RADIO EMISSION FROM ACTIVE GALACTIC NUCLEI

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ABSTRACT. Active Galactic Nuclei and quasars are characterized at radio wavelengths by a high surface brightness, a flat spectrum, variations in intensity on time scales of a few days to a few years, and by large internal motions which probably reflect Doppler beaming from a synchrotron source which is moving with relativistic velocity away from the central energy source and toward the observer. The observations do not support interpretations based on simple ballistic models where the observed motion and core strength depends only on the geometric orientation of a relativistic beam, but appear to require significant dispersion in intrinsic properties as well as complex dynamics.

1. INTRODUCTION

There has been much discussion at this symposium about how to distinguish an active galaxy from a passive one. It seems to me that if you have to ask if a galaxy is active then it can't be very active. Particularly at radio wavelengths, high resolution observations of collimated jets which extend hundreds of kiloparsecs or even megaparsecs from an active core give dramatic visual evidence for activity in the nucleus of a wide variety of galaxies and quasars. VLBI observations, in particular, show high velocity outflow from AGN's and provide direct evidence for a relativistic outflow from the central engine of the type postulated by Rees (1971) to supply energy to the outer radio lobes.

Active radio nuclei are observed over a remarkably wide range of power and galaxy type ranging from our own Galactic Center at 10^{33} ergs per sec to the most powerful quasars with radio luminosities extending up to 10^{46} ergs per sec. Normal spiral and elliptical galaxies have intermediate luminosity ranging from about 10^{37} ergs per sec for spirals to 10^{41} ergs per sec for ellipticals, while the radio galaxy nuclei and quasars extend from about 10^{41} to 10^{45} ergs per sec. The corresponding linear dimensions range from less than a hundredth of a

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parsec for the nearby AGN's to a few tens of parsecs for the active nuclei of radio galaxies and quasars. The magnetic field strength, surface brightness, and the volume emissivity are remarkably similar for all active radio nuclei. Generally, B ~ 10^{-3} Gauss; the peak brightness temperature close to the inverse Compton limit of 10^{12} K; and the emissitivity within a few orders of magnitude of one milli Watt per cubic kilometer in the Galactic Center, the weak radio nuclei of nearby spirals, ellipticals, and the nuclei of the most powerful radio galaxies and quasars. A fundamental question is how the wide variety of observed AGN's are related. Are the differences simply intrinsic or are they related through an evolutionary sequence? Of special interest are the so called unified schemes which attempt to account for the apparent different properties purely in terms of the geometry of a relativistic beam.

Radio observations give, at the present time, the only direct method of examining AGN's. Unfortunately, however (at least from the point of view of a radio astronomer), the energy radiated at radio wavelengths is small compared, for example, with that in the infra-red, optical, or X-ray part of the spectrum. Moreover, even though the linear resolution of modern radio astronomy techniques is extraordinarily good, except for very nearby galaxies, it is still poorer than the supposed accretion disk or other energy source.

In this review we concentrate on the non-thermal synchrotron emission from AGN's, with particular emphasis on the VLBI observations of morphology and internal dynamics, and on their interpretation in terms of the widely discussed relativistic beaming models. We do not discuss the radio emission from the less active Seyfert I or starburst galaxies, such as NGC 1068 or M 82, or from supernovae remnants in spiral galaxies.

Where numerical values of linear size, velocity, and power are discussed, we use a Hubble constant of 100 km/sec/Mpc and $q_o = 0$.

2. MORPHOLOGY OF AGN'S

At radio wavelengths AGN's are characterized by a bright compact radio source which usually has an asymmetric structure consisting of an unresolved core plus one or more components or blobs located some parsecs away and moving with apparent superluminal velocity. Because the moving components are aligned or lie along a well defined curved trajectory, they are usually referred to as jets, although they show little similarity to their kiloparsec sized counterparts. Indeed, some of the so-called compact jets contain no more than two or three pixels along their main axis.

