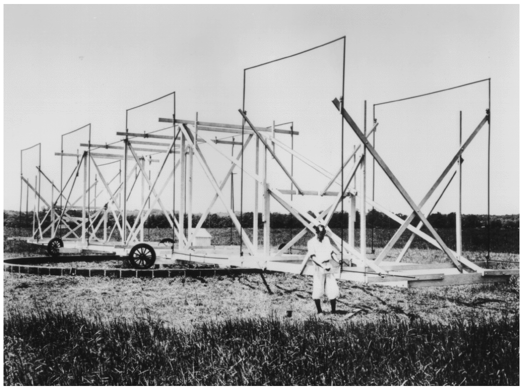
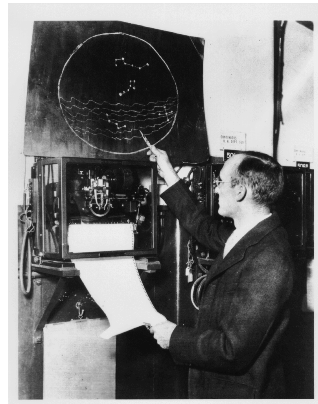
20 – Active Galactic Nuclei Part 1

Radio Astronomy of the 1940's





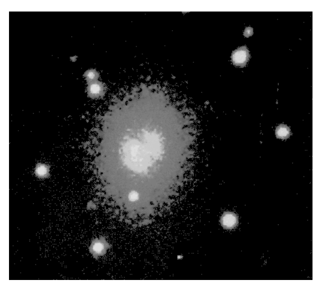
1931 – Karl Jansky discovers radio emission from the Galaxy

"Brightness T" T_{br} = Temperature a blackbody would have to have to produce the observed surface brightness. T_{br} (observed)~few x 10^5 K $\Rightarrow$ nonthermal origin.

Many of these, especially the strongest ones, seemed to be confined to the plane of the MWG, and were presumed to be galactic in origin (supernova remnants, etc.). Others, mostly faint, were isotropically distributed over the sky, and were extragalactic.

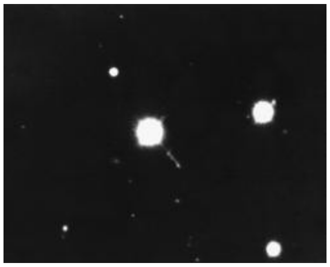
"Galactic" $L_{radio} \sim 10^6 L_{\odot,radio}$
"Extragalactic" $L_{radio} \sim 10^3 L_{MWG,radio}$

1954 – Cygnus A identified with a 17.5 mag galaxy – Strong radio sources can be optically faint!



Mid 50's-60's

Due to the low spatial resolution of radio telescopes, it was difficult to identify these sources with an optical counterpart. 1 arcsec positional accuracy was needed. This was provided through *Lunar Occultations* for sources near the ecliptic.



April 1962 – Cyril Hazard observes occultation of 3C 273

Aug 1962 – 3C 273 re-observed – found to be a *double* source.

Oct 1962 – 3C 273 observed again

Position of 3C 273 now known to an accuracy of 1 arcsec

R. Minkowski, visiting, helps identify 3C 273 with a 13th mag star with an associated patch of nebulosity.

Similar to appearance of M 87 (Virgo A) photo by Curtis (1918)

M 87 nucleus

The position of 3C 273 sent to M. Schmidt at Palomar Observatory.

Schmidt obtains a spectrum of 3C 273, but cannot immediately identify the emission lines present. Many weeks later, realizes that the lines are the *Balmer series of hydrogen, redshifted to z=0.16!* 3C 48 (being studied by other astronomers), then identified as a source with z=0.37. Quasi-Stellar Radio Sources (Quasars).

