Seyfert Galaxies - Jim Ulvestad - July 5, 1984

1. Context

Seyfert galaxies are one of the many types of "active galaxies," a category that also includes quasars, radio galaxies, BL Lacertae objects, and other things with weird names. All of these objects differ from "normal" galaxies in that they seem to have strong energy sources at their centers. Since the energy is thought to be produced in the galaxy nuclei, the generic name "active galactic nuclei," or AGNs, has come to be common nomenclature. This reflects the fact that the same physical processes seem to be occurring in a wide variety of active objects. Although I will restrict this lecture to Seyfert galaxies (with a little bit about quasars), it should be remembered that a great many properties are shared by the different kinds of AGN's.

Spiral nebulae were first noticed in the 19th century, before their extragalactic nature was known. In the 1920's, the fact that these nebulae were island universes separate from our Milky Way became established. Two major classes of galaxies, spiral galaxies and elliptical galaxies, were used. In a classic paper entitled "Nuclear Emission in Spiral Nebulae," (Astrophysical Journal, Vol. 97, p. 28, 1943), Carl Seyfert studied 6 galaxies whose spectra showed high excitation emission lines superposed on a normal stellar spectrum. These galaxies had bright compact nuclei which were unresolved optically, unlike the diffuse nuclei seen in most spiral galaxies. Seyfert pointed out that the hydrogen (Balmer) emission lines in several of the galaxies were extremely broad, with line widths corresponding to velocities of close to 10,000 km/sec. (Note that the line widths are generally explained as being due to rapid motion of the emitting gas, which causes Doppler shifts that change the apparent wavelength of the radiation.) There are now several hundred Seyfert galaxies known.

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2. Definition, Description of Seyfert Galaxies

There are two basic components to the definition of an object as a Seyfert galaxy:

1) It has a bright, unresolved, optical continuum nucleus.
2) It has broad, high excitation optical emission lines.

In addition, there are two other secondary criteria:

3) The galaxy has a spiral morphology.
4) A Seyfert is only a very weak radio emitter.

Some galaxies are two distant for us to determine whether point 3) applies, while point 4) is a recent addition to the Seyfert classification.

~~The most obvious~~

The connoisseurs of AGNs will note that the two primary components to the Seyfert definition also apply to quasars. This fact is probably not a coincidence. Seyfert galaxies are generally thought to be much more common, weaker examples of the quasar phenomenon. This is one of the common justifications for studying Seyferts -- we have sufficient resolution to study many aspects in more detail than we can study them in the much more distant quasars, but what we learn can be applied to quasars.

The most obvious property of a Seyfert galaxy is its broad emission lines. These must be examined in some detail in order to begin to understand what is going on.

First, a definition. Emission lines can be either "permitted" or "forbidden." Permitted lines are those that arise from normally permitted atomic transitions, transitions that are allowed by standard transition rules. These transitions occur very quickly ~~so~~ when an atom has been excited above the ground state. Examples of permitted lines are the Balmer lines generated by hydrogen atoms.

Forbidden lines are those arising from transitions that are not allowed by normal quantum mechanical selection rules. Atoms have low probabilities of undergoing these transitions. The forbidden lines are only important when collisions are relatively unimportant at changing the internal structures of atoms. Such a situation arises in a low density regime, in which case forbidden lines may be comparable to permitted lines in strength. Forbidden emission lines are normally specified by using brackets; a forbidden emission line due to doubly ionized oxygen is written as [O III].

Seyfert galaxies show both permitted and forbidden emission lines. Some of the forbidden lines are lines of high excitation ions, such as nine-times ionized Fe. (Fe^{+9}). Hundreds of electron volts are required to ionize iron so highly. Stars simply cannot get hot enough to make photons of 100 eV energy. Thus the high excitation emission lines tells us that stellar processes are not dominant in creating Seyfert galaxy spectra. Instead, nonthermal high energy processes generate the spectra. Models show that a nonthermal, point-like source of photons at the center of a Seyfert galaxy can produce the observed optical spectrum. Some of the more prominent emission lines in Seyfert galaxies are listed below:

Permitted lines: Balmer lines ($H\alpha$, $H\beta$, ...), He II λ4686, He I, Fe II.
Forbidden lines: [O III] $\lambda\lambda$ 4959, 5007; [O II] λ 3727; [S II] $\lambda\lambda$ 6716, 6731; [N II] $\lambda\lambda$ 6548, 6584; [O I] $\lambda\lambda$ 6300, 6363; [Ne III] λ 3868; [Ne V] λ3426; [Fe VII] λ6087; [Fe X] λ 6374.

