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EXTRAGALACTIC RADIO SOURCES WITH STEEP LOW FREQUENCY SPECTRA

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SUMMARY

A asmple of radio sources at high galactic latitudes with spectral indices $\alpha_{38}^{178} > 1{\cdot}2$ has been selected; 38 per cent are found to be associated with Abell's rich clusters of galaxies. The data support a direct relation between the steep radio spectra and X-ray emission from the clusters. This result is most easily explained by ascribing a thermal origin to the X-ray emission.

1. INTRODUCTION

Many attempts have been made in recent years to correlate the radio spectral index, α (defined as $S \propto \nu^{-\alpha}$), of extragalactic radio sources with their other properties. Significant results have been hard to find and only three distinct categories have been isolated. Kellermann, Pauliny-Toth & Williams (1969) found some evidence that, for sources in the 3C catalogue, large values of α were associated with large values of intrinsic radio luminosity, P. On the other hand, many authors have found that sources having flat spectra, and in some cases negative values of α at high frequencies, are associated with quasars. Assuming their redshifts to be cosmological in nature, these sources also have the largest known values of P. The third category comprises a very small number of sources associated with clusters of galaxies and having very steep spectra at low radio frequencies (van den Bergh 1965) including the radio sources associated with the Coma cluster (Willson 1970) and Abell 2256 (Costain, Bridle & Feldman 1972). Their intrinsic radio luminosities are comparatively small.

In this paper we attempt a systematic investigation of sources having very steep spectra at low frequencies with the aim of establishing whether or not they constitute a well-defined class.

2. THE SELECTION PROCEDURE

It was decided to examine only those sources having the largest values of α. The distribution of spectral indices at 178 MHz given by Williams & Bridle (1967) for the sources in the 3C catalogue indicates that only ~ 2 per cent of all sources have $\alpha > 1{\cdot}2$ at this frequency. To obtain a reasonable sample of sources it was therefore necessary to use catalogues with a much lower limiting flux density. The largest such catalogues at low frequencies are the 4C survey (Pilkington & Scott 1965; Gower, Scott & Wills 1967) and the 38 MHz survey of Williams, Kenderdine & Baldwin (1966). These were used as the basis of the search and from them one would expect to find about 40 sources having $\alpha_{38}^{178} > 1{\cdot}2$. The limiting flux densities in the two surveys, $2{\cdot}0 \times 10^{-26}$ W m^{-2} Hz^{-1} and 14×10^{-26} W m^{-2} Hz^{-1}, are such that the detection limits for sources of this type are similar.

To prevent bias of the sample it was necessary to allow for the fact that the 4C survey was an interferometric one, sources having angular sizes $\gtrsim 2$ arc min having catalogued flux densities lower than their true values. Such sources would have artificially steep spectra and would tend to be at comparatively small distances with low values of P. A further precaution was the omission of obscured areas of sky so as to facilitate the subsequent search for associated optical objects.

The selection procedure was as follows:

(i) From the 38 MHz and 4C interferometer surveys a list was compiled of all sources having apparent spectral indices $> 1{\cdot}10$ between these frequencies.

(ii) Sources in this list falling outside the area within which Abell (1958) believes his catalogue of clusters of galaxies to be complete and also those south of declination $+05°$ (and not covered by the 81·5 MHz survey referred to below) were deleted.

(iii) For the remaining sources, data on their flux densities at other frequencies were collected, in particular from the work of M. A. Smith (Ph.D. thesis, Cambridge University) at 81·5 MHz, Caswell & Crowther (1969) at 178 MHz (the 4 CT survey) and the compilation of data at other frequencies by Dixon (1970). The data used were all from pencil beam surveys and therefore largely unaffected by the appreciable angular sizes of some sources.

