AGN Taxonomy

Introduction

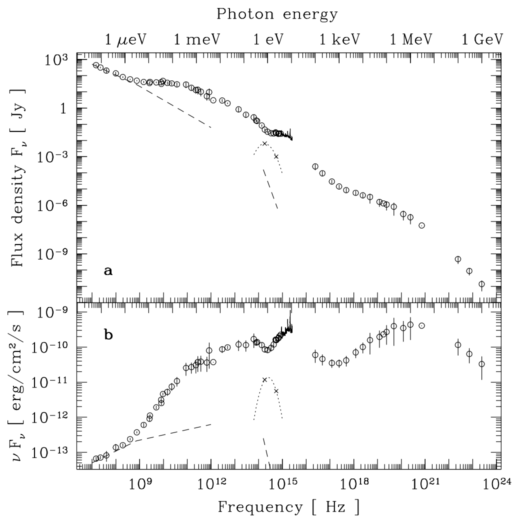
Purpose of this lecture: Phenomenology of AGN

Structure:

1. Broad band continuum of AGN
2. The AGN Zoo
   (a) Seyfert galaxies
      - Reminder: Atomic Physics of Line Emission
      - Seyfert Line Emission
   (b) Quasars, QSOs
   (c) Radio Galaxies:
   (d) Fanaroff-Riley classification
   (e) BL Lacs, OVVs, Blazars
   (f) The Unification Paradigm

See Urry & Padovani (1995) and Lawrence (1987) for the gory details.

AGN Continua



Türler et al. (1999): Spectral Energy Distribution (SED) of 3C 273

AGN Broad Band Spectra are Powerlaws

The observed flux density, F_ν, is roughly

$$F_\nu \propto \nu^{-\alpha} \tag{3.1}$$

where $\alpha \sim 1$

$\Longrightarrow \nu F_\nu$-spectrum is flat.

Continuum: Nomenclature

Continua of AGN often resemble power law spectra:

$$F_\nu = C\nu^{-\alpha} \tag{3.1}$$

where

- F_ν: observed flux density (units: $\mathrm{erg\,s^{-1}\,Hz^{-1}}$).
- α: energy index
- C: some constant

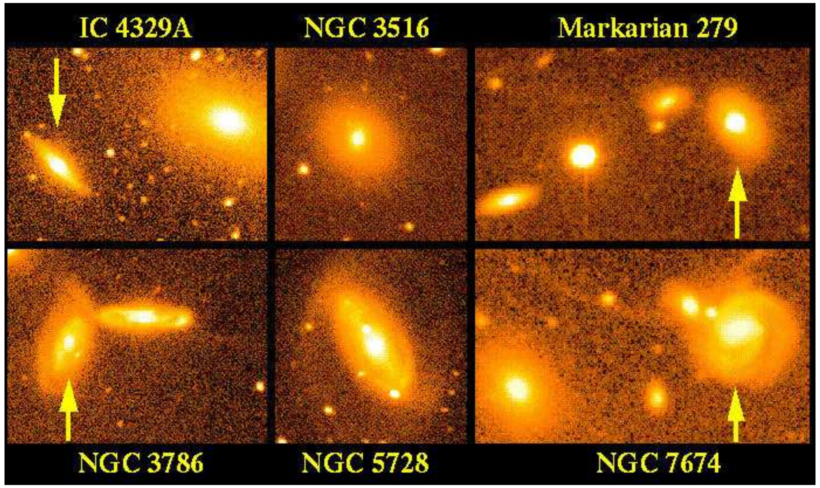
Power recieved in frequency range ν_1 to ν_2:

$$P = \int_{\nu_1}^{\nu_2} F_\nu \, d\nu = \begin{cases} \frac{C}{1-\alpha}\left(\nu_2^{1-\alpha} - \nu_1^{1-\alpha}\right) & \text{for } \alpha \neq 1 \\ C \ln\left(\frac{\nu_2}{\nu_1}\right) & \text{for } \alpha = 1 \end{cases} \tag{3.2}$$

Constant νF_ν implies: same amount of energy emitted per frequency decade $\Longrightarrow$ nonthermal emission.

X-ray astronomy generally uses photon index, Γ, where $\Gamma = \alpha + 1$.

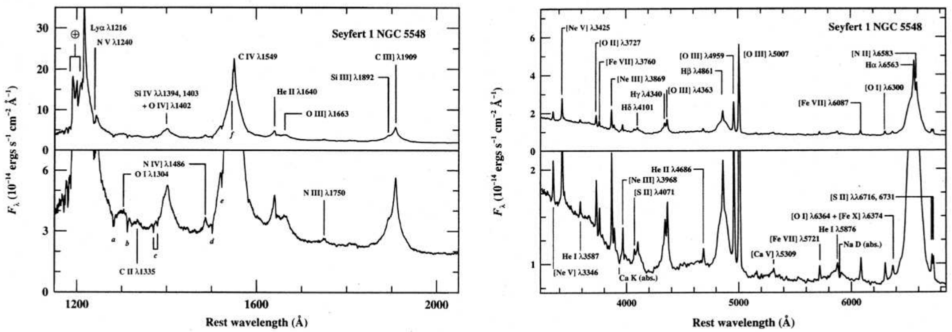
Seyfert Galaxies: Optical Images



W. Keel

Seyfert galaxies: point-like centers of galaxies, generally host galaxy detectable.

