Physics of AGN
The Emission-Line Regions

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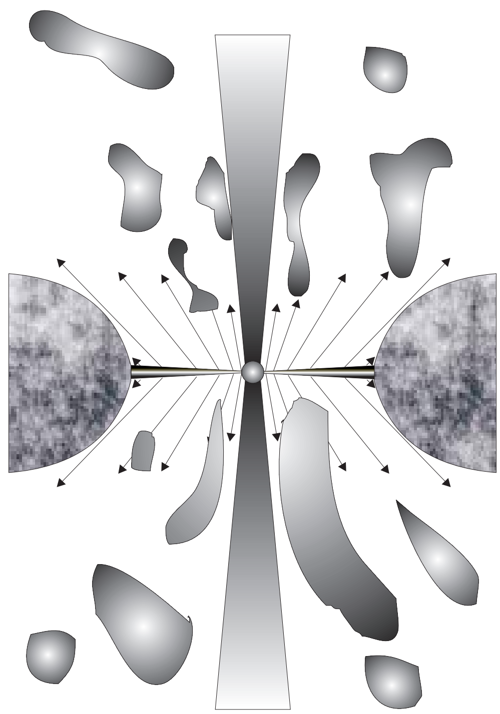


Contents:

- Broad-Line Region
- Narrow-Line Region
- Reverberation Mapping
- Ionization

Literature:
"An Introduction to Active Galactic Nuclei", Bradley M. Peterson, Cambridge University Press, Cambridge (Chap. 5, 6, &7)
"Active Galactic Nuclei", Ian Robson, John Wiley & Sons, Chichester (Chap. 9)

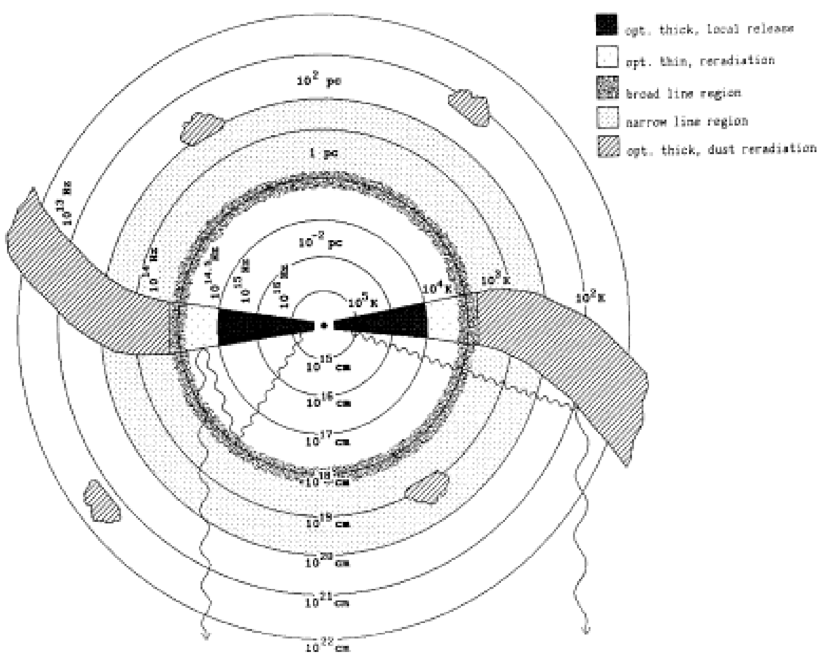
■ Reprocessed Radiation

An AGN produces a lot of ionizing radiation, most likely from the accretion disk.

This emission is intercepted by gas and dust in the host galaxy.