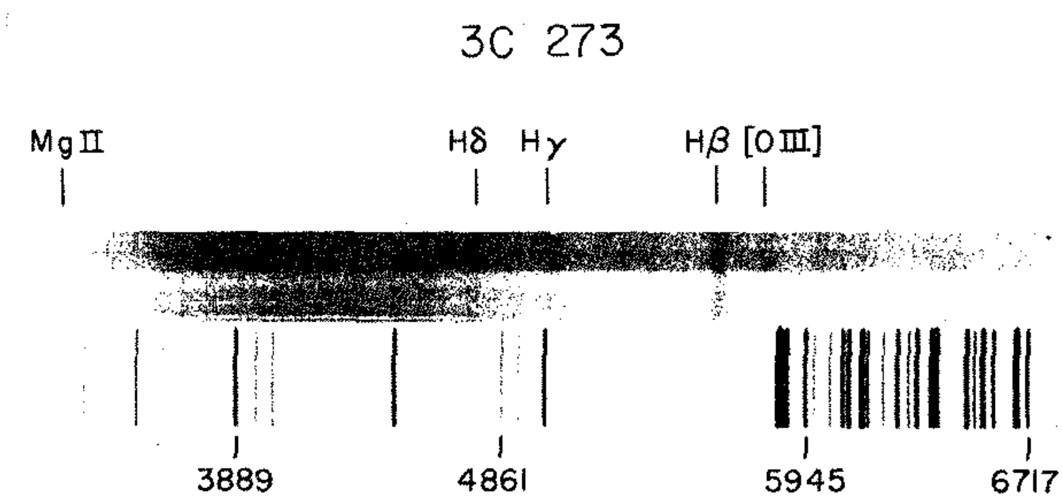


FIG. 2.—Spectrum of the quasi-stellar object 3C 273B, 400 Å/mm original, 103a-F, January 23, 1963. The comparison spectrum is H + He + Ne. Exposure over the upper half of slit was three times that over the lower half. Redshifted emission lines of H and [O III] are indicated; also the barely visible line of Mg II, confirmed on denser exposures.

The redshift implied $L_{opt} \geq L_{MWG}$
Line widths implied $v_{internal} \sim 10^4$ km s^{-1}

Parallel History

1943 – Carl Seyfert – survey of galaxies with star-like nuclei & bright emission lines:

Type 1 – broad and narrow emission lines seen
Type 2 – narrow lines only.

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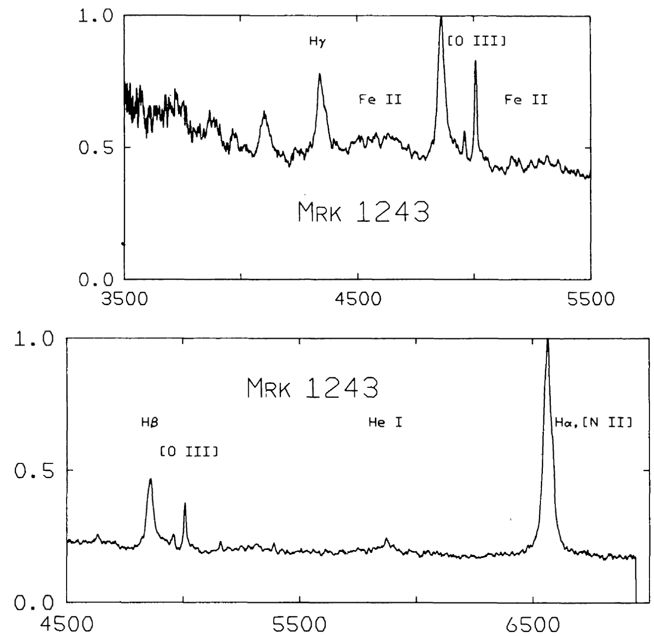


FIG. 1. Spectrum of Seyfert 1 galaxy Mrk 1243, *above*, λλ3500–5500; *below*, λλ4500–7000 in the rest system of the object. *Vertical scale*, relative energy flux in flux units per unit wavelength interval, *horizontal scale*, wavelength in Angstrom units.

No. 1 ACTIVE GALACTIC NUCLEI 3

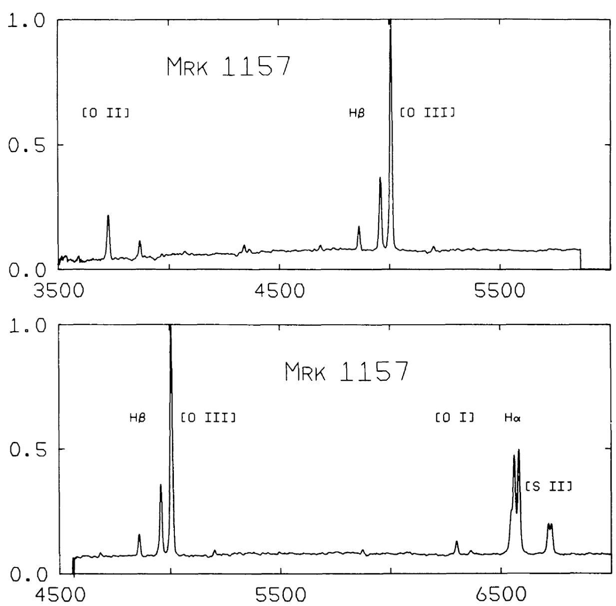


FIG. 2. Spectrum of Seyfert 2 galaxy Mrk 1157, scales and units as in Fig. 1.

