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Radio Galaxies and their Environment

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“What you see is what you get”

Wild Bill Hickock

1 Introduction

The relationships between radio galaxies and their environment are varied, complex, and evolve with cosmic epoch. Basic questions are what role the environment plays in triggering and fuelling (radio) galaxy activity, what the effects of this activity are on its environment, and how radio galaxies and environment evolve. Clearly, this could be the topic of a workshop all in itself and the scope of this review will necessarily be limited. A review of the connections between environment and galaxy activity in general has been given by Heckman (1990).

First, I will briefly summarize the relationships between parent galaxy and cluster environments, and radio galaxies. A more detailed discussion of various aspects of this will be given elsewhere by F. Owen, J.O. Burns and R. Perley. I will then discuss the current status of investigations of extended emission-line regions in radio galaxies, again referring elsewhere in this volume for more detailed discussions of some particular aspects (kinematics and ionization mechanisms by K. Meisenheimer; polarization and spectral index lobe asymmetries by G. Pooley). I will conclude with a brief discussion of the current status of observations of high redshift radio galaxies.

2 Parent Galaxies, Neighbourhoods and Cluster Environments

Optical observations have shown that a large fraction (30% to 50%) of nearby ($z < 0.5$), *powerful* ($P_{1400,\text{rest}} > 10^{33} \text{ ergs Hz}^{-1} \text{ s}^{-1}$)²² FR-II type radio galaxies exhibit peculiar optical features (tails, fans; Heckman *et al.* 1986; Hutchings 1987) and unusually blue, extra-nuclear colors (Smith and Heckman 1989). While their $r^{-1/4}$ surface brightness profiles still classify them as ellipticals, the morphological distortions strongly suggest

²² $H_0 = 50$, $q_0 = 0.0$

that they are interacting or merging with nearby gas rich companions (see Toomre and Toomre 1972). Support for this also comes from stellar dynamics studies which show that powerful radio galaxies which are morphologically peculiar exhibit more stellar rotation than other radio galaxies and normal ellipticals, presumably because of recent merging with a disk galaxy (Smith *et al.* 1990).

On the other hand, low power ($P_{1400, \text{rest}} < 10^{33} \text{ ergs Hz}^{-1} \text{ s}^{-1}$), FRI type radio galaxies appear associated with relatively normal elliptical galaxies, albeit generally of the D or cD type (*e.g.* Owen and Laing 1989). In addition to this morphological difference between the parent galaxies of low and high power radio sources, investigations reported at this workshop by F. Owen further suggest that the radio FRI / FRII type break may be a function of optical luminosity as well.

Several studies have been made of the galaxian/cluster environments of radio galaxies (*e.g.* Heckman, Carthy and Bothun 1985; Yates, Miller and Peacock 1989; Smith and Heckman 1990; Hill and Lilly 1991). These studies have shown that, at low redshifts, powerful FRII type radiogalaxies inhabit relatively sparsely populated regions with average galaxy densities a factor 2-3 lower than those of low power FRI type radio galaxies. At larger redshifts ($z \gtrsim 0.5$), the cluster environments of FRII type radio galaxies appear to be richer, while no change in environment has been found for FRI types (Hill and Lilly 1991). This suggests that FRII activity may somehow be related to the evolution of its cluster environment (intergalactic medium, galaxy richness, or both). Incidentally, the cluster environments of powerful radio galaxies and quasars are very similar (Smith and Heckman 1990; Hill and Lilly 1991), suggesting that these types of objects are also closely related.

While much about the detailed interpretation of these results remains unclear, the difference in parent galaxy types, environments, and stellar kinematics suggests that the two classes of radio sources do not simply evolve into one another, at least not on typical FRII timescales which may be at most a few times 10^7 years (Leahy 1991). The evidence strongly suggests that the interaction and merging of elliptical galaxies with gas rich companions plays an important role in triggering or fuelling powerful, FRII type radio source activity. The resulting decrease in galaxy density surrounding the radio galaxies would be consistent with the observed decrease in cluster richness with redshift. The importance of galaxy interactions in connection with galaxy activity and central star formation is being recognized in a variety of galaxy types, including star burst galaxies, Seyferts and quasars, as well as radio galaxies (see Heckman 1990). The processes of galaxy activity and star formation may occur simultaneously, or may even be causally connected, when dense gas rapidly accumulates in the central regions of the interacting galaxies (Norman and Scoville 1988; Hernquist 1989; Shlosman, Begelman and Frank 1990).

