SEYFERT GALAXIES

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ABSTRACT. Observations of sample of Markarian Seyferts with the VLA indicate that a large fraction possess linear radio structure on a scale of a few hundred parsecs to a few kiloparsecs. The radio components generally straddle the optical nucleus and several sources are simple doubles. Similar structures are seen in the classical Seyferts NGC 1068, 4151, and 5548. NGC 4151 is probably best interpreted as a jet. A few sources (e.g. Mark 315, NGC 7469) exhibit diffuse, non-aligned radio structure on a scale similar to that of the linear sources. The radio axis in linear sources is misaligned with respect to the rotation axis of the galaxy disc by a large angle. The linear sources are discussed in terms of a model of a supersonic beam or jet which is "disrupted" by interaction with interstellar gas in the inner part of the galaxy (often a spiral). Two aspects of this interaction are emphasised. Firstly, the curved shape of the radio sources in NGC 1068 and NGC 4151 is ascribed to beam bending by the ram pressure of the rotating interstellar medium. Simple models of this process are shown to be consistent with the observations. Secondly, it is suggested that the broadened forbidden lines in Seyferts originate in part from interstellar gas accelerated outwards by the beam. This picture accounts for some of the empirical correlations found between radio and optical forbidden line properties.

1. INTRODUCTION

When investigating Seyfert galaxies, astronomers find a quite different form of active galactic nucleus to radio galaxies, the major topic of this meeting. The radio luminosity of a Seyfert is typically 10^{39-41} erg s^{-1} which, although greater than a normal spiral, is orders of magnitude weaker than is characteristic of most radio galaxies. Furthermore, the luminosity of a Seyfert nucleus in the radio band represents only a small fraction of its total electromagnetic luminosity, which is dominated by infra-red, X or gamma radiation (10^{43-46} erg s^{-1}). For these reasons, it has until recently been unclear whether the non-thermal emission from these objects is a consequence of an enhancement of the processes found in normal spirals (such as pulsars, supernova remnants and disk interstellar cosmic rays and magnetic fields) or

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whether it represents activity related to, but weaker than, the kind responsible for extended double radio galaxies (ejection of radio emitting gas from a compact nucleus). I hope to demonstrate in this paper that for a large fraction of Seyfert galaxies the second point of view is appropriate i.e. the radio sources may be crudely termed "mini radio galaxies".

2. RADIO STRUCTURE OF A "COMPLETE" SAMPLE

In studying statistical properties of radio sources, it is desirable to deal with well defined samples in order to avoid bias introduced by observational selection effects. Unfortunately a complete sample of Seyferts is not readily available. In the meantime, the best that can be done is to use the Seyfert galaxies in the lists of Markarian, but we must bear in mind that these lists are incomplete in apparent magnitude and discriminate against edge-on or otherwise obscured systems, since UV excess is the basis selection criterion.

Of the 41 Seyferts (Huchra and Sargent 1973) in the first 4 lists of Markarian, 16 have radio flux densities S(1415 MHz) > 10 mJy (de Bruyn and Wilson 1976). These 16 have all been observed at the VLA at 4885 MHz and some at 1465 or 15035 MHz. The present section is a preliminary report on the structure of this sample (Ulvestad and Wilson, in preparation). I divide the radio maps into 4 structural classes:

U: 7 galaxies (Mark 1, 110, 176, 231, 268, 279, 374). The radio emission is too compact for the structure to be defined. The source is either slightly resolved or unresolved.

L: 5 galaxies (Mark 3, 6, 34, 78, 270). The galaxies show discrete radio components, or a distribution of emission, lying along a line and straddling the optical continuum nucleus. These are mostly double or triple sources.

D: 1 galaxy (Mark 315). The radio emission is diffuse and not linear in structure.

A: 1 galaxy (Mark 348). The source structure cannot be classified into one of the above categories unambiguously.

A/L: 2 galaxies (Mark 79, 273). The radio emission may fall in the linear (L) category, but further observations are needed. Thus, of the 9 well resolved galaxies, at least 5 (56%) and possibly as many as 7 (78%) exhibit aligned components straddling the optical continuum nucleus. Maps of some of the sources in this sample are given in Fig. 1.

