RADIO SOURCES IN CLUSTERS OF GALAXIES

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Sixty-five radio sources in the 4C catalogue lie within 0.3 of the radius, $R_c$, defined by Abell (1958), of the centre of an Abell cluster of galaxies. Statistically few of these are expected to be chance coincidences and hence they provide a well defined statistical sample of sources in rich clusters of galaxies. Over the last 6 years sources from this sample having declinations greater than $10^o$ have been observed with high resolution using the Cambridge One-Mile telescope by Slingo (1974(a) and (b)), Riley (1975) and by myself (1977, in preparation). The number of sources observed and the number expected by chance at different distances from the cluster centre are shown in Table I; the radio positions used are from the 4C catalogue.

Table I

| Distance from cluster centre in terms of cluster radii. | 0 - 0.1 | 0.1 - 0.2 | 0.2 - 0.3 |
|---|---|---|---|
| Number observed | 22 | 17 | 11 |
| Number expected | 1.3 | 3.1 | 4.1 |

Virtually all of the sample has now been observed and some preliminary conclusions may be drawn about the properties of radio sources in rich clusters of galaxies.

## 1. PROCEDURE

The positional accuracy of the 4C interferometer survey is only sufficient to demonstrate the statistical association of the 4C radio sources with Abell clusters. Our procedure is to make high resolution radio maps of the sources at 408 and 1407 MHz using the One-Mile telescope and these maps are usually adequate to determine whether or not the radio source is associated with a cluster member. Using these maps and the much improved radio positions the number of sources definitely and probably associated with cluster members may be compared with those which are found not to be associated with the cluster. The

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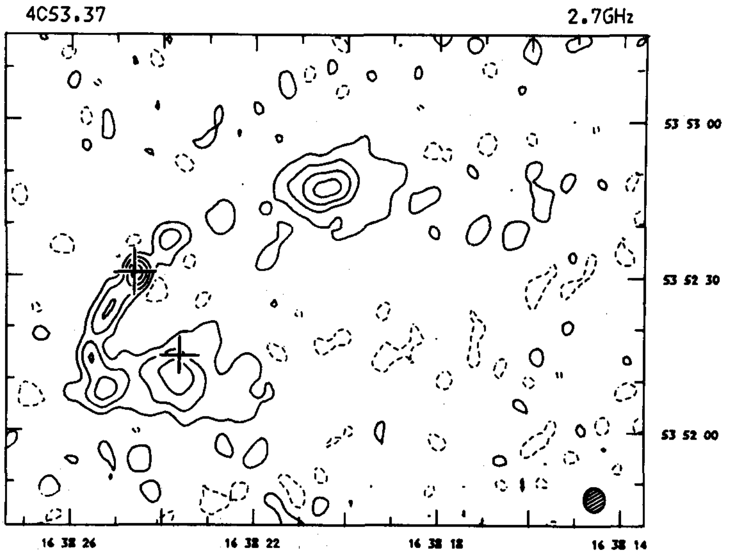


Fig. 1. Map of 4C 53.37 at 2.7 GHz. The contour interval is 0.003 Jy (beam area)$^{-1}$; the half-power beam shape is shown by the shaded ellipse. The crosses mark the positions of galaxies in the field of the source; the more northerly cross shows the position of the brightest galaxy in the cluster.

results are shown in Table II which refers only to the brightest radio source coincident with the cluster.

Table II

| Distance from cluster centre in terms of cluster radii. | 0 - 0.1 | 0.1 - 0.2 | 0.2 - 0.3 |
|---|---|---|---|
| Sources definitely associated with the cluster. | 24 | 8 | 3 |
| Sources probably associated with the cluster. | 3 | 3 | 1 |
| Sources not associated with the cluster. | 1 | 3 | 3 |

The results confirm the statistics of Table I. (There is a total of 49 sources in Table II rather than 50 as in Table I because the new radio position for 4C 10.31 shows that it lies outside 0.3 Rc). These observations also provide detailed source structures with resolution 23" arc and spectral information about the sources in the cluster. If the sources appear particularly interesting, such as radio trail sources, or if the identifications are ambiguous with 23" arc resolution, observations are made with 5-km telescope at either 2.7 or 5 GHz at which frequencies the resolution of the telescope is 3".8 arc and

