Introduction Active Galactic Nuclei

Lecture -7- Broad/Narrow-Line Regions
Reprocessed Radiations

AGN produce a lot of ionizing radiation <- Accretion Disk

Radiation is intercepted by gas & dust and reprocessed

- **Dust Torus**: IR radiation (previous lecture)

- **Gas**: Emission lines
  - Narrow Lines  -> NLR
  - Broad Lines   -> BLR
Reprocessed Radiations

What is the origin of the BLR and NLR?
Different types of AGN Spectra: Some General Features

- **Seyfert and radio galaxies** come in flavors with all emission lines about the same width (Seyfert 2, narrow-line radio galaxy or NLRG) and with certain emission lines much broader (Seyfert 1, broad-line radio galaxy or BLRG).

- These pairs are similar in optical spectrum, except that BLRGs may have emission lines that are broader and contain more profile structure than found in Seyfert 1 nuclei.

- Quasars, represented here by a composite produced from many individual objects, have a family resemblance to Seyfert 1 nuclei, and in most cases, the bumps of Fe II emission are even more prominent in quasars, rippling the spectrum between the strong individual lines.
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Different types of AGN Spectra

BL Lac object 0814+425

Mean quasar

Seyfert 1 NGC 4151

Seyfert 2 NGC 4941

LINER NGC 4579

Normal galaxy NGC 3368

BLRG 3C 390.3

NLRG Cygnus A

Emitted wavelength (Å)
Different types of AGN Spectra: Some General Features -3-  

- **BL Lacertae** objects have virtually featureless spectra, making even their redshifts difficult to measure unless the surrounding galaxy can be detected, or emission lines show up when the nucleus is temporarily much fainter than usual.

- At lower activity levels, many galaxies contain nuclear emission regions known as **LINERs** (Low-Ionization Nuclear Emission-Line Regions), which are in at least some cases a lower-luminosity version of the processes seen in more traditional active nuclei.

- Finally, a **normal galaxy** spectrum is shown for comparison. Most of its spectrum shows the combined absorption features from the atmospheres of individual stars, with weak emission lines from gas in star-forming regions ionized by hot young stars.
Different types of AGN Spectra

- BL Lac object
  0814+225

- Mean quasar

- LINER
  NGC 4579

- Normal galaxy
  NGC 3368

- Seyfert 1
  NGC 4151

- Seyfert 2
  NGC 4941

- BLRG
  3C 390.3

- NLRG
  Cygnus A
Different types of AGN Spectra: Some General Features -4-

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Different types of AGN Spectra: Some General Features -5-

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The AGN Paradigm

- The black-hole + accretion-disk model is finally fairly secure.

- No generally accepted models for emission and absorption regions, though disk-related outflows seem most promising.
The Broad Line Region

Is the BLR just simply a collection of gas clouds in the gravitational field of the SMBH, or a smoother filamentary structure with high velocity gradients?
BLR: Some Simple Inferences

- Temperature of gas is $\sim 10^4$ K: Thermal width $\sim 10$ km s$^{-1}$

- Density is high, by nebular standards ($n_e \geq 10^9$ cm$^3$)

- Efficient emitter, can be low mass

- Line widths FWHM 1000 – 25,000 km/sec -> Gas moves supersonically
Broad-Line Flux and Profile Variability

- Emission-line fluxes vary with the continuum, but with a short time delay.

- Inferences:
  - Gas is photoionized and optically thick
  - Line-emitting region is fairly small
Correlations: The Baldwin Effect

- Average line spectra of AGNs are amazingly similar over a wide range of luminosity.
- Exception: Baldwin Effect
  - Relative to continuum, C IV 1549 is weaker in more luminous objects
  - Origin unknown

SDSS composites, by luminosity
Vanden Berk et al. (2004)
BLR Scaling with Luminosity

BRL size scale with luminosity:

\[ L \propto R^{1.7} \]

Hence flux and energy density are similar for different AGN when looking at similar lines.

- QSOs (Kaspi et al. 2000)
- Seyfert 1s (Wandel, Peterson, Malkan 1999)
- Narrow-line AGNs
- NGC 4051 (NLS1)
BLR Size vs. Luminosity

• The Hβ response in NGC 5548 has been measured for 14 individual observing seasons.
  – Measured lags range from 6 to 26 days
  – Best fit is $\tau \propto L_{\text{opt}}^{0.9}$
  – However, UV varies more than optical:
    \[ \forall \tau \propto L_{\text{opt}}^{0.9} \propto (L_{\text{UV}}^{0.56})^{0.9} \propto L_{\text{UV}}^{0.5} \]
What Fine-Tunes the BLR?

• Why are the ionization parameter and electron density the same for all AGNs?
• How does the BLR know precisely where to be?
• Answer: Gas is everywhere in the nuclear regions. We see emission lines emitted under optimal conditions.
What is the BLR?

- First notions based on Galactic nebulae, especially the Crab system of “clouds” or “filaments.”
- Merits:
  - Ballistic or radiation-pressure driven outflow -> logarithmic profiles
  - Virial models implied very large masses
- Early photoionization models overpredicted size of BLR
What is the BLR?