Statistical studies of the original sample of 41 and the 16 with structural information indicate (assuming $H_o = 50$ km s^{-1} Mpc^{-1}):

a. P(1415 MHz) ranges between $<3 \times 10^{20}$ and 1.5×10^{23} W Hz^{-1} Ster^{-1}.

b. Type 2 Seyferts tend to be more radio luminous than type 1's (Sramek and Tovmassian 1975; de Bruyn and Wilson 1978).

c. The linear sizes of the radio sources range from below a few hundred parsecs to a few kiloparsecs, comparable to the classical Seyferts.

Very tentative results from this study, which require a larger sample for a definite conclusion include:

d. A higher fraction of the most radio luminous sources may be of linear (L) type; however aligned structure may also be found in intrinsically weak sources (like Mark 270 and NGC 5548).

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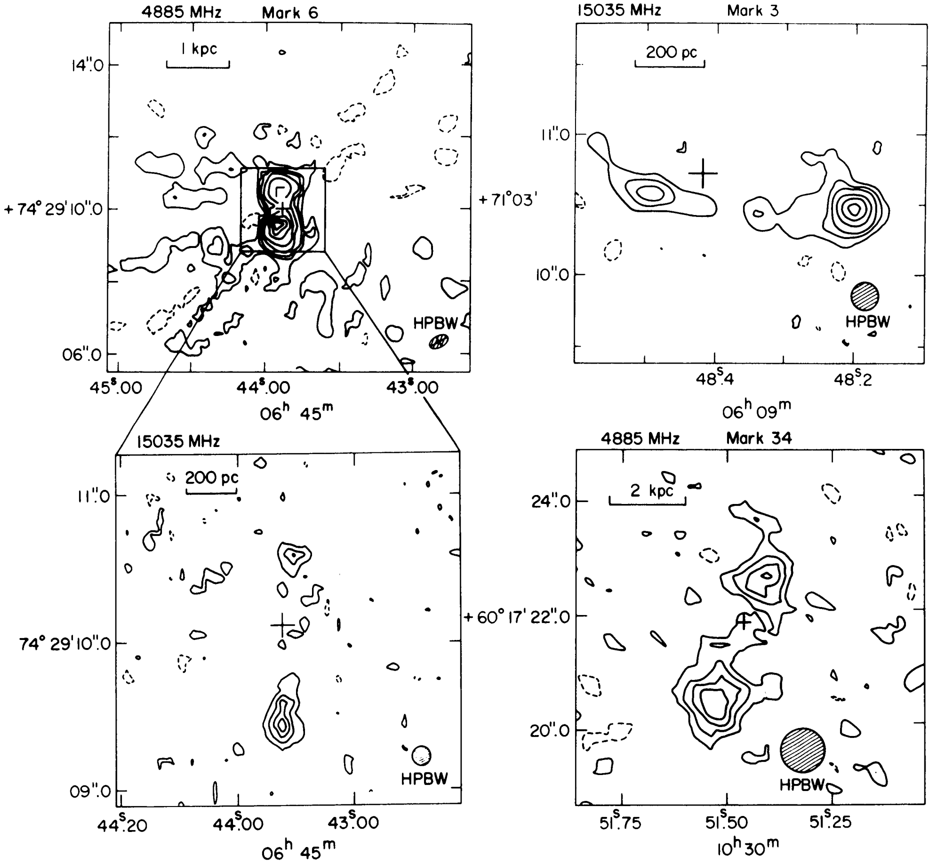

