Special Lecture: Black Holes and Galaxy Formation

Surely you didn't think I'd abandon my beloved black holes entirely in this class? In fact, there is even a good excuse to bring them in at this point. Although black holes are commonly imagined to be surly loners that send matter to its doom but don't interact much, recent observations and numerical simulations suggest that they may have a key role to play in shaping galaxies and galaxy clusters. In this lecture we'll first survey black holes themselves, then the evidence of a link between supermassive black holes and galaxies.

Black Holes

Ah, black holes: objects of mystery, darlings of Hawking. Black holes are interesting for many reasons: they are one of only three possible endpoints of stellar evolution (the others being white dwarfs and neutron stars), they are the powerhouses of the most luminous things in the universe (quasars and other active galactic nuclei), and they are the simplest macroscopic objects in the universe, with only two parameters important for their astrophysical properties. They are also way cool. Their simplicity means that it is possible to study them in a way impossible for any other astronomical object: with mathematical rigor. There was, for example, a flurry of activity in the late 1960s and early 1970s about proving theorems related to black holes, something which is mightily difficult to do with a star! However, our main interest is in astrophysics, and specifically in explaining observed phenomena. People with a desire to see the mathematical details can consult "The Mathematical Theory of Black Holes" by Chandrasekhar, or "Black Holes" by Novikov and Frolov, both of which are in our library.

Let us start by defining "black hole". A black hole is an object with an event horizon instead of a material surface. Events inside that horizon cannot be seen by any external observer. This is the fundamental property of black holes that distinguishes them from all other objects. It should be noted that (as we'll get to later) although there is compelling evidence for the existence of black holes in the universe, never has the existence of the horizon itself been demonstrated. An observation that unambiguously indicates the presence of a horizon would be a major advance. From time to time there are press releases announcing proofs of event horizons based on theoretical arguments, but so far these are unconvincing.

Ask class: how, though, can we see black holes? What goes in doesn't come out, so they are essentially silent. The basic answer is that we'd have to see the effect that black holes have on other things. For example, if there is a lot of gas around, it tends to spiral around the hole (thus forming an "accretion disk"). Note that in principle the gas could just fall straight in, but in reality everything has at least a little angular momentum, and black holes are small, so gas tends to spiral in slowly and release energy as it does so (caveat:

this actually glosses over some details, and in some circumstances not much energy might be released). In principle, this could mean that the gas releases $\sim 5-40\%$ of its mass-energy in the form of X-rays or other radiation. It can also be that, although black holes themselves don't have magnetic fields, magnetic fields in the disk can be dragged in the direction of rotation of the hole, and this might produce some of the very powerful directed jets of matter seen from a number of supermassive and stellar-mass black holes.

Black holes can also be detected by their effect on things orbiting them, as we now discuss.

Evidence for SMBH: Stellar Motions

We now focus on supermassive black holes (SMBH) in the centers of galaxies, as these have the greatest effect on the galaxies as a whole.

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. For our own Galaxy, the mass interior to stars levels off at about 0.1 pc, at about $3.5\times 10^6\,M_\odot$. 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 $10^{12}\,M_\odot$ 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 ~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 galaxies). 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.

By now, the evidence for a supermassive black hole in the center of the Galaxy seems rock-solid. In addition, there are a number of other galaxies for which black hole masses can be measured in various ways. Remarkably, it has become clear over the last 10–15 years that somehow the black hole masses “know” about their surroundings, as we now explain.

The $M-\sigma$ relation

One of the obvious things to do when measuring things in astronomy is to plot one quantity versus another for some set of objects. As a familiar example, think about the

Hertzprung-Russell diagram: most stars occupy a narrow band on a plot of color versus absolute magnitude. When applied to black holes and their surrounding galaxies, there are several such correlations. For example, more massive SMBH tend to inhabit more massive galaxies that are thus typically also more luminous. The one that has received the most attention, however, is the so-called $M - \sigma$ relation.

Recall that most galaxies have some basically spheroidal component. That is, they have a region in which the stars move every which way (instead of basically in one direction, like the Sun and its nearby fellow travelers) and thus the distribution is "fat" rather than disklike. This is often called the "bulge" of spiral galaxies, and is basically the whole galaxy in the case of ellipticals. As a result, one cannot characterize the motion of stars in a bulge with a rotation speed (since some things move one way, and others in other ways), but we can define a "velocity dispersion" by determining the square root of the average squared speed. Yes, that sounds like the long way around, but notice that the average *velocity* is close to zero because of the random movements. We use σ to indicate the velocity dispersion.

