Physics of AGN

Introduction

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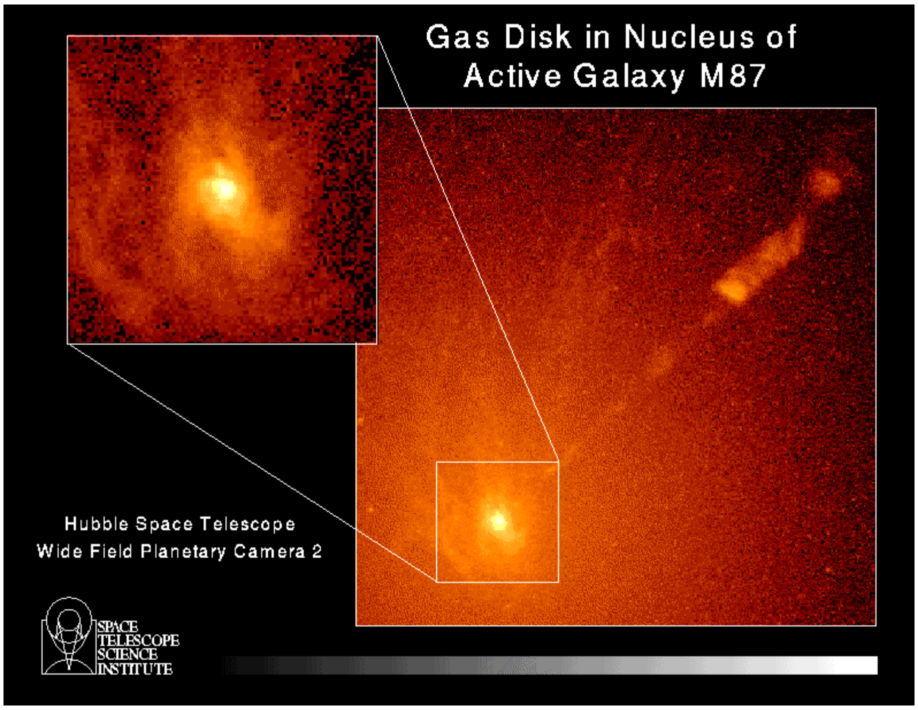

Contents:

Literature:
"An Introduction to Active Galactic Nuclei", Bradley M. Peterson, Cambridge University Press, Cambridge
"Active Galactic Nuclei", Ian Robson, John Wiley & Sons, Chichester

Definition

■ What are Active Galactic Nuclei?

Active Galactic Nuclei (AGN) are nuclei of galaxies which show energetic phenomena that cannot be clearly and directly attributed to stars.

Signs of Activity:

- Luminous UV emission from a compact region in the center of a galaxy
- Strongly Doppler-broadened emission lines
- High variability
- strong non-thermal emission
- compact radio core
- extended, linear radio structures (jets+hotspots)
- X-ray, γ-ray, and TeV-emission
- Cosmic ray production (?)

In some luminous AGN (quasars) the radiation from a region comparable to the solar system can be several hundred times brighter than the whole galaxy.

Historical Perspective

■ First detections

- NGC 1068 (E.A. Fath 1908, Lick Obs.) and V.M. Slipher (Lowell Obs.) - strong emission lines similar to planetary nebulae, line widths of several hundred km/sec
- detection of an optical jet in M87 (Curtis 1913)
- Same period: Einstein develops GR, Schwarzschild metric (1916) but no connection seen yet
- Hubble (1926) - Nebulae are extragalactic (galaxies)
- Carl Seyfert (1943) - found several galaxies similar ro NGC1068 (henceforth named Seyfert galaxies), i.e. galxies with a bright nucleus and strong emission lines (NGC1275, NGC3516, NGC 4051, NGC 4151, NGC7469)
- Detection of radio emission from NGC1068 & NGC1275 (1955)
- Woltjer (1959) - Timescale for Seyfert-activity $\sim 10^8$ years (1% of Galaxies are *luminous* Seyferts), Mass of nucleus is very high $10^{8-10} M_\odot$ (velocity dispersion/line width several thousand km/sec at base in unresolved nucleus)

