PROPERTIES OF RADIO SOURCES IN CLUSTERS OF GALAXIES

Daniel E. Harris
Radiosterrenwacht, Dwingeloo The Netherlands.

"The properties of radio sources in clusters" presupposes that we know something about radio sources out of clusters, or that we even know whether a radio source is "in" or "out" of a cluster. Thus we are faced with the problem of defining what we mean by a cluster. Most of us use Abell's catalogue of RICH clusters and assume that we are really "in" a cluster. However, most radio sources are identified with faint, distant objects and it is often difficult to know whether the remark "galaxy in a group" or "galaxy in a cluster" indicates a cluster such as the Coma Cluster, a cluster similar to an "open" Zwicky cluster, or a group of galaxies which may be gravitationally bound.

This uncertainty must not be forgotten, and in the following discussion, we will try to limit the effects of this by concentrating on catalogued clusters; ignoring most distant radio galaxies, many of which may be in rich clusters; and also by neglecting quasars, some or all of which may be in clusters.

As a further point of introduction, it is helpful to consider the radio luminosity function (RLF) of galaxies. Radio galaxies with high luminosity are relatively rare and there are very few if any in the local volume ($z < 0.2$) of space. Therefore most of the radio galaxies under discussion here are of only moderate or low luminosity and when we compare properties of radio sources in and out of clusters, it is necessary to restrict the comparison to moderate luminosity sources: a comparison for the high luminosity radio galaxies should be undertaken only after detailed optical studies of distant clusters have been achieved. (see Fanaroff and Riley, 1974, for a comparison of low and high luminosity sources).

The Radio Luminosity Function and Optical Identifications.

The RLF sketched in figure 1 (Auriemma et al. 1977) is for ellipticals and SO galaxies. This form of the RLF gives the probability of a galaxy of a given absolute magnitude being a radio source as a function of the radio luminosity. A concensus is developing that the RLF for radio galaxies in clusters is essentially the same as this - at least for the flat part of the curve where comparable data are available (Jaffe and Perola, 1976; Auriemma et al. 1977).

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part I, 321-328.

https://doi.org/10.1017/S1539299600002732 Published online by Cambridge University Press

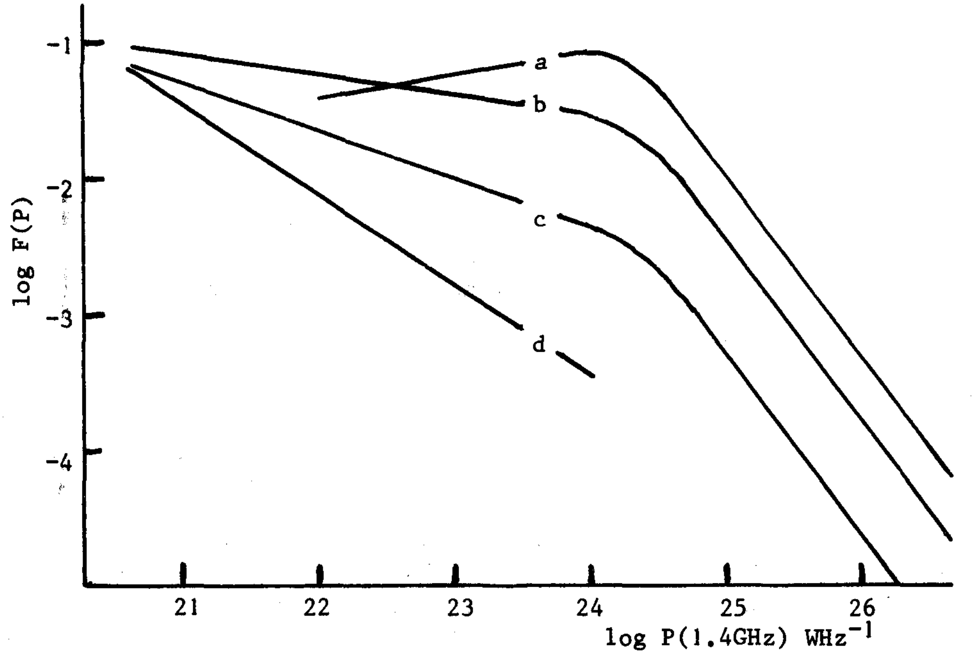

Figure 1 The radio luminosity function for ellipticals and S0 galaxies. (a)$-22<M_p<-21$, (b)$-21<M_p<-20$, (c)$-20<M_p<-19$, (d)$-19<M_p<-18$

