KILOPARSEC SCALE RADIO STRUCTURE IN ACTIVE GALAXIES

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ABSTRACT. A substantial fraction of active galaxies contain linear radio sources with sizes of a few hundreds or thousands of parsecs. Such sources are found in essentially all classes of active galactic nuclei, including Seyfert galaxies of both types, X-ray selected active nuclei, radio galaxies and quasars. The radio emission is clearly energised by the active nucleus, probably in the form of a jet. A number of observable consequences of the interaction of the jet with the interstellar medium of the galaxy are discussed. These processes include jet disruption by instabilities, acceleration of cosmic rays by shocks or turbulence, ionization and radial acceleration of interstellar clouds, creation of a hot thermal component through the agency of shock waves and bending of the jet by the ram pressure of a rotating interstellar medium.

1. INTRODUCTION

It has been known for many years that radio galaxies and quasars exhibit radio emission from a wide range of scales. On the one hand, some objects, especially those selected through radio surveys at low frequencies, have widely spaced (hundreds or even thousands of kpc) steep spectrum radio lobes (e.g., Miley 1980). On the other hand, very compact ($\simeq$ pc) scale structure is also found; these sources most commonly show a "core-jet" morphology when mapped with modern VLBI techniques (e.g., Readhead and Pearson 1982). It has recently become clear that radio emission from an intermediate scale - a few hundred parsecs or a few kiloparsecs - is a common feature of active galaxies. As I shall show, such sources transcend the conventional boundaries between the different types of activity; linear (i.e., double, triple or jet-like) kiloparsec scale sources have been found in Seyferts of types 1 and 2, X-ray galaxies with relatively narrow lines, as well as radio galaxies and quasars. These radio results may then be added to the large inventory of similarities between Seyferts, quasars and radio galaxies, such as optical line spectra (e.g., Baldwin and Netzer 1978; Osterbrock 1977), infrared excesses (e.g., Rieke 1978, 1982; Ward et al. 1982; Hyland and Allen 1982) and X-radiation (e.g., Kriss et al. 1980;

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Tananbaum et al. 1979).

Before discussing the radio properties in greater depth, it is worthwhile to recall other components of active galaxies occupying the kpc scale. Optical spectroscopic observations have led to the well known concept of the forbidden line region - filaments or clouds of low density gas at 10^4K with a small filling factor. It is obviously a gross oversimplification to think of this region as a single entity since lines like [Fe X] and [Fe XI] probably originate from dense regions of high velocity dispersion within ≃ 1 pc of the central source (e.g., Grandi 1978; Wilson 1979) while species of low ionization, such as [OII], are found in much lower density condensations, spread over hundreds of parsecs. Nevertheless, we shall see there are close correspondences between the nonthermal radio emission and the spatially resolved gas clouds visible in lines like [OIII] and Hα. Another important component is dust, some of which may be heated by the central optical/UV source and radiate powerfully in the infrared. The presence of dust also produces differential extinction across the region, giving asymmetric forbidden line profiles (Heckman et al. 1981) and steep Balmer decrements (e.g., Koski 1978). Lastly we must not forget the intense flux of optical, UV and X-radiation from the small central source, which is usually considered the dominant ionizing input to the line emitting gas.

The results given on Seyfert galaxies in this article are from a program by J. S. Ulvestad and the author.

2. KILOPARSEC SCALE RADIO SOURCES

I wish to emphasise the similarities of the radio structures of galaxies normally considered to belong to different classes of activity. Therefore I have selected, from a large body of data, one Markarian type 1 Seyfert (Mark 79), one type 1.5 Seyfert (NGC 5548), one nearby Seyfert of type 2 (NGC 1068), one galaxy whose activity was first recognized through X-ray observations (NGC 2110) and one radio galaxy from the 3C catalog (3C 305). Fig. 1 shows VLA maps of the Seyfert 1 galaxy Mark 79. The source is triple with the central component coincident with the optical nucleus (Clements 1981). The fainter, northern component only shows up on the 20 cm map (top) whose brightness sensitivity is superior to the higher resolution map at 6 cm (bottom). Fig. 2 gives VLA maps of NGC 5548 (from Wilson and Ulvestad 1982a), a Seyfert of type 1.5. The source comprises an unresolved core coincident with the optical continuum nucleus and two diffuse lobes straddling it in p.a. 165^o. The total source extent is 5.9 kpc and the radio luminosities of the two diffuse lobes only 2.5 and 1.2 x 10^{39} erg s^{-1}.

