RADIO SOURCES IN CLUSTERS OF GALAXIES

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Summary

Fifty-eight clusters from Abell's catalogue have been examined for radio emission using the Arecibo 1000 ft reflector and the Molonglo 1 mile Cross. The positions, sizes, and flux densities at 408 MHz of 30 radio sources close to these clusters have been measured. Nineteen of these offer reasonable identifications with galaxies or blue stellar objects. Thirteen appear to be identifiable with individual cluster galaxies. No evidence for integrated cluster emission has been obtained. It has been concluded that either the centroid of radio sources may sometimes be well displaced from the parent galaxies or, in a significant number of cases, the only detectable radio source in a cluster is associated with a faint cluster galaxy, not a giant.

I. Introduction

There have been many investigations of the statistical association between radio sources and clusters of galaxies. The present aim is rather different, namely, to identify the sources of emission where there is an apparent association between a radio source and a cluster. This may lead to a better understanding of the types of galaxies that may become radio galaxies and, providing there is a statistically significant association of clusters and radio sources, may provide some positive evidence about the nature of unidentified sources and the radio luminosity function. Also, it allows a direct check on the existence of intergalactic emission unassociated with any particular galaxy.

The investigation has, in the first instance, been limited to an examination of a relatively small number of clusters, 58 in all. However, the results are promising and a full-scale programme has now been undertaken with the 1 mile Cross at the Molonglo Radio Observatory. The results from the preliminary investigation are described here.

A selection of clusters was made from Abell's (1958) catalogue and the Arecibo 1000 ft reflector was used as a finding instrument to detect nearby radio sources and roughly measure their position and flux densities. More accurate positions and also the angular sizes and flux densities of these sources were then measured again with the 1 mile Cross. From the 58 clusters observed, a selection of 30 radio sources stronger than about 1 f.u.† at 408 MHz was made for detailed examination using the Palomar Sky Atlas together with some direct photographs made at Mt. Stromlo Observatory. Not all the chosen sources are physically associated with the clusters, so that we have also obtained information about a random selection of comparatively weak sources.

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† 1 flux unit = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

II. Observations

Selections were made from Abell's catalogue of clusters in the declination range common to the Arecibo and Molonglo radio telescopes, i.e. between about $+18^\circ$ and -1°. Clusters in this range were selected according to three criteria.

(1) All clusters of distance 3 or closer on the Abell scale.

(2) More distant clusters for which an association with a radio source had been found earlier by Mills (1960); this category extended only to a declination of $+10^\circ$, which was the limit of an earlier survey (Mills, Slee, and Hill 1958).

(3) Rich clusters (richness 3 or greater on Abell's scale) not included in either of the above categories.

Table 1

Clusters observed

Listed according to their numbers in Abell's catalogue

Category 1			Category 2			Category 3		
Cluster	Distance	Richness	Cluster	Distance	Richness	Cluster	Distance	Richness
76	3	0	16	5	2	41	6	3
102	3	0	55	5	0	750	5	3
119	3	1	520	6	3	1437	5	3
147	3	0	526	4	1	1525	6	3
168	3	2	623	5	1	1530	6	3
240	3	0	732	6	1	1882	5	3
397	3	0	862	6	1	1942	6	3
399	3	1	869	6	0	2204	5	3
400	1	1	1148	6	1	2224	6	3
401	3	2	1346	5	1	2397	6	3
539	2	1	1620	5	0	2610	6	3
592	3	1	1850	6	1	2623	5	3
999	3	0	2029	4	2	2631	6	3
1139	3	0	2050	5	1			
1142	3	0	2512	5	1			
1773	3	1	2551	6	1			
1890	3	0	2644	5	1			
1983	3	1						
2052	3	0						
2063	3	1						
2147	1	1						
2151	1	2						
2152	1	1						
2572	3	0						
2589	3	0						
2593	3	0						
2630	3	0						
2657	3	1						

There are 28 clusters in the first category, 17 in the second, and 13 in the third; they are listed in Table 1. The first category was chosen to give a homogeneous sample of clusters to a fixed limiting distance. The second was included to check on the physical reality of the associations noted earlier. The third was added in the thought that rich clusters might be likely to exhibit a weak integrated emission which may have been overlooked in the earlier investigation.