Correspondingly an AGN spectrum shows reprocessed radiation from this gas and dust. The respective features are

- Broad-Line Region (BLR)
- Narrow-Line Region (NLR)
- IR-bump from a molecular (dusty) "torus"

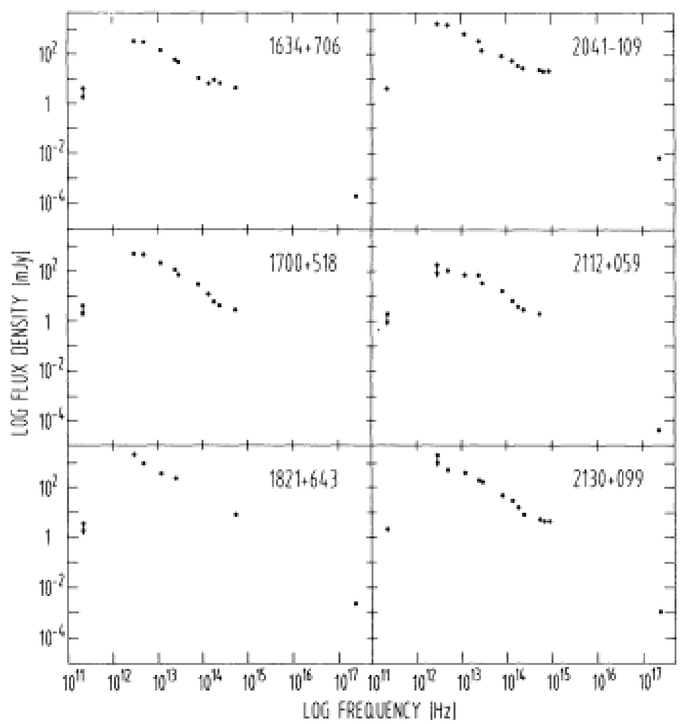


(Sanders et al. 1989)

IR-radiation

■ Thermal Nature

The SED of quasars shows a strong infrared-bump. At the longest wavelengths (mm-submm) the emission has an inverted spectrum which requires thermal dust emission (dust emission can have a steeper power-law then black-body or synchrotron when the grain size is smaller than the wavelength).



(Chini, Kreysa, Biermann 1989)

The SED has a minimum at 1 μm ($3 \cdot 10^{14}$ Hz) and the hottest dust emission would be at

$$T_{\rm dust} < \frac{h\nu_{\rm max}}{2.82 k_{\rm b}} = 1700\,{\rm K}\,\left(\frac{\nu_{\rm max}}{10^{14}\,{\rm Hz}}\right)$$

■ Spatial Distribution

The radiation from the hottest dust has to come from the innermost region where dust can survive.

Dust sublimates at temperatures above ∼2000 K, hence the 1 μm minimum is readily understood.

We can estimate the radius of this region by using the Stefan-Boltzmann law, assuming a thin disk:

$$L_{\rm IR} = 2\pi R_{\rm dust}^2 \sigma T_{\rm dust}^4$$

For the parameters of quasars we find

$$\Rightarrow R_{\rm dust} = \sqrt{\frac{L_{\rm IR}}{2\pi\sigma T_{\rm dust}^4}} = 0.4\,{\rm pc}\ \left(\frac{L_{\rm IR}}{10^{46}\,{\rm erg\,sec^{-1}}}\right)^{0.5} \left(\frac{T_{\rm dust}}{2000\,{\rm K}}\right)^{-2}$$

The emission a the shortest wavelengths should therefore come from the pc-scale. Near-infrared (NIR) variability studies (Clavel, Wamsteker, and Glass 1989) show that the NIR lags the UV by about 400 days, which confirms such rough estimates.

The fact that IR and UV bump are of the same order of magnitude suggests that the dust intercepts a large faction of the nuclear ionizing continuum.

⇒ We can use the IR emission as a natural bolometer for the AGN emission.

BLR

■ Properties

Broad, permitted emission lines (Hα) in the optical spectrum:

- FWHM several thousand km/sec up to 30000 km/sec FWZI (zero intensity)
- derived gas temperatures are several 10^{4-5}, $\Rightarrow c_{\rm s} \simeq \sqrt{k_{\rm B}T/m_{\rm p}} =$ 9 km/sec $(T/10^4$ K$)$
- Doppler broadening through bulk motion of gas in gravitational field
- with velocities as high as 0.1c, the distance from the Black Hole can be as close as 100 $R_{\rm g}$ $(v \propto r^{-1/2})$.
- Comparison of continuum and BLR fluxes indicate that only 10% of the continuum radiation is absorbed by BLR clouds
- The volume filling factor is very low — a few millionth of the central region is occupied by BLR 'clouds'
- The necessary mass in the BLR to produce the observed luminosity is only a few solar masses
- Broad-lines are very smooth — they are either made up of a huge number of small clouds $(R \sim R_\odot,\ N_{\rm c} > 10^9)$ or represent a coherent structure

