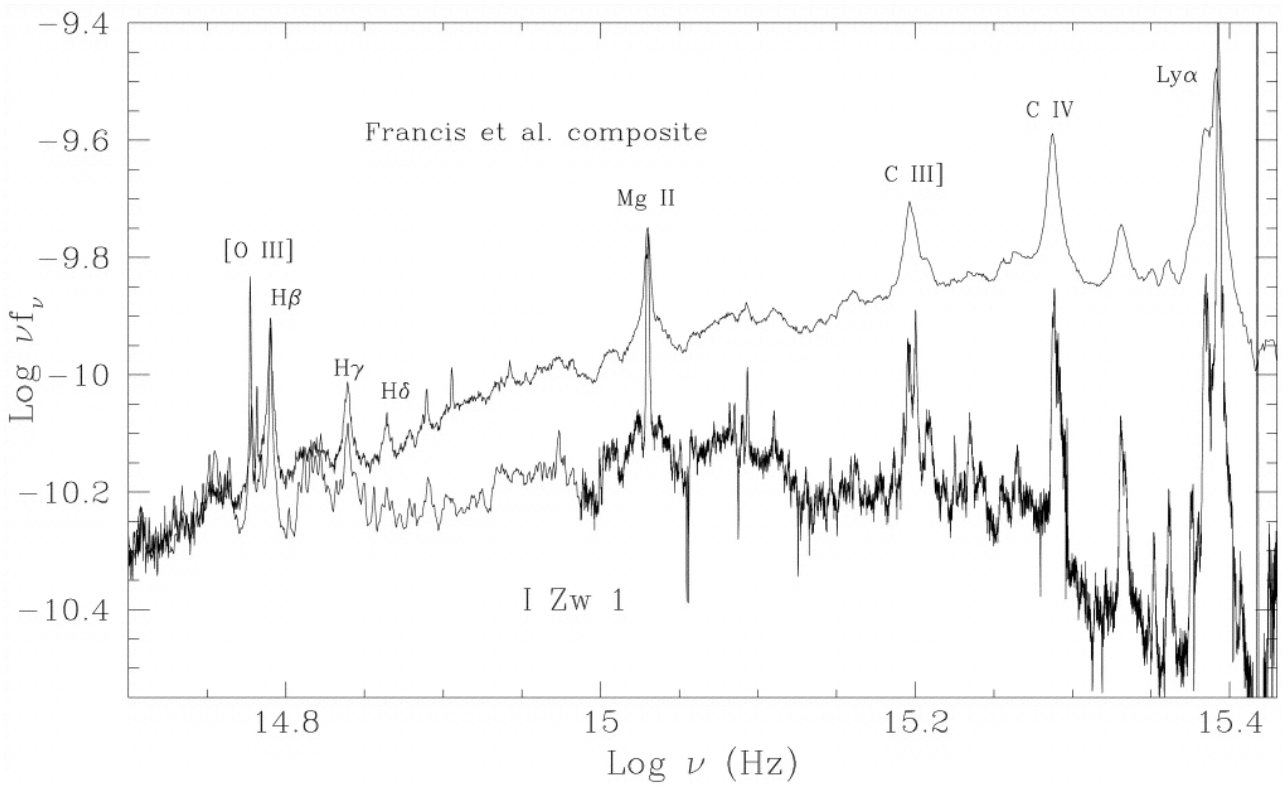
AGN II: DIAGNOSTICS

- Photo-ionization (BLR/X-ray absorber)
- BLR physical properties
- BLR size and velocity field
- NLR properties

Optical emission lines from:
BLR = Broad Line Region (~few 1000 km s^{-1})
NLR = Narrow Line Region (~few 100 km s^{-1})

AGN LINE SPECTRUM



Line naming example: CIII] λ1549

Element

Ionization state

Indicates line is "forbidden"