Seyfert 1: Optical Spectrum

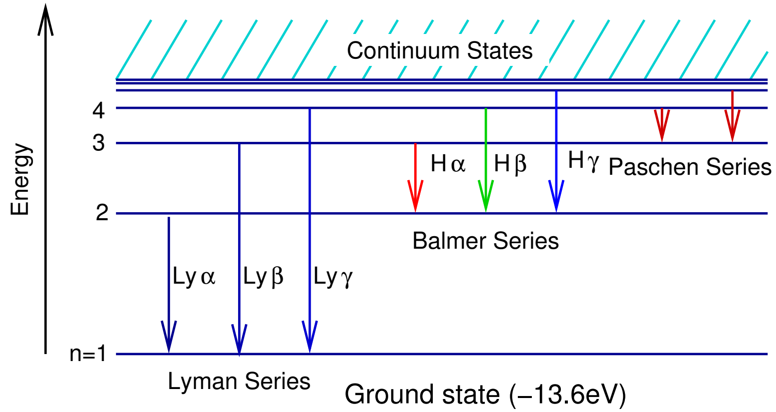


(Peterson, 1997)

UV/optical spectrum of NGC 5548: a typical Seyfert 1 Galaxy.

Before interpreting Seyfert spectrum: need to take quick look at atomic physics and spectroscopic notation.

Reminder: Atomic Physics, I

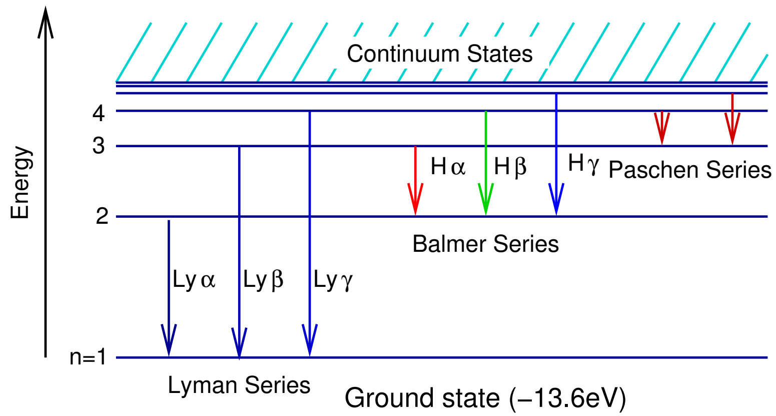


Quantum mechanics: Energy of electron's bound to nucleus is quantized.

For the Hydrogen atom:

$$E_n = -\frac{2\pi^2\mu e^4}{\hbar^2} \cdot \frac{Z^2}{n^2} \qquad (3.3)$$

Reminder: Atomic Physics, II



Line emission: electrons excited into orbit n_2, transit back into orbit n_1 ($n_2 > n_1$):

$$h\nu_{21} = E_{n_2} - E_{n_1} = \frac{2\pi^2\mu e^4 Z^2}{\hbar^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \qquad (3.4)$$

where the constant is called 1 Rydberg, $1\,\mathrm{Ry} := 2\pi^2\mu e^4/\hbar^2 \sim 13.6\,\mathrm{eV}$.

Reminder: Atomic Physics, III

In multi-electron atom, specifying principal quantum number, n, is not enough.

$\Longrightarrow$ State of each electron described by set of quantum numbers:

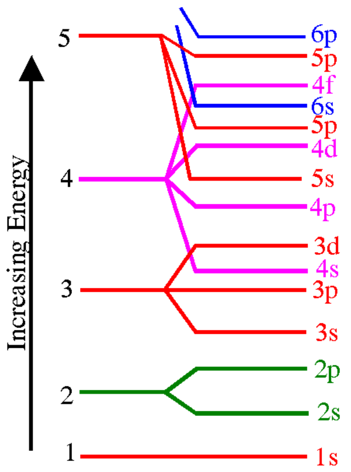
n: principal quantum number, $n = l+1, l+2, \dots$

l: angular momentum quantum number, $l = 0, 1, 2, \dots$

m: magnetic quantum number, $m = -l, -l+1, \dots, l-1, l$

m_s: spin quantum number, $m_s = \pm 1/2$

Reminder: Atomic Physics, IV



http://WWW.BHS.BERKELEY.K12.CA.US/departments/science/chemistry/amosslee/chapter6/overlap.GIF

Quantum numbers define Atomic Structure.

Typical notation:

$l =$	0	1	2	3	(subshell)
	s	p	d	f	
$n =$	0	1	2	3	(shell)
	K	L	M	N	

Figure shows order of filling from QM calculations

Note that $4s$, $5s$,... out of order $\Longrightarrow$ s-subshell closer to nucleus. Reason: effective potential gives more binding energy to electrons close to nucleus!

For example, Sodium ($Z = 11$) ground state configuration

Na: $1s^2\, 2s^2\, 2p^6\, 3s^1$

(upper indices denote number of electrons).

Filled shells do generally not participate in producing lines $\Longrightarrow$ only give valence electrons, e.g., by writing [Ne] $3s^1$ for the above configuration. Furthermore, the "1" is often omitted: [Ne] $3s$.