Initially, constant declination scans were made at the nominal cluster positions with the Arecibo 1000 ft reflector using the 430 and 195 MHz radio astronomy feeds plus, occasionally, the 610 MHz feed. If a radio source was observed within about 1 min in right ascension from the cluster position on any of these frequencies, a scan in declination at the indicated right ascension was made to locate the source more accurately and to measure its flux density. In a few cases, several such scans were necessary to isolate confused sources.

As a result of this programme some 37 sources were listed with flux densities greater than about 0·5 f.u. at 430 MHz. A search was then made for these sources at the Molonglo Radio Observatory using both the fan beam of the east–west antenna and the multiple pencil beams of the full Cross. The former beam measures $1'\cdot5$ east–west by 4° north–south, the latter $2'\cdot8$ east–west by about $4'$ north–south at the mean declination of the observations. After excluding some of the more remote sources which had been listed in the analysis of confused regions and two in which the Arecibo observations had been confused by solar interference, it was decided to restrict the analysis to sources equal to or stronger than 1 f.u. at 408 MHz, which should form a homogeneous sample.

There are 30 such sources and these are listed in Table 2. The associated cluster is indicated, although it is not suggested that the association is physical in all cases. The positions given are those measured at Molonglo. Because the completed Cross had been in use for only a short time and was relatively untested, it was used only where necessary, i.e. for declination measurements and for obtaining the structure of the larger extended sources. Right ascensions and flux densities were obtained from the fan beam measurements, for which the calibration had been well established over nearly two years of observation. Flux densities are based on the absolute scale derived by Wyllie (1968), which is about 10% higher than the commonly used CKL scale (Kellermann 1964) when averaged over the southern sources common to both. For many of the stronger sources, however, flux densities given in the Parkes catalogue (Day *et al.* 1966) have been used in order to avoid a separate determination, particularly where the source is resolved and an integration is necessary. Such flux densities are given in parentheses in the table. Angular sizes or structural details quoted are based usually on the east–west extension (EW) measured on the fan beam but, if the source is large or appears confused, pencil beam contours have been used. The observational class divides the measurements into good (a), average (b), or poor (c); the overall standard errors in the measured positions in each of these classes is believed to be approximately as follows: for right ascensions, (a) $3''$, (b) $5''$, (c) $10''$; for declinations, (a) $6''$, (b) $9''$, (c) $12''$. The right ascension estimates are based on considerable accumulated experience and should be reliable; the largest values are due principally to confusion effects. The declination accuracy has been checked against a few source positions determined from lunar occultations and is believed to be conservative; with the higher resolution of the pencil beams, confusion is not a problem. Most of the sources have been listed in one or more of the principal radio catalogues, and the appropriate catalogue numbers are quoted in Table 2 for easy reference.

TABLE 2

LIST OF RADIO SOURCES SELECTED FOR EXAMINATION

Although the appropriate Abell cluster number is quoted the association is not always physical