(iv) The list was then reduced to sources having values of $\alpha > 1{\cdot}20$ between 38 and 178 MHz, taking into account the additional data provided by (iii), but sources were rejected from this sample if their inclusion was based on (a) a 38 MHz flux density unsupported by other data, or (b) a 38 MHz flux density and a 178 MHz interferometric flux density unsupported by other data.
If, for instance, the spectral index between 38 and 81·5 MHz was significantly less that 1·2 then the source was rejected.

Where a choice between a 178 MHz flux density from the interferometer (4C) and the pencil beam (4 CT) surveys could be made, the latter was preferred on the grounds that it was unaffected by the angular size of the sources and that the confusion level was smaller. It was to allow for the possible differences in flux density between these two surveys that the range of $\alpha > 1{\cdot}10$ used in (i) was less restrictive.

(v) A final selection was made in which sources were rejected if there was poor positional agreement at different frequencies or where there was evidence that an apparently single source at, say, 38 MHz might be associated with more than one source at higher frequencies thus leading to a spuriously large value of α. Some of the sources which fell in this category (e.g. 4C 13·50 and 4C 16·43) may indeed have values of $\alpha > 1{\cdot}20$ but the present evidence is insufficient to decide with certainty.

We believe that all of the 29 remaining sources (which are listed in Table I) have genuinely steep spectra in the frequency range 38–178 MHz. Errors in the flux densities will naturally introduce into the sample some objects having values of α slightly less than 1·20 and remove from it some having α slightly greater than 1·20. This is unlikely to affect conclusions concerning the nature of these sources unless their properties are a very rapidly varying function of α.

Because of the rigorous selection procedure this sample is almost certainly not complete. We find it hard to assess how many sources may have been lost from the sample but believe the number may be about 10.

TABLE I

Data on the 29 sources with steep spectra

Source number or author	Frequency MHz	Flux density 10^{-26} W m^{-2} Hz^{-1}	R.A. h	m	s	Declination °	′	Spectral index α_{38}^{178}
	38	52 (1)						
	81·5	26 (1)						
4C 12·1	178	7·4	00	01	07·2	12	48·0	
4C (T)	178	7·8	00	01	26	12	41·1	1·27
Munro	408	3·9	00	01	07·0	12	49·8	
OB+102	1415	1·28	00	01	09	12	52	
	38	23						
	81·5	<8						1·54
4C 23·1	178	2·1	00	19	47·7	23	04·4	
	38	20						
	81·5	~5						
4C 20·4	178	2·4	00	43	53·0	20	14·0	
VRO 20·00·02	610	1·2	00	43	45	20	16·8	
PKS 0043+20	635	1·6	00	43	49	20	12	1·40
NRAO 0039	750	1·24	00	44	00·0	20	14·3	
NRAO 0039	1400	0·74						
PKS 0043+20	1410	0·8						
PKS 0043+20	2650	0·3						
Merkelyn *et al.*	2700	0·36	00	43	52·2	20	11·7	
	38	24						
	81·5	7·1						
4C 20·9	178	3·0	01	53	49·4	20	48·5	
VRO 20·01·03	610	1·1	01	53	30	20	45·1	1·38
PKS 0153+20	635	0·9	01	53	47	20	49	
PKS 0153+20	1410	0·4						
PKS 0153+20	2650	0·4						
	38	27						
	81·5	9·1						
4C 17·11	178	4·0	02	13	47·5	17	51·6	
Munro	408	2·8	02	13	47·4	17	52·3	1·25
PKS 0213+17	408	2·1	02	13	52	17	52·6	
VRO 17·02·01	610	1·6	02	13	43	17	45·6	
PKS 0213+17	1410	0·7						
PKS 0213+17	2650	0·5						
	38	30 (2)						
	81·5	11 (2)						
4C 13·17	178	3·9 (2)	02	56	52·9	13	41·4	
4C (T)	178	3·5 (2)	02	55	50	13	21·4	
PKS 0255+13	408	1·8	02	55	49	13	22·1	1·32
PKS 0255+13	1410	0·5						
OD+193	1415	0·40	02	55	40	13	31	
FR 26	1445	0·52						
PKS 0255+13	2650	0·3						
	38	35						
	81·5	19						
MSH 03+006	85	24	03	34	06	09	51	1·22
4C 09·15	178	2·4	03	35	33·8	09	46·1	
4C (T)	178	5·3	03	35	36	09	52·7	
OE+060	1415	0·47	03	35	35	09	56	