50's, 60's, 70's – Radio galaxies observed & cataloged – 3C, 4C, PKS, Ohio State

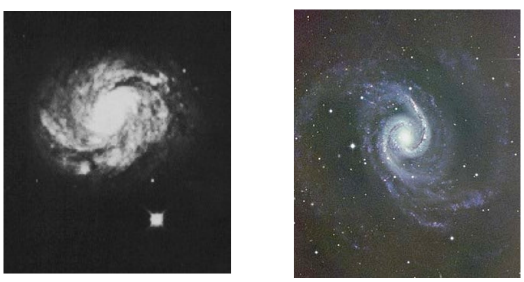
1968 – "variable star" BL Lacertae (BL Lac) identified with the radio source VRO 42.22.01 – rapid variability & highly polarized

Surveys

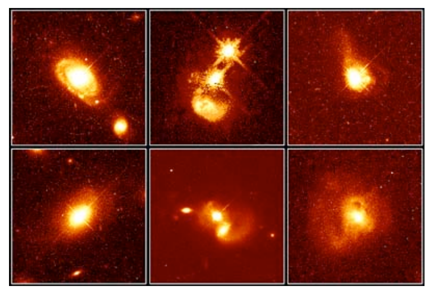
1. Radio – followed by optical pictures and spectra
2. Objective Prism
3. UV-excess – followed by spectra
4. X-ray – followed by images & spectra

Most quasar-like objects are actually "radio-quiet"! Quasi-Stellar Objects (QSOs). "Quasars" often considered to be just the most radio-powerful subset of QSOs.

Are all these Active Galactic Nuclei (AGN) related?



Seyfert Galaxies



QSO "fuzz"

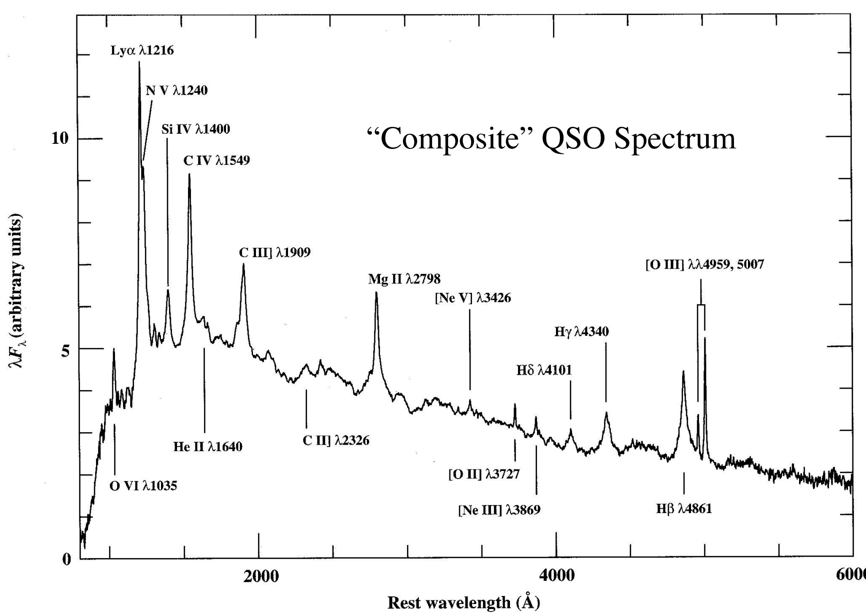
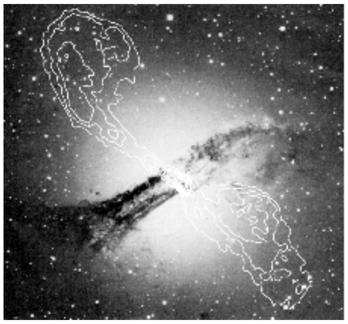
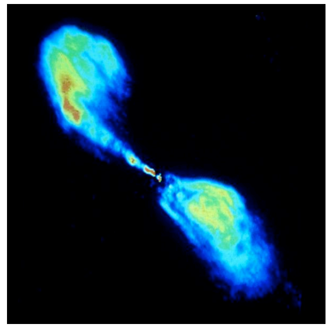


Fig. 2.2. A mean QSO spectrum formed by averaging spectra of over 700 QSOs from the Large Bright Quasar Survey (Francis *et al.* 1991). Prominent emission lines are indicated. Data courtesy of P. J. Francis and C. B. Foltz.