Source No.	Abell No.	Position (1950·0) R.A. h	m	s	Dec. °	′	Flux Density (f.u.)	Class	Size and Structure	Catalogue References
1	55	00	30	39·9	+06	11·9	3·0	b	<1′	MSH00+0*7*, PKS0030+06, 4C06/1
2	119	00	53	39·1	−01	34·6	(10)	b	Double sp–nf sep. 7′	MSH00−0*17*, PKS0053−01, 4C−01/4
3	119	00	55	01·5	−01	39·6	(12)	b	<0′·5	MSH00−0*17*, PKS0055−01, 4C−01/5
4	240	01	37	59·6	+07	21·5	1·2	b	∼2′EW	
5	400	02	55	04·3	+05	50·6	(16)	b	Ext. np–sf ∼4′	MSH02+0*10*, PKS0255+05, 4C06/15
6	400	02	54	32·5	+06	25·9	4·3	b	∼1′EW	MSH02+0*9*
7	539	05	15	34·6	+06	21·8	1·5	b	∼1′·5EW	4C06/22
8	623	08	03	03·3	−00	49·4	(5·8)	b	<0′·5	MSH08−0*2*, PKS0803−00, 4C−00/32
9	862	09	41	37·0	+10	00·0	(8·7)	c	<0′·5	MSH09+0*5*, PKS0941+10, 4C10/27
10	1139	10	55	55·6	+01	50·3	3·8	a	<0′·5	MSH10+0*10*, PKS1055+01, 4C01/28
11	1142	10	59	40·3	+10	45·4	2·5	b	<1′	4C10/31
12	1148	10	59	30·7	−01	00·1	(8·1)	a	<0′·5	MSH10−0*21*, PKS1059−01, 4C−00/42
13	1346	11	38	36·4	+06	00·6	(1·8)	b	<1′	MSH11+0*9*, PKS1138+05, 4C06/42
14	1850	14	01	04·4	+09	14·2	1·1	b	<1′	MSH14+0*1*
15	1890	14	15	02·0	+08	26·8	1·8	c	3′EW	
16	1942	14	35	03·2	+03	53·2	4·3	c	∼4′EW	MSH14+0*10*
17	2029	15	08	28·2	+05	56·0	(3·4)	c	<1′	MSH15+0*3*, PKS1508+05, 4C06/53
18	2050	15	14	06·0	+00	25·9	(4·4)	b	Ext. np–sf ∼5′	MSH15+0*6*, PKS1514+00, 4C00/56
19	2052	15	14	17·2	+07	12·3	(26)	a	<0′·5	MSH15+0*5*, PKS1514+07, 4C07/40
20	2147	15	59	06·2	+15	45·8	4·6	b	∼1′EW	4C15/52
21	2147	16	00	20·9	+15	52·3	2·9	b	∼2′EW	4C15/53
22	2151	16	02	54·2	+17	52·2	2·3	b	∼2′EW	4C17/66
23	2224	16	43	09·9	+13	28·0	2·6	a	<1′	PKS1643+13

TABLE 2 (*Continued*)

Source No.	Abell No.	Position (1950·0) R.A. h	m	s	Dec. °	′	Flux Density (f.u.)	Class	Size and Structure	Catalogue References
24	2551	23	08	08·9	+07	19·1	(5·8)	a	2′EW	MSH23+02, PKS2308+07, 4C07/40
25	2593	23	21	55·0	+14	22·0	1·0	c	~2′EW	
26	2610	23	26	04·8	+16	58·3	1·9	b	<1′	4C16/83
27	2610	23	29	28·5	+17	12·2	3·7	b	~1′EW	PKS2329+17, 4C17/94
28	2644	23	38	27·3	−00	11·8	2·7	c	~3′EW	MSH23−0*15*, 4C−00/83
29	2657	23	43	49·0	+08	36·4	1·4	c	~1′EW	
30	2657	23	44	03·9	+09	14·1	2·4	b	<1′	PKS2344+09, 4C09/74

As a rough indication of the completeness of the earlier catalogues it is interesting to see what proportion of the present sources are listed. For example the 4C (Gower, Scott, and Wills 1967) and Parkes (Day *et al.* 1966) catalogues contain 70% and 53% of the sources respectively, while the MSH catalogue (Mills, Slee, and Hill 1958), which extends only to a declination of +10°, contains 77% of the sources within this area.

Finally, no evidence could be found for integrated emission either from the intergalactic gas or from more than one galaxy in a cluster. When a source is detectable the radio emitting area occupies only a small fraction of the total area of the cluster; an extended region would be easily recognizable by comparing the low resolution Arecibo and high resolution Molonglo responses.

III. IDENTIFICATIONS

In searching for optical identifications, the usual criteria have been employed, namely, that only galaxies or blue stellar objects close to the centroid of a radio source have been considered. In general we have accepted an identification when the radio centroid lies within two standard errors of the optical image, but when the radio source is resolved and extended we have considered the overlap of optical and radio images to be an alternative criterion. As shown below it has proved necessary to consider also the position of giant members of a cluster with respect to the radio source. For the 30 sources listed, reasonable identifications can be suggested for 19.

It has been found convenient to examine the first category of 28 close clusters separately as it is believed to form a homogeneous sample. The beamwidths given by the Arecibo 430 and 195 MHz radio astronomy feeds are approximately 17′ and 30′ arc respectively, and the sensitivity is such that it is believed all sources stronger than 1 f.u. at 408 MHz within 10′ arc of the nominal cluster centre have been detected in the finding programme. However, half of the total number of sources listed fall outside this angular distance. For a statistical analysis we have taken 10′ arc as a convenient limiting separation to define a possible physical association with the cluster; it is found that only a small proportion of the remaining sources are likely to be so associated.