Wavelength

Correlation of L(Hβ) with continuum

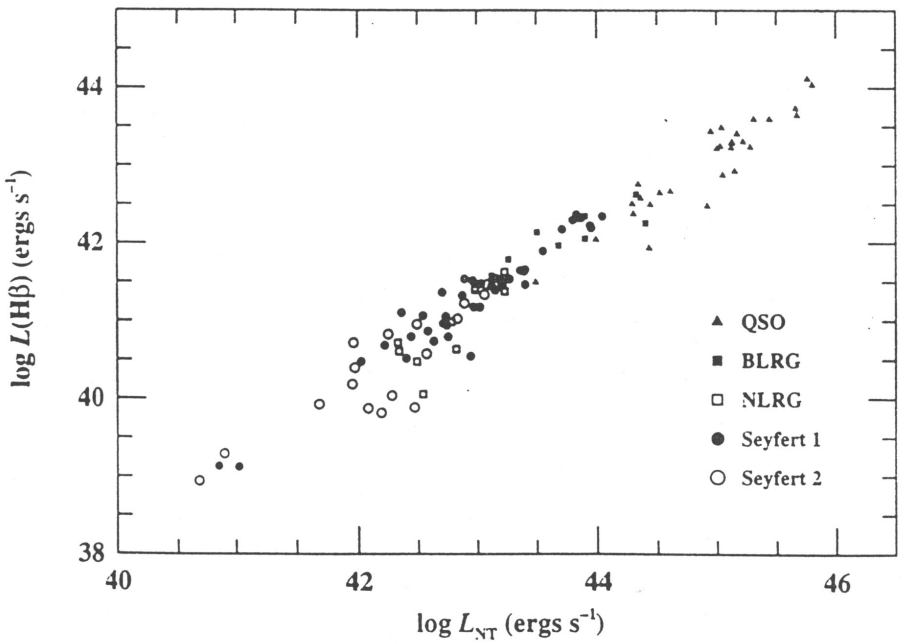


Fig. 5.7. The total Hβ line luminosity is proportional to the AGN continuum luminosity (here called the 'non-thermal continuum luminosity' L_{NT}) over the entire range of AGN luminosities. Values of $h_0 = 1$ and $q_0 = 0.5$ (see Chapter 9) are assumed. Adapted from Yee (1980).

PHOTOIONIZATION

- **Broad emission line** intensities are correlated with the continuum luminosity, implies photoionization rather than collisional ionization.
- **Photoionization equilibrium**: number of ionizations per second = number of recombinations per second.
- **Ionization parameter** characterizes the ionization state of the gas.

$$U = Q/(4\pi R^2 c n_e)$$

  - Q = number of ionizing photons emitted per second; R is the distance of the gas "cloud" from the ionizing source. n_e is the density of the cloud.
  - U is the ratio of ionizing flux at the face of the cloud (controls ionization rate) to the density (controls recombination rate).
- **Temperature** of the plasma determined by thermal equilibrium (Heating = Cooling). Heating mainly Compton heating. Cooling by bremsstrahlung but mainly emission lines produced by recombination of ionized atoms.

X-RAY EVIDENCE FOR PHOTOIONIZATION

- Line-of-sight absorption leaves imprints of absorption edges in the X-ray spectrum.
- Mainly oxygen and iron edges observed.
- The edge energy depends on the ionization state, with more highly ionized atoms showing higher energy edges (due to reduction in shielding).
- Thus measuring edge energies and depths gives constraints on the ionization parameter.

X-RAY “WARM ABSORBER”

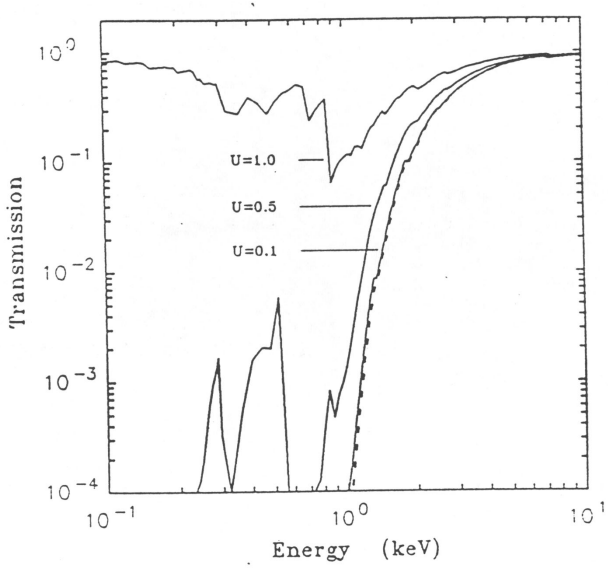


Figure 5.9 The fraction of flux transmitted by a single-cloud warm absorber model, as a function of energy. The cloud has a column density of 50 $\times 10^{21}$ cm^{-2} , is photoionized by the continuum of NGC 4151 (with $\Gamma = 1.7$ and a γ-ray cut-off of 1 MeV) and is assumed to be in radiative thermal equilibrium. The solid curves correspond to values of the ionization parameter , U, of 0.1, 0.5 and 1.0 (as indicated). The dashed curve corresponds to an ionization parameter of 0.01 (i.e. almost 'cold'). Note that, due to electron scattering, the transmission is never 1.0.

