Active Galactic Nuclei

Matthias Kadler and Jörn Wilms

Sommersemester 2010

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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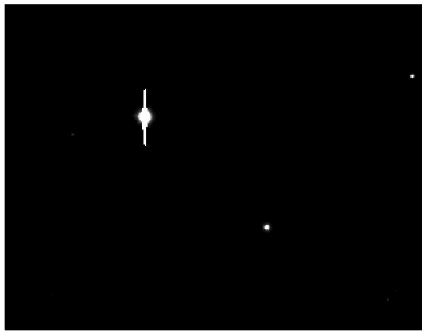
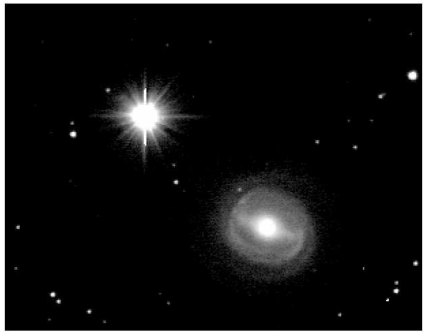
M87 – R. Gendler

http://www.robgendlerastropics.com/M87NM.html

What are AGN?



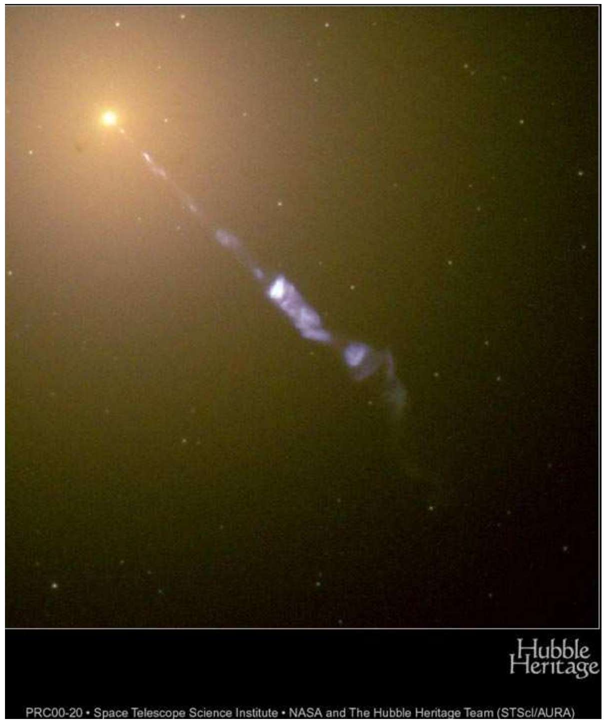
NGC 3783: *linear* intensity scale



logarithmic intensity scale

Active Galactic Nuclei (AGN): supermassive black holes ($M \sim 10^{6...8}\,M_\odot$), accreting $1\ldots 2\,M_\odot$/yr

$\Longrightarrow$ luminosity $\sim 10^{10}\,L_\odot$ (comparable to galaxy luminosity)



What are AGN?

Observational characteristics of AGN:

- (Normally) high luminosity
- Emission throughout the electromagnetic spectrum (radio to keV, MeV, TeV) $\Longrightarrow$ spectrum is "nonthermal"
- flat νf_ν spectra: similar emission per frequency decade
- strong variability (days to years)
- radio loud sources: relativistic jets, which can be superluminous ($v_{\text{apparent}} \gg c$)
- broad optical lines ($v_{\text{characteristic}} \sim$ several $1000\,\text{km}\,\text{s}^{-1}$)

Outline

19 April	JW	Introduction, History, Taxonomy
26 April	MK	Unification
03 May	JW	Accretion and Accretion Disks
10 May	MK	Measurement Methods
17 May	MK	Seyfert continuum/Fe Kα lines
24 May	Pentacost	
31 May	JW	Line Diagnostics, Photoionization
07 June	JW	BLR/NLR
14 June	MK	Radio loud AGN
21 June	JW	Jets
28 June	JW	AGN Surveys
05 July	MK	AGN Surveys
12 July		EXAM
19 July	MK	Summary

Grading and Homework

This is a 5 ECTS module $\Longrightarrow$ need assessment and exam.

- ~biweekly recitation sessions (90 Minutes, led by Cornelia Müller and Thomas Dauser). Attendance is mandatory
  (6–7 sessions in total)
- 50% of final grade: a $\geq$ 4 page summary paper on one Active Galaxy and a 10 minute presentation on that AGN.
  Details will be given in mid-May.
- 50% of final grade: exam (12 July).

Date and time of recitation sessions:

http://www.doodle.com/t7ggfr82isk8sfwa

with deadline

In addition: non-mandatory homework assignments

Textbooks on AGN

PETERSON, B.M., 1997, An Introduction to Active Galactic Nuclei, Cambridge: Cambridge Univ. Press, 254pp., $45
Undergraduate level introduction to Active Galactic Nuclei, level is slightly lower than ours.

KROLIK, J., 1999, Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment, Princeton: Princeton Univ. Press, 632pp., $57.50
The most comprehensive textbook on AGN available, covers much more material than what is possible here.

KEMBHAVI, A.J. & NARLIKAR, J.V., 1999, Quasars and Active Galactic Nuclei: An Introduction, Cambridge: Cambridge Univ. Press, 476pp., $50
Graduate level textbook, similar to Krolik, but often explains things from a somewhat different point of view.

Other Textbooks

BRADT, H., 2003, Astronomy Methods: A Physical Approach to Astronomical Observations, Cambridge: Cambridge Univ. Press, 458pp., €57.50

Summary of many technical details that are useful to know if you want to become a professional astronomer. Detectors, radiation processes, etc.

PADMANABHAN, T., 2000, Theoretical Astrophysics: Volumes 1–3, Cambridge: Cambridge Univ. Press, ∼ 500pp. each, ∼€60 per volume

Introduction to the (theoretical) physics of astrophysics. Short, concise, great. Graduate level, but understandable, although not for the faint hearted. . .

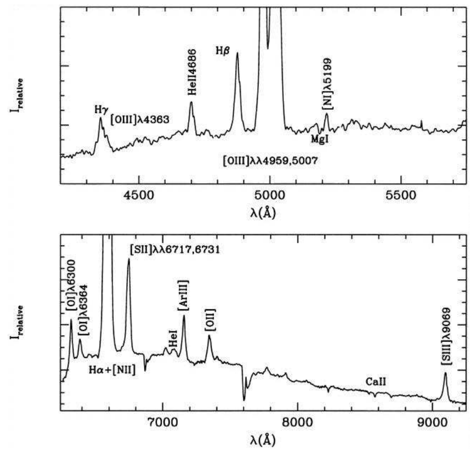
FRANK, J., KING, A., RAINE, D., 2002, Accretion Power in Astrophysics, 3rd edition, Cambridge: Cambridge Univ. Press, 398pp., €55.90

The standard textbook on accretion, covering all relevant areas of the field, including AGN.

NGC 1068 (M77) courtesy Nordic Optical Telescope

History of AGN research

1908: E. Fath



Optical spectrum of NGC 1068

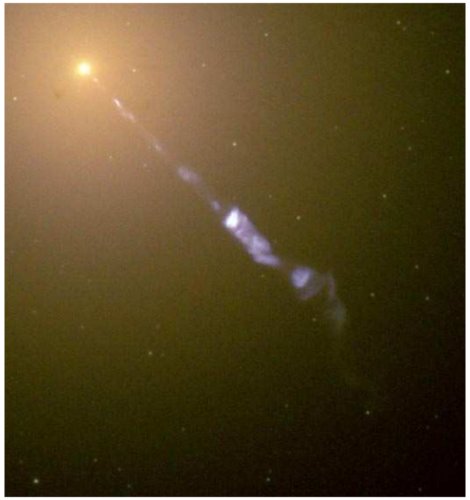
(García-Lorenzo, Mediavilla & Arribas, 1999, Fig. 4)

1908: Edward A. Fath: There are emission lines in NGC 1068, similar to planetary nebulae.

This was part of Fath's PhD!