An example is shown on the next page:

D.E. Osterbrock, 1977, Astrophysical Journal, 215, 733. (4)

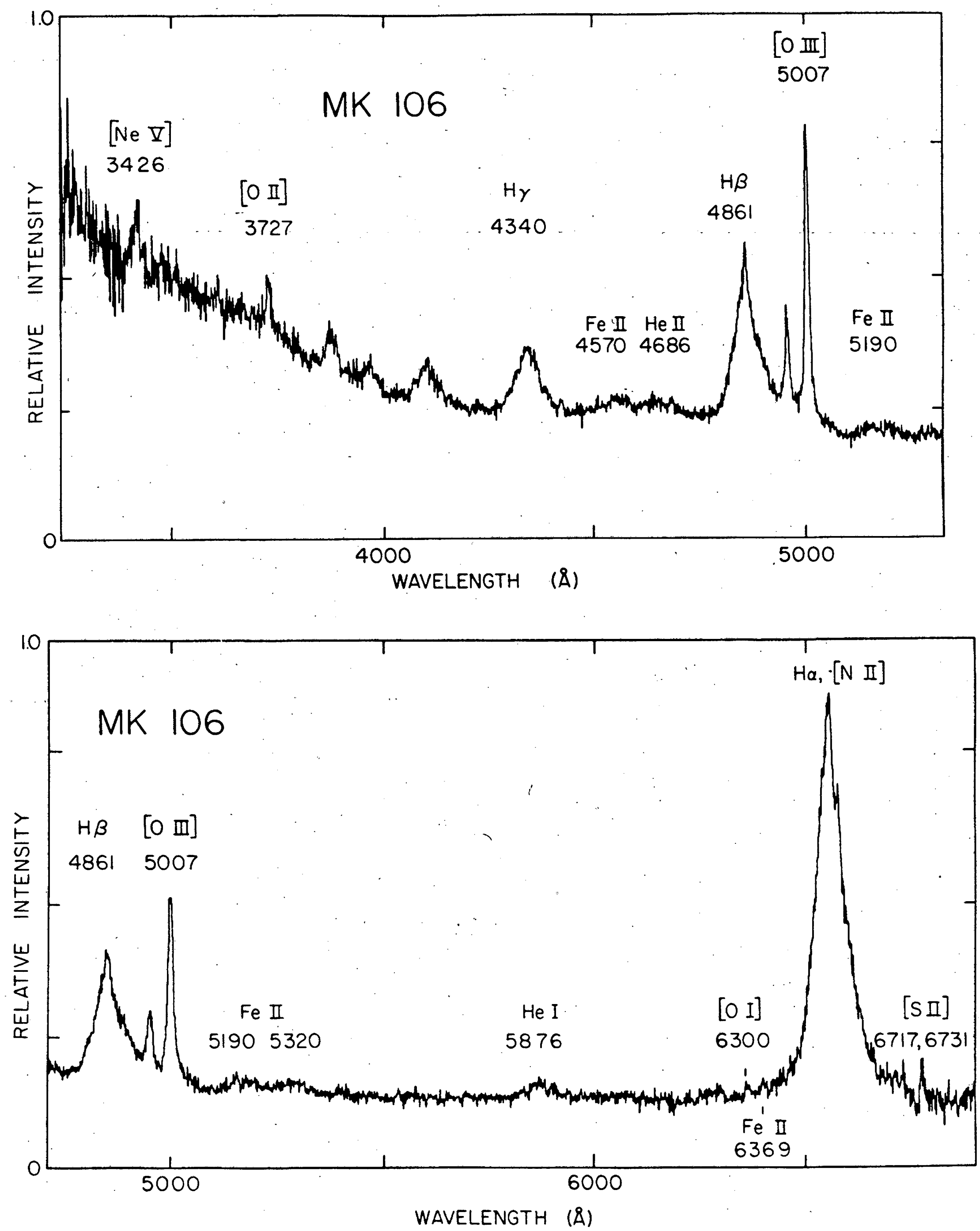

FIG. 1.—Spectral scans of Seyfert 1 galaxy Markarian 106, in relative energy units (ergs cm^{-2} s^{-1} $Å^{-1}$) versus wavelength units (Å). Upper scan shows "blue" spectral region, lower shows "red" region; wavelengths are indicated in the rest system of Mrk 106.