In those sources where large scale jets are also visible, the parsec and kiloparsec jets are always well aligned, although there is often pronounced curvature within a few parsecs from the origin. This simple geometric alignment has several important implications. Most important, it means that the beams are focussed on a scale of less than a parsec and remain collimated over distances up to a few megaparsecs; thus there must be a common axis which is effective over a large range of linear scales. Second, propagation time arguments require that the direction of this axis remains essentially constant for up to a few million years in some sources. Finally, in some radio galaxies, the kiloparsec jet ends up in a hot spot of the outer lobes. The continuity of the hot spots, the extended jet, and the AGN jet are evidence that the AGN is indeed the source of energy which powers the entire radio source.

2.1 Radio Galaxies

Nearly all radio galaxies and quasars which have been examined with sufficient sensitivity and resolution contain a compact central radio source, extended radio lobes, and often a narrow jet which extends from the central source to the outer lobes. One of the best studied radio galaxies of course is the powerful source Cygnus A illustrated in Figure 1. VLBI observations of the central core show the characteristic core-jet structure which is aligned with the much larger jet thought to transport energy from the central engine to the outer radio lobes.

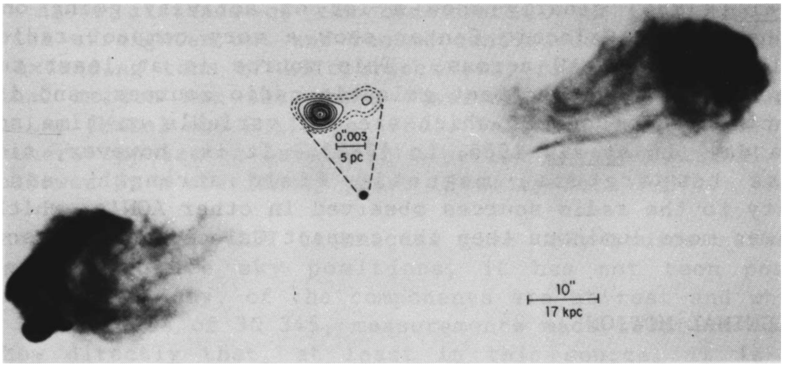

Fig. 1. Image of the radio galaxy Cygnus taken from Perley et al. 1985, Astrophys. J. (Lett.) 285, L35. (extended structure) and Kellermann et al. 1981, Astron. & Astroph. 97, L1 (compact structure). The AGN is unresolved in the VLA map but shows the classical asymmetric core-jet structure when observed with VLBI. The compact jet, which is only 10 parsecs in extent, is seen to be aligned with the 100 kpc jet which points toward the northwest extended lobe.

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2.2 Normal Spiral and Elliptical Galaxies

Ekers (1978) has discussed the radio emission from the nuclei of E and SO galaxies. Elsewhere in this volume Sadler discusses their integrated properties. VLBI observations show the same type of asymmetric core-jet structure seen in the nuclei of the more powerful radio galaxies (e.g., Jones et al. 1984, Wrobel et al. 1985, Schilizzi et al. 1983).

The discovery of flat spectrum, compact, variable radio sources in the nucleus of M 81 and M 104 gave the first evidence of activity in "normal" spiral galaxies (de Bruyn et al. 1976). VLBI observations confirmed that the linear dimensions of the radio core of M 81 is less than 0.01 parsec across, making it one of the smallest extragalactic radio sources known (Kellermann et al. 1976, Bartel et al. 1982), and optical observations of narrow emission lines now classify M 81 as a weak Seyfert galaxy (Peimbert and Torres-Peimbert 1981). Weak compact radio sources have also been found in the nuclei of a number of other nearby spirals (e.g., Preuss 1983), and it seems that low level radio activity is not uncommon in spiral galaxies.

2.3 The Galactic Center

Although in terms of luminosity or energy content our own Galactic Center is unremarkable, the dramatic radio images obtained by Yusef-Zadeh et al. (1984) clearly show a lot of activity going on. VLBI observations of the Galactic Center show a very compact radio source which is less than 20 AU across. This source is at least ten times more luminous than other compact galactic radio sources, and is unlike other galactic radio sources which are all variable on time scales as short as a day (Lo et al. 1985, Lo 1986). It is, however, similar in brightness temperature, magnetic field strength, and volume emissitivity to the radio sources observed in other AGN's, which are up to 10^{12} times more luminous than the compact Galactic Center source.