Recent VLA maps of the central region of NGC 1068, a famous type 2 Seyfert with unusually broad lines, are shown in Fig. 3. The main map is at 6 cm with resolution ≃ 0".4 and the inserts show pictures of three of the brighter regions at 2 cm with resolution ≃ 0".1. The brightest feature on the 6 cm map is resolved by the beam and is associated with the optical nucleus (whose position is α_o = 02^h 40^m $07^s.076$, δ_o = -00^0

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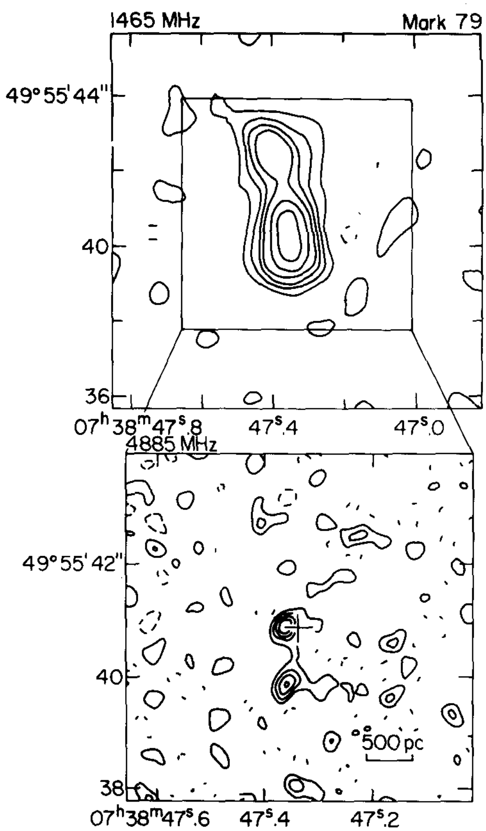


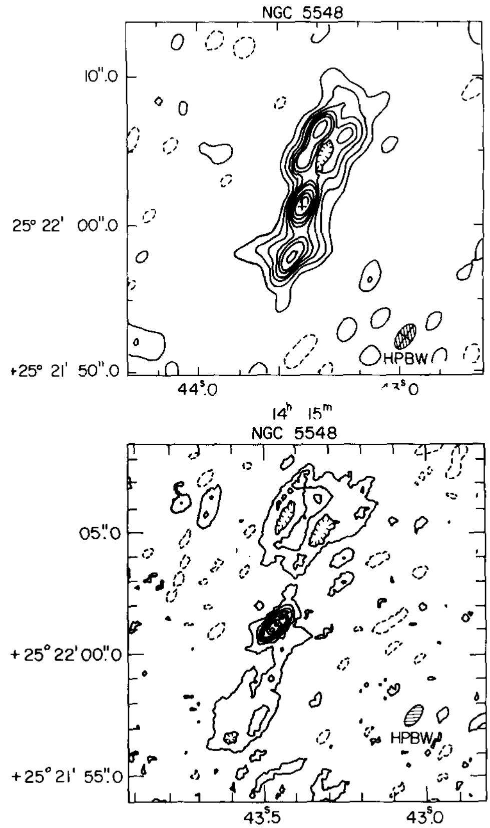


Fig. 1 (left). VLA maps of the nucleus of Mark 79. Top at 20 cm, contours at -10% (dotted), 10%, 20%, 30%, 40%, 60% and 80% of the peak brightness of 3.65 mJy (beam area)$^{-1}$. Bottom at 6 cm, contours at -20% (dotted), 20%, 40%, 60%, 80% of the peak brightness of 1.08 mJy (beam area)$^{-1}$. The cross marks the optical position of Clements (1981). The 20 cm resolution is ≃ 1".2 and that at 6 cm ≃ 0".4. Fig. 2 (right). VLA maps of the nuclear radio source of NGC 5548. Top at 20 cm, contours at -7.5%, 7.5%, 15%, 22.5%, 30%, 37.5%, 45%, 60%, 75% and 90% of the peak brightness of 3.38 mJy (beam area)$^{-1}$. The cross marks the optical position of Clements (1981). Bottom at 6 cm, contours at -10%, 10%, 20%, 30%, 40%, 50%, 70% and 90% of the peak brightness of 1.38 mJy (beam area)$^{-1}$. The resolutions are 2" x 1" in p.a. 147^{o} at 20 cm and 1".0 x 0".4 in p.a. 139^{o} at 6 cm.

13' 31".48, with an accuracy of order ± 0".1 - 0".2, see Clements, 1981). With the higher resolution afforded by the 2 cm observations, this nuclear source is found to be a bent triple, with a distance between the outer components of only ≃ 0".7 (for NGC 1068, 1" = 110 pc if H_o = 50 km s^{-1} Mpc^{-1}). The central component of this triple is coincident, to within the errors, with Clement's optical position. The axis of the

