Astronomy 401/Physics 903
Lecture 16
Active Galaxies II

1 Accretion by supermassive black holes, continued

1.1 The Eddington Limit

We can't get an arbitrarily high luminosity from accretion because eventually the gas surrounding the black hole will be blown away by radiation pressure. This leads to a maximum luminosity for accreting black holes.

At a distance r from the AGN, the photons have an energy flux

$$F = \frac{L}{4\pi r^2}. \tag{1}$$

The photons also have momentum $p = E/c$ and momentum flux

$$F_p = \frac{F}{c} = \frac{1}{c}\frac{L}{4\pi r^2}. \tag{2}$$

The photons can transfer momentum to particles in the ionized gas surrounding the black hole. The force exerted on a particle is the rate at which momentum is transferred to it, and the rate of momentum transfer depends on the particle's cross-section for interaction with photons. Electrons have a much larger cross-section for interaction than protons (because $\sigma \propto m^{-2}$), and the relevant cross-section is the Thomson cross-section

$$\sigma_e = \frac{8\pi}{c}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 = 6.65 \times 10^{-29}\ \mathrm{m}^2. \tag{3}$$

The force transferred is the product of the momentum flux and the cross-section:

$$f_{\rm rad} = \sigma_e F_p = \frac{\sigma_e L}{4\pi c r^2}. \tag{4}$$

As each electron is accelerated, it drags a proton along with it. The gravity of the black hole provides the inward force on the proton-electron pair

$$f_{\rm grav} = -\frac{GM_{\rm bh}(m_p + m_e)}{r^2} \simeq -\frac{GM_{\rm bh} m_p}{r^2} \tag{5}$$

since $m_p \gg m_e$.

The maximum possible luminosity (the **Eddington luminosity** or **Eddington limit**) of the black hole is the luminosity at which the radiation pressure balances the gravitational force:

$$\frac{\sigma_e L_E}{4\pi c r^2} = \frac{GM_{\rm bh} m_p}{r^2} \tag{6}$$

The Eddington luminosity for a black hole of mass is

$$L_E = \frac{4\pi G m_p c}{\sigma_e} M_{\rm bh} = 1.3 \times 10^{39}\ \mathrm{W}\left(\frac{M_{\rm bh}}{10^8\ \mathrm{M}_\odot}\right) \tag{7}$$

$$= 3.3 \times 10^{12}\ \mathrm{L}_\odot\left(\frac{M_{\rm bh}}{10^8\ \mathrm{M}_\odot}\right) \tag{8}$$

This leads to a maximum accretion rate for black holes,

$$\dot{M}_E = \frac{L_E}{\eta c^2} = 2\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{M_{\mathrm{bh}}}{10^8\ \mathrm{M}_\odot}\right) \left(\frac{\eta}{0.1}\right)^{-1}. \tag{9}$$

It's sometimes useful to express the accretion rate in terms of the Eddington rate,

$$\dot{m} = \frac{\dot{M}}{\dot{M}_E}. \tag{10}$$

This is the **Eddington ratio**.

1.2 Accretion disks

Accreting matter can't go directly into the black hole because it has angular momentum. General consensus is that the black hole is surrounded by an accretion disk in which matter slowly spirals inward. Viscosity (internal friction) causes the matter to lose its angular momentum and converts kinetic energy into random thermal motion. This heats the accretion disk to temperatures of 10^5 K.

The spectrum of a blackbody with $T \sim 10^5$ K peaks in the UV, and the blue bump in the SED of AGN is probably thermal emission from the accretion disk.

2 The AGN unification model

The AGN zoo of Seyfert galaxies, radio galaxies, QSOs and BL Lac objects seems complicated, with variations in morphologies and spectra. However, most of the properties of various types of AGN can be explained by a unified model in which the structure of AGN is flattened, not spherical, and the strength of various components depends strongly on the angle of the AGN axis relative to our line of sight.