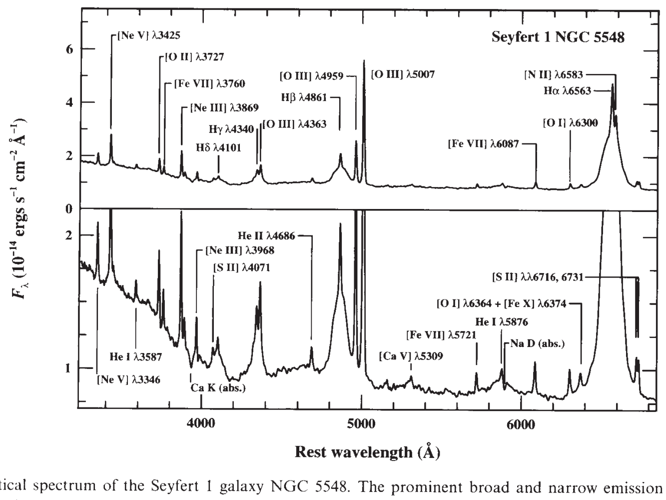

Fig. 1.1. The optical spectrum of the Seyfert 1 galaxy NGC 5548. The prominent broad and narrow emission lines are labeled, as are strong absorption features of the host galaxy spectrum. The vertical scale is expanded in the lower panel to show the weaker features. The full width at half maximum (FWHM) of the broad components is about 5900 km s^{-1}, and the width of the narrow components is about 400 km s^{-1}. The strong rise shortward of 4000 Å is the long-wavelength end of the 'small blue bump' feature which is a blend of Balmer continuum and Fe II line emission. This spectrum is the mean of several observations made during 1993 with the 3-m Shane Telescope and Kast spectrograph at the Lick Observatory. Data courtesy of A. V. Filippenko.

Historical Perspective

■ Radio Surveys & Quasars

Early radio surveys were very important for the discovery of quasars.

- **3C and 3CR**: The third Cambridge (3C) catalog (Edge et al. 1959) at 158 MHz. Revision: 3CR catalog (Bennett 1961) at 178 MHz down to limiting flux density of 9 Jy (1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}). Basis for extragalactic radio astronomy and first cosmological studies, discovery of first quasars. Famous examples: 3C273, 3C279, and many radio galaxies. Naming format 3C NNN - numbering by right ascension. 3CR adds decimal to keep ordering.
- **PKS**: Parkes (Australia, Ekers 1969) survey of southern sky at 408 MHz ($>$ 4 Jy) and 1410 MHz ($>$ 1 Jy). Naming: PKS HHMM$\pm$DDT (IAU convention for naming is similar)
- **4C**: Fourth Cambridge survey (4C $\pm$DD.N), today 8C available - surveys to lower and lower sensitivity limits but also restricted to smaller and smaller areas.
- **AO**: Arecibo Occultation survey — occultation by moon, high positional accuracy (Hazard et al. 1967)

Sources found:

- Surveys usually exclude the Galactic Plane, otherwise they would have found the Galaxy and the Galactic Center first.
- Normal Galaxies
- Stars with weird broad emission lines!?

Historical Perspective

■ Detection of Quasars

Radio ID of quasars by Hazard et al. 1963), Maarten Schmidt (1963): The lines in 3C273 are highly redshifted (z=0.158) emission lines $\rightarrow$ first detection of quasars (3C 48, 3C273), from Hubbles law follows ($h_0 = H_0/(100$ km s^{-1} Mpc^{-1})

$$d = cz/H_0 = 3000 z h_0^{-1}\mathrm{Mpc} = 470 h_0^{-1}\mathrm{Mpc}$$

$\Rightarrow$ Luminosity of 3C273:
$B = 13.1 \Rightarrow S_\mathrm{B} = 2.55\,10^{-25}$ erg sec^{-1} Hz^{-1} cm^{-2}

$$\Rightarrow L = 2 \cdot 10^{46}\mathrm{erg/sec} = 5 \cdot 10^{12} L_\odot$$

(100 times larger than normal galaxy)

quasar = quasi-stellar radio source, QSO = quasi-stellar object
(no longer distinguished)

Important difference to stars: quasars are significantly bluer than main-sequence stars.