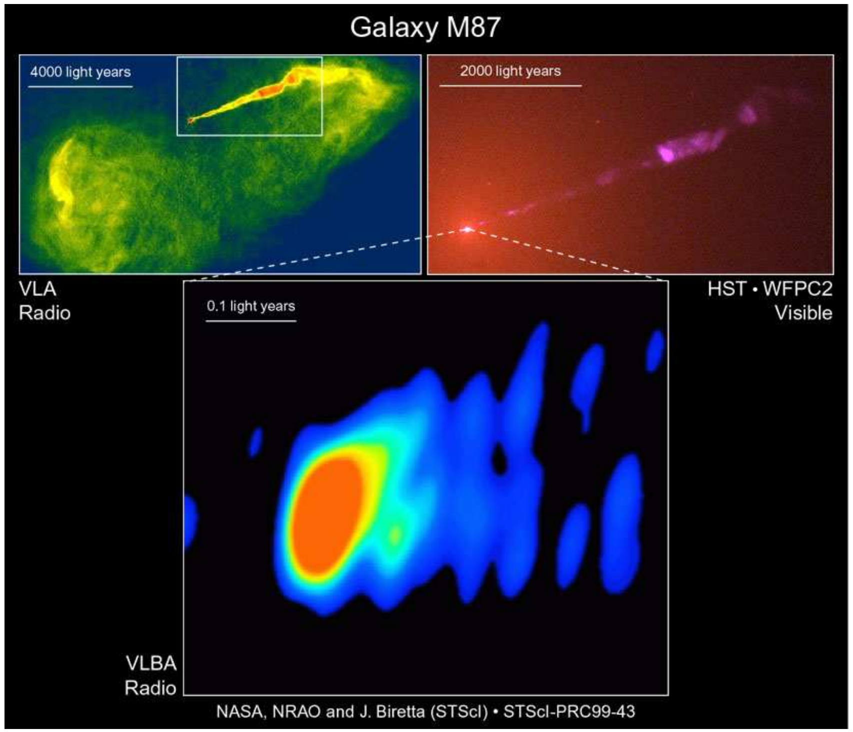
Note: High ionization levels, large width of lines

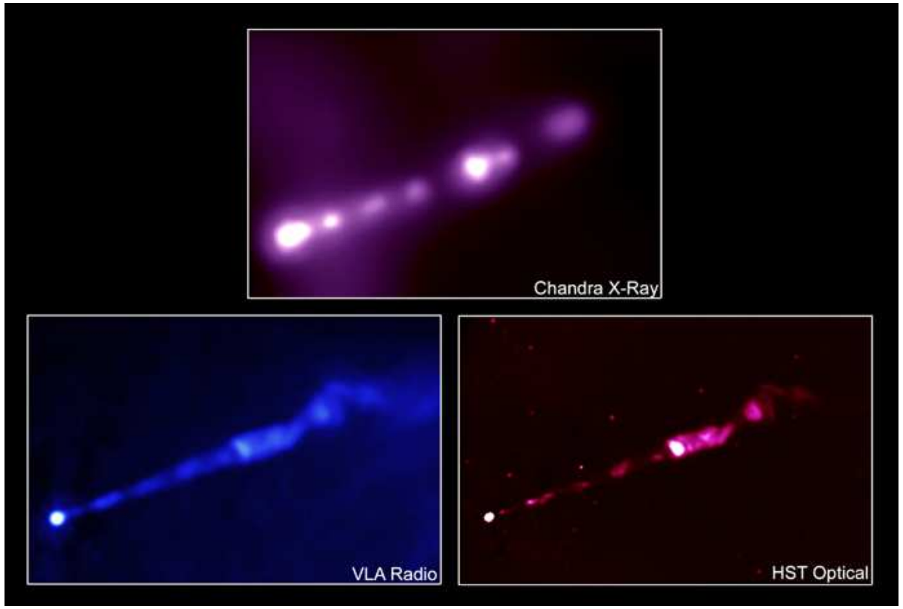
1918: H. Curtis



HST

1918: Heber D. Curtis: "[M87 exhibits] a curious straight ray. . . apparently connected with the nucleus by a thin line of matter".
$\Longrightarrow$ M87 contains an optical jet

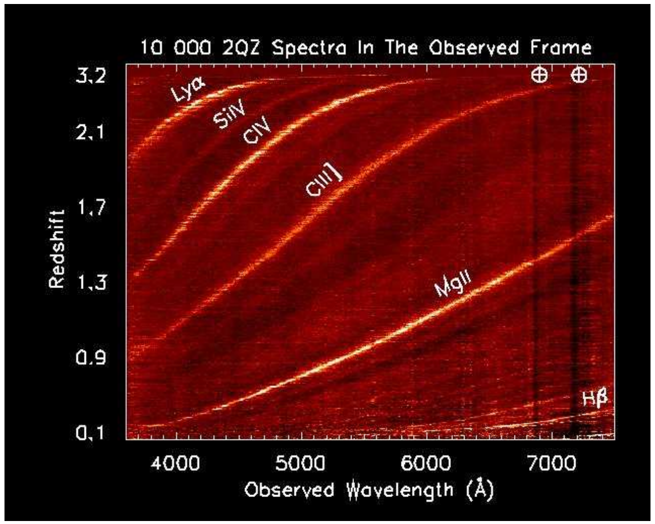




X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F.Zhou, F.Owen (NRAO), J.Biretta (STScI)
Optical: NASA/STScI/UMBC/E.Perlman et al.

Jets are visible in all wavebands

1926: E. Hubble



courtesy 2DF survey

1926: Edwin Hubble:

- Emission lines in NGC 1068, NGC 4051, NGC 4151
- Spectral features in nebulae are redshifted $\Longrightarrow$ nebulae are extragalactic!

Reminder: $z = \Delta\lambda/\lambda = v/c$, $v = Hd$ where $H \sim 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

1943: C. Seyfert

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.

(Seyfert, 1943)

1943: Carl Seyfert: Recognization of spiral galaxies with optical emission lines as a class $\Longrightarrow$ Seyfert galaxies

1954: W. Baade and R. Minkowski

W. Baade (Mt. Wilson Obs.)

IDENTIFICATION OF THE RADIO SOURCES IN CASSIOPEIA, CYGNUS A, AND PUPPIS A

W. BAADE AND R. MINKOWSKI
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY
Received June 19, 1953

ABSTRACT

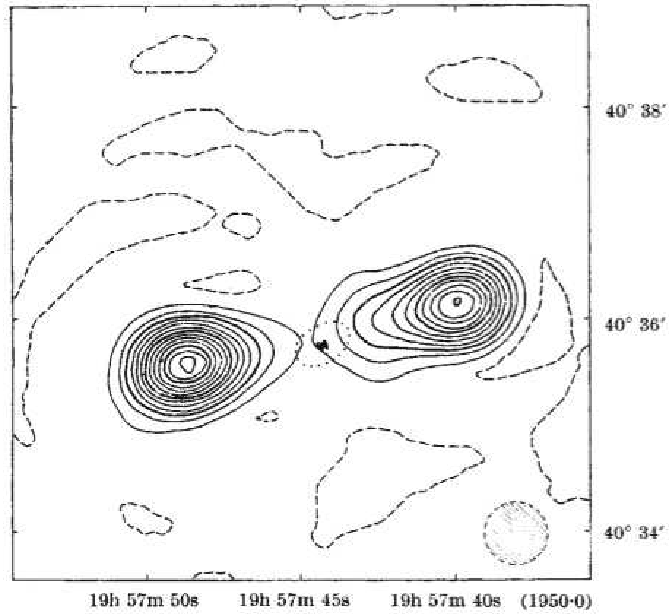
The radio sources in Cassiopeia and Puppis A are identified with a new type of galactic emission nebulosity. The outstanding features of these nebulosities are very large internal random velocities. The radio source Cygnus A is an extragalactic object, two galaxies in actual collision.

Only very few individual sources of cosmic radio emission have been identified with conspicuous astronomical objects.[1] Although the sources in Cassiopeia[2] and Cygnus A[3]

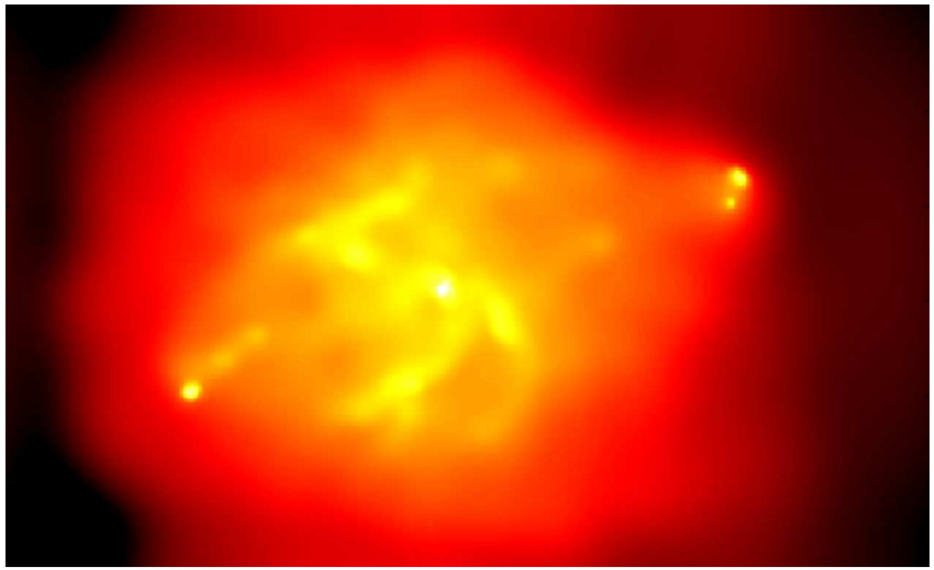
(Baade & Minkowski, 1954)

1954: Walter Baade and Rudolph Minkowski: optical counterparts to radio sources Cyg A (NGC 5128), Vir A (M87), Per A (NGC 1275).