Reminder: Atomic Physics, V

To specify state of ion: take into account electrostatic interaction between electrons and spin orbit interaction.

QM perturbation theory: Total state of ion determined from combining spin and orbital angular momenta:

$$\boldsymbol{S} = \sum_i \boldsymbol{s}_i \qquad \text{and} \qquad \boldsymbol{L} = \sum_i \boldsymbol{l}_i \tag{3.5}$$

and then forming total angular momentum

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S} \tag{3.6}$$

following quantum mechanical combination rules. This is called LS-coupling or Russell-Saunders coupling. A combination of S and L is called a "term" or "multiplet".

Result for energy: Hund's rules:

1. Terms with larger S have lower energy

   Larger $S \Longrightarrow$ spins coaligned $\Longrightarrow$ Pauli principle: larger separation of electrons.

2. For same S, terms with largest L are lower in energy

   Large $L \Longrightarrow$ similar $\boldsymbol{l}_i \Longrightarrow$ electrons go around nucleus in similar directional sense $\Longrightarrow$ have to be farther separated because of Pauli principle.

Reminder: Atomic Physics, VI

Within a term with L, S, energy can split further due to spin-orbit interaction ("Thomas precession"). This split is related to

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S} \tag{3.7}$$

Individual energy change is $\propto J(J+1)$, giving

$$E_{J+1} - E_J \propto C((J+1)(J+2) - J(J+1)) = 2C(J+1) \tag{3.8}$$

where

$$C \begin{cases} > 0 & \text{if shell less than half-full (normal term)} \\ < 0 & \text{if shell more than half-full (inverted term)} \end{cases}$$

Full state then denoted as follows

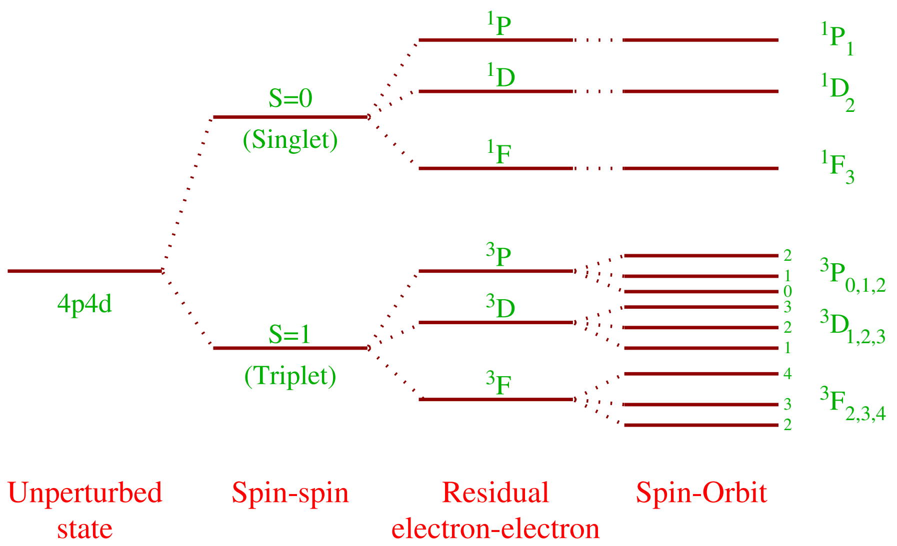
$$^{2S+1}L_J \tag{3.9}$$

where $L = S, P, \dots$ for $L = 1, 2, \dots$.

Examples: $^2P_{1/2}$, $^3D_2, \dots$

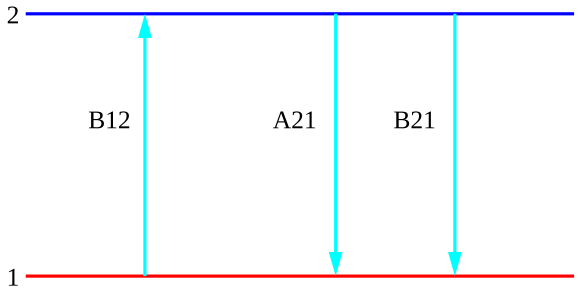
When constructing states, need to look whether n, l of two electrons to be combined are identical (nonequivalent electrons) or not (equivalent electrons), since for equivalent electrons, some possible terms are unavailable because of the Pauli principle.

Reminder: Atomic Physics, VII



Example: $4p\,4d$ configuration in LS Coupling (Rybicki & Lightman, 1979, Fig. 9.2a)

Reminder: Atomic Physics, VIII



Line emission for transition $m \longrightarrow n$ described by Einstein A coefficient: Power emitted per unit volume:

$$\frac{\mathrm{d}P}{\mathrm{d}V} = N_2 h\nu_{21} A_{21} \quad (3.10)$$

where N_2: number density of atoms in level 2, $h\nu_{21}$: energy of transition.

