

## Part 4

# Extragalactic Radio Sources

## **Extended Extragalactic Radio Emission**

F.N. Owen

*NRAO, P.O. Box O, Socorro, NM 87801 USA*

M.J. Ledlow

*University of New Mexico, Albuquerque NM USA*

J.A. Eilek

*New Mexico Tech, Socorro, NM 87801 USA*

N.E. Kassim

*NRL, Washington, DC USA*

N. Miller

*NRAO, P. O. Box O, Socorro, NM 87801 USA*

K.S. Dwarakanath

*Raman Institute, Bangalore, India*

R.J. Ivison

*University College London, Gower Street, London WC1E 6BT UK*

**Abstract.** Extended radio emission and its relation to parent galaxy properties is briefly reviewed. Our current understanding of the relation between absolute radio and optical luminosity, radio morphology and linear size is discussed. The impact of radio jets on dense cluster cores is discussed using M87 as an example. Finally, the relation of AGN's to star-bursting galaxies at high redshift is considered.

### **1. Introduction**

Extended emission from radio galaxies is much too big a subject to cover in a short talk or meeting proceedings. In this contribution I will attempt to summarize some recent developments on the properties of radio galaxies as a function of their environment and their impact on that environment.

## 2. Evolution of Extended Radio Emission

One important goal of the study of extragalactic radio sources is to understand the life history of this phenomenon as a function of time in the same way as we currently understand stellar evolution. It seems likely that the evolutionary tracks of these sources depend on several variables, including local environment and parent galaxy properties. We can now begin to study these variables by looking at fairly large samples of radio galaxies and studying the dependence of the radio properties on the optical and X-ray data we can assemble for them.

Given that most radio sources with luminosities with  $L_{20\text{cm}} > 10^{23} \text{ W Hz}^{-1}$  ( $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) are believed to be formed by interactions between the jets and the external medium, one would think that there would be differences in radio properties in and out of cataloged rich clusters. However, studies of the statistical properties of these two classes of sources has revealed little difference (Fanti 1984; Ledlow & Owen 1996).

The lack of correlation of radio galaxy properties with rich clusters is confusing. We can really only make this statement about FR I's right now since the samples studied have been dominated by this class. While it appears that clusters and their environments are not important, another explanation is that the clusters are actually there but we are missing them. Abell's sample of clusters, still the dominant source list for these systems, is not based on a physical cutoff in properties between "clusters" and the field but on the contrast between these concentrations and the random galaxies along the line-of-sight considered. The probability of a galaxy being a radio source does not depend on richness (Ledlow & Owen 1995). We find numerous radio galaxies down into Abell's richness class 0. Thus it might be reasonable to expect the cluster population to continue down into lower richness systems.

Recent X-ray and optical studies support this picture. Miller *et al* (1999) and Hardcastle & Worrall (1999) find evidence for both significant optical clustering for the Palomar DSS and diffuse X-ray atmospheres surrounding most of the nearby FR I's studied with the short RASS exposures. Worrall (2000) also finds a similar result using deeper, pointed ROSAT imaging. These results are consistent with almost all FR I's being found in some sort of clustering with an external hot atmosphere to confine the sources. However, lower richness and size make the clusters harder to detect.

On the other hand, the shape of the radio luminosity function seems to depend on galaxy absolute magnitude. The FR I/II radio morphology also seems to depend on absolute magnitude in roughly the same way. That is, for each absolute magnitude, the radio morphology type changes at about the same radio luminosity as the break occurs in the radio luminosity function. This break is a strong function of optical absolute magnitude. In figure 1 we show this relation for a recently completed sample of radio galaxies taken from the Wall & Peacock (1985) 2 Jy sample, the Abell cluster sample and the Bologna radio galaxy sample. The line shows the location of the break in properties as a function of absolute radio and optical luminosity. Please refer to Ledlow *et al* (2000a,b) for details.

The correlation with optical galaxy properties may partly be a result of the correlation of optical galaxy luminosity (and thus presumably mass) with degree of clustering. More massive galaxies tend to live in deeper, bigger potential wells