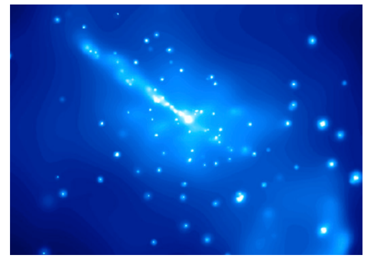
Radio Galaxies & BL Lac Objects



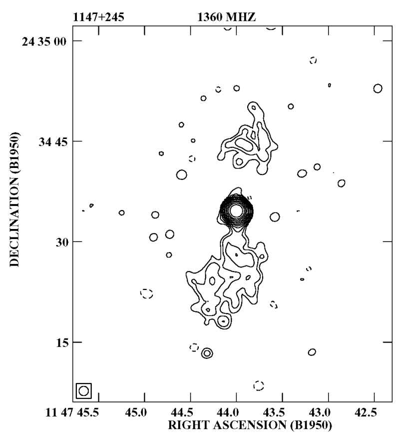
Cen A – Radio & Optical

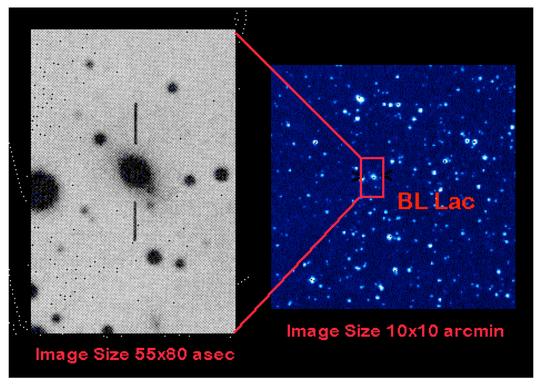


Cen A – 6 cm

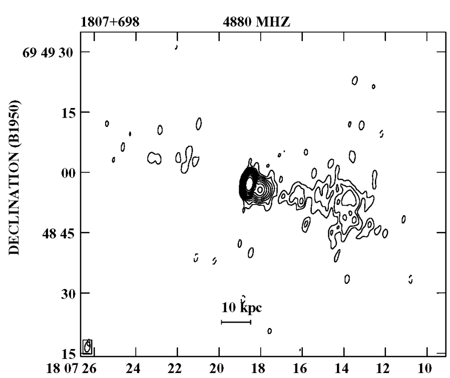


Cen A in X-rays

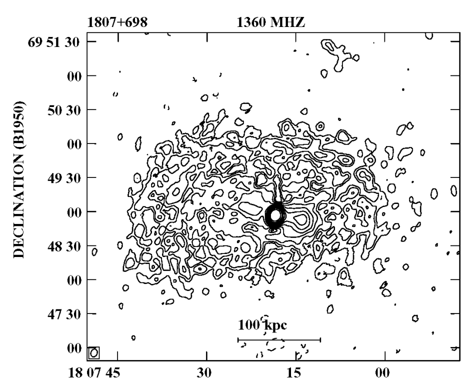




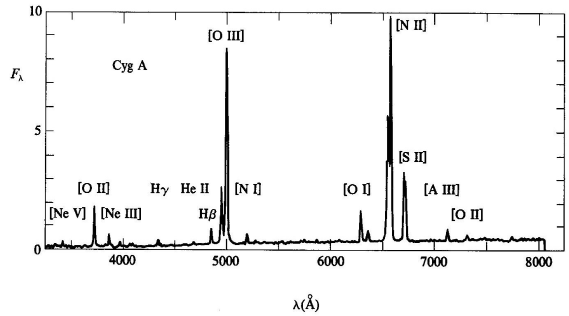
BL Lac Object 1147+245 VLA – B configuration



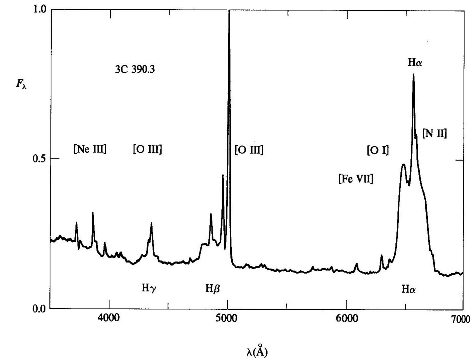
BL Lac Object 1807+698
VLA – B configuration



