass all the way to core collapse. If they can, then if when core collapse happens the stellar mass is at least $40 M_{\odot}$, simulations suggest that there isn't a supernova, because not enough energy couples to the envelope to unbind it. A failed supernova will produce a black hole, and the rest of the mass will fall in, so the ultimate black hole that results will have almost the same mass as the original star. There is some excitement around the $150 - 260 M_{\odot}$ mass range, in which an oxygen core of tens of solar masses fuses catastrophically and blows the whole star to bits, but above that range again we expect a black hole with nearly the initial stellar mass.

It is not yet clear how high a mass this would imply, but it seems possible for at least hundreds and possibly thousands of solar masses to result. It seems difficult for there to be enough of these to explain the ULXs, but they probably play an essential role as seeds of supermassive black holes in the early universe. If their mergers with each other can be observed with the *LISA* experiment, that will provide a unique view of the early nonlinear universe.

The second IMBH formation mechanism involves direct collisions of young massive stars in young massive star clusters. Consider a "super star cluster" at birth, which might have a few hundred thousand solar masses within a radius of a few parsecs. This implies that there are 10^{5-6} stars in that region, so the gravitational potential is somewhat grainy. The graininess means that stellar orbits will change due to two-body perturbations. In addition, the heaviest things will sink systematically because of dynamical friction.

Suppose that the heaviest stars, with $M \sim 50 - 100 M_{\odot}$, are able to sink into the center before they evolve off the main sequence (which takes $\sim 2.5 \times 10^6$ yr; it asymptotes at that value rather than continuing to decrease rapidly at higher masses). These are large enough objects that they can physically collide. If two of them do collide, simulations suggest that they stick together like balls of clay with very little mass loss (a physical reason for this is that their escape speeds are > 100 times larger than their relative speed at infinity). The new, larger, star has a higher mass and therefore a higher cross section for further collisions.

This is a condition for a runaway, and simulations suggest that this does indeed happen (for one example application to a specific ULX, see Portegies Zwart et al. 2004, *Nature*, 428, 724). The stellar mass can get to $> 1000 M_{\odot}$ fairly easily, with collision rates high enough that mass losses are compensated easily. The big question is whether the collision product actually then evolves into an IMBH. The issue is that the collision product isn't properly a star; collisions happen faster than the collision energy can be radiated away, so this is probably an extended envelope with lots of stellar cores moving around. In some cases, more than one IMBH might be formed, if the initial binary fraction is more than 10% (Gürkan et al. 2006, *ApJ*, 640, L39).

If the product does become an IMBH, then supernovae of other stars calls a temporary halt to mass growth. That's because supernovae throw mass out of the center of the cluster, so the core expands. Subsequently, though, we get to the third possible way to grow an IMBH.

This is where I've concentrated most of my effort. Consider a cluster after a few hundred million years, where the most massive things around are the IMBH, stellar-mass black holes, and maybe stellar remnants such as neutron stars and heavy white dwarfs. All of those objects are basically points, meaning that they don't hit each other directly. However, if there are binaries around, their effective cross section is the size of the binary rather than the sizes of the individual objects. This can lead to three-body interactions.

If such an interaction has negative total energy then simulations show that typically (1) the two heaviest of the three objects end up in the final binary, and (2) the binary tends to increase its binding energy. Therefore, repeated such interactions will tighten the binary. This will continue until either (1) the Newtonian recoil from the interaction kicks the binary out from the cluster (this is likely for stellar-mass black holes, but not for IMBHs with $M > 1 - 2 \times 10^2 M_{\odot}$ initially), or (2) the orbital pericenter distance is small enough that gravitational radiation causes a merger and thus growth of the IMBH. Whether this can happen many times also depends on the recoil due to release of gravitational radiation, but if the IMBH starts out at $M > 200 M_{\odot}$ then survival seems likely (implying to me that for this growth to be successful, some aspect of runaway collisions had to happen). This can grow the IMBH to $\sim 500 M_{\odot}$ before it kicks out its supply of stellar-mass black holes. Several of my papers have dealt with this, notably including Kayhan Gültekin's thesis papers (2004, *ApJ*, 616, 221; 2006, *ApJ*, 640, 156).

These interactions are the ones that might lead to gravitational wave emission, so let's finish up with those.

Implications of IMBHs for gravitational radiation

Because IMBHs have a unique mass range, they have a potentially unique frequency range of their gravitational waves. In addition, the likely dynamical origin of IMBHs

means that if we do detect gravitational waves from them, we learn about dynamics and maybe aspects of star formation. Basically, you can pair IMBHs with stellar-mass objects (specifically BHs or NSs); with other IMBHs; or with SMBHs.

In a stellar cluster, the third growth mechanism above requires mergers with stellar-mass black holes or neutron stars. There are a lot of uncertainties, and full simulations need to be done including dynamical and stellar evolution, but it appears that a ground-based instrument such as Advanced LIGO might be able to see several to tens of events per year. Ideally one would have detectors that could reach down to a few Hz, instead of a few tens of Hz, but seismic noise kills you on the ground, and LISA focuses on lower frequencies.

As also mentioned above, some simulations suggest that two IMBHs could form in the same cluster, if the initial binary fraction was at least a modest 10%. If these merged, then their gravitational waves could be seen out to a redshift $z \sim 1$ or potentially larger with LISA (see Fregeau et al. 2006, ApJ, 646, L135). This would be a new way to probe the dynamics of star clusters, and would reach into where the star formation rate is an order of magnitude larger than it is now.

IMBH-SMBH mergers could happen if clusters containing IMBHs sink to the center of a galaxy, where the IMBH would then eventually spiral in to the SMBH (see Miller 2005, ApJ, 618, 426). These would be very strong events for LISA, and would at the same time be extreme mass ratio inspirals (EMRIs) because the mass ratio would be > 100 , and typically > 1000 . The attraction of EMRIs is that the small object (the IMBH in this case) would trace out the spacetime of the large object. This would therefore be a sensitive test of whether the Kerr spacetime really does describe spinning black holes.

We'll see! There are lots of frontiers here, which is why I have enjoyed studying this subject. The main future development that would change things is if a dynamical mass were obtained for a ULX (e.g., by identifying a companion and following its radial velocity). We can't legislate such developments, though, so in the meantime I suspect that theoretical developments will be key.