Figure 1. VLA maps of double radio sources in Markarian Seyfert galaxies. The cross marks the optical position (Clements 1981); the r.m.s. errors are typically ≃ 0″.1 and are represented by the arms of the cross (except in the top left diagram). Left hand panel: Markarian 6 at 4885 (top) and 15035 MHz (bottom). In the top left diagram, contours are at −2 (dotted),2,4,6,10,20,40,60,80% of the peak brightness of 24.1 mJy (beam area)$^{-1}$. In the bottom left diagram, contours are at −20,20,40,60,80% of the peak brightness of 5.2 mJy (beam area)$^{-1}$. Top right is Markarian 3 at 15035 MHz; contours are at −10,10,20,30,50,70, 90% of the peak brightness of 24.8 mJy (beam area)$^{-1}$. Bottom right is Markarian 34 at 4885 MHz; contours are at −20,20,40,60,80% of the peak brightness of 1.2 mJy (beam area^{-1}).

e. The radio sources in type 1 Seyferts may be physically smaller, on average,than those in type 2′s.

3. THE CLASSICAL SEYFERTS

The "classical" Seyferts are much closer than those found in Markarian′s lists and may be mapped in correspondingly more detail.

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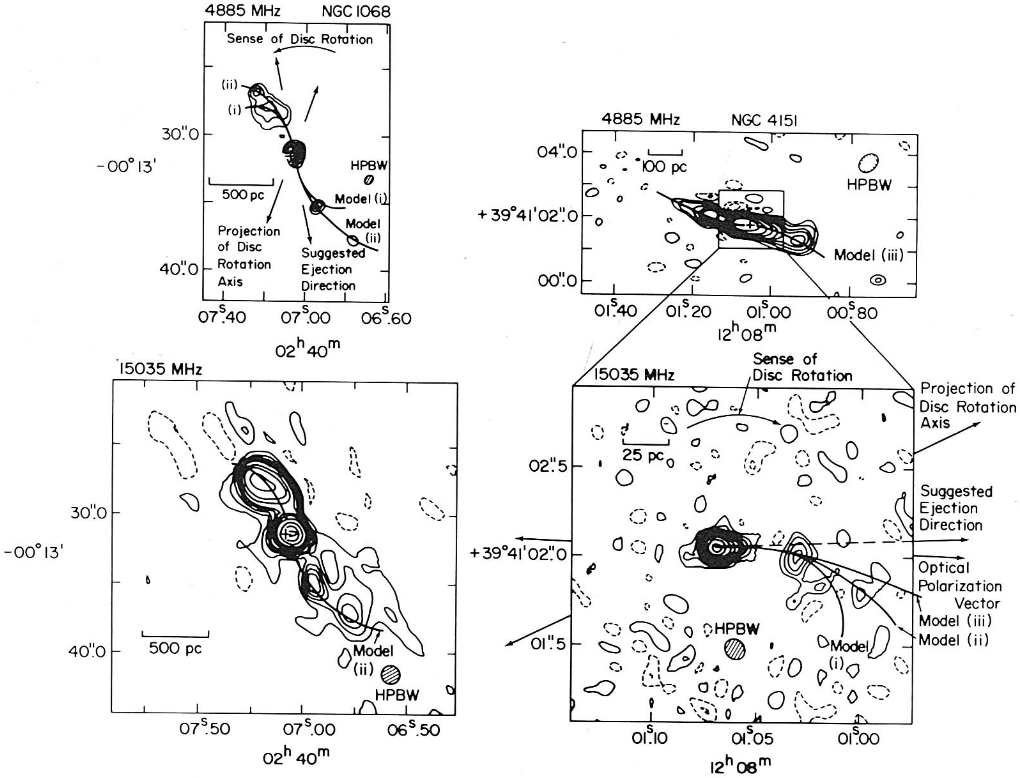

Figure 2. VLA maps of NGC 1068 and NGC 4151. The cross represents the optical nucleus in each case. The lines represent the "bent beam" models of Section 5.1. Left-hand panel is NGC 1068. Top left at 4885 MHz; contours at -2,2,4,6,10,15,20,25,30,35,40,45 times 6.83 mJy (beam area)$^{-1}$ (= 1000K). Bottom left at 15035 MHz; contours at -2,2,4,6,8,10,15,20,30,50,70,90% of the peak brightness of 161 mJy (beam area)$^{-1}$. Right hand panel is NGC 4151. Top right at 4885 MHz; contours at -5,5,10,15,20,30,40,50,60% of the peak brightness of 35 mJy (beam area)$^{-1}$. Bottom right at 15035 MHz; contours at -12,-6,6,12,18,24,30,40,50,70,90% of the peak brightness of 12.2 mJy (beam area)$^{-1}$.