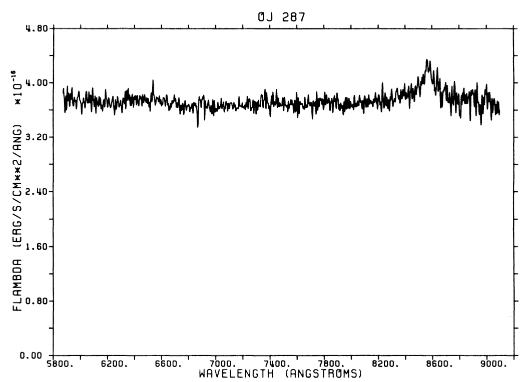
1807+698 – A+B+D
configurations



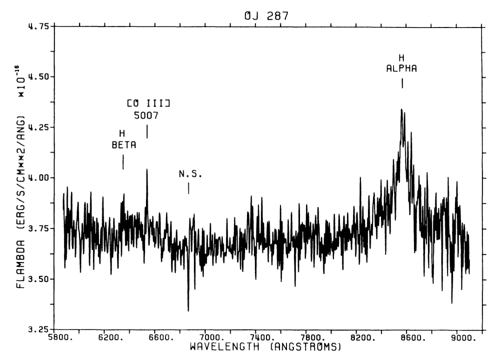
Narrow-Line Radio Galaxy (NLRG)



Broad-Line Radio Galaxy (BLRG)



BL Lac object OJ 287 at minimum light



Detail of OJ 287 spectrum

<u>Radio-Loud versus Radio Quiet AGN</u>

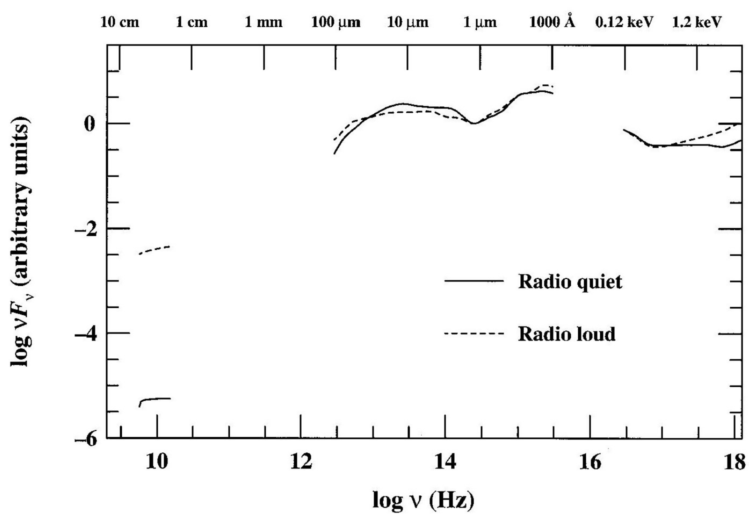
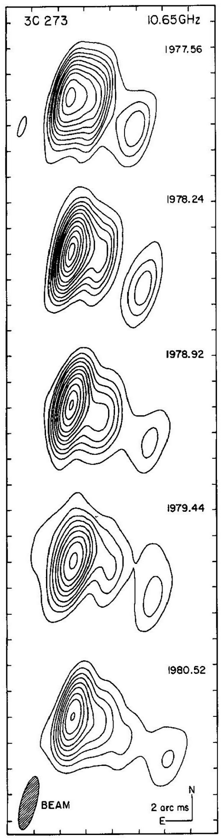


Fig. 4.1. Mean spectral energy distributions (SEDs) for a sample of radio-quiet (solid line) and radio-loud (dashed line) QSOs (from Elvis *et al.* 1994). The flux scale has been arbitrarily normalized at a wavelength of 1 μm.

Superluminal Motion



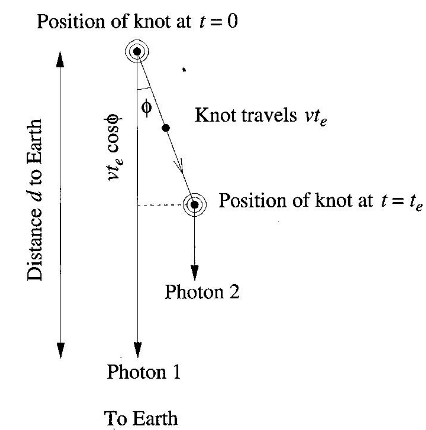


Figure 26.31 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Fig. 4.5. VLBI maps at a frequency of 10.65 GHz of the quasar 3C 273 ($z = 0.158$) made at five different epochs, showing apparent 'superluminal' (i.e., faster than light) expansion of the source (from Pearson *et al.* 1981). Figure courtesy of T. J. Pearson and the California Institute of Technology. Reproduced by permission from *Nature*, Vol. 290, pp. 365–367. Copyright 1981 Macmillan Journals Limited.