Table I—*continued*

Source number or author	Frequency MHz	Flux density 10^{-26} W m^{-2} Hz^{-1}	R.A. h	m	s	Declination °	′	Spectral index α_{38}^{178}
	38	40						
	81·5	13						
4C 63·10	178	3·9	06	59	45·4	63	27·1	1·51
4C (T)	178	3·9	06	59	48	63	22·2	
	38	33						
NB 74·13	81·5	9·2	07	35	28	74	18·7	1·69
4C 74·13	178	2·9	07	35	36·3	74	20·5	
4C (T)	178	2·2	07	35	38	74	19·8	
	38	18						
4C 66·7	178	2·3	08	10	17·9	66	35·7	1·38
4C (T)	178	2·0	08	10	19	66	36·7	
	38	28						
	81·5	10						1·37
4C 06·36	178	3·5	09	27	37·7	06	29·5	
Munro	408	1·3	09	27	38·7	06	29·0	
	38	16	09	42		67	36	
	81·5	6						1·32
4C 67·17·1	178	1·9	09	42	05	67	43·2	
4C (T)	178	2·1						
	38	35						
	81·5	13						1·29
4C 58·22	178	4·0	11	40	08·5	58	21·3	
4C (T)	178	5·1	11	40	11	58	25·3	
	10	150						
	22	95						
WKB 1304/46·8	38	32	13	04		46	48	1·76
	81·5	10						
4C	178	1·4	13	04	31·1	46	52·9	
	38	27						
	81·5	8						
4C 26·41	178	2·2	13	39	35·6	26	38·7	
WK 328	408	1·37	13	39	31·4	26	38·0	1·31
B2 1339 26 B1	408	1·26	13	39	33·5	26	37·6	
OP+265	1415	0·26	13	39	27	26	29	
FR 80	1445	0·4						
	38	27						
	81·5	9						1·31
4C 23·37	178	2·0	14	13	37·9	23	12·7	
OQ+223	1415	0·25	14	13	46	23	12	
	38	50						
	81·5	18						
4C 38·39	178	3·5	14	24	03·9	38	01·2	1·74
4C (T)	178	~4·5						
B2 1424 38	408	0·67	14	24	03·1	38	02·6	
	38	20						
	81·5	8						1·20
4C 23·39	178	2·3	14	43	20·9	23	55·1	
OQ+272	1415	0·35	14	43	33	23	19	