Review of the major components of an AGN, starting at the center:

- **Supermassive black hole**. Suspected for many years based on arguments of energetics and time variability, more recent evidence from high speed motions of stars and gas in galactic nuclei. The Schwarzchild radius of a $10^8\ \mathrm{M}_\odot$ black hole is $\sim 3 \times 10^{11}$ m ~ 2 AU.
- **Accretion disk**. Surrounds the black hole, responsible for the UV and visible continuum emission of AGN. For a $10^8\ \mathrm{M}_\odot$ black hole, the UV and visible emission arises on a scale of 10^{12}–10^{13} m (from considerations of gravitational potential energy being converted into heat in the disk). X-rays apparently produced in a hot corona surrounding the accretion disk.
- **Jets**. Ionized gas is ripped from the accretion disk by electromagnetic fields, and spirals along magnetic field lines away from the disk, producing a jet. Accelerated electrons in the ionized gas emit synchrotron radiation, accounting for the radio emission from the jet.
- **Broad-line region**. Size is measured by timing the delay between flux variations in the UV and visible continuum and the response of the emission lines. The delay is due to the light travel time across the broad line region. This is called **reverberation mapping**. The size of the broad-line region scales with luminosity:

  $$\left(\frac{R_{\mathrm{BLR}}}{10^{15}\ \mathrm{m}}\right) \approx 0.26 \left(\frac{L_{\mathrm{bol}}}{10^{37}\ \mathrm{W}}\right)^{1/2} \tag{11}$$

  The broad-line region may be the outer edge of the accretion disk.

- **Obscuring torus**. Outer edge of the broad-line region is defined by the **dust sublimation radius**, the closest point to the continuum source (i.e. the accretion disk) where dust grains can survive the UV radiation. At smaller radii, where equilibrium blackbody temperature exceeds ~ 1500 K, dust is vaporized. Dust is important because it provides the opacity that blocks our direct view of the inner regions from some directions. The dust sublimation radius is the inner edge of a dusty structure with a larger scale height than the inner regions—this is the obscuring torus or dusty torus (this may actually be a cool, dense wind arising from the accretion disk).
- **Narrow-line region**. At about the same radius as the obscuring torus, but can extend out to hundreds of pc along the jets. Morphology is often wedge-shaped or conical, and along the axis of the black hole/accretion disk system. Seems to be the interstellar medium of the host galaxy: interstellar gas that isn't shielded from the central source by the obscuring torus is photoionized by the UV radiation from the AGN.