- Number of clouds $N_c$ of radius $R_c$:
  - Covering factor $\propto N_c R_c^2$
  - Line luminosity $\propto N_c R_c^3$
  - Combine these to find large number ($N_c > 10^8$) of small ($R_c \approx 10^{13}$ cm) clouds.
  - Combine size and density ($n_H \sim 10^{10}$ cm$^{-3}$), to get column density ($N_H \sim 10^{23}$ cm$^{-2}$), compatible with X-ray absorption.
  - Total mass of line-emitting material $\sim 1M_{\odot}$.

Crab Nebula with VLT
Large Number of Clouds?

• Even in NGC 4395, the least luminous Seyfert 1, the profiles are smooth.

• This effectively eliminates “bloated stars” scenario.
  – BLR becomes too small to contain a sufficient number of stars.
Double-Peaked Emission Lines

- A relatively small subset of AGNs have double-peaked profiles that are characteristic of rotation.
  - Disks are not simple; non-axisymmetric.
  - Sometimes also seen in difference or rms spectra.
- Disks probably can't explain everything.

NGC 1097  
Storchi-Bergmann et al. (2003)
Large Number of Clouds?

- If clouds emit at thermal width (10 km/sec), then there must be a very large number of them to account for lack of small-scale structure in line profiles.

NGC 4151
Arav et al. (1998)
Disk Wind

- Missing component is probably a wind originating at the accretion disk.
  - Radiatively or hydromagnetically driven?
- Accretion disks in galactic binaries and young stellar objects also have winds and jets
  - These may be common to accretion disks on all scales.
Evidence for Outflows in AGNs

- X-Ray/UV absorption
  - Ubiquitous property of AGNs
  - Absorption is uniformly blueshifted relative to systemic.
  - Large column densities, multiple velocity components, massive outflows
  - Connection to BALs in luminous QSOs?

*Chandra*: Kaspi et al. (2002)
*HST*: Crenshaw et al. (2002)
*FUSE*: Gabel et al. (2002)
Evidence for Outflows in AGNs

- Widths of BASES (width at 20% maximum) are larger in edge-on sources.
  - Implies wind has strong radial component.

Increasing radio core dominance → Decreasing disk inclination →

Vestergaard, Wilkes, & Barthel (2000)
Evidence for Outflows in AGNs

- Clear blueward asymmetries in higher ionization lines in narrow-line Seyfert 1 galaxies

Leighly (2001)
Evidence for Outflows in AGNs

- Peaks of high ionization lines are blueshifted relative to systemic.
- Maximum blueshift increases with luminosity.

Espey (1997)
A Plausible Disk-Wind Concept

A Structure for Quasars

GEOMETRY

- 40-45%
- 10-20%
- \( \tau = 1 \)
- \( \text{Compton scattered radiation} \)
- \( \text{UV/X-ray luminosity source} \)

TAXONOMY

- No Absorbers
- BAL
- NAL

Massive Black Hole

- \( v_{\text{vertical}} = v_{\text{radial}} \)
- \( v = 1000 \text{ km/s} \)
- \( v = 10,000-60,000 \text{ km/s} \)
- \( \Delta v = 10,000-60,000 \text{ km/s} \)

PHYSICS

- \( \text{NH} = 10^{22} \)
- \( \text{NH} = 10^{24} \)

KINEMATICS

• Emission line widths up to thousands km/s or even tens of thousand km/s

• Gas temperatures $10^{4-5}$ K (~10 km/s)

• Doppler broadening through bulk motion of the gas in the gravitational field

• High velocities imply distances of ~100 $R_s$

• Only ~10% of continuum emission is absorbed by BLR
Summary of BLR properties -2-

• Volume filling factor is low, $10^{-6}$

• Mass in BLR is only a few solar mass

• Broad lines are very smooth:
  either they are made of many clouds ($10^9$ with $R \sim R_{sun}$)
  or it is a coherent structure (wind?)

• Suppression of forbidden lines indicates $n > 10^9$ cm$^{-3}$

• Size of BLR is few upto a hundred light days (reverberation)
The Narrow Line Region

- Assumed clouds
  - Density $10^{3-5}$ cm$^{-3}$
  - Large and small column density
  - Location $\sim 300$ pc
  - Radial distribution
  - Confinement
  - Covering factor $>0.02$

- The extended NLR
- Is there an intermediate line region?

- Bound system?
- FWHM $\sim 500$ km/sec
- Small EW lines
The Narrow Line Region

The cone-shaped emission line regions suggests that the NRL is simply gas in the host galaxy illuminated by the AGN through the opening angle of the dust-torus.
The Narrow Line Region

- The NLR spectrum
  - optical and UV lines
    - permitted, semi-forbidden and forbidden lines
  - IR lines
    - coronal lines
  - line profiles
  - line asymmetry
Summary of NLR properties

• FWHM of lines ~400-500 km/s

• Forbidden lines -> low gas densities of $10^{3-5}$ cm$^{-3}$

• Total gas mass can be several million solar mass

• Size >100 pc (resolved in many Seyferts)

• Excess blueward flux -> radial outflow and attenuation on backside through dust(?)

• HST shows highly structure NLR with signs of jet impact
Summary

- The BLR originates close to the SMBH (high velocities), has a high gas density and a low total mass. It might consist of many (billions of clouds) and/or a outflowing wind.

- Reverberration mapping (previous lecture) can be used to map the BLR and measure the SMBH mass.

- The NLR originates further from the AGN (seen in HST images), has lower velocities and millions of solar mass in gas.