RADIO ACTIVE NUCLEI

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INTRODUCTION

For the purpose of this survey we shall use the term radio active nucleus to refer to compact radio sources which are found in galactic nuclei and which show activity either in the form of flux density variations or outward flow of material from the nucleus. There is great similarity between the observed properties of radio active nuclei with those of radio active quasars, and it is widely supposed that the quasar phenomena represents an extreme case of an active galaxy. In this paper however, we shall concentrate on compact radio sources found in the nuclei of identifiable galaxies, and quasars are discussed only to the extent that they help to understand the origin and evolution of radio active galactic nuclei.

Since radio active nuclei are typically $\lesssim 0\farcs01$ in extent, they can be mapped only with VLBI techniques. Detailed maps are available for only a few of the strongest nuclei, but a much larger number can be identified from conventional interferometry with a resolution $\sim 1''$. In the few radio galaxies where most of the observed radio flux comes from the active nucleus, activity is observed directly on a time scale of months or even weeks. In others, it may be inferred from arguments based on synchrotron lifetime.

Some of the active nuclei are very powerful radio sources, and have a luminosity comparable to many quasars; others are much less luminous and, even when nearby, can be observed only with the most sensitive radio telescopes. The radiated power ranges from 10^{37} ergs sec^{-1} to 10^{43} ergs sec, a range of 10^6 in luminosity. The corresponding linear dimensions range from less than $0\farcs001$ pc to a few tens of parsecs. If the radio source at the Galactic Center, Sgr A, is included, then the range of luminosity and linear size is extended by a factor of 10^4 and 10^2 respectively. Over this tremendous range of luminosity (10^{10}) and

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volume (10^{12}), the specific luminosity remains remarkably constant at $\sim$ 1 milli watt km^{-3}. Likewise, the brightness temperature ($10^{10.5\pm1}$ K) and magnetic field strengths ($10^{-3\pm1}$ gauss) are very similar over this wide range of luminosity and size. Even the quasars which may be more luminous by up to a factor of 1000 and larger by a factor of 10 have comparable specific luminosity, brightness temperature, and magnetic field strength.

How are these radio active nuclei related and can we explain the differences in some simple way? Most simply, of course, there may be intrinsic differences in the properties leading to the formation of radio active nuclei in different galaxies, or they may be related through an evolutionary sequence. Geometric models have also received considerable attention in the past few years and have been invoked to interpret a wide range of phenomena.

Intrinsic models are often discussed in terms of accretion onto black holes, since this process naturally scales with the mass of the black hole. Evolutionary scenarios have also been attractive since quasars and radio active nuclei are often supposed to be connected with the early epochs of galaxy formation.

RELATIVISTIC BEAMING IN ACTIVE NUCLEI

Geometric interpretations have concentrated on the relativistic focusing of synchrotron radiation from a source which is moving with a bulk velocity close to the speed of light. These models are currently of great interest and this review will emphasize the successes and failures of models invoking bulk relativistic motion to interpret the luminosity, structure, and motions observed in radio active nuclei.

Because of the relativistic beaming, the synchrotron radiation from a rapidly moving source is focused in a narrow cone $\theta \sim 1/\gamma$, where $\gamma = (1 - v^2/c^2)^{-1/2}$; therefore the observed luminosity will depend critically on the angle between the motion and the line of sight to the observer. As a further consequence of the relativistic motion, the source almost catches up with its own radiation. The apparent time scale for intensity changes and component motions is compressed by a factor up to γ, and this provides a natural explanation for both the rapid flux density variations and superluminal motion which are seen in the nuclei of active galaxies and quasars.

In any sample of randomly oriented galaxies, the probability of suitably oriented motion is $\sim 1/2\gamma^2$ so that the a-priori probability of seeing superluminal motion with $v/c \sim 7$ ($\gamma \sim 7$) is only 1% or less. But in the very limited and incomplete sample of 10 or so bright radio sources which have been observed in some detail, at least half appear to show evidence of superluminal motion (e.g. Cohen and Unwin 1981).