provided by the Fe II emission lines which are present in nearly every Seyfert 1 galaxy (Osterbrock 1975; Boksenberg *et al.* 1975). These permitted lines, first identified in the quasar 3C 273 by Wampler and Oke (1967) and confirmed in the Seyfert galaxy I Zw 1 by Sargent (1968), occur in several closely spaced multiplets and are blended to greater or lesser degrees in all Seyfert 1 galaxies, depending upon the widths of the Fe II lines. In the present survey the blend of Fe II lines between Hγ and Hβ, due to multiplets (37) and (38), was measured as one feature, called λ4570 in the figures and tables. The group of Fe II lines just to the

3. Type 1 and Type 2 Seyfert Galaxies

From the spectrum shown on the previous page, you will note that the permitted emission lines are much broader than the forbidden lines. This is most obvious when comparing Hβ λ4861 to [O III] λ5007. It is an empirical fact that the forbidden lines are always relatively narrow. Typical line widths are ~500 km s^{-1}, which is still ~3 times broader than the emission lines in "normal" spiral galaxies. The permitted lines, on the other hand, are much broader. They have typical line widths of ~10,000 km/sec.

Remember that forbidden lines are generated only when the density is fairly low, say 10^3-10^4 particles per cubic centimeter for [O III]. Therefore, we deduce that Seyfert galaxies have a region of about this density in which typical motions are ~500 km/sec. The forbidden lines are suppressed relative to the permitted lines at densities above 10^9 per cubic centimeter. This fact and the observed spectra imply that Seyfert galaxies also have a region where the density is $\gtrsim 10^9/cm^3$ and typical motions are ~10,000 km/sec.

In some Seyfert galaxies, the permitted lines are no broader than the forbidden lines. The reason for this is not clear. Possible explanations are

i) There is no ionized gas at a very high density.
ii) Dust blocks the radiation from the high density region.
iii) Some Seyfert galaxies have no very rapid motion.
iv) ??

I favor i) or iv).

The Seyfert galaxy shown on page 4 is a type 1 Seyfert, having very broad permitted lines and relatively narrow forbidden lines. Those galaxies whose permitted lines are no broader than the forbidden lines are type 2 Seyfert galaxies. The difference is illustrated in the spectra on the next page. As you will note, there are also type 1.5 Seyfert galaxies (along with 1.2, 1.8, and 1.9), but we will not be concerned with these.

The region where the 10,000 km/sec lines is generated is called the broad line region. The 500 km/sec lines are generated in the narrow line region, also known as the forbidden line region. These regions also seem to exist in other AGNs, with the possible exception of BL Lac objects.

Page 8 shows a currently accepted picture of the center of a Seyfert galaxy. The broad line region is about 0.1 parsecs in diameter, while the narrow line region is 100-1,000 parsecs in diameter.

It is important to note that these regions cannot be filled with the ionized gas producing the emission lines. If they were, the lines would be much stronger than observed. In fact, the ionized clouds fill less than 0.1% of their respective regions; the remainder is probably occupied by a low density, hot gas.

Mon. Not. R. Astron. Soc. 176, 61P (1976). (7)