3. SUPERLUMINAL MOTION

Perhaps the greatest insight given to the problem of understanding the physics of the observed radio emission from AGN's is due to the ability of VLBI systems to observe not only the small scale structure of the radio clouds but to also observe directly the dynamics of the radio emitting clouds as they are ejected from the central engine. Indeed, only with radio VLBI is it possible to observe spatial changes in extragalactic objects on time scales comparable with those of human observers.

However, multiple epoch VLBI observations are very time consuming, and at each epoch most of the world's major radio telescopes are simultaneously committed to a single observing program. Sensitivity limitations have so far restricted the observations primarily to the stronger radio sources, but the recent use of broad-band recording equipment now permits the measurements to be extended to much weaker sources.

Well over half of all sources which have been studied in detail show evidence of internal motion with apparent transverse velocity in excess of the speed of light. This superluminal motion is observed in a variety of radio sources ranging from relatively nearby radio galaxies and BL Lac objects to the more distant and more powerful radio galaxies and quasars. The effect is seen primarily in sources with asymmetric extended features and strong radio cores, the core-jet sources. However, superluminal motion is also observed in symmetric doubles with relatively weak radio cores. We describe below the observed dynamics of some of the best studied AGN's and quasars and then review their interpretation in terms of the widely discussed relativistic beaming models.

3.1. Superluminal Sources

The best studied superluminal radio sources are the quasars 3C 273 (Unwin et al. 1985) and 3C 345 (Biretta et al. 1986). The motion in these sources is characterized by the one-sided ejection of multiple blobs on time scales of a few months to a few years. The motion appears to be along a curved trajectory particularly close in to the origin. At a distance of the order of 10 pc from the core, the trajectories straighten out and become continuous with the large-scale features extending tens of kiloparsecs away from the core. One-sided superluminal motion has also been observed in the relatively nearby object BL Lac (Mutel and Phillips 1986). In the distant powerful quasar 3C 454.3 there appears to have been a period of superluminal component motion followed by a stationary phase (Pauliny-Toth 1987).

In general, because VLBI techniques give only source structure and do not give absolute sky positions, it has not been possible to determine which, if any, of the components are at rest and which move. However, in the case of 3C 345, measurements made relative to a nearby quasar show directly that, at least in this source, it is the core which is at rest and the jet-like blobs which move (Bartel 1986).

Superluminal motion has also been observed in the cores of several lobe dominated quasars, including 3C 179 (Porcas 1981), 3C 263 Zensus et al. 1987), and the extended radio galaxies 3C 111 (Goetz et al. 1987) and 3C 390.3 (Alef et al. 1987).

The best studied superluminal AGN is 3C 120 which, like 3C 111 and 3C 390.3, has strong extended radio lobes surrounding the AGN. 3C 120 was one of the first active radio sources to be identified with a galaxy and the relatively short lived but intense outbursts which are frequently observed make it the most active AGN's known.

Regular VLBI observations of 3C 120 show multiple ejections of superluminal clouds which occur on a time scale of the order of a year and are apparently related to the intensity outbursts (Walker 1986). As shown in Figure 2, new blobs appear near the origin at a rate of about one per year and propagate outward, always in the same direction, with an apparent velocity of about 2.5 milli arcsec per year (v = 4c). Through a dramatic series of VLBI and VLA images shown in Figure 3, the ejecta may be traced through a curved trajectory extending from a few parsecs, where the motion is directly observed, through a highly collimated jet extending about 20 kpc from the core to a more diffuse feature several hundred kiloparsecs in extent. Probably more than in any other source the combined VLBI/VLA observations of 3C 120 provide convincing evidence for motions over a wide range of scale sizes in an individual source (e.g., Walker 1986). But, we should not forget the beautiful optical work of Arp (1981), who has argued that 3C 120 is a very peculiar galaxy, and in several respects appears unique. There is only a negligible a-priori probability that the relativistic beam in 3C 120 happens to point within the small solid angle required for Earth-based radio astronomers to observe superluminal motion.

