Astronomy 401/Physics 903
Lecture 15
Active Galaxies I

A few percent of galaxies are peculiar in that they produce huge amounts of energy in excess of the normal stellar light. These are called **active galaxies** or **AGN (Active Galactic Nuclei)**.

Distinctive characteristics of active galaxies:

- Large amounts of nonstellar emission, some of it nonthermal in origin. Active galaxies produce more X-ray and radio emission than would be produced by their stars.
- Much of the light is concentrated in a small, central region called an active galactic nucleus, AGN
- Light from AGNs is variable on short timescales, at virtually all wavelengths. Timescale for variability depends on luminosity and wavelength, with most rapid variability seen at short wavelengths and low luminosities. X-rays in low luminosity AGNs can vary on timescales of minutes
- Some active galaxies have jets detectable at X-ray, visible and radio wavelengths. The jets contain ionized gas flowing outward at relativistic speeds
- The UV, visible and IR spectra of AGNs are dominated by strong emission lines

Not all active galaxies have all of these features.

Accumulated evidence indicates that the activity in AGN comes from accretion onto massive black holes. Most bright galaxies have black holes in their centers, but not all bright galaxies are active galaxies. To be an active galaxy, the central black hole must be accreting gas rapidly enough to produce luminosity as bright or brighter than the galaxy's stars. We will start by discussing the different types of active galaxies. The situation initially seems very complicated, but we'll see that most of the observations can be explained by a unifying scenario.

1 Types of Active Galaxies

1.1 Seyfert galaxies

History: galaxies with broad (500–5000 km s^{-1}) emission lines discovered by Carl Seyfert in 1943

Properties:

- Emission lines come from center of galaxies
- $\sim 0.5\%$ of galaxies are Seyfert galaxies
- $\gtrsim 95\%$ of Seyferts are spirals
- In addition to broad emission lines, center often has a power law ($F_\nu \propto \nu^{-\alpha}$) continuum excess of light, giving Seyferts their blue color compared to normal galaxies
  - Power law continuum is non-thermal in origin—not emitted by stars. $F_\nu \propto \nu^{-\alpha}$: α is **spectral index**, ν is frequency

Aside: Emission lines are divided into **permitted** and **forbidden** lines.

Permitted lines have high transition probabilities. Common examples are the Balmer lines, Hα, Hβ, etc.

Forbidden lines have lower transition probabilities and occur in low density regions. Because of the lower transition probability, an excited electron will be collisionally de-excited before it can emit a photon if the density is too high. Forbidden lines are indicated by square brackets: [O III], [N II], etc.

Two types of Seyfert galaxies

- Seyfert I (Sy I)
  - very broad permitted lines (1000–5000 km s^{-1})
  - narrower forbidden lines (~ 500 km s^{-1})
  - often X-ray luminous
- Seyfert II (Sy II)
  - permitted and forbidden lines both relatively narrow (~ 500 km s^{-1})

1.2 Radio galaxies

History: sky studied at radio wavelengths after WWII

- 1946: discovery of discrete radio source Cygnus A—poor resolution, no optical counterpart found
- 1949: positions to 10 arcmin achieved (still not very good!). M87 and NGC5128 found to be associated with double radio sources
- 1951: optical counterpart to Cygnus A found to be peculiar galaxy at $z = 0.06$ (~ 240 Mpc! the only brighter radio sources are the Sun and the nearby (3 kpc) supernova remnant Cas A)
  - Cyg A is $\gtrsim 10^6$ times more powerful at radio wavelengths than the Milky Way
- 1953: Cyg A resolved as double radio source

Properties:

- Usually elliptical
- Non-thermal power law spectrum in radio
- Optical spectra of nucleus similar to Seyferts. Distinguish broad line radio galaxies (BLRGs) and narrow line radio galaxies (NLRGs).
- ~ 100 times less abundant than Seyfert galaxies
- May have extended jets and lobes

1.3 QSOs (Quasi-Stellar Objects)

History:

- 1960: 3C 48 (#48 in the Third Cambridge catalog of radio sources) identified with star-like object (quasi-stellar). Thought to be a star, but spectrum very weird
- 1963: Maarten Schmidt recognizes the spectrum of another "radio star" (3C 273) as Balmer lines redshifted to $z = 0.158$. Then 3C 48's spectrum understood as redshifted to $z = 0.367$ (these objects weren't expected to be so far away because they are so bright)

Properties:

- Most QSOs radio quiet
- Look like stars. Some have optical jets, and some are the very bright nuclei of fuzzy-looking host galaxies
- Blue. UV excess called the "blue bump"
- Optical fluxes often variable on timescales of years
- Broad emission lines resemble Seyfert I galaxies
- Almost always strong X-ray emitters
- Bright! can be detected to high redshifts
- Radio-quiet QSOs found by looking for extremely blue stars. Followup spectroscopy needed for confirmation

2 Variability and physical size

Flux from AGN can vary significantly on very short timescales (except for Sy IIs and NLRGs)

