Midterm: closed-book, closed-notes. Bring a calculator, but don't program it. In-class on Wednesday.

Evidence for BH: Orbits and Stellar Sources

In the previous lecture we talked about AGN, and the evidence that these are powered by supermassive black holes. This evidence, though compelling, is indirect. Here we'll talk about more direct lines of evidence.**Ask class:** what is the most direct astronomical way of measuring mass? Observation of orbits.

Star motions in galactic centers

One set of observations, which has had promise for years but has only come into its own in the past decade, is the observation of star motions in the centers of galaxies. One expects that the most massive things will settle into the centers of galaxies by gravitational interactions, so it is reasonable to look for black holes there. If the hole is not accreting actively, its presence can be sensed by the motion of stars near it. In particular, if many stars are moving rapidly in ways that are consistent with an orbit, then by determination of their velocity and their radius of orbit one can infer the mass interior to them. This is something that has plenty of potential hazards. For example, the motion had better be due to the gravity of the central mass(es), and not something else. About a decade ago there was a press release announcing the discovery of a $10^{11}\,M_\odot$ black hole in the center of one galaxy, that the authors had to retract when it was discovered that they were actually looking at the center of two galaxies merging; the high velocities were ballistic, not orbital! However, many examples have by this time been found, particularly with telescopes or techniques that allow excellent angular resolution, so one can look at many individual stars as close as possible to the central object. For our own Galaxy, the mass interior to stars levels off at about 0.1 pc, at about $2.6 \times 10^6\,M_\odot$. The leveling off indicates that the mass responsible for the orbits is more tightly concentrated yet, which is essentially conclusive evidence that this is a black hole. To get around this would require a cluster of stars with a density exceeding $10^{12}\,M_\odot\ \mathrm{pc}^{-3}$. **Ask class:** why is this a problem? Actual collisions might not be a problem: even at such densities, the average distance between stars is $\sim$10 AU, and if the stars were stellar remnants such as white dwarfs or neutron stars they wouldn't collide. It is dynamical instabilities that are the problem. (the stars would fling each other out too rapidly). Another way out would be to have a (dark!) object that is not a black hole, but has several million solar masses of material (several hundred million in other cases). This seems impossible. Movies of the motion of the stars near Sgr A*, the candidate center of the Galaxy, can be found at http://www.mpe.mpg.de/www_ir/GC/prop.html.

Black holes in binaries

The above is enough to demonstrate that black holes must exist. However, complementary (and in some ways more convincing) evidence exists from the study of X-ray binaries. In many cases one sees X-rays coming from a region that contains a visible star that is orbiting around something not evident in optical. **Ask class:** do they know what needs to be measured to get a constraint on the mass? One can measure the period P of the orbit and the radial velocity v_1 along the line of sight of the visible companion in its orbit. Here the "1" indicates that the visible object is labeled 1 (the invisible object is labeled 2). From these observables and Kepler's third law one can calculate an important quantity called the "mass function",

$$f(M_1, M_2, i) = \frac{Pv_1^3}{2\pi G} = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} \ . \tag{1}$$

Here M_1 is the mass of the visible star 1, M_2 is the mass of the invisible star 2, and i is the inclination angle of the orbital axis relative to the line of sight (e.g., $i = 0$ for face-on, $i = 90$ for edge-on). You can convince yourself that the minimum mass of the unseen star is just f, which occurs for $M_1 = 0$ and $i = 90$. Therefore, from just these two measured parameters, it is possible to get a lower limit on the mass of the unseen object. Extremely general considerations (the assumption that GR is the correct theory of gravity!) indicate that neither a neutron star nor any other object with a surface that is supported by degeneracy pressure can have a gravitational mass more than $3\,M_\odot$ (the real limit is probably closer to $2\,M_\odot$). Therefore, if $f > 3\,M_\odot$, you've got a black hole. This is the case for $\sim$7 sources in the Galaxy, and this (in my opinion) is the very best evidence for the existence of black holes. Incidentally, there are some systems where one can say something about the inclination angle i (mainly by modeling the variation in the optical light curve as the distorted star orbits around). For those, one can get fairly precise estimates of the black hole mass. The seven examples in which $f > 3\,M_\odot$ all have companions with low masses, unlike better-known candidates such as Cyg X-1. **Ask class:** why would it be easier to get mass estimates when the hole has a low-mass companion? Because the companion is moved around more by the gravity of the black hole. For higher-mass stars, the mass function is typically low because $M_1 > M_2$. Uncertainties in the true mass of the companion then make rigorous identification of the black hole very difficult if not impossible. There are also significant differences between accretion onto a black hole from a low-mass or a high-mass companion. We will now investigate them.

