Lecture 9 : Active galaxies (II)

1 The blackhole paradigm

The most important clue to the nature of the source of energy in AGNs is their rapid time variability. Consider an optically thick sphere of radisu r that simultaneously brightens everywhere. The news of the change reaches a distant observer first from the nearest part, and last from the farthest edge. The brightening is thus smeared out over a time interval of $\Delta t \sim r/c$. The rapidity of a luminosity change can then be used to set an upper limit on the size of the object involved. (If the source is moving relativistivally, then $\Delta t \sim r\gamma/c$.) Taking an hour to be a typical variability time scale, one gets a size of 10^{14} cm as the upper limit of the size of the source.

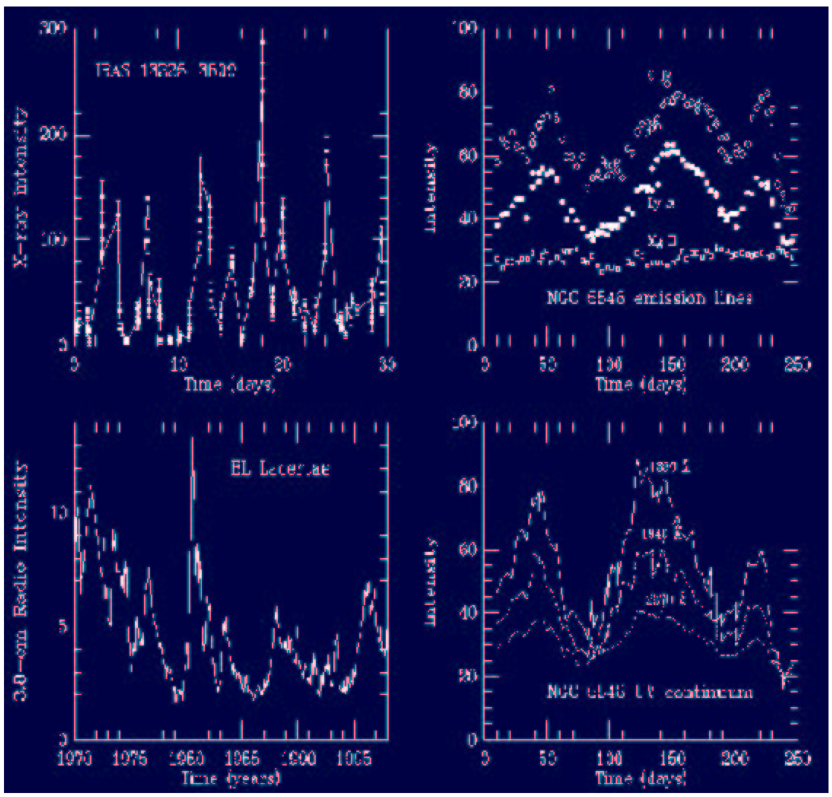

Figure 1: A sample of light curves of AGNs.

There is however an upper limit to the luminosity of any object that is in equilibrium. If the luminosity is large enough to disrupt the object itself by radiation pressure, then it is unrealistically high. Suppose the gas around the object is compsed of ionized hydrogen. The outward force due to Thomson scattering by electron, at a certain radius

r from the centre, is $\sigma_T L/4\pi r^2 c$ (momentum received by an electron per second). Electrostatic attraction between electrons and protons are strong so that the electrons cannot be pushed outward without also moving the protons. Equating this to the gravitational force on a proton at the same radius, which is GMm_p/r^2, where M is the central mass, one gets a limiting luminosity, called the **Eddington luminosity**, of

$$L_E = \frac{4\pi GMm_p c}{\sigma_T} \sim 1.3\times10^{38}\frac{M}{M_\odot}\,\text{erg/s} \sim 30000\times\frac{M}{M_\odot}L_\odot. \tag{1}$$

Stars like Sun therefore shine nowhere near the Eddington luminosity, although some supergiants come close to it. If we use a typical quasar luminosity of 5×10^{46} erg/s, we get a lower limit to the mass of the central source to be of order $\sim 3.3\times10^8$ $M_\odot$.

Such a large mass tucked inside a small lengthscale as derived above is actually a clear evidence for a black hole. In fact the Schwarzschild radius of a black hole of mass 3×10^7 $M_\odot$ is approx 10^{14} cm.