- Luminosity of broad lines and continuum can vary by a factor of ~ 2 on day to month timescales
- Variations in broad emission lines typically lag behind those of continuum by ~ 1 month
- Variations of a few percent in visible, X-rays. X-ray flux can vary on timescales of minutes

AGN with rapid time variability are often called **BL Lac objects** (after prototype BL Lacertae) or **blazars**. Changes in flux can be up to $\sim$30% in a day, up to $\sim$100% over longer periods. Nearly devoid of emission lines (continuum dominates flux)

The timescale of variability puts limits on the size of the source. A source with size R will take a time of at least $\Delta t = R/c$ to change its luminosity, since information can't travel from one side of the source to the other faster than c. If we observe $\Delta t = 1$ hour,

$$R \simeq c\Delta t = 7.2 \text{ AU}. \tag{1}$$

This is very small for something so energetic!

3 Accretion by supermassive black holes

3.1 Energetics

The release of gravitational potential energy through mass accretion is a very efficient way to generate energy. Consider a mass m falling a large distance $r \gg r_{\rm Sch}$ toward the Schwarzchild radius of a black hole. Recall

$$r_{\rm Sch} = \frac{2GM_{\rm bh}}{c^2}. \tag{2}$$

The loss of gravitational potential energy will be

$$\Delta E = -\frac{GM_{\rm bh}m}{r} + \frac{GM_{\rm bh}m}{r_{\rm Sch}} \approx \frac{GM_{\rm bh}m}{r_{\rm Sch}} \approx \frac{1}{2}mc^2. \tag{3}$$

If the mass doesn't stop before it reaches the Schwarzchild radius it will pass the event horizon with speed $v \sim c/\sqrt{2}$, and its kinetic energy will increase the mass of the black hole. If instead it's decelerated by an accretion disk, its kinetic energy will be converted into thermal energy and then radiation. This process isn't perfectly efficient, and we write the energy carried away by photons as

$$\Delta E_{\rm phot} = \eta mc^2 \tag{4}$$

where η is a dimensionless number called the efficiency of the black hole. We expect $\eta \leq 1/2$ from Equation 3 above. In practice, we think $\eta \approx 0.1$, which means that a gram of matter falling toward the black hole gives 9 trillion joules of radiation energy (!).

As gas falls into the black hole at rate $\dot{M}$, the **accretion luminosity** of the AGN is

$$L = \eta \dot{M} c^2. \tag{5}$$

We can therefore estimate an AGN's accretion rate $\dot{M}$ from its luminosity:

$$\dot{M} = \frac{L}{\eta c^2} = 0.018\ {\rm M_\odot\ yr^{-1}} \left(\frac{L}{10^{37}\ {\rm W}}\right)\left(\frac{\eta}{0.1}\right)^{-1}. \tag{6}$$

We don't expect $\dot{M}$ to be constant with time, which probably accounts for some of the variability of AGN.

4 Accretion by supermassive black holes

4.1 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

$$F = \frac{L}{4\pi r^2}. \tag{7}$$

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

$$F_p = \frac{F}{c} = \frac{1}{c}\frac{L}{4\pi r^2}. \tag{8}$$

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

$$\sigma_e = \frac{8\pi}{c}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 = 6.65 \times 10^{-29}\ \mathrm{m}^2. \tag{9}$$

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

$$f_{\mathrm{rad}} = \sigma_e F_p = \frac{\sigma_e L}{4\pi c r^2}. \tag{10}$$

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

$$f_{\mathrm{grav}} = -\frac{G M_{\mathrm{bh}}(m_p + m_e)}{r^2} \simeq -\frac{G M_{\mathrm{bh}} m_p}{r^2} \tag{11}$$

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:

$$\frac{\sigma_e L_E}{4\pi c r^2} = \frac{G M_{\mathrm{bh}} m_p}{r^2} \tag{12}$$

The Eddington luminosity for a black hole of mass is

$$L_E = \frac{4\pi G m_p c}{\sigma_e} M_{\mathrm{bh}} = 1.3 \times 10^{39}\ \mathrm{W}\left(\frac{M_{\mathrm{bh}}}{10^8\ \mathrm{M}_\odot}\right) \tag{13}$$

$$= 3.3 \times 10^{12}\ \mathrm{L}_\odot\left(\frac{M_{\mathrm{bh}}}{10^8\ \mathrm{M}_\odot}\right) \tag{14}$$

This leads to a maximum accretion rate for black holes,

$$\dot{M}_E = \frac{L_E}{\eta c^2} = 2\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}\left(\frac{M_{\mathrm{bh}}}{10^8\ \mathrm{M}_\odot}\right)\left(\frac{\eta}{0.1}\right)^{-1}. \tag{15}$$

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

$$\dot{m} = \frac{\dot{M}}{\dot{M}_E}. \tag{16}$$

This is the **Eddington ratio**.

4.2 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.