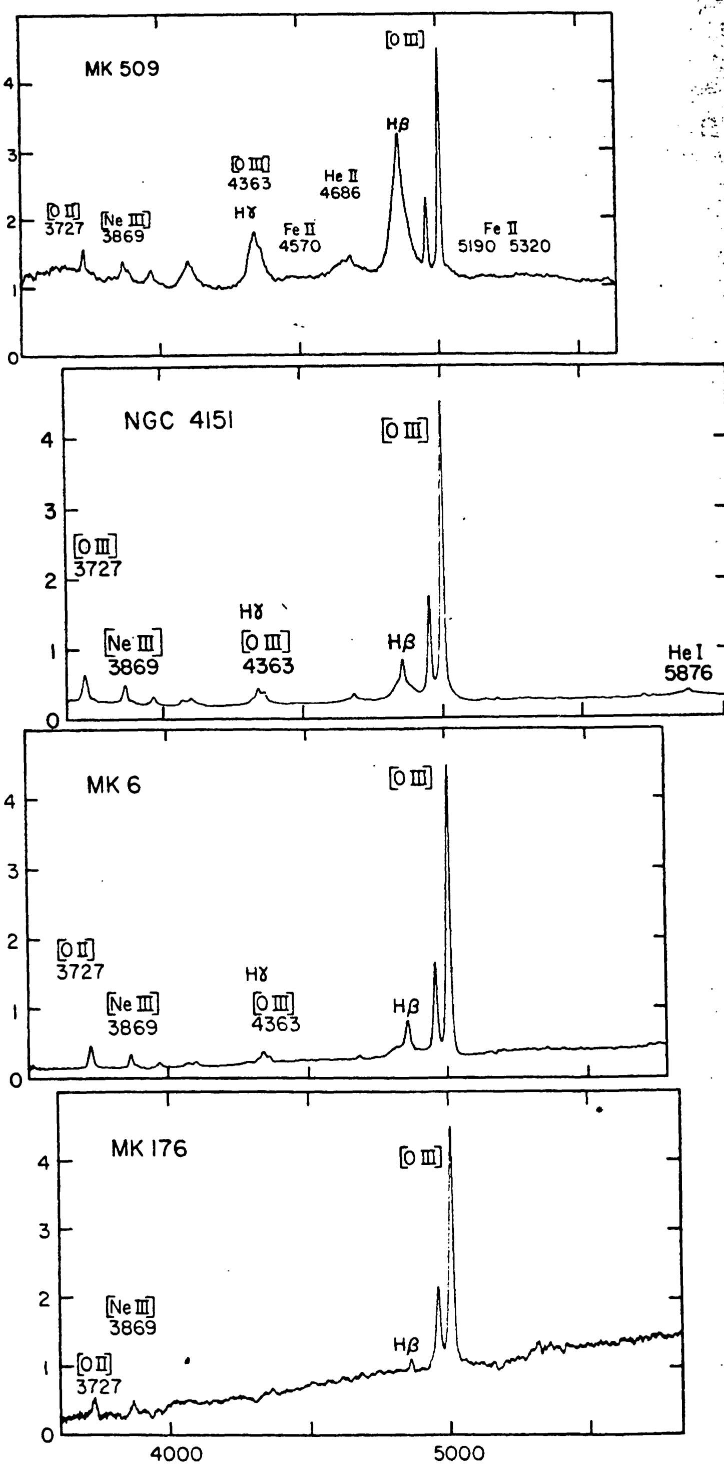

FIG. 1. *Spectra of four Seyfert galaxies, from Mk 509, typical Seyfert 1, with broad Balmer emission lines, to Mk 176, typical Seyfert 2, with narrow Balmer lines. NGC 4151 and Mk 6 have Balmer-line profiles with both narrow and broad components and are intermediate between these two classes.*

Logarithmic Picture of a Seyfert Galaxy

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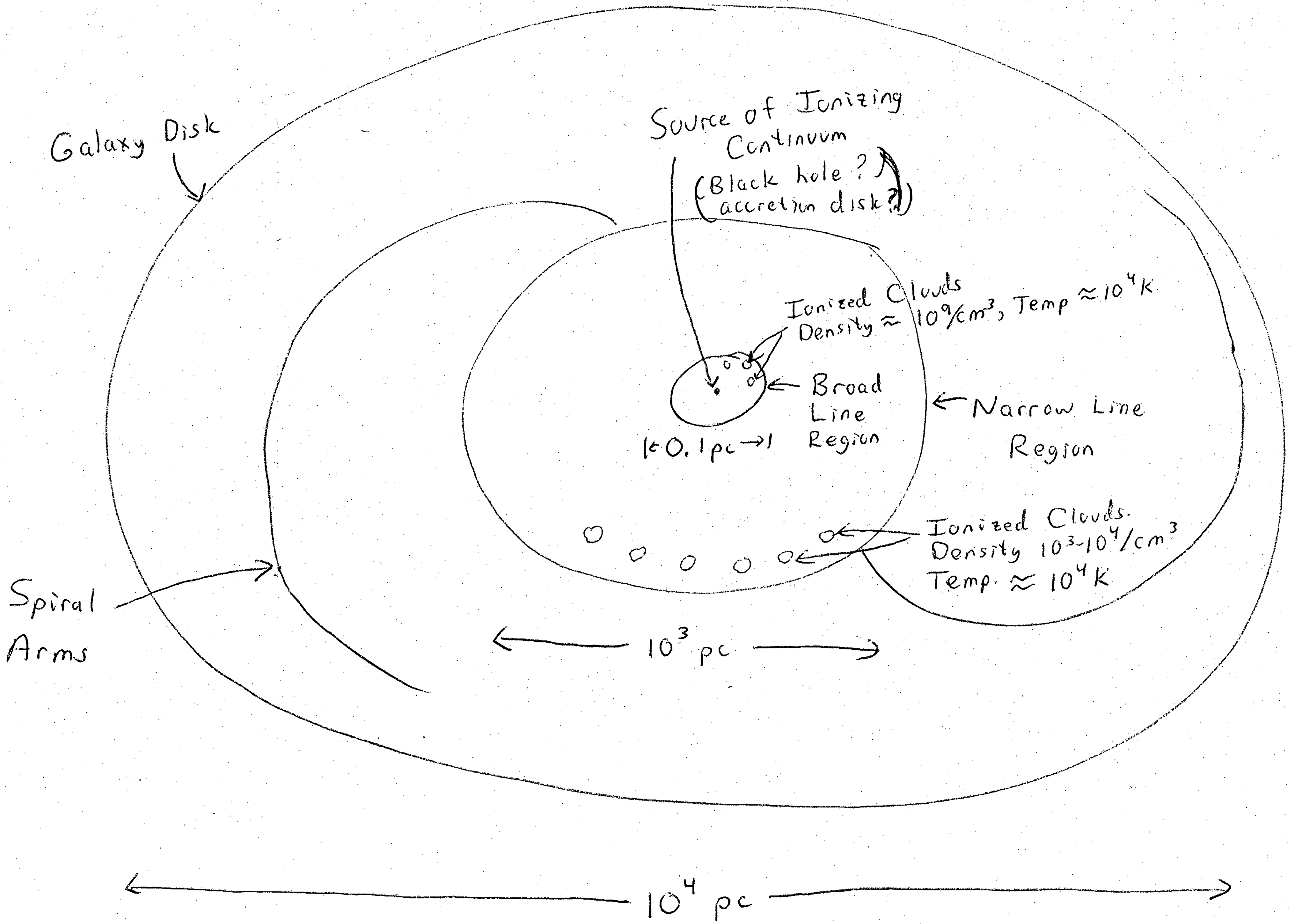