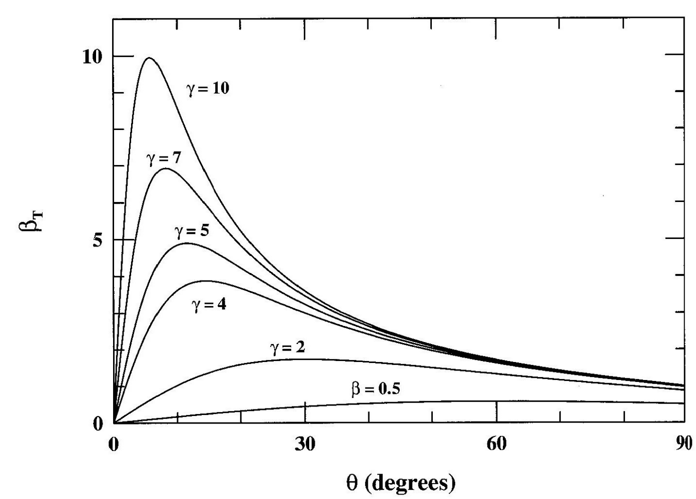


Fig. 4.7. The apparent transverse velocity $\beta_T = v_T/c$ of a source moving at an angle θ to the observer's line of sight (as in Fig. 4.5) as a function of the Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$. For $\gamma \gg 1$, the apparent transverse velocity can exceed the speed of light.

Doppler Boosting & 1-Sided Jets

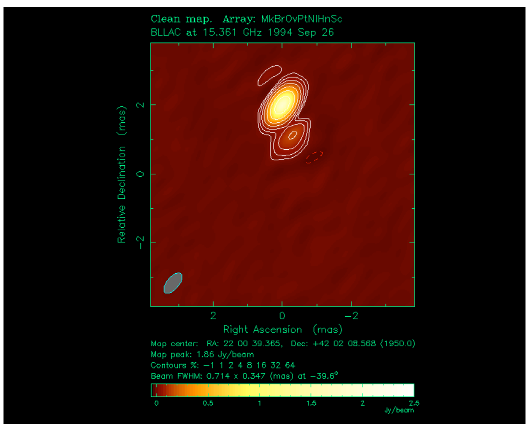
Due to the large degree of brightening that occurs when material with large Lorentz factors approaches the observer, in a 2-sided jet source, the approaching jet will be relativistically enhanced in brightness and the receding jet will be similarly diminished in brightness.

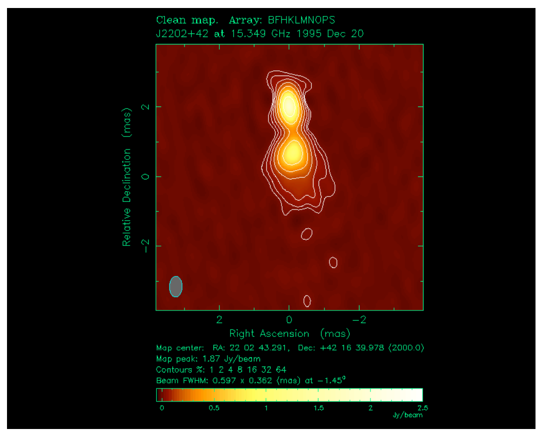
CONSEQUENCE #1: Objects with superluminal motion will be "1-sided" (actually a very weak second jet should be present), while 2-sided just should not exhibit superluminal motion.

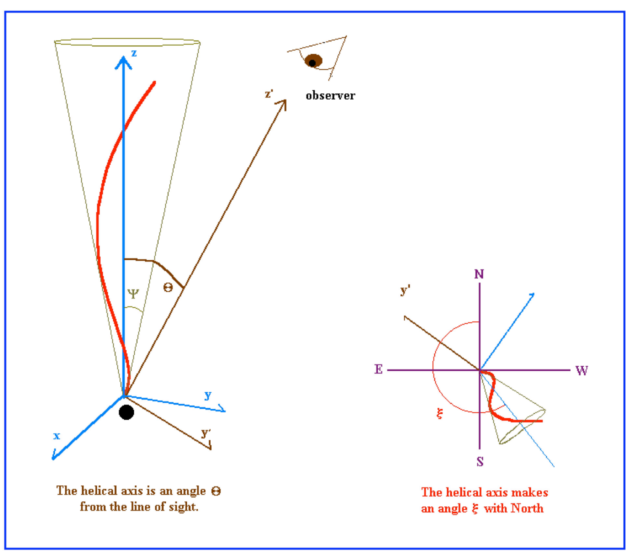
CONSEQUENCE #2: Objects with 1-sided jets (and/or superluminal motion) will probably have faster variability. Note: some radio-quiet BL Lacs have been found, and they do NOT show rapid variability (Liu qt al. 2015, A&A).