Accretion from a low-mass companion

If the companion is a low-mass star, then it has few innate processes by which it loses mass. Mass transfer therefore happens when the star evolves or spirals close enough to the black hole that the star's radius exceeds the radius of its Roche lobe (that is, the matter becomes gravitationally unbound with respect to the companion, and hence flows over to the black hole). **Ask class:** would the mass that makes its way to the black hole therefore have high or low angular momentum? High. **Ask class:** so, what happens to the mass as it spirals in? An accretion disk forms, as we've discussed previously. The long evolutionary times of low-mass stars means that this kind of accretion can continue for hundreds of millions of years.

Many candidate black holes in low-mass systems are not steady accretors, but transients. That is, they will have very low luminosities for long stretches (10^{30-32} erg s^{-1} in many cases), but will then undergo periods of greatly increased luminosity, near Eddington. This is thought to be analogous to the so-called "dwarf nova instability". The picture is that the matter in the accretion disk initially has low temperature and low ionization, with the result that the viscosity in the disk is not sufficient to have the disk spread and accrete much. Therefore, matter piles up at the outer reaches of the disk. When enough matter has piled up, the ionization increases, the viscosity goes up, and most of that accumulated matter flows in rapidly, releasing a large amount of energy very quickly. The outbursts of black hole transients typically last for a couple of months, with some exceptions. The fact that these sources identify themselves with outbursts but are usually not active is another reason why they are good to observe for black hole candidacy. After a source has died down, its companion is easy to observe because there is no contaminating emission. This gives clean light curves.

Accretion from a high-mass companion

High-mass stars have substantial winds, and can lose a great deal of mass to them (as much as $10^{-6} - 10^{-5}\, M_\odot$ yr^{-1}). This is essentially because the opacities of their atmospheres (dominated by metal-line transitions) are high enough that radiation force exceeds gravity, given their high luminosities. This means that matter from them can accrete onto a compact star, e.g., a black hole, but the process is very different from that of Roche lobe overflow.

Bondi-Hoyle accretion.—the new type of accretion is the same as would apply for a compact object moving in the interstellar medium. Suppose first that the gas to be accreted is completely cold, i.e., it has no internal motions. Assume, however, that it has some residual ionization, and so will interact with itself if there is some relative motion. A black hole of mass M moves with a velocity v with respect to the gas. The gas is gravitationally bent and focused by the black hole, so it collides with itself behind the black hole. The first-order Bondi-Hoyle assumption is that the transverse velocity cancels out, and that if the remaining velocity relative to the black hole is less than the escape velocity at that point, the gas is captured and accreted.

Ask class: before we derive the accretion rate, do they expect it to go directly or inversely with M? With v?

The actual accretion rate depends on a number of details about the flow, particularly because as stated the black hole is moving supersonically, so there will be a shock. The result would have to be calculated numerically, but there is no definite answer. We'll give a quick derivation good to a factor of a few. To that accuracy, a particle will be captured if its kinetic energy is less than the gravitational binding energy at a distance equal to its impact parameter relative to the black hole. That is,

$$\frac{GM}{b_{\rm cap}} = \frac{1}{2}v^2 \ , \tag{2}$$

so the cross section for capturing matter is $A_{\rm cap} = \pi b_{\rm cap}^2 = \pi(2GM/v^2)^2$. The rate at which matter is captured is then $\dot{M} = \rho_\infty A_{\rm cap} v$, where ρ_∞ is the density of the gas far from the hole. Therefore, $\dot{M} = 4\pi\lambda(GM)^2 v^{-3}\rho_\infty$. Uncertainties about the accretion are usually put in a factor $\lambda < 1$. In addition, if the matter is not cold but has a sound speed c_s far from the hole, there is a correction. This correction is of a similar form, because for a stationary black hole with particles moving at c_s, the same capture mechanism operates. The Bondi-Hoyle mass accretion rate, including these effects approximately, is then