Cyg A: First ultra-luminous AGN (2nd brightest radio source in the sky; $L \sim 10^{45}\,\mathrm{erg\,s^{-1}}$).



Cyg A in radio (Ryle, 1965)



Cyg A in X-rays (Wilson & Young/CXC/NASA)
Hot gas in cavity produced by the radio jets $\Longrightarrow$ AGN shape their environment!

1959: L. Woltjer

EMISSION NUCLEI IN GALAXIES

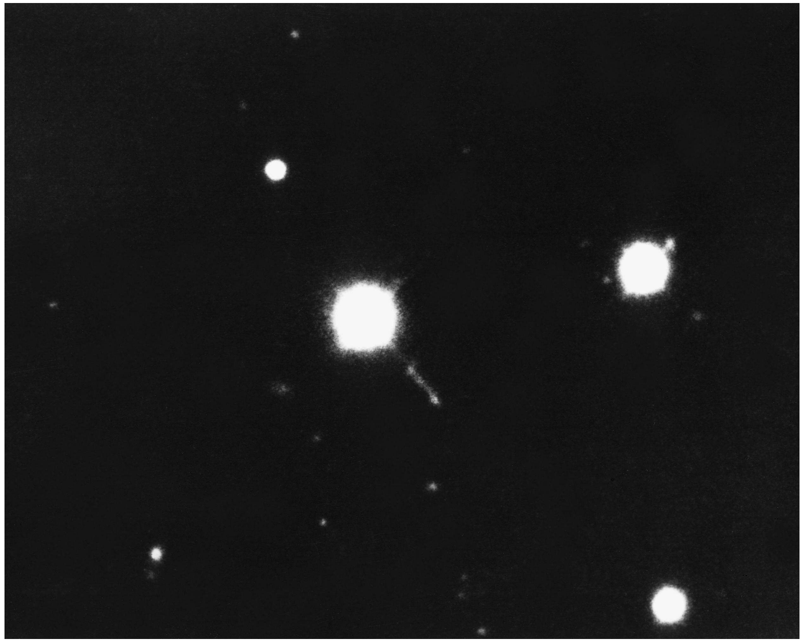
L. Woltjer*
Yerkes Observatory, University of Chicago
Received February 16, 1959

ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

(Woltjer, 1959)

1959: Lodewijk Woltjer: AGN have huge masses.



3C273 (4 m Myall telescope, NOAO/AURA/NSF)

1963: M. Schmidt

1950s and 1960s: Radio surveys $\Longrightarrow$ large lists of (unknown) radio sources

Most important surveys:

$\Longrightarrow$ Cambridge:

- "Third Cambridge Catalogue" (Edge et al., 1959): $f = 159$ MHz, 471 sources >8 Jy for $-22^\circ < \delta < +71^\circ$.
- "Revised Third Cambridge Catalogue" (Bennett, 1962): $f = 178$ MHz, $-22 < \delta < +90^\circ$, same numbering scheme

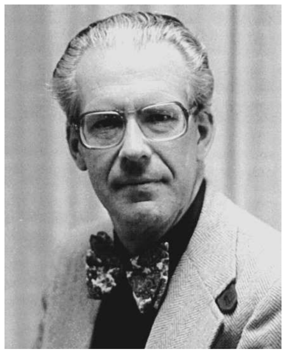
Objects have names like 3C273, 3C279, 3C405 (aka Cyg A), sometimes "3CR" is used.

$\Longrightarrow$ Parkes surveys (Bolton, Gardner & Mackey, 1964; Price & Milne, 1965; Day et al., 1966), $f = 408$, 1410, and 2650 MHz, ~900 sources with $F > 1$ Jy and $-90^\circ < \delta < +20^\circ$.

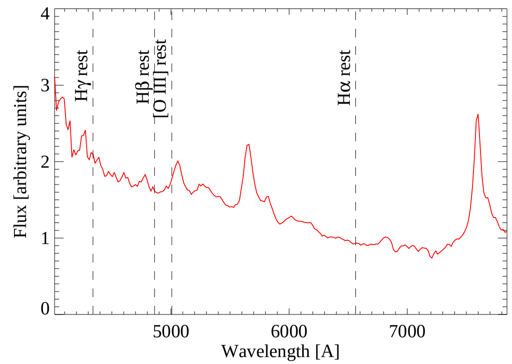
Sources have names such as PKS 2155−304 (a blazar) or PKS 405−385 (intra-day variable source).

1 Jansky = 1 Jy = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$

1963: M. Schmidt

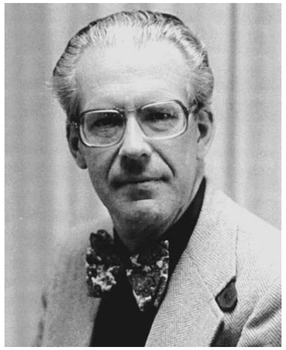


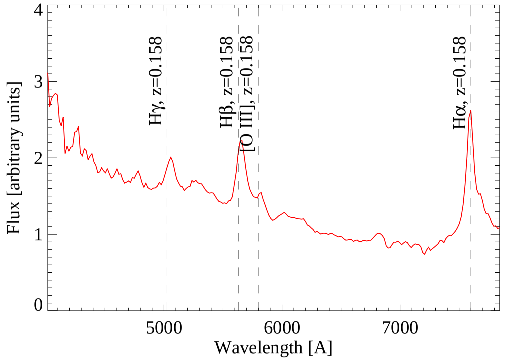
M. Schmidt (Caltech)



3C273 (Rondi et al., Pic du Midi)

1963: M. Schmidt





M. Schmidt (Caltech)

3C273 (Rondi et al., Pic du Midi)

1963: Maarten Schmidt: 3C273 has $z = 0.158 \Longrightarrow$ AGN are far away!

shortly later: 1963: J. Greenstein and Th. Matthews: 3C48 has $z = 0.368$

Nomenclature: Quasar/QSO (from “quasi stellar radio source”: radio emitting AGN)

Interlude: Accretion Power

AGN have high luminosities: What is the energy source?

1. Nuclear Fusion
Typical reactions à la

$$4\text{p} \longrightarrow {}^4\text{He} + \Delta mc^2$$

Liberated energy:

Fusion produces ~6 × $10^{18}\,\text{erg}\,\text{g}^{-1} = 6 \times 10^{11}\,\text{J}\,\text{g}^{-1}$

$(\Delta E_{\text{nuc}} \sim 0.007 m_{\text{p}} c^2)$

2–16

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2. Gravitation
Accretion of mass m from ∞ onto a black hole with radius R_{S} gives

$$\Delta E_{\text{acc}} = \frac{GMm}{R_{\text{S}}} \quad \text{where} \quad R_{\text{S}} = \frac{2GM}{c^2}$$

Accretion yields ~$10^{20}\,\text{erg}\,\text{g}^{-1} = 10^{13}\,\text{J}\,\text{g}^{-1}$

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$(\Delta E_{\text{acc}} \sim 0.1\, m_{\text{p}} c^2)$

$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source

. . . to power a luminous AGN, 1 . . . 2 $M_{\odot}\,\text{yr}^{-1}$ are sufficient.

Baade, W., & Minkowski, R., 1954, ApJ, 119, 206

Bennett, A. S., 1962, Mem. RAS, 68, 163

Bolton, J. G., Gardner, F. F., & Mackey, M. B., 1964, Aust. J. Physics, 17, 340

Day, G. A., Shimmins, A. J., Ekers, R. D., & Cole, D. J., 1966, Aust. J. Physics, 19, 35

Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., & Archer, S., 1959, Mem. RAS, 68, 37

García-Lorenzo, B., Mediavilla, E., & Arribas, S., 1999, ApJ, 518, 190

Perley, R. A., Dreher, J. W., & Cowan, J. J., 1984, ApJ, 285, L35

Price, R. M., & Milne, D. K., 1965, Aust. J. Physics, 18, 329

Seyfert, C. K., 1943, ApJ, 97, 28

Woltjer, L., 1959, ApJ, 130, 38

AGN Taxonomy

Introduction

Purpose of this chapter: Phenomenology of AGN

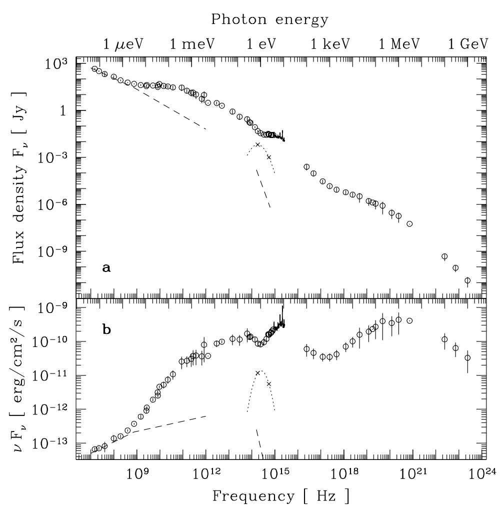
Structure:

