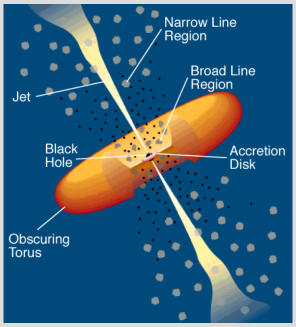
Introduction Active Galactic Nuclei

Reprocessed Radiation: IR, NLR/BLR, X-rays



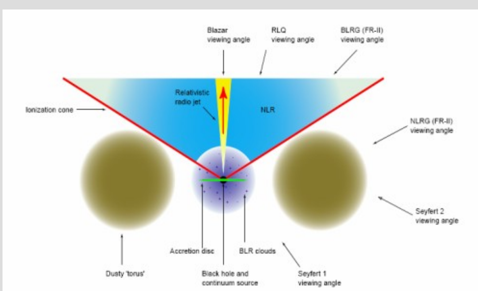
Reprocessed Radiations

AGN produce a lot of ionizing radiation <- Accretion Disk

Radiation is intercepted by gas & dust
and reprocessed

- Dust Torus: IR radiation
- Gas: Emission lines
  - Narrow Lines -> NLR
  - Broad Lines -> BLR
  - X-ray fluoresence

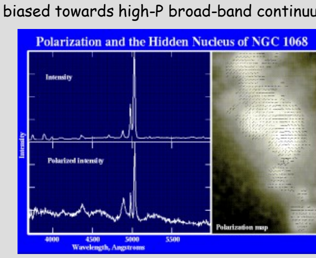
Effects of the orientation to AGN



Support for unification: hidden emission lines

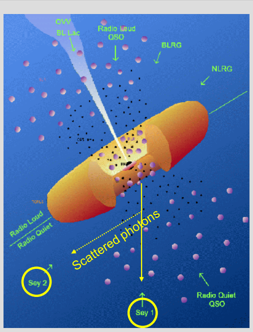
Some Sy2s show broad lines in polarized light:

The fraction is still unclear since the observed samples
are biased towards high-P broad-band continuum objects.



(Bill Keel s web page with data from Miller, Goodrich & Mathews 1991, Capetti et al. 1995)

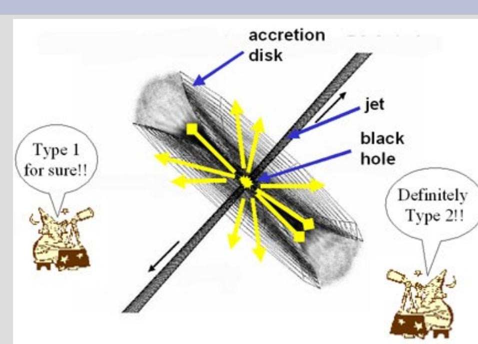
Support for unification: hidden emission lines



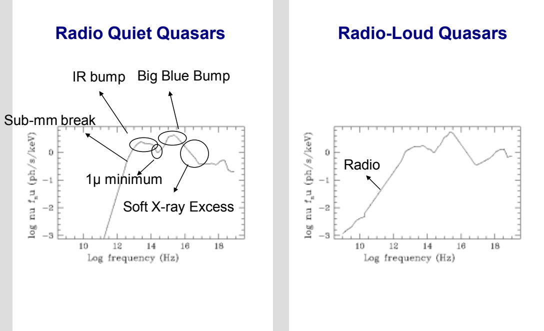
Hot electrons scatter photons from the BLR near the nucleus to the observer. Dust torus shield direct line-of-sight to the nucleus

Hence, Sy2 look a bit like Sy1 in polarised light

Support for unification: hidden emission lines



Spectral Energy Distribution of Seyferts, QSOs, BLRGs



The Blue and IR bumps

- L_{IR} contains up to 1/3 of L_{bol}
  L_{BBB} contains a significant fraction of L_{bol}
- IR bump due to dust reradiation, BBB due to blackbody from an accretion disk
- The *3000 A bump* in 4000-1800 A:
- Balmer Continuum
- Blended Balmer lines
- Forest of FeII lines

Infrared Continuum

- In most radio-quiet AGN, there is evidence that the IR emission is thermal and due to heated dust

- However, in some radio-loud AGN and blazars the IR emission is non-thermal and due to synchrotron emission from a jet.