Generally speaking, however, the structures of the two groups are quite similar. Both linear (L) and diffuse (D) class sources may be found and brief notes on individual cases follow.

NGC 1068. Early aperture synthesis maps by Crane (1977) and Wilson and Willis (1980) showed a triple source with angular size ≃ 13" (1.37 kpc). Maps with the completed VLA are shown in Fig. 2. Top left is a "snapshot" observations in the ´A´ configuration at 4885 MHz by Condon et al. (1981) while bottom left is the result of a longer integration in the ´C´ configuration at 15035 MHz (Wilson and Ulvestad, in preparation). Both maps show aligned structure in p.a. ≃ 33^{o}; at least four components

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may be recognised. The brightest component coincides with the optical continuum nucleus and is resolved at 4885 MHz, with size 0".7x0".3 in p.a. 28° (Condon et al. 1981). This direction is similar to that of the outer structure.

NGC 3227. A VLA observation at 4885 MHz by Ulvestad et al. (1981) shows an unresolved point source plus emission extending over 3-4" (290-390 pc).

NGC 4151. Fig. 2 gives two maps of this famous galaxy. Top right is from the incomplete VLA at 4885 MHz (Johnston et al. 1981) while bottom right is a VLA map of the central region at 15035 MHz (Wilson and Ulvestad, in preparation). A map at 1666 MHz has also been made by Booler et al. (1981) with the MTRLI (see talk by R.D. Davies in this volume). These maps show a highly elongated structure of length ≃ 3".5 (340 pc) in p.a. 77°-92°, with the optical continuum nucleus lying close to the brightest radio peak. Comparison of the 1666 and 15035 MHz maps shows that the brightest component has a flatter spectral index (α = 0.43, $S \propto \nu^{-\alpha}$) than the one 0".46 (44 pc) to the west (α = 0.90), supporting its association with the true nucleus. The brightest component is resolved at 15035 MHz with (deconvolved) size 0".11 (11 pc) in p.a. ≃ 272°.

NGC 5548. VLA maps reveal an unresolved component coincident with the optical continuum nucleus and two extended lobes straddling it (Wilson and Willis 1980; see also paper by Ulvestad et al. in this volume).

NGC 6764. This galaxy exhibits faint, diffuse asymmetric radio structure on a scale of ≃ 10" (2.6 kpc); see Wilson and Willis (1980) and Ulvestad et al. (1981).

NGC 7469. VLA maps of this object show an unresolved (<0".3 or <0.15 kpc in p.a. 62°) core coincident with the optical continuum nucleus, plus a halo of total extent ≃ 10" (4.9 kpc); see Ulvestad et al. (1981) and Condon et al. (1981).

4. ORIGIN OF THE RADIO EMISSION

The spectral indices of the total radio emission from Seyfert galaxies lie in the range $0.4 < \alpha < 1.1$, although a few have flat spectrum cores with $\alpha \simeq 0$ (e.g. de Bruyn and Wilson 1978). The radiation mechanism is, therefore, non-thermal and presumably synchrotron. The general lack of polarization in these sources at 1415 MHz (de Bruyn and Wilson 1976) may be ascribed to Faraday depolarization by the large quantities of thermal material responsible for the optical emission lines. Calculations of the thermal radio radiation expected on the basis of the optical emission line properties confirms it is negligible at 4885 MHz (Ulvestad et al. 1981).

"Starburst" models are clearly relevant to some non Seyfert spirals, especially those whose light is dominated by hot young stars and HII regions. However, I feel there are serious difficulties in application of this picture to Seyferts, such as the very high supernova rates needed (~ 10^2 yr^{-1} for NGC 1068, see Condon et al. 1981, Ulvestad 1981), the large fraction of linear sources, the general lack of evidence for large quantities of young stars and the need for photoionization by power law, rather than stellar, continua to account for the optical line spectra.