Figure 1 shows that the probability of a bright galaxy being a fairly strong radio source is quite large. Since most clusters contain one bright galaxy which has a high probability of being a radio source, we can understand the following observational results of Riley, Slingo, and others:

1) Most radio galaxies in clusters are associated with the brightest or one of the brightest galaxies (Riley, 1975b).

2) There is no relation between the richness of a cluster and the probability that any particular galaxy will be a radio source of a given radio luminosity: i.e. increasing the richness has the effect of increasing the number of fainter galaxies which are less likely to be radio sources anyway (Riley, 1975a; Owen, 1975). So it seems that when "deciding" about radio emission, any individual galaxy is relatively unconcerned as to whether it is in a cluster or not.

Finally, it seems likely that most clusters have experienced epochs of moderately strong radio galaxy activity, even if they are now quiescent. "Likely" in this context depends on whether bright galaxies migrate from low to high radio luminosities (and back) or whether just a few of them are always high luminosity objects.

Spectra and Morphologies.

We now discuss the properties of radio sources which depend on cluster membership. Many workers have demonstrated the association

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between steep-spectrum radio sources and Abell clusters: Baldwin & Scott (1973), Slingo (1974) and Riley (1975b) have used the 3C and 4C samples and shown both that very few steep-spectrum radio galaxies from the 3C list are outside clusters and that 6 of 25 4C sources associated with clusters have steep spectra. Results at low frequencies from the Clark Lake Radio Observatory show a similar effect for a sample of X-ray clusters (Erickson, unpublished).

Most explanations interpret this association as an excess of low energy electrons, i.e. well aged electrons. Whether they are confined by the inter-galactic medium (IGM), and still reside close to the parent radio galaxy, or whether they have leaked out and away from the galaxy, but are still visible in the cluster core as an extended low frequency halo, is still a matter of debate.

Direct evidence for halo sources is hard to obtain. From synthesis observations we have: the Coma Cluster (Jaffe et al. 1976), A2142 (Bahcall et al. 1976), A2256 (Bridle and Fomalont, 1976), and A2319 (Harris and Miley, unpublished). Costain (unpublished) has also measured angular diameters of several X-ray clusters at 22 MHz, obtaining values of 10-30 arc min.
All of the known halos occur in X-ray clusters: at least 3 clusters observed with similar sensitivity and resolution and chosen because they were not X-ray clusters, showed no evidence of halo sources (Harris and Miley, unpublished).

We now consider the compact sources which are usually unresolved with most instruments and which lie within the optical boundaries of a galaxy. Many galaxies with radio luminosities comparable to those we observe in clusters are core sources and indeed, this is a common class of radio galaxy morphology in clusters (see the preceding paper by McHardy). Although statistics of the detailed properties of core sources in clusters have not been compiled, there are examples of extremely compact sources as shown by VLBI observations (NGC1275) and by spectra which are indicative of synchrotron self-absorption (Harris et al. 1977).

The situation with doubles is quite different. Here we are plagued with the problem that classical doubles (Class II of Fanaroff and Riley, 1974) are found at large distances and with high radio luminosities and there are few, if any, in our volume of space. Those which have been reported in the literature are usually in Abell clusters of distance class 5 or 6. One can thus understand why both DeYoung (1972) and Hooley (1974) had to operate with small samples in the search for any significant differences in the sizes of double radio galaxies inside vs. outside clusters. We need more optical work on the areas around distant galaxies before this type of comparison will yield convining results.

Perhaps the most intriging of the morphology classes in clusters are the tailed radio galaxies, subdivided into "narrow tails" (also referred to as "TRG" or "radio trails")and wide angle tails (also referred to as "bent double" or IRG", for intermediate radio galaxy).

The number of known TRGs is always increasing: the table given here is meant as a finding list and it does not include several

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probable TRGs nor most IRGs.

Finding List of Tailed Radio Galaxies.

