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Monday, August 27, 2012
Active Galactic Nuclei

- Blazars
- Radio Loud Quasars
  - Narrow Line Region
- Jet
- Broad Line Radio Galaxies
- Narrow Line Radio Galaxies
- Obscuring Torus
- Black Hole
- Accretion Disk
  - Viewing Angle
- Seyfert Galaxies Type 2
- Seyfert Galaxies Type 1
- Radio Quiet Quasars

Radio Loud
Radio Quiet
Active Galactic Nuclei

Sy 2, NLRG

Narrow Line Region

Torus

Accretion Disk

Jet

Broad Line Region

Ionized Gas

Neutral Gas

Sy 1, BLRG, QSO

Blazar

Blazar

Monday, August 27, 2012
Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk

380 Arc Seconds
88,000 LIGHTYEARS

1.7 Arc Seconds
400 LIGHTYEARS

Jaffee/Ford/NASA

Monday, August 27, 2012
Active Galactic Nuclei

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Decreasing angle to line of sight
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Active Galactic Nuclei - Variability

IRAS 13225-3809

X-ray Intensity

Time (days)

3.8-cm Radio Intensity

Time (years)

BL Lacertae

NGC 5548 emission lines

Intensity

Time (days)

NGC 5548 UV continuum

Intensity

Time (days)
Variability studies show that the luminosity of Quasars can vary by a factor of 2 within days.

Some objects (mostly Blazars) vary by factors of 10-100 over short timescales.

Variability gives an estimate of the size of the emission region because the region must be connected by the speed of light.
Active Galactic Nuclei

Variability gives as estimate of the size of the emission region because the region must be connected by the speed of light.

\[ R = c \Delta t (1 - v^2/c^2)^{1/2} = c \Delta t /\gamma \]

For \( \Delta t = 1 \) hr, taking \( \gamma = 1 \) (can only be larger, making \( R \) smaller)

\[ R = 1.1 \times 10^{12} \text{ m} = 7.2 \text{ AU (between Jupiter and Saturn).} \]

Considering that the luminosity is \( >100 \) than the Milky Way, this is an incredibly small size!

Recall that there is a maximum luminosity before an object will blow itself apart due to radiation pressure. This the Eddington Limit.

\[ L < L_{\text{Ed}} \approx (1.5 \times 10^{31} \text{ W}) \times (M /M_{\odot}) \]

For \( L = 5 \times 10^{39} \text{ W} \) you can solve for the mass, which would be \( M > 3.3 \times 10^8 M_{\odot}. \)

Finding such a large mass in such a small space is clear evidence for a supermassive black hole. The mass for an object with a Schwarzschild radius =7.2 AU (above) is \( M = 3.7 \times 10^8 M_{\odot}. \)
The Principle of Accretion - Gas falling into gravitational field of compact object converts potential energy to kinetic energy. If there is any angular momentum, infalling gas will form an accretion disk. Friction in the disk will generate heat, resulting in momentum transfer. Locally, the disk rotates following Kepler, but there will be differential rotation (as velocity decreases with radius).
Geometrically thin, optically thick accretion disk:

\[ \Delta E = \frac{G M_{\text{BH}} m}{r} - \frac{G M_{\text{BH}} m}{r + \Delta r} \approx \frac{G M_{\text{BH}} m}{r} \frac{\Delta r}{r} \]

By the virial theorem, 1/2 of the potential energy is available.

\[ E_{\text{heat}} = \frac{\Delta E}{2} \]

The Luminosity is the rate of change of energy with time. Take $\dot{m}$ to be the accretion rate. In this approximation, we assume the same amount of matter per unit time flows through any radius.

\[ \Delta L = \frac{G M_{\text{BH}} \dot{m}}{2r^2} \Delta r \]
Active Galactic Nuclei - Central Engine

Geometrically thin, optically thick accretion disk:

\[ \Delta L = \frac{GM_{BH} \dot{m}}{2r^2} \Delta r \]

In the optically thick case, the local emission is thermal (black body). The ring with annulus \( r \) and \( r+\Delta r \) emits a luminosity of:

\[ \Delta L = 2 \times 2\pi r \Delta r \times \sigma T^4(r) \]

Solving for \( T(r) \) gives the radial temperature profile:

\[ T(r) = \left( \frac{GM_{BH} \dot{m}}{8\pi \sigma r^3} \right)^{1/4} \]

More accurate derivation including dissipation by friction (advection inwards):

\[ T(r) = \left( \frac{3GM_{BH} \dot{m}}{8\pi \sigma r^3} \right)^{1/4} \]
Active Galactic Nuclei - Central Engine

Geometrically thin, optically thick accretion disk:

\[ T(r) = \left( \frac{3GM_BH \dot{m}}{8\pi \sigma r^3} \right)^{1/4} \]