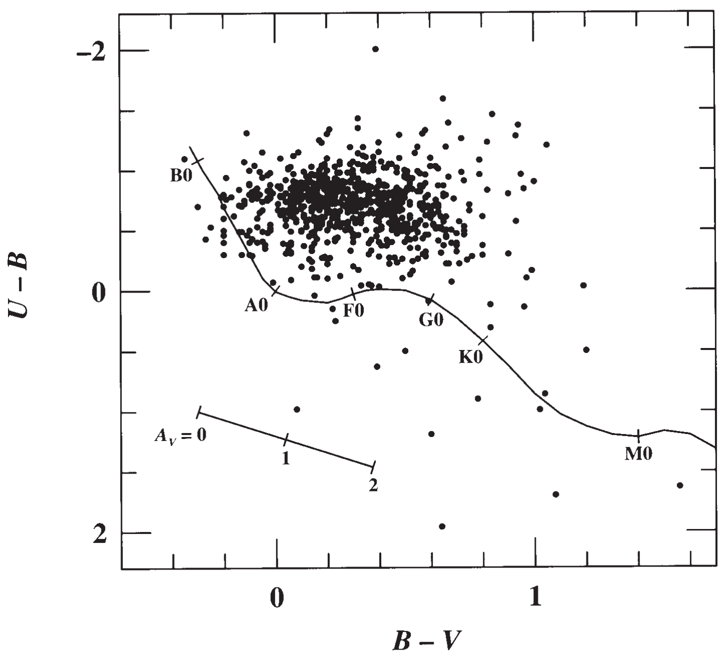

Fig. 1.6. The locations of 788 quasars from the Hewitt and Burbidge (1993) catalog on a two-color ($U - B$ vs. $B - V$) diagram. The locus of the zero-age main sequence, with spectral types indicated, is also shown. The line in the lower left shows how points will be translated due to amounts of reddening corresponding to visual extinction A_V (based on the extinction curve of Cardelli, Clayton, and Mathis (1989) with $R_V = A(V)/E(B - V) = 3.1$). Most quasars with measured UBV magnitudes are color-selected, i.e., identified as quasar candidates on the basis of their blue colors, especially $U - B < 0$.

Spectral Energy Distribution

AGN show emission in all astrophysically relevant wavelengths regimes

Old view - still roughly correct, yet meaningless: The Spectral Energy Distribution (SED) of AGN can be described by a simple powerlaw of the form:

$$F_\nu = C\nu^\alpha$$

typical values for quasars: $-1 > \alpha > 0$, but a single powerlaw doesn't really fit.

For $\alpha = -1$ follows $\nu F_\nu \simeq$const $\Rightarrow$ equal energy per logarithmic frequency interval (per decade)

Bolometric luminosity is

$$P(\nu_1, \nu_2) = C \int_{\nu_1}^{\nu_2} \nu^\alpha d\nu$$

$$= C(1+\alpha)^{-1} \left(\nu_2^{1+\alpha} - \nu_1^{1+\alpha}\right) \quad \text{or} \quad C \ln(\nu_2/\nu_1)$$