TABLE I—*continued*

Source number or author	Frequency MHz	Flux density 10^{-26} W m^{-2} Hz^{-1}	R.A. h	m	s	Declination °	′	Spectral index α_{38}^{178}
	38	37						
	81·5	~18						
MSH 14+014	85	19	14	45	00	07	54	
4C 07·38	178	4·0	14	44	04·0	07	40·1	
4C (T)	178	3·9						
Clarke *et al.*	408	2·3	14	44	04·5			1·22
Munro	408	2·2	14	44	04·5	07	41·7	
PKS 1444+07	408	3·0	14	44	03	07	41·1	
PKS 1444+07	1410	0·6						
OQ+073	1415	0·74	14	44	06	07	40	
PKS 1444+07	2650	0·3						
	38	28						
	81·5	10						
4C 10·40	178	3·1	15	09	02·9	10	13·4	
4C (T)	178	2·9	15	09	46	10	16·1	1·49
Clarke *et al.*	408	1·7	15	09	03·9			
Munro	408	2·0	15	09	04·2	10	13·0	
OR+117	1415	0·37	15	09	04	10	11	
	38	119						
	81·5	52						
MSH 15+007	85	50	15	19	18	07	55	
4C 07·41	178	12	15	19	23·8	07	51·2	
4C (T)	178	11·3	15	19	22	07	53·1	
3C 318·1	178	11·0	15	19	23·8	07	05·3	1·51
Clarke *et al.*	408	2·4	15	19	24·1			
PKS 1519+07	408	3·4	15	19	20	07	52·8	
NRAO 477	750	0·68				07	50	
NRAO 477	1400	0·20						
PKS 1519+07	1410	<0·5						
	38	25						
	81·5	8						1·31
4C 45·30	178	3·5	15	55	46·2	45	30·1	
	38	22						
	81·5	7						
4C 19·53	178	2·7	16	08	55·1	19	0·42	1·38
Munro	408	1·4	16	08	54·7	19	07·2	
H 1608+19	750	1·7	16	08	21·2	19	05·6	
	38	17						
4C 71·16	178	2·4	16	45	01·8	71	03·9	1·32
4C (T)	178	2·1	16	44	35	71	04·4	
	22	77 (3)						
	38	22 (3)						1·75
NB 78·26	81·5	7·1	17	06	10	78	44	
WKB 1712/64·1	38	54	17	12		64	06	
	81·5	13						
4C 64·20·1	178	~1·4						1·58
4C (T)	178	4·7	17	12	25	64	07·0	
FR 107	1445	0·8						

TABLE I—*continued*

Source number or author	Frequency MHz	Flux density 10^{-26} W m^{-2} Hz^{-1}	R.A. h	m	s	Declination °	′	Spectral index α_{38}^{178}
	38	22						
	81·5	6						
4C 08·66	178	2·1	22	17	38·2	08	36·9	1·55
4C (T)	178	2·1						
Munro	408	<0·5						
	38	55						
	81·5	25						
3C 464	159	8·0	23	33	58	20	53	1·48
4C 20·57	178	5·2	23	33	59·9	20	51·5	
Slingo	408	1·1	23	33	59·5	20	51·5	
	38	31						
	81·5	11						
4C 19·78	178	4·0	23	54	58·6	19	00·2	1·35
H 2354+18	750	0·8	23	54	56·2	18	59·7	
H 2354+18	1410	0·5						
OZ+192	1415	0·44	23	54	59	18	51	

Notes to Table I

(1) The estimated contribution from 4C 12·2 has been subtracted.

(2) The flux densities include a contribution from the source OD+194.

(3) The flux densities have been corrected for the contribution from NB 79·34 (4C 79·16).

Data not referred to elsewhere:

408 MHz Clarke, T. W., Frater, R. H., Large, M. I., Munro, R. E. B. & Murdoch, H. S., 1969. *Aust. J. Phys. astrophys. Suppl. No.* 10.

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3. THE NATURE OF THE SOURCES

3.1. *Identification with galaxies and clusters of galaxies*

An attempt was made to identify the 29 sources with objects on the prints of the National Geographic Society Palomar Sky Survey and details are given in Table II. Some were already known (Pilkington 1964; Wills 1966) to coincide with rich clusters of galaxies in Abell's catalogue (1958) and four others lay close to galaxies brighter than 18^{m} but the errors in the radio positions make it impossible to be sure that they are true identifications.

The criterion used for coincidences with Abell clusters was that found to be significant by Pilkington (1964) and Wills (1966), namely that the radio source should be within 0·3 r_c of the centre of the cluster. The fraction of sources, 38 per cent (11 out of 29), associated with Abell clusters is very much higher than that found in the 4C catalogue as a whole; in Abell's area of completeness north of $\delta = -07°$ the fraction of 4C sources associated with Abell clusters is only 2·2 per cent. The fact that one of the remaining 18 sources, (4C 07·41), is definitely asso-

