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THE DISTRIBUTION OF RADIO SOURCES TOWARDS RICH CLUSTERS OF GALAXIES

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ABSTRACT. We analysed Dixon's Master List of Radio Sources and four large radio surveys for a concentration of sources towards the centres of Abell clusters of galaxies. Using all radio sources, regardless of optical identification, we find that at all frequencies the amount of concentration increases strongly with increasing flux density. The density enhancement of sources within 0.1 Abell radii ranges from 3 to 10 above background for the analysed surveys, but rises to ~20 for all of them, when only strong sources are considered. The richer (R ≥ 2) clusters show the highest concentration of sources above background and generally a broader distribution, while the early Bautz-Morgan types (BM < II) show the narrowest one. Often a source deficiency relative to the survey mean is found in the cluster peripheries.

Key words: CLUSTERS-GALAXIES — RADIO SOURCES-GENERAL

I. INTRODUCTION

The sky distribution of extragalactic radio sources in complete surveys is very close to random, i.e. the sources do not show significant clustering among themselves (e.g. Webster 1976). However, the number of radio sources towards Abell's (1958) rich clusters of galaxies was found to exceed the random expectation by large factors (Wills 1966). Seldner and Peebles (1978) used the 4C radio survey to confirm that a cross-correlation between radio source and galaxy distribution exists down to low levels of galaxy clustering as found in the Lick galaxy counts, with the Abell clusters contributing only 10% of the radio-optical correlation amplitude. The radio source excess for the Abell clusters was found to be directly proportional to the number of galaxies in the cluster, suggesting that a galaxy's chance to be a radio source is independent of cluster richness.

The few quantitative works on the radial source distribution around the centres of rich clusters mainly agree in that the source excess is significant only within ~0.4 Abell radii (= R_A = 1.5 h^{-1} Mpc, where H_o = 100 h km s^{-1} Mpc^{-1}). Re-analysing the 4C survey at 178 MHz (S_{lim} = 2 Jy), McHardy (1979) found the source density within 0.2 R_A to be ~10 times above the average. From the Culgoora (CUL) survey at 160 MHz (S_{lim} = 1.6 Jy) Slee et al. (1982) arrive to the much larger factor of ~25 times the background within 0.2 Abell radii. Part of this could be due to the smaller beam of the CUL survey, resolving more of the sources near the cluster centres, and causing an underestimate of the CUL background source density, which Slee et al. extrapolate directly from the 4C catalogue.

Here we report the first steps in a long-term project of selection and subsequent study of a much larger sample of radio sources in the direction of rich clusters, further stimulated by the recent extension of Abell's survey to the south (Abell et al. 1989), comprising now a total of 5250 catalogued (A- and S-) clusters over the entire sky. To this end we have analysed some of the larger arcmin-resolution radio surveys published recently. Abell radii were taken from the most recent compilation of measured and estimated redshifts for Abell clusters (Andernach, 1990). We subdivided the clusters according to their distance (D), richness (R) and morphological (BM) classes. All radio data (Table 1) were available in computer-readable form, and counts of radio sources were performed in concentric annuli of 0.1 R_A. The width was increased when too few sources were found in a single bin. We counted all sources, regardless of optical identification. Table 2 summarizes the search results.

Table 1: Characteristics of the Analysed Radio Surveys

	Dixon's MLRS	6CII	B3.1	Effelberg	MGII
Obs. frequency (MHz)	(10-15000)	151	408	2700	4830
Area surveyed (sq.deg.)	(41253)	2030	2560	44	4960
Angular resolution	(20"-3°)	4.2'	2.6'x4.8'	4.4'	2.8'
Limiting flux (mJy)	(~1)	200	100	~20	~50
Number of entries absolute	(79493)	8278	13354	403	6182
Number of entries per sq.deg.	(~2)	4.1	5.2	9	1.2

Table 2: The Abell Cluster Search Areas (not corrected for overlap)

Subsample		MLRS	6CII	B3.1	Eff.	MGII
All	N (clusters)	5250	427	233	80	537
	Area within R_A (□)	2406	111	91	25	169
	Sources within R_A	4412	480	516	223	208
R ≧ 2	N (clusters)	856	68	36	21	93
	Area within R_A (□)	206	14.2	17.4	6.7	31.8
	Sources within R_A	696	67	183	79	38
BM<II	N (clusters)	1015	15	9	12	32
	Area within R_A (□)	997	13.2	5.9	3.9	22.3
	Sources within R_A	1306	38	49	42	18

II. THE MASTER LIST OF RADIO SOURCES (MLRS)

Being a master catalogue, the MLRS (originally published by Dixon, 1970), is necessarily very heterogeneous, and contains positions and fluxes over a large range of frequency, angular resolution and positional accuracy. We included it in the hope that the large amount of entries over the entire sky would show some general trends. We used the 42nd version of 1976 with 79,493 entries. According to Dixon (1989, priv. comm.) the most recent, 43rd version has ~6% more entries. (In the course of analyzing the MLRS, we compiled a list of some errors and inconsistencies in the MLRS which is available from H.A. upon request.)