Of course, in any flux limited sample of beamed synchrotron sources, those sources that have large values of γ and are also moving toward the observer will be selected. Scheuer and Readhead (1979) have proposed that the vast majority of optically selected quasars which are not radio active, reflects the large fraction which are beamed away from the Earth. However, the statistics of observed radio emission found in optically selected samples of quasars argues against any purely geometric interpretation of quasar core luminosities (e. g. Shaffer et al. 1981, Strittmatter et al. 1980). Moreover, since quasars often contain extended asymmetric jet structure, quasar nuclei which are beamed away from the observer would appear as isolated jets and these are never seen. It is also difficult within the framework of a simple geometric model to understand the strong correlation between radio and X-ray flux density for quasars, and in particular the unusually large luminosity of 3C 273 in all parts of the electromagnetic spectrum, unless the optical, IR, and X-ray emission is beamed as well. There is some attraction to this model as the rapid polarization and flux density variations sometimes seen in the infrared and optical part of the spectrum are otherwise difficult to understand (e.g. Angel and Stockman 1980). But the geometric models are not relevant to the bright redshifted emission line radiation which is observed in quasars and active galactic nuclei. Since the emission line regions radiate isotropically, the relativistic beaming model would predict many isolated emission line regions without any non thermal continuum emission, and these are never found.

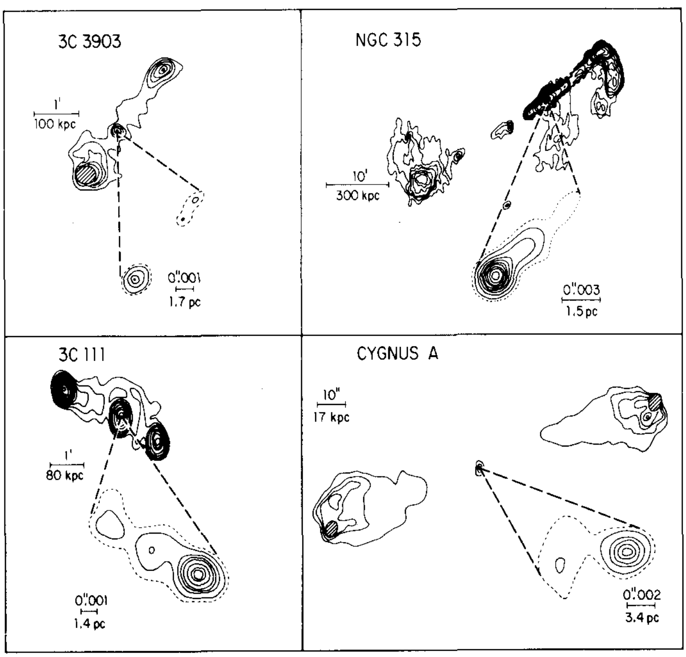

Figure 1. Structure of four radio galaxies taken from Linfield (1981), Kellermann et al. (1981), and Preuss et al. (1980).

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Radio galaxies or quasars selected from long wavelength surveys may be assumed to be randomly oriented, and so relativistic enhancement of the core should not be important in more than a few percent of any such sample. Although there are as yet no complete surveys published, it appears that more than half of all radio galaxies and nearly all quasars contain a compact central radio core (Schilizzi 1976, Preuss et al. 1977, Preuss 1981, Gopal Krishna 1980).

High resolution radio observations are available only for a few relatively bright nuclei. As shown in Figure 1, the radio nuclei generally contain a bright core, are asymmetric, elongated, and aligned along the direction of the large scale jets and the line connecting the extended components (Kellermann 1978, Schilizzi et al. 1979, Fomalont 1980, Preuss et al. 1980, Kellermann et al. 1981, Linfield 1981a). A very similar morphology has been measured in the nuclei of normal galaxies with extended radio emission (Jones et al. 1981).

In the case of sources with symmetric extended structure, the axes are closely aligned and there is no evidence of curvature. But radio galaxies with asymmetric extended structure such as NGC 6251 show some slight curvature close to the nucleus itself (Cohen and Readhead 1979). This remarkable alignment over size scale from a few parsecs to hundreds of kiloparsecs or even megaparsecs indicates that there is a stable preferential axis in radio galaxies and the collimation of the large jets occurs on a scale of the order of one parsec or less.

Kapahi, V. K. and Saikia (1982) have shown that in radio galaxies containing a bright core, the radio axis appears to be aligned within 30 degrees of the minor optical axis of the galaxy. But in radio galaxies with weak cores or no cores, the axis of the radio source is randomly oriented.