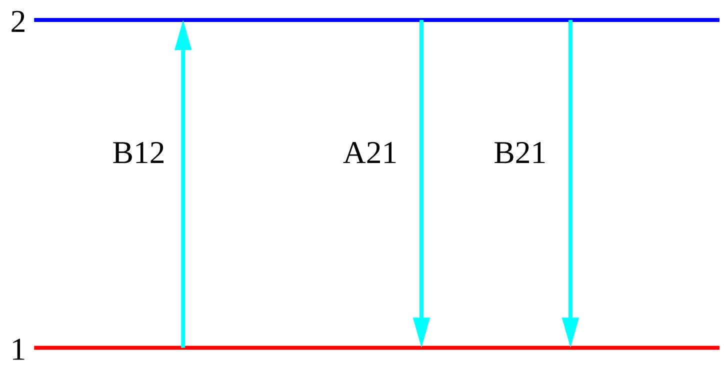
Relationship to QM:

$$A_{12} = \left(\frac{8\pi^2 e^2}{m_e c^3}\right) \nu_{12}^2 f_{12} \quad (3.11)$$

where f_{12}: "oscillator strength" (from QM).

B-coefficients: stimulated absorption and emission, i.e., for B_{21}: $\mathrm{d}P/\mathrm{d}V = N_2 h\nu_{21} B_{21} I_{\nu_{21}}$

Reminder: Atomic Physics, IX



Knowing the coefficient for spontaneous emission, A_{12}, obtain other Einstein coefficients with the Einstein relations

$$g_1 B_{12} = g_2 B_{21} \quad \text{and} \quad A_{21} = \frac{2h\nu_{21}^3}{c^2} B_{21} \quad (3.12)$$

Reminder: Atomic Physics, X

Allowed lines are lines that are allowed in the dipole approximation:

- $\Delta S = 0$ (no spin flip)
- $\Delta L = 0, \pm 1$ (ang. momentum)
- $\Delta l = \pm 1$ for jumping electron
- $\Delta J = 0, \pm 1$ (but $0 \not\to 0$)
- $\Delta M_J = 0, \pm 1$ (but $0 \not\to 0$ if $\Delta J = 0$).

Allowed lines from/to ground state are called resonance lines and are mainly found in the ultraviolet.

Example: Lyman-Series of Hydrogen.

Typical Einstein Coefficient: $A_{21} \gtrsim 10^8\,\mathrm{s}^{-1}$

For Hydrogen, $f_{1n} \propto 1/n^3$, i.e., lines from higher levels to the ground state get rapidly weaker.

Reminder: Atomic Physics, XI

Lines where the dipole selection rules are not obeyed are called semi-forbidden lines or forbidden lines.

Semi-forbidden lines: typically due to magnetic dipole (M1) transitions with selection rule $\Delta S = 1$.

Typical Einstein coefficient: $A_{21} \sim 10^4\,\mathrm{s}^{-1}$.

Example: C III]λ1909Å.

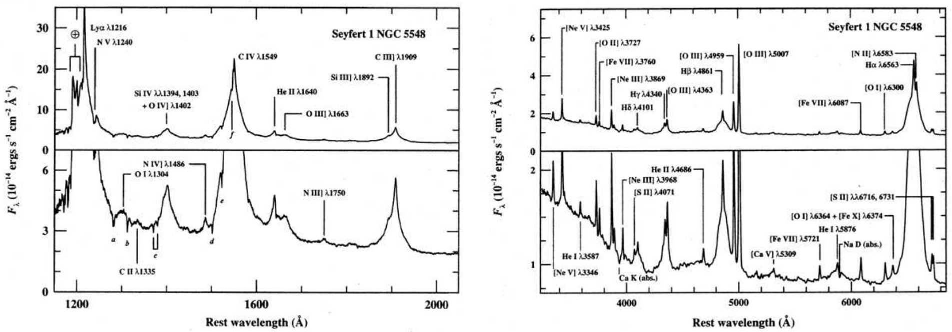
Forbidden lines: electric quadrupole (E2) transitions, selection rules $\Delta L = 0, \pm 1, \pm 2$, $\Delta J = 0, \pm 1, \pm 2$ (but still $0 \not\to 0$!).

Typical Einstein coefficient: $A_{21} \sim 10\,\mathrm{s}^{-1}$.

Example: O III]λ5007Å.

Generally, forbidden lines are observed in emission (after collisional excitation) $\Longrightarrow$ require low density medium!

Seyfert 1: Optical Spectrum, cont'd.

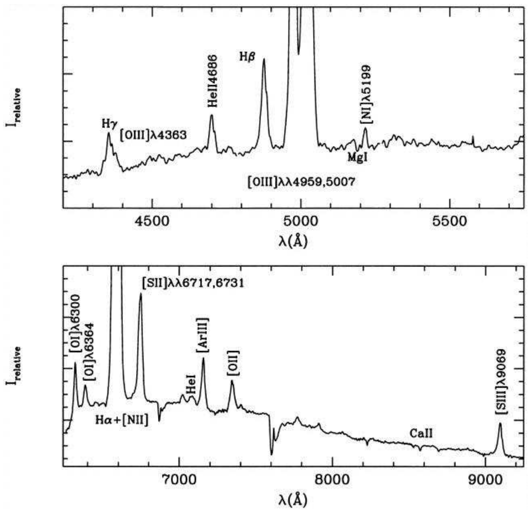


Let's look at the Seyfert 1 NGC 5548 again:

- broad allowed lines (e.g., Balmer series), Full width at half maximum (FWHM) up to $10^4\,\mathrm{km\,s^{-1}}$ from high density medium ($n_\mathrm{e} \gtrsim 10^9\,\mathrm{cm}^{-3}$).
- narrow forbidden lines (e.g., [O III5007]), FWHM $\sim$ few $\cdot\, 10^2\,\mathrm{km\,s^{-1}}$ from a low density medium ($n_\mathrm{e} \sim 10^3\,\mathrm{cm}^{-3} \ldots 10^6\,\mathrm{cm}^{-3}$).

