Powering “Active” Galaxies

Relativity and Astrophysics
Lecture 35
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Outline

- Active Galaxies
  - Luminosities & Numbers
  - Descriptions
    - Seyfert
    - Radio
    - Quasars

- Powering AGN with Black Holes
  - What powers these things? Size limits.
  - Standard model (accretion disk around black hole)
  - Eddington Luminosity
    - Limit on luminosity depends on size of black hole
Active Galaxies

- Galaxies exist which have luminosities much greater than the Milky Way (our Galaxy).
  - In some cases more than a thousand times brighter
  - What are they? What makes them shine so brightly

<table>
<thead>
<tr>
<th>&quot;Galaxies&quot;</th>
<th>Luminosity ($L_{MW}^*$)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>&lt; 10</td>
<td></td>
</tr>
<tr>
<td>Seyfert</td>
<td>0.5 - 50</td>
<td>spiral w/ bright nucleus</td>
</tr>
<tr>
<td>Radio</td>
<td>0.5 - 50</td>
<td>radio bright elliptical</td>
</tr>
<tr>
<td>Quasar</td>
<td>100 - 5,000</td>
<td>star-like in appearance</td>
</tr>
</tbody>
</table>

*where $L_{MW} = Luminosity$ of the Milky Way $\sim 2 \times 10^{10} L_{sun}$

Rough Local Space Densities

<table>
<thead>
<tr>
<th>Object Type</th>
<th>Number/Mpc$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Galaxies</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Luminous Spirals</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Seyfert Galaxies</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Radio Galaxies</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Radio-Quiet Quasars</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Radio-Loud Quasars</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

From Osterbrock, 1989, (AGN)$^2$
Seyfert Galaxies

- 1943 – Carl Seyfert, strong nuclear emission
  - Seyfert 1 and 2 – broad vs. narrow wings on spectral lines
- Spectral lines don’t resemble normal stars.
  - Highly ionized heavy elements, e.g. iron!
  - Lines very “wide” ⇒ tremendously hot (>10^8 K) or rapidly rotating (~1000 km/s)
- Nearly all emission comes from the galactic nucleus (a small central region).
  - ~ 10^4 times brighter than the center of our galaxy
- Emitted energy varies with time!
  - ⇒ Compact source of energy
  - ⇒ Emitting region < 1 lyr across
- Most energy emitted in infrared and radio parts of the spectrum.
  - Look very much the same as normal galaxies in the visual.

Radio Galaxies

- Very bright in the radio
  - Cosmic rock stations?
- Core-Halo radio galaxies
  - Most emission from a very small core (< 1 parsec across)
- Extended (or Lobe) radio galaxies
  - Emission extends hundreds of kiloparsecs!
Core-Halo Radio Galaxies

M87

- jet
- v \approx 0.1 \text{c in jet}
- extended halo
- bright core

Optical Image

Optical Jet

HST Image
Extended Radio Galaxies

Visible Galaxy

Radio Lobe

> 200,000 pc

Cygnus A

“Original” extragalactic radio source, Cygnus A.

~120 kpc
Centaurus A (Peculiar Galaxy)

Radio emission (green)

Nearest Radio Galaxy
Quasars

- Galaxies with extremely luminous sources
  - Look like stars in photographs.
  - Some evidence of faint "parent" galaxy
- Energy originates in a very small region
  - Quasars are variable
- Can see to great distances
  - Most distant objects seen in the universe
  - Such a source at 50 pc (163 lyr) would appear as bright as the Sun!

What powers these objects?

- We need to produce up to 5000 times the luminosity of the M.W.
  - But within a region ~ 1 pc in size !!!!
  - Less than the distance between the Sun and its nearest neighbor
- Leading theory is a black hole with an accretion disk:
  - Material gains energy as it falls towards the black hole.
  - The gas heats up, and radiates energy.
Active Galaxies

Accretion disk model

- Gas falling onto disk
- Accretion disk
- Black hole
- Jets of high speed particles

Accretion Disks

Black Hole Disk Model

NGC 4261
Energetics

- Material needs to keep flowing onto the black hole to power the source.
- For 1 $M_{\text{sun}}$ / decade $\Rightarrow \sim 10 \ L_{\text{MW}}$
- For 10,000 $L_{\text{MW}} \Rightarrow 100 \ M_{\text{sun}}$ / year!!
- Large black holes ($10^8 - 10^9 \ M_{\text{sun}}$) are needed, otherwise the accretion disks blow themselves apart.

What makes AGN tick?

- Over the last decade or more, a “standard model” of AGN has developed.
- The aim of this standard model is to explain and unify the plethora of observed phenomena.
- The following slides go into more of the details of structure about the black hole and limits to the luminosity.
  - Some of this material is a bit more advanced but is within the scope of what we have already covered.

Figures that follow are from Merrifield and can be found at http://www.astro.soton.ac.uk/PH308/AGN/Seyferts.html
AGN Standard Model

- Central engine
  - Surrounded by an accretion disk powers the source
  - High energy electrons are ejected at the poles
- Broad line clouds are close to the monster
  - High Keplerian velocities give broad lines
- A dust torus surrounds the central engine, and broad line region.
- “Narrow line” clouds surround are located outside torus.

