RADIO EMISSION FROM CLUSTERS OF GALAXIES

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Summary

From Abell's (1958) list of clusters of galaxies, 137 clusters of distance group 5 were observed at 1410 MHz with the 210 ft radio telescope of the Australian National Radio Astronomy Observatory at Parkes. The detected radio sources were further confirmed by observations at 2650 MHz with the same telescope and at 408 MHz with the east–west arm of the Mills Cross at the Molonglo Radio Astronomical Observatory. A total of 25 radio sources was detected within 5′ arc of the centres of corresponding clusters of galaxies, while the mathematical expectation of the number of random coincidences with clusters is about two or three. The dimensions of most of the radio sources associated with clusters of galaxies are less than 1′ arc, while the dimensions of the clusters are about 25′ arc, which means that, as a rule, a single galaxy of the cluster is responsible for the observed radio emission. There is no correlation between the presence of the radio emission and the richness of the cluster of galaxies.

I. Introduction

The fact that most of the prominent radio galaxies are members of clusters of galaxies suggests that other clusters should be examined for the presence of radio emission. Identifications of catalogued radio sources with clusters of galaxies have been made by Mills (1960), van den Berg (1961), Tovmassian and Shahbazian (1961), Matthews, Morgan, and Schmidt (1964), and Pilkington (1964). An investigation of these previously suggested identifications is reported in the following paper (pp. 725–30, present issue). The first special search for radio emission in the direction of a large number of selected clusters of galaxies was made by Fomalont and Rogstad (1966). They investigated 120 clusters of galaxies, mainly of distance group 3 or nearer, from Abell's (1958) catalogue of clusters of galaxies. Sholomitsky and Kokin (1965) earlier reported observations of 15 clusters of galaxies.

In the present survey 137 clusters of galaxies of distance group 5 from Abell's catalogue were observed. The observed clusters (listed in Table 1) are those included by Abell in statistically homogeneous samples and situated south of the celestial equator. Practically all clusters of this group were observed, except the few that were near the Sun during the period of observations in August–October 1965.

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II. Observations

Observations were made with the 210 ft radio telescope of the Australian National Radio Astronomy Observatory at Parkes, N.S.W., and with the 1-mile-long east–west arm of the Mills Cross at the Molonglo Radio Astronomical Observatory of the University of Sydney.

Table 1

observed clusters

No.	Cluster	No.	Cluster	No.	Cluster	No.	Cluster
1	A303	36	A1584	71	A2377	106	A2543
2	329	37	1603	72	2383	107	2546
3	367	38	1605	73	2385	108	2547
4	371	39	1606	74	2394	109	2548
5	380	40	1635	75	2400	110	2549
6	420	41	1754	76	2401	111	2550
7	423	42	1772	77	2420	112	2554
8	438	43	1796	78	2426	113	2555
9	440	44	1876	79	2428	114	2556
10	458	45	1882	80	2434	115	2557
11	474	46	2035	81	2436	116	2559
12	477	47	2045	82	2438	117	2566
13	484	48	2094	83	2441	118	2569
14	487	49	2333	84	2442	119	2579
15	512	50	2338	85	2446	120	2580
16	522	51	2339	86	2455	121	2583
17	524	52	2340	87	2456	122	2587
18	531	53	2341	88	2461	123	2599
19	536	54	2343	89	2480	124	2600
20	543	55	2345	90	2490	125	2605
21	944	56	2351	91	2496	126	2606
22	1041	57	2353	92	2499	127	2608
23	1075	58	2354	93	2500	128	2613
24	1200	59	2356	94	2509	129	2638
25	1252	60	2357	95	2518	130	2644
26	1295	61	2361	96	2521	131	2654
27	1309	62	2362	97	2523	132	2655
28	1323	63	2363	98	2529	133	2659
29	1426	64	2365	99	2531	134	2686
30	1448	65	2367	100	2533	135	2697
31	1469	66	2369	101	2538	136	2709
32	1502	67	2371	102	2539	137	2710
33	1521	68	2374	103	2540		
34	1535	69	2375	104	2541		
35	1555	70	2376	105	2542		