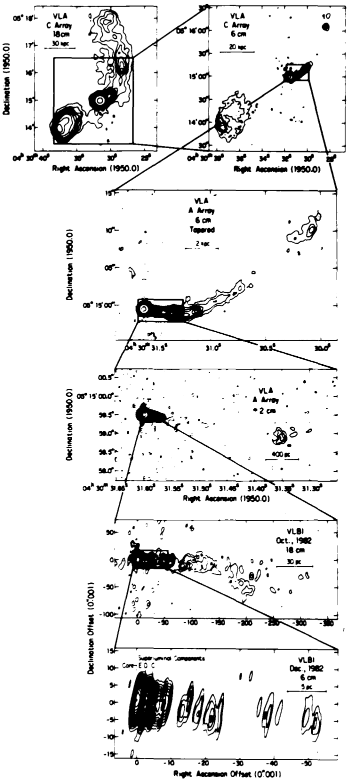

Fig. 2. Structure of the radio galaxy 3C 120 observed over a wide range of resolution using both the VLA and VLBI. Taken from Walker, 1985, in Physics of Energy Transport in Extragalactic Radio Sources (NRAO: Green Bank), p. 20.

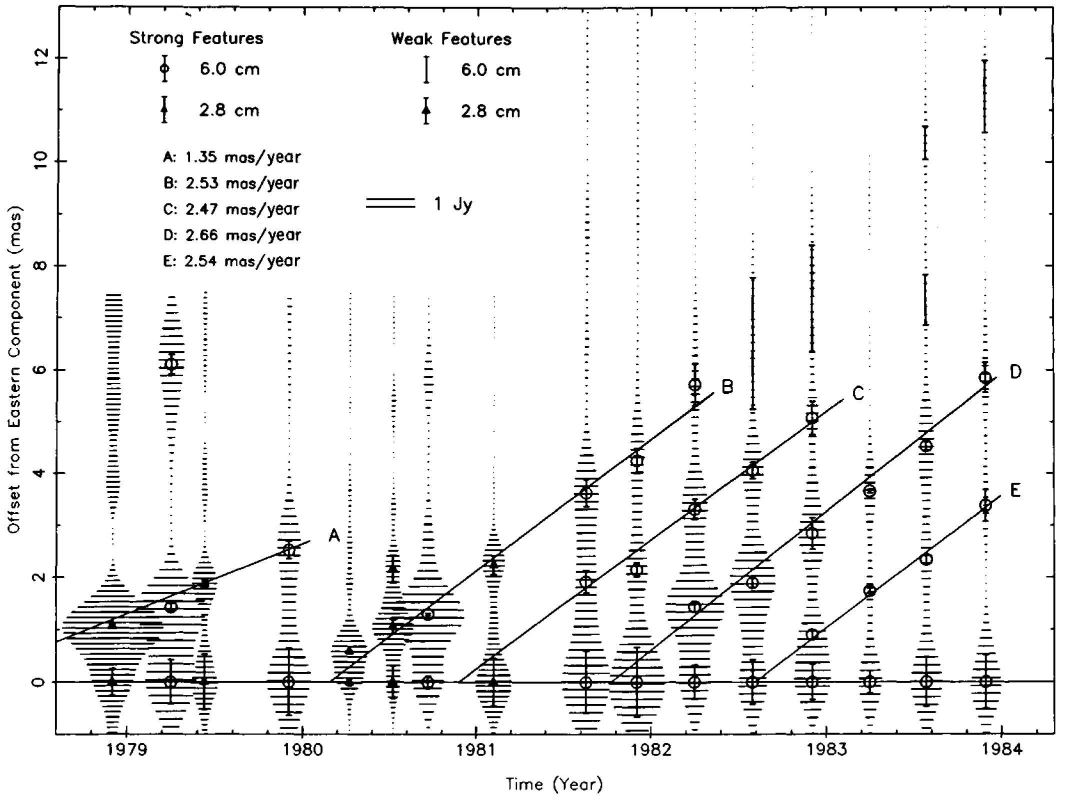

Fig. 3. Plot showing the motion of the components of the 3C 120 as function of time assuming the eastern most component to be stationary. Taken from Walker 1986, Canadian J. of Phy. 64, 452.