■ Densities

- Suppression of forbidden lines indicates $n_e > 10^9\mathrm{cm}^{-3}$
  - [OIII] $\lambda\lambda$4363 is absent in the broad-line region, the critical density for collisional de-excitation of the $^1S_0$ level in O^{++} is $\sim 10^8\mathrm{cm}^{-3} \Rightarrow$ lower limit
  - broad CIII]λ1909 is present, critical density for de-excitation of the $^3P_1$ level in C^{++} is $\sim 10^{10}\mathrm{cm}^{-3}$ (upper limit?)
  - reverberation mapping, however, shows this line is further out than Lyα

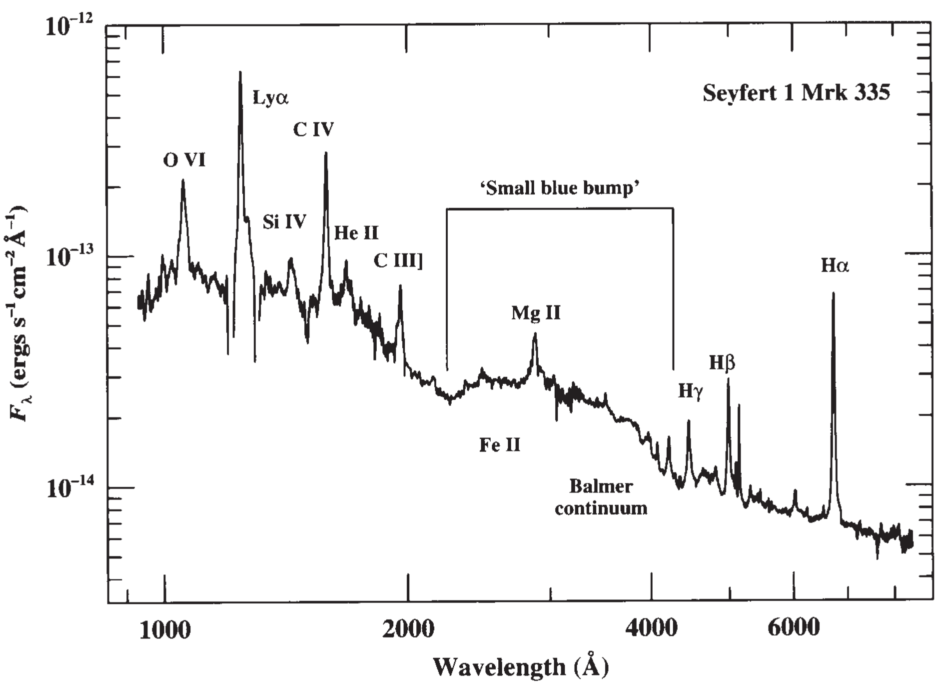
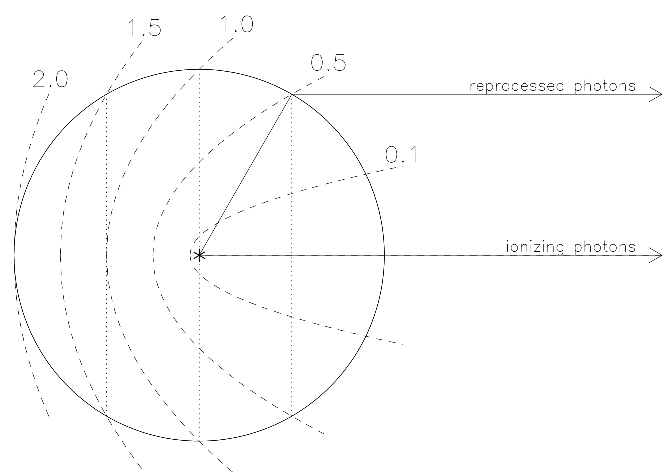


Fig. 5.2. The 'small blue bump', a blend of Balmer continuum and Fe II line emission is prominent in the Seyfert 1 galaxy Mrk 335 (Zheng *et al.* 1995a) and shows up particularly well on a log–log plot. Other strong features are also labeled. Data courtesy of W. Zheng.