The basic survey of all the clusters of galaxies listed in Table 1 was made at Parkes at a frequency of 1410 MHz late in August 1965. The beamwidth of the 210 ft dish at 21 cm is equal to 14′ arc, which is about half the mean diameter of clusters of distance group 5 (24′ arc). This favourable ratio of the beamwidth to the diameter for clusters of group 5 was the reason for choosing this group for investigation. The receiver described by Gardner and Milne (1963) was used for the observations. It consists of a parametric amplifier followed by a crystal mixer. The input of the receiver was switched between the aerial feed and a backward-looking reference horn. With the overall system noise temperature of 110°K, the 10 MHz bandwidth, and the 2 sec time constant, the peak-to-peak fluctuations were about 0·15 degK. The general observing procedure consisted of making from two to four scans through the centre of the cluster under investigation, both in right ascension and in declination, with a scan rate of 0·5 deg/min. When one of the scans revealed the presence of a radio source, a perpendicular scan through the determined right ascension (or declination) was made to measure the other coordinate. Sometimes it was necessary to make a further scan in declination (or in right ascension) through the determined right ascension (or declination). The length of each scan was between 1° and 2°. With such multiple observations it was possible to detect and measure both the position and the flux density of sources with flux densities greater than about 0·2 flux units (1 f.u. = 10^{-26} W m^{-2} Hz^{-1}). A sample observation of such a weak source is presented in Figure 1, in which the record of the cluster A1772 is reproduced. The radio source detected has a flux density of 0·26 f.u.

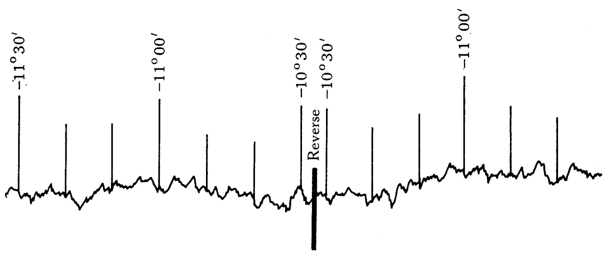

Fig. 1.—Record at 21 cm of the source in cluster A1772 (epoch 1965). Its flux density is 0·26 f.u. and it is one of the weakest sources detected.

Early in September 1965, the second set of observations was carried out at 2650 MHz using the 210 ft telescope and the degenerate parametric receiver described by Cooper, Cousins, and Gruner (1964). Switching between the aerial feed and a sky horn reference was used. The system noise temperature was 150°K and the i.f. bandwidth about 40 MHz. The sensitivity of the equipment with a 2 sec time constant was such that sources with flux densities in excess of 0·3 f.u. could be recorded. This set of observations was mainly restricted to those clusters from which radio emission was detected during the previous observations at 21 cm. The aim of these 11 cm observations, where the beamwidth of the telescope is 7′·5 arc, was to obtain more precise positions of the sources detected at 21 cm. At the same time they provided a measurement of the spectra of the sources. The observing procedure was similar to that at 21 cm except that the positions of the sources under investigation were roughly known. In Figure 2 the scan through the cluster A1772 is shown. The flux density of the radio source at 11 cm is 0·16 f.u.

Further improvement in the measurement of the right ascensions of the detected sources was achieved by observations at 75 cm with the east–west arm of the Mills Cross at Molonglo. These observations were made in October 1965. The beamwidth of the telescope is about 1′·5 arc in right ascension and about 4° in declination. Observations with such a large beamwidth in one coordinate were still valuable, since the declinations of the sources were already known reasonably accurately from the observations at 21 and 11 cm. Radio sources with flux densities greater than about 1·0 f.u. at 75 cm could be easily recognized on the records. The record of the radio source in the position of the cluster A531 is shown in Figure 3(*a*). Its flux density is 1·1 f.u. at 75 cm. Figure 3(*b*) shows the record of the source identified with cluster A371. Its flux density is 0·8 f.u. Almost all sources were observed only once during their transit through the beam of the telescope.

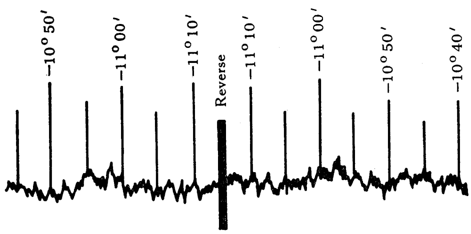

Fig. 2.—Record at 11 cm of the source in cluster A1772 (epoch 1965). Its flux density is 0·16 f.u. (11 of the 22 sources detected at 11 cm had flux densities less than 0·2 f.u.).