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

$$F_\nu \propto \nu^{-\alpha} \quad (3.1)$$

where $\alpha \sim 1$

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

Continuum: Nomenclature

Continua of AGN often resemble power law spectra:

$$F_\nu = C\nu^{-\alpha} \quad (3.1)$$

where

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

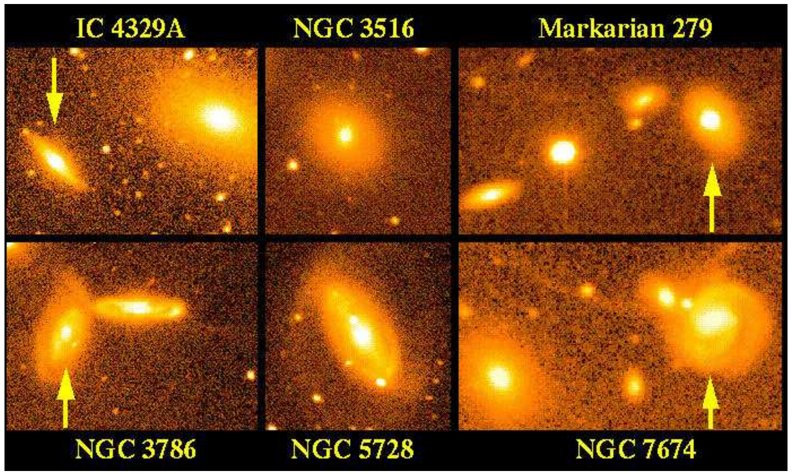
Power received in frequency range ν_1 to ν_2:

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

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

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

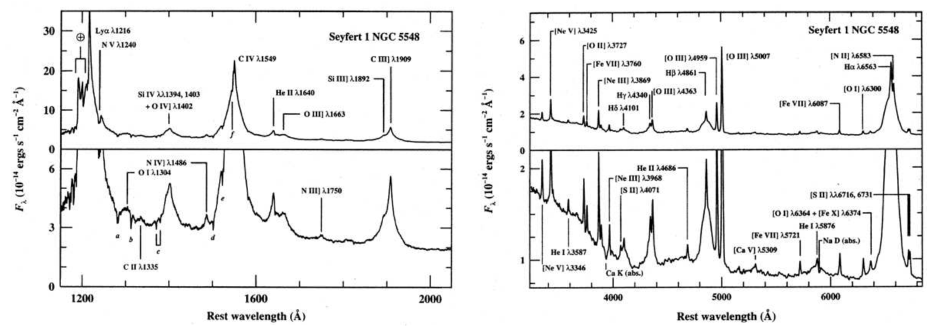
Seyfert Galaxies: Optical Images



W. Keel

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

Seyfert 1: Optical Spectrum

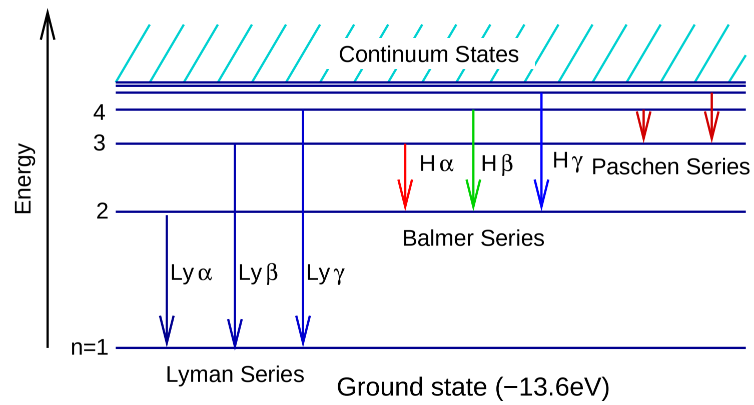


(Peterson, 1997)

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

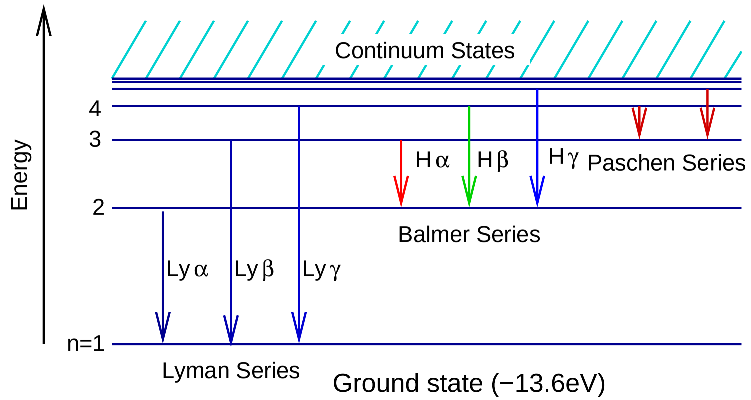


Quantum mechanics: Energy of electron's bound to nucleus is quantized.

For the Hydrogen atom:

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

Reminder: Atomic Physics



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

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

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

Reminder: Atomic Physics

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

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

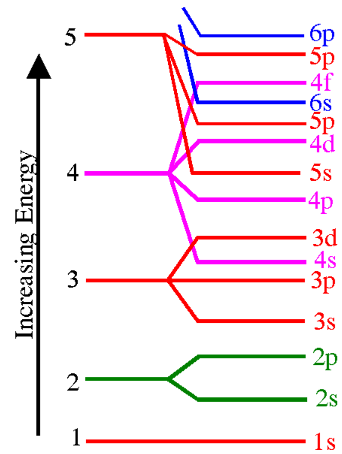
n: principal quantum number, $n = l+1, l+2, \ldots$

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

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

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

Reminder: Atomic Physics



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] $3s$.

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

Reminder: Atomic Physics

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:

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

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

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

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S} \quad (3.7)$$

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

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

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

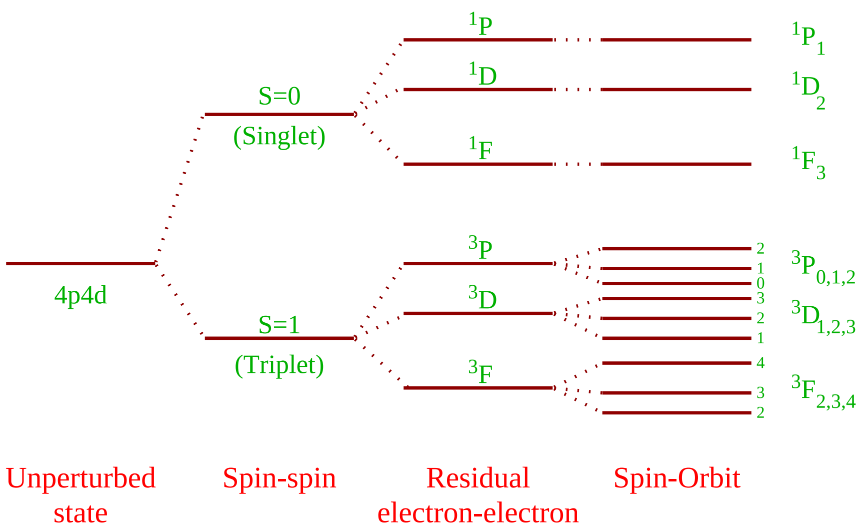
$$^{2S+1}L_J \quad (3.9)$$

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

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

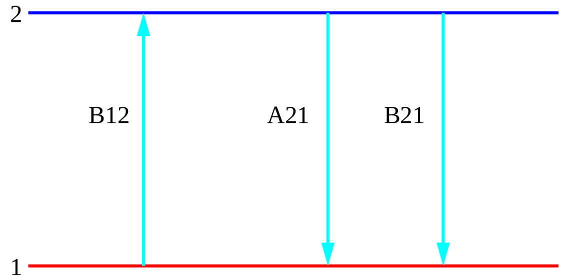
When constructing states, need to look whether n, l of two electrons to be combined are identical (nonequivalent electrons) or not (equivalent electrons), since for equivalent electrons, some possible terms are unavailable because of the Pauli principle.

Reminder: Atomic Physics



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

Reminder: Atomic Physics



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.

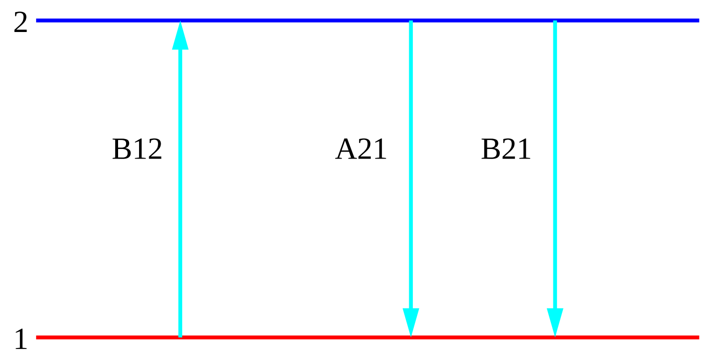
Relationship to QM:

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

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



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

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

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.