4. Identification of Seyfert Galaxies

Relative to normal galaxies, Seyfert galaxies have excess X-ray, ultraviolet, and infrared emission. The X-ray emission comes from the galaxy core, possibly from an accretion disk around a black hole. The ultraviolet emission comes from the source of the ionizing continuum, possibly the accretion disk. The infrared emission may come from this source directly, from dust heated by the ionizing source, from dust heated by stars, or a combination of the three.

There are two classical ways of identifying Seyfert galaxies:

i) Take a spectrum of a random galaxy and find broad emission lines ("Random" is not necessarily true, but there are too many reasons for taking spectra to detail them here).

ii) Markarian and co-workers in the U.S.S.R. have done surveys identifying ~1500 galaxies with "ultraviolet excesses." About 10% of these are Seyfert galaxies. Galaxies listed as Mrk 3 or Mkn 106 or Mk 1018 are from the Markarian lists, although many have other names as well.

In addition, a few Seyfert galaxies have been identified as the optical counterparts of X-ray sources, and there may be many coming from the IRAS surveys of strong infrared sources.

Seyfert galaxies can also be radio emitters, though they are generally much weaker than radio galaxies. They are also stronger than most normal spirals. Jim Condon will talk about radio emission from spiral galaxies tomorrow.

5 Radio Emission from Seyfert Galaxies

Seyfert galaxies exhibit nonthermal radio emission which has a power-law dependence on frequency. This emission is synchrotron radiation, produced by relativistic electrons in magnetic fields. For active galaxies, Seyferts are quite weak radio emitters. In this way, they appear to be closely related to radio-quiet quasars (especially type 1 Seyferts).

VLA observations show that the radio sources in Seyfert galaxies are generally restricted to the inner one or two kiloparsecs of the galaxies. Typically, the radio source strengths are only a few mJy at 6 cm; only the VLA can detect and map these sources. Still, since they are often only a few (or less) arcseconds in extent, there is not always enough resolution to make detailed maps as in powerful, extended radio galaxies.

The radio emission seems to be related to the narrow line region, as the radio source extents are usually similar to the narrow line region in size. In addition, the radio source strength is correlated with strength of the [O III] emission line. Finally, the radio sources are more prominent in type 2 Seyfert galaxies, those in which the narrow line regions are most important.

There have been two competing models for the origin of the radio emission in Seyferts. One is that the energy for the radio sources is supplied directly by the active nucleus of the object as in radio galaxies. The other is that bursts of star formation lead to multiple supernovae whose remnants produce the radio emission. Similar environmental circumstances may lead to either scenario.