Although intended to include only finder surveys, an important bias of the MLRS for our concern is the repetition of sources, either due to their presence in different catalogs or to an entry at two or more frequencies. As a first-order removal of the latter bias, we skipped all entries of the MLRS with repeated names or with positions less than 10" away from the preceding entry. For consistency with the counting prescription, we determined the randomly expected density of entries (n_r) in areas of identical size and distribution, but shifted by a few degrees from the ACO-clusters, resulting in only 70% of the density obtained with all entries, i.e. 79493/(4π sr). Figure 1a shows the radial profiles of source number density in units of n_r. Since overcounting of those sources present in more than one survey is likely to be most important for the strongest (i.e. on average closer) sources, we tentatively excluded the nearby (D ≦ 2) clusters. The result was not significantly different from the black solid line for all 5250 ACO-clusters. This seems to prove the efficiency of the prescription used to eliminate the repetition bias of the MLRS.

As in earlier studies, the contrast is highest for the richest (R≧2) clusters and it remains high ($n>n_r$) out to one Abell radius. Contrary to that, the optically very concentrated clusters (BM<II) show a deficiency of sources beyond 0.4 R_A, and a very steep

profile within 0.2 R_A. While these distributions are based on sources found at any frequency, we also looked at the distributions at low and high frequencies and found the central concentration to be at least as strong at frequencies above 2 GHz. The open circles in Fig. 1a were obtained using only strong sources above the 4C limit (2 Jy at 178 MHz, scaled to other frequencies with the median spectral index of extragalactic sources α=.75, $S \sim \gamma^{-\alpha}$). We comment on this in section VI.

III. THE 6CII SURVEY AT 151 MHz

The zone defined by $30^o < \delta < 51^o$; $b^{II} < +30^o$ was mapped at MRAO (Hales et al. 1988). The survey frequency is only slightly lower than that of the 4C and CUL surveys. Its angular resolution is 4.2', i.e. two times worse than that of CUL, but several times better than that of 4C. Thus it is surprising that the peak density contrast derived for all clusters in the 6CII area (filled circles in Fig. 1b) is only a third of that obtained for the 4C catalog. We found this to be due to the increased sensitivity of 6CII (~10 times better than both 4C and CUL). For sources with S_{151} >2 Jy (open circles in Fig. 1b) we find good agreement with the 4C results, except for a relative deficiency of strong sources beyond 0.5 R_A.

The richer (R≧2) clusters show again the largest contrast, but do not exhibit the broad distribution as in the MLRS. Instead, all cluster samples show a fairly pronounced underdensity (i.e. below the survey average!) between 0.5 and 0.8 R_A. This "zone of avoidance" is even wider for the BM < II clusters (similar to the MLRS distribution), again balanced by an extremely narrow central peak.

IV. THE B3.1 SURVEY AT 408 MHz

Sensitivity and resolution of this survey (Ficarra et al., 1985) are similar to that of 6CII, scaling the flux limit with α=.75. Choosing a flux limit comparable to that of the 4C survey, i.e. 1 Jy at 408 MHz, we find again a rise by a factor ~5 of the density within 0.1 R_A and a deficiency of strong sources beyond 0.3 R_A (open circles in Fig. 1c). The richer clusters show a source density excess out to one Abell radius. For the early Bautz-Morgan (BM<II) clusters the distribution shows the steepest slope and approaches the background level beyond 0.4 R_A. For the R≧2 and BM<II subsamples we find a source excess beyond one Abell radius (at least up to our present count limit of ~1.4 R_A).