CONSEQUENCE #3: Objects with 1-sided jets (and/or superluminal motion) will have continua that will overwhelm the spectral features (gas, stars) of unboosted material.

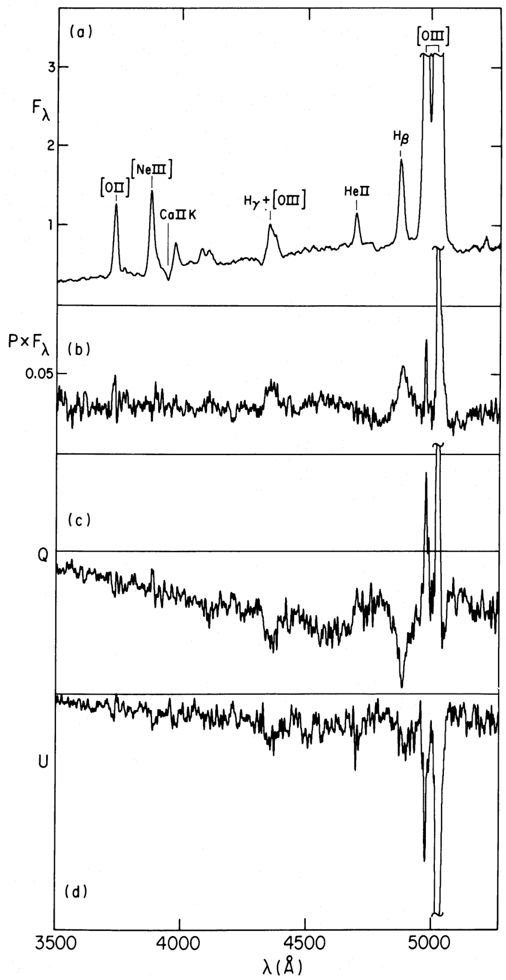
This seems to be the case, generally. If so, then *BL Lac objects are just radio galaxies seen "down the barrel of the gun"*.

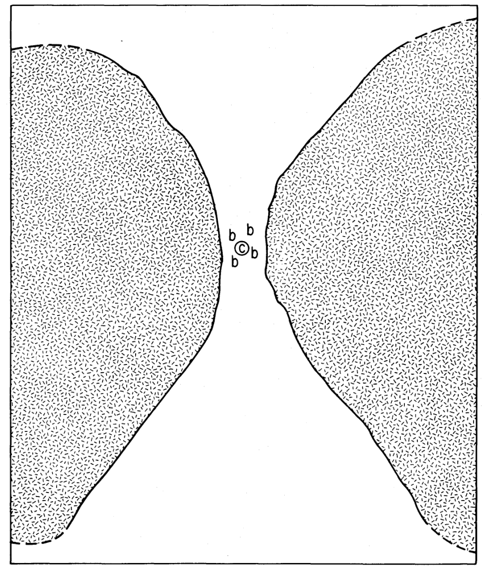






Spectropolarimetry of Seyfert 2 Galaxies





Total flux and polarized flux (left) and model of NGC 1068 (Seyfert 2 galaxy) from Antonucci & Miller (1985, ApJ, 297, 621).

By looking just at the polarized flux, one can detect weak polarized components and eliminate the much stronger unpolarized light.

The spectropolarimetric measurements of are detecting broad Seyfert 1 lines in Seyfert 2 galaxies. This suggests that to a large degree, *the difference between Seyfert 1's and Seyfert 2's is simply a matter of orientation of the inner obscuring torus/disk.* In Seyfert 1's, we are looking down the rotation axis of the disk.

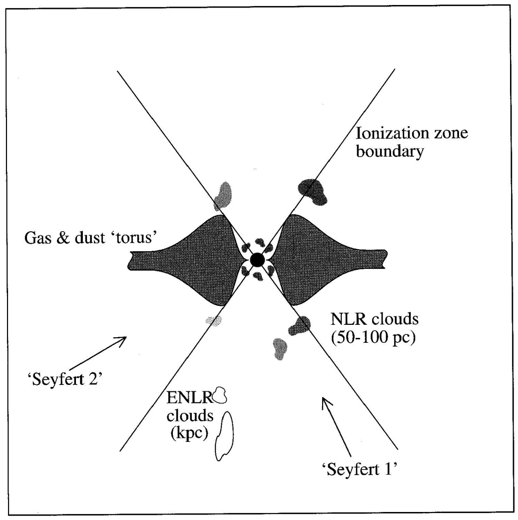


Fig. 7.1. A conceptual scheme for unification of Seyfert 1 and Seyfert 2 galaxies, not to scale. A highly opaque dusty torus surrounds the continuum source (black dot at center) and broad-line region (clouds near center). These cannot be viewed directly by an observer close to the torus midplane, although the narrow-line region and extended narrow-line region can be seen directly. This would lead the observer to classify the galaxy as a 'Seyfert 2'. An observer closer to the torus axis would have an unobscured view of the nuclear regions and classify the same galaxy as a 'Seyfert 1'. Figure courtesy of R. W. Pogge.