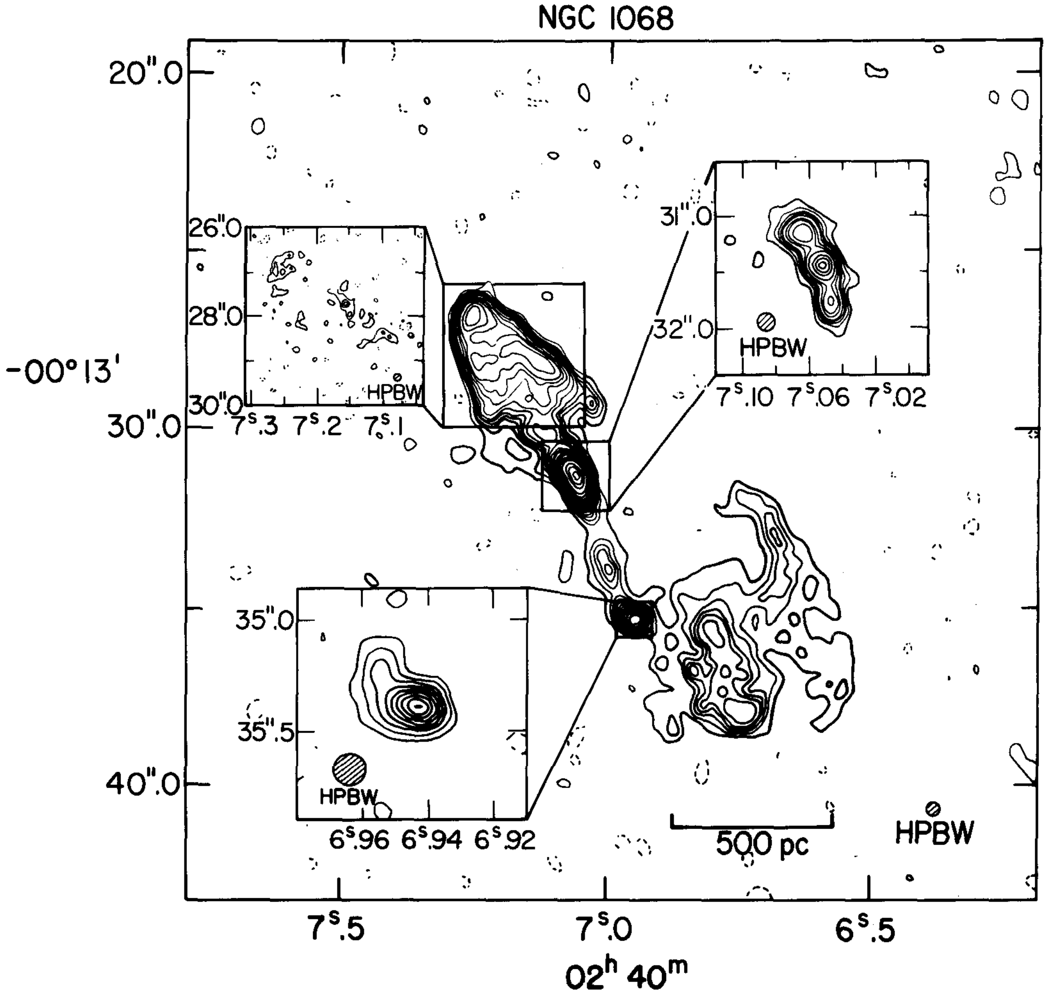
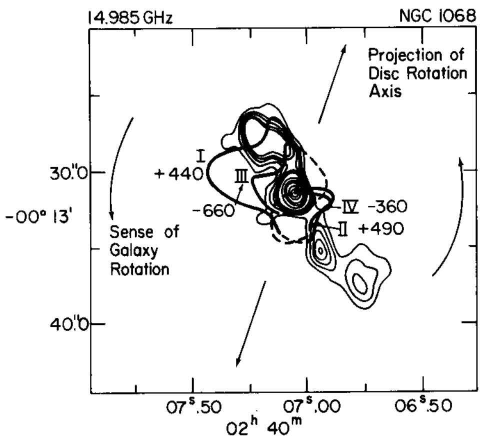


Fig. 3. VLA maps of the nuclear region of NGC 1068. The main map is at 6 cm (resolution ≈ 0".4), with the three insets showing higher resolution details at 2 cm (resolution ≈ 0".12). The optical nucleus coincides with the brightest part of the source on the 6 cm map. 6 cm contours are plotted at -0.2%, 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, 1.4%, 2%, 3%, 4%, 5%, 7%, 10%, 15%, 20%, 30%, 50%, 70% and 90% of the peak brightness of 0.276 Jy (beam area)$^{-1}$. The top right inset shows the nucleus at 2 cm; contours are plotted at -2%, 2%, 4%, 6%, 8%, 10%, 15%, 20%, 30%, 50%, 70%, and 90% of the peak brightness of 56.8 mJy (beam area)$^{-1}$. The top left inset shows the NE lobe at 2 cm; contours at -1.5%, 1.5%, 3%, 4.5% of 56.8 mJy (beam area)$^{-1}$. The lower left inset shows the "hot spot" to the SW of the nucleus at 2 cm; contours at -1.5%, 1.5%, 3%, 4.5%, 6%, 7.5%, 9%, 10.5%, 12%, 13.5% of 56.8 mJy (beam area)$^{-1}$.