Infrared Continuum: Evidence

Obscuration :

- Many IR-bright AGN are obscured (UV and optical radiation is strongly attenuated)
- IR excess is due to re-radiation by dust

Infrared Continuum: Evidence

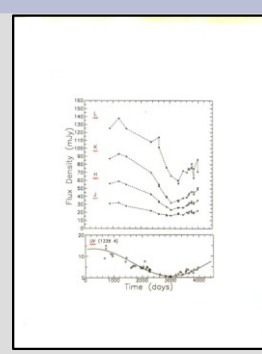
IR continuum variability :

- IR continuum shows same variations as UV/optical but with significant delay
- Variations arise as dust emissivity changes in response to changes of UV/optical that heats it

Dust Reverberation

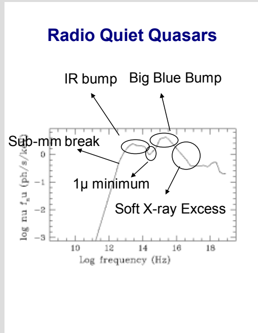
- Optical varied by factor ~20
- IR variations follow by ~1 year
- IR time delays increased with increasing wavelength

Evidence for dust(torus) a light year from the AGN nucleus, with decreasing T as function of radius

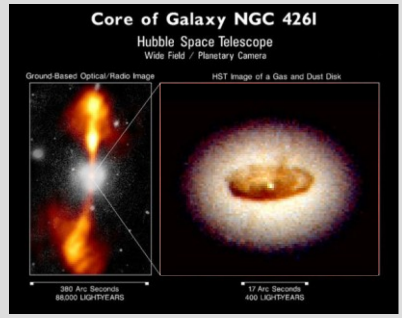


Emerging picture

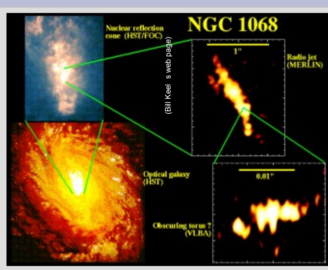
- The 2μ-1mm region is dominated by thermal emission from dust (except in blazars and some other radio-loud AGN)
- Different regions of the IR come from different distances because of the radial dependence of temperature
- 1μ minimum: hottest dust has T~2000 K (sublimation T) and is at ~0.1 pc (generic feature of AGN)



Support for unification: direct imaging of torus?

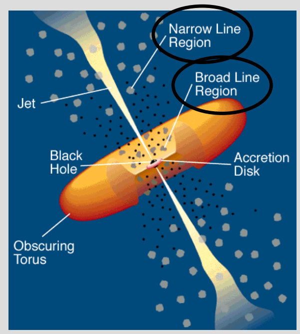


Support for unification: direct imaging of torus?



VLBA observations of the nucleus of NGC1068 (Sy 2) at 8.4GHz reveals a small elongated structure, probably an ionized disk of ~1.2pc at T≥$10^{6.5}$ K that radiates free-free continuum or scattered light.(Gallimore, et al. 1997).

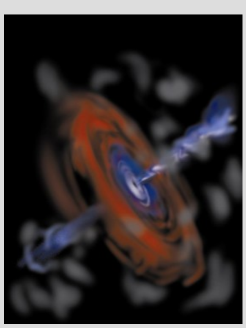
Reprocessed Radiations



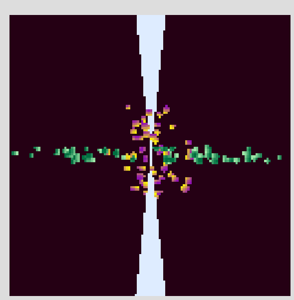
What is the origin of the BLR and NLR?