In a few radio sources, the morphologies give strong indications of direct energy supply from the galaxy cores. The classic Seyfert NGC 1068, whose map is shown on the next page, is the best example. Many Seyferts contain double radio sources, with lobes straddling the core of the galaxy. This would be ~~explained~~ expected in the jet or ejection hypothesis, but could also be explained by proponents of starbursts. Some typical Seyfert galaxy maps are shown following the NGC 1068 map.

from Wilson and Ulvestad, Ap. J., 275, 8 (1983)

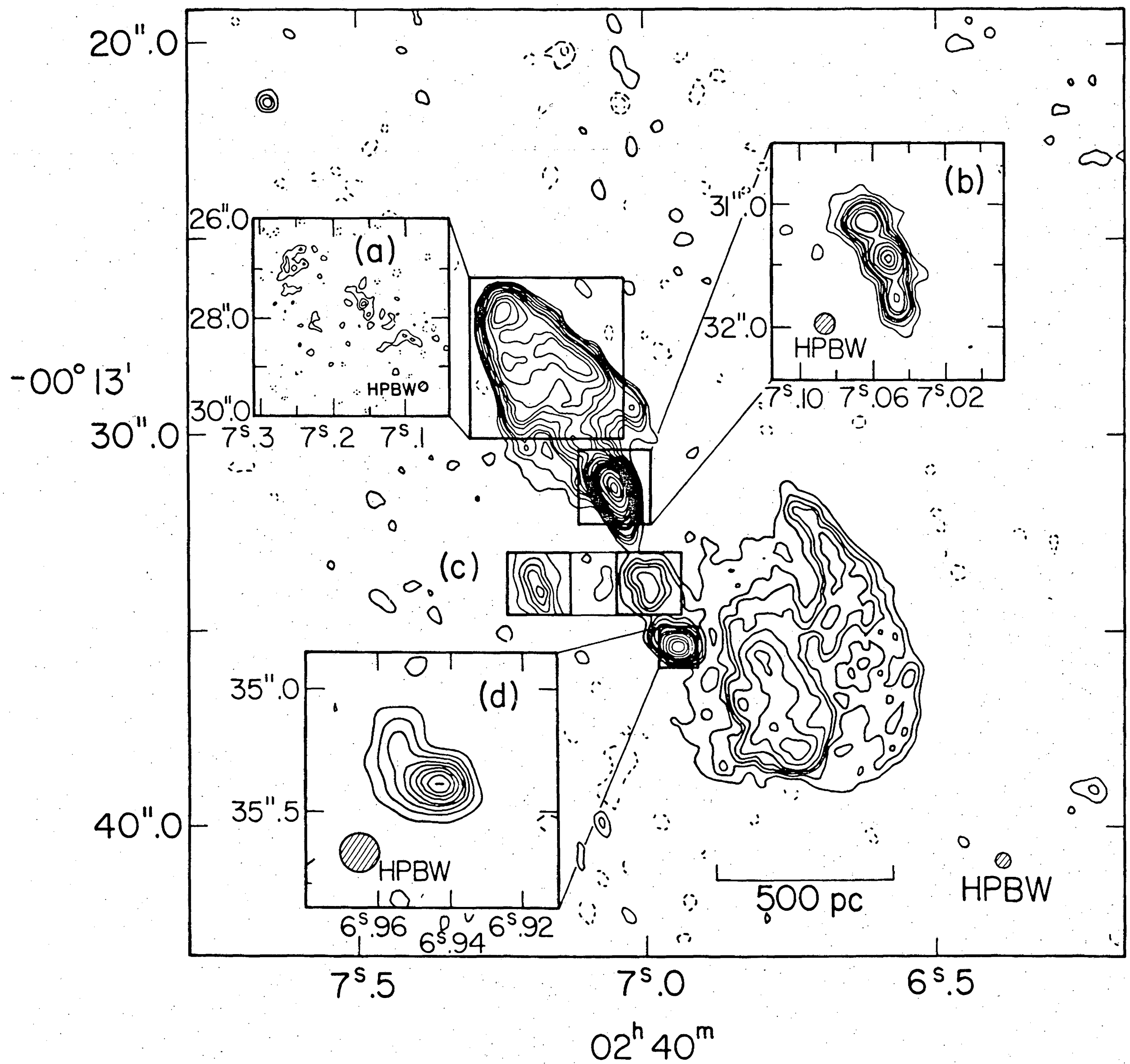
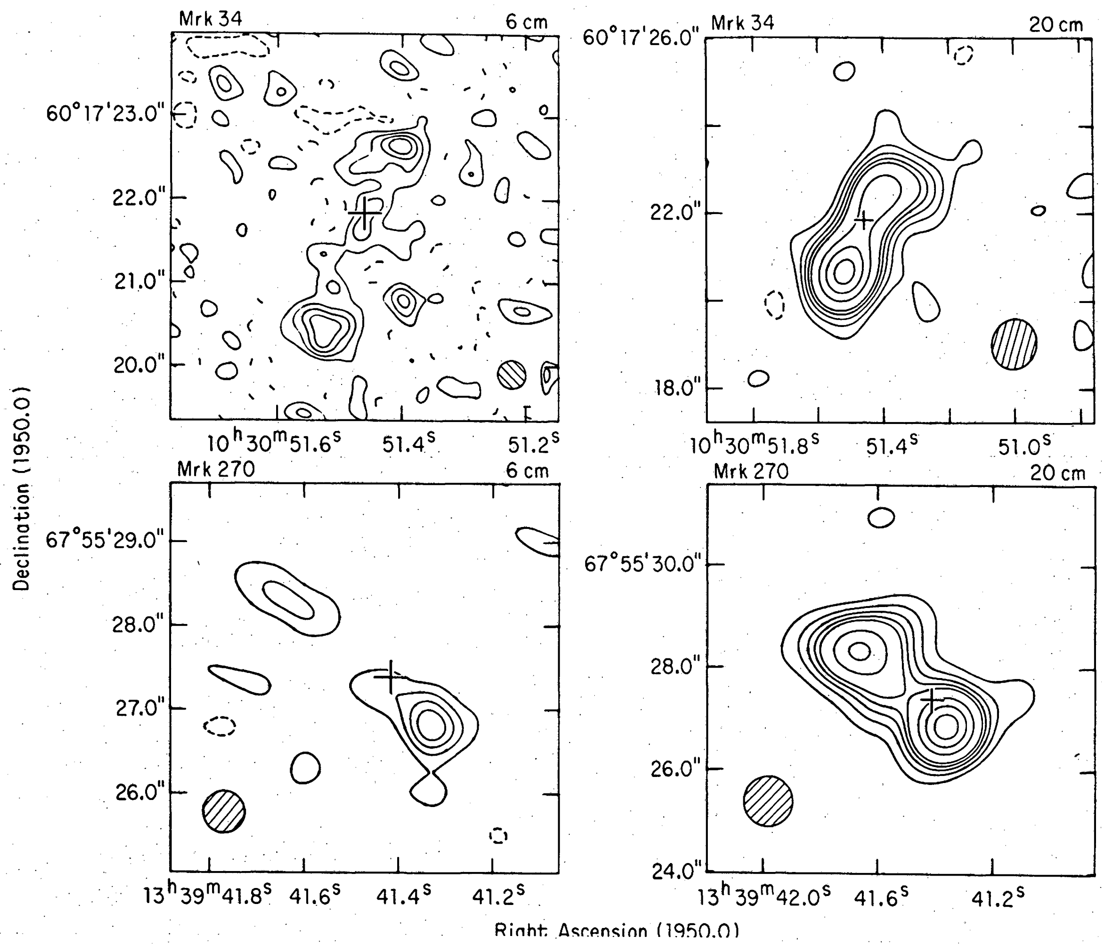
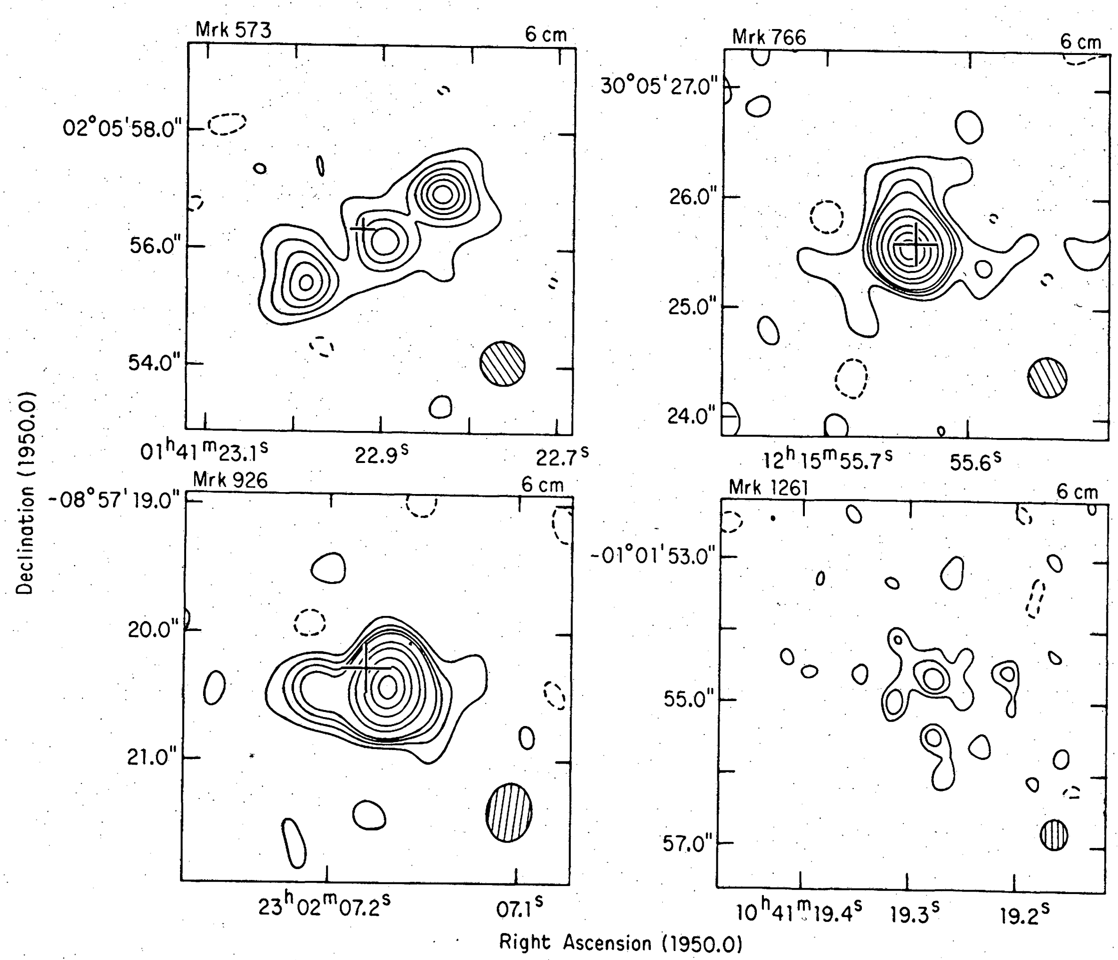