■ Reverberation mapping

The size of the BLR can be determined through **reverberation mapping**. If the ionizing continuum in the center varies, the line excitation will change accordingly. The delay between continuum and line-variation will be caused by light-travel time delays and hence are proportional to the distance of the BLR from the (point-like) continuum source. The exact form of the response will also depend on the exact distribution of the ionized gas (hence 'mapping').

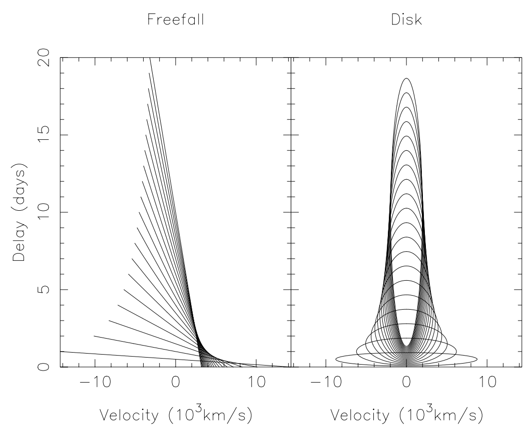


Ionizing photons from a compact source are reprocessed by gas clouds in a thin spherical shell. A distant observer sees the reprocessed photons arrive with a time delay ranging from 0 for reprocessing at the near edge of the shell to 2R/c for reprocessing at the far edge. The iso-delay paraboloids slice the shell into zones with areas proportional to the range of delays (from K. Horne 2001).

Reverberation mapping

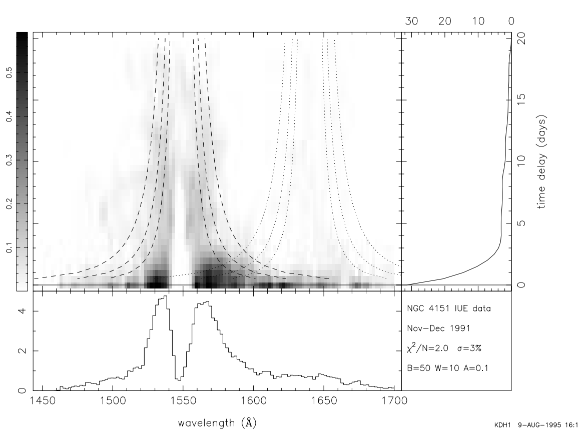
■ Structure

The velocity of BLR clouds as a function of radius should be different for different models of the BLR kinematics. Therefore one should be able to distinguish them in a velocity vs. time-lag diagram.



Velocity-delay map for spherical free-fall and Keplerian disk kinematics. Spherical shells map to diagonal lines, and disk annuli map to ellipses (inclination $i = 60°$; from Horne 2001)

The problem is that one needs very good time coverage and long uninterrupted campaigns to make such maps. Gaps in the light curves lead to spurious features and have to be removed similar to what is done in image reconstruction (e.g. Maximum-Entropy).



*Velocity-delay map of C*IV *1550 emission in NGC4151 recovered by fitting 44 IUE (ultra-violet explorer) spectra. Shown are models for virial motion of clouds for various escape speeds around a black hole (0.5–2·$10^7 M_\odot$). The symmetry rules our purely inflow or outflow (from K. Horne 2001).*

Reverberation mapping

■ Time Lags

Instead of a full mapping procedure one can also just use the time lags observed in various lines.