Observations at 75 cm supplied a third point for the determination of spectral index and significantly decreased the upper limit of dimensions for unresolved sources.

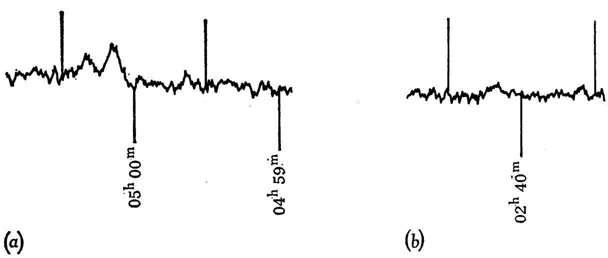

Fig. 3.—Records at 75 cm of the sources in clusters (*a*) A531 and (*b*) A371 (epoch 1965). The respective flux densities are 1·1 and 0·8 f.u.

The gain of all receivers was checked by injection of a known signal from a noise discharge tube into the input of the receivers. (In the case of the 75 cm observations the calibration signal was injected into one of the preamplifiers of the system.) The overall calibration of the radio telescopes was checked a few times a day by observations of sources with well-known flux densities and positions (Hydra A, Hercules A, 3C 33, 3C 71, 3C 98, 3C 212, 3C 327, 3C 353, 3C 444, 04−2*22*).

The accuracy of the flux measurements for the weak sources is of the order of 30% at all three wavelengths. The accuracy of the position measurements is about 1′·5 to 2′ arc for the sources observed at 11 and 21 cm, while the accuracy of right ascensions determined at 75 cm is better than 1′ arc.

III. Results

Previous identifications of radio sources with galaxies that belong to clusters showed that the sources usually coincided with centrally situated bright galaxies of the corresponding clusters. For this reason, in the present search for the radio emission from clusters of galaxies the main attention was focused on the central parts of the clusters. Assuming that the central galaxy of a cluster may not be situated exactly in the geometrical centre of the cluster (given with some uncertainty by Abell), and taking into account the errors of our positional measurements, it may be expected that a radio source associated with a cluster will be observed within a radius of 5′ arc of its centre. Only in such cases were the detected radio sources considered to be identified with the corresponding clusters.

To avoid false conclusions the expected number of chance coincidences of radio sources with clusters of galaxies must be calculated. For this purpose the number of radio sources per unit solid angle having flux densities greater than a given value must be known. The number of sources per steradian can be estimated using the source counts of the Parkes catalogue of radio sources (Bolton, Gardner, and Mackey 1964; Price and Milne 1965; Day *et al.* 1966), which are based on observations with the same telescope and receivers. The catalogue extends to sources with flux densities as low as 0·5 f.u. at 21 cm. By linearly extrapolating the $(\log N)/(\log S)$ curves given in the catalogue to sources with flux densities of 0·2 f.u., it is found that the expected number of sources with flux densities greater than 0·2 f.u. is about 5000 per steradian. For a random distribution of radio sources the mathematical expectation of the number of sources in 137 areas each 5′ arc in diameter is thus less than 5. In fact, in 25 cases the detected radio sources are situated not further than 5′ arc from the centres of the corresponding clusters, which is much more than the expected number.

More than half of the sources detected at 21 cm have flux densities between 0·2 and 0·4 f.u., so that, if they were observed at this wavelength only, the existence of some of them could not be considered as very reliable owing to probable confusion. However, the reality of the sources was confirmed by their observation at 11 and 75 cm with much better angular resolution.

Of the 25 sources detected, 24 were found in our basic survey at 21 cm. Of these 24 sources, 9 were also observed at both 11 and 75 cm, another 8 at 11 cm only, and 3 others at 75 cm only. The remaining 4 sources, observed at 21 cm only, are relatively strong and well defined. One more source (A2606) was observed at 11 and 75 cm. The 21 cm record of it was of no use owing to interference.