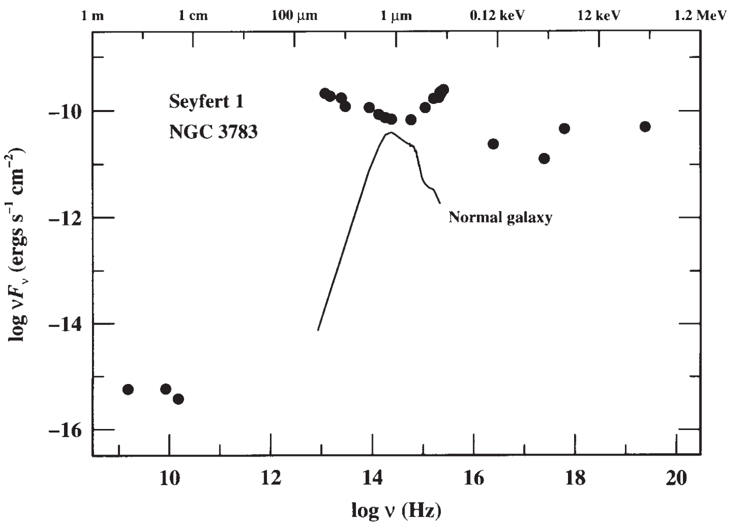

Fig. 1.3. The spectral energy distribution (SED) of the Seyfert 1 galaxy NGC 3783 (Alloin *et al.* 1995), from radio to γ-ray energies. Shown for comparison is SED for a normal (type Sbc) galaxy, from a template spectrum compiled by Elvis *et al.* (1994). The flux scale of the normal galaxy spectrum has been adjusted to give the correct relative contribution of AGN component and starlight for NGC 3783 (in mid-1992) at 5125 Å through a $5'' \times 10''$ spectrograph aperture.

Classes of AGN

A very rough classification of a typical SED:

- Radio: non-thermal radiation from jets
- IR: thermal radiation from dust
- opt/UV: thermal radiation from central engine
- x-rays to γ-rays: comptonized thermal and non-thermal radiation

However, not always are all parts equally strong and present in a spectrum. This gives rise to many different classes of AGN.
Some AGN a relatively bright in the radio

- Radiogalaxies
  - FRII R.G.: powerful collimated jets with hotspots (Fanaroff & Riley 1974)
  - FRI R.G.: less-powerful, less-collimated, no hotspots
  - CSS: Compact-Steep-Spectrum R.G. (mini-RGs, stopped within Galaxy)
  - GPS/CSO: Gigahertz-Peaked-Spectrum R.G. or Compact-Symmetric-Objects (baby quasars)
  - Blazars, BL Lacs: core-dominated, flat-spectrum quasars with significant non-thermal radiation throughout SED

Depending on the optical properties of the RG, they can be called broad-line RG, narrow-line RG, or radio-loud quasar (usually no longer called a RG).

Classes of AGN

■ Radiogalaxies

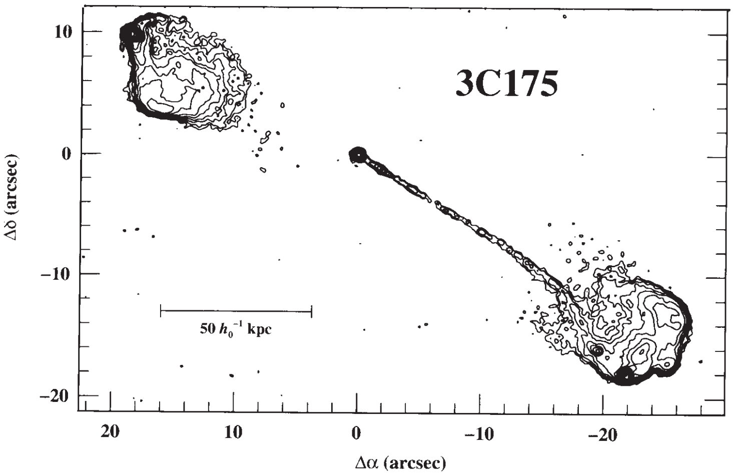

Fig. 1.5. Example of Fanaroff Riley type II (FR II) galaxy. This is a map of the $z = 0.768$ quasar 3C 175, as observed with the VLA at 4.9 GHz (Bridle *et al.* 1994). The quasar itself is coincident with the bright compact source at $(\Delta\alpha, \Delta\delta) = (0, 0)$. A jet extending from the compact source to the extended radio lobes is observed on one side of the source. FR II sources are edge-brightened, probably because of shock heating as the radio-emitting plasma interacts with the ambient intergalactic medium. FR I sources are not edge-brightened, which suggests that their outflows are subsonic. Data courtesy of A. H. Bridle, figure by R. W. Pogge.