Reminder: From the Doppler effect: $\Delta\lambda/\lambda = v/c$.

Seyfert 2

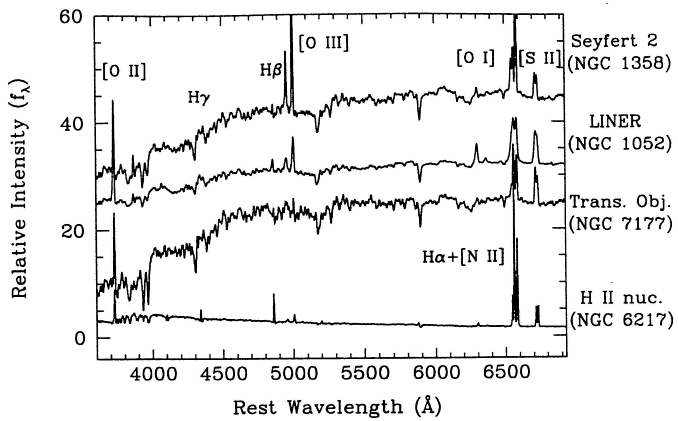


Optical spectrum of the Seyfert 2 Galaxy NGC 1068:

- Weak continuum (compared to Seyfert 1s).
- Narrow forbidden lines, FWHM $\sim$ few $\cdot\, 10^2\,\mathrm{km\,s^{-1}}$.
- No broad lines
- Absorption lines from underlying galaxy (mainly late-type giants).

(García-Lorenzo, Mediavilla & Arribas, 1999, Fig. 4)

LINERS

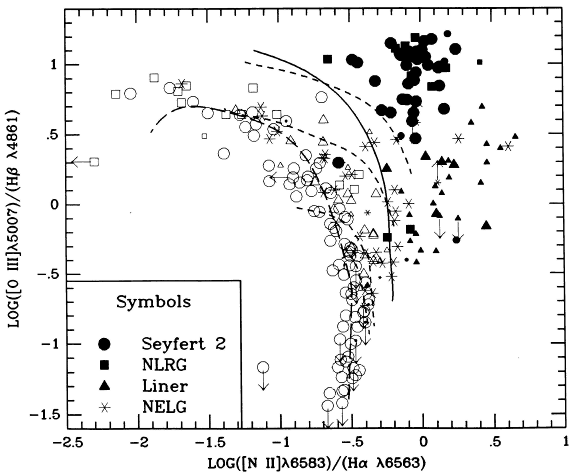


(Ho, 1996)

LINER (Low-Ionization Nuclear Emission Line Region galaxies): optical spectrum very similar to Seyfert 2 galaxies, but weaker continuum.

Most galaxies show weak LINER activity.

Summary: Narrow Line Systems



Veilleux & Osterbrock (1987, Fig. 1)

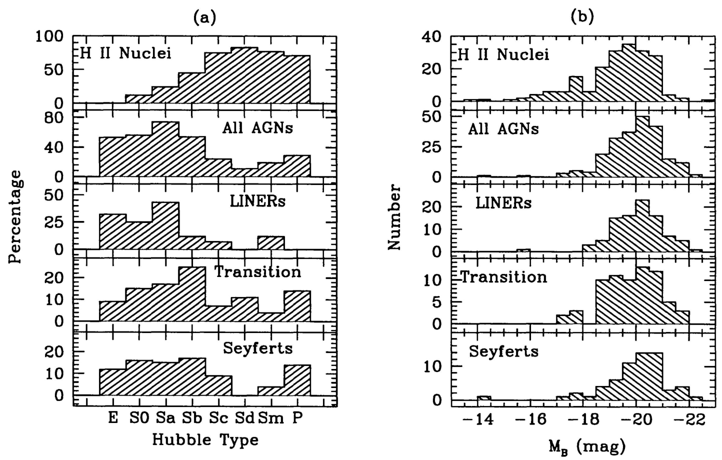
Final classification of Narrow Line Systems: ratios of prominent lines

⟹ see Baldwin, Phillips & Terlevich (1981) and Veilleux & Osterbrock (1987) for details ("BPT diagram").

For Seyferts, there are also intermediate classes, e.g., Sy 1.5, Sy 1.7, Sy 1.9, sorted by decreasing width of Balmer lines.

Generally: Seyferts: $[\text{O III}]/\text{H}\beta > 3$ and not a H II region.

Summary: Narrow Line Systems



(Ho, 1996, Fig. 4)

Seyferts and LINERS are predominantly found in early type spirals (Sa, Sb).

QSOs and Quasars, I

The brightest AGN:

Quasars: Quasi-stellar Radio Sources

QSOs: Quasi-Stellar Objects

Typical absolute luminosities: $M_\text{B} < -21.5 + 5\log h_0$ where $h_0 = H_0/100\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

All quasars show at least some radio emission.