It is very efficient to generate energy by the release of gravitational potential energy through accretion of mass. Suppose mass is falling onto an object of mass M and radius R. The kinetic energy at any point is then matched by its potential energy, $(1/2)mv_{ff}^2 = GMm/r$. When the mass finally hits the surface, its KE is released as heat. For an accretion rate of $\dot{m}$, the KE is turned into heat at a rate $(1/2)\dot{m}v_{ff}^2$,and the luminosity is

$$L = \frac{GM}{R}\dot{m} = \frac{GM}{Rc^2}\dot{m}c^2\,, \tag{2}$$

where the factor GM/Rc^2 denotes the efficiency of conversion of rest mass energy into luminosity. For a white dwarf the efficiency is of order 10^{-4}, for a neutron star it is of order 0.1. For a black hole of course there is no hard surface and an observer at infinity finds the matter slow to a halt and disappear at the Schwarzschild radius R_s. In general, however, the infalling mater will always possess a certain amount of angular momentum and this will prevent it from falling directly onto the black hole. The matter will instead form a disk, in quasi-rotational equilibrium around the central mass, and in which viscous forces will take away the angular momentum of the matter slowly, allowing it to spiral down inward. The matter can release energy as it slowly spirals inward through the accretion disk. For a non-rotating black hole the smallest stable circular orbit for a massive particle is at $3R_s$, where the gravitational binding energy is $0.057mc^2$, so mass spiraling down would release this much energy. For the most rotating black hole the smallest stable radius and the event horizon is at $0.5R_s$ with a gravitational binding energy of $0.42mc^2$. So the efficiency of accretion luminosity is of order $\eta\sim0.1$. This is much larger than the efficiency of thermonuclear reactions which is of order 0.007.

It is therefore believed that an accretion disk around a supermassive black hole is the central engine for AGNs.

If we assume that the accretion process emits radiation at the Eddington rate, then we can get an idea of the accretion rate required for AGNs. One has,

$$\dot{m}_{Edd} \sim L_{Edd}/\eta c^2 \sim 2.2(M_{BH}/10^8 M_\odot)(0.1/\eta)\frac{M_\odot}{yr}\,, \tag{3}$$

Therefore (1) supermassive black holes require only about a solar mass per year to produce the required luminosity, and (2) they can grow fairly fast, by an order of magnitude per Gyr. One can ask if this growth rate is enough to explain the existence of quasars in the early universe.

2 Observational support for accretion disk around SMBH

An indirect support comes from the fact that AGNs have UV excess, which is supposed to be from the disk. If we say that a shell in a thin (and time steady) disk at radius r of thickness r emits as a blackbody, then we can get,

$$2(2\pi r)\sigma T^4 dr = \frac{d}{dr}\left(-\frac{GM\dot{m}}{2r}\right) = \frac{GM\dot{m}}{2r^2} dr\,, \tag{4}$$

since the total energy per unit mass is (KE+PE) is $-GM/2r$. This gives a temperature of the disk as,

$$T = \left(\frac{GM\dot{m}}{8\pi\sigma r^3}\right)^{1/4} = \left(\frac{3c^6\dot{m}}{8\pi\sigma G^2 M^2}\right)^{1/4}, \tag{5}$$

where the second equality is obtained for the inner edge of a maximally rotating black hole, with $r = 0.5R_s = GM/c^2$. Now, for a disk that is Eddington luminous, we have $L_{disc} = \eta\dot{m}c^2 = \frac{4\pi GcMm_p}{\sigma_T}$, implying,

$$T_{disk} = \left(\frac{3c^5 m_p}{2\sigma\sigma_T GM\eta}\right)^{1/4}. \tag{6}$$

For the typical mass inflow rate derived above, one then gets a typical temperature of the disk of few $\times 10^5$ K, which radiates in UV.

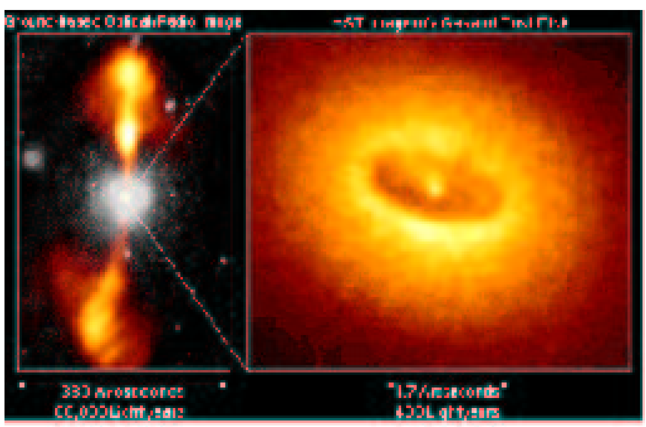

Figure 2: The dynamics of the central region of NGC4261, as imaged by HST, suggests the presence of a supermassive blackhole.