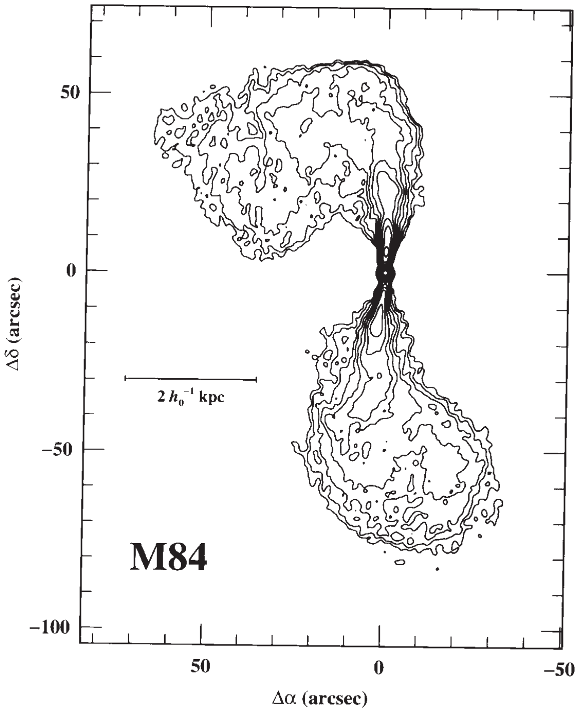

Fig. 1.4. Example of an Fanaroff Riley type I (FR I) galaxy. This is a radio map of the Virgo cluster elliptical galaxy M84 (3C 272.1 = NGC 4373), based on 4.9 GHz data obtained with the VLA by Laing and Bridle (1987). Data courtesy of A. H. Bridle, figure by R. W. Pogge.

Classes of AGN

Classification can also be a function of luminosity (relative to the host galaxy)

- Quasars - quasi-stellar
- Seyferts - host galaxy is visible but has bright nucleus
- LINERs - host galaxy is visible, not so bright nucleus, low-excitation lines in spectrum.

AGN are not restricted to luminous quasars and Seyferts. A big survey with the Palomar 5m telescope of nearby galaxies has shown: 30-40% of all galaxies show signs of an AGN! (Ho, Filippenko, & Sargent 1995)