triple is roughly similar to that of the larger scale structure of the source seen at 6 cm. Immediately to the NE and SW of the nucleus, in p.a. ≈ 30° and 210°, narrow, elongated radio features are seen on the 6 cm map. The feature to the NE blends into a radio lobe whose tip is almost 6" from the nucleus. This lobe has an intriguing morphology; it is roughly triangular in shape, with the apex at its NE end, has very sharp edges on the E, N and NW sides and is strongly limb-brightened. This limb-brightening may be seen more clearly in the 2 cm picture. SW of the nucleus, the narrow radio feature ends in a "hot spot" some 4" away. This "hot spot" contains structure on a scale of $\lesssim$ 20 pc, as evidenced by the 2 cm data. S and W of the "hot spot" is found a diffuse lobe of diameter ≈ 6". In the radio band, then, NGC 1068 shows all the morphological features characteristic of its larger and more radio powerful cousins, the radio galaxies. In particular, the narrow elongated feature to the SW of the nucleus satisfies the operational definition of a radio jet given by Bridle (1982) and the one to the NE may do. Such jets are generally found to extend from a galactic nucleus at one end to "hot spots" or radio lobes at the other, and NGC 1068 is quite typical in this respect. While our observations are unable to distinguish in detail between "jet" models (i.e., steady, continuous high velocity flows), multiple plasmoids or quasi-continuous sequences of bubbles, they strongly suggest that the same phenomenon is responsible for the radio lobes in Seyfert and radio galaxies. In line with current thinking on the fuelling of radio galaxies, I shall refer to the narrow radio features in NGC 1068 as radio jets. A similar conclusion has been reached by Pedlar et al. (1982).

The relationship between the non-thermal (see Wilson and Ulvestad 1982b for the spectral indices of the various components) radio emission of NGC 1068 and the optical properties on the same scale is very interesting. Speckle interferometric observations (Meaburn et al. 1982) show that most of the nuclear emission of NGC 1068 in the 5000-5600Å band originates within a region of size $\lesssim$ 0".03 or < 0.03 pc. Presumably, this compact source is associated with the central component of the nuclear radio triple. On the other hand, Meaburn et al. (1982) did not detect compact spatial structure in similar observations of the [OIII] 5007Å line. In fact, direct short exposure photographs (Bertola 1966; Walker 1968) of the nucleus of NGC 1068 show it to be resolved and to measure 1".5 x 1".2 in p.a. 30° with a seeing disc of 0".9. This elongated structure seems to be dominated by line emission and is of similar size and shape to the bent nuclear triple radio source. On a somewhat larger scale, a faint optical "flare" is visible in p.a. 30° extending to 5" from the nucleus, as well as a "very distinct narrow prominence" about 5" in the opposite direction, p.a. 210° (Bertola 1966). Although the nature of the radiation from these narrow optical features is unknown, it seems reasonable to interpret them as optical emission from the radio jets. The high velocity line emitting clouds ("forbidden line region") are spatially extended in NGC 1068 and have been mapped out in [OIII] emission by Walker (1968). He distinguishes four clouds, whose outlines and velocities (w.r.t. the systemic velocity of NGC 1068) are shown in Fig. 4, superposed on a 2 cm contour



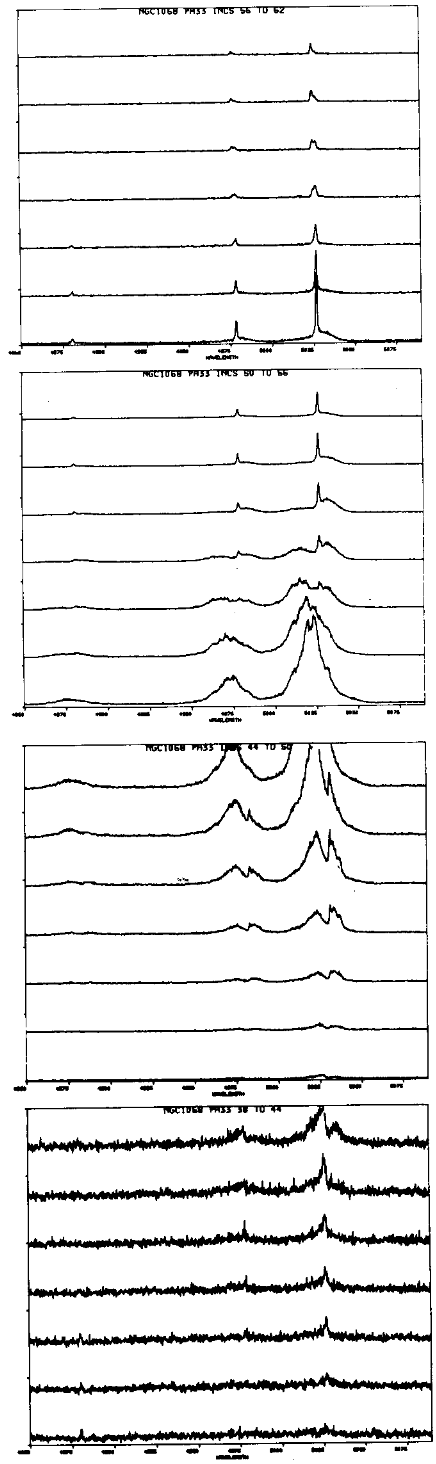
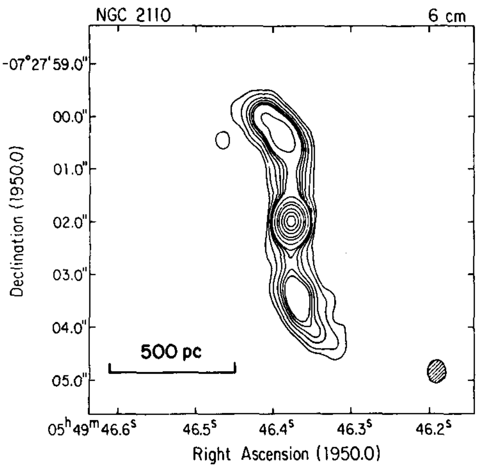