The lower radio luminosities of the less disturbed parent galaxies of FRI type radio sources suggest a different origin and evolution of their activity. In these cases the "gas-supply" to their galaxy nuclei may be due to infall from their halos or clusters (cooling flows), and is presumably more sedate, continuous and of a lower level than is provided by the rapid merging processes thought to occur in FRIIs.

3 Interaction of Radio Galaxies with Their Environment

3.1 Extended Emission-Line Regions

Extended emission-line regions (EELRs) in radio and other active galaxies are being

Fig. 1. These histograms show the increasingly better alignment of EELR (left panels) and optical continuum emission (right panels) as function of redshift/radio power in the 3CR sample studied by McCarthy (1989).

studied by many groups. Important new developments since the last Ringberg workshop in 1988 are the realization that emission-line “cones” may be ubiquitous in active galax-

ies (Seyferts and radio galaxies), and the extremely good correlation between EELR and radio lobe asymmetries. I briefly summarize the current status and refer for a more detailed discussion of many relevant aspects to my previous review (van Breugel 1988), and to the proceedings of the ESO workshop on "Extranuclear Activity in Galaxies" (1989).

3.1.1 Occurrence

Narrow-band surveys of representative samples of nearby and distant radio galaxies show that a large fraction ($\sim 70\%$) have extended optical emission line regions (*e.g.* Baum and Heckman 1989*a, b*; McCarthy, Spinrad and van Breugel 1992).

3.1.2 Alignments

In relatively powerful radio galaxies the EELRs are usually within $\sim 20^\circ$ of the radio axes, in most cases between the galaxy nucleus and radio hotspots (Baum, Heckman and van Breugel 1990; McCarthy, Spinrad and van Breugel 1992) but sometimes extending beyond radio hot spots (van Breugel 1988). The alignment between the EELRs and radio sources becomes better for high redshift / more powerful objects (McCarthy 1989; Fig. 1).

3.1.3 Luminosities

The EELR and radio luminosities are surprisingly well correlated (Baum and Heckman 1989*a, b*; McCarthy 1989; McCarthy *et al.* 1991) This, together with 3.1.2., strongly suggests that the EELRs and radio lobes have a common source of energy (presumably the nucleus).

3.1.4 Asymmetries

EELR and radio lobe asymmetries are strongly correlated: the strongest line emission is always found on the side where the lobe is closest to the nucleus (McCarthy, van Breugel and Kapahi 1991; Fig. 2). It suggests that the gaseous environments of radio galaxies are asymmetric, and that the radio lobes are slowed down most on the side of the densest gas. As a corollary, this means that radio lobe distance asymmetries cannot be used to constrain lobe advance speeds and radio source ages. I am referring to the contribution by G. Pooley at this workshop for the discussion of observed asymmetries in radio lobe polarizations and spectral indices.

3.1.5 Kinematics

The kinematics of EELRs in nearby radio galaxies appears to be dominated by gravitational forces, including rotation of gaseous disks acquired through merging with gas-rich companions or accretion from halos or cooling flows (*e.g.* Baum *et al.* 1991; Tadhunter 1991). However, radio jets/lobes can significantly affect the kinematics of emission-line gas at locations where they interact with ambient gas. Recent examples are Cygnus A and 3C 265, with EELR velocities of as much as 1800 km s^{-1} (Tadhunter 1991). Other

Fig. 2. An example of the correlation between EELR and radio lobe asymmetries (McCarthy, van Breugel and Kapahi 1991): shown are a 6 cm, 1'' resolution VLA map of 3C 280, $z = 0.99$ (top), and a continuum subtracted narrowband [OII] $\lambda 3727$ image (bottom). Note that EELR is on the side with the lobe nearest to the nucleus (lobe distance ratio 1/1.27).

examples are 3C 277.3, 4C 29.30 and 3C 321, and it is worth repeating (see van Breugel 1988) that the velocities of emission-line gas seem to be nearly always blue-shifted on the side of the brightest jets. This might mean that these jets are Doppler boosted and pointed towards us. The question remains, however: where are the redshifted EELRs near radio knots of unseen (counter-) jets, which in such models should also exist and be pointed away from us? It is clearly of interest to continue studies of the kinematics of EELRs associated with radio jets. The emission-line kinematics near hotspots may also be interpreted in terms of gas entrainment by lobes propagating through dense gas (*e.g.*

van Breugel *et al.* 1985a [3C 277.3]; Wilson and Ulvestad 1987 [NGC 1068]; Pedlar *et al.* 1989 [Seyfert's]). A nice and detailed interpretation of the kinematics of emission-line gas entrained by the radio lobes of 3C 368 has been presented by K. Meisenheimer (this workshop).