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On the other hand, a number of arguments favor nuclear ejection as the mode of generation of the linear sources.

1. The classical Seyferts with linear radio structure are viewed close to "face-on" (the angle between the plane of the disc and that of the sky is i = 39° for NGC 1068 (Burbidge et al. 1959), i = 21° for NGC 4151 (Simkin 1975) and i = 28°-45° for NGC 5548 (Simkin et al. 1980)). Furthermore the radio axis does not seem to correlate with the projected major axis of the optical disc (Section 4). These considerations rule out the suggestion by Condon et al. (1981) that the elongated radio structures in these galaxies are a consequence of a disc of radio emitting material coplanar with the stellar disc and viewed obliquely. Their suggestion probably is valid, however, for non-Seyfert spirals with strong radio sources. Although the precise orientations of the more distant Markarian Seyferts are often difficult to determine, the high fraction of these galaxies containing linear, often double or triple sources (Section 2), again indicates that the structures are truly aligned and are not caused by projection effects.
2. The radio components in double sources are commonly elongated along the radio axis (e.g. Mark 3, 6, 270).
3. The radio structure of NGC 4151 (Fig. 2) is strongly suggestive of quasi-continuous nuclear ejection (Ulvestad et al. 1981), probably in the form of a jet (Johnston et al. 1981; Booler et al. 1981).
4. The direction of elongation of the radio source in NGC 4151 (p.a ≃ 272° in the center) is close to the polarization vector of the optical continuum (p.a. ≃ 268°, Schmidt and Miller 1980). If this agreement is not coincidental, a connection between an inner (light months, the timescale of the optical variability) nuclear axis and the much larger scale (380 pc) shape of the radio source is implied. Furthermore, this alignment is similar to that found for radio-loud, double lobed quasars (Stockman et al. 1979).
5. There may be a continuity, both in radio luminosity and in the correlation between radio luminosity and forbidden line width (Wilson and Willis 1980; Heckman et al. 1981) between Seyfert galaxies and the kpc size cores of radio galaxies (e.g. 3C 236, 3C 293, 3C 305).
6. The "ridge-lines" of the radio sources in NGC 1068 and NGC 4151 describe a curve which "leads" the rotation of the galaxy. As will be argued in Section 5, this shape is readily accounted for by the bending of a supersonic jet under the ram pressure of the rotating interstellar gas disc. On the other hand, models of propagating star formation would be expected to yield "trailing" ´S´ shapes.

Some simple consequences of the nuclear ejection model bear mentioning.

a. Because double radio sources are not, in general, found outside the optical isophotes of Seyfert galaxies (de Bruyn and Wilson 1976), the beam or plasmoids must not escape the nuclear environment (~ kpc scale). The most natural means of achieving this is to "disrupt" the beam or "halt" the plasmoids by friction with the dense interstellar medium in the inner part of the spiral (Wilson and Willis 1980). This interaction is further discussed in Section 5.

b. A large fraction of Seyferts appear to form aligned radio sources and

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Seyferts comprise ≈ 1-2% of all galaxies (Woltjer 1959). Thus the ability to eject radio components seems to be present in at least ≈ 1% of all galaxies.

c. Spiral galaxies as well as ellipticals and lenticulars can form linear radio sources. It should be borne in mind that, of the sources with unambiguous linear structure, only NGC 1068 (Rev. Morph. type (R)SA(rs)a) and NGC 4151 ((R′)SAB(rs)b) show, without doubt, spiral arms, although NGC 5548 ((R′)SA(r)0/a) and Mark 34 may do. Mark 79, which is probably a linear source, shows clear spiral arms.

d. The evidence for activity on an ultracompact scale in type 2 Seyferts is less convincing than for type 1 Seyferts and radio galaxies. The existence of double radio sources in such galaxies suggests (but does not imply) that they too are fuelled from a compact object.

e. A comparison of the radio axis in linear sources with the minor axis of the outer optical isophotes (which will represent the projected rotation axis in simple disc systems) shows no apparent relation. This result suggests that if the radio sources are ejected perpendicular to the plane of an accretion disc, this disc is misaligned with the outer stellar disc by a large angle (Ulvestad et al. 1981). Some caution must be exercised in applying this result since the beam, which is presumed to power the radio source, may be bent by pressure gradients or ram pressure in the interstellar gas, so that the observed radio axis may differ from the true direction of ejection.