The probability of a chance location of one of these radio sources within a 20′ arc circle is quite small. From some rough counts we would expect about 1 source stronger than 1 f.u. per 4 square degrees. This corresponds to a probability of 0·022 or, in the 28 clusters of category 1, the expectation of chance coincidences is 0·6. Actually there are 8 sources within 10′ arc, one of which is listed as a double; it is reasonable to assume that practically all of these are physically associated with the clusters. For example, from the first three terms of the Poisson series, we find the probability that more than two chance associations are involved is

$$p = 1-e^{-0\cdot 6}(1+0\cdot 6+0\cdot 18) = 0\cdot 02 .$$

The eight sources concerned are numbers 2, 5, 10, 15, 19, 21, 22, and 25 in Table 2. In four cases (5, 19, 21, and 22) there is a clear identification with a giant cluster member, in which the radio source overlaps the optical image of the galaxy. In the remaining four there is some degree of ambiguity: if the identification is made with the brightest or second brightest member of the cluster one must accept a radio source well displaced from the parent galaxy; on the other hand three of the four sources may be identified with much fainter galaxies, presumably cluster members, within the positional uncertainty. The remaining source, number 10, coincides in position with a blue stellar object that is displaced by nearly 5′ arc from the brightest cluster member, and it seems likely that this represents the chance coincidence expected. Source number 2 is a well-separated double in which one of the components is some 2′ arc from a giant elliptical cluster member (14^m). It would not be impossible to identify this component with the galaxy and to assume that the other component is a chance interloper; there is, however, a faint cluster member (approximately 17^m) close to the centroid of the two components.

It seems one must accept either that the centroid of radio sources may be well separated from their parent galaxies or that, in a significant number of cases, the strongest radio source in a cluster is associated with a faint cluster galaxy, not a giant. Because the radio sources do not always overlap the images of the giant galaxies it is clear that acceptance of these identifications, and consequent displacements, implies the probability that galaxies can sometimes eject single as well as double "plasmoids".

The other groups of clusters may also be investigated to help resolve this uncertainty. The distant rich clusters of category 3 may be eliminated immediately as there are no radio sources within the limit of 10′ arc. However, of the 17 sources in category 2, there are 6 within the selection limit, numbers 1, 8, 13, 14, 17, and 28. Four of these (8, 13, 17, and 28) meet the earlier identification criteria and can be identified with a giant cluster galaxy. The remaining two sources are quite distant from the brightest cluster member and, in fact, cannot reasonably be identified with any of the cluster galaxies. No reasonable identification can be suggested for number 14, but number 1 is 0′·4 arc distant from a faint blue stellar object which may prove to be a quasar. Because of the strong selection imposed on the group of clusters in category 2 we cannot come to any reliable statistical conclusion, but the results are certainly consistent with an assumption that only the giant galaxies in clusters are the source of radio emission.

TABLE 3

PROJECTED SEPARATIONS OF PROBABLE CLUSTER SOURCES

Separations from (1) brightest or second brightest galaxy of cluster and (2) closest galaxy

Source No.	Abell No.	Distance (Mpc)	Angular Separation (′) Giant Galaxy (1)	Angular Separation (′) Closest Galaxy (2)	Spatial Separation (kpc) Giant Galaxy (1)	Spatial Separation (kpc) Closest Galaxy (2)
Close Clusters						
2	119	200	5·1	0·6	300	35
5	400	80	1·4		32	
10	1139	200	5·1		300	
15	1890	200	3·0	0·7	180	40
19	2052	200	0·05		3	
21	2147	80	1·2		28	
22	2151	80	0·6		14	
25	2593	200	1·6	0·1	90	3
Distant Clusters						
1	55	420	14·9		1800	
8	623	420	0·6		72	
13	1346	420	0·3		36	
14	1850	540	7·8		1200	
17	2029	270	0·35		38	
28	2644	420	1·8	0·2	220	24

To investigate this assumption statistically we have derived the actual projected separation in kiloparsecs, between the centroid of the radio source and the first or second brightest galaxy in a cluster, whichever is closest. For this, we have taken Abell's own calibration of his distance scale in terms of redshift and have assumed a Hubble constant of 100 km sec^{-1} Mpc^{-1}. Distances for the 14 sources already