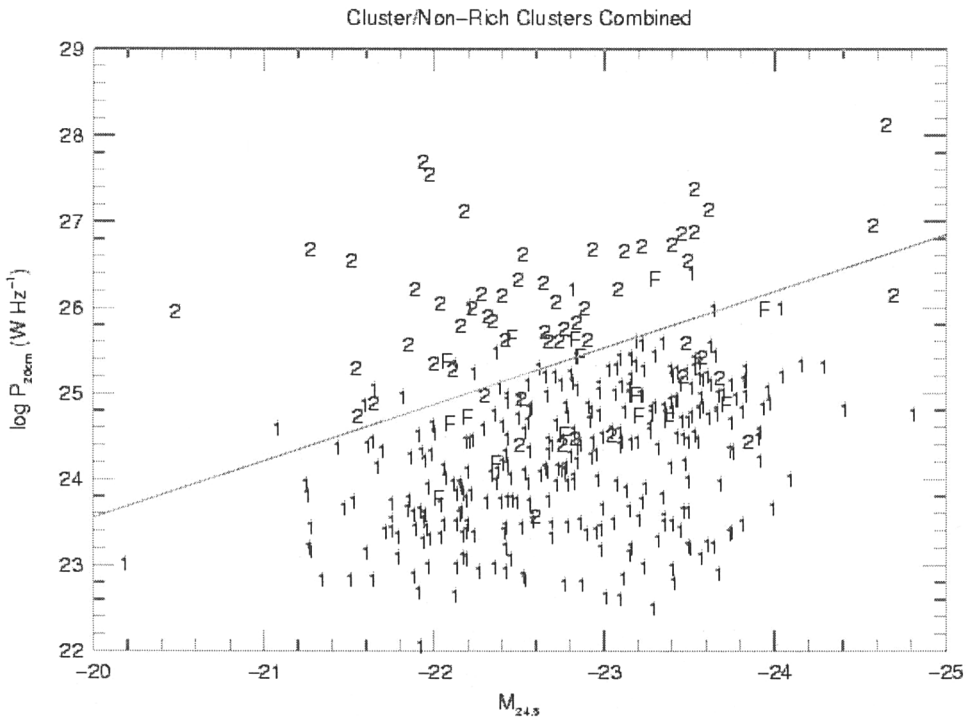


Figure 1. Correlation between Radio Luminosity, Optical Absolute Magnitude and Fanaroff-Riley class. 1's are FR I's, 2's are FR II's and F's are fat doubles. See Owen & Laing (1989) and Ledlow et al (2000a,b) for details.

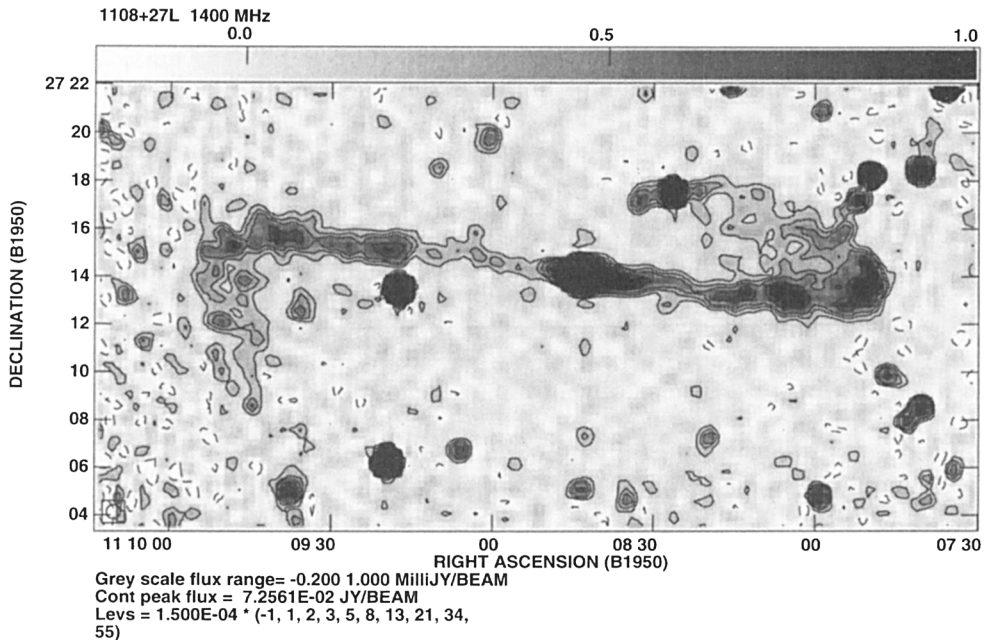


Figure 2. VLA image 1108+27 at 20cm with 2 hour integration

and the properties of the associated radio sources may depend primarily on this correlation. Investigators need to be careful that correlations of properties of radio galaxies with redshift, including the degree of clustering, are not a result of selecting objects from different parts of figure 1 as a function of redshift.