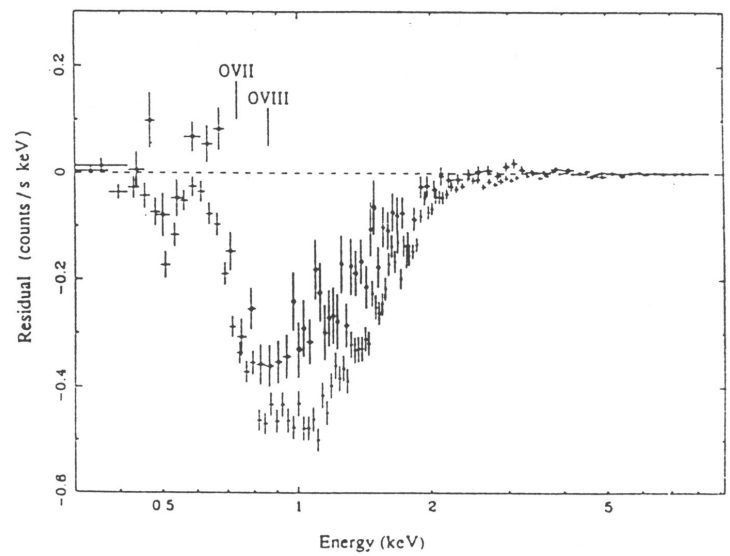


Fig. 2. Comparison of the residuals from the spectra shown in figure 1. Note that the drop in counts sets in at the O VII edge. There may also be possible features at lower energy (C VI and N VI) and at higher energy (O VIII and Ne IX).

ABSORPTION EDGE ENERGIES

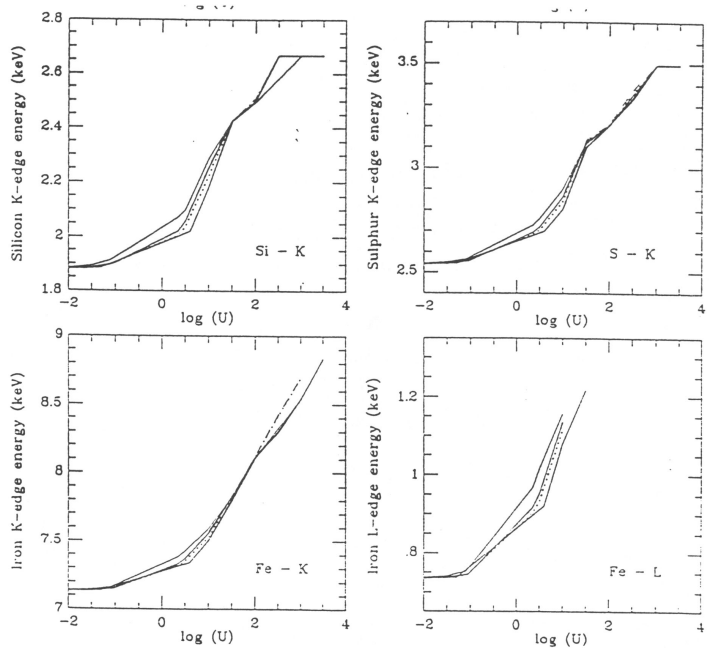


Figure 5.11 The K–edge energies due to Oxygen, Neon, Silicon, Sulphur and iron, as a function of ionization parameter, in the spectrum emerging from a cloud photoionized by the 'mean' AGN continuum. Also shown is the L–edge energy of iron. Calculations have been performed assuming radiative equilibrium. The solid curves correspond (from top to bottom) to cloud column densities of 25, 50 and 100 $\times 10^{21}$ cm^{-2}, an X-ray photon spectral index of 1.7 and a γ-ray cut-off of 100 keV. The dotted curves correspond to a cloud column density of 50 $\times 10^{21}$ cm^{-2} , an X-ray photon index of 1.5 and a γ-ray cut-off of 100 keV. The dashed curves correspond to a cloud column density of 50 $\times 10^{21}$ cm^{-2} , an X-ray photon index of 1.7 and a γ-ray cut-off of 500 keV. All models have a neutral Hydrogen density of $10^{9.5}$ cm^{-3}.

BLR COVERING FRACTION

- Absorption only in line of sight. Need to measure emission to determine covering fraction.
- BLR clouds are “optically thick” to ionizing continuum ($\tau=\sigma N_H >>1$ ie. the probablity of absorption is very high)
- If so, photoionization of H-atom ultimately results in a Lyα photon (n=2 to n=1 transition)
- Thus can predict Lyα strength (Equivalent Width) wrt continuum theoretically. If BLR completely covers the ionizing source, this value is 580Å.