FIG. 1.—VLA maps of the central region of NGC 1068. The main map is at 4.9 GHz with resolution $0''.4 \times 0''.4$, and the optical nucleus coincides with its brightest part. Contours are plotted at −0.1% (*dotted*), 0.1%, 0.2%, 0.3%, 0.4%, 0.6%, 1%, 1.5%, 2%, 3%, 5%, 7%, 10%, 15%, 20%, 30%, 50%, 70%, and 90% of the peak brightness of 0.273 Jy (beam area)$^{-1}$. Insets (*a*), (*b*), and (*d*) show details of the brighter regions at 15.0 GHz with resolution $0''.15 \times 0''.15$, while inset (*c*) shows 4.9 GHz contours of the region immediately to the SW of the nucleus with slightly better resolution than the main map. We give contour levels for the insets as percentages of the peak brightness in the *entire* map. Contours for inset (*a*), the NE lobe at 15.0 GHz, are plotted at −1.5% (*dotted*), 1.5%, 3%, and 4.5% of 56.8 mJy (beam area)$^{-1}$. Contours for inset (*b*), the central component at 15.0 GHz, are plotted at 2%, 4%, 6%, 8%, 10%, 15%, 20%, 30%, 50%, 70%, and 90% of the peak brightness of 56.8 mJy (beam area)$^{-1}$. Contours for inset (*c*), the SW "jet" at 4.9 GHz, are plotted at 0.2%, 0.4%, 0.6%, 0.8%, and 1% of 0.276 Jy (beam area)$^{-1}$. Contours for inset (*d*), the "hot spot" to the SW of the nucleus at 15.0 GHz, are plotted at −1.5% (*dotted*), 1.5%, 3%, 4.5%, 6%, 7.5%, 9%, 10.5%, 12%, and 13.5% of 56.8 mJy (beam area)$^{-1}$.



from Ulvestad and Wilson, Ap. J., 278, 544 (1984).



6. <u>Summary</u>

Seyfert galaxies are one of several classes of active galactic nuclei. They are probably intimately related to quasars. The basic energy source is probably a compact object in the galaxy center that "eats" gaseous fuel and produces energy by exotic processes. A strong optical continuum (and X-ray) source is generated at the center, photoionizing gas to account for both the broad and narrow emission lines. The rapid motions of the line-emitting clouds are probably due to a combination of radial and random motions (<u>not</u> orbital motion) near the galaxy nuclei. Type 2 Seyfert galaxies lack a broad line region but show quite strong narrow lines. Seyfert galaxies contain weak radio sources that may be accounted for by ejection of material from the galaxy nuclei, or (less likely, in my opinion) bursts of star formation.

7. <u>References</u>

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