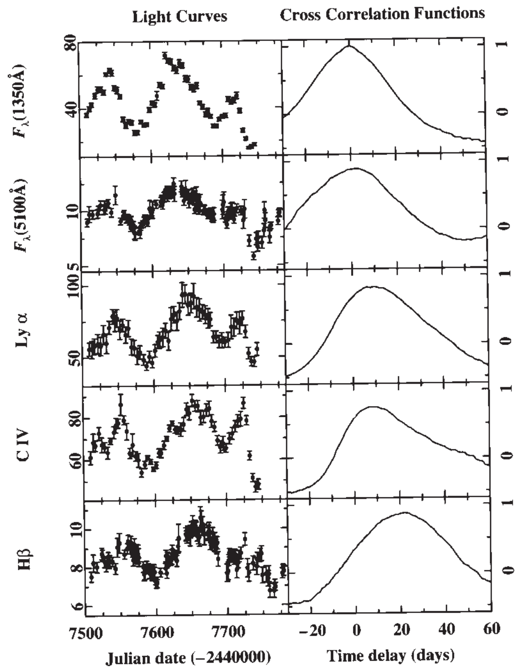


Fig. 5.6. The left-hand column shows continuum and emission-line light curves for the Seyfert 1 galaxy NGC 5548 that were obtained in 1988–89 (Clavel *et al.* 1991, Peterson *et al.* 1991). The ultraviolet (1350 Å) and optical (5100 Å) fluxes (in units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1}) appear to vary in phase. The variations of the strong emission lines (Lyα λ1216, C IV λ1549, and Hβ, in units of 10^{-13} ergs s^{-1} cm^{-2}) show the same general pattern of variations, but with a time delay due to light travel-time effects in the BLR. The time delay is calculated by cross-correlation of each light curve with the 1350 Å light curve. The cross-correlation functions are shown in the right-hand column for each light curve. The panel to the right of the 1350 Å shows the autocorrelation function, i.e., the result of cross-correlating the 1350 Å continuum with itself.

- Lines from highly ionized gas (He II λ1640, C IV λ1549) respond faster than lines from lower ionization levels (e.g. Balmer lines)

⇒ ionization structure in BLR

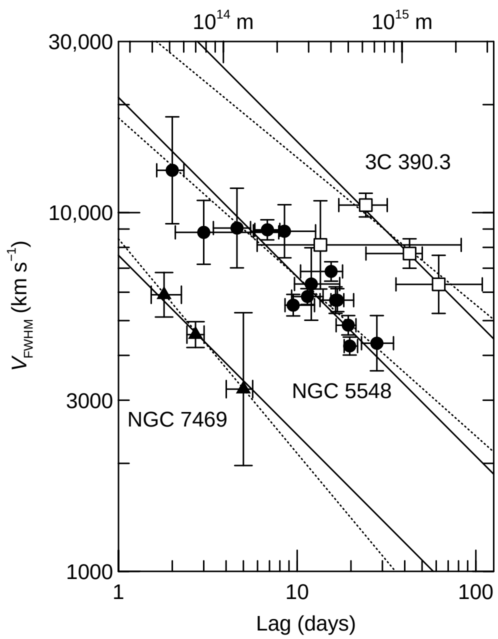
⇒ more highly excited lines are further in

Reverberation mapping

■ Size of BLR

For Keplerian rotation, the FWHM of the lines should correspond to the typical velocity dispersion at the radius where the line is produced.

More highly ionized lines, which are closer in, should have larger FWHM and shorter time-lags.