3.1.6 Ionization

Quite generally, the emission-line ratios of EELRs, both in nearby and distant radio galaxies, can be adequately modelled with simple photoionization models in which the radio galaxy nuclei are also sources of ionizing (UV, X-ray) radiation directed or collimated in cone-like fashion along the same axes as their bulk outflow (jets, winds). I consider it beyond the scope of this review to give a complete discussion of the pros and cons of this "standard interpretation" except to mention that 1) the low ionization EELRs and their associated (?) low power radio sources in cooling flow clusters may well require a different dominant source of ionization see (Heckman *et al.* 1986), 2) close scrutiny of emission line ratios reveals some inconsistencies which require either more sophisticated AGN photoionization models, or leave room for alternative explanations (i.e. shock ionization) in specific cases. Two such cases are discussed in detail by K. Meisenheimer (3C 368) at this workshop.

3.2 Extended Optical Continuum

There is increasing evidence that the presence of very blue optical continuum emission associated with radio galaxies may be a relatively common phenomenon. The origin of this continuum may be young stars, scattered light or synchrotron emission, all of which are related to different aspects of the interaction of a radio source with its environment.

This is perhaps most dramatically illustrated by the discoveries that distant radio galaxies exhibit blue optical continuum which is nearly always aligned with the axes of their associated radio sources (McCarthy *et al.* 1987; Chambers *et al.* 1987; McCarthy *et al.* 1990, 1991). While it is likely that most of this optical emission is probably due to young stars (see for example Chambers and McCarthy 1990), optical polarization observations have shown that at least some of the UV excess may be due to scattered light from the nucleus (Scarrott *et al.* 1990; Januzzi and Elston 1991). Furthermore, as emphasized by Meisenheimer at this workshop, objects with very bright EELRs such as 3C 368 may significantly "contaminate" broadband images if strong emission-lines such as [OII] λ 3727 fall in the filter band pass. This is really only an issue for objects in the redshift range 0.6 – 1.1 (for example with the Lick/"Spinrad" R_s filter covering 6000 – 7700 Å), and even in this redshift range emission-line free "intermediate broadband" images have confirmed the basic alignment effect (Rigler *et al.* 1992).

Also, in several *nearby* radio galaxies blue continuum emission has been found. There are the wellknown cases of optical synchrotron knots associated with radio jets (M87, 3C 66B, 3C 277.3, PKS 0521–36 etc.) and lobes (3C 33, Pictor A and others; see elsewhere in these proceedings and those of the first Ringberg workshop). Young stars and scattered continuum are not as commonly found, although some spectacular examples are known (Minkowski's Object, van Breugel *et al.* 1985b; PKS 2152–69, di Serego Alighieri *et al.* 1988).

Fig. 3. Radio and optical images of 3C 285 showing the location of a star forming region behind the eastern hot spot. Fig. 3a shows a smoothed $2''.1$ resolution 21 cm image of 3C 285. Fig. 3b shows a narrow-band image centered at the H α emission-line (Baum *et al.* 1990; continuum not subtracted). Note the small, slightly extended EELR at $\sim 45''$ east of the parent galaxy. Lick spectra have shown that this EELR is an HII region at the redshift of 3C 285. Its location relative to the radio hot spot is shown in Fig. 3c (see arrow).

Motivated by the rather general presence of UV continuum associated with distant radio galaxies, and by evidence that similar effects — on a more modest scale — also seem to occur in nearby, less powerful radio galaxies, A. Dey (UC Berkeley) and I are conducting a systematic optical U- and R-band survey of a well defined sample of relatively nearby radio galaxies selected from the 3CR and PKS catalogs. All objects

are constrained to have redshifts between 0.085 – 0.200 so that no bright emission-lines fall in the U- ([OII] λ 3727) and R- ([OIII] λ 5007) passbands (when convolved with the detector/telescope/atmosphere throughput).

