Lec 29: 05/02/2012

Supermassive Black Holes (Cont'd):

Nearby objects:

Not all members of the AGN class are necessarily very powerful or very distant. The energy requirements of more abundant low-luminosity objects are less demanding, and long jets or apparent superluminal motion are seen less frequently or not at all. The evidence for a supermassive black hole is even stronger in these systems due to their proximity. We can study them at a level of detail we cannot even hope to achieve with the others. We will begin with the galactic center.

The material within several parsecs of the nucleus shines (in the radio) as a three-armed spiral consisting of highly ionized gas radiating a thermal continuum. Each arm is ~ 3 lyr long. At a distance of 3 lyr from the center, the plasma moves at a velocity about 105 km s^{-1}, requiring a mass concentration of $\sim 3.5 \times 10^6 M_\odot$. The hub of the gas spiral corresponds to the very bright pointlike radio source known as Sagittarius A^*, which defines the dynamical center of our galaxy.

X-ray emission has been observed in our galaxy on all scales, from structure extending over kiloparsecs down to a fraction of a light year, with contributions from thermal and non-thermal, pointlike and diffuse sources. The high spatial resolution of the Chandra X-ray observatory allows for a spearation of the discrete sources from the diffuse X-ray components pervading the galactic center. A fit to the X-ray emission, assuming optically thin bremsstrahung, yields the total inferred mass of $M_{gas} > 0.1 M_\odot$ for the emitting gas near Sgr A^*. The hot plasma within a few parsecs of Sgr A^* appears to be injected into the interstellar medium via stellar winds, and the diffuse X-ray emission provides an excellent probe of the gas dynamics near the black hole.

There is ample observational evidence for the existence of strong outflows in and around the nucleus (obtained via the measurement of emission line Doppler shifts). It reveals the presence of 500 - 1000 km s^{-1} winds and number densities $\sim 10^{3-4}$ cm^{-3} near the mass ejecting stars. The implied total mass injection rate into the galaxy's central region is $\sim (3-4) \times 10^{-3}$ $M_\odot$ yr^{-1}.

This helps us understand the low average accretion rate ($\sim 10^{-2}$ $M_\odot$ yr^{-1}) onto black holes at $z \simeq 0$. If the medium surrounding the central black hole contains little gas, then the accretion cannot grow at rates like those seen at high redshifts.

Comprehensive numerical simulations of wind-wind interactions indicate creation of a complex configuration of shocks that efficiently convert the kinetic energy of the outflows into internal energy of the gas. The resulting bremsstrahlung emission produces the entire diffuse X-ray flux detected from the region near Sgr A* by Chandra. It turns out that the outflows bring the environment near the black hole into steady state within ~4000 yrs yea

What we are seeing at the center of our galaxy may be quite typical of nearby galactic nuclei in which the gas content of the central medium has been largely depleted due to black hole accretion and star formation.

The **material** accreting onto a supermassive black hole from its environment carries a variable angular momentum, which at times may even cancel some of the angular momentum already in the disk. Accretion in such a case is initiated by the stochastic infall of gaseous clumps whose specific angular momentum is sufficiently small to allow them to circularize within the black hole's gravitational sphere of influence. Indeed, several observational lines of evidence suggest that the dynamically most interesting region of the accretion flow is restricted to the inner $\sim 20 r_s$. We know this in part because of remarkable observations by Chandra, which shows a significant transient change in the system's physical state as compared with its quiescent emission. The observed short timescale for the variation ($\sim$40 min), together with the light travel time arguments, delimits the emitting region to a size $\sim$5 AU.

The shortest observed period ($\sim$17 min) in the light curve of the X-ray flare corresponds to the angular frequency in an orbit close to the last stable orbit $r \sim 3 r_s$. Since the inner edge of the accretion disk is unlikely to be truncated cleanly, one might be able to explain the observed modulation in the light curve by this argument.