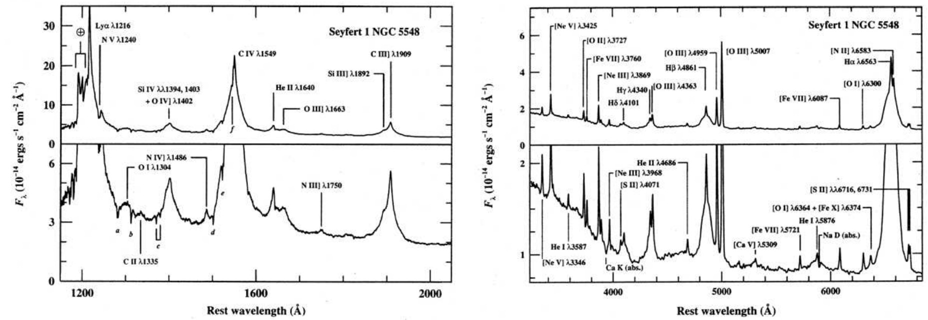
Forbidden lines: electric quadrupole (E2) transitions, selection rules $\Delta L = 0, \pm 1, \pm 2$, $\Delta J = 0, \pm 1, \pm 2$ (but still $0 \not\to 0$!).

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.

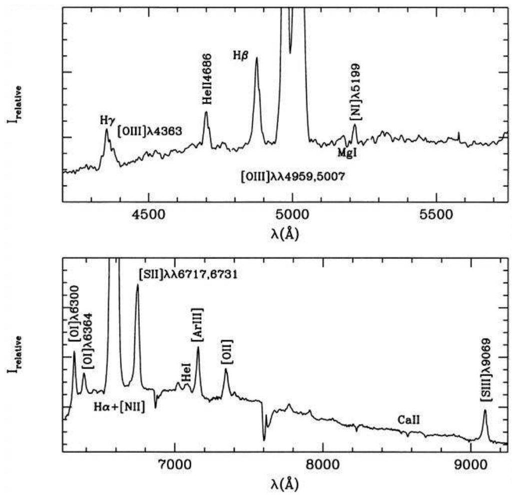


Let's look at the Seyfert 1 NGC 5548 again:

- 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 ($n_e \gtrsim 10^9\,\mathrm{cm}^{-3}$).
- narrow forbidden lines (e.g., [O III 5007]), FWHM $\sim$ few$\cdot 10^2\,\mathrm{km\,s^{-1}}$ from a low density medium ($n_e \sim 10^3\,\mathrm{cm}^{-3} \ldots 10^6\,\mathrm{cm}^{-3}$).

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

Seyfert 2

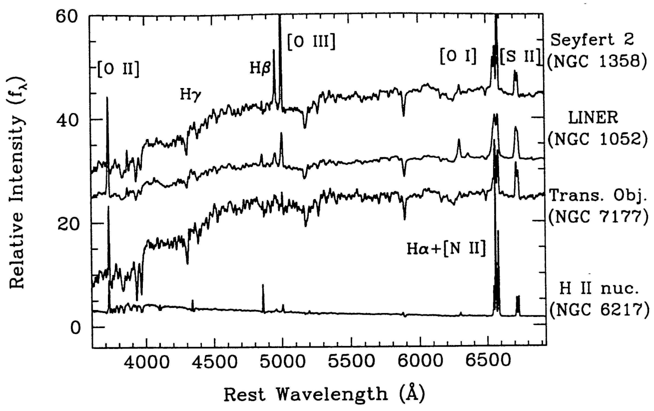


(García-Lorenzo, Mediavilla & Arribas, 1999, Fig. 4)

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).

LINERS

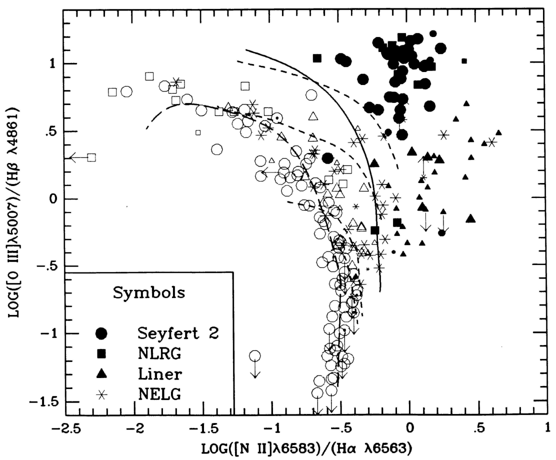


(Ho, 1996)

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)

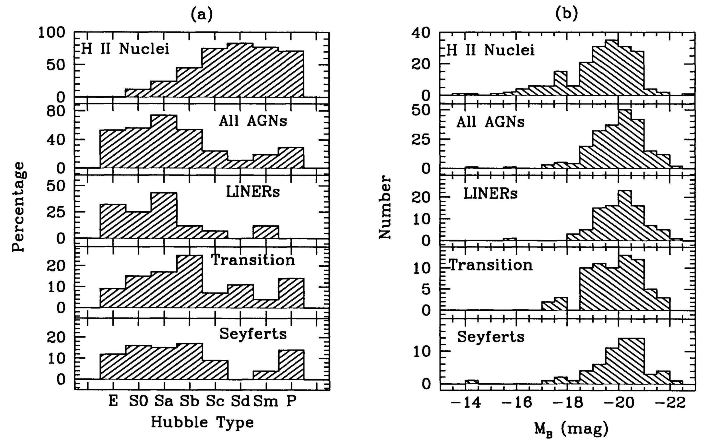
Final classification of Narrow Line Systems: ratios of prominent lines

⟹ 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: [O III]/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

The brightest AGN:

Quasars: Quasi-stellar Radio Sources

QSOs: Quasi-Stellar Objects

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

All quasars show at least some radio emission.

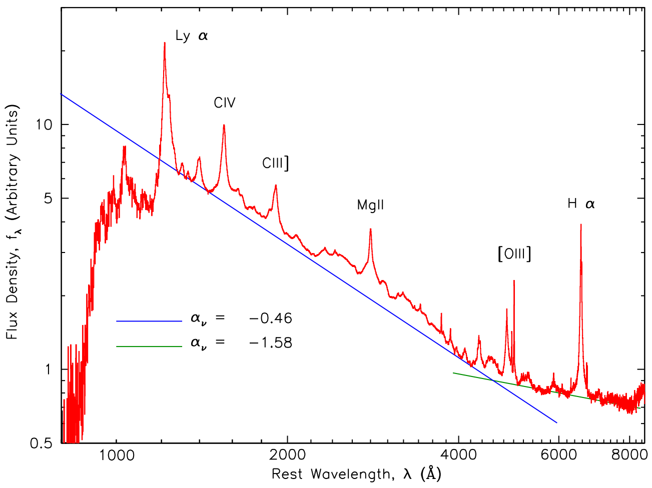
To distinguish, use radio to optical flux ratio (Kellermann et al., 1989), $R_\text{r-o} = F(6\,\mathrm{GHz})/F(4400\,\text{Å})$:

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.

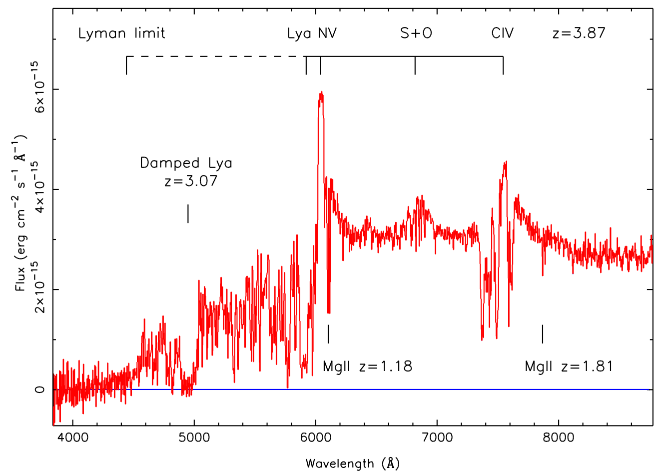
QSOs and Quasars



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

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

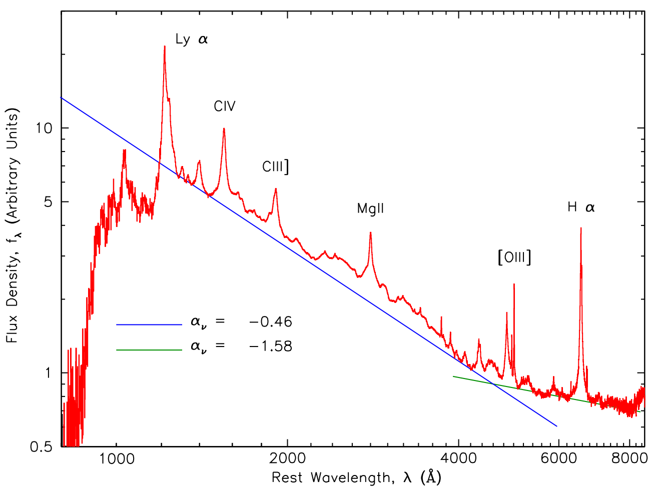
BAL QSOs



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.