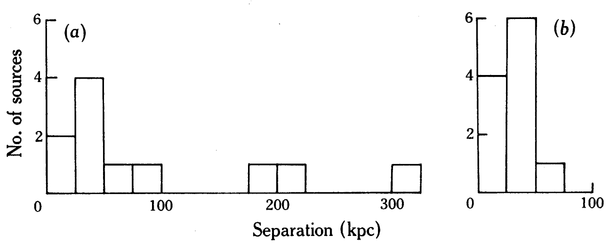

Fig. 1.—Histograms of the projected linear separations between radio sources within 10′ arc from the nominal cluster position and
(a) the brightest or second brightest galaxy in the cluster, and
(b) the closest galaxy.

discussed are tabulated in Table 3 and the results are displayed as a histogram in Figure 1(*a*). It seems obvious that the two large separations in the case of numbers 1 and 14 represent chance coincidences; the probability of a chance association increases with the square of the separation. The others could all be cluster sources, but number 10, with a separation of 300 kpc, seems most probably also a chance coincidence because of the likely quasar identification. Also, identifications with fainter galaxies much closer to the radio centroid may be suggested for four of the other sources of large separations, namely, numbers 2, 15, 25, and 28; the corresponding histogram when these identifications are assumed is shown in Figure 1(*b*). In view of the

TABLE 4

RADIO SOURCES THAT MAY BE IDENTIFIED WITH GALAXIES OR BLUE STELLAR OBJECTS

Source No.	Abell No.	Size and Structure	Possible Ident.*	Position of Source w.r.t. Object		Refs.†	Remarks
1	55	< 1′	20^mB.S.O.	0′·1W.	0′·4S.		Only on Palomar O print
2	119	Double sp–nf sep. 7′	14^mE	1′·0W.	4′·5S.		Position of centroid of double source w.r.t. brightest galaxy in cluster
		Early source ~1′EW Late source < ½′EW	17^mG	0′·2W.	0′·2S.		Position of centroid w.r.t. nearest galaxy. The earlier source is close to some very faint objects on the E Palomar print, but there is a plate fault on the O print in this region. The later source is close to a star, which, however, is not blue
3	119	< 0′·5	15^mE	< 0′·1	< 0′·1	1,6	Galaxy 20′ from A119
5	400	~4′nf–sp	15^mdb E	0′·4E.	1′·3N.	1,2, 3,5	Brightest in cluster
6	400	~1′EW	17^mE	< 0′·1	0′·4N.		Probably the giant in a very faint dense cluster. 25′N. of A400
8	623	< 0′·5	15^mE	0′·6W.	< 0′·1		Brightest in cluster
10	1139	< 0′·5	18^mB.S.O.	< 0′·1	0′·1N.	5	Source is 4′·6E. and 2′·2S. of brightest galaxy
13	1346	< 1′	15^mE	0′·2E.	0′·2N.		Brightest in cluster
15	1890	3′EW	15^mE	1′·7W.	2′·3N.		Brightest in cluster
			16^mE	0′·4W.	0′·6N.		Second brightest in cluster
17	2029	< 1′	14^mE	0′·4E.	0′·1N.		Brightest in cluster
18	2050	~5′ np–sf	15^mE	0′·4E.	< 0′·1	5	11′ from cluster and brighter than cluster giant. Therefore probably a field galaxy
19	2052	< 0′·5	14^mE	< 0′·1	< 0′·1	1,4, 5	Brightest in cluster
21	2147	~2′EW	15^mE	0′·2W.	1′·2S.		Many 14^m–16^m galaxies in this region, including several clusters
22	2151	~2′EW	14^mE	0′·6E.	< 0′·1		Second brightest in cluster
24	2551	2′EW	14^mE	0′·4W.	1′·3N.	5	One of 3 bright gals. in a loose cluster 19′S of 2551 (not listed by Abell)
			16^mdb G	0′·6E.	0′·5S.		Possibly a faint member of this cluster
25	2593	~2′	14^mE	1′·5E.	0′·5S.		Brightest in cluster
			17^mG	0′·2W.	< 0′·1		Faint member
28	2644	~3′	15^mE	1′·5W.	1′·0N.		Brightest in cluster
			16^mTriple	0′·2E.	0′·1S.		Triple galaxy extended to SE. (on O print). Third brightest in cluster
29	2657	~1′EW	16^mG	0′·2E.	0′·1S.		28′SE. of A2657
30	2657	< 1′	16^mB.S.O.	0′·1E.	< 0′·1		30′NE. of A2657

* Many of the E galaxies may be SO types, or even spirals. For galaxies 16^m or fainter, it is generally not possible to be certain of whether the outer extensions have spiral structure or not.