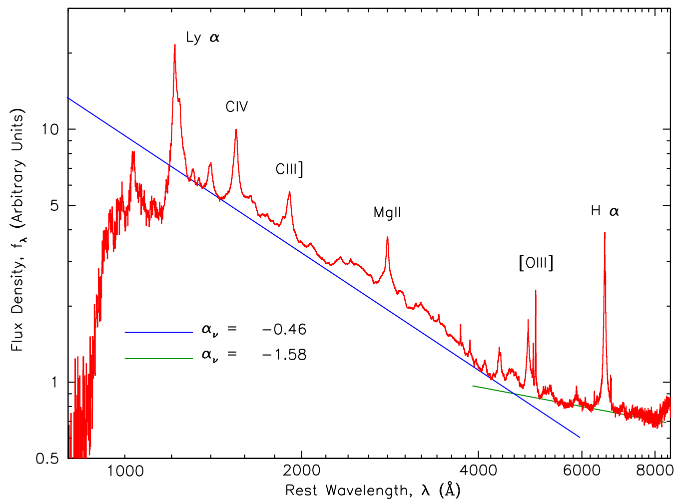
To distinguish, use radio to optical flux ratio (Kellermann et al., 1989), $R_\text{r-o} = F(6\,\text{GHz})/F(4400\,\text{Å})$:

radio-loud: $R_\text{r-o} = 10$–1000

radio-quiet: $0.1 < R_\text{r-o} < 1$

There are $\sim$10$\times$ more radio-quiet QSOs than radio-loud ones.

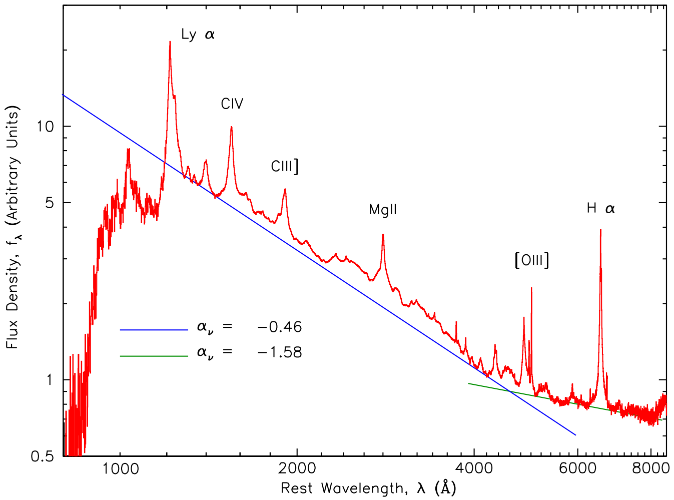
QSOs and Quasars, II



Average SDSS QSO spectrum, based on $\sim$2200 spectra (after Vanden Berk et al., 2001)

Optical spectra of QSOs are very similar to those of Seyfert galaxies.

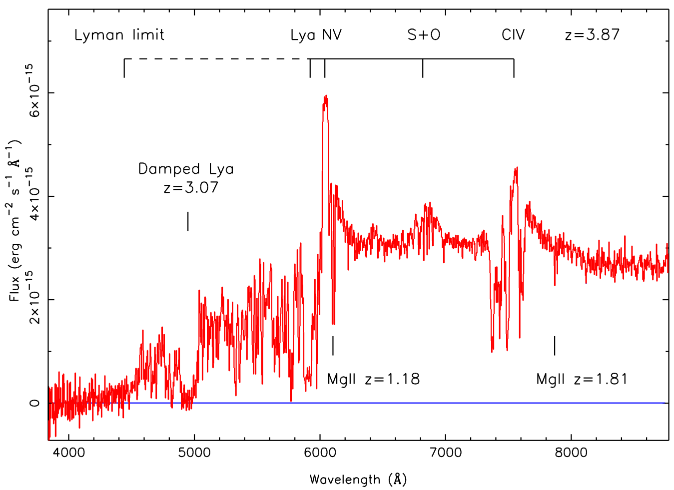
QSOs and Quasars, III



Average SDSS QSO spectrum, based on ∼2200 spectra (after Vanden Berk et al., 2001)

but: compared to Seyferts: weaker absorption features from galaxy, and weaker narrow lines.

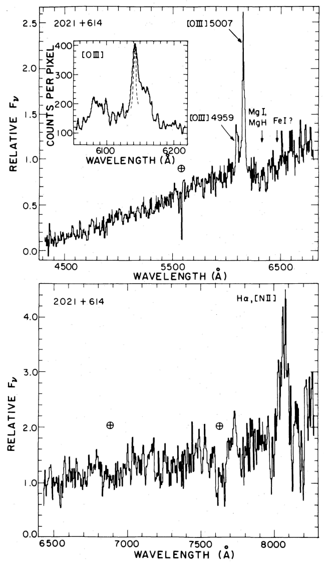
BAL QSOs



Optical spectrum of APM 08279+5255, a BAL-QSO at $z = 3.87$ (Irwin et al., 1998)

Broad Absorption Line QSOs (BAL-QSOs): QSOs at high z with blueshifted absorption lines, e.g., from CIV.

Radio Loud Galaxies



Radio galaxies: Typically elliptical galaxies, but fainter than QSOs.