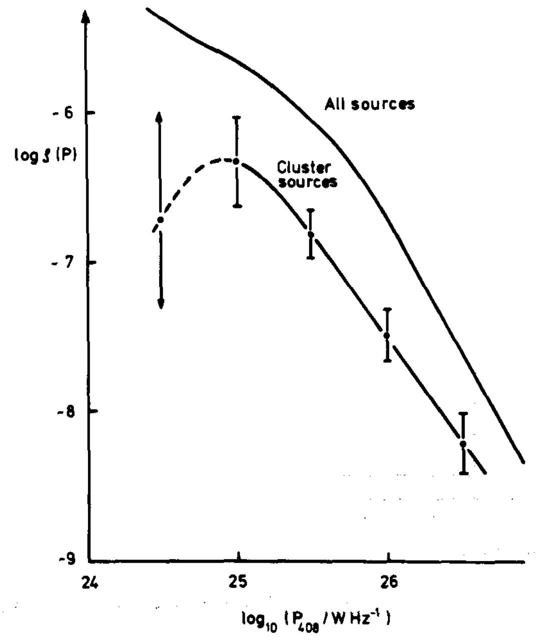


Fig. 2. The observed luminosity function at 408 MHz of 4C and 4CT radio sources occurring in Abell clusters, using only those clusters for which Abell says his catalogue is complete. For comparison the local luminosity function for all sources is shown. The density in units of $\mathrm{Mpc}^{-3}$ of sources of a given power, $\rho(P)$, is defined by

$$\rho(p) = \int_{P \times 10^{-0.25}}^{P \times 10^{0.25}} \rho_o(P)\, dP$$

The function is presented in equal logarithmic intervals of $P_{408}$.

2" arc respectively.

A wide variety of interesting sources have been discovered, particularly striking examples being the radio trail sources and the "bent double" sources. A very clear example of a radio trail source is 4C 53.37 which turns out to be associated with the brightest member of the cluster Abell 2220. The 5-km telescope observations at 2.7 GHz show it to have a component associated with the nucleus of the galaxy and the distinctive "jets" of radio emission sweeping behind the galaxy (Fig. 1). Another striking radio trail source is 4C 10.35 which is associated with the brightest galaxy in Abell 1684.

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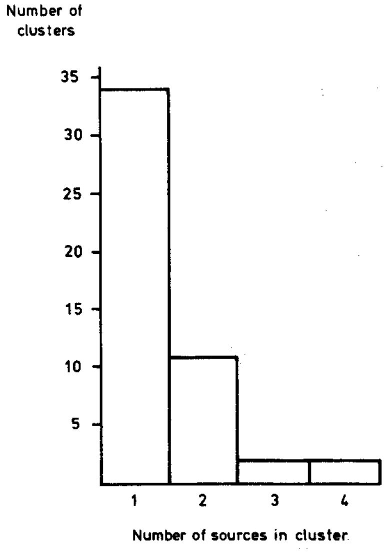


Fig. 3. The distribution of the number of sources per cluster for all the observed clusters.

## 2. PRELIMINARY RESULTS

A preliminary analysis has been made of the statistical properties of the radio sources associated with galaxies in the Abell clusters and the following results have been established.

### 2.1. The luminosity function of radio sources in clusters

Fig. 2 shows the luminosity function for the radio sources in Abell clusters compared with the luminosity function for all extragalactic radio sources derived by Wall, Pearson & Longair (1976). It can be seen that the luminosity function for cluster radio sources lies parallel to the overall luminosity function over the radio luminosity range $10^{25} < P_{408} < 10^{26.5}$ W Hz$^{-1}$. Throughout this range, roughly 20 - 25 per cent of all radio sources are found within rich clusters of galaxies. This result is in agreement with the earlier results of Riley (1974).

### 2.2. How often is more than one cluster galaxy a strong radio source?

This analysis is still at a preliminary stage. The simplest diagram to illustrate this result is the distribution of the number of radio sources per cluster but it must be emphasised that this diagram is fraught with many selection effects. In particular, the limiting radio luminosity to which clusters are surveyed depends upon the distance of the cluster and on the number of interferometer spacings used to observe it. Bearing in mind these selection effects, Fig. 3