3.2 Subluminal Sources

Only one extragalactic source, NGC 1275 (3C 84), shows measurable motion which is clearly less than the speed of light. When first observed at centimeter wavelengths in the early 1960's, 3C 84 contained only a relatively weak radio nucleus. However, during the 1960's the luminosity of the core steadily increased and by the 1970's 3C 84 had become the most luminous extragalactic source in the centimeter sky. VLBI observations which began in the early 1970's showed a complex structure not unlike the classical core-jet morphology seen in the superluminal AGN's and quasars (e.g., Readhead et al. 1983). However systematic VLBI observations show only small motions with an apparent velocity less than half the speed of light (Romney et al. 1984).

3.3 Stationary Sources

For only two sources where there have been adequate measurements, the radio galaxies M87 (Reid) and NGC 6251 (Jones 1986), are the observed limits to any internal motion clearly less than half the speed of light.

4. VARIABILITY, SUPERLUMINAL MOTION, AND BEAMING

Superluminal motion was discovered quite unexpectedly (Cohen 1971, Whitney 1971). With the benefit of hindsight it could have been (and nearly was) predicted earlier as a consequence of the rapid flux density variations first reported by Sholomitsky (1963). For three reasons, however, this remarkable discovery was not generally accepted by radio astronomers:

a. The observations were made with an instrument which was ordinarily used for tracking Soviet space vehicles; its properties were unknown, and thus suspect by the international radio astronomy community.

b. The reported variations were not confirmed by observations made at other times and/or other frequencies at other radio observatories. Perhaps more credibility would have been given to the original report had it not claimed a periodic variation in the flux density of CTA 102 with a 102 day period.

c. Elementary causality arguments relating the maximum size apparently permitted by the time scale of the observed fluctuations were inconsistent with generally accepted simple synchrotron theory. This was understood by the Moscow group, and believing both the observations and synchrotron theory, they suggested that the unusual "signals" from CTA 21 and CTA 102 might be the result of a transmission from an extraterrestrial intelligence (Kardashev 1964). This speculation also did not contribute to the credibility of the reported data.

We now know that the radio emission from AGN's and quasars do vary essentially in the manner reported by Sholomitsky. We also still believe in synchrotron radiation. At IAU Symposium No 29 held here in Byurakan just 20 years ago I discussed some of the problems we faced in reconciling the observed flux density variations with conventional synchrotron theory (Kellermann 1968). We now interpret the time scale of flux density variations as the result of relativistic beaming, and the observations of superluminal motion in AGN's provides dramatic evidence for both the required large velocity and favorable geometry.

The idea of relativistic beaming appears to have been developed independently by several workers to solve different problems, although none of them explicitly discussed the possibility of observationally measuring apparent superluminal transverse velocities. Rees (1967) and Woltjer (1966) invoked bulk relativistic motion to resolve the apparent inconsistency of the rapid time scales of the observed intensity variations and the minimum dimensions set by inverse Compton cooling (e.g., Hoyle, Burbidge, and Sargent (1966). About the same time, Shklovsky (1968) suggested that the observed one-sided jet in M87 might be the result of differential Doppler beaming of an intrinsically two-sided jet. Ozernoi and Sazinov (1969) interpreted the multipeaked spectrum observed in compact radio sources as the result of "multiple components flying apart with relativistic speed."

When the first VLBI observations of superluminal motion were reported in 1971, it was immediately realized that the relativistic beaming model also provided an obvious interpretation of the observed rapid motions (Whitney et al. 1971, Cohen et al. 1971). However, objections were raised to this interpretation due to the expected large difference in brightness between the approaching and receding components in apparent contradiction to the observed near equality of the observed flux densities. Moreover, some workers (e.g., Dent 1972) including this author (Kellermann et al. 1974) discussed the possibility that the reported superluminal motion was not real but simply an illusion due to properly (albeit unrealistically) phased flux density variations in stationary components.