All 25 radio sources detected in the central regions of the observed clusters of galaxies are listed in Table 2. In the first column of the table Abell's designation of the cluster of galaxies is given, while column 2 gives the richness group of the cluster. Columns 3 and 4 contain the right ascensions and declinations of the clusters, for epoch 1950, and columns 5 and 6 the displacements in right ascension and declination of the position of the radio source (in min of arc) with respect to the cluster centre (positive displacement is to the east for right ascension and to the north for declination). The right ascensions and declinations of the sources were determined

TABLE 2

CLUSTERS OF GALAXIES WITH DETECTED RADIO EMISSION

(1) Cluster No.	(2) Richness Group	(3) Cluster Position (1950·0) R.A. h m s	(4) Dec. ° ′	(5) Displacement of Source Position R.A. ′	(6) Dec. ′	(7) Flux Densities* (flux units) 11 cm	(8) 21 cm	(9) 75 cm	(10) Spectral Index	(11) Remarks†
A367	1	02 34 18	−19 36·9	0	+1	—	0·28(4)	0·8(1)	0·8	1
371	1	02 38 42	−11 26·2	0	0	0·15(1)	0·30(2)	0·8(1)	0·8	2
420	1	03 06 56	−11 42·8	0	0	—	0·24(4)	1·5(1)	1·6	
474	1	04 05 33	−16 49·4	−1	+2	0·17(7)	0·25(2)	0·8(1)	0·8	3
531	1	04 58 48	−03 36·9	+1	0	0·21(5)	0·38(4)	1·1(1)	0·9	
944	1	10 08 39	−01 47·7	−4	+2	—	1·40(5)	—	—	
1041	1	10 30 26	−08 38·0	+2	+4	—	0·43(5)	—	—	
1772	1	13 39 26	−10 51·1	−1	0	0·16(5)	0·26(7)	—	0·8	
2094	1	15 34 01	−01 52·4	0	0	0·25(7)	0·43(4)	—	0·9	
2333	1	20 58 01	−19 26·2	−2	−3	—	0·42(7)	—	—	
2343	1	21 19 49	−05 37·2	0	−1	0·36(4)	0·51(6)	1·4(1)	0·7	
2345	2	21 24 22	−12 22·3	−1	0	0·40(4)	0·69(6)	1·4(1)	0·7	4
2354	2	21 33 08	−15 09·0	−3	+3	0·16(8)	0·31(4)	1·3(1)	1·1	
2363	1	21 38 22	−08 33·2	+5	+1	0·23(5)	0·38(10)	0·8(1)	0·7	
2365	2	21 40 12	−18 55·4	+3	+6	0·30(6)	0·54(4)	1·7(1)	0·9	5

2374	1	21	42	33	−07	40·2	+1	+1	0·16(7)	0·24(6)	—	0·7	
2456	1	22	32	25	−15	33·8	+4	−1	0·22(8)	0·40(4)	1·8(1)	1·0	
2480	1	22	43	24	−17	57·3	−3	+3	0·35(5)	0·56(4)	1·8(1)	0·9	
2523	1	23	00	57	−17	26·5	−7	+1	0·17(5)	0·25(4)	—	0·6	6
2538	1	23	05	58	−20	09·3	0	+2	0·18(8)	0·29(8)	<0·7(1)	0·8	7
2547	2	23	08	10	−21	24·3	+1	−1	0·27(4)	0·43(6)	1·0(1)	0·7	8
2557	1	23	10	26	−17	15·2	−8	0	—	0·31(7)	—	—	9
2559	1	23	10	30	−13	58·1	+2	−2	0·19(5)	0·28(4)	—	0·6	
2569	1	23	15	17	−13	09·0	−4	+2	0·15(6)	0·25(6)	—	0·8	
2580	1	23	19	03	−23	30·9	−1	+3	0·15(6)	0·22(7)	<0·7(1)	0·5	
2587	2	23	20	56	−22	41·8	−2	−2	0·20(6)	0·29(8)	0·7(1)	0·7	
2606	1	23	27	01	−21	29·6	0	0	0·55(4)	C	2·3(1)	0·8	10
2644	1	23	38	33	−00	11·5	−1	−1	0·42(4)	0·79(4)	—	1·0	
2709	1	00	04	04	−10	15·3	+4	−2	—	0·42(4)	—	—	

* C, record confused.