In all of the active radio nuclei which have been mapped by VLBI, the structure is clearly asymmetric, although the large scale lobe structure is nearly always symmetric. It is tempting to interpret the small scale asymmetry as the result of differential Doppler beaming which will cause an apparent flux density ratio of

$$R = [(1+\beta\cos\theta)/(1-\beta\cos\theta)]^{n+\alpha} \qquad (1)$$

for an intrinsically symmetric twin jet. In eqn. (1) α is the spectral index and $n = 2$ or 3 depending on whether there is a continuous streaming of material or only two discrete components (e.g. Blandford and Konigl 1979), and θ is the inclination of the jet to the line of sight. For the case where $\alpha = 0$ and $n = 3$, the Doppler beaming gives an enhancement $\sim \gamma^3$ when the observer is within the radiation cone $\theta \sim 1/\gamma$, and a diminution $\sim \gamma^{-3}$ when the beam is pointed in the opposite direction.

Linfield (1981b) has shown how a precessing relativistic jet model can also explain the observed curvature seen in one-sided radio sources, and the presence of bright knots which are due to the "piling up of

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material along the line of sight rather than from increased Doppler enhancement during part of the precession cycle."

In a sample of radio galaxies, Gopal-Krishna et al. (1980) find that in "small" extended sources believed to be end-on doubles, the core emission appears enhanced, a result which they attribute to Doppler beaming. Likewise, Kapahi and Saikia (1981) report an anti-correlation between the projected linear size and the fractional flux density found in the central component of double radio galaxies and quasars.

But, at least in the case of Cygnus A, Saikia and Wiita (1982) point out that the rotational axis which appears close to the position angle of the small jet, lies only $\sim 6°$ out of the plane of the sky (Simkin 1977) and it is therefore unlikely that Doppler beaming can account for the apparent jet asymmetry in the nucleus of this radio galaxy.

There are also more general arguments which would appear to limit the applicability of relativistic beaming models. For example, the projected linear size of radio galaxies such as NGC 315, 3C 236, and NGC 6251 with bright asymmetric nuclei are already quite large. If the cores of these galaxies are substantially Doppler boosted, then they are seen nearly end on, and the true linear size must be much larger - at least 10 to 20 Mpc.

Also Saikia (1981a) has argued that the existence of a well defined correlation between the spectral index α, and radio luminosity P, for radio galaxies with a steep spectrum core places a strong upper limit on the velocity of the radio emitting material. For $\gamma > 2$, the differential Doppler boosting should destroy any correlation in a randomly oriented sample of radio galaxies. and he concludes that for the radio galaxies in his sample $\gamma < 2$. It is interesting that for a sample of quasars, Saikia did not find any α-P correlation. This is consistent with the presence of strong Doppler beaming in quasars, but not in the nuclei of radio galaxies.

In unpublished samples, Ekers and Shaver and Ekers, Ekers, and Kellermann find that in at least half of the radio galaxies more than 1% of the flux density is contained in the core; in some the fraction may be nearly 100%. Because this spread in the luminosity of the core is so small, it follows that $\gamma < 3$ in the core of the typical radio galaxy.

Saikia (1981b) has considered the possibility that the radio galaxy cores appear asymmetric because of thermal absorption of the far component by a flattened cloud of gas perpendicular to the emerging jets. But purely intrinsic models of one-sided jets apear to be inconsistent with symmetric double structure if the compact jets reflect the transport of energy from the central engine into the outer lobes.

This leads to the so-called "flip-flop" models where the beams

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alternately squirt in opposite directions. There is some evidence for two-sided but asymmetric jets in the quasar 3C 147 (Preuss et al. 1981) and in the radio galaxy 3C 390.3 (Preuss et al. 1980, Linfield 1981a) consistent with this picture.

In galaxies which have a dominant nuclear jet as well as a large scale jet (e.g. NGC 6251, NGC 315, M87, 3C 120), and in the superluminal quasars, both jets lie on the same side of the nucleus. Since the large scale jets are many kpc in extent, this would imply switching times in excess of 10^5 years. The presence of large scale jets located on the same side of the nucleus as the small jets also argues against a relativistic interpretation of the small scale asymmetry, since the absence of Doppler brightening in the region of bends implies non-relativistic velocities in the large jets (von Groningen et al. 1980).

EXAMPLES OF RADIO ACTIVE NUCLEI

Table 1 lists those galaxies with radio active nuclei that have been observed in some detail with VLBI systems. In this section we discuss further some specific examples which illustrate the range of phenomena which has been observed.