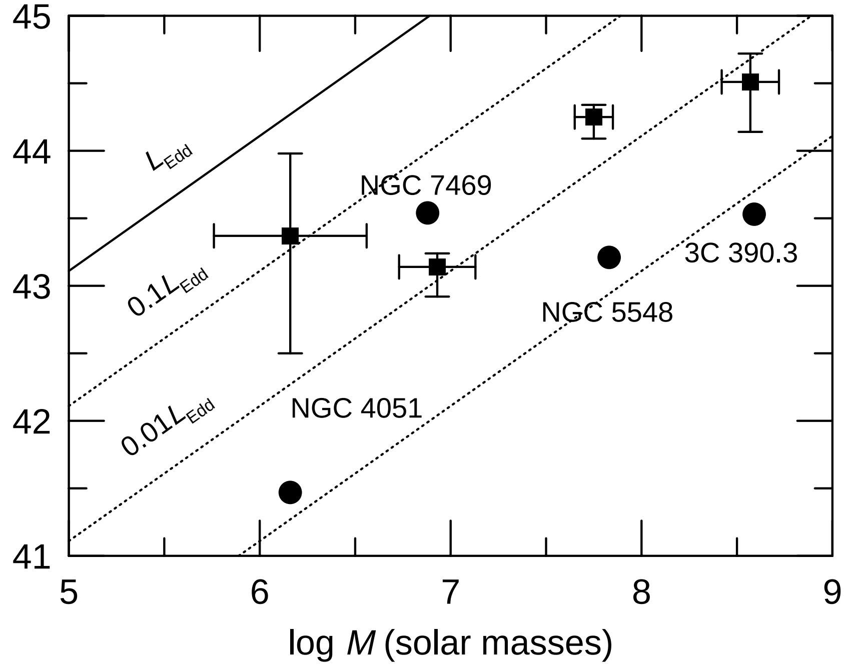


FWHM of different emission lines in three different sources versus the measured time lags w.r.t. the continuum. The solid lines show the $1/\sqrt{\tau}$ *dependence expected for a Keplerian velocity distribution. The interception is proportional to the black hole mass and range from* $6 \cdot 10^7 M_\odot$ *to* $3 \cdot 10^8 M_\odot$ *(from Peterson & Wandel 2000).*

These measurements show that the gravitation in the BLR is dominated by a central dark mass and further strengthens the black hole paradigm.

■ Eddington Luminosities

Comparing the BH mass and luminosity one can also estimate how close the AGN are to the Eddington-limit.



Luminosity vs. virial mass relationship for four AGNs. Squares with error bars denote the ionizing luminosity, with virial masses based on all the lines shown in the previous figure. The filled circles represent L_{vis}, with virial masses based on Balmer lines only, as by Wandel et al. (1999) and Kaspi et al. (2000), with the error bars omitted for clarity. The lines show constant values of the Eddington ratio L/L_{Edd} between 0.001 and 1. (from Peterson & Wandel 2000).

As expected, the Seyfert galaxies and quasars radiate below the Eddington limit.

Reverberation mapping

■ Size of BLR

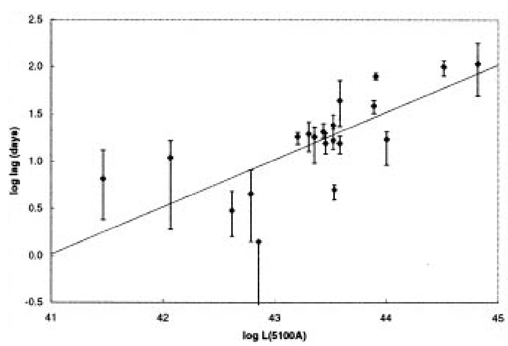
Consider the ionization of a BLR cloud. The excitation is to first oder determined by the number of ionizing photons per particle, parameterized by the ionization parameter:

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

(*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

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



Reverberation centroid lags vs. monochromatic luminosity at 5100 Å. The dotted line shows the best linear fit weighted by the uncertainties in the lag. Formally, the uncertainties in the photo-ionization estimates are the uncertainties in L(5100), which are very small. The intrinsic uncertainties in the photo-ionization estimates are not shown (from Wandel, Peterson, & Malkan 1999).

The size of the BLR indeed seems to be a function of luminosity with the naively expected scaling. Normalized to CIV in NGC 5548:

$$r = 10 \text{ lightdays} \left[\frac{L_\lambda(CIV)}{10^{40}\text{erg sec}^{-1}\,\text{Å}^{-1}}\right]^{1/2}$$

(Multiply with eqivalent width (EW) in $\AA$ to get luminosity.)

■ Mass and Filling Factor

Take, as an example, the C IV emission of a Seyfert galaxy. The emissivity in the line is:

$$j(C\text{IV}) = n_e n_{C^{3+}} q \frac{h\nu}{4\pi}$$

(j: emissivity in erg sec^{-1} cm^{-3} ster^{-1}; q: is the collisional excitation rate $\sim 2.6 \cdot 10^{-9}$ cm^3 s^{-1}; Osterbrock 1998)

$$\begin{aligned} L(C\text{IV}) &= \int\int j(C\text{IV}) d\Omega dV \\ &= \frac{4\pi r^3}{3} \varepsilon n_e n_{C^{3+}} q h\nu \\ &\simeq \varepsilon r^3 n_e^2 \, 4.6 \cdot 10^{-23} \text{erg s}^{-1} \end{aligned}$$

(for cosmic abundance of C – all triply ionized; ε: volume filling factor)
Assume spherical clouds of radius l in spherical BLR with radius r:

$$\varepsilon = \frac{N_\mathrm{c} \cdot 4\pi l^3/3}{4\pi r^3/3} = \frac{N_\mathrm{c} l^3}{r^3}$$

The radius of the BLR from reverberation mapping is

$$r = 2 \cdot 10^{16} \,\text{cm}\; h_0 L_{42}^{0.5}(C\text{IV})$$

for $L(C\text{IV}) = L_{42}(C\text{IV}) \cdot 10^{42}$ erg s^{-1}.

$$\Rightarrow \varepsilon = 2.7 \cdot 10^{-7} h_0^{-3} L_{42}^{-0.5}(C\text{IV})$$

for a density of 10^{11} cm^{-3}.