The AGN Paradigm

- The black-hole + accretion-disk model is now fairly secure.
- No generally accepted models for emission and absorption regions, though disk-related outflows seem most promising.



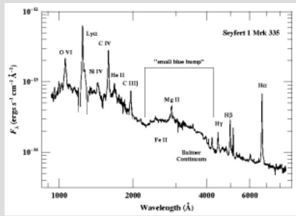
The Broad Line Region



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?

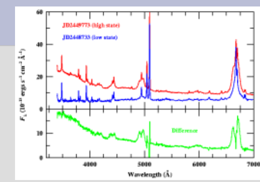
BLR: Some Simple Inferences

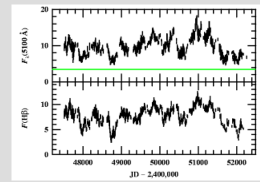
- Temperature of gas is ~10^4 K: Thermal width ~10 km s^{-1}
- Density is high, by nebular standards ($n_e \geq 10^9$ cm^3)
- Efficient emitter, can be low mass
- Line widths FWHM 1000 – 25,000 km/sec -> Gas moves supersonically



Broad-Line Flux and Profile Variability

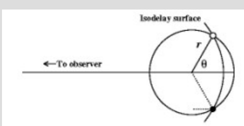
- Emission-line fluxes vary with the continuum, but with a short time delay.
- Inferences:
  - Gas is photoionized and optically thick (based on line-ratios, EW, linestrengths, etc.)
  - Line-emitting region is fairly small (variability).





Reverberation Mapping: SMBH Mass Measurement

The BLR is photoionized, since it responds to continuum variations, with a certain delay, which is a function of the BLR geometry, viewing angle, line emissivity, etc.



e.g., for a thin spherical shell, the BLR would respond at a delay time τ given by the parabolid

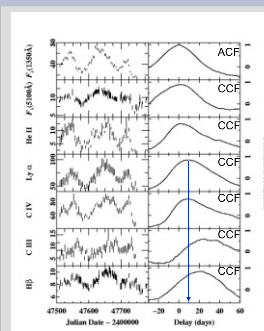
In general the line response is given by

where Ψ is called transfer function.

The centroid of the cross-correlation function between the continuum and the line gives the mean radius of emission:

where ACF is the autocorrelation function of the continuum.

Reverberation Mapping: SMBH Mass Measurement



(Peterson 2001, data from Clavel et al. 1992, Peterson et al. 1992)

← Measure time-lag

If the kinematics of the BLR are Keplerian, we can apply the virial theorem

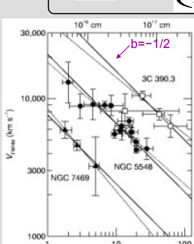
$$\frac{GM}{r_{BLR}} = f\sigma^2$$

with f, a factor close to 1. Measuring the line widths (FWHM) of the emission lines, we have an estimate of the velocity dispersion σ.

Reverberation Mapping: SMBH Mass Measurement

The central mass is then given by:

(Wandel, Peterson & Malkan 1999)



(Peterson & Wandel 2000)

Different lines give you the same answer, even if the r_{BLR} measured is different.

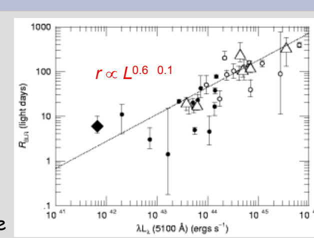
The masses derived by this method range from $M = 10^7\ M_{sun}$ for Sy 1s (i.e., in the range of the LINER NGC 4258) to $M = 10^9\ M_{sun}$ for QSOs

BLR Scaling with Luminosity

BRL size scale with luminosity:

$L \propto R^{1.7}$

Hence flux (~L/R^2) and energy density in shells are similar for different AGN when looking at similar lines.