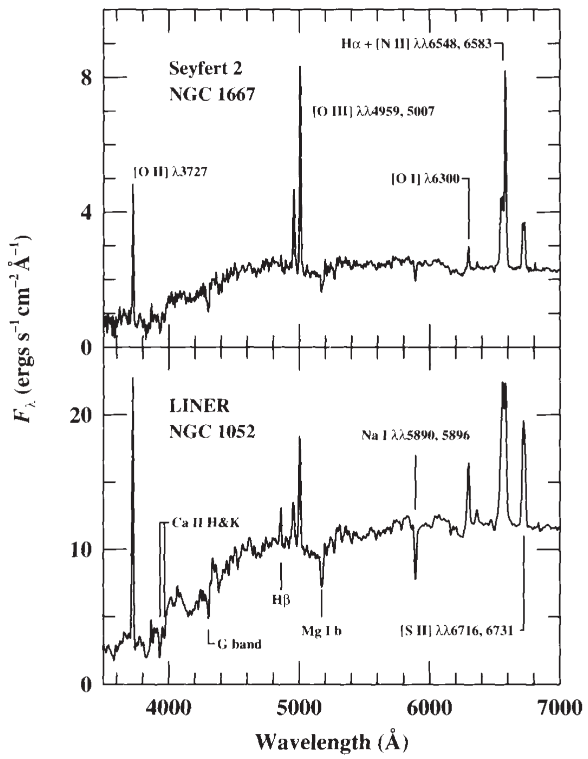

Fig. 2.1. The optical spectra of the Seyfert 2 galaxy NGC 1667 (top) and the LINER (see §2.4) NGC 1052 (bottom) are shown, with important emission lines identified (Ho, Filippenko, and Sargent 1993). Some strong absorption lines that arise in the host galaxy rather than the AGN itself are also identified. These spectra can be compared with the Seyfert 1 spectrum shown in Fig. 1.1, and the QSO spectrum shown in Fig. 2.2. Important differences between Seyfert 2s and LINERs are apparent: the [O III] λ5007/Hβ flux ratio is much larger in Seyfert 2s (in NGC 1667, the weak Hβ line is obscured by blending with the stellar Hβ *absorption* line) than in LINERs, and low-ionization lines ([N II] $\lambda\lambda$6716, 6731, [S II] $\lambda\lambda$6548, 6583, [O II] λ3727, and [O I] λ6300) are all relatively prominent in LINER spectra. Data courtesy of A. V. Filippenko.

Classes of AGN

■ Seyfert Galaxies

- Seyferts are lower-luminosity AGN with $M_{\rm b}$ >-21.5+5logh_0

  Reminder: absolute magnitude is magnitude scaled to distance of 10 pc

$$S_{\rm B}(0{\rm mag}) = 4.44 \cdot 10^{-20}\ {\rm erg/sec/cm^2/Hz}$$
$$\nu = 6.8 \cdot 10^{14}\ {\rm Hz} \quad (\lambda = 4400\AA)$$
$$4\pi(10{\rm pc})^2 = 1.2 \cdot 10^{40}\ {\rm cm}^2$$
$$\Rightarrow \nu L_\nu = 4.44 \cdot 10^{-20} \times 10^{0.4\cdot 21.5} \times 6.8 \cdot 10^{14} \times 1.2 \cdot 10^{40} {\rm erg/sec}$$
$$\Rightarrow \nu L_\nu \simeq 10^{44}\ {\rm erg/sec}$$
$$(-19.4 + 8.6 + 14.8 + 40.1 \sim 44)$$

- Host galaxy is still visible, mostly spirals
- Two types
  Seyfert 1: have two sets of emission lines
  - *narrow emission lines:* characteristic of low-density gas (forbidden lines, $n_{\rm e} \simeq 10^3 - 10^6 {\rm cm}^{-3}$) with FWHM (full width half maximum) of several hundred kilometers per second ($\frac{400{\rm km/sec}}{c} \sim 1.3 \cdot 10^{-3} \Rightarrow$ FWHM ~ 6Å at $\lambda = 4500$Å)
    The region in the galaxy producing these lines is called **Narrow-Line Region=NLR**!
  - broad emission lines: characteristic of high-density gas (no forbidden lines, $n_{\rm e} > 10^9 {\rm cm}^{-3}$) with FWHM (full width half maximum) of several thousand kilometers per second ($\frac{5000{\rm km/sec}}{c} \sim 1.6 \cdot 10^{-2} \Rightarrow$ FWHM ~ 75Å at $\lambda = 4500$Å)
    The region in the galaxy producing these lines is called **Broad-Line Region=BLR**!

  Seyfert 2: only have narrow lines.

Classes of AGN

■ Seyfert Galaxies

Other features in the spectrum:

- *Weak absorption lines* from late-type giant stars in underlying galaxy, but diluted by
- *featureless continuum (FC)*: Optical contiuum emission produced by the AGN. Some people suggest the presence of a FC2 - continuum emission seen, e.g. in some Seyfert 2s, which comes from a more extended region, outside the AGN.