5. THE INTERACTION OF THE BEAM WITH THE INTERSTELLAR MEDIUM OF THE GALAXY

5.1 The Shapes of the Radio Sources

Examination of direct photographs of NGC 1068 (NGC 4151) indicates that the galaxy rotates in a counter-clockwise (clockwise) sense, if the spiral arms are trailing. Figure 2 shows that the "ridge line" of the SW side of the radio source in NGC 1068 curves towards the west with increasing distance from the optical nucleus. For NGC 4151, the initial direction of ejection is P.A. ≃ 272° (as judged from the elongation of the central source) which changes to P.A. ≃ 257° at ≃ 2" from the nucleus. These bendings are in the sense expected if they are consequence of the ram pressure of the rotating gas in the discs of the galaxies, as noted independently for NGC 4151 by Booler et al. (1981). The sharp boundary of the radio emission on the SE side of the SW ridge in NGC 1068 and the diffuse boundary on the opposite (NW) side support this interpretation. In order to explore this possibility quantitatively, I have developed a simple model to describe the jet shape, making assumptions similar to those of Begelman et al. (1979) in their model of head-tail radio galaxies. The flow along the jet is assumed to be mass conserving, adiabatic and of constant speed (v_j). Presuming the rotation velocity of the interstellar gas to be supersonic, there will be a cylindrical stand-off bow shock associated with the jet. By equating the acceleration of jet material, $g = v_j^2/R_j$ (where R_j is the instantaneous radius of curvature of the jet) to the ram pressure per unit length per unit mass of material, $-p/\rho_j h$ (where p is the pressure, ρ_j the jet density and h its scale height), a second order

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differential equation is obtained for the jet shape. This equation is then integrated numerically to derive the trajectory in x,y coordinates. The situation differs from the head-tail case in that the interstellar gas is taken to perform purely rotational motion, with velocity as a function of distance from the center (r) appropriate to a typical spiral galaxy rotation curve. An assumption about the variation of interstellar gas density with r must also be incorporated. At present, only ejection in the plane of the galaxy has been considered and gravitational forces on the jet are neglected.

Some illustrative results are given as the solid lines in Figure 2. Neither NGC 1068 nor NGC 4151 can be fitted by a rotation curve which is solid-body over the whole jet region with a constant interstellar density (model i). The reason is that if the parameters are chosen to fit the inner parts of the source, the rapid rise in interstellar ram pressure with r causes more rapid bending than is observed in the outer parts. The problem may be alleviated by flattening the rotation curve and/or allowing the interstellar density to decrease with r. Model (ii) has an initial solid body portion plus a flat part for the rotation curve, along with constant interstellar density; it provides a good fit to NGC 1068. Model (iii) incorporates the same rotation curve as (ii) but the density drops as r^{-2} beyond the turnover. Even these assumptions do not provide a particularly good fit for NGC 4151, in which the jet seems to bend rapidly in the inner 1" and thereafter moves almost straight. Possibly the ejection in this galaxy is at an angle to the plane; such would render a rapid density fall off more plausible.

Models of this type can be checked by finding more objects with curved radio structure in spirals. As long as the ejection is close to the plane of the galaxy, the ´S´ shape defined by the radio emission should curve in the <u>opposite</u> sense to that defined by the normal spiral arms. In this picture, the shape of the radio source represents a steady-state situation in which a constant velocity, continuous beam is bent by ram pressure. It may be contrasted with the related picture advanced by van der Kruit et al. (1972, see also talk by J. H. Oort in these proceedings) for NGC 4258 in which the ejection is essentially instantaneous but covers a wide range of velocity. In this case, the "radio arms" show the current position of the ejected material after deflection by gravitational and ram pressure forces; they curve in the <u>same</u> sense as the normal spiral arms.