Fig. 4 (above). The contours are a VLA map of NGC 1068 at 2 cm, with resolution 1."1 x 1."3 in p.a. 6° (from Wilson and Ulvestad 1982b). The thick lines show the outlines of the four high velocity clouds mapped out by Walker (1968). Fig. 5 (right). A long slit spectrum across the nucleus of NGC 1068 in p.a. 33°. The lines are Hβ and [OIII] λλ4959, 5007, and the spectral resolution is ≈ 0.5Å. The plot shows the spectra at different points along the slit every 0."78. Within any one of the four panels the vertical scale, in counts per centimeter, is constant, but is different from the adjacent panel. The top spectrum of any panel is the same spectrum as the bottom spectrum of the panel immediately above, but is rescaled. The top of the diagram corresponds to the NE and the nucleus is at the bottom of the next to the top panel. The data were obtained with the Image Photon Counting System and the Anglo Australian Telescope.



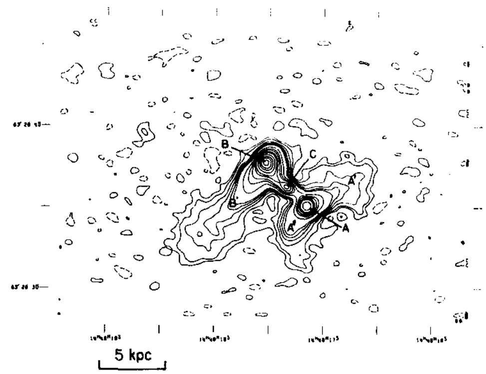


Fig. 6 (left). VLA map of the nuclear region of the X-ray galaxy NGC 2110 at 6 cm with resolution 0".44 x 0".35 in p.a. -1^{o}. Contours are plotted at 0.5, 1, 2, 3, 4, 5, 10, 20, 30, 50, 70 and 90% of the peak flux density of 96 mJy (beam area)$^{-1}$. Fig. 7 (right). VLA map of the radio galaxy 3C 305 at 6 cm (from Heckman et al. 1982). Contours are plotted at -0.5, 0.5, 1, 2, 3, 4, 5, 10, 15, 20, 29, 38, 60, 90, 120, 160, 200 mJy (beam area)$^{-1}$ (0".5 FWHM circular Gaussian).

map of NGC 1068 (Wilson and Ulvestad 1982b) with resolution close to the optical seeing. The clouds to the NE correspond quite well to the radio emission. Although the spatial resolution of the optical measurements is low, it seems likely that the "ridges" of clouds I and III extending N from the nucleus are related to the limb brightening effects seen in the higher resolution radio maps (Fig. 3). To the SW, Walker's (1968) cloud outlines do not extend as far as the radio source does. In order to investigate the gas motions with higher spectral resolution and sensitivity than available to Walker, a series of long slit spectra of NGC 1068 at medium or high dispersion have been obtained at the AAT and CTIO by the author, J. A. Baldwin, A. E. Wright and J. S. Ulvestad. Fig. 5 shows the central 25 increments of one observation with the slit along the radio source axis. Walker's clouds may be clearly recognized. The broad components of the emission lines are seen as far as 6" to the NE and 8" to the SW of the nucleus, with the line profiles changing with position in a complicated manner. These extents are identical to those of the radio source along the same axis. The data thus show a close correspondence between the relativistic electrons and magnetic fields responsible for the radio emission and the thermal gas which gives rise to the broad optical line radiation. I shall return to this topic later (Section 4).

Fig. 6 is a VLA 6 cm map of the galaxy NGC 2110 (from Ulvestad and Wilson (1982). The active nature of this object was first recognized through X-ray observations and it was subsequently found to have an optical spectrum similar to a Seyfert 2 (Bradt et al. 1978); however, there are probably broad wings on Hα (Shuder 1980). The radio data show an unresolved, probably flat spectrum, central component coincident with the optical nucleus plus a symmetric 'S' shaped, jet-like radio source. The total source extent is 830 pc.

As a final example of a kpc scale radio source in an active galaxy, Fig. 7 shows a VLA 6 cm map of the object 3C 305, from Heckman et al (1982). Although this source is much smaller (≈ 3 kpc) than a typical double radio galaxy, it is comparable to them in radio luminosity (≈ 10^{42} erg s^{-1}) and of higher radio luminosity than Seyferts. The data show oppositely directed radio jets feeding distorted radio lobes. Heckman et al. (1982) show that the optical line emission is closely related to the radio source. They also argue that the dust, ionized gas, young stars and faint, one-armed spiral structure may be the result of a recent merger of a luminous early-type galaxy and a late-type galaxy. This merger may have triggered the ejection of radio plasma into the relatively dense interstellar medium supplied by the late-type galaxy.