Cluster	D	R	X-ray	Length of tail (kpc)	Reference.
A84	5	1		(120)	Riley 1975b
A401	3	2	X	500	Slingo 1974
A426	0	2	X	260	Riley & Windram 1968
				190	" "
				50	Miley et al. 1972
3C129	1	-	X	600	Hill & Longair 1971
				50	Miley 1973
A629	5	1		(150)	Rudnick & Owen 1976
A1314	1	0		820	Vallée & Wilson 1976
				80	" " "
A1367	1	2	X	350	Gavazzi (unpublished)
A1452	4	0		220	Rudnick & Owen 1976
A1656	1	2	X	240	Willson 1970
A1775	4	2		380	Owen (unpublished)
A2142	4	2	X	(360)	Harris et al. 1977
Zw1615.8	2	-		760	Ekers et al. 1977
A2250	5	1		440	Rudnick & Owen 1976
A2255	3	2		200	Slingo 1974
A2256	3	2	X	600	Bridle & Fomalont, 1976
				30	Rudnick & Owen 1976
Zw2247.3	2	-		600	Schilizzi & Ekers 1975.

D is the Abell distance class; R is the Abell richness. "X" means that the cluster is an X-ray source. The values for the length of the tails are based on H=50 km/s Mpc^{-1}. Parentheses indicate that the distance to the cluster is estimated from the magnitude of the tenth brightest galaxy rather than from a measured velocity.

Most of the TRGs and IRGs occur in Abell clusters: there are a few in Zwicky clusters but none are known to be associated with completely isolated galaxies. Consequently, most explanations of the morphology involve the interaction of a radio galaxy with the IGM: pressure balance arguments lead to IGM number densities of 10^{-3} cm^{-3} and T $\sim 10^8$K. Owen and Rudnick (1976) have divided a sample of these sources according to the optical dominance of the galaxy and the radio luminosity, suggesting that the wider angles of the IRG occur either because the parent galaxy is on the average more massive and thus moving more slowly with respect to the IGM or that the radio outburst is more powerful than in a TRG, making the ram pressure less effective in stopping the radio emitting lobes.

The general properties of TRGs which must be accounted for by the ubiquitous "any viable theory" are:

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length: 50-900 kpc (for H=50), often curved.
spectral index: 0.5 up to 1.5 or more, often increasing along the tail.
polarization: the magnetic field is directed along the tail and the percentage polarization increases along the tail in the few cases studied.
substructure: active nucleus, wiggly twin tubes in two cases, and the tails often have areas of enhanced emission ("blobs").

Current models for TRGs include Jaffe & Perola (1973) - independent blob: predicts too great a change in the spectral index. Jaffe & Perola (1973) - magnetospheric model: does not allow for adiabatic losses. Cowie & McKee (1975) - tails from electrons leaked from ejected plasmoids: attempts to solve the adiabatic loss problem. Pacholczyk & Scott (1976) - acceleration in the tail by turbulence: an IGM density ten times lower than in other models is derived.

One of the values of the Pacholczyk & Scott model is that it incorporates an acceleration mechanism and evidence has been accumulating that acceleration of electrons is necessary in the tail. This has been discussed by Vallée and Wilson (1976) and Coleman et al. (1976) for IC711 (in Abell 1314) and by Ekers et al. (1977) for B2 1615+35. Basically the case revolves around the origin of the electrons at the end of the tail. Some tails are 800 kpc long (H=50 km/s Mpc^{-1}) and since the lifetime of electrons responsible for the 1400 MHz radio emission is $\lesssim 10^8$ yrs, the velocity needed to transport the electrons from the galaxy to the end of the tail must average 8000 km/s or more. This figure is much greater than the velocities of the galaxies with respect to the IGM or of the estimated Alfvén velocities. Thus it seems that in situ acceleration of electrons is necessary in TRGs as it is in normal radio galaxies. If one wants to use a beam mechanism to circumvent this problem, the beam must be deflected by the IGM (e.g.NGC 1265).

The Inter-Galactic Medium and X-ray Emission.