OBSERVED value ~10% of predicted value

$\Rightarrow$ BLR covering fraction = 10%

EQUIVALENT WIDTH

ABSORPTION LINE

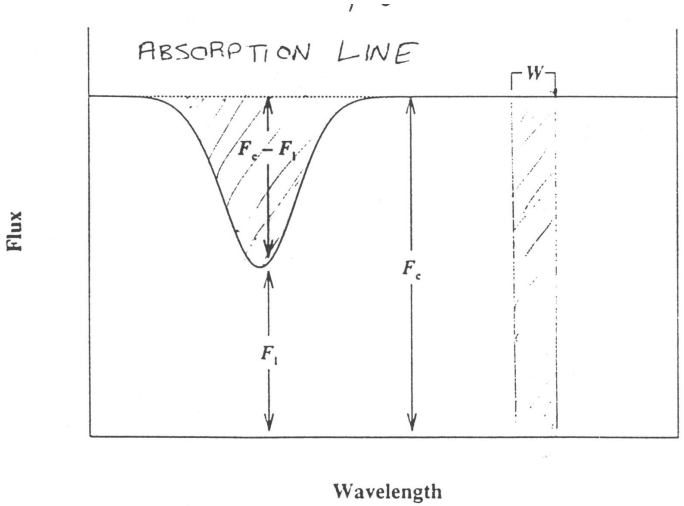
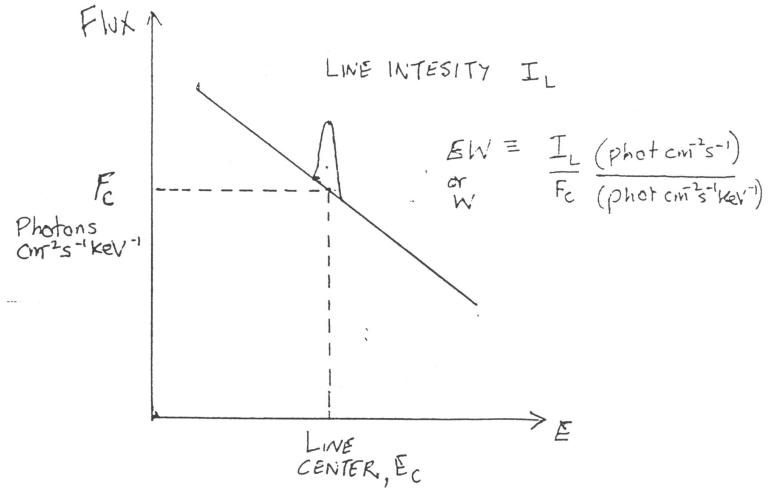


Fig. 12.1. The equivalent width W of an absorption line, as defined by eq. (12.11). The shaded areas of the two lines shown are the same: the amount of energy absorbed by the Gaussian profile on the left is equivalent to that absorbed by an idealized rectangular absorption feature of width W, which is measured in wavelength units.

EMISSION LINE



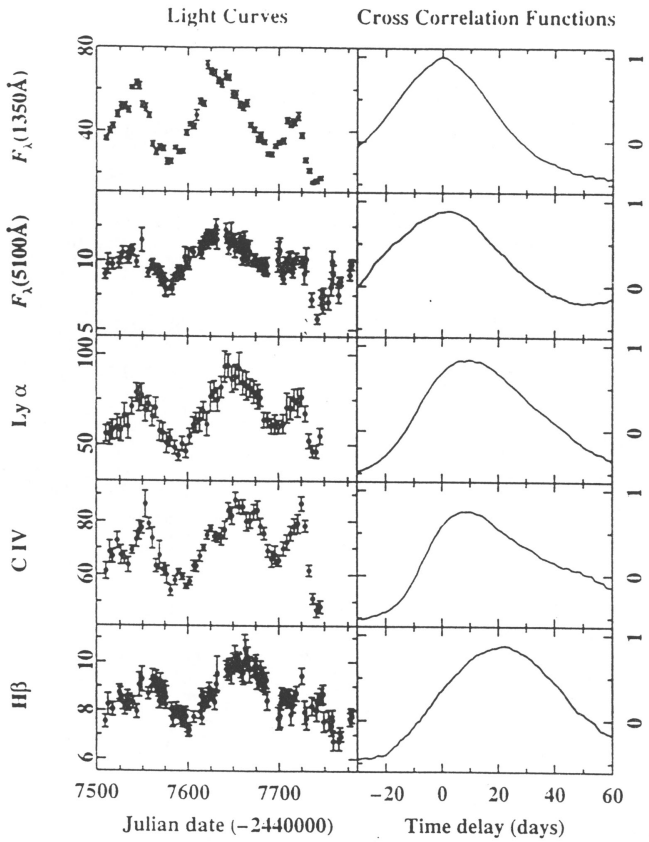
BLR SIZE: REVERBERATION MAPPING

- **BASIS:** Measure time lags between continuum and emission lines. Size of lag gives distance between continuum and line region
- **ASSUMPTIONS:**
  - Ionic recombination timescale negligible (time taken to emit line photon after continuum photon is absorbed: $t_{rec} \sim 40\ n_{11}$ sec)
  - Continuum size << BLR size
  - BLR filling factor is small (ie clouds occupy a small fraction of the available volume)
  - Simple relationship between the OBSERVED continuum and the REAL ionizing continuum (which is in the EUV and unobservable)
  - Time scale for BLR to chance geometry << light crossing time. Former is ~dynamical timescale ~time for cloud to travel BLR radius. The ratio is $\sim c/v_{FWHM} \sim 100$ so this works
- **OBSERVATION:** Observe variations in line and continuum and use cross-correlation to deduce time delay