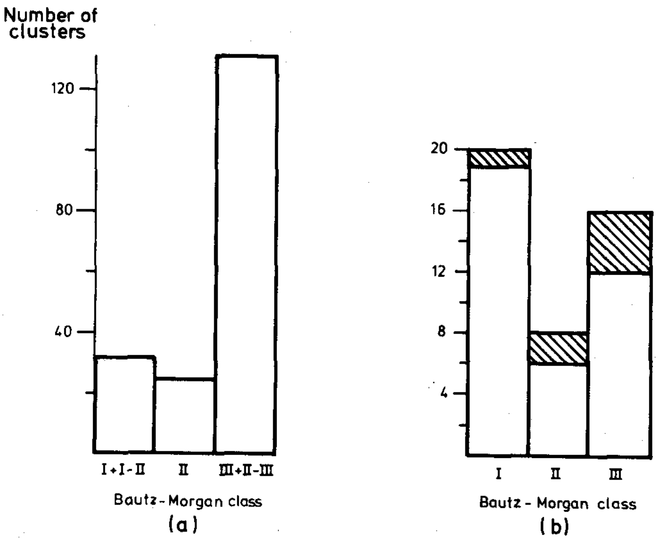


Fig. 4. (a) The Bautz-Morgan classification of a general sample of clusters having no radio bias. (b) The Bautz-Morgan classification of clusters definitely containing a 4C source.

shows the result of the present survey. It can be seen that more than one radio source per cluster is found relatively frequently and up to 4 sources may be observed in some clusters.

2.3. Correlations with Bautz-Morgan class

By far the most striking correlations are found between the properties of the cluster and its Bautz-Morgan class. In Bautz-Morgan class I there is the maximum contrast in optical luminosity between the brightest member, which is often a D or cD galaxy, and the second and third ranked galaxies; in class III, there is little difference in magnitude between the brightest members of the clusters (Bautz & Morgan 1970; Bautz 1972).

2.3.1. <u>Distribution of radio sources among Bautz-Morgan types</u>. Fig. 4 shows the distribution of Bautz-Morgan classes among clusters in general and those which contain radio sources. It can be seen that there is a strong tendency for radio sources to be associated with class I clusters (McHardy 1974). Since many of the latter contain cD galaxies there is also a strong correlation with the cD clusters in Rood & Sastry's and Oemler's classification schemes.

2.3.2. <u>Spectral index distribution as a function of Bautz-Morgan type</u>. The mean spectral indices ($\bar{\alpha}$, in which $\alpha$ is defined by $S \propto \nu^{-\alpha}$) for different samples of cluster radio galaxies are shown in Table III.

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Table III

| | $\bar{\alpha}$ |
|---|---|
| All cluster sources | 0.97 ± 0.07 |
| Bautz-Morgan class I | 1.16 ± 0.15 |
| All except Bautz-Morgan class I | 0.86 ± 0.10 |

It can be seen that in Bautz-Morgan class I clusters, the mean spectral index is significantly steeper than the mean for all other clusters which is close to the mean spectral index for all radio sources of $\approx$ 0.80.

2.3.3. Morphology of radio sources as a function of Bautz-Morgan class. The radio sources associated with cluster galaxies have been divided into the following simple morphological classes: unresolved, slightly resolved, double, bent double, radio trail and diffuse; the distribution amongst these classes is shown in Table IV. The terms 'resolved' and 'unresolved' refer to observations made with a beam width of 23" arc in RA and 23" cosec $\delta$ in Dec. In Table IV a distinction is made between the most powerful radio source associated with the cluster which is referred to as the 'brightest radio source', and the other fainter radio sources associated with the cluster. Clusters of all distance classes are distributed fairly uniformly throughout the table and so inspection of Table IV shows that powerful unresolved sources in Bautz-Morgan class I clusters are generally physically smaller than the other powerful sources in the table.

A number of conclusions of astrophysical interest may be drawn from examination of Table IV. The most significant of these is that ten of the twelve radio trail sources occur in Bautz-Morgan class III clusters whereas the double, bent double and diffuse sources are distributed

Table IV

| Source type | Bautz-Morgan Class | | | | | |
|---|---|---|---|---|---|---|
| | Class I | | Class II | | Class III | |
| | Brightest radio source | Faint | Brightest radio source | Faint | Brightest radio source | Faint |
| Unresolved | 5 | 8 | 0 | 0 | 1* | 5 |
| Slightly resolved | 2 | 1 | 0 | 1 | 3 | 2 |
| Double | 3 | 1 | 2 | 0 | 4 | 1 |
| Bent double | 4 | 0 | 2 | 0 | 0 | 0 |
| Trail | 1 | 0 | 1 | 0 | 6 | 4 |
| Diffuse | 4 | 0 | 2 | 0 | 5 | 1 |

* This source is 4C 10.30E which is a low power radio galaxy ($P_{408}$ = $10^{23.9}$ W $Hz^{-1}$) but is the only radio source probably associated with the cluster.

relatively uniformly throughout the different classes. It is also interesting that only class I clusters contain powerful unresolved sources; these sources have steep spectra ($\bar{\alpha} \gtrsim 1.2$). The fainter unresolved sources generally lie in the outer reaches of the cluster and are approximately evenly distributed between classes I and III. The lack of such sources in class II merely reflects the relatively small numbers of such clusters.