A more direct evidence comes from the HST observation of a rotating gaseous disk, on the scale of 20 pc, around the nucleus of a few galaxies like M87.

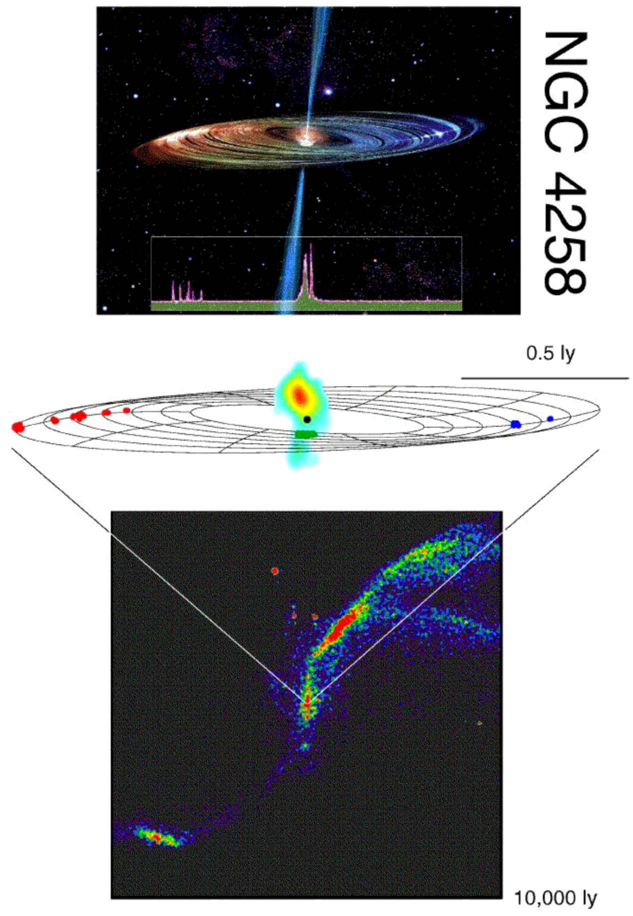

Figure 3: Observations of masers in the central region of NGC 4258

A very definitive evidence is provided by the discovery of megamasers, which are located in a disk around the nucleus of the mildly active galaxy, NGC4258. Keplerian orbits were confirmed VLBI observations (Greenhill et al 1995). Based on the correlation bewteen the spatial locations and the radial velocities of the masers, it was inferred that the masers are located at distances ~ 0.15 pc around a black hole of mass 3.5×10^7 solar mass.

3 Broad line region of quasars

We have seen that a characteristic feature of Seyfert 1 and quasar spectra is the presence of broad emission lines from a wide range of ions. Some of these lines, such as the Balmer lines of Hydrogen and lines of singly ionized species such as MgII, can be excited by ultraviolet photons (they are also seen in HII regions). Other lines, such as the Lyman series of hydrogen, or from ionized species such as N[V] or O[VI] require higher energies. The standard basic model for these lines supposes that these species are photoionized by radiation from the nucleus. One visualizes the **broad line region (BLR)** as being composed of dense clouds with $n_H \geq 10^{10}$ atoms cm^{-3} (from the absence of broad forbidden lines). One finds continuum radiation with $\lambda < 912\mathring{A}$ so that the filling factor of these clouds must be small (of order 10^{-6}). The emission lines we detect are the sum of Doppler shifted components from many individual clouds in the BLR. As the continuum radiation varies with time, so do the broad emission lines. The high-ionization lines follow the continuum with a delay of a few days, whereas those of low-ionization species respond later, showing that they originate further from the nucleus.

The narrow emission lines, which are seen in all Seyferts, come from forbidden transitions, which are seen only when the density $n_H \leq 10^8$ atoms cm^{-3}. These lines have not been observed to vary as the nucleus brightens, which means that they are situated further away. This is referred to as the **narrow line region (NLR)**.

The standard BLR models of course has many problems. For example, some high ionization lines are stronger than predicted; some objects show too strong FeII lines than can be explained, and so on.