TABLE II

Optical identifications of the steep spectra sources

Source No.	Identification	Source No.	Identification
4C 06·36	—	4C 23·37	15^{mg} at 4C RA, $\delta+23°\ 16'$
07·38	—	23·39	18^{mg} 1′ Sf 4C position
07·41	NGC 5820 in Zwicky cluster	26·41	Abell 1775
08·66	17^{mg} at 4C RA, $\delta+08°\ 46'$	38·39	Abell 1914
09·15	18^{mg} at 4C RA, $\delta+09°\ 52'$	45·30	—
10·40	—	1304/46·8	Abell 1682
12·1/2	—	58·22	—
13·17	Abell 401	63·10	Abell 566
17·11	—	64·20·1	Abell 2255
19·53	—	66·07	Abell 629
19·78	—	67·17·1	—
20·04	Abell 98	71·16	—
20·09	—	74·13	—
20·57	Abell 2626	NB 78·26	Abell 2256
23·01	Abell 24		

ciated with a cluster of galaxies in Zwicky's catalogue (1961) adds further weight to this result.

In view of its significance we give in Table III a list of 31 sources which have $\alpha > 1 \cdot 2$ but lie *outside* the area of Abell's complete sample. We have not examined data at frequencies other than 38, 81·5 and 178 MHz as closely as for the sources in Table I but many of them must have genuinely steep spectra. It is of interest that even in this sample of 31 sources, where the influence of obscuration is certainly important, four are associated with Abell clusters and one with a cluster in Zwicky's catalogue.

It is clear from this discussion that the distribution of spectral indices among radio sources associated with Abell clusters must differ from that of a sample of all radio sources. Fig. 1 illustrates this with normalized distributions of α at 178 MHz (a) for those sources in the 4C catalogue associated with Abell clusters for which

TABLE III

Sources outside Abell's area of completeness having $\alpha_{38}^{178} > 1 \cdot 2$

Source No.	Identification	Source No.	Identification
4C 09·19		4C 27·54	
09·23		29·06	
10·15·1		31·29	?Zwicky near open cl (pop 178)
10·16		34·16	
12·76	Abell 2396	34·55	
13·66		35·06	Abell 407
15·71		0712·1/ 37·00	?Zwicky MD med compact cl (pop 185)
17·89	Abell 2443	41·07	(= 3C 84) Abell 426
18·62		43·46	?Zwicky near med compact cl (pop 157)
19·70		44·14	
20·13		50·44	
20·37		53·47	
23·18		56·28	
24·15		57·06·1	
25·15		74·06	
26·11			