2.3.4. Is the brightest radio source always associated with the brightest galaxy? The rank of the galaxy associated with the brightest radio source is indicated as a function of Bautz-Morgan class in Table V. For Bautz-Morgan class I clusters the brightest radio source is virtually always associated with the brightest galaxy; for Bautz-Morgan class III clusters, there is somewhat more spread among the brightest 3 members, which have roughly the same absolute optical magnitudes.

Table V

| Rank of galaxy | BMI | BMII | BMIII |
|---|---|---|---|
| 1 | 18* | 4 | 9* |
| 2 | 0 | 2 | 1 |
| 3 | 0 | 0 | 2 |
| > 3 | 1 | 1 | 2 |

* Includes one where identification is not certain.

The numbers in this table do not add up to 49 as information is not available for 4 sources, 5 4CT sources have been included, and a number of sources have been rejected as being either foreground or background objects.

## 3. INTERPRETATION

These results suggest the following general model for the evolution of radio galaxies in rich clusters of galaxies.

In Bautz-Morgan class I clusters, the central massive cD galaxy is always the brightest radio source. It is natural to suppose that it is stationary at the centre of the cluster where the intergalactic gas density will be greatest. Because the galaxy is stationary it is natural that the radio sources produced should be simple doubles and slightly bent doubles. The high gas density implies effective confinement of the source components and hence there may be time for synchrotron and inverse Compton losses to steepen the radio spectra of these sources accounting for point 2.3.2.

In Bautz-Morgan class III clusters, there is no dominant galaxy and hence all the brightest galaxies must be in motion with respect to

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the dynamical centre of the cluster. Since there is not much difference in the absolute optical magnitudes of the brightest members of Bautz-Morgan class I and class III clusters, it is reasonable to suppose that the central energy-producing regions in the massive galaxies responsible for the radio emission are very similar in all types of cluster. However, in Bautz-Morgan class III clusters, as the ejected material leaves the protection of the galaxy it is swept backwards by the ram pressure of the intergalactic medium, forming the distinctive radio trails. One might therefore expect radio trail sources to be located further from the cluster centre than other types of powerful source, but this cannot yet be definitely established. The observation that to be a bright radio source a galaxy must be massive means that in a relaxed cluster we would not expect to find the radio galaxies far from the cluster centre. As the positions of the dynamical centres of Abell clusters differ from the rough positions given by Abell by roughly 0.1 $R_c$, it is not yet possible, in general, to measure small deviations from the centre with sufficient accuracy. Obviously when there is more than one relatively powerful radio source associated with the cluster, some of the sources must be moving with respect to the intergalactic medium giving rise to the possibility of a radio trail source.

This model accounts naturally for the difference in radio properties of the Bautz-Morgan type I and type III clusters. One puzzle concerns the nature of the radio sources associated with fainter cluster members in the outer regions of the clusters. The absence of such sources from the centres of clusters may be readily explained by the fact that gas would be swept out of them by ram pressure if they were to approach the dense central regions. When galaxies move through the outer regions of a cluster, ram pressure forces are expected to be greatly reduced, because of the smaller particle density and lower velocities allowing galaxies which have come from the centre of the cluster to replenish their interstellar medium through mass loss from stars or to maintain their primordial gas if they never passed through the central region. Therefore of the small galaxies, only far-out members of the cluster can hold onto their interstellar gas, a result in agreement with the observation of spirals in the outer regions of rich clusters. This may allow for the production and containment of emission from the nuclear regions of such galaxies but as they are of low mass they would presumably be incapable of producing trail sources similar to those of the more massive central galaxies. Any small trails produced would very quickly suffer catastrophic adiabatic losses in the tenuous outer regions of the cluster and so be undetectable.

There are several ways in which the bright unresolved sources of high spectral index which occur in Bautz-Morgan class I clusters might fit into this picture. They may be very compact nuclear sources, small double sources which have been very well contained or some intermediate case. An example of the second possibility is 4C 12.76 (Slingo 1974b). An example of what has been called an intermediate case may be 4CT 12.76.1E; this source has been observed at 2.7 GHz with the 5-km telescope and appears to be slightly extended ($\sim$ 28 kpc) along the major

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axis of the galaxy within which it lies. More detailed structural information, especially at lower frequencies, is needed in this and in the other cases to determine the nature of these sources.

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