The nearest example of an active radio nucleus is found right in our own Milky Way system. Although the compact radio source found in Sgr A has a luminosity of only $\sim 10^{33}$ ergs sec^{-1} or 0.01% that of the next weakest active nucleus, it has a comparable brightness temperature to other radio nuclei, and shows the characteristic flux density variations on a time scale of a few years (Lo et al. 1981, Brown and Lo 1982) seen in other radio galaxies. It may be assumed that active radio phenomena at this level is common in galaxies, but except for the very nearest galaxies, activity comparable to the Sgr A source would be below the limit of detection.

Active radio nuclei have been observed not only in radio galaxies and quasars, but in some otherwise normal-looking spiral and elliptical galaxies (Condon and Dressel 1978, Crane 1979, Jones et al. 1981, Shaffer and Marscher 1979).

M81. One of the nearest active nuclei is found in the center of the spiral galaxy M81 which has a luminosity $\sim 10^{37}$ ergs sec^{-1}. This is the smallest extragalactic source known and is only $\sim$ 1000 AU in size (Kellermann et al. 1976, Bartel et al. 1982).

NGC 1052 is a nearby E galaxy with a bright variable radio nucleus. Observations made at mm wavelengths by Heeschen and Puschell (1982) show the same characteristic flux density outbursts seen in more powerful radio galaxies and quasars, but unlike its more powerful counterparts, the expansion of the synchrotron cloud in NGC 1052 appears to be non-relativistic.

Table I. Galaxies with Radio Active Nuclei

Galaxy	Type	Ref.	Galaxy	Type	Ref.
III Zw Z	Sey	(1)	NGC 4278	E(RG)	(2,4)
NGC 262	Sey	(2)	NGC 4374	E	(2)
NGC 315	E(RG)	(3)	NGC 4552	E	(2)
NGC 1052	E	(4)	NGC 4594	Sa	(4,12)
NGC 1218	E(RG)	(2)	Cen A	E(RG)	(13)
NGC 1275	E(RG)	*	NGC 5635	S	(2)
3C 109	E(RG)	(5)	NGC 5675	S	(2)
3C 111	E(RG)	(3,6)	ARP 102	E	(1)
3C 120	S(RG)	*	NGC 6500	Sa	(11)
NGC 2911	SO	(2)	3C 371	N(RG)	(14)
NGC 3031	S	(7,8)	3C 390.3	N(RG)	(3,15)
NGC 3034	Irr	(2,4,9)	Cyg A	E(RG)	(3,16)
3C 236	E(RG)	(10)	NGC 7052	E	(2)
NGC 3894	E	(11)	3C 465	E(RG)	(5)
NGC 4261	E	(2)	NGC 7728	E	(2)

RG Radio Galaxy
* Numerous references, see text.

(1) Wittels, J.J.,Cotton, W.D., and Shapiro, I.I. 1978, Astrophys. J. Letters 225, L47.
(2) Jones, D.L., Sramek, R.A., and Terzian, Y. 1981, Astrophys. J. 246, 28.
(3) Linfield, R. 1981, Astrophys. J. 244, 436.
(4) Shaffer, D.B. and Marscher, A.P. 1979, Astrophys. J. Letters 233, L105.
(5) Preuss, E. et al. 1977, Astron. & Astrophys. 54, 297.
(6) Pauliny-Toth, I.I.K. et al. 1976, Astron. and Astrophys. 52, 471.
(7) Bartel, N. et al. 1982, Astrophys. J. (in press).
(8) Kellermann, K.I. 1976, Astrophys. J. 210, L121.
(9) Geldzahler, B.J. et al. 1977, Astrophys. J. Letters 215, L5.
(10) Schilizzi, R.T. et al. 1979, Astron. & Astrophys. 77, 1
(11) Biermann, P. et al. 1981, Astrophys. J. Letters 250, L49.
(12) Jauncey, D. et al., Nature (in press).
(13) Kellermann, K. I. et al. 1975, Astrophys. J. Letters 197, L113.
(14) Pearson, T. and Readhead, A.C.S. 1981, Astrophys. J. 248, 61.
(15) Preuss, E. et al. 1980, Astrophys. J. Letters 240, L7.
(16) Kellermann, K.I. et al. 1981, Astron. & Astrophys. 97, L1.