† Relevant remarks are:

1. There is a nearby stronger source 02−*10* at R.A. $02^h 35^m 25^s$, Dec. −19° 45′.
2. There is a nearby stronger source at R.A. $02^h 37^m 02^s$, Dec. −11° 41′.
3. There is a nearby stronger source at R.A. $04^h 06^m 36^s$ and the same declination.
4. There is another source at R.A. $21^h 24^m 39^s$, Dec. −12° 04′.
5. Source is at a distance of 6′ arc from the centre of the cluster and is considered as a chance coincidence.
6. Source is at a distance of 7′ arc from the centre of the cluster and is considered as a chance coincidence.
7. There is a second source at R.A. $23^h 05^m 32^s$, Dec. −20° 06′.
8. Size in right ascension is about 2′ arc.
9. Source is at a distance of 8′ arc from the centre of the cluster and is probably a chance coincidence.
10. There is a nearby stronger source at R.A. $23^h 26^m 00^s$, Dec. −21° 22′.

by averaging the data on individual scans. Where results were available with better resolution the data based on these are given. It was assumed that the same source was observed at different frequencies if the positions obtained were within the limits of errors. In columns 7, 8, and 9 of Table 2 the flux densities of the sources at 11, 21, and 75 cm respectively are given together with the number of scans (in parentheses) used for the determination of the source coordinates. Column 10 gives the

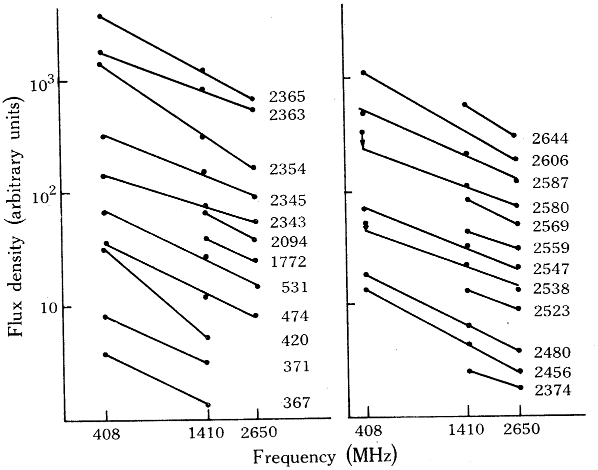

Fig. 4.—Radiofrequency spectra of the sources associated with clusters of galaxies.

spectral index of the source. The last column (11) contains a reference to the remarks given as footnotes to the table. Besides these 25 sources already discussed, another three sources are included in Table 2. They are situated within the area of the corresponding clusters but are at distances of about 6′ to 8′ arc from the centres of the clusters. They are probably associated with the clusters, but the certainty that they are members of the clusters is less.

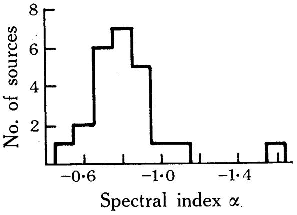

Fig. 5.—The distribution of spectral indices for the sources associated with clusters of galaxies.

Other sources detected are out of the region of the clusters (further than 12′ arc from the centres) and are not included in the discussion.

Thus the number of radio sources situated within 5′ arc around the centres of corresponding clusters is equal to 25, which is much more than the expected number of chance coincidences. This permits us to conclude that the majority of the cases of coincidences of positions of radio sources and clusters of galaxies are not casual but are real physical associations of the objects of both types.

It is remarkable that only 1 source out of 25 is resolved by our observations. All the others are unresolved. In the 13 cases of sources observed at 75 cm it means that their dimensions are not larger than 1′ arc. The dimensions of the remaining 12 sources are not larger than about 5′ arc.

The spectra of those sources observed at, at least, two frequencies are presented in Figure 4. Each spectrum is denoted by the number of the cluster with which the corresponding radio source is identified. The distribution of spectral indices is shown in Figure 5. We see that most of the sources have spectral indices near $-0 \cdot 8$.