The BLR is highly filamentary or clumpy.

■ Mass and Filling Factor

Using

$$\begin{aligned} L(C\,\textrm{IV}) &\simeq \varepsilon r^3 n_e^2 4.6\cdot 10^{-23}\textrm{erg s}^{-1} \\ L(C\,\textrm{IV}) &= L_{42}(C\,\textrm{IV})\cdot 10^{42}\,\textrm{erg}\,\textrm{s}^{-1} \end{aligned}$$

we get

$$\varepsilon r^3 = 2.2\cdot 10^{64} n_e^{-2} L_{42}(C\,\textrm{IV})$$

The total mass of the BLR is then

$$\begin{aligned} M_{\textrm{BLR}} &= \frac{4\pi}{3} l^3 N_c n_e m_p \\ &= \frac{4\pi}{3} \varepsilon r^3 n_e m_p \\ &= 1.5\cdot 10^{41} n_e^{-1} L_{42}(C\,\textrm{IV}) \\ &= 10^{-3} M_\odot\, L_{42}(C\,\textrm{IV}) \end{aligned} \tag{1}$$

The mass needed in the BLR is tiny!

Assuming the BLR clouds are distributed on a shell of radius r and are non-overlapping, we get a sky-covering factor of

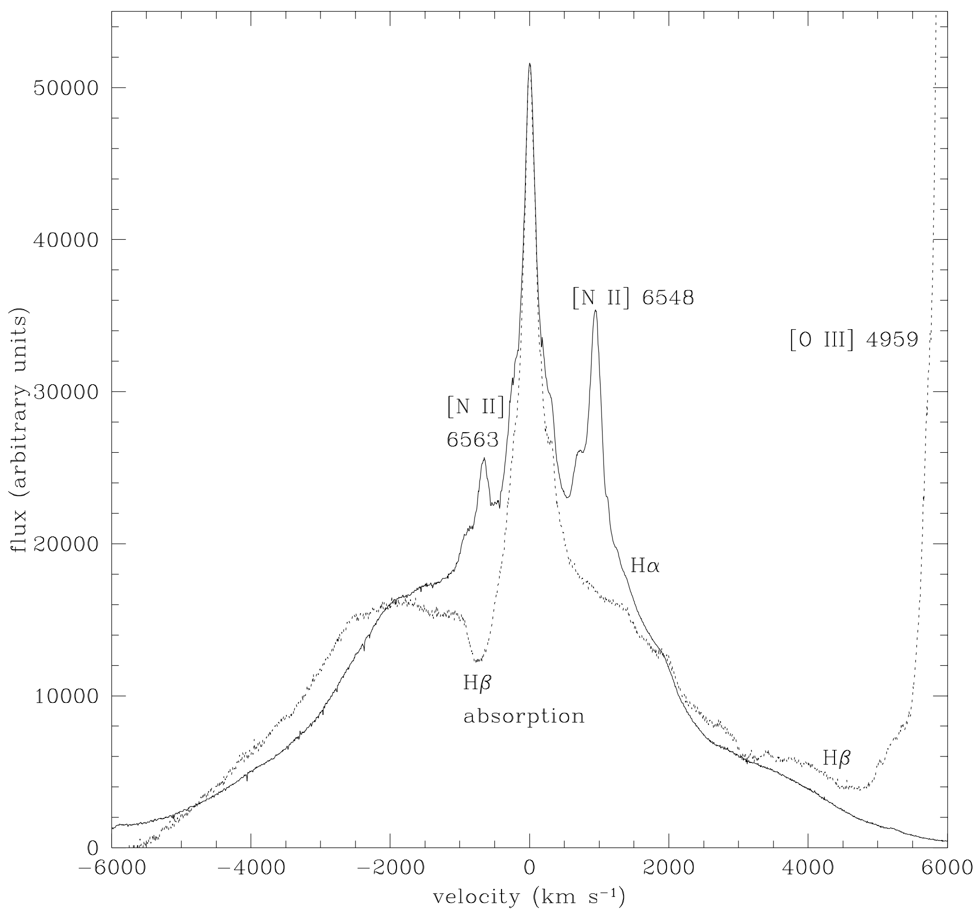
$$\simeq \frac{N_c \pi l^2}{4\pi r^2} \simeq \frac{N_c l^2}{1.6\cdot 10^{33}} \simeq 0.1$$