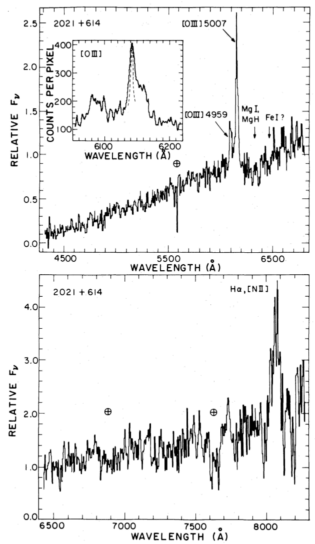
QSOs and Quasars



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.

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.

⟹ 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.

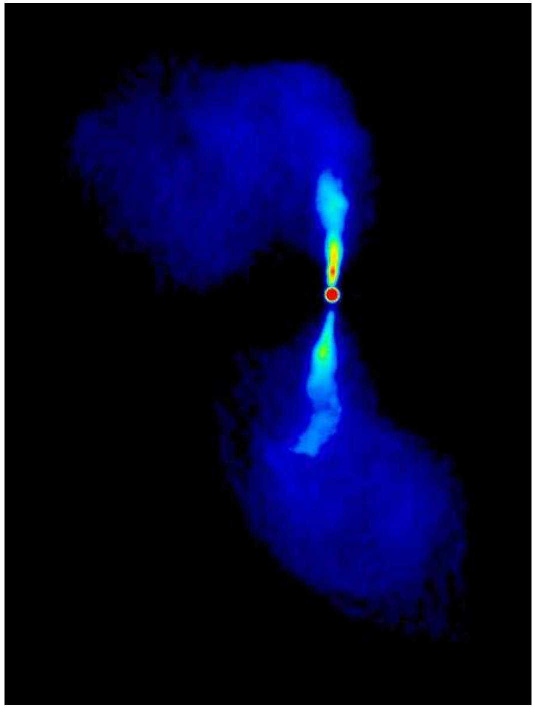
Classification: Fanaroff-Riley Classes (after Fanaroff & Riley 1974):

FR 1: "Fanaroff-Riley type 1"

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

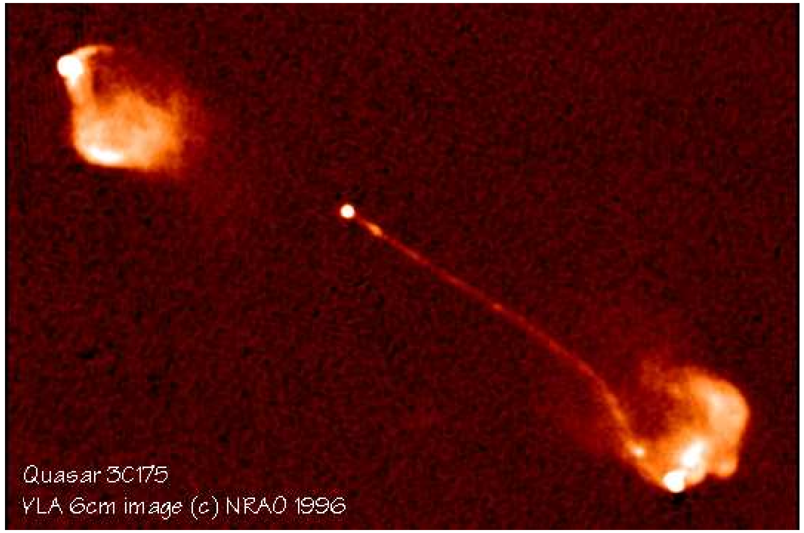
FR 2: "Fanaroff-Riley type 2"

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



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

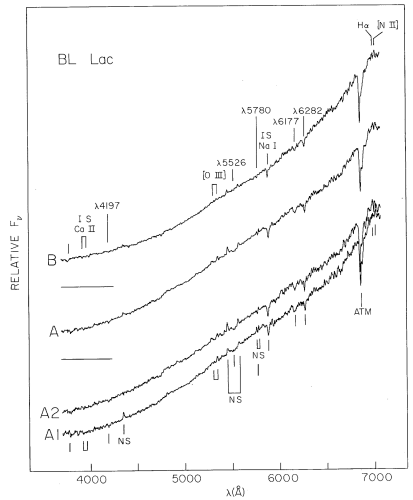
Laing & Bridle (1987); VLA 4885 MHz, 134″ × 170″; see also http://www.jb.man.ac.uk/atlas/other/3



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 intergalactic medium (IGM)

BL Lac and OVVs



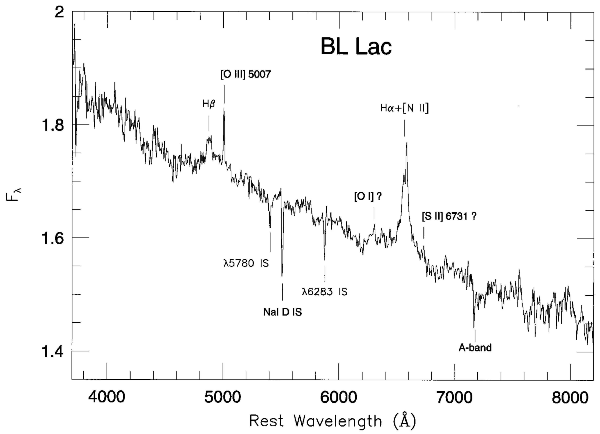
(Miller & Hawley, 1977, Fig. 1)

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

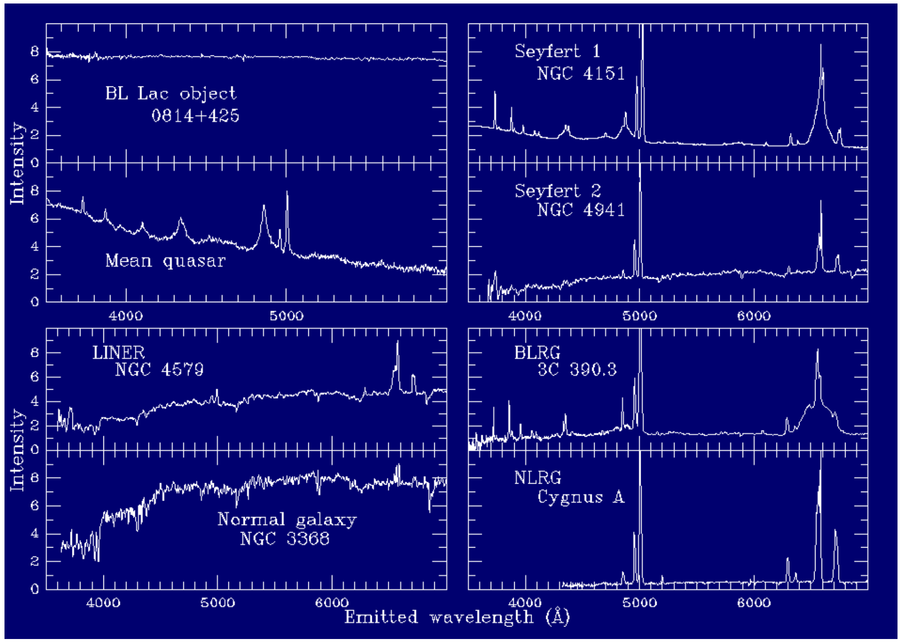
BL Lac and OVVs



(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 ⟹ typical AGN continuum!

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



(W. Keel, priv. comm.)

Summary of optical spectra of different AGN types

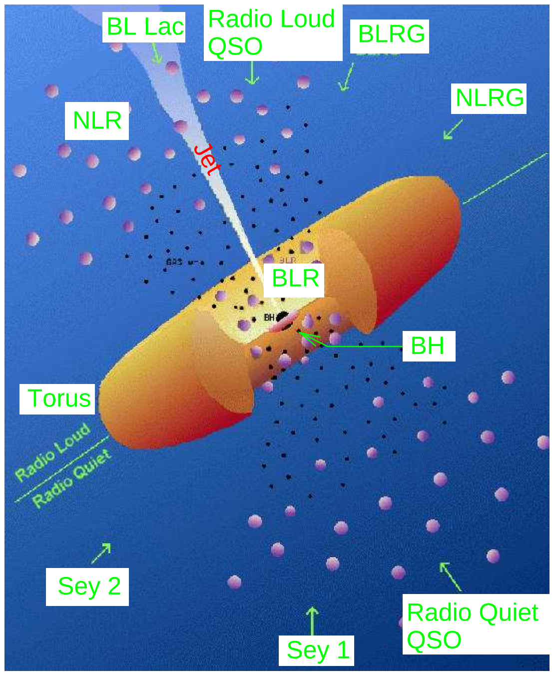
Space Densities

Current space densities of various AGN (Peterson, 1997; Marzke et al., 1994):

Type	Density (Gpc^{-3})
Total Galaxy Density	
Spirals	$1.5 \times 10^7\, h_0^3$
Ellipticals	$1.0 \times 10^7\, h_0^3$
Radio Quiet AGN	
Sy 2	$8 \times 10^5\, h_0^3$
Sy 1	$3 \times 10^5\, h_0^3$
QSO	$800\, h_0^3$
Radio Loud AGN	
FR 1	$2 \times 10^4\, h_0^3$
BL Lac	$600\, h_0^3$
FR 2	$80\, h_0^3$
Radio loud QSOs	$20\, h_0^3$