Centaurus A. The closest radio galaxy is Centaurus A. In addition to the large system of extended radio emission and the inner double, there is a radio, optical, X-ray jet (e.g. Fiegelson 1981) which points from the nucleus toward the north-west lobe. The nucleus contains a very compact (Kellermann et al. 1975) and active radio source (Kaufman et al. 1981).

M87. In the more luminous radio galaxy M87 (Virgo A), low resolution maps made with the VLA show the classical double lobe source (Owen et al. 1980) while the high resolution VLA map shows a narrow radio jet extending away from a bright nucleus and essentially coincident with the well known optical jet. The structure of the radio nucleus has been studied by Reid et al. (1982). In addition to a bright core, the VLBI map shows a small jet ∿ 0.05 arc sec in extent precisely aligned with the extended jet. There is some evidence that the VLBI jet wiggles with an amplitude of ∿ 3 milliarcsec and a wavelength of 15 milliarcsec possibly reflecting precession in the jet system similar to what is observed in SS 433. The core feature itself is very small - $\lesssim$ 0.1 light year in extent; but still this limit is much larger than the hypothetical black hole postulated to be at the nucleus of M87 (Young et al. 1978).

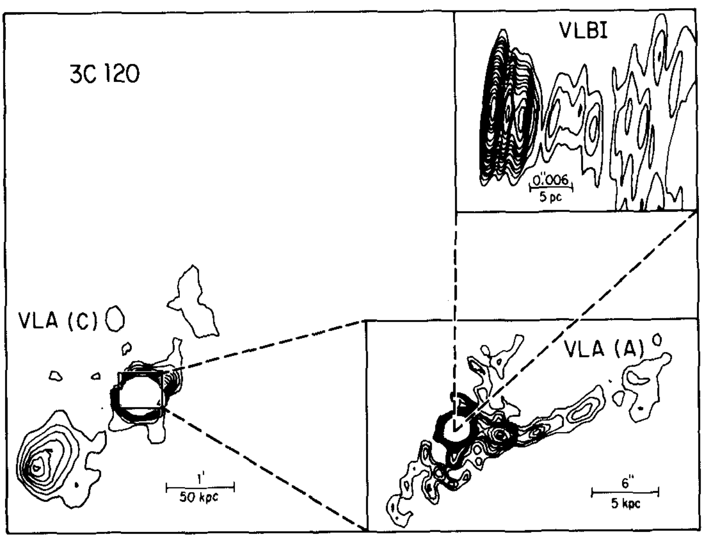

Figure 2. Structure of the radio galaxy 3C 120 taken from Clark (unpublished), Walker (unpublished), and Walker et al. (1981).

NGC 1275. One of the most exhaustively studied radio active nuclei is the one in NGC 1275. In this active galaxy, there is a bright core component plus a complex "jet-like" feature extending about 3 pc toward the south (e.g. Unwin et al. 1982). This southern component appears to be moving away from the bright core with an apparent velocity of about 0.6c (Romney et al. 1981). This is consistent with the overall size and the age of the source deduced from the most recent flux density outburst which began about 1960.

3C 120. In the nucleus of 3C 120, which has frequent flux density outbursts on a time scale of a year or so, the components appear to be moving away from the nucleus with apparent superluminal velocities. As shown in Figure 2, 3C 120 is a classical double-lobed radio source with components spaced $\sim$ 100 kpc on either side of the bright nucleus. Because most of the flux density is in the nuclear component, the extended features are difficult to observe. VLA observations by Walker (unpublished) show a well-defined jet extending from the nucleus toward the north-east lobe. Within a few kpc from the nucleus the jet curves through an angle $\sim$ 60° and becomes aligned with the nuclear jet. The VLBI observations show several bright features in the nuclear jet laying between $\sim$ 1 pc to $\sim$ 15 pc from the nucleus which flow outward with an apparent velocity $\sim$ 7c (Walker et al. 1982).

Arp (1981) has emphasized that 3C 120 is a very peculiar galaxy, and in several respects is unique. The a-priori probability that this particular galaxy should have its relativistic beam pointed in just the right direction to show superluminal motion is only $\sim$ 1%. But the unusual brightness of the radio core compared with the extended features, is consistent with a beaming model and Doppler enhancement of a core seen end on.