There have been several discussions as to the origin and heating of the IGM. Is it gas being expelled from the cluster or rather primordial gas falling in or even bouncing (Lea, 1976)? If the radial streaming velocity were greater than the velocity of the galaxies associated with the tails, it could be that the tails would act as wind vanes and show the direction of streaming. Neither Lea (1976) nor Rudnick and Owen (1976) have found any preferential tail direction. Figure 2 is a sketch of what I call the "Lea Cluster" a single cluster which contains most of the TRGs we have observed. Of course it is not always easy to determine the precise center of a cluster and one must remember that the observations are not uniform in sensitivity or in resolution. Even so, no preferred tail direction is evident. It would seem that if the gas is primordial, it has, as Gull and Northover (1975) have proposed, already established an adiabatic atmosphere with very little systematic motion remaining.

Most TRG models support the thermal bremsstrahlung interpretation of the X-ray emission although that of Pacholczyk and Scott favors a low density in the IGM, which would be consistent with inverse Compton emission of X-rays. There also appears to be a relation between the low frequency radio emission and the X-ray

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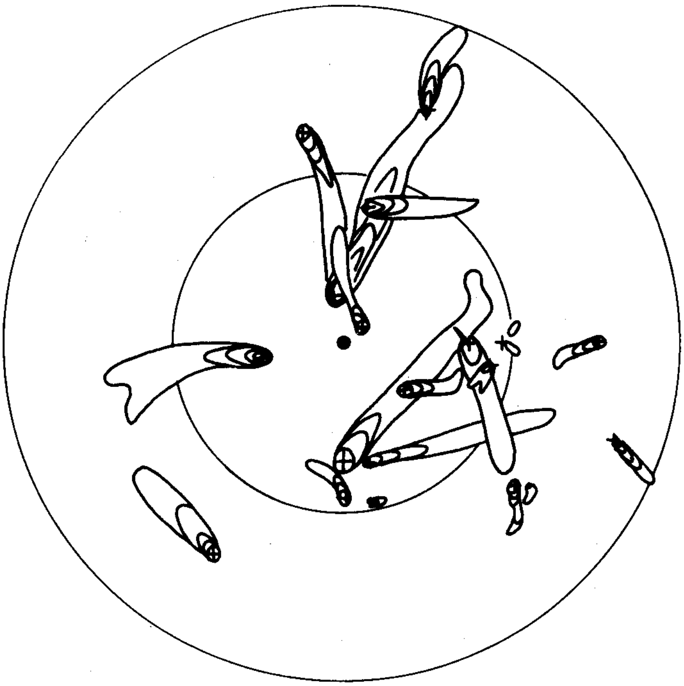

Figure 2 The "Lea Cluster": a sketch of tailed radio galaxies. 3C129 and 3C129.1 are not included. The outer circle has a radius of 1 Mpc (H=50 km/s Mpc^{-1}).

intensity for some clusters. Both Costain (unpublished 22 MHz data) and Erickson (unpublished 26 MHz data) find a much better correlation between X-ray intensity and low frequency radio power than between X-ray intensity and 1400 MHz luminosities.

Whether or not the inverse Compton model is viable, there remain problems for the thermal bremsstrahlung model. If the hot IGM is to be primordial, why are not all rich clusters X-ray sources? We have observed two D=3, R=2 Abell clusters (A1035 and A1904) which are not known to be X-ray clusters (Harris & Miley, unpublished). In neither did we detect any strong radio galaxies, (tailed or otherwise) or extended emission. If the gas had an abnormally short cooling time and had already collapsed to the center of the cluster, it should now be fueling an active radio galaxy according to some theories (Silk, 1976).

One should not overlook the problem of TRGs in poor clusters which may be too cool to be X-ray sources. Pressure is still needed to confine the tail in conventional models. If the gas is cooler than 10^8K, the density must be at least as high as that in the centers of rich clusters and cooling times may become too short.

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Many authors who consider the details of X-ray emission from clusters ignore the association of radio sources and X-ray clusters. Notable exceptions are Ipavich (1975), Pacholczyk and Scott (1975), Christiansen and Holman (1976), and Mufson and Owen (1976). However, I believe that the full consequences of this association are not yet understood and we must remember that X-ray clusters are not limited to rich clusters: rather they are clusters with active radio galaxies, often with tailed radio galaxies, and sometimes with low-frequency halo sources.

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