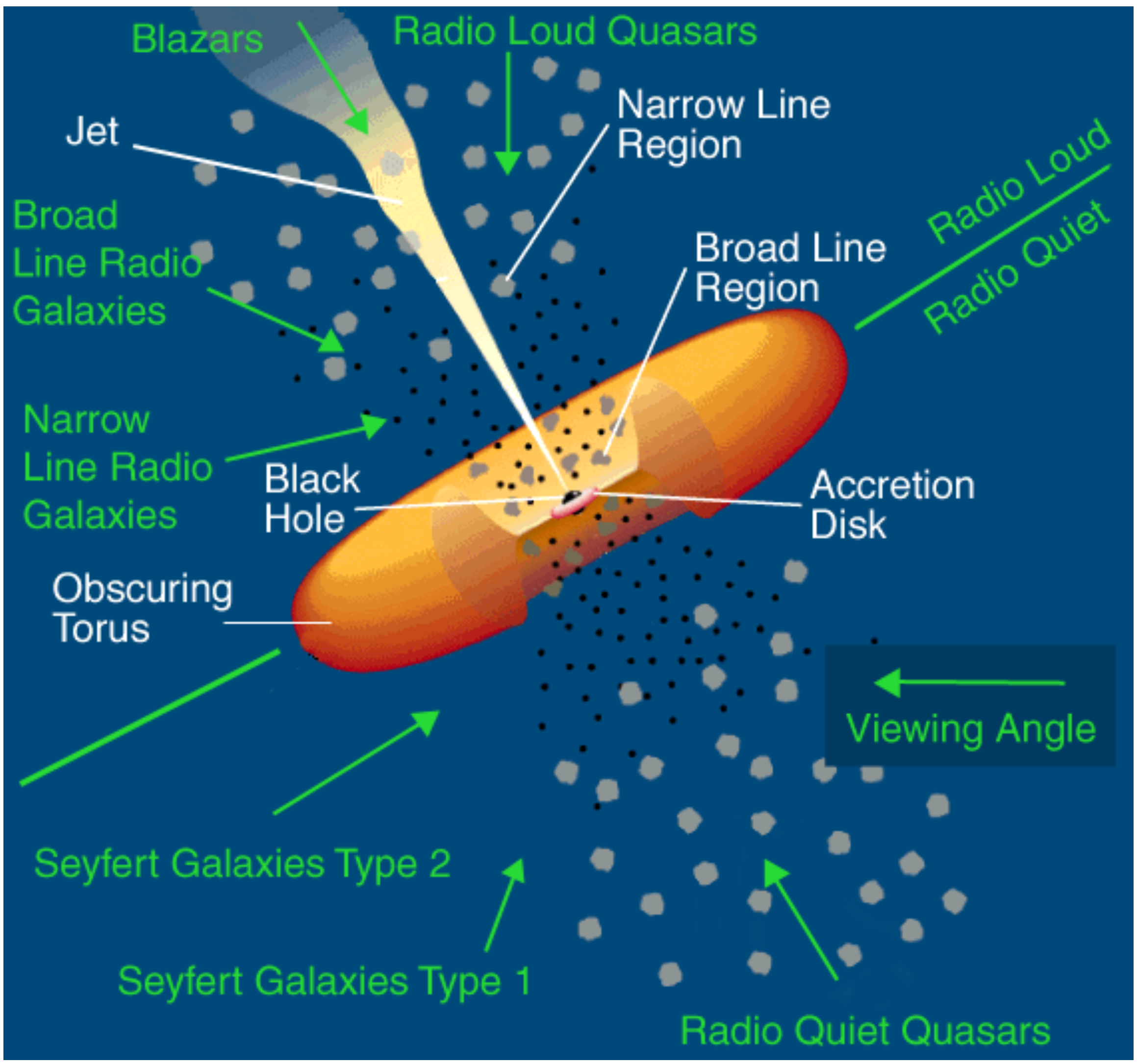

Figure 1: Components of the AGN unification model and dependence on viewing angle. Top half is for radio loud objects, bottom half for radio quiet.

The type of AGN we see depends on the orientation of the outer, dusty torus relative to the line of sight.

Looking directly along the jet, we see primarily synchrotron emission from the jet: the featureless continuum of BL Lac objects. Looking at an angle close to the jet gives a good view of the accretion disk and the broad-line region, so the AGN is classified as a Seyfert I. At an angle closer to the disk the broad-line region is hidden by dust and we see only the narrow-line region: Seyfert II. For strong radio sources, a quasar is seen from an angle near the jet, a blazar when looking directly along the jet, and a radio galaxy when the torus hides the active nucleus from view.