† References to previously published identifications and optical data are: 1, Mills (1960); 2, Minkowski (1960); 3, Maltby, Matthews, and Moffet (1963); 4, Schmidt (1965); 5, Clarke, Bolton, and Shimmins (1966); 6, Shimmins *et al.* (1966).

statistics of chance association quoted earlier, it would be expected that, if these identifications are correct, the galaxies in question would all be cluster members.

With the present small number of cases it is not possible to decide between the two possibilities (giant galaxies with a wide radio–optical separation or faint galaxies with a small separation) on a purely statistical basis. None of the separations exceed displacements already observed for the components of double sources. It would be helpful to measure redshifts of all the suspected identifications, particularly in the case of the fainter galaxies, in order to check for cluster membership of the galaxy. Even if the closest galaxies are taken as identifications, projected separations of the order of 30 kpc between the radio and optical centroids appear to be common.

Let us now turn to the 16 sources located more than 10′ arc from the nominal centres of their associated clusters. Only 6 of these, or 37% offer reasonable identifications, namely, numbers 3, 6, 18, 24, 29, and 30. Two of these, 6 and 24, may be identified with galaxies in clusters not listed in Abell's catalogue. Number 6 is approximately 0′·4 arc from what appears to be a giant galaxy (17^m) in a very faint but rich cluster, while number 24 may be identified either with a giant member (14^m) of a loose cluster or a faint member (16^m) of the same cluster. Number 18 is identified with a galaxy only 11′ arc from the cluster centre. It is, however, brighter than the giant near the cluster centre and is therefore probably a field galaxy. Numbers 3 and 29 may be identified with field galaxies. Number 30 coincides well with a blue stellar object, quite possibly a quasar. Thus in this effectively random sample of six identified sources we have probably two cluster members, three field galaxies, and one quasar.

Approximate data for all possible identified objects are given in Table 4.

IV. Unidentified Sources

One of the interesting questions arising out of the above results concerns the unidentified sources; there are 11 sources which are definitely in this category. It has been possible rather easily to eliminate radio–optical displacements of the magnitude discussed above as a cause. For example, if it is assumed, that radio galaxies have an optical magnitude of $-21 \cdot 0$ and that a linear displacement between radio and optical positions of 100 kpc is common, we would expect that a 17th magnitude radio galaxy would be commonly displaced by about 1′ arc from the associated radio source. Brighter galaxies might be found at correspondingly greater angles. However, a search of the fields surrounding the unidentified sources has yielded no such displaced identifications.

To compare the average properties of identified and unidentified sources we have calculated the geometric mean flux densities of each class. These are shown below, along with corresponding angular size data.

	Geometric Mean Flux Density (f.u.)	Number Resolved	Number Unresolved
Identified sources	3·7	12	7
Unidentified sources	3·2	4	7

The mean flux densities are comparable but there is a clear suggestion that the unidentified sources have a smaller angular size because a smaller proportion can be resolved. There still remain four unidentified sources with sizes between 1′ and 4′ arc, namely, 7, 16, 20, and 27. However, these again are smaller than the maximum sizes of identified sources.

The usual assumption is that such unidentified sources represent known categories of objects at distances too great for the corresponding optical image to be registered on a photographic plate. In the present instance this would require that the unidentified sources have a very much greater ratio of radio to optical emission than those we have been able to identify. It is, however, well known that in a random collection of strong radio sources the most numerous identifications are made with the most distant powerful radio emitters; in a given volume of space, however, the most numerous radio sources are the weakest radio emitters. This exemplifies the difference between the apparent and true luminosity functions. The random collection of weak sources unassociated with clusters will thus be dominated by the distant very strong radio emitters; the selection of cluster sources in a limited volume of space is likely to be weighted towards the lower radio luminosities.