Rewriting in terms of the Schwarzchild radius:

\[ r_S := \frac{2GM}{c^2} = 2.95 \times 10^5 \text{ cm} \left( \frac{M}{M_\odot} \right) \]

\[ T(r) = \left( \frac{3GM_BH \dot{m}}{8\pi \sigma r_s^3} \right)^{1/4} \left( \frac{r}{r_s} \right)^{-3/4} \]

Or rewriting a little:

\[ T(r) = \left( \frac{3c^6}{64\pi \sigma G^2} \right)^{1/4} \dot{m}^{1/4} M_BH^{-1/2} \left( \frac{r}{r_s} \right)^{-3/4} \]

Conclusions:

1. Temperature increases as \( r^{-3/4} \). Emission is a superposition of a series of rings emitting at different blackbody temperatures.
2. Temperature increases with the accretion rate.
3. Temperature decreases with \( M_{BH} \). (Explained by decrease in tidal forces at fixed \( r / r_s \)).
Active Galactic Nuclei - Central Engine

Mass Estimates of Super Massive Black Hole (SMBH)

Eddington Luminosity (Radiation Pressure):

\[ F_{\text{rad}} = \sigma_T \frac{L}{4\pi r^2 c} \]

For interaction of photons with free electrons, depends on Thompson cross section,

\[ \sigma_T = \frac{8\pi}{3} \left( \frac{e^2}{m_e c^2} \right)^2 = 6.65 \times 10^{-25} \text{ cm}^2 \]

Gravitational force is: \[ F = \frac{G M_{BH} m_p}{r^2} \]

where \( m_p \) is the mass of a proton (since electron mass is negligible in comparison).

For \( F_{\text{rad}} < F_{\text{grav}} \) matter accretes, else it is blown outwards by radiation force.
Active Galactic Nuclei - Central Engine

Mass Estimates of Super Massive Black Hole (SMBH)

Eddington Luminosity (Radiation Pressure):

For $F_{\text{rad}} < F_{\text{grav}}$ matter accretes, else it is blown outwards by radiation force.

\[
\frac{\sigma_T L}{4\pi r^2 c} < \frac{G M_{BH} m_p}{r^2}
\]

\[
L < L_{\text{edd}} = \frac{4\pi G c m_p}{\sigma_T} M_{BH} \approx 1.3 \times 10^{38} \left( \frac{M_{BH}}{M_\odot} \right) \text{ erg s}^{-1}
\]

Note that $\sigma_T$ is independent of photon frequency, so $L$ here is bolometric luminosity.
**Active Galactic Nuclei - Central Engine**

**Mass Estimates of Super Massive Black Hole (SMBH)**

**Eddington Luminosity (Radiation Pressure):**

\[ L < L_{edd} = \frac{4\pi G m_p}{\sigma_T} M_{BH} \approx 1.3 \times 10^{38} \left( \frac{M_{BH}}{M_\odot} \right) \text{ erg s}^{-1} \]

For accretion to occur \( L < L_{edd} \). Turn equation around to derive a lower limit on an accreting SMBH:

\[ M_{BH} > \frac{\sigma_T}{4\pi G m_p c} L \approx 8 \times 10^7 \left( \frac{L}{10^{46} \text{ erg s}^{-1}} \right) M_\odot \]

**Note!** We assumed isotropy in this derivation. Much evidence suggests accretion disks are anisotropic. In these cases \( L \) can exceed \( L_{edd} \) by a small amount.
Mass Estimates of Super Massive Black Hole (SMBH)

Eddington Accretion rate

\[ \dot{m} = \frac{L}{\epsilon c^2} \approx 0.18 \epsilon^{-1} \left( \frac{L}{10^{46} \text{ erg s}^{-1}} \right) M_\odot \text{ yr}^{-1} \]

Maximal efficiency is \( \epsilon \approx 0.1 \) based on accretion, angular momentum considerations (maximum of <30%).

Can rewrite accretion rate in terms of the maximum, the eddington accretion rate:

\[ \dot{m}_{\text{edd}} = \frac{L_{\text{edd}}}{\epsilon c^2} \approx \frac{1}{\epsilon} 2 \times 10^{-9} M_{BH} \text{ yr}^{-1} \]

Maximum accretion rate leads to characteristic timescale for SMBH growth:

\[ t = \frac{M_{BH}}{\dot{m}} \approx \epsilon \left( \frac{L}{L_{\text{edd}}} \right)^{-1} 5 \times 10^8 \text{ yr} \]

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Active Galactic Nuclei - Central Engine

Mass Estimates of Super Massive Black Hole (SMBH)

Use velocity width of emission lines:

\[ M_{\text{BH}} = \frac{f \left( \Delta V^2 R \right)}{G} \]

f is a dimensionless factor of order unity (depends on structure, dynamics and orientation of BLR). R is distance from SMBH to BLR.