$$\dot{M} = 4\pi\lambda(GM)^2(c_s^2 + v^2)^{-3/2}\rho_\infty \ . \tag{3}$$

Let's work out some numbers. Suppose a black hole of mass $10\,M_\odot$ is moving supersonically with $v = 100$ km s^{-1} through a medium of density 10^{-25} g cm^{-3}, typical of the hot ISM. The accretion rate is then $\dot{M} = 5\times10^9\lambda \approx 2\times10^9$ g s^{-1} for fully ionized hydrogen. This is a low rate, so accretion from the ISM is not expected to produce bright sources, although some might be observable if there are black holes in dense, low-temperature regions such as the cores of molecular clouds. Note also that the Bondi-Hoyle capture radius, $R_{\rm BH} = GM/v^2$, is around 10^{13} cm for $M = 10\,M_\odot$ and $v = 100$ km s^{-1}.

So, back to accretion from a high-mass companion. Stellar winds typically have velocities comparable to the escape velocity from the surface (they need about the escape velocity to leave at all, and very high velocities are improbable tails to the velocity distribution). For an O or B star this could be 1000 km s^{-1} (up to 3000, in fact). That would mean a capture radius of 10^{11} cm. The orbital separation is typically 10^{12-13} cm, so something like $10^{-4} - 10^{-2}$ of the wind is captured by such a black hole. That translates to accretion rates of $10^{-9} - 10^{-7}\,M_\odot$ yr^{-1} for many systems, or $10^{37} - 10^{39}$ erg s^{-1}, which is a few to a hundred percent of the Eddington rate. These sources can therefore be very bright. They don't live long, though, because the evolutionary timescales of the massive companions are only a few million years, typically. Cyg X-1 is a famous example of this type of black hole binary. Its mass function is only about 0.2 $M_\odot$, but the companion mass is high enough that the compact object is almost certainly a black hole.

Ask class: given that the wind is spherical and the orbital velocity is small compared to the wind velocity, do you expect the net angular momentum of accretion to be high or low? Low. It is therefore questionable whether these sources have accretion disks at all. In the homework you will estimate the size of the accretion disk formed by such accretion in a special case.

Comment: mass and spin of stellar-mass black holes

From the above, we realize that stellar-mass black holes probably have close to the mass and angular momentum that they were born with. If a black hole has a low-mass companion, there simply isn't enough mass accreted to make a difference, even if the whole companion is eventually eaten. If the companion is high-mass, the mass transfer episode lasts only a few million years, which even at Eddington rates transfers at best a few hundredths of a solar mass, again not nearly enough to make a difference in either mass or spin. This means that if there is some way to determine the mass and spin accurately, there is a lot of information to be had about the supernova process. This is in distinction to neutron stars, which spin down actively due to magnetic dipole radiation, and which can accrete a significant fraction of their mass from a companion. Unfortunately (and as we'll explore in the next lecture), no accurate way currently exists to determine the spin.

Signatures of black holes?

The paucity of confirmed black holes (only 7!) is frustrating, because we'd like some way of expanding the population and hence studying a large set of known black holes; after all, astronomy is full of peculiar sources and we don't know whether we're seeing typical ones or not. There have therefore been many attempts to find signatures of black holes that do not require mass function measurements. The typical strategy has been to examine a source that is almost certainly a black hole (such as Cyg X-1), then posit that its behavior guarantees black hole status. Proposed signatures include rapid variability, the presence of a hard component to the spectrum, and certain aspects of how the spectrum changes as a function of observed flux. So far, it is a frustrating enterprise, because a number of the proposed signatures (e.g., rapid variability and the hard spectral component) are also seen in known neutron stars, so clearly these aren't unique to black holes. In retrospect, this isn't a surprise, because all of the emission from accreting black holes comes from the accretion disk, which is also present around neutron stars (and may reach down to the same inner radius, the ISCO for example), so what is really being seen is purely the result of gravity. Work goes on, and the state transitions may be a good signature, but it is a dicey prospect. Next lecture we'll talk more about possible signatures of strong gravity.