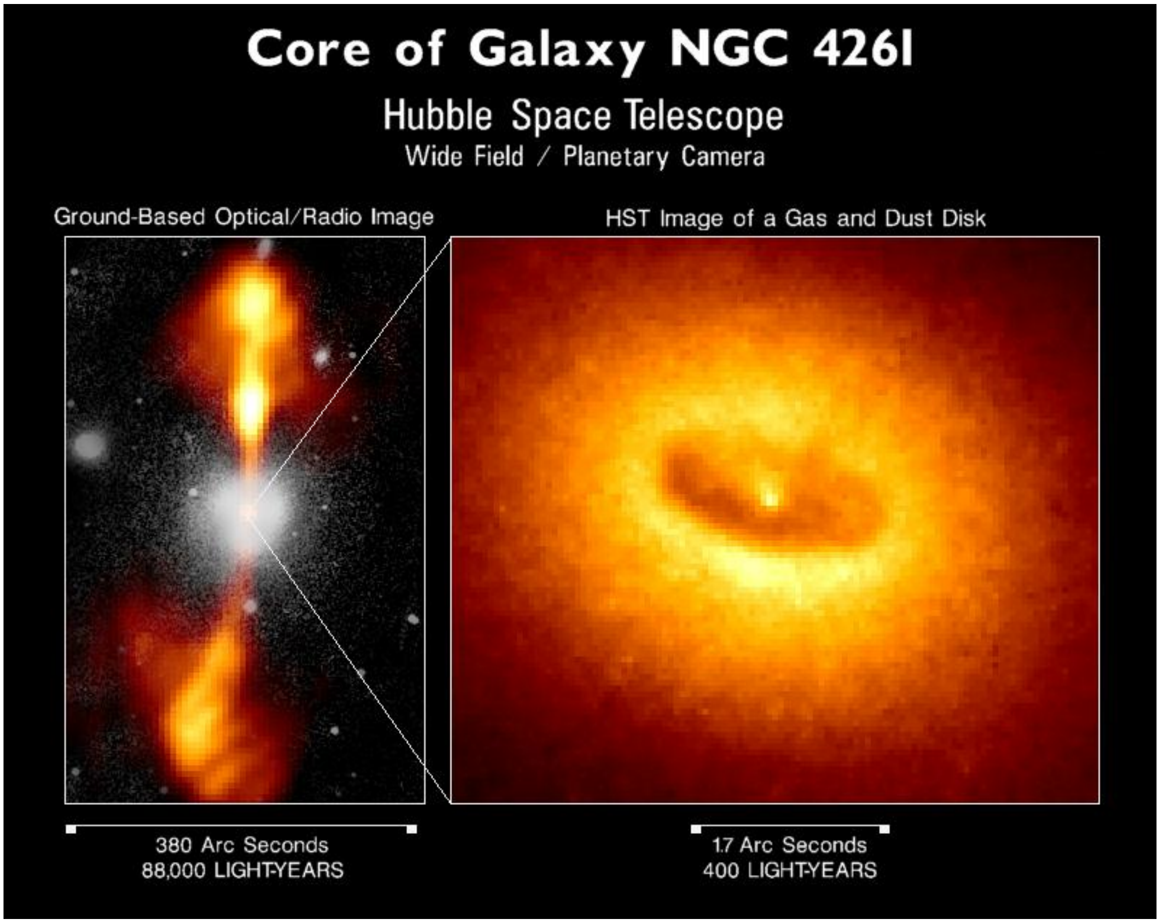

Figure 2: Two images of NGC 4261. Left: ground-based composite optical and radio image showing the jets. Right: Optical image from HST showing the dusty torus around the nucleus.

3 Quasars over cosmic history

We can tell from the masses of black holes today that quasars must have relatively short lifetimes. Most luminous quasars have $L \approx 3 \times 10^{14}\ \mathrm{L}_\odot$ and must have accretion rates $\dot{M} \approx 200\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ to maintain that luminosity. The biggest supermassive black holes today have masses $M_{\rm bh} \sim 4 \times 10^9\ \mathrm{M}_\odot$. To grow to that mass at the accretion rate of the most luminous quasars would take

$$t \approx \frac{M_{\rm bh}}{\dot{M}} \approx \frac{4 \times 10^9\ \mathrm{M}_\odot}{200\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}} \approx 20\ \mathrm{Myr}. \tag{12}$$

Not long! If quasars maintained their luminosity for a long time the black holes would be much more massive than observed.

There were more than 1000 times as many bright quasars per Mpc^3 (comoving, i.e. corrected for the expansion of the universe) at $z \sim 2$ than there are today. This appears to be an evolutionary effect caused by a decrease in quasar luminosity with time. Beyond $z \sim 3$, the density of quasars declines again.