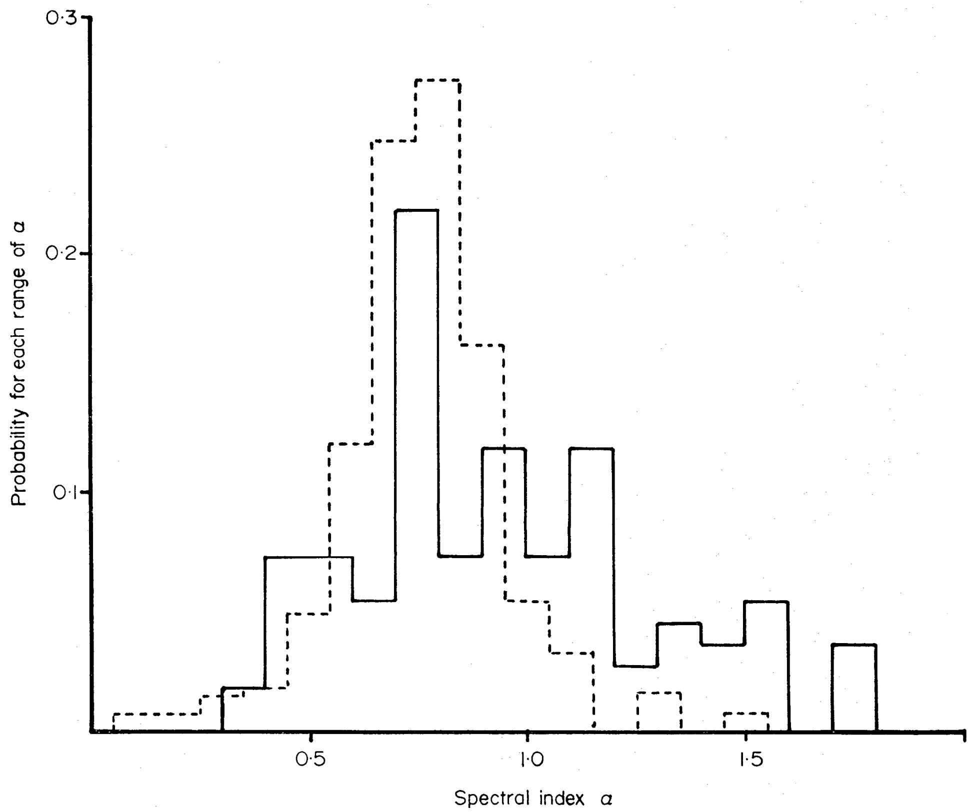

FIG. 1. *The distribution of spectral index at 178 MHz for radio sources in clusters and for all radio sources. Solid line, 4C radio sources in Abell clusters; dotted line, 235 sources from the 3C catalogue (Williams & Bridle 1967).*

definite values of α can be ascribed (66 in number), and (b) for 235 sources in the 3C catalogue having $|b| > 20°$ (Williams & Bridle 1967).

3.2. *The distribution in radio luminosity of the sources with steep spectra*

The large fraction of the sample of steep-spectra sources which are definitely identified with galaxies (12 out of 29) shows at once that these objects are typically of much lower radio luminosity P than a sample of all extragalactic sources. A calculation of the intrinsic radio luminosity of each of the identified sources, based on the magnitude of the 10th brightest galaxy in the cluster and the relationship between this quantity and the redshift given by Abell (1958), shows that 41 per cent of the steep-spectra sources (i.e. those for which P is known) have values of P at 178 MHz all lying between 4×10^{24} and 4×10^{25} W Hz^{-1} ster^{-1} (assuming $H = 50$ km s^{-1} Mpc^{-1}). If the identified sources are typical of the sample as a whole, this type of sample based on spectral index may prove to represent a useful class of objects of known radio properties at distances beyond that at which optical identification is possible. Better positional measurements leading to identification of the remainder of the present sample are therefore desirable.

3.3. *Correlations with richness of cluster and X-ray sources*

Pilkington (1964) showed that the probability of an Abell cluster having an associated radio source was proportional to the number of galaxies in the cluster, suggesting that cluster membership had no influence on the probability of any one

TABLE IV

Richness of cluster R	0	1	2	3
Steep spectra sources	1 (9%)	2 (18%)	7 (64%)	1 (9%)
All Abell cluster sources	16 (33%)	16 (33%)	14 (28%)	3 (6%)

galaxy being a radio source. The statistics (Table IV) for the sources with steep spectra, however, show that they occur preferentially in the richer clusters.

A similar correlation with rich clusters has previously been found in the case of extragalactic X-ray sources (Brecher & Burbidge 1972; Gursky 1972); it is therefore to be expected that the steep spectra sources also correlate with X-ray sources and a number of examples have already been noted (Bridle & Feldman 1972; Costain *et al.* 1972). To establish a *direct* relationship between steepness of the radio spectrum and X-ray emission would clearly be important.

We shall consider clusters of richness, $R>2$ and in Abell's distance groups, $D<3$, in which range the X-ray and radio observations may be expected to be reasonably complete. Abell's statistical sample contains 10 such clusters in the area north of declination $+05°$ (Table V). Four of these have been associated

TABLE V

Abell clusters having $D>3$; $R>2$; $\delta> +05°$, in the statistically complete sample