Our first results have been very encouraging and suggest that in as many as 30% of the objects extra-nuclear UV continuum knots exist which may in some way be associated with their radio sources. One example is 3C 285 (Fig. 3), which was already known to have a very blue compact object along its radio axis (Saslaw, Tyson and Crane 1978), at some 60 kpc from the nucleus. Although noted by the authors it was not the main focus of their attention, which was aimed at the eastern “hot spot” of 3C 285. Narrow-band imaging observations by Baum *et al.* 1990 of the 3C 285 field showed, by chance, that this compact, blue object also exhibits extended optical line emission, with the brightest line and continuum emission facing the nucleus. Our spectroscopic observations at Lick have subsequently shown that it is an H-II region at the redshift of 3C 285. Thus, in many ways this object resembles Minkowski’s Object, suggesting that the expanding radio lobes may have induced star formation in dense gas along the radio axis (possibly a cloud of cold gas or gas associated with a small, gas-rich galaxy which happened to be in the path).

Of course, unlike in Minkowski’s Object and also NGC 7385 (Hardee, Owen and Eilek 1980), in 3C 285 there is no direct morphological association between the star forming region and a relatively bright radio component (jet or hot spot). This is perhaps not too surprising though since 3C 285 is a nearly 100 times more powerful, FR II type radio source. Presumably its jet and hot spot propagation speeds are much larger than those of lower power, FR I type sources and any star forming regions triggered by its passage will correspondingly lag further behind. In fact, by studying the spectral energy distribution (SED) of this object one can in principle determine the age of its star burst using stellar population synthesis techniques (see for example Chambers and Charlot 1990). This in combination with the known (projected) distance behind the hot spot (43 kpc) yields a new way of estimating the lobe advance speed, independent of the usual methods based on spectral ageing or ram pressure arguments (*e.g.* Leahy 1991).

We are currently still lacking sufficient data for a detailed SED analysis, but it is probably safe to assume that the age of the starburst is somewhere between 10^7 and 10^8 years. Assuming, for example, an age of 5×10^7 years, we derive a hot spot advance speed of 900 km/s. Allowing for projection effects, which may lead to underestimate this velocity by a factor of 2 to 3, and an uncertainty of a factor of 3 or so in the starburst age, which may go either way, I would conclude at this point that the hot spot speed is probably more than 1000 km/s, but probably less than 10,000 km/s. The upper estimate is consistent with the expansion speed derived for 3C 285 from spectral ageing arguments (8400 km/s; Alexander and Leahy 1987). Studies of H-II regions behind radio hot spots in nearby FR II sources may thus provide unique new constraints for radio galaxy models.

Fig. 4. Two examples of high redshift radio galaxies with very compact parent galaxies (left hand panels; MRC 0030-219 and 0152-209 with $z = 2.168$ and $z = 1.890$ respectively) and equally compact steep spectrum radio sources (right hand panels; from McCarthy *et al.* 1990, 1991).

4 Quasi-Stellar Distant Radio Galaxies

While high redshift ($z > 1$) radio galaxies generally have multi-modal, elongated morphologies more or less directed along their radio axes, it has also become clear from ongoing searches for distant radio galaxies that some of them can be rather compact or even stellar in good seeing images. Two such examples are the Molonglo sources MRC 0152-209 (McCarthy *et al.* 1991) and MRC 0030-219 (McCarthy *et al.* 1990; Fig. 4). Interestingly, in both cases the associated radio sources are also very compact ($0''.6$ and $< 0''.3$ respectively). Their optical spectra show relatively narrow Ly- α , indicating that these objects are galaxies, not quasars.

Another example is MRC 0349-211 ($z = 2.310$; McCarthy *et al.* 1991). In this case, the galaxy is relatively compact but the radio source is fairly large ($7''.4$; 94 kpc), and has a relatively strong core. There is also evidence that the CIV 1549 line is fairly broad. Together these observations suggest that MRC 0349-211 might be an example of a high redshift "broad-line radio galaxy" (this class includes nearby sources such as 3C 390.3 and 3C 445, and their parent "N-type" galaxies usually have strong nuclear continua). I would conclude from these ongoing investigations that there is increasing evidence that distant radio galaxies may exhibit a wide variety of properties and it will be interesting to compare these with those of quasars at similar redshifts to investigate a possible connection, evolutionary or otherwise (*e.g.* Heckman *et al.* 1991; Neff and Hutchings 1990; Barthel 1989).

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