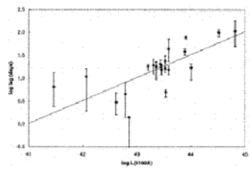
○ QSOs (Kaspi et al. 2000)
● Seyfert 1s (Wandel, Peterson, Malkan 1999)
△ Narrow-line AGNs
◆ NGC 4051 (NLS1)

$$U = \frac{L_{\rm ion}}{h\nu \cdot 4\pi R^2 c} \cdot \frac{1}{n}$$

(n: *particle density*, R: *radius*, ν: *average frequency of ionizing photons, and* $L_{\rm ion}$: *ionizing luminosity.*)

Assuming that certain lines are always produced preferentially at the location with a constant ionization parameter and density, one predicts the size of the BLR (measure in one line) to scale as

$$R_{\rm BLR} \propto \sqrt{L_{\rm ion}}$$



What Fine -Tunes the BLR?

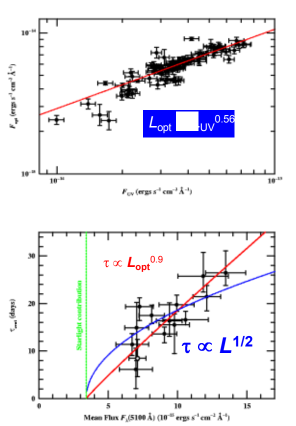
- Why are the ionization parameter and electron density the same for all AGNs?
- How does the BLR know precisely where to be?
- Answer:

Gas is everywhere in the nuclear regions. We see emission lines emitted under optimal conditions.

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 $\tau \propto L_{\rm opt}^{0.9}$
  - However, UV varies more than optical:

$\tau \propto L_{\rm opt}^{0.9} \propto (L_{\rm UV}^{0.56})^{0.9} \propto L_{\rm UV}^{0.5}$

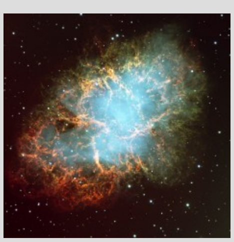


What is the BLR?

Crab Nebula
with VLT

- First notions based on Galactic nebulae, especially the Crab
  - system of "clouds" or "filaments."
- Merits:
  - Ballistic or radiation-pressure driven outflow -> logarithmic velocity profiles
  - Virial models implied very large masses (radiation pressure balance)
    - Early photoionization models overpredicted size of BLR

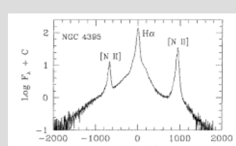
What is the BLR? Simple Cloud Model



Crab Nebula
with VLT

- 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} from lines), to get column density ($N_H \sim 10^{23}$ cm^{-2}), compatible with X-ray absorption.
  - Total mass of line-emitting material ~1M_{sun}

Large Number of Clouds?

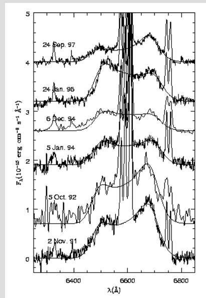


NGC 4395
Laor (2004)
From Filippenko & Ho

- Even in NGC 4395, the least luminous Seyfert 1, the profiles are smooth.
- This effectively eliminates "bloated stars" scenario (lines come from stellar atmospheres).
  - BLR becomes too small to contain a sufficient number of stars.

Double-Peaked Emission Lines

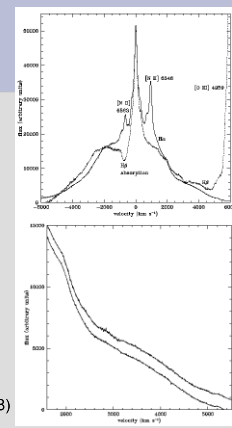
- A relatively small subset of AGNs have double-peaked profiles that are characteristic of rotation.
  - Disks are not simple; non-axisymmetric.
  - Sometimes also seen in difference or rms spectra.
- Disks probably can't explain everything.



NGC 1097
Storchi-Bergmann et al. (2003)

Large Number of Clouds?

