Black Holes in Galaxies

1. Basics

Astronomical evidence now suggests that every galaxy in the Universe with a mass $M \sim M_*$ hosts a supermassive ($\sim 10^7$–10^{10} $M_\odot$) black hole at its center. While early evidence for the existence of such black holes originally came in the 1960s through their manifestation as extremely luminous quasars, nowadays there is direct evidence for extremely massive objects at the centers of galaxies. There are a number of ways to estimate the masses of these black holes, using the orbital velocities of stars and gas surrounding the black hole as a function of distance. These masses correlate well with global properties of the galaxies, such as the total luminosity or velocity dispersion of the galaxies; apparently these correlations are especially good with relation to the properties of the galactic bulges.

1.1. Sphere of influence

Supermassive black hole masses are measured dynamically. However, these black holes are surrounded by the host galaxy, and therefore we need to define their *sphere of influence* within which the black hole dominates the dynamics. This region extends to the radius that the circular velocity around the black hole is comparable to the velocity dispersion of the galaxy as a whole:

$$r_{\rm infl} = \frac{GM_{\rm BH}}{\sigma^2} \tag{1}$$

1.2. The Milky Way's Black Hole

At the center of the Milky Way exists a dense stellar cluster as well as neutral, molecular and hot X-ray-emitting gas. The gas emits radio continuum emission, and there exists a very compact radio source known as Sgr A$*$. VLBI observations have constrained its size to be roughly a few light-minutes. Sgr A$*$ is the location of a massive ($\sim 4 \times 10^6$ $M_\odot$) black hole. The study of this black hole and its environment is reviewed by Genzel et al. (2010).

The first spectroscopic observations of individual stars in the central region were in the 1990s, with near-infrared speckle imaging and (later) adaptive optics based imaging and spectroscopy that definitively characterized the central black hole through study of individual orbits. The population of stars within 1 arcsec (or about 0.04 pc) consists primarily of a cluster of old stars (> 1 Gyr) with apparently random orbits, and a much smaller group of young massive stars that appear to be mostly in one disk, with a second distinct disk possibly existing. The orbital times are 10s of years.

1.3. Stellar dynamics signatures

For other galaxies the observations are less detailed. High resolution imaging and spectroscopy from space have allowed central stellar velocity dispersion and rotation maps of galaxies within a fraction of an arcsec (10s of pc for galaxies within 10 Mpc or so). These observations, showing central spikes in velocity dispersion point to the common existence of central point masses that we associate with black holes (e.g. Kormendy et al. 1996).

1.4. Gas dynamic signatures

Ionized gas dynamics near the centers of galaxies also reveal rapid rotation near the galactic centers for some of these galaxies. For example, M87 shows these signatures.

In some cases, the gas near the centers of the galaxies are *masers* (the microwave versions of *lasers*). Continuum radio emission from the central AGN provides the pumping mechanism. In at least one case (NGC 4258), the masing gas is in a convenient disk-like geometry that allows its angular and Doppler rotational velocity to be measured, allowing measurement of the mass and distance to the black hole.

1.5. Reverberation mapping

Reverberation mapping provides a third measurement of black hole mass. In this case we measure the continuum and line emission of quasars over time. The continuum varies over week-to-month long time scales. The broad line emission is powered by the continuum but with a delay of months (depending on the line, since different ionization stages have different ionization energies) because of the size of the broad line emitting region. Measurement of the delay determines the size of the region emitting for any given line, and the Doppler width of the line then allows the use of the virial theorem to determine the mass. A dimensionless factor associated with the geometry still must be determined.

1.6. M–σ relation

Measurements of the black hole masses can be correlated with the galaxy stellar mass and other properties. $M_{\rm BH}$ and the stellar mass are generally correlated, with a fair amount of scatter and a typical black hole to stellar mass ratio of a few tenths of a percent. A smaller scatter is obtained between $M_{\rm BH}$ as measured by central stellar dynamics and the bulge velocity dispersion (the center of the galaxy, but outside the black holes sphere of influence; Ferrarese & Merritt 2000; Tremaine et al. 2002). There is some evidence that maser-based black hole mass measurements, which can probe smaller spheres of influence, find a smaller mass population of black holes; this finding raises the possibility that some of the correlation with velocity dispersion is a selection effect (Greene et al. 2016).

2. Commentary

The significance of the M-σ relation is unclear. It is not particularly surprising that the black hole mass correlates with the galaxy mass, because with with its central location the black hole can grow as a result of the accretion and merging processes that also drive the galaxy growth. However, the specific scaling of the black hole mass must tell us something about how these processes are linked. Furthermore, the improved correlation with bulge properties may indicate that the black hole growth is related mostly to the processes that grow the bulge specifically.

3. Key References

- *Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies, Kormendy & Ho (2013)*

Gunn et al. (2006)

4. Order-of-magnitude Exercises

1. Calculate the sizes of the spheres of influence for
2. Ionization energies of BLR lines

5. Analytic Exercises

1. Sphere of influence

6. Numerics and Data Exercises

1. Effect of resolution on central velocity dispersion measurements

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