Lo and behold, there is a pretty tight correlation between the estimated mass of the black hole and the velocity dispersion of the bulge/spheroid. The precise form of the correlation (and credit for discovering it!) is the subject of an unusually rancorous dispute, but we'll take the relation advocated by Tremaine et al. 2002 (ApJ, 574, 740):

$$M_{BH}/M_{\odot} = 10^{8.13}(\sigma/200 \text{ km s}^{-1})^{4.02} \tag{1}$$

with relatively small error bars on the parameters. Figure 1 shows a recent plot of the data, due to Jenny Greene of the Harvard-Smithsonian Center for Astrophysics.

What does it all mean? At first, you might be tempted to think that this is pretty obvious: of course bigger black holes will whip things around faster. However, we need to consider an issue of scale, and in particular the so-called "radius of influence". This is the distance out to which the black hole dominates the total mass; beyond $r_{\rm infl}$, most of the mass is in stars and thus the SMBH contributes a minority of the gravity. For a SMBH mass M and velocity dispersion σ, $r_{\rm infl} = GM/\sigma^2$. For the Galaxy, this turns out to be $r_{\rm infl} = 3$ pc. In comparison, the Galactic bulge is roughly 1 kpc in radius. This means that the SMBH directly affects only a very small fraction of the bulge!

Chicken and Egg

What, then, accounts for the $M-\sigma$ relation? There have been dozens of papers published on this, most of them claiming to have the one true answer. We could, however, generically imagine a couple of extremes. At one extreme, the black holes just follow their host galaxies: somehow, the amount the holes can eat is determined by the velocity dispersion (e.g., maybe there is some fixed amount of mass within reach of the SMBH). At another, maybe there is

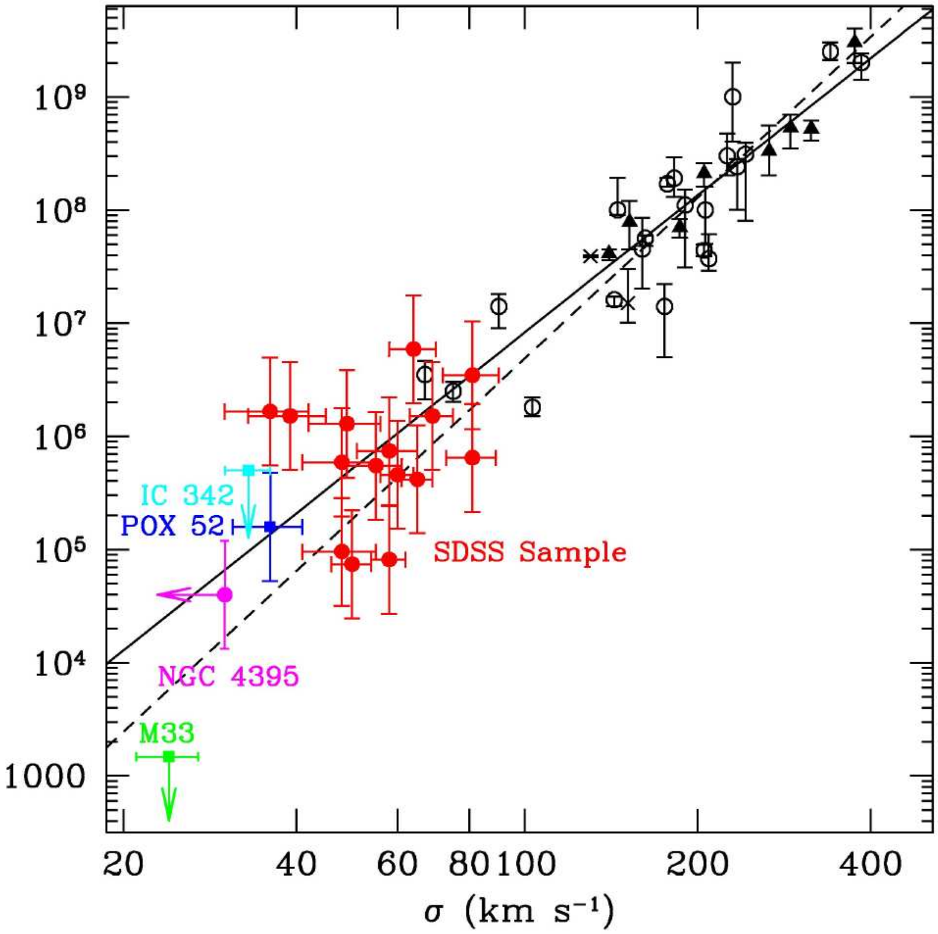

Fig. 1.— Estimated SMBH mass (vertical axis) versus velocity dispersion (horizontal axis) for a number of galaxies. Note that there are uncertainties in the measurements themselves, so this correlation is really remarkably tight. From http://cfa-www.harvard.edu/∼jgreene/msigma_v2.jpg

some dynamical interaction that allows the SMBH to influence the velocity dispersion even far outside the radius of influence.