Our understanding of radio size as a function of radio power also gives us a hint about radio source evolution. (de Ruiter et al 1990, Ledlow et al 2000a,b). There appears to be slow rise in the maximum linear sizes as a function of radio power. However, for FR I's one worries that the picture may not be complete. In figure 2, we show a new VLA image of B2 1108+27. Previous observations of this source ( $z = 0.0331$ ) suggested a small FR I,  $\sim 1$  arcmin in size (Fanti et al 1987). However, the NVSS image of this source suggested to us that there might be a larger extension, although the ability to see this was at or below the believable detection limit of the NVSS. The image with two hours integration with the VLA D-array reveals the 30 arcmin scale, 1 Mpc structure of this source.

The radio size versus optical and radio properties may be more complicated and incomplete than the other relations. The large sizes for many FR II's, and now FR I's, suggest very much larger diffuse gaseous atmospheres than are usually detected by existing X-ray observations. The present size diagrams, limited by surface brightness sensitivity, may be part of the picture and may indicate that characteristic scales for the surrounding medium. But figure 2 may suggest that this is not the complete picture and that we have much more to learn about the evolution of individual radio galaxies and their lifetimes.

### 3. Radio Galaxy Effects on the External Medium: M87

Many non-radio astronomers have often calculated the absolute radio luminosity for a galaxy and then discounted its importance given the usually much larger radiated luminosity in other bands. However, most theoretical models of radio jets suggest we are only seeing a small portion of the energy being pumped out of the galaxy nucleus into the surrounding medium. This energy input into the intracluster medium must be important to the total energy budget of these systems. An example of this can be seen in the recent VLA images of M87 at 90cm.

In figure 3, we show the new 90cm VLA image (Owen, Eilek & Kasim 2000) of the full M87 system at 6 arcsec resolution and 50,000:1 dynamic range. Note the large scale,  $\sim 15$  arcmin. Most radio images to date have concentrated on the inner, much higher surface brightness part of the source which contains the 20 arcsec long optical jet. The relationship of the inner structure to the large-scale image shown here can be studied on the web site (<http://www.aoc.nrao.edu/~fowen/M87.html>). The new observations suggest that the flow seen in the inner part of the source extends to much larger scales. The jet seems to be depositing its energy on this scale and blowing up two bubbles in the process. The radio emission appears to be distributed very non-uniformly in a complex system of filaments some tens of kpc in length. The bubbles appear to have a clear outer boundary which has the same maximum size over a broad range of wavelengths from 4m to 20cm.

The inner jet is modeled from a number of different points of view as having a total kinetic energy flux of  $\sim 10^{44}$  ergs  $s^{-1}$  or more. However, the region occupied by the radio source has an X-ray luminosity of only  $10^{43}$  ergs  $s^{-1}$ . This implies that more energy is flowing into the region from the jet than out due to bremsstrahlung radiation. This is consistent with net heating of the volume and a subsonic expansion of the bubbles.

This region has traditionally been modeled as a “cooling flow” using only the energy budget calculated from the X-ray emission. This result suggests that the situation is currently much more complicated for M87 at the center of the Virgo cluster. Of course, the radio event may be transient on the time-scale of the cluster, so whether the cooling inflow or the jet (black hole) driven outflow dominates may vary with time. The great variety of central radio sources in clusters we see supports this qualitative picture. But as with the radio jet sources, we need to study the problem statistically to understand the evolutionary tracks of this phenomenon.

### 4. High- $z$ Starformation and AGN's

Recently extragalactic, high-redshift dust emission has been discovered using the SCUBA array on the JCMT. The positional accuracy obtained for these weak sources with the relatively large JCMT beam is limited. However, it turns out that many of the weak submm sources are detected in deep 20cm surveys with the VLA as well. The higher accuracy VLA positions can be used to identify the optical/IR counterparts to these sources and when they are bright enough allow optical spectroscopy to determine their redshift and other properties.