Spiral Host Galaxy

- The observed spectrum and continuum will depend on the viewing direction.

  - Seyfert 1
  - Seyfert 2
Elliptical Host Galaxy

- The observed spectrum and continuum will depend on the viewing direction.

BL Lac

Name taken from prototype thought to be a variable star in Lacerta constellation. Have a smooth continuum (lack of spectral lines)

Radio Galaxy

Mass of the Central Object

- An estimate of the mass of the central source for AGN can be made with two simple assumptions
  - Isotropy
  - Stability
- Both of these are not entirely correct but should give reasonable limits
- These arguments date back to Zel’dovich and Novikov (1964) and Salpeter (1964)
  - Much of the discussion here follow that of Peterson (1997)
  - See Krolick (1999) for a more detailed discussion
- We will use “conventional units” in the following discussion
Radiation Pressure

- Consider a parcel of gas located a distance $r$ from an central source of luminosity $L$.
- The flux from the central source (ignoring the intervening opacity) at this distance is:
  \[ F = \frac{L}{4\pi r^2} \]
- The momentum carried by a photon is $E/c$, so that the outward momentum flux (photon pressure) is:
  \[ P_{rad} = \frac{F}{c} = \frac{L}{4\pi r^2 c} \]

Force due to Radiation Pressure

- In general, the opacity of the gas will be very complicated.
- If the gas is completely ionized the opacity is due to electron scattering (the proton momentum transfer is down by $3 \times 10^6$).
  - Opacity is a measure of how much light is scattered or absorbed by a region.
- For $h\nu < \sim 100$ keV the opacity is determined by the Thomson cross-section.
  \[ \sigma_T = \frac{8\pi}{3} \left( \frac{e^2}{m_e c^2} \right)^2 = 6.65 \times 10^{-25} \text{ cm}^2 \]
- The outward force due to radiation pressure is:
  \[ F_{rad} = \sigma_T \frac{L}{4\pi r^2 c} \]

The quantity $r_e = \frac{e^2}{m_e c^2} = 2.82 \times 10^{-13}$

$m$ is the classical electron radius.

It is obtained by setting (roughly) the energy required to assemble a charged sphere with the rest mass, e.g.

\[ m_e c^2 = \frac{e^2}{r_e} \]

This does not take into account quantum mechanics.
Eddington Luminosity

- For the system to be stable (or accrete gas) the force of gravity must be greater than the force due to radiation pressure (recall homework problem)
  \[ \frac{\sigma_e L}{4\pi r^2 c} \leq \frac{GMm_p}{r^2} \]
- \( M \) is the mass of the central object and \( m_p \) is the proton mass.
- Thus we must have
  \[ L \leq \frac{4\pi Gc m_p}{\sigma_e} M \]
- This is known as the Eddington limit. The maximum luminosity for a given mass is known as the Eddington Luminosity.
  \[ L_E \approx 3.2 \times 10^4 \left[ \frac{M}{M_{\odot}} \right] \quad \text{(in solar luminosities)} \]

Eddington Mass

- Equivalently we can define a minimum mass that is needed to balance or overcome the radiation pressure
- This is the Eddington Mass given by
  \[ M_E = 3.1 \times 10^{-4} \frac{L}{L_{\odot}} \quad \text{(in solar masses)} \]
- Where \( L \) is the central source luminosity. A characteristic luminosity of a Seyfert galaxy.
  - This is the bolometric (total) luminosity because of the frequency independence of \( \sigma_e \).
- For a typical quasar luminosity \( L \sim 3 \times 10^{12} \ L_{\odot} \), so that a mass of \( M_E \sim 10^8 \ M_{\odot} \) is needed so that the accretion disk is not blown apart by the photon pressure.
Accretion Luminosity

- The conversion of gravitational potential energy to kinetic energy is thought to provide the luminosity source for AGNs.
- For a black hole this is given by:

\[ L = \eta \dot{M} c^2 \quad (\dot{M} = \frac{dM}{dt}) \]

- Where \( \eta \) is the conversion efficiency and \( \dot{M} \) is the mass accretion rate.
- Estimates for \( \eta \) give \( \eta \approx 0.1 \), which is more than a factor of 10 higher than the efficiency of hydrogen fusion (\( \eta = 0.007 \)).
  - The innermost stable orbit around a non-rotating black hole is \( 3 R_s \), \( R_s = \frac{2GM}{c^2} \).
- For a quasar with \( L \approx 3 \times 10^{12} L_{\text{sun}} \) then \( \dot{M} \approx 2 M_{\text{sun}} \text{ yr}^{-1} \) is needed.

Eddington Accretion Rate

- The Eddington accretion rate is the mass accretion rate needed to sustain the Eddington luminosity.

\[ \dot{M}_E = \frac{L_E}{\eta c^2} \approx 2.2 M_8 M_{\text{sun}} \]

- This is the maximum possible accretion rate for a mass \( M \) (in units of \( 10^8 M_{\text{sun}} \)), for a simple spherical accretion model.