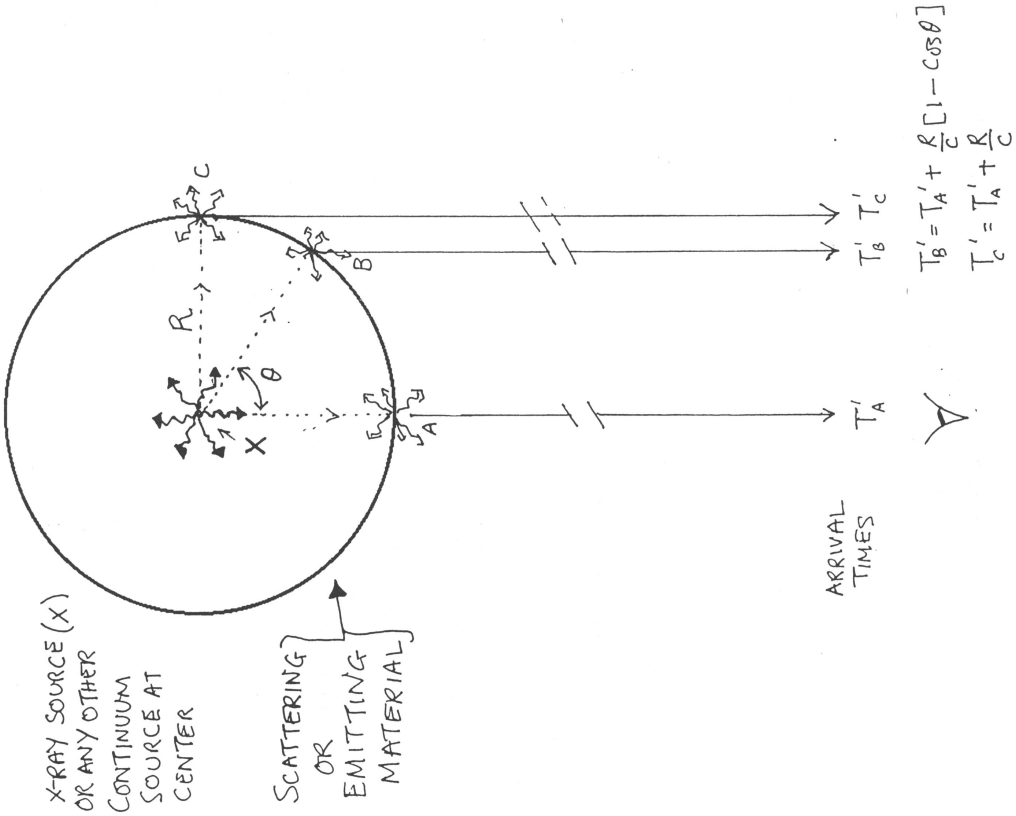
REVERBERATION MAPPING OF NGC 5548

Table 5.2
NGC 5548
Cross-Correlation Lags

Feature	τ (Days)
N v λ1240	2
He II λ1640	2
'Small blue bump'	6
He II λ4686	7
He I λ5876	9
Lyα λ1216	10
C IV λ1549	10
Hγ λ4340	13
Hα λ6563	17
Hβ λ4861	20
C III] λ1909	22



TIME DELAY FROM A SPHERICAL EMITTING SHELL



MASS OF BLACK HOLE

- If BLR gas is gravitationally bound in Keplerian orbits:

  $mv^2/R = GMm/R$

  $v = \sqrt{GM/R}$ *or*

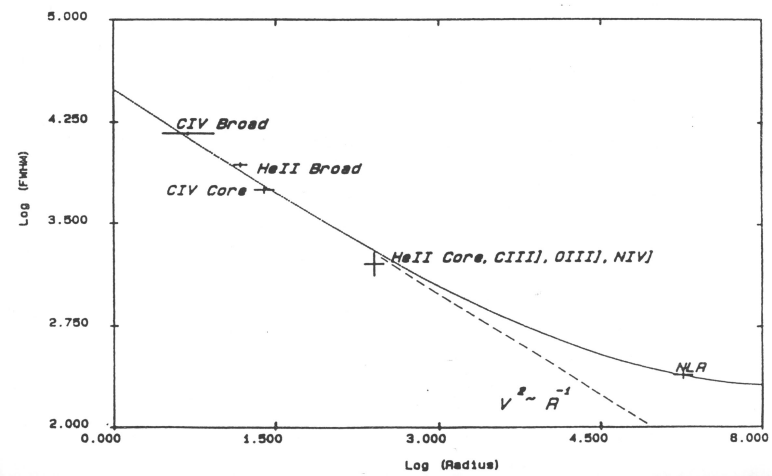
  $v/c = \sqrt{R_g/R}$

  R_g=gravitational radius = $1.48 \times 10^{13}\ M_8$ cm

  M_8 is mass in units of 10^8 solar masses
- Velocity v is known from width of line. R is known from time delay. Therefore can calculate mass.