Perhaps unsurprisingly, current thinking and simulations appear to be converging on interdependence rather than one or the other dictating the action. Recent numerical work seems to confirm an general idea presented by Joseph Silk and Martin Rees in 1998. If gas spirals into a SMBH, it emits energy, at a maximum rate limited by the mass of the SMBH (too much energy, and the accretion is prevented by the luminosity itself). If some of that energy or momentum couples to gas in the galaxy, it heats up or drives away the gas. The mass of the SMBH thus grows until ejection of gas is efficient, at which point it stops. This point is in turn determined by the depth of the gravitational well in the bulge, which itself depends on the velocity dispersion.

It turns out that this picture also does a good job of explaining other aspects of galaxies. For example, it has long been thought that elliptical galaxies (which have very little gas or recent star formation) are produced by the collisions of two galaxies. However, simulations suggest that if two gas-rich galaxies did not have SMBH at their centers, then even though shocks and subsequent cooling in the collided gas would lead to significant star formation, for large galaxies one would not expect almost all the gas to be ejected. This would therefore be inconsistent with observations. In contrast, when large black holes are involved, much more gas can be removed.

The picture that is emerging is thus as follows. Suppose that two large gas-rich galaxies (i.e., spirals) collide with each other. The stars don't hit because they are too far separated, but the interstellar media do. This produces shocks and rapid cooling, leading to a flow of gas towards the merged center. At the center, the two SMBHs will have spiraled together and merged. As the gas flows towards the (now single) SMBH, energy and momentum from the radiation and jets exerts an ever-increasing force on the gas in the galaxy. Eventually, this becomes large enough that the gas is mainly expelled, and hence the accretion rate drops and the energy emission decreases.

This general picture explains a lot about the correlations between active galactic nuclei and galaxy mergers, as well as about specific bimodal properties of galaxies (the red and blue types). It may also find application to clusters of galaxies, where without a significant central heating source one would expect a rapid flow of cold gas towards the center (which isn't seen). However, there are still a lot of issues to confront. We'll now look at a couple of them.

Potential Difficulties

One limitation of the numerical simulations is that since they have to explore such a huge range of physical scales (from >100 kpc down to <1 pc), they rely on processes below the resolution scale (called "subgrid physics"). A critical example of this is the mechanism by which energy released by accretion couples to the gas in the galaxy. It turns out that the energy in photons doesn't couple very efficiently. Therefore, many people have turned to the idea that a strong outflow of matter from the inner accretion disk, in the form of directed motion called "jets", do the job. It is true that the energy and momentum of a jet couples very well to surrounding gas *if it is in the path of the jet.* However, that's not enough to eliminate most of the gas, which after all is distributed everywhere. You need the energy to couple in a more or less spherical fashion. It has been suggested that the jet gets stopped and thus forms a cocoon through which all the gas is affected. However, simulations by John Vernaleo and Chris Reynolds at Maryland show that this is very inefficient: essentially, the gas can still accrete just fine at right angles to the jet and isn't dissuaded by the kinetic energy being deposited in a few directions.

Another interesting point to consider relates to the black holes themselves. As they spiral in, they emit gravitational radiation. In generic cases, the radiation is emitted with some asymmetry, which means that the final merged black hole moves with respect to the original center of mass of its two inspiralling parents. Only serious numerical computations can determine the magnitude of the kick, but this has been managed in the last two years, and it turns out that for rapidly spinning black holes in particular orientations the kick can be up to a maximum of nearly 4,000 km s^{-1}!! That's enough to eject the black hole entirely from any galaxy in the universe. Even though most mergers won't be oriented just right, one would expect that for the observed rapid spins and mass ratios, tens of percent of merged galaxies would have lost their black holes. We don't see this. Motivated by this apparent discrepancy, Tamara Bogdanović, Chris Reynolds, and I suggested that as the black holes spiral their way through the gas in the center of the merged galaxy, torques from the gas align the spin vectors of the holes with each other and with their mutual orbital axis. This reduces the kicks to manageable values < 200 km s^{-1}. We'll see how this holds up against future observations.

In any case, it's an exciting time for black holes. They now appear to have major effects on galaxy or cluster scale, so even on the grand stage of cosmology black holes have an important role!

Intuition Builder

A galaxy such as the Milky Way might have $> 10^8$ stellar-mass black holes, of average mass $\sim 10\,M_\odot$. In comparison, our SMBH has a mass of about $3.5 \times 10^6\,M_\odot$, so the total mass in black holes is overwhelmingly dominated by the little guys. Why, then, aren't we thinking in terms of the effect the host of stellar-mass black holes has on galaxies?