5.2 Acceleration of Interstellar Clouds

There are a number of correlations between the radio and forbidden optical emission line properties of Seyfert galaxies. These relations include a similarity in overall spatial scale and possibly shape (de Bruyn and Wilson 1978; Ulvestad et al. 1981) and correlations between radio continuum and forbidden line powers and between radio continuum power and forbidden line width (de Bruyn and Wilson 1978; Wilson and Willis 1980; Heckman et al. 1981). Although the precise relation between the beam which fuels the radio emission and the thermal gas in its vicinity is probably very complicated, I shall briefly discuss one

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aspect, namely the possibility that the high velocity thermal gas (broadened forbidden lines) represent interstellar clouds "blown outwards" by the beam.

The equation of motion of an interstellar cloud (mass M_c, velocity V_c, scale height h) immersed in a particle beam (density n_b, velocity V_b) is:

$$M_c dV_c/dt = C_F n_b m (V_b - V_c)^2 h^2 \qquad (1)$$

where C_F is a constant and m is the mean mass per particle in the cloud (Blandford and Königl 1979). For h = constant, the time for the cloud to be accelerated to $V_c (<< V_b)$ is

$$t_{acc} = M_c V_c V_b / 2 C_F L_b$$

or

$$t_{acc} = 2x10^5 \; (M_c/10^6 M_\odot) \; (V_c/500 \text{ km s}^{-1}) \qquad (2)$$

$$x \; (V_b/10^4 \text{ km s}^{-1}) \; (C_F/8.11)^{-1} \; (L_b/10^{42} \text{ erg s}^{-1})^{-1} \text{ years}$$

where $L_b = n_b m h^2 V_b^3/2$ and represents approximately the total power of the beam incident on the cloud. Interstellar clouds are presumably carried into the beam by the general galactic rotation, are accelerated radially outwards while in it and leave it with both a rotational and radial component of velocity.

A stand-off bow shock is formed in the beam on the upstream side of the cloud, where roughly half of the bulk kinetic energy incident on the cloud is converted into internal energy. In models of this type, the radio radiation represents a fraction C_L of this dissipated power:

$$L_{rad} \simeq C_L C_F \; \{(V_b - V_c)/V_b\}^3 \; L_b \qquad \text{or} \qquad (3)$$

$$L_{rad} \simeq 10^{40} (C_L/10^{-2})(C_F/8.11)\{2(V_b - V_c)/V_b\}^3 (L_b/10^{42} \text{ erg s}^{-1}) \text{ erg s}^{-1}$$

Thus, for a beam luminosity of $L_b \simeq 10^{42}$ erg s^{-1}, an efficiency factor $C_L \simeq 10^{-2}$ would yield $\simeq 10^{40}$ erg s^{-1} of radio emission, a typical value for a Seyfert galaxy.

There are a number of advantages in this type of model:

a. It accounts for the similarities in the spatial distribution of radio emission and thermal clouds since radio emission can only be generated when the beam impinges on a cloud.

b. With the parameters indicated by equations (2) and (3), it is possible for the observationally derived cloud masses ($\sim 10^6 M_\odot$) to be accelerated to the observed velocities in reasonable time scales (10^5-10^6 years).

c. Models of this kind lead naturally to a relation between L_{rad} and V_c since higher cloud velocities will be associated with faster or more luminous beams, which also generate more radio emission. The exact exponent in the L_{rad} vs V_c relation is model dependent but behavior close to the observed relation $L_{rad} \propto V_c^{3.5-4.5}$ is not unreasonable (Wilson 1981).

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DISCUSSION

HENRIKSEN: Should the Seyfert jets be directed out of the plane of the disc, pressure gradient effects should be at least as important as the rotation ram.

WILSON: The present model for the shapes of the radio sources assumes that the ejection is in the plane of the galaxy. Under these circumstances only ram pressure need be included.

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