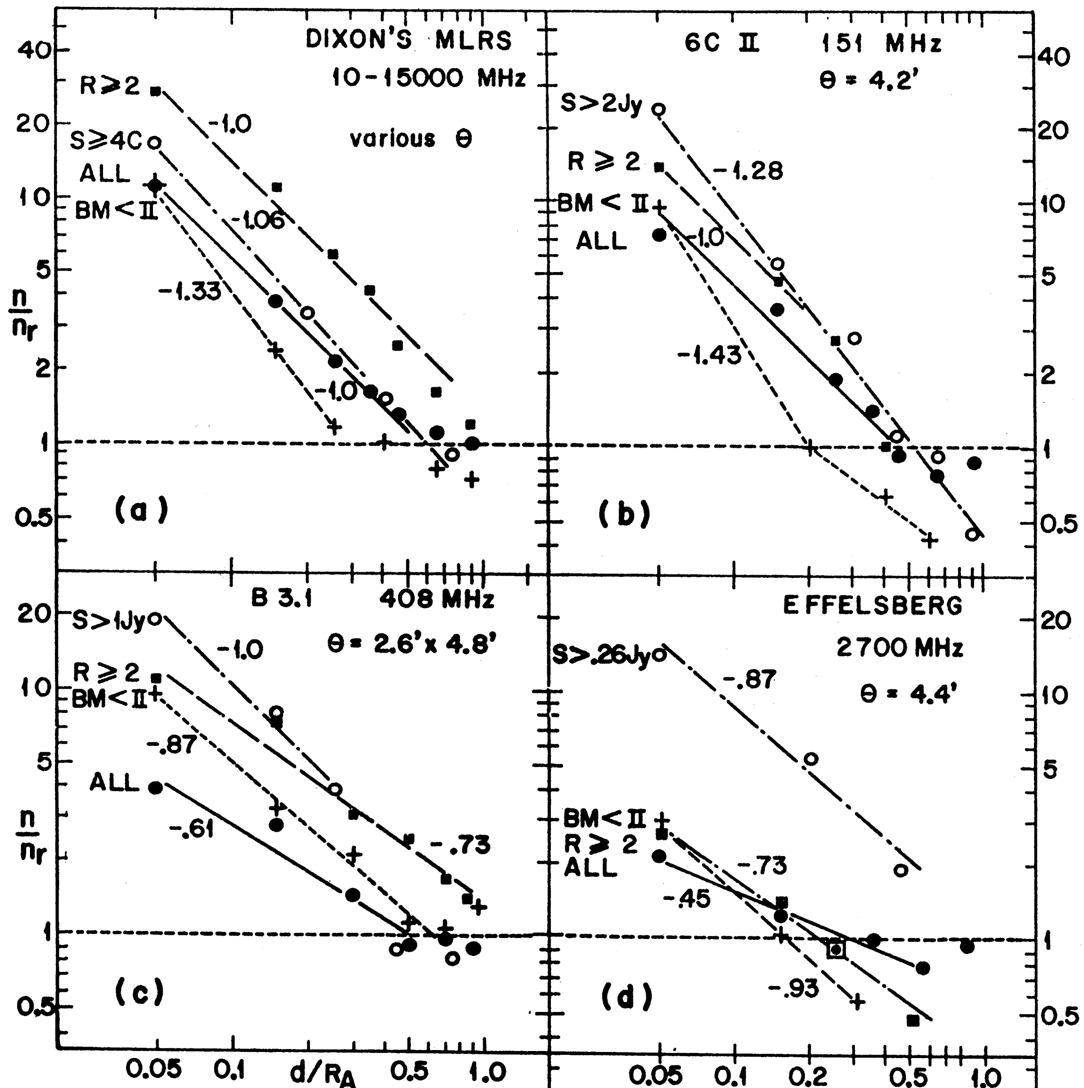
V. THE EFFELSBERG ABELL CLUSTER SURVEY AT 2700 MHz

Since 1976 a radio continuum survey of Abell clusters has been performed at 2.7 and 4.8 GHz with the MPIfR 100 m dish at Effelsberg (see Reuter and Andernach, 1990 and references therein). The maps are not identical in sensitivity and cover different fractions of the cluster areas. To work on a homogeneous sample we considered here only maps at 2.7 GHz with a source detection limit $S_{lim}=4*\sigma_{map} \leqq 22$ mJy. Only sources above this limit have been counted in concentric rings around cluster centres, out to the largest, fully observed circle (median radius is ~0.7 R_A) within the map. Source densities were derived by summing up the total observed area in each radial bin. These were then normalized by the source density $n_r(\geqq 22$ mJy$) = 23000$ sr^{-1} obtained in a survey of the North Ecliptic Pole area with the same equipment (Loiseau et al. 1988).