For reasons of space, I shall not extend the discussion to cover the more luminous kpc radio structure associated with quasars; maps of such sources may be found in Wilkinson (1982).

3. ON THE NATURE OF CENTRAL RADIO SOURCES IN SPIRAL GALAXIES

Clearly, the linear (i.e., double, triple or jet-like) radio sources in Seyfert galaxies cannot reflect a disk of radio emitting material coplanar with the stellar disk and viewed obliquely. Fig. 8 shows histograms of number of Seyfert galaxies versus optical axial ratio, for two samples. In each case, the upper line is the full sample, the intermediate line the galaxies which have been observed with the VLA and the shaded area those found to contain linear radio sources. The linear radio sources do not tend to be seen in near edge-on galaxies. Further, the high fraction of Markarian Seyferts containing linear sources (Wilson 1982) also indicates that the structures are truly aligned and are not caused by projection effects. Arguments that these radio sources result from nuclear ejection are deployed, for example, by Wilson (1982). It is then clear that the radio luminosities of radio components ejected by active galactic nuclei can range from only ≃ 10^{38} erg s^{-1} for NGC 4051 up to ≃ 10^{45} erg s^{-1} for an object like Cygnus A.

It is curious that some spiral galaxies, often with little other apparent evidence for nuclear activity, contain central radio sources on the few hundreds pc scale with radio luminosities well above the norm for spirals (e.g., Condon et al. 1982). Condon et al. (1982) showed that these sources are commonly coplanar with the disk of the galaxy and interpreted them in terms of the integrated radiation from supernova remnants formed in a large burst of star formation. van der Hulst, Crane and Keel (1981) have surveyed the central radio structures in 81 spiral galaxies. They classified the source morphologies as simple, core-halo or complex and showed that the simple radio sources tend to be

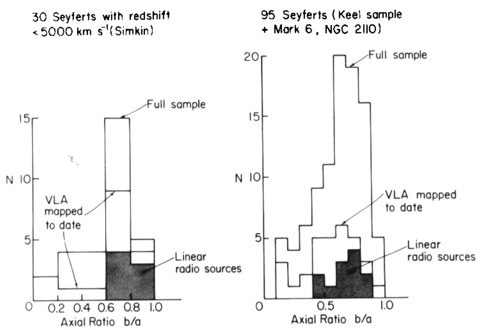


Fig. 8. Histogram of number of Seyfert galaxies versus axial ratio b/a of the optical isophotes. The left-hand panel is for the 30 Seyferts with redshift below 5000 km s^{-1} given by Simkin, Su and Schwarz (1980). The right-hand panel is for the sample of 95 galaxies measured by Keel (1980) plus Mark 6 and NGC 2110.

luminous ($P_{6cm} > 10^{20}$ W Hz^{-1} $Ster^{-1}$) and to occur in early-type (Sab and earlier) spirals, while those with complex morphologies tend to be weak ($P_{6cm} < 10^{20}$ W Hz^{-1} $Ster^{-1}$) and to occur in late-type (Sb and later) spirals. The core-halo sources span an intermediate range of power ($P_{6cm} \sim 10^{19-22}$ W Hz^{-1} $Ster^{-1}$) and morphological type (S0-Sc). It is most unlikely that the strong sources seen in early-type spirals are due to "starbursts". The central regions of these bulge dominated galaxies contain predominantly old stellar populations. It is not impossible that bulge dominated spirals with strong central radio sources harbor a weak active nucleus; higher resolution mapping of such galaxies would be very interesting. Such activity would be consistent with the strong trend for nuclear activity to occur in galaxies with prominent bulges - radio galaxies are associated with ellipticals and Seyferts are preferentially found in early-type spirals.

4. MANIFESTATIONS OF THE INTERACTION BETWEEN THE JET AND THE INTERSTELLAR MEDIUM

Assuming that the linear radio sources originate from the interaction between an outwardly directed fluid jet and interstellar gas, a number of observable effects may be expected. In this Section, I should like to discuss some of these processes.

Firstly, it is natural to account for the confinement of the radio sources to the inner region of the galaxy via "disruption" of the jet by a surrounding, dense interstellar medium. It should be noted that this process is likely to occur not only in the spiral Seyferts but also in the radio galaxies with kpc cores, since this latter type is commonly found to possess a dense interstellar medium as evidenced by HI emission/absorption, optical emission lines and dust (e.g., Baan and Haschick 1981; Heckman et al. 1982). The ability of a radio galaxy to power large radio lobes outside the parent galaxy is presumably related to a high jet momentum flux and a low interstellar density. The dominant mechanism in the disruption of the jet and the necessary combination of jet and interstellar medium parameters which determine "escape" versus "disruption" are unknown.