The observational evidence for superluminal motion is now well established (e.g., Cohen and Unwin 1984). Building on the ideas of Shklovsky, Ozernoi and Sazinov; Rees; and Woltjer, superluminal motion is generally interpreted in terms of the twin relativistic beam model essentially as described by Blandford and Konigl (1979). In this model, two relativistic effects modify the observed emission from a source which is rapidly moving nearly along the line of sight. First, since the approaching components nearly catch up with their own radiation, time scales appear compressed to a suitably located observer.

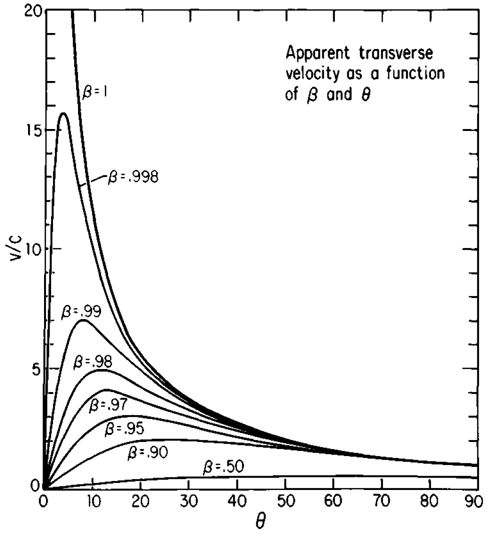

Fig. 4a. Apparent transverse velocity as a function of β and θ.

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Thus both the characteristic time scale of intrinsic intensity variations appear to be shortened, and the apparent transverse velocity can then appear to exceed the speed of light. As shown in Figure 4a, the maximum velocity occurs when $\sin\theta = 1/\gamma$, and is $\sim \gamma c$.

The second effect of bulk relativistic motion is the apparent enhancement of the radiation along the direction of motion caused by the relativistic focusing of the radiation into a narrow cone of the order of $1/\gamma$. This is commonly referred to as Doppler boosting or relativistic beaming and is illustrated in Figure 4b. Begelman et al. (1984) and Kellermann and Pauliny-Toth (1981) give more detailed presentations of these relations.

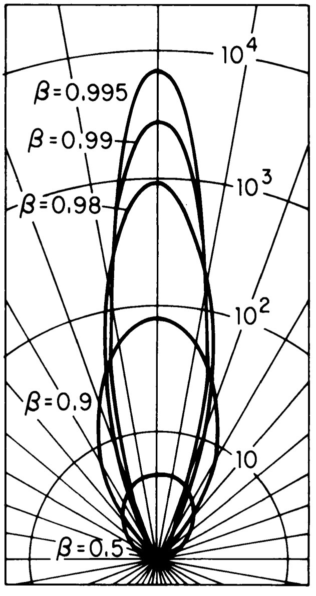

Fig. 4b. Power radiated as a function of β and θ relative to an isotropic source.

For a typical value $\gamma \sim 7$, the maximum transverse velocity is observed at an angle $\theta \sim \sin^{-1}(1/7) \sim 8^o$ and is about 7c. The corresponding Doppler boosting factor is between 100 and 1000 when observed close to the critical angle.

This simple model predicts that only a small fraction, of the order of $1/2\gamma^2$ or only one percent of a sample of randomly oriented sources, should show superluminal motion. Yet, the observed fraction is well over 50 percent. However, flux density limited samples are not expected to be randomly oriented because Doppler boosting will preferentially select sources which are favorably oriented to exhibit superluminal motion. But, the much larger number of sources with misdirected beams must be accounted for. There has been considerable discussion in recent years of so-called unified schemes which attempt to interpret the observed differences in morphology and luminosity in terms of simple geometric effects.

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Scheuer and Readhead (1979) explain the absence of strong radio emission from the great majority of optically selected quasars as the result of misdirected relativistic beams. But the observed number of radio quasars does not rise monotonically as the flux density limit is decreased in the manner expected from simple geometric models (e.g., Strittmatter et al. 1980, Kellermann et al. 1986). Moreover, for the most part, the emission from radio-loud quasars originates in very extended regions which cannot be interpreted as the result of relativistic beaming.