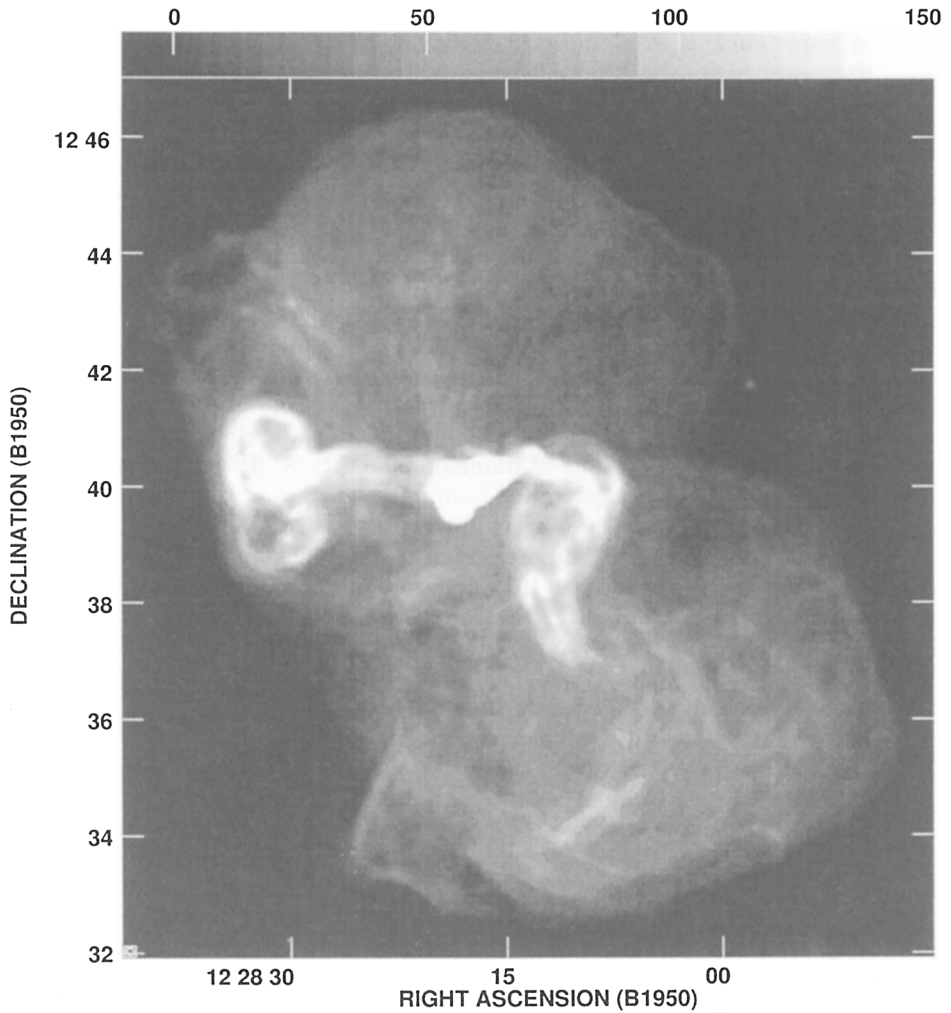


Figure 3. M87 image at 90cm. This image shows the structure of the “halo” extending over 70 kpc. The saturated, triangular region near the center of the image contains the famous 2 kpc jet and the inner lobes.

Although these sources have clear dust spectral signatures in most cases, many of the identifications have turned out to have AGN optical spectra. Also studies of nearby ultra-luminous FIR galaxies have shown that often there is strong evidence for an AGN as well as active star formation. This raises the important question of whether the two processes (very high star-formation rates and active galactic nuclei) are related in their origin, especially at high redshift.

One of the first such objects discovered is JM2399–0136 (Ivison et al 1998). This object has a fairly bright radio counterpart which allowed its confirmation. Optically, it consists of two components separated by about 3 arcsec, both with  $z = 2.8$ . One of the objects has an AGN spectrum while the other lacks the high excitation lines and thus is more consistent with star-formation. The B-array radio imaging shows a radio source with an extent of 10 arcsec or more, consistent with an FR I morphology. Recently we imaged this field with the VLA at 20 and 90cm in the A-array, producing images with 1.5 and 6 arcsec resolution respectively. An earlier image at 1.5 arcsec resolution had been obtained at 5 GHz. In the 20cm image we see two components which align with the two optical objects. However, the one with the AGN spectrum appears to have a much flatter spectrum typical of a normal, optically thin synchrotron source. The lower excitation object appears to have a steeper spectrum and is not detected at 5 GHz. The whole source, based on the 90cm results, appears to have a spectrum steeper than one.

At  $z = 2.8$ , the spectrum of a synchrotron source in a weak magnetic field should be steepened by Inverse Compton losses. This might well steepen the spectrum of the low surface brightness parts of an FR I or the synchrotron emission from the ISM of a galaxy. However, an AGN, perhaps with a jet, could resupply the relativistic electron population rapidly enough to maintain a normal spectrum. Thus this observation could suggest that both processes are active in this object and that many starforming sources at high redshift may have steep radio spectra. The extended, FR I-like radio emission may mean that there is connection at high redshift between radio jet sources and star-formation which we do not often see nearby.

## 5. Conclusions

There are many exciting and important areas which the new low frequency capabilities such as the GMRT can address and make major progress. These are allowing us to ask questions about radio sources like those we have posed for years about stellar evolution. Also, when combined with other wavelength bands, we can begin see the connection and importance of the phenomenon we study to the rest of extragalactic astronomy and our very broad understanding of the universe.

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