Secondly, acceleration of relativistic particles is probably occurring throughout the jet. There are well-known difficulties with the hypothesis that the radiating relativistic electrons are accelerated only very close to the primary energy source. In the type 1 Seyferts, at least, such electrons will lose energy rapidly through inverse Compton scattering on photons from the small, luminous optical and X-ray sources, unless they stream outwards radially with relativistic velocities (e.g., Woltjer 1966). Synchrotron and adiabatic losses will further deplete the cosmic ray energies. "In situ" acceleration could presumably be achieved through the agency of turbulence (e.g., Eilek and Henriksen 1982) or shock waves (e.g., Bell 1978; Blandford and Ostriker 1978) within the jet fluid. The shock waves would be generated through velocity irregularities in the jet (Rees 1978) or through entrainment of interstellar clouds (Blandford and Königl 1979; De Young 1981).

The next processes relate to the connection between the radio radiation and the forbidden line clouds. The radio and forbidden line distributions are often similar (e.g., Ulvestad et al. 1981; Heckman et al. 1982), the radio and forbidden line luminosities are broadly correlated for Seyferts (e.g., Wilson and Willis 1980) and the radio power also appears related to the forbidden line width (Wilson and Willis 1980; Heckman et al. 1981). Fig. 9 shows this last relationship, with only those Seyferts known to contain linear radio sources being plotted. A correlation of the form $P_{21cm} \propto (\mathrm{FWHM[OIII]})^{\beta}$ with $\beta=3.53\pm0.7$ is found. Heckman et al. (1981) have suggested that such a trend may also extend to radio galaxies with kpc cores. There are various ways of explaining this correlation. One scheme involves direct transfer of energy from the kinetic energy of the emission line clouds into magnetic fields and relativistic particles. Another (Blandford and Königl 1979; Wilson 1982) supposes that the jet which fuels the radio emission also accelerates outwards any interstellar clouds which drift into it. For radio luminosities $L_r = \varepsilon\rho_j h_j^2 V_j^3$ (ε is the efficiency with which jet power is converted into radio radiation; ρ_j, h_j and V_j are the density, cross-section and velocity of the jet) and if the clouds attain velocities $V_c \propto V_j$, a relation of the form $L_r \propto V_c^3$ can result under simple assumptions. The shock waves generated in this

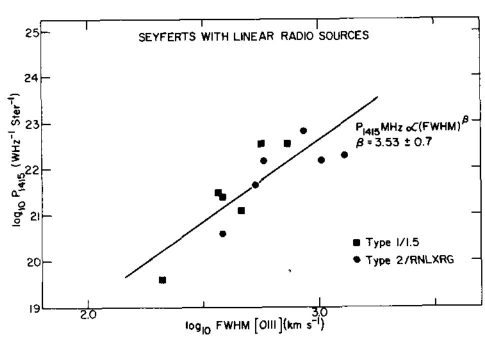
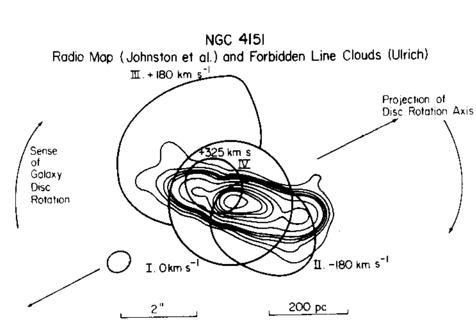


Fig. 9. The relation between the monochromatic radio power at 21 cm (mainly from de Bruyn and Wilson 1976) and the FWHM of [OIII] λ5007 (mainly from Heckman et al. 1981) for galaxies known to have linear (i.e., double, triple or jet-like) radio sources. Types 1, 1.5 and 2 Seyfert galaxies and X-ray galaxies with relatively narrow lines (RNLXRG) are plotted as indicated. The line represents the best fit power law.



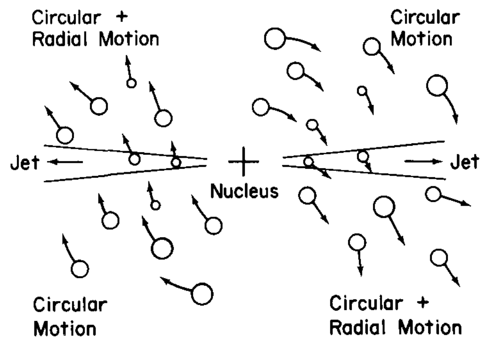


Fig. 10 (left). Contours of brightness at 6 cm in the nuclear radio source of NGC 4151 (from Johnston et al. 1982) along with the outlines of the forbidden line clouds (from Ulrich 1973). Contours are plotted at 1, 2, 3, 4, 5, 10, 20, 30, 40, 50 and 75% of the peak brightness of 41 mJy (beam area)$^{-1}$. The beam size is 0".64 x 0".53 in p.a. -64^{o}. The mean radial velocities of the clouds w.r.t. the systemic velocity of NGC 4151 are indicated. Fig. 11 (right). Model for the motions of the high velocity forbidden line clouds in NGC 4151. Interstellar clouds rotate into the jet, are accelerated radially by it and leave it with both a circular and radial component of motion.