Optical spectra similar to Seyferts:

NLRG: Narrow Line Radio Galaxy

BLRG: Broad Line Radio Galaxy.

$\Longrightarrow$ NLRG and BLRG can be considered radio-loud counterparts of Seyferts

but: different properties of host galaxies!

Optical spectrum of 2021+614, a NLRG (although with lots of dust present, cf. asymmetric shape of [OIII] line; Bartel et al. 1984)

Fanaroff-Riley Classes

Many radio loud objects show jets.

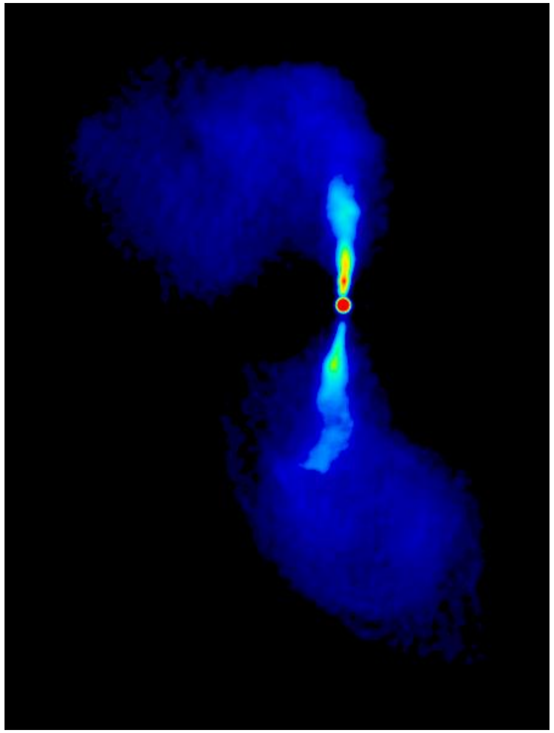
Classification: Fanaroff-Riley Classes (after Fanaroff & Riley 1974):

FR 1: "Fanaroff-Riley type 1"

- nucleus dominates
- less luminous
- bright
- broad jets ending in plumes
- two asymmetric jets

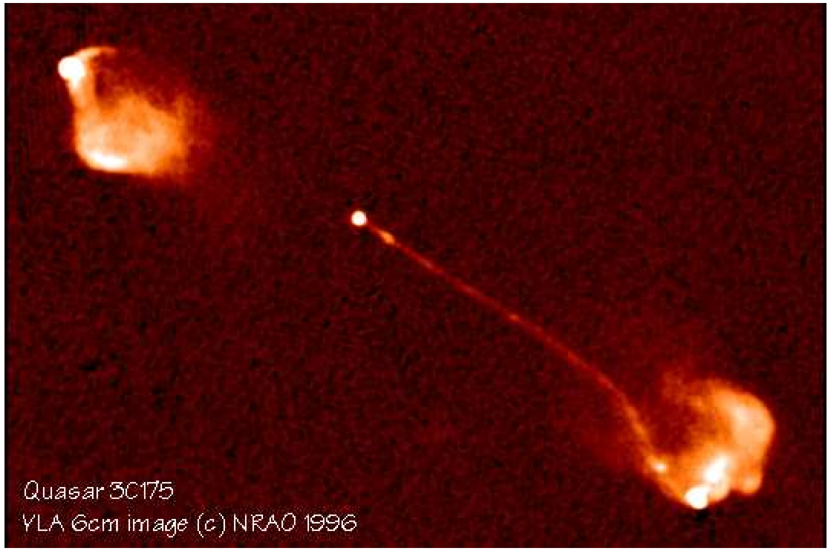
FR 2: "Fanaroff-Riley type 2"

- luminous radio sources
- lobes dominate
- weak jets ending in radio lobes



Radio image of M84 (3C272.1):
A typical FR 1 galaxy

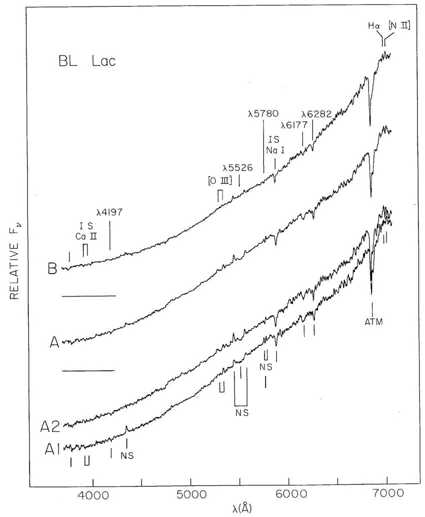
Laing & Bridle (1987); VLA 4885 MHz, $134'' \times 170''$; see also `http://www.jb.man.ac.uk/atlas/other/3C272P1.html`



A. Bridle (priv. comm.)

Radio image of 3C175 ($z = 0.768$):
A typical FR 2 galaxy with an one sided jet
Edge brightening $\Longrightarrow$ Shock heating due to interaction with ambient