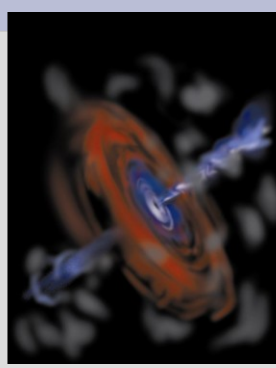
- If clouds emit at thermal width (10 km/sec), then there must be a very large number of them to account for lack of small-scale structure in line profiles.



NGC 4151
Arav et al. (1998)

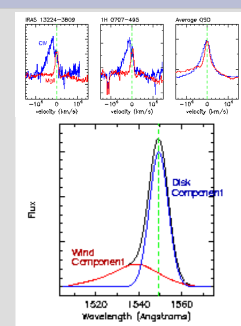
Disk Wind

- 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.



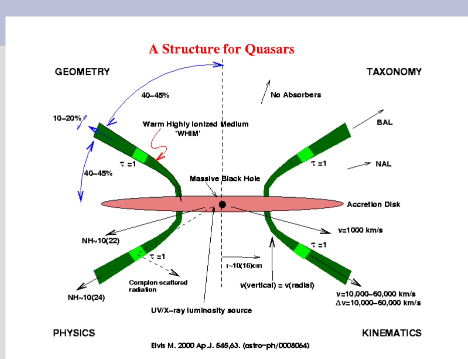
Evidence for Outflows in AGNs

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



Leighly (2001)

A Plausible Disk-Wind Concept



Summary of BLR properties -1-

Read old lecture on NLR/BLR on calculation of basic parameters

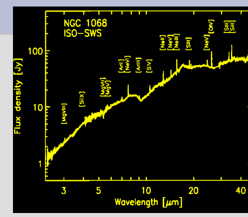
- Emission line widths up to thousands km/s or even tens of thousand km/s
- Gas temperatures 10^{4-5} K (~10 km/s)
- Doppler broadening through bulk motion of the gas in the gravitational field
- High velocities imply distances of ~100 R_s
- Only ~10% of continuum emission is absorpted by BLR

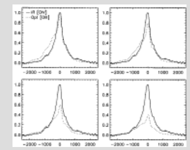
Summary of BLR properties -2-

- 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?)
- Suppresion of forbidden lines indicates $n > 10^9$ cm^{-3}
- Size of BLR is few upto a hundred light days (reverberation)

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 (flows)