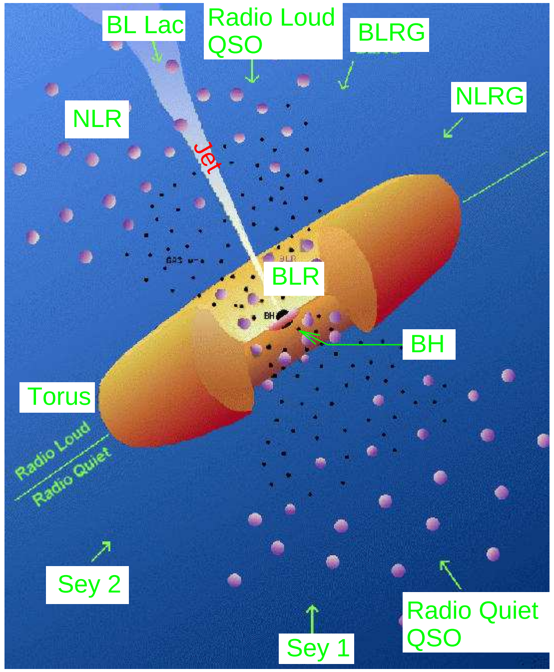
⟹ ∼10% of all galaxies are AGN.

⟹ ∼2% of all AGN are radio loud.



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!)



Physical properties of components:

Accretion disk: $r \sim 10^{-3}$ pc,
- $n \sim 10^{15}\,\mathrm{cm}^{-3}$,
- $kT \sim 50\,\mathrm{eV} \cdot r^{-3/4}$,
- $v \sim 0.3c$ at inner edge.

Broad Line Region (BLR):
- $r \sim 0.01$–0.1 pc (=light days),
- $n \sim 10^{10}\,\mathrm{cm}^{-3}$,
- $v \sim 1000$–$5000\,\mathrm{km\,s}^{-1}$,
- $T \sim 10^4$ K

Torus: $r \sim 1$– few 10 pc,
- $n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
- T: cold

Narrow Line Region (NLR):
- $r \sim 100$–1000 pc,
- $n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
- $v \sim$ few $\cdot\,100\,\mathrm{km\,s}^{-1}$,
- $T \sim 10^4$ K

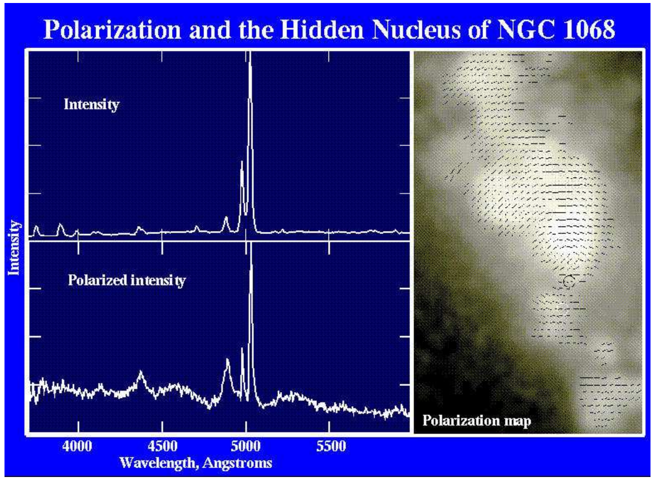
See, e.g., Antonucci (1993) for a review.

Unification

Simplified Unification (Peterson, 1997)

Radio Properties	Orientation: Face-on	Orientation: Edge-on
Radio Quiet	Seyfert 1	Seyfert 2
	QSO	Far IR Galaxy?
Radio Loud	BL Lac	FR I
	BLRG	NLRG
	Quasar/OVV	FR II

Observational Evidence: NGC 1068



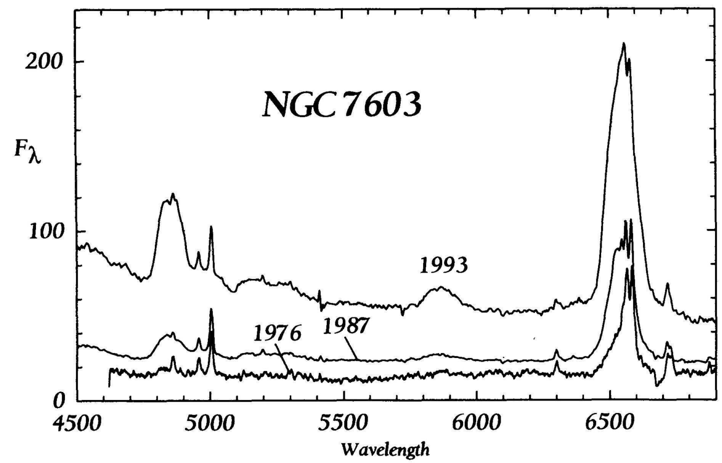
W. Keel

Antonucci & Miller (1985): In polarized light, the Seyfert 2 NGC 1068 shows broad lines and a spectrum similar to Seyfert 1 galaxies.

$\Longrightarrow$ Scattered radiation from the BLR!

16% polarization $\Longrightarrow$ single scattering (multiple scatterings would depolarize!); note that lines from NLR are *not* polarized $\Longrightarrow$ no scattering!

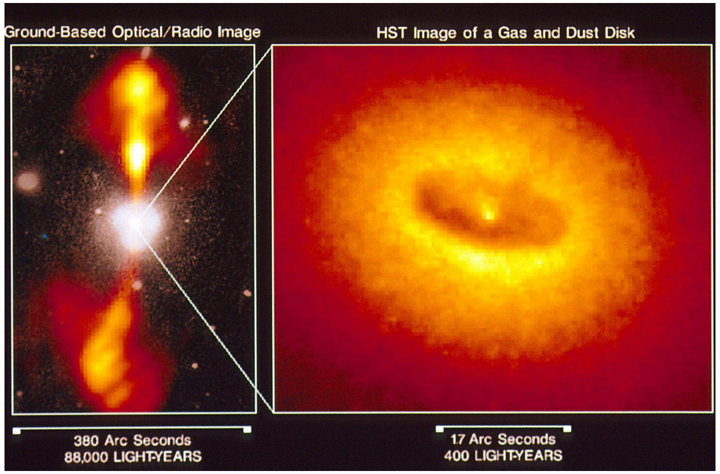
Observational Evidence: Spectral Variations



(Goodrich, 1995, Fig. 7)

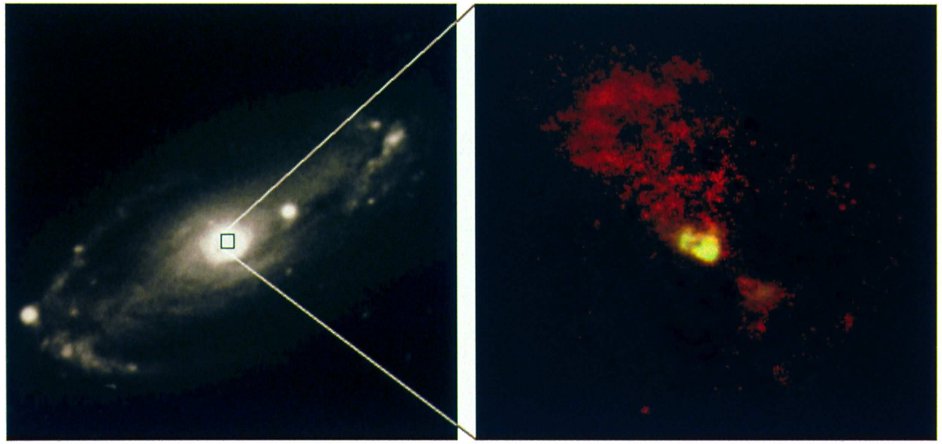
Some Seyferts change type, e.g., from Sy 2 to Sy 1 within a few years.

Observational Evidence: Imaging of the Torus?



NGC 4261 (HST/WFPC)

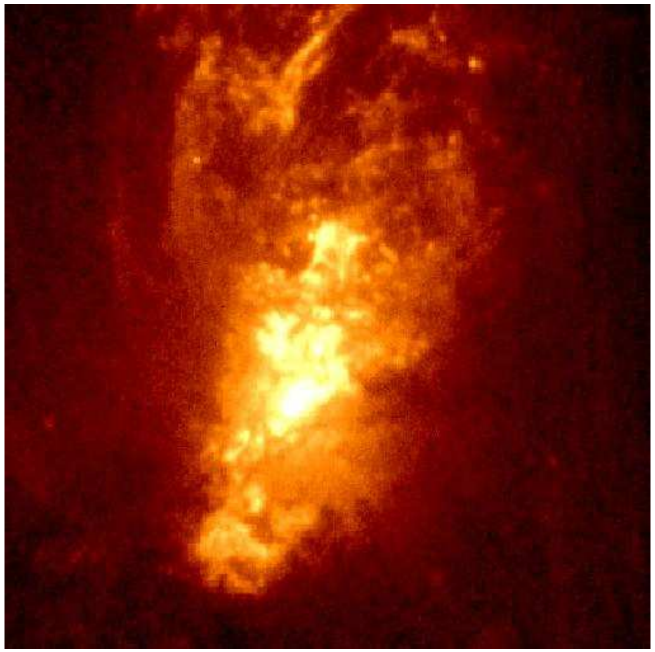
Some nearby Seyferts show torus-like structures in their centers.