CENTRAL MASS

- Can estimate mass using FWHM and radius of a single line, but it is better to plot FWHM vs. width for several lines and obtain mass from the correlation. Should follow $v_{FWHM} \propto R^{-0.5}$



BLR SIZE-LUMINOSITY RELATION

- Line spectra of AGN similar over several orders of magnitude in luminosity. Suggests that U and n_e are the same

  $$Un_e = Q/(4\pi R^2 c) = \text{const.}$$

  or

  $$r \propto L^{0.5} \quad (\text{as } L \propto Q)$$

- Can obtain proportionailty constant from the data

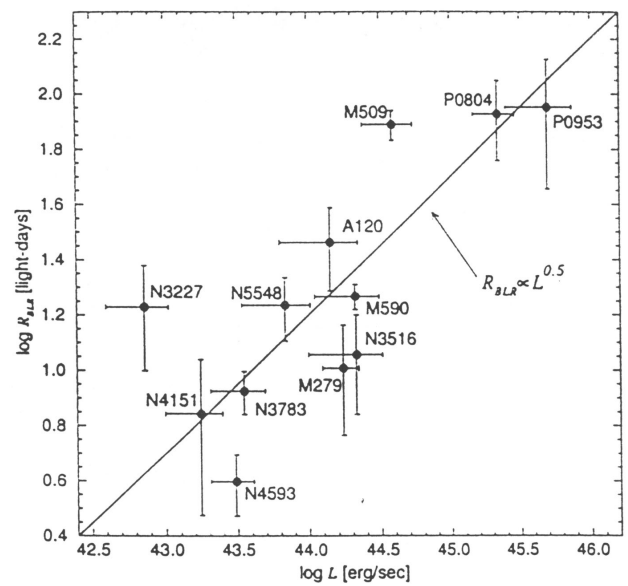


FIG. 4.—BLR radius–luminosity relation. All sizes based on Balmer-line lags. References: NGC 5548, Korista et al. (1995) and references therein; NGC 4151, Maoz et al. (1991) and Kaspi et al. (1996); NGC 3227, Salamanca et al. (1994); NGC 3783, Stirpe et al. (1994a); Akn 120, Peterson (1988) and Peterson & Gaskell (1991); Mrk 279, Maoz et al. (1990) and Stirpe et al. (1994b); NGC 3516, Wanders et al. (1993); Mrk 590, Peterson et al. (1993); NGC4593, Dietrich et al. (1994); Mrk 509, Carone et al. (1996); PG 0804+762 and PG 0953+414, this work.

MORE LINE DIAGNOSTICS

- Strengths and Ratios of emission line can give important constraints on physics of emission regions. Examples:
  - Can divide lines into two classes of “permitted” or “forbidden”. Forbidden lines have low radiative transition probability as they are collisionally suppressed. Higher density means more collosions, therefore there is a critical density above which no line is emitted. EXAMPLE CIII]λ1909 has critical density 10^{10} cm^{-3}. Broad CIII]λ1909 is observed. Therefore some gas has n_e less than this. Critical density of OIII]λ4363 is 10^8 cm^{-3}. Broad OIII]λ4363 is NOT observed. Therefore density of BLR> 10^8 cm^{-3}.
  - Hα/Hβ is a “redenning” indicator (also called the Balmer decrement). Ratio should be fixed by atomic physics, but Hβ is more suppressed by dust absorption than Hα. This ratio gives a measure of the dust.
  - Other ratios sensitive to density, temperature, abundance etc.