Abell No.	X-ray source	Radio source	α_{38}^{178}	Comments
401	2 U 0258+13	4C 13·17	1·35	
1035	—	—		
1367	2 U 1144+19	3C 264	0·77	$\alpha = 2\cdot2$ at low frequencies
1656	2 U 1257+28	Coma cluster	1·0	$\alpha = 1\cdot2$ for halo
1904	—	—		
2065	—	—		
2151	—	4C 17·66	0·52	
2199	—	4C 39·45	0·99	
2255	—	4C 64·20·1	1·58	
2256	2 U 1706+78	NB 78·26	1·75	
		Outside Abell's complete sample area.		
426	2 U 0316+14	3C 84	1·16	

with X-ray sources and three are included in the present sample of steep-spectra sources. Two of these steep-spectra sources are seen to fall in the X-ray sample; moreover, both of the other X-ray sources are associated with radio sources which have a steep low frequency component (Bridle & Feldman 1972). Although the sample is very small the data favour a direct relationship between the steep low frequency spectrum and the X-ray emission and we shall consider briefly the implications of this suggestion.

Two mechanisms have been proposed to explain the X-ray emission from clusters of galaxies:

(a) Inverse Compton scattering in which the photons of the 2·7 K blackbody radiation are scattered by high energy electrons originating from the radio source;

(b) Bremsstrahlung from hot gas in the cluster. Either of these mechanisms can provide an explanation of the correlation of steep radio spectra with X-ray sources.

As Bridle & Feldman (1972) have pointed out, in cases where both the X-ray source and the low frequency radio source are known to be extended (e.g. the halo source in the Coma cluster), Compton scattering of the blackbody radiation provides an explanation not only for the X-rays but also, due to the resulting electron energy losses, for the steepened radio spectrum. However, the steep-spectrum component of NGC 1275 (3C 84A (iii)) has dimensions comparable with the galaxy rather than with the whole of the cluster. There is also no evidence to suggest that the radio sources associated with A401 and A2256 have angular extents comparable with those of the clusters. If the sources do indeed have small sizes then the above explanation relating the X-rays and the steep radio spectra meets with serious difficulties. Since, for a given observed radio flux density the X-ray intensity due to Compton scattering is inversely proportional to the square of the magnetic field, the greatest contribution to the X-ray emission will be from radio components of large angular extent (in which the magnetic fields are presumably weaker). Indeed it is clear both from the fact that the majority of radio sources do not produce significant X-radiation and also from the calculations of Okoye (1972) that, if the inverse Compton mechanism is responsible, the observed X-ray intensities imply that the electrons producing the X-ray and radio emission occupy volumes considerably larger than those associated with typical radio galaxies although not necessarily as large as the cluster itself.

An alternative explanation of the correlation of X-ray emission with steep-spectra radio sources may be based on the origin of the X-rays as thermal bremsstrahlung from hot gas in the cluster. The calculations of Lea *et al.* (1973) using the most recent X-ray data give values for the central density and temperature of the gas in three X-ray sources in clusters of about 5×10^{-3} cm^{-3} and 10^8 K. The thermal pressure in such a gas is equal to the magnetic pressure associated with a field of about 10^{-5} Gauss, typical of the probable field strengths in the components of many radio sources. Thus the gas in a cluster may slow down or halt the adiabatic expansion of the components of radio sources. The lifetime of the radio source might then be increased sufficiently for energy losses of the electrons by synchrotron radiation to cause the steep radio spectra observed.

Measurements of the X-ray and low-frequency radio structures of these sources should make it possible to distinguish between these two explanations.

4. CONCLUSIONS

This analysis has established that, for radio sources having spectral indices greater than 1·2 between 38 and 178 MHz,

(i) A high proportion (38 per cent) are associated with clusters of galaxies in Abell's list.

(ii) They may constitute a homogeneous class of sources of low radio luminosity; and

(iii) The X-ray emission from clusters of galaxies is probably directly associated with the steepness of the low frequency radio spectra of sources in these clusters. A thermal origin for the X-ray emission provides a likely explanation of this association.

Further radio observations needed are positional measurements of the unidentified steep-spectra sources in order to establish their nature, and mapping with high angular resolution to discriminate between theories of the association of X-ray emission with steep radio spectra.

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