Table 7.1
Possible Simple Unifications

Radio Properties	Orientation: Face-On	Orientation: Edge-On
Radio Quiet	Seyfert 1	Seyfert 2
	QSO	FIR galaxy?
Radio Loud	BL Lac	FR I
	BLRG	NLRG
	Quasar/OVV	FR II

FR I = Fanaroff-Riley Type I radio galaxies – brightest at core. Ex.: Cen A
FR II = Fanaroff-Riley Type II radio galaxies – limb-brightened - more luminous than FR I's. Ex.: Cyg A
OVV = Optically Violent Variable quasars

UNSOLVED PROBLEMS

Should see continuum polarization in Seyfert 2's – *Don't!*
"Quasar 2's"? Missing for decades, but began to be detected in mid-1990's. But some studies suggest they are *not entirely* a matter of orientation (e.g. Greene et al. 2014, ApJ, 788, 91). There seems to be some evidence that "2" objects might have thicker dust tori, biasing them toward being more obscured (Bouquin et al. 2015, ApJL). Also at least 1 changes between types (LaMassa et al. 2015, ApJ, 800, 144)!!

Reverberation Mapping & the Broad Line Region

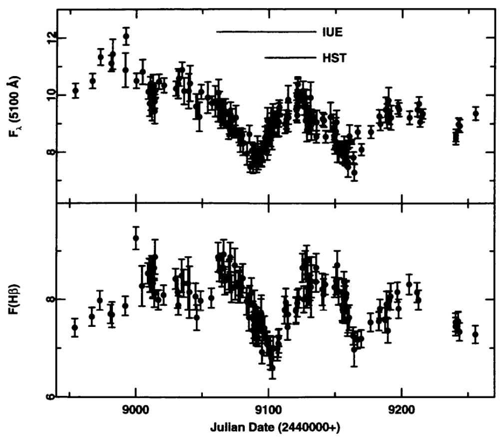
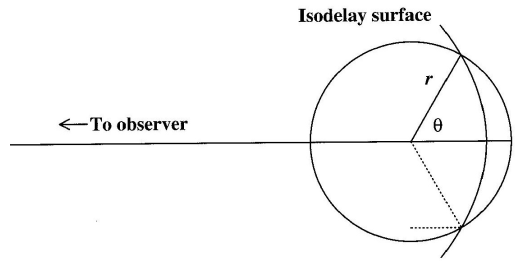


FIG. 12.—Continuum fluxes at 5100 Å (*top panel*) and Hβ emission-line fluxes (*bottom panel*) for NGC 5548, as given in Tables 21 and 23, from 1992 November through 1993 September. Fluxes are in the rest frame of NGC 5548, and are in units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1} for the continuum and 10^{-13} ergs s^{-1} cm^{-2} for the line. The periods during which NGC 5548 was monitored by *IUE* (UT 1993 March 19–1993 May 27) and by *HST* (UT 1993 April 19–1993 May 27) are also shown.



Time-delay between the continuum flux and the Hβ line flux (Korista et everyone 1995, ApJS, 97, 285.

Light echo from V838 Mon ⟶

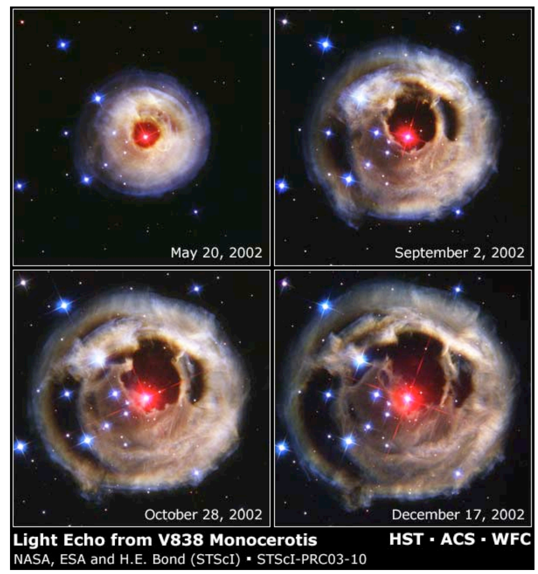


Table 5.2
NGC 5548
Cross-Correlation Lags

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