Some general considerations show that this interpretation is possible. For example, if we consider the sources associated with distance 3 clusters, the geometric mean flux density is 4 f.u. and the mean distance 200 Mpc. The geometric mean luminosity of the radio sources is therefore $1\cdot5\times10^{24}$ W Hz^{-1} sr^{-1}. The median luminosity of identified radio galaxies in the 3C catalogue was obtained by Longair and Scott (1965) at a frequency of 178 MHz. Assuming a spectral index of $0\cdot8$, their result at 408 MHz is 4×10^{25} W Hz^{-1} sr^{-1}. That is, the restriction to a fixed volume has weighted the apparent luminosity function towards the weaker and more numerous radio emitters.

This analysis may be extended a little further to predict the identifications expected from the collection of 16 sources unassociated with clusters. We will assume that their median luminosity is 4×10^{25} W Hz^{-1} sr^{-1}, as above, and that the mean absolute magnitude of the associated radio galaxies has the commonly accepted value of $-21\cdot0$. It is easily shown that the mean flux density of these sources, $3\cdot2$ f.u., corresponds to a median photographic magnitude of the associated galaxies of about $19\cdot5$. The identification limit is about magnitude 20, so that one might reasonably expect that rather more than half of the 16 sources would be identifiable with galaxies. In fact only 5 could be identified but, in view of the low numbers involved, this is probably not a significant discrepancy. Note, however, that the lack of quasar identifications is more significant, for their mean ratio of radio to optical emission appears to be rather less than for radio galaxies; consequently a greater proportion of quasar identifications might have been expected. However, the small number of sources involved at this stage does not permit an adequate statistical investigation either of quasars or radio galaxies.

V. Conclusions

The numbers of clusters in the preliminary investigation have proved to be too small for definite conclusions to be made about some of the questions raised. However, it can be seen that the procedure of seeking statistically valid identifications between radio sources and clusters of galaxies has considerable promise, both for studying individual sources and for obtaining information about the radio luminosity function.

It has been possible to show that quite substantial displacements can occur between the optical and radio centroids of emission of a radio galaxy. In several cases the overall size of the radio source is less than the displacement from the presumed parent galaxy and there is no evidence of a corresponding source on the opposite side. However, in the most striking of these cases an identification with a faint but closer galaxy is not unlikely, so that it is not possible to state with confidence that ejection of a single plasmoid from a galaxy has been observed. The alternative explanation is that faint cluster members are often radio sources.

In future programmes it will be necessary to measure the redshifts of all possible galaxy identifications. Also, it is clear that many more clusters must be observed for better statistical checks. In fact all clusters in distance category 4 are included in our current programmes.

The 11 unidentified sources can probably be explained as distant radio galaxies or quasars beyond the limit of the Palomar Sky Atlas prints. No cases were found of a likely spatial displacement from a bright galaxy. However, there are some indications that this may not be the complete explanation and a special investigation of strong unidentified sources is desirable.

Finally, none of the clusters investigated show evidence of general intergalactic emission. When it occurred, the radio emitting area occupied only a very small fraction of the total area of the cluster.

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VII. References

Abell, G. O. (1958).—*Astrophys. J. Suppl. Ser.* **3**, No. 31.
Clarke, Margaret E., Bolton, J. G., and Shimmins, A. J. (1966).—*Aust. J. Phys.* **19**, 375.
Day, G. A., Shimmins, A. J., Ekers, R. D., and Cole, D. J. (1966).—*Aust. J. Phys.* **19**, 35.
Gower, J. F. R., Scott, P. F., and Wills, D. (1967).—*Mem. R. astr. Soc.* **71**, 49.
Kellermann, K. I. (1964).—*Astrophys. J.* **140**, 969.
Longair, M. S., and Scott, P. F. (1965).—*Mon. Not. R. astr. Soc.* **130**, 379.
Maltby, P., Matthews, T. A., and Moffet, A. T. (1963).—*Astrophys. J.* **137**, 153.
Mills, B. Y. (1960).—*Aust. J. Phys.* **13**, 550.
Mills, B. Y., Slee, O. B., and Hill, E. R. (1958).—*Aust. J. Phys.* **11**, 360.
Minkowski, R. L. (1960).—*Proc. natn. Acad. Sci. U.S.A.* **46**, 13.
Schmidt, M. (1965).—*Astrophys. J.* **141**, 1.
Shimmins, A. J., Day, G. A., Ekers, R. D., and Cole, D. J. (1966).—*Aust. J. Phys.* **19**, 837.
Wyllie, D. V. (1968).—An absolute flux density scale at 408 MHz. *Mon. Not. R. astr. Soc.* (in press).