2.6. The hydrogen energy spectrum

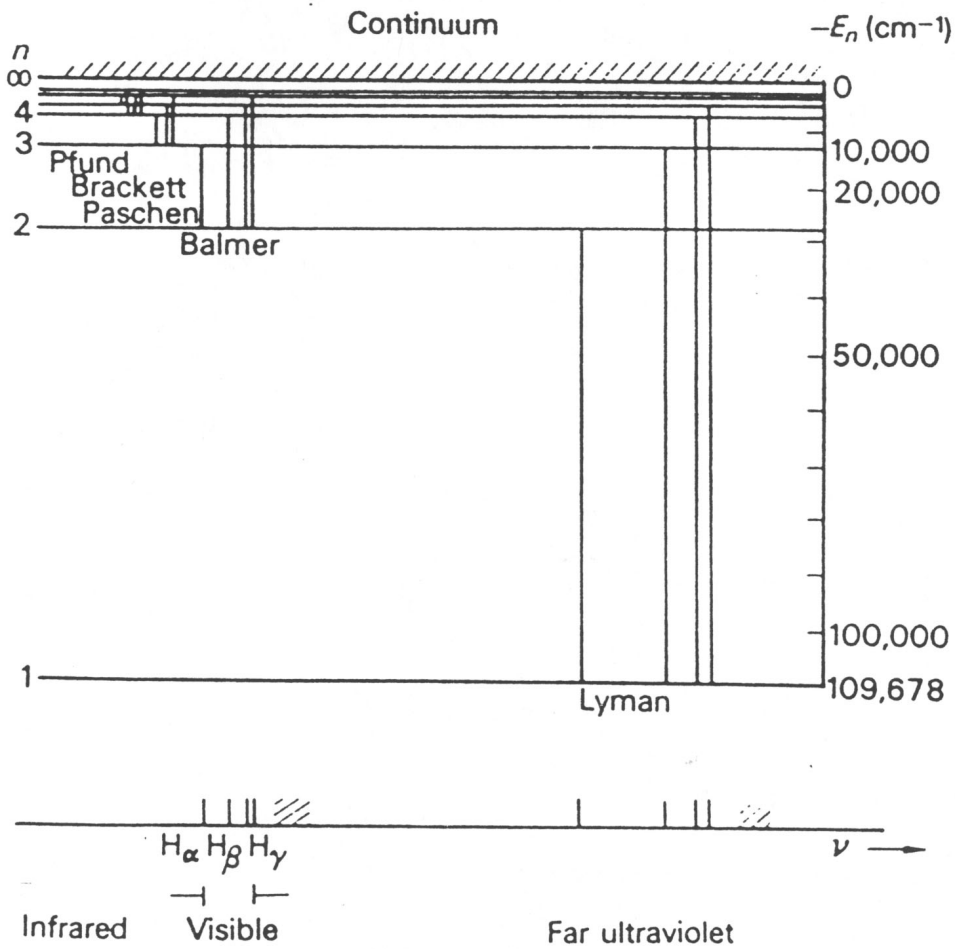


Fig. 2.3. Energy level diagram for hydrogen.

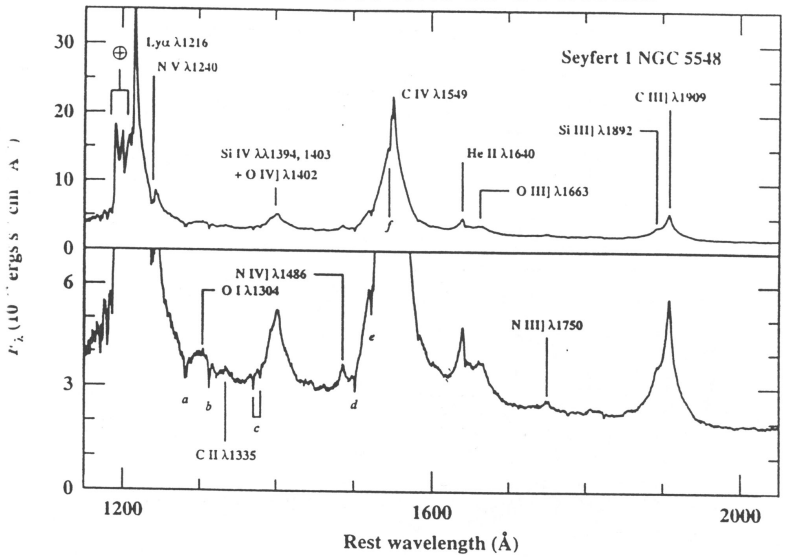
BLR STRATIFICATION

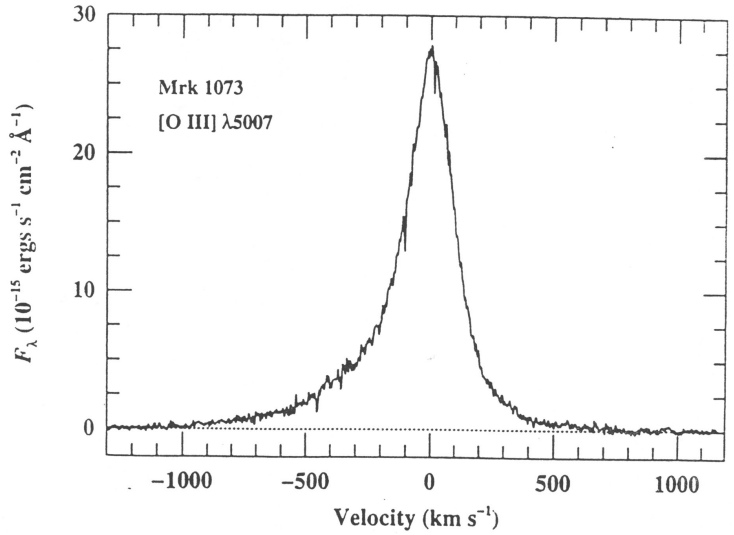
- High ionization lines are broader than low ionization lines. He II λ1640, CIV λ1549 and NV λ1240 are broader and have higher ionization potential than, e.g. Balmer lines (Ha, Hb) and CIII]λ1909.
- Reverberation mapping shows that time lags of high ionization lines are shorter than low ionization lines
- Higher ionization lines are produced closer to the continuum source, hence gas more highly ionized
- Thus the BLR is not a single region, but “stratified”
- Also density in inner BLR probably very high