Finally, it was quite surprising that the air Cerenkov telescopes detected a significant source of TeV radiation coming from the direction of Sgr A^*. It is too early to tell whether this TeV source should really be identified with the Sgr A^* itself. There is no obvious mechanism by which the black hole could radiate in this energy range. One possibility is that the most energetic particles that are present within $\sim 20 r_s$ of the central object could scape into the surrounding medium and initiate a series of interactions with the ambient plasma. The protons undergo a series of interactions as they diffuse through the interstellar gas and produce new particles. The most notable is the neutral pion, which decays into a pair of photons, which inherit most of the energy transferred to them from the parent particles.

Several other nearby galactic nuclei also have much to offer in terms of providing a picture of the physical processes taking place near a supermassive black hole. At a distance of 780 kpc, the black hole known as $M31^*$ at the nucleus of the Andromeda galaxy is the nearest along Sgr A^*. The nucleus of the Andromeda comprises a central dark-matter distribution and three concentrations of starlight. Two of these have been known for many years. Recent observations with the Hubble Space Telescope have confirmed the existence of a third stellar component. This latter one contain stars with the highest average circular rotation velocity measured so far in any galaxy ($\sim 1{,}700\ \mathrm{km\,s^{-1}}$). This implies a mass $\gtrsim 10^8 M_\odot$ for the central object. By using the X-ray emission, and assuming optically thin bremsstrahlung radiation, one can estimate the temperature and density of the gas, thus the sound speed c_s, near the supermassive black hole. One can then calculate (in the Bondi-Hoyle scenario) the accretion radius to be $r_{acc} \sim 3,4$ pc.

Under optimal conditions for converting accreting mass into radiant energy, we could expect ~10% efficiency. This results in a maximum luminosity of $\sim 3 \times 10^{40}$ erg s^{-1} from M31*, whereas the measured X-ray power is about 5 orders of magnitude smaller.

This is not unique to M31*, rather it is a common trait among all the nearby weak nuclei(including Sgr A*). It is an open question that why the quantity of gas captured at r_{acc} does not provide an accurate indication of its emissivity. The possibilities are that either $\dot{M}$ changes with radius, so that much of the captured matter scapes or is ejected before reaching the region where X-rays are produced, or the radiative efficiency of the plasma is very low.

The nucleus of M87 provides another illustration of a weak AGN, but its mass is significantly larger than both Sgr A* and M31*. This giant elliptical galaxy contains a black hole of mass $M \sim 3 \times 10^9 M_\odot$. The estimated Bondi-Hoyle accretion radius is $r_{acc} \sim 5 \times 10^5 r_s \sim 20$ AU in this case. The corresponding accretion rate is $\dot{M} \simeq 0.1 M_\odot \, yr^{-1}$, which translates into a maximal luminosity of $\sim 5 \times 10^{44}$ erg s^{-1} (assuming a standard 10% efficiency). On the other hand, the implied X-ray power of the central point source is $\sim 7 \times 10^{40}$ erg s^{-1}, which is about four orders of magnitude less than theoretical prediction. However, in the case of M87*, there is a one-sided jet. Most of the radiation in such relativistic outflows appears to be produced by incoherent synchrotron and synchrotronself-Compton emission (in the radio and X-rays respectively). It is straightforward to estimate from the measured luminosity the kinetic power **needed** to sustain the observed radiative output over its full extent. For M 87*, it is $\sim 10^{44}$ erg s^{-1}, which implies the Bondi-Hoyle accretion **ra**te matches the overall energetics.

One can wonder whether this outflow of power may itself provide feed back to the interstellar medium, possibl**y** heating it and altering the mass capture rate. We note that an **in**crease in the medium temperature will result in decrease in r_{acc}, thus reducing $\dot{M}$.

It is also interesting to note that this may also explain the observed correlation between the muss of the supermassive black hole and the velocity dispersion of the stars in the host galaxy.