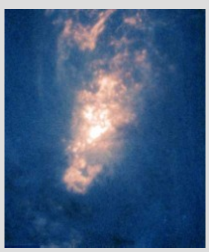


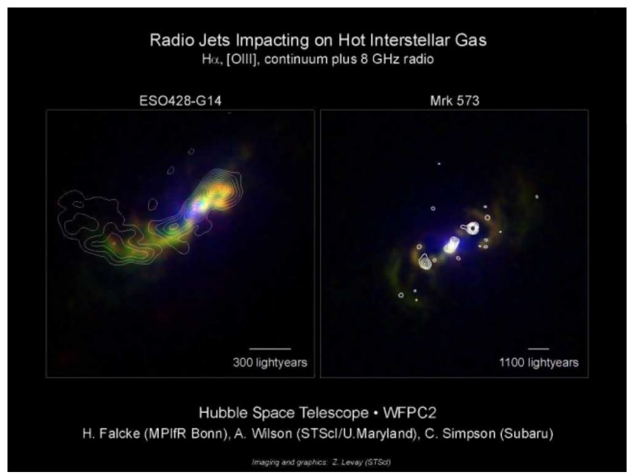


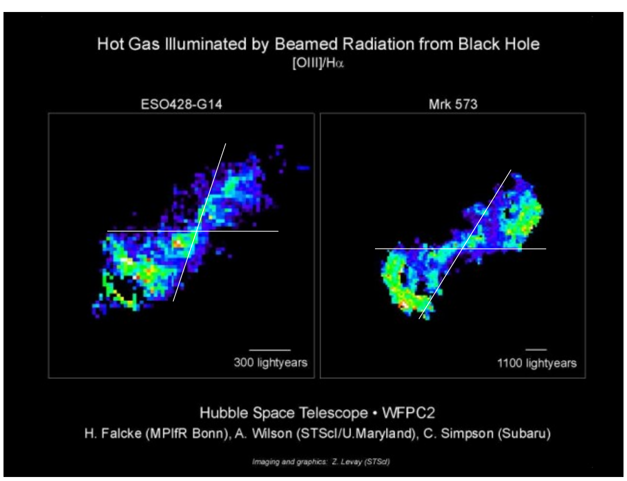
The Narrow Line Region

- Assumed clouds
  - Density $10^{3\text{-}5}$ cm^{-3}
  - Large and small column density
  - Location ~300 pc
  - Radial distribution
  - Confinement
  - Covering factor >0.02
- The extended NLR
- Is there an intermediate line region?

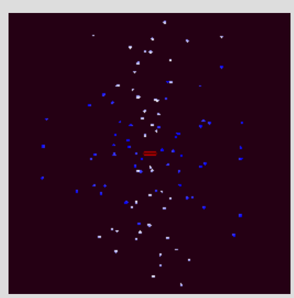
- Bound system?
- FWHM ~ 500 km/sec
- Small EW lines







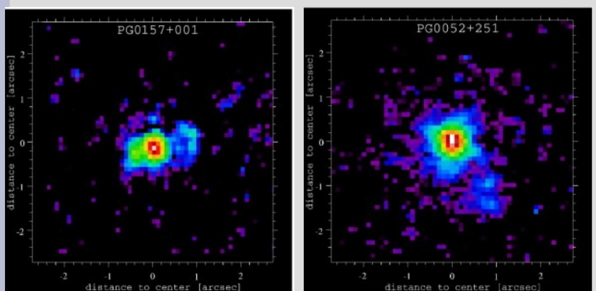
The Narrow Line Region



The OII/Hα map outlines the areas of high-excitation by a central source.

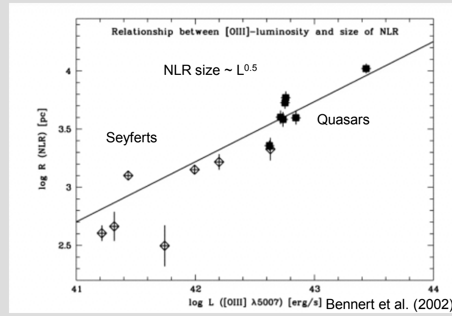
The "ionization cone" suggests that the NRL is simply gas in the host galaxy illuminated by the AGN through the opening angle of the dust-torus.

HST observations of the NLR of RQQs



Bennert, Falcke, Schulz et al. (2002)

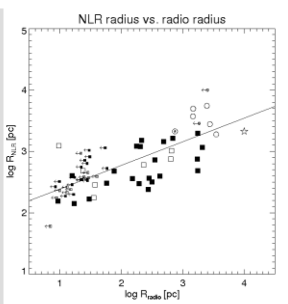
Seyfert – Quasar Unification:
HST Observations



Bennert et al. (2002)

Radio vs. NLR

Fig. 12. Correlation of the radii of the [O III] and radio emitting regions. Filled symbols represent type–2, open symbols type–1 objects, arrows denote upper limits. The RQQs data (circles) were taken from Bennert et al. (2002) and from this paper, while the Seyfert data were taken from Falcke et al. (1998), Schmitt et al. (2001 & 2003) and Kinney et al. (2000). The linear least square fit corresponds to $R_{NLR} \propto R_{radio}^{0.38\pm0.05}$. Note that a fit excluding data points with upper limits is the same within the errors. See text for details on the star.