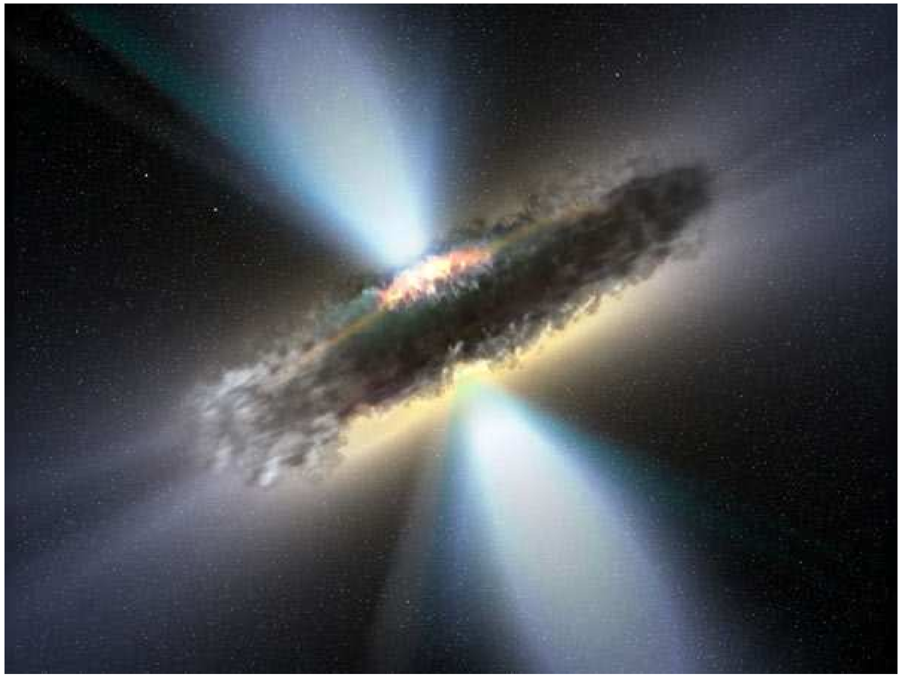
NGC 5728 (Sy 2, HST; green: [O III] $\lambda\lambda$ 4959, 5007 Å, red: Hα and [N II], $\lambda\lambda$ 6548, 6583 Å, plus continua)

Wilson et al. 1993

Ionization cone of NGC 5728: line emission of ionized species aligned with radio structure (to within 2°), *not* aligned with galaxy. Extent of structure: $\sim$1.8 kpc



Ionization in the center of NGC 1068 (Sy 2; HST)



ESA/V. Beckmann

Observational Evidence: Ionization Cones

Interpretation of ionization cones: gas ionized by hard continuum of nucleus.

Shape of cone due to blockage by the torus.

We can try to quantify things, assuming a pure hydrogen gas for simplicity.

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The luminosity of Hβ line is given by

$$L(\mathrm{H}\beta) = \iint j_{\mathrm{H}\beta}\, d\Omega dV = \alpha^{\mathrm{eff}}_{\mathrm{H}\beta} h\nu_{\mathrm{H}\beta} \int n_{\mathrm{e}}^2 dV \tag{3.13}$$

where $j_{\mathrm{H}\beta}$: emissivity, $\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}$ coefficient of recombination (from atomic physics, see later; n_{e}: electron number density; $n_{\mathrm{e}}^2\alpha$: rate of recombinations).

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Assuming photoionization equilibrium, the rate of ionizations of hydrogen equals the rate of photons which can ionize H emitted by the sorce, $Q(\mathrm{H})$, and the photoionization rate equals the recombination rate:

$$Q(\mathrm{H}) = \int_{\nu_1}^{\infty} \frac{L_\nu d\nu}{h\nu} = \alpha_{\mathrm{B}} \int n_{\mathrm{e}}^2 dV \tag{3.15}$$

where $\alpha_{\mathrm{B}} n_{\mathrm{e}}^2$: total recombination rate ($\alpha_{\mathrm{B}} = 2.6 \times 10^{13}\,\mathrm{cm^3\,s^{-1}}$ for $T = 10^4$ K).

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Therefore:

$$Q(\mathrm{H}) = \frac{L(\mathrm{H}\beta)}{h\nu_{\mathrm{H}\beta}} \frac{\alpha_{\mathrm{B}}}{\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}} \sim 2.1 \times 10^{53} L_{41}(\mathrm{H}\beta)\ \mathrm{photons\,s^{-1}} \tag{3.18}$$

Observational Evidence: Ionization Cones

The number of ionizing photons was

$$Q(\mathrm{H}) = \frac{L(\mathrm{H}\beta)}{h\nu_{\mathrm{H}\beta}} \frac{\alpha_{\mathrm{B}}}{\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}} \sim 2.1 \times 10^{53} L_{41}(\mathrm{H}\beta)\,\mathrm{photons\,s^{-1}} \quad (3.18)$$

while the observed ionizing production rate is:

$$Q_{\mathrm{obs}}(\mathrm{H}) = 4\pi d^2 \int_{\nu_1}^{\infty} \frac{F_\nu d\nu}{h\nu} \quad (3.19)$$

Observations show: $Q(\mathrm{H})/Q_{\mathrm{obs}}(\mathrm{H}) > 1$, i.e., cone sees more luminous continuum

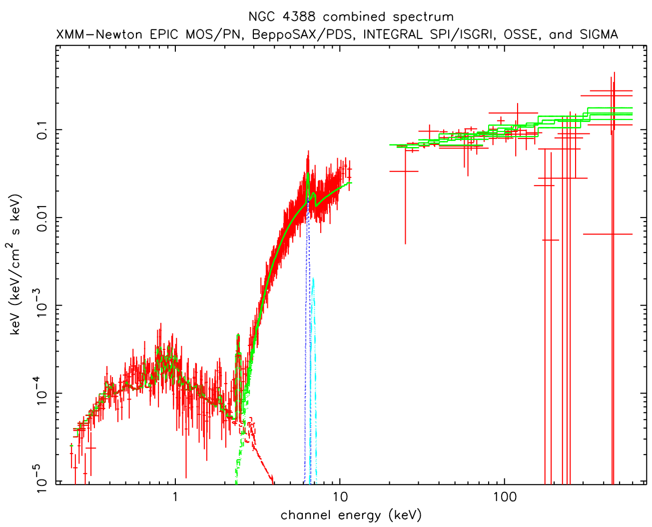
$\Longrightarrow$ blockage due to torus?

But note: calculation ignores that cone probably consists of clouds

$\Longrightarrow$ need to modify $Q(H)$ to take geometry into account. Gives factor $r_{\mathrm{cloud}}/(\epsilon r_{\mathrm{cone}})$, where ϵ is unknown filling factor

$\Longrightarrow$ large uncertainty!

Observational Evidence: Absorption

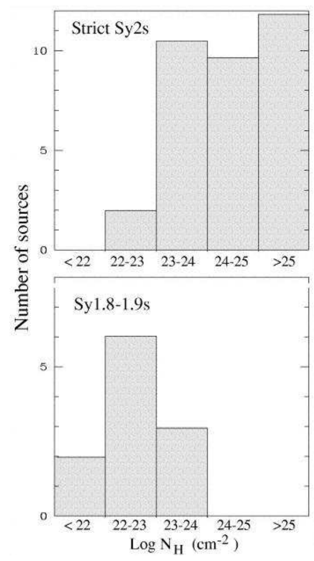


X-ray spectroscopy allows to penetrate even high columns of absorbing gas.

(Beckmann et al., 2004)

Reason: photo-absorption cross section is $\propto E^{-3}$, crosses Thomson cross section at $\sim$10 keV.

Observational Evidence: Absorption



Risaliti, Maiolino & Salvati (1999): From X-ray studies:

- 75% of Seyfert 2's are heavily obscured, i.e., have $N_{\mathrm{H}} \geq 10^{23}\,\mathrm{cm^{-2}}$.
- 50% of Seyfert 2's are Compton thick, i.e., have $N_{\mathrm{H}} \geq 10^{24}\,\mathrm{cm^{-2}}$.
- N_{H} for Sy 2 is higher than that for Sy 1.8, 1.9.

where N_{H} is the column density of Hydrogen,

$$N_{\mathrm{H}} = \int_0^r n_{\mathrm{H}} dr \quad (3.20)$$

determined from X-ray absorption.

(Risaliti, Maiolino & Salvati, 1999, Fig. 5)

Summary

- Puzzling zoo of AGN can be described by simple geometric model: black hole surrounded by obscuring torus
- Radio loud vs. radio quiet: presence of jet
- Observations mainly support unified model

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