BL Lac and OVVs

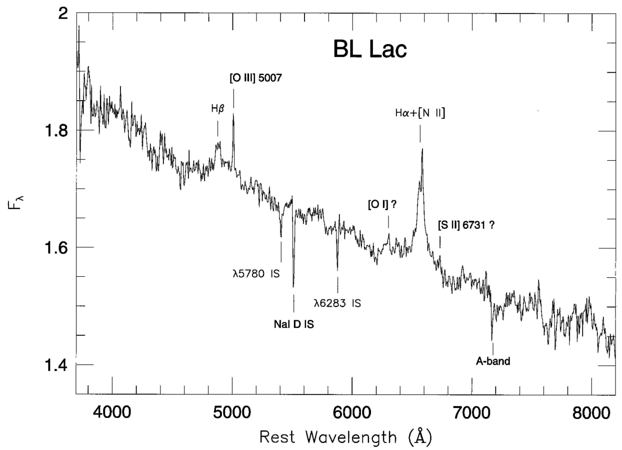


(Miller & Hawley, 1977, Fig. 1)

Most AGN show continuum variability (see later), but some show fast, large amplitude variability: blazars.
Subclasses:

- Optically Violent Variables: OVVs: $\Delta m \gtrsim 0.1$ mag.
- BL Lac Objects: after prototype BL Lacertae (originally classified as a star, $m_B = 14$–16 mag): virtual absence of emission lines above continuum

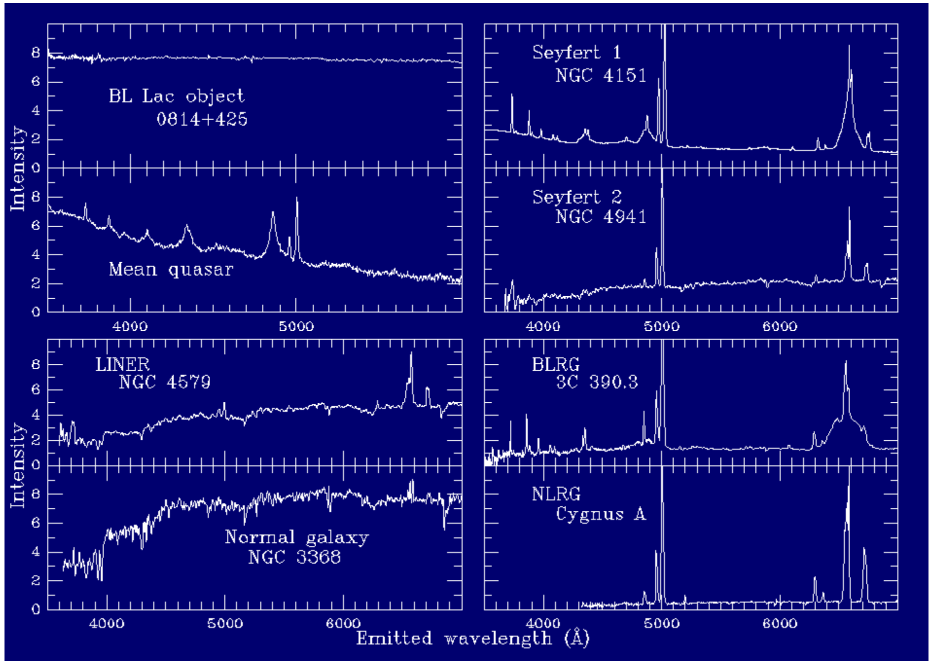
BL Lac and OVVs



(Vermeulen et al., 1995, "When is BL Lac not a BL Lac?", Fig. 3)

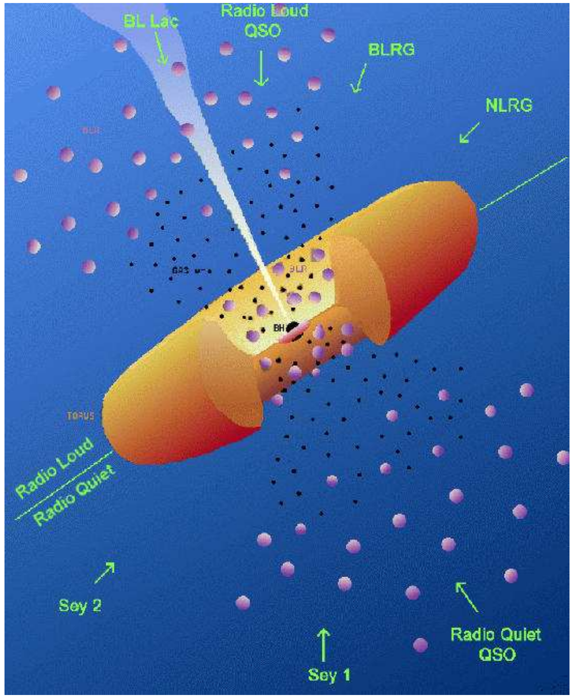
In weak phases, BL Lac shows a spectrum $F_\nu \propto \nu^{-1.7}$ (strongly polarized, synchrotron radiation) and broad emission lines $\Longrightarrow$ typical AGN continuum!

$\Longrightarrow$ There seems to be a continuum between Seyferts, QSOs, and Blazars $\Longrightarrow$ Same physics? $\Longrightarrow$ Unification.



(W. Keel, priv. comm.)

Summary of optical spectra of different AGN types



Unified Model: All AGN types are due to the same physics, different phenomenology just due to different viewing angle.

(Urry & Padovani, 1995, NOTE: logarithmic length scale!)