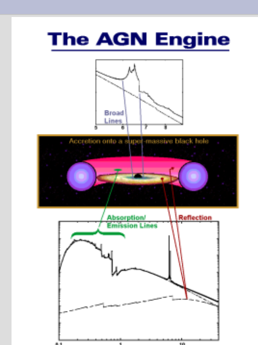
Summary of NLR properties

- 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 of Quasar NLR Properties

- RQQs have extended radio emission
- Radio is morphologically related to emission line region
- Radio emission is likely related to disrupted jets (results from VLBI)
- Size scales with luminosity and with NLR size
- RQQs are just powerful Seyferts

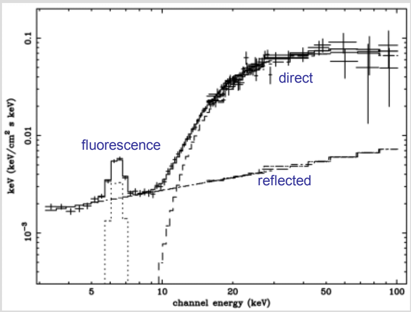
X-ray Reflection and Fluorescence



The MBH is surrounded by an accretion disk. Suppose that X-rays are generated above the disk:

- We observe some photons directly.
- Others hit the accretion disk. Some are reflected. Some eject an inner shell electron from an atom to give fluorescent line emission.

NGC 4945



Madejski et al. 2000

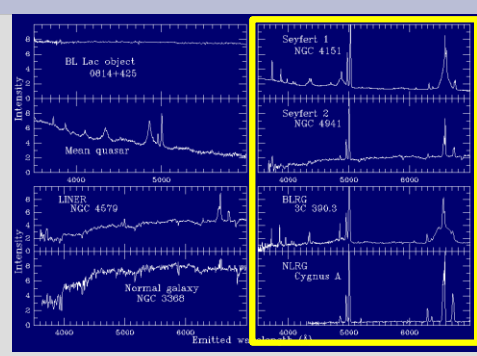
Summary
Reprocessed Radiation

- IR emission (IR bump) is due to a compact dust distribution (torus) heated by the AGN.
- 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 an outflowing wind or be part of a coherent structure (disk/wind).
- Reverberation mapping 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. It is illuminated by a light cone shaped by a dust torus.
- X-ray fluorescence lines can come from very close to the black hole, where X-ray continuum emission illuminates the accretion disk. Narrow lines come from further out.

Different types of AGN Spectra: Some General Features -1-

- 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.

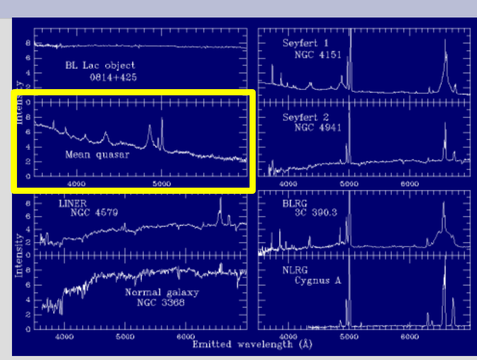
Different types of AGN Spectra



Different types of AGN Spectra: Some General Features -2-

- 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.

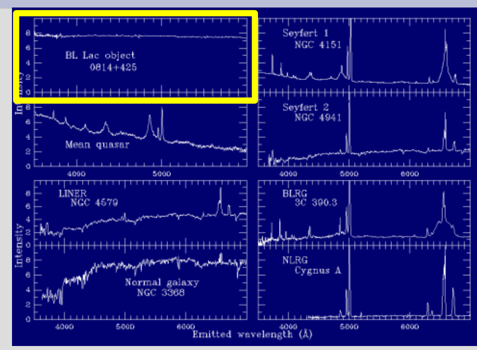
Different types of AGN Spectra



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.

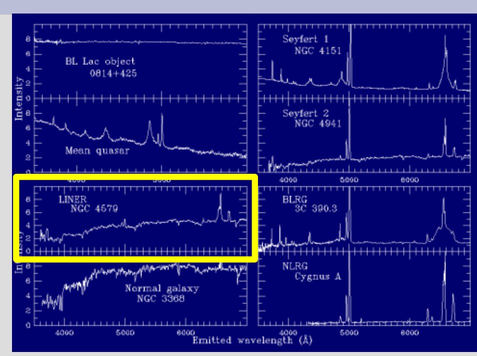
Different types of AGN Spectra



Different types of AGN Spectra: Some General Features -4-

- 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



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

- 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