Some people also define intermediate types between Seyfert 1 & 2, i.e. Seyfert 1.5, 1.8, and 1.9 (Osterbrock 1981) with weaker broad-line components relative to the narrow lines. In Seyfert 1.9 the broad component is only detected in Hα.

Shape and flux of broad-lines can vary and in some sources the BLR has *almost* disappeared. The FC shows also variation which seems to be related to the line emission $\rightarrow$ reverberation mapping
Emission from NLR does not vary.

Classes of AGN

■ Distinguishing Seyfert/LINER/HII Galaxies

Seyferts are clearly separated from HII regions—which also produce emission-lines by photionization from stars—by their line-ratios.

- Common criterion for Seyferts: [OIII]λ5007/H$\beta > 3$ (requires relatively hard, non-stellar ionizing continuum)

$\triangledown$ Problem: reddening can affect line-ratios

$\triangledown$ Solution:

a) Use line ratios of lines which are very close in wavelength $\rightarrow$ reddening independent

b) Use two sets of widely separated lines $\rightarrow$ line ratio depends on *continuum shape*

- LINERs have lower-ionization levels: lower [OIIIλ5007/Hβ ratio compared to [NII]λ6583/Hα than Seyferts, but higher [NII]λ6583/Hα ratios than HII regions.

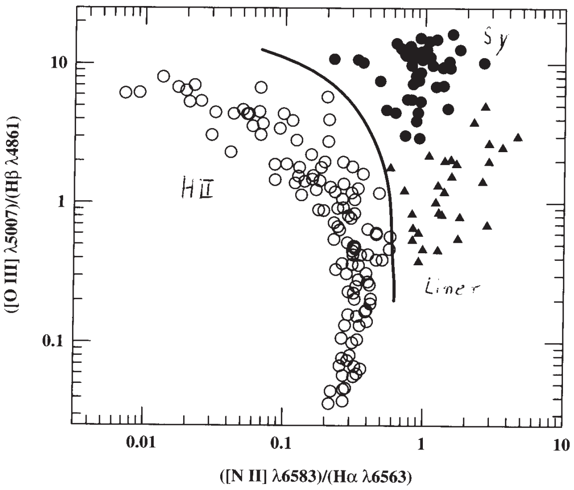

Fig. 2.3. A diagnostic (or BPT) diagram for emission-line galaxies. The vertical axis is the [O III] λ5007/Hβ flux ratio and the horizontal axis is the [N II] λ6583/Hα flux ratio. Both ratios are based on lines close in wavelength and are therefore nearly reddening independent. The open circles are for H II regions and similar sources that are clearly ionized by hot stars. The closed circles are narrow-line AGNs (Seyfert 2s and NLRGs) which are ionized by 'harder' continua (i.e., with a greater fraction of high-energy photons, such as a power-law spectrum); the solid line is an empirical division between these two classes of object. The triangles represent LINERs, which can be distinguished from H II regions by higher values of [N II] λ6583/Hα, and from Seyfert galaxies by lower values of [O III] λ5007/Hβ, as can also be seen in Fig. 2.1. Based on a similar diagram from Osterbrock (1989), p. 346. Figure courtesy of R. W. Pogge, based on data from Veilleux and Osterbrock (1987).

NOTE: It is not clear that all LINERs are really AGN, some clearly are, but many other processes can also lead to a LINER spectrum (starformation, cooling flows, jets, etc.)

▪ What are they good for?

- Study black hole physics
- Study high energy physics
- Background sources on cosmological scales:
  - Ly-α forrest in optical spectra (absorbing gas in cosmic walls?)
  - Are gravitationally lensed by clusters, get Hubble constant from time delay
  - Background radiation to detect absorption lines in host galaxies at large z
  - Produce cosmic background radiation, e.g. at X-ray wavelengths
- find galaxies at highest redshifts ($z \gtrsim 5.8$!)
- Constrain cosmology
- Use radio cores as cosmic reference points to define fixed coordinate system
- History of Milky Way: Have all galaxies been an AGN at some point? Or are they still?