IV. Discussion

The present survey of 137 clusters of galaxies of distance group 5 from Abell's (1958) catalogue has shown that about 18% of them (25 clusters) have measurable radio emission with a flux density greater than $0 \cdot 2$ f.u. at 21 cm. Observations made to the same limit of detection by Fomalont and Rogstad (1966) resulted in the detection of radio emission from 39% of the clusters of distance group 3. This latter survey was made with an interferometer at almost the same frequency (1445 MHz) as the present survey. The percentages of clusters with detected radio emission in the two surveys are consistent with each other, because the clusters of distance group 5 are on the average about twice as distant as clusters of distance group 3. If the clusters of distance group 3 were moved to the distance of group 5, only those sources that now have fluxes greater than $0 \cdot 8$ f.u. could be detected. The number of such sources in Fomalont and Rogstad's list is equal to 14% of the number of clusters observed.

Some of the earlier identifications of radio sources with individual galaxies in clusters of galaxies suggest that usually a single peculiar galaxy in a cluster is responsible for the observed radio emission. The present observations confirm this idea, since the detected radio sources are generally unresolved. The dimensions of the majority of them are less than 1′ arc while the dimensions of the clusters studied are about 25′ arc. This means that the radio emission, which comes from a very limited volume of space in the central region of the cluster, originates in a single or at most in two galaxies and is not due to the integrated emission of many members of the cluster. Thus there is no doubt that in almost all cases the bright central galaxies of the clusters are responsible for the observed radio emission.

All the observed clusters of galaxies will be inspected on the Palomar Sky Survey prints to try to identify the detected sources with individual members of the clusters and to see whether there is any difference between the appearance of the clusters that possess radio emission and those clusters that have no measurable radio emission.

Table 3 shows the total number and percentage of the observed clusters in each richness class and the corresponding values for those clusters with detectable radio emission. For each group the percentages agree within the statistical errors, i.e. there is no correlation between the presence of radio emission and the richness of the cluster. Calculation of the same values for the clusters of galaxies observed by

Fomalont and Rogstad also shows, as they themselves have pointed out, the absence of a relation between the presence of radio emission and the richness of the clusters. The same conclusion was obtained earlier by Tovmassian (1962) and Tovmassian

TABLE 3

NUMBER AND PERCENTAGE OF OBSERVED CLUSTERS IN EACH RICHNESS CLASS

Richness Group	Number of Clusters Observed	Percentage in Group	Number of Clusters with Radio Emission	Percentage in Group
1	109	80	21	84
2	26	19	4	16
3	2	1	0	0
All groups	137	100	25	100

and Kalloglian (1962), who have made identifications of catalogued radio sources with clusters of galaxies and probable identifications with individual members of clusters.

V. Acknowledgments

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VI. References

Abell, G. O. (1958).—*Astrophys. J. Suppl. Ser.* **3**, 211.

van den Berg, S. (1961).—*Astrophys. J.* **134**, 970.

Bolton, J. G., Gardner, F. F., and Mackey, M. B. (1964).—*Aust. J. Phys.* **17**, 340.

Cooper, B. F. C., Cousins, T. E., and Gruner, L. (1964).—*Proc. Instn Radio Engrs Aust.* **25**, 221.

Day, G. A., Shimmins, A. J., Ekers, R. D., and Cole, D. J. (1966).—*Aust. J. Phys.* **19**, 35.

Fomalont, E. B., and Rogstad, D. H. (1966).—*Obs. Owens Valley Radio Observ.* No. 5/1966, p. 1.

Gardner, F. F., and Milne, D. K. (1963).—*Proc. Instn Radio Engrs Aust.* **24**, 127.

Matthews, T. A., Morgan, W. W., and Schmidt, M. (1964).—*Astrophys. J.* **140**, 35.

Mills, B. Y. (1960).—*Aust. J. Phys.* **13**, 550.

Pilkington, J. D. H. (1964).—*Mon. Not. R. astr. Soc.* **128**, 103.

Price, R. M., and Milne, D. K. (1965).—*Aust. J. Phys.* **18**, 329.

Sholomitsky, G. B., and Kokin, Y. F. (1965).—*Astr. Zh.* **42**, 674.

Tovmassian, H. M. (1962).—*Soobshch. byurak. Obs.* **31**, 19.

Tovmassian, H. M., and Kalloglian, A. T. (1962).—*Soobshch. byurak. Obs.* **31**, 31.

Tovmassian, H. M., and Shahbazian, R. K. (1961).—*Izv. Akad. Nauk armyan. SSR* **14**, 121.