for a BLR radius of 8 light days (or $2\cdot 10^{16}$ cm), or

$$N_c \left(\frac{l}{R_\odot}\right)^2 \simeq 3\cdot 10^{10}$$

■ Structure of BLR

A high number of BLR clouds or a filamentary structure with velocity gradients is also indicated by the smoothness of the BLR profile.



High-resolution Keck-spectra of emission-lines in NGC4151 showing their smoothness. Cross-correlation of Hα and Hβ shows that at least $3 \cdot 10^7 - 10^8$ *discrete clouds would be needed to reproduce this (from Arav et al. 1998).*

In some cases, like NGC4151, the upper limit on the number of dicrete clouds is even below the lower limit required from an analysis of the line profiles.

■ Narrow-Line Region

- FWHM of typically 400-500 km/sec
- forbidden-lines, low densities 10^{2-4}
- total mass in NLR can be several million solar masses
- size $\gtrsim$ 100 pc - resolved in many Seyfert galaxies
- excess blue-ward flux $\Rightarrow$ radial (outflow) plus attenuation (of back side) through dust?

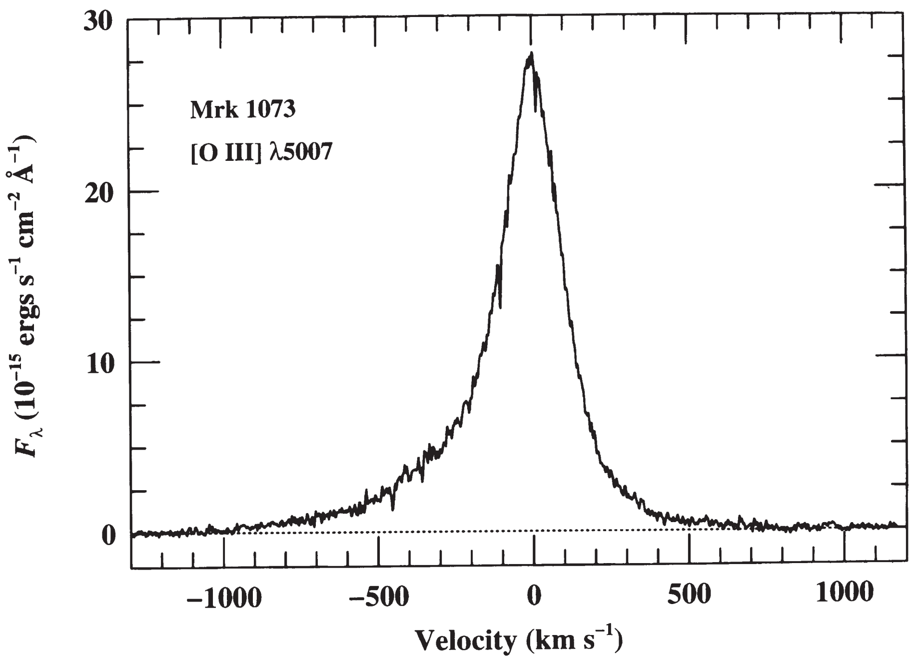


Fig. 6.5. The [O III] λ5007 emission-line profile in the Seyfert 2 galaxy Markarian 1073 (Veilleux 1991) at a resolution of 10 km s^{-1}. The line is asymmetric about the peak (which is defined to be $v = 0$), with more flux shortward than longward of line center. Data courtesy of S. Veilleux.

- in many cases HST sees a highly structured NLR with signs of significant jet impact

(Figures: HST Images of NLR in Seyferts ...)