SUMMARY

While relativistic effects may well be important in radio active nuclei, it is clear that purely geometric models are inadequate to interpret observations of radio active nuclei and probably quasars as well. Intrinsic difference must exist in the nuclei of normal spiral and elliptical galaxies, radio galaxies and quasars which give rise to the wide range of luminosity, size, and motion which is observed.

REFERENCES

Angel, J.R.P., and Stockman, H.S.: 1980, Ann. Rev. 18, 321.
Arp, H.: 1981, ESO Workshop on Optical Jets in Galaxies.
Bartel, N. et al.: 1982, Astrophys. J. (in press)
Blandford, R.D., and Konigl, A.: 1979, Astrophys. J. 232, 34.
Brown, R., and Lo, K-Y.: 1982, Astrophys. J. 253, 108.
Condon, J.J., and Dressel, L.L.: 1978, Astrophys. J. 221, 456.
Cohen, M.H., and Readhead, A.C.S.: 1979, Astrophys. J. Letters 233, L101.

Cohen, M.H., and Unwin, S.: 1981, IAU Symp. No. 97, Extragalactic Radio Sources, p. 345.
Crane, P.C.: 1979, Astron. J. 84, 281.
Fiegelson, E.D.: 1981, IAU Symp. No. 97, Extragalactic Radio Sources, p. 107.
Fomalont, E.B.: 1980, IAU Symp. No. 94, The Origin of Cosmic Rays, p. 111.
Gopal-Krishna et al.: 1980, Nature 288, 344.
Heeschen, D.S., and Puschell, J.J.: 1982 (in press).
Jones, D.L. et al.: 1981, Astrophys. J. 247, L57.
Kapahi, V.K., and Saikia, D.J.: 1981, Bulletin of the Astronomical Society of India 9, 177.
Kapahi, V.K., and Saikia, D.J.: 1982, Indian Journal of Astrophysics and Astronomy (in press).
Kaufmann et al.: 1981, Astron. & Astrophys. 100, 189.
Kellermann, K.I. et al.: 1975, Astrophys. J. Letters 197, L113.
Kellermann, K.I. et al.: 1976, Astrophys. J. Letters 210, L121.
Kellermann, K.I. et al.: 1978, Physica Scripta 17, 257.
Kellermann, K.I. et al.: 1981, Astron. & Astrophys. 97, L1.
Linfield, R.: 1981a, Astrophys. J. 244, 436.
Linfield, R.: 1981b, Astrophys. J. 250, 464.
Lo, K.Y. et al.: 1981, Astrophys. J. 249, 504.
Owen, F.N. et al.: 1980, Astrophys. J. Letters 239, L11.
Preuss, E. et al.: 1977, Astron. & Astrophys. 54, 297.
Preuss, E. et al.: 1980, Astrophys. J. Letters 240, L7.
Preuss, E.: 1981, ESO/EAS Workshop on Jets, p. 97.
Preuss, E. et al.: 1981, IAU Symp. No. 97, Extragalactic Radio Sources, p. 289.
Reid, M. et al.: 1982, Astrophys. J. (in press).
Romney, J. et al.: 1981, IAU Symp. No. 97, Extragalactic Radio Sources, p. 291.
Saikia, D.J.: 1981a, Monthly Notices Roy. Astron. Soc. 197, 1097.
Saikia, D.J.: 1981b, Monthly Notices Roy. Astron. Soc. 197, 11p.
Saikia, D.J., and Wiita, P.J.: 1982, Monthly Notices Roy. Astron. Soc. 200, 83.
Scheuer, P. and Readhead, A.C.S.: 1979, Nature 277, 182.
Schilizzi, R.T.: 1976, Astron. J. 81, 946.
Schilizzi, R.T. et al.: 1979, Astronomy & Astrophys. 77, 1.
Shaffer, D.B. et al.: 1981, IAU Symp. No. 97, Extragalactic Radio Sources, p. 367.
Shaffer, D.B., and Marscher, A.P.: 1979, Astrophys. J. Letters 233, L105.
Simkin, S.: 1977, Astrophys. J. 217, 145.
Strittmatter, P.A. et al.: 1980, Astron. & Astrophys. 88, L12.
Unwin, S. et al.: 1982, Astrophys. J. 256, 83.
von Groningen et al.: 1980, Astronomy & Astrophys. 90, L7.
Walker, R.C. et al.: 1982, Astrophys. J. 257, 56.
Young, P. et al.: 1978, Astrophys. J. 221, 721.