An alternate and widely discussed unified scheme is the one advocated by Orr and Browne (1982) which interprets the observed range of core to extended emission in radio galaxies as the result of purely geometric effects. Again, however, the observed statistics do not appear consistent with the predictions of simple beaming models (e.g., Saika 1981, 1984 and Schilizzi and deBruyn 1983).

A critical test of beaming models would be measurements of superluminal motion in a sample of sources thought to be randomly oriented in the sky. The classical strong one-sided quasars, such as 3C 273 and 3C 345, do not satisfy this criteria since they were originally selected for observation on the basis of their strong compact radio emission which, of course, also preselects sources with geometry favorable to observe Doppler boosting and superluminal motion.

There is so far no systematic observations of an unbiased sample of AGN's contained in symmetric double sources. However, as emphasized by Porcas (1981), superluminal motion requires both relativistic motion and favorable geometry. The detection of superluminal motion in the lobe dominated sources 3C 111, 3C 179, 3C 263, and 3C 390.3 means that not only must these particular sources be favorably oriented but that bulk relativistic motion must be common among lobe dominated as well as among core dominated radio sources. However, the extended structure of superluminal AGN's is no smaller than for the typical radio source, contrary to what would be expected from projection effects (Schilizzi and de Bruyn 1983).

It is also not clear how the apparent stationary sources in M 87 and NGC 6251, or the slowly moving source in NGC 1275, fit into the big picture. In each case the absence of any counter jet suggests differential Doppler boosting, but the lack of any detectable motion appears to require a fortuitous alignment of the motion exactly along the line of sight. Perhaps these sources are truly asymmetric as suggested by Shklovsky (1982) and Jones (1986), but their apparent similar morphology to the superluminal sources suggests otherwise. Moreover, if these sources are truly aligned along the line of sight, then the deprojected size of the extended components can become embarrassingly large. In the case of NGC 6251, the overall dimensions would exceed 10 Mpc (Jones 1986). Purely intrinsic models of one-sided jets also appear to be inconsistent with the extended symmetric double structure if it is assumed that the AGN supplies energy to the lobes by means of a Rees twin-jet. This would suggest a flip-flop mechanism where the beam alternately squirts in opposite directions.

But, it is also difficult within the framework of simple geometric models to understand the strong correlation between radio, IR, optical, and X-ray flux density of quasars and AGN's unless all of the radiation is beamed. But then quasars with misdirected beams should show only emission lines with no optical continuum, and this is never observed.

Several remarks may be made about the difficulty of reconciling the observed morphology and statistics of superluminal sources with the predictions of the unified schemes.

First, the apparent discrepancies disappear by introducing a dispersion in the value of γ and/or intrinsic core luminosity, or by allowing the relativistic beam to have an intrinsic spread, which is significantly broader than the beaming angle. But then the observed properties no longer depend simply on geometry alone as required by the unified schemes.

Second, Lind and Blandford (1985) have emphasized that the simple ballistic or flow models are unrealistic. Variations in opacity or possible differences between flow velocities (which give rise to Doppler boosting) and the velocity of shock fronts (which are seen as superluminal component motion) may eliminate the stringent constraints apparently imposed. It may be noted, however, that where there is a direct measure of the flow velocity in SS 433 it is essentially equal to the observed component velocity.

For at least two radio galaxies with jets and active nuclei, the powerful radio galaxy Cygnus A and the nearby galaxy NGC 5128, optical evidence suggests that the jet lies close to the plane of the sky (Simkin 1977) or points away from the observer, respectively. The detection of superluminal motion in either of these sources would be difficult to explain with beaming models.

The introduction of an intrinsic dispersion in γ and/or intrinsic AGN luminosity or the distinction between flow velocity and the velocity of shock fronts of course greatly complicates the beaming models. Certainly much of the predictiveness is lost and along with it perhaps much of the attractiveness. Nevertheless, even if they turn out wrong in the end, the proposed unified schemes have served to focus considerable research on the radio properties of AGN's, and for this reason alone they have contributed greatly to our understanding of the activity in the nuclei of galaxies.

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