interaction would presumably accelerate cosmic rays so radio emission and high velocity gas should be closely related spatially. A refinement to this scenario is suggested by the observations of NGC 4151 (Fig. 10). In this galaxy the jet-like radio source and the high velocity forbidden line clouds (Ulrich 1973) occupy the same spatial scale (4" ≃ 400 pc). However, the axis of the cloud complex is some 30^{o} - 40^{o} clockwise of the radio source. If the spiral arms of NGC 4151 are assumed to be "trailing", then the cloud complex is twisted downstream (in the rotational sense) of the radio jet. A schematic explanation for this situation (Booler et al. 1982; Wilson 1982) is indicated in Fig. 11. Normally rotating interstellar clouds in the inner part of the galaxy are carried into the jet, are accelerated by it and leave it with both radial and circumferential components of motion. The jet to the NE of the nucleus is then directed away from the earth and that to the SW towards it (cf., Booler et al. 1982). The faintness of clouds III and IV (II is the brightest cloud after I, Ulrich 1973) might then be attributed, in part, to their location behind absorbing dust in the disk of the galaxy. In NGC 1068 too, there is a suggestion (Fig. 4) that the clouds to the NE of the nucleus tend to be associated with, or be downstream of, the radio source. In this case, however, the two clouds on any given side (NE or SW) of the nucleus have opposite signs of velocity with respect to it, suggesting a more complicated model is necessary to account for their motions.

The close relation of the forbidden line clouds to the radio sources impacts on their mode of ionization, as well as their dynamics. It has been convincingly argued (e.g., Osterbrock 1983 and references therein) that the dominant form of ionization process in Seyferts is photoionization by a power law continuum, presumably the compact, non-stellar optical/UV source which is observed directly. And yet, the ionization mode in NGC 1068 and NGC 4151 seems to possess "directional information" - the ionized clouds are seen close to the radio axis. It is natural to expect the jet to emerge along the axis of some disk-like structure in the inner nucleus. Osterbrock (1982) further suggests that the disk, perhaps the broad line region, is optically thick to rays in the equatorial plane so that ionizing radiation can only escape in a cone around the rotation axis. This could account for the general location of the clouds, but it is unclear whether their detailed optical spectra are consistent with such a model and why the ionized gas should show a preference for the boundaries of the radio lobes (NGC 1068, Fig. 4; 4C 26.42, van Breugel and Heckman 1982). The alternative is, of course, that the jet itself plays a role in ionizing the clouds; such has been proposed by Heckman et al. (1982) for 3C 305, where no non-thermal nuclear optical source is apparent. Presumably the ionization in such cases will be either by collisions with thermal or sub-relativistic particles or by photons generated from synchrotron radiation within the jet. Independent of the details, if the jet does, indeed, accelerate and/or ionize the clouds, its luminosity must be at least 2 orders of magnitude higher than the radio luminosity (e.g., Heckman et al. 1982) i.e., the efficiency factor for generation of radio emission $\varepsilon \lessdot 0.01$.

Models which generate shock waves in ambient or entrained interstellar gas may be expected to lead to thermal bremsstrahlung X-rays. This process might be relevant to the X-rays from, for example, the Cen A jet (Feigelson 1982) and to the possible detection of an extended X-ray source to the SW of the nucleus of NGC 4151 (Elvis et al. 1982). Obviously searches for extended X-ray sources in active galaxies will be a worthwhile undertaking when the powerful AXAF observatory becomes available.

A further consequence of the jet-interstellar gas interaction involves distortion of the shape of a radio source, even when the axis of the nuclear "engine" remains fixed. There seems to be little trend for the radio components in Seyferts to be ejected along the rotation axes of the stellar disks (Ulvestad et al. 1981). Under such conditions, source distortion can occur through "buoyancy", i.e., a differential thermal pressure across a lobe or jet, or through the "ram pressure" of the interstellar gas. The former process was invoked by Henriksen et al. (1981) to account for the shape of 3C 293. Elsewhere (Wilson 1982; Wilson and Ulvestad 1982b) we have argued that ram pressure bending by a rotating interstellar medium will dominate over buoyancy and have fitted the 'S' shaped sources in NGC 1068 (Fig. 4), NGC 4151, 3C 293 and NGC 2110 (Fig. 6) with such a model. The new, higher resolution, maps of NGC 1068 (Fig. 3) cast doubt on the existence of systematic jet bending to the NE side of the nucleus; to the SW, however, is seen a progressive curling of the radio source towards the downstream direction with increasing distance from the nucleus. Perhaps the non-colinearity of the nuclear triple (Fig. 3) indicates that the trajectory of one component has already been bent by the very dense interstellar medium within 80 pc of the nucleus. It is interesting to note that the direction of ejection (p.a. $11^o/191^o$) in our model of NGC 1068 is essentially perpendicular to the optical continuum polarization vector in the nucleus (p.a. 97^o, Miller 1982). Miller (1982) interprets this polarization either in terms of scattering in an accretion disk, with the radio jet emerging along the rotation axis, or as optical synchrotron radiation from the jet itself. The polarization observations of NGC 1068 and NGC 4151 (Schmidt and Miller 1980) fit in well with the concept that the centers of Seyfert galaxies contain gaseous disk-like structures which are tilted with respect to their large scale stellar disks (c.f., Ulvestad et al. 1981; Tohline and Osterbrock 1982).

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