BLR VELOCITY FIELD

- Line profiles/asymmetry
  - Inflow: red asymmetry
  - Outflow: blue asymmetry
  - But if you see the other side (beyond the central source) then there may be the opposite effect!
  - Absorption there may be attenuation of line emission by, e.g. dust or resonance absorption lines. Complicates matters.
- Observations
  - Blue and red asymmetries both observed
  - Profile of same line different in different AGN
  - Profiles of different lines in same AGN are different
  - Inconclusive: profiles can be made by a variety of dynamical models.
  - “2D” reverberation mapping may be the key

TYPICAL LINE PROFILE





NLR DIAGNOSTICS

(easier than BLR as the density is lower)

- **DENSITY:** Flux ratio of two forbidden lines that arise from closely spaced level de-exciting to the same lower level. Don't need to worry about chemical composition or ionization differences. Flux ratio depends only on density and atomic physics. Typically $n_e \sim 10^3 - 10^6$ cm^{-3}.

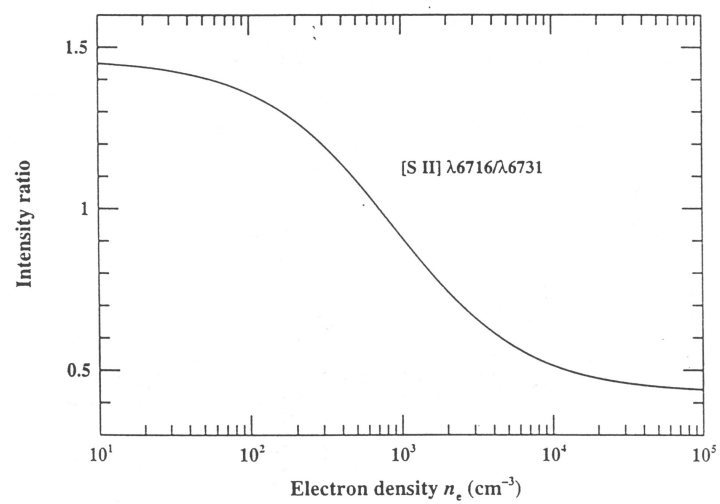


Fig. 6.2. The [S II] λ6716/[S II] λ6731 intensity ratio is a sensitive function of the electron density over the range 10^2 cm^{-3} $\lesssim n_e \lesssim 10^4$ cm^{-3} as depopulation of the upper levels changes from being primarily radiative at low densities to primarily collisional at high densities. The 'critical density' that marks the transition between these two regimes is a function of the Einstein coefficient A_{21} and cross-section for collisional de-excitation σ_{21}, which differ from line to line. The intensity ratio of these lines can be used to determine n_e as long as both lines are not in either the low or high density limit. Data courtesy of R. W. Pogge, based on atomic data from Cai and Pradhan (1993). The values given here are for $T_e = 10^4$ K.

NLR DIAGNOSTICS

- **TEMPERATURE:** Flux ratio of two forbidden lines that arise from levels widely spaced in ionization potential. Ratio depends predominantly on temperature. Typical temperatures for the NLR are 10^4 K

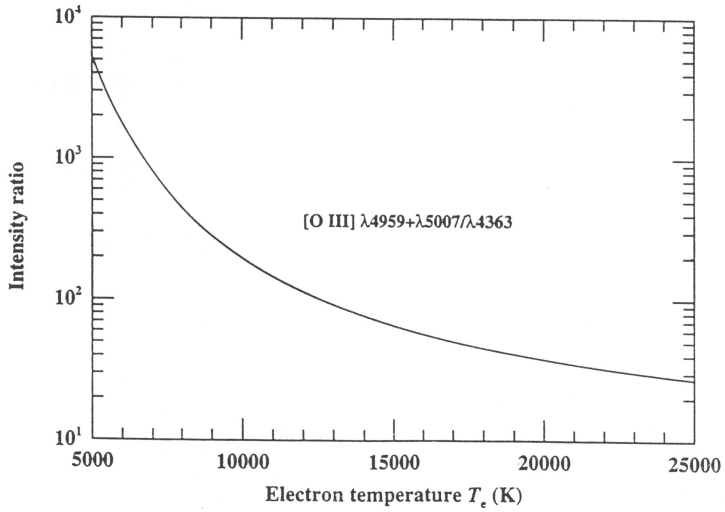


Fig. 6.4. The dependence of the [O III] λλ4959, 5007/[O III] λ4363 intensity ratio on electron temperature T_e, as given in eq. (6.12) for negligible density ($n_e = 0$). Adapted from Osterbrock (1989), p. 120.