The radial profiles (Fig. 1d) are the lowest of all surveys studied here. One reason for this could be an overestimate of n_r, since with the same telescope Stute et al. (1980) found $n_r(\geqq 22$mJy$)=11500$ sr^{-1} around strong sources. Also, the Effelsberg cluster survey is the most sensitive with respect to the 4C limit (S_{2700}=.26Jy), which might reduce the level of the profiles (see sect. VI). Above this limit (open circles in Fig. 1d) the profile is consistent with the other surveys.

VI. THE MGII SURVEY AT 4830 MHz

The flux limit (~40 mJy) of this survey (Langston et al. 1989) is ~4 times lower than that of the 4C survey, when scaled to 4830 MHz. The radial distribution of sources around all Abell clusters (filled circles in Fig. 1e) is comparable to that of 6CII and B3.1. Even the increase of relative source density for sources above the scaled 4C limit (S_{4830} = .17 Jy) is very similar, proving this effect to be frequency-independent. This effect was already



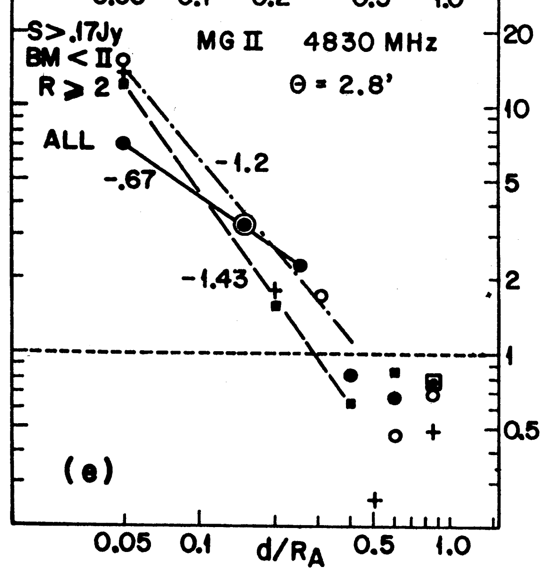


Fig. 1a-e: Radial profiles of radio source density (in units of random expectation) vs. projected cluster centre distance (in Abell radii) for five radio catalogs. Four different subsamples of clusters are indicated: all ACO with all catalogued sources (•), all ACO with sources above the indicated flux limit (o), clusters with R ≥ 2 (▪) and BM=I or I-II (+), the latter two with all sources. Power laws and slopes are off-hand fits to the inner parts of the profiles. The horizontal broken line indicates the density expected at random. Note a frequent deficiency of sources in the cluster peripheries.

noted by van den Bergh (1961) and ascribed to the fainter sources being more distant than the Abell cluster limit. The weakness of the effect in the MLRS (Fig. 1a) is due to its proximity to the 4C limit at the various frequencies. The richer (R≧2) clusters show a much narrower distribution than at lower frequencies, while the distribution for the BM<II clusters is affected by small numbers per bin. All distributions (most notably for the BM<II) show a deficiency of sources beyond 0.3 R_A.

VII. CONCLUSIONS AND OUTLOOK

The rapid increase of radio survey data in recent years suggests the use of this material to complement the data on cluster radio sources obtained in dedicated studies. The present work extended previous ones to higher frequencies and revealed a few features worth to be investigated further. One is the source deficiency in the cluster periphery, similar to what Webster (1976) called 'anticlustering'. His explanation - based on an increase of anticlustering with source density n_b per telescope beam - is a confusion or blending effect, causing faint sources near bright ones to be missed. However, the profiles of Fig. 1 (though at smaller angular scales) show the opposite trend between n_b and the peripheral source deficiency. The effect cannot be due to an overestimate of the background level, since exclusion of the cluster areas in the 6C, B3 and MG surveys reduces n_r by only ~1% (see Tables 1 and 2). In future we plan to analyse the relation between source deficiency, limiting flux and angular scales involved. Other improvements would be calculation of error bars and more appropriate radial fits (King, deVaucouleurs, Hubble laws), and a check for consistency of the counts with the background for $d >> R_A$. A cross-correlation of southern radio surveys (PKS, CUL, MOL) with the new ACO extension is desirable. Some of the radio surveys (like 6CII/B3.1 and 6CII/MGII) overlap and allow determination of spectral indices for a large number of sources. Obviously a search for optical counterparts should be done (as started for B3.1 by Vigotti et al. 1989). This should answer e.g. the question if there is a population of relic (i.e. optically unidentified) radio sources associated with clusters.

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