Good constraints from *Reverberation Mapping* which gives sizes \( R = ct \) where \( t \) is emission-line time delay (see Peterson et al. 2004, *ApJ*, 613, 682).
Mass Estimates of Super Massive Black Hole (SMBH)

Active Galactic Nuclei - Central Engine

Active Galactic Nuclei - Central Engine

Mass Estimates of Super Massive Black Hole (SMBH)


Best fit relation:

$$\log\left(\frac{M}{10^8 M_\odot}\right) = -0.12(\pm 0.07) + 0.79(\pm 0.09) \log\left(\lambda L_\lambda(5100 \, \text{Å})/10^{44} \, \text{erg s}^{-1}\right)$$
Components of AGN

UV, Optical, near-IR continuum

![Graph showing components of AGN](image-url)
Components of AGN

UV, Optical, near-IR continuum

Consider accretion disk with our temperature profile derived earlier:

\[
T(r) \approx 6.3 \times 10^5 \text{ K} \left( \frac{\dot{m}}{\dot{m}_{\text{edd}}} \right)^{1/4} \times \left( \frac{M_*}{10^8 M_\odot} \right)^{-1/4} \left( \frac{r}{r_S} \right)^{-3/4}
\]

For QSOs continuum spectrum shows a broad continuum with maximum in UV. Also seems to be thermal emission in X-ray domain with a powerlaw behavior, \( S_\nu \sim \nu^{-\alpha} \), down to energies \(~0.5 \text{ keV} \).
Luminosity Functions of Quasars are characterized by a “double powerlaw”:

$$\Phi(L, z) = \frac{\Phi^*}{L^*(z)} \left[ \left( \frac{L}{L^*(z)} \right)^\alpha + \left( \frac{L}{L^*(z)} \right)^\beta \right]^{-1}$$

Good fit to evolution is

$$L^*(z) = L_0^*(1+z)^k$$

with $k \sim 3.5$

Croom et al. 2009
AGN and Cosmology

Luminosity Function of Quasars

Strong Evolution in Quasar population. L*(z) at z~2 is about 50 times brighter than today.

Spatial Density of bright QSOs was more than 1000 times larger at z~2 than today.

Luminosity function of Quasars is considerably broader than galaxies (latter decrease exponentially at large luminosity).

At z > 3, evolution of QSOs seems to reverse. # and luminosities of QSOs decline.
AGN and Cosmology

Luminosity Function of Quasars

- This work
- 2QZ
- SDSS

Brown et al. 2006

Fan et al. 2004

Croom et al. 2004

Space Density ($M_B < -28.5$) (Mpc$^{-3}$)

Redshift

Monday, August 27, 2012
Quasar Absorption Lines

AGN and Cosmology

QSO 1331+17, $z_{\text{em}}=2.081$ (Rauch et al. 1998)
Shows absorption systems, including a system at $z=1.776$
Quasar Absorption Lines

AGN and Cosmology

QSO 0122+0338, z_{em}=1.202 (Papovich et al. 2000)
Shows absorption systems, including a system at z=1.166, z=1.199, z=1.207

Monday, August 27, 2012
AGN and Cosmology

Quasar Absorption Lines

1. **Metal systems.** Generally see narrow absorption lines. Mg II and C IV are most common. Because $0 < z_{abs} < z_{em}$, these are generally caused by gas along the line of sight, that has been enriched by star formation. Typical column densities are $10^{17} \text{ cm}^{-2} < N_H < 10^{21} \text{ cm}^{-2}$. At $> 2 \times 10^{20} \text{ cm}^{-2}$ Damped Ly-alpha systems occur.

2. **Associated Metal systems.** These have $z_{abs} \sim z_{em}$. Absorption in host galaxy of QSO?

3. **Ly-alpha forest.** Range the gamut of $N_H$ column densities, from $<10^{14} \text{ cm}^{-2}$ to $>10^{24} \text{ cm}^{-2}$.

Lyman-$\alpha$ in QSO 1422+231 at $z_{em}=3.62$

Wallace et al. 1989
4. **Lyman-limit systems.** Part of Lyman-alpha forest. Systems with $N_H > 10^{17} \text{ cm}^{-2}$ will absorb nearly all UV flux at $< 912 \, \text{Å}$ in the rest-frame of the absorber.

Lyman-α in QSO 2000-330 at $z_{\text{em}}=3.75$

Lyman-limit system

Turnshek 1998
5. **Broad Absorption lines.** About $\sim$10-15% of QSOs show very broad absorption lines, with $\sim$10,000 km/s widths. Typically $z_{\text{abs}} \sim z_{\text{em}}$. Interpretation is these are winds blown off accretion disk driven by radiation pressure (confined along magnetic field lines?)