Astron. Astrophys. 73, 54–66 (1979)

ASTRONOMY AND ASTROPHYSICS

A Westerbork Survey of Rich Clusters of Galaxies

IX. The Radio Luminosity Function of the Hercules Supercluster at 610 MHz

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Received June 8, 1978

Summary. Three WSRT full synthesis observations at 610 MHz of an area comprising the Hercules supercluster (A 2151 and A 2147) yielded the detection of 40 galaxies brighter than m_p $=17.5$–18. 28 of these, which are members or probable members of these clusters, are used to construct the Radio Luminosity Function (RLF) separately for the elliptical and SO galaxies, (E+SO), and the spiral and irregular galaxies, (S+I). The results confirm the finding based on the 1415 MHz survey (Pap. II) at a somewhat higher statistical level. The RLF of the (E+SO)'s does not show significant differences with respect both to other clusters and to the galaxies in the general field. On the contrary the (S+I) galaxies appears to be weaker radio-emitters when compared to the Coma Cluster (Pap. III) and to a sample of nearby galaxies, the difference being especially marked for the very bright spirals ($M_p \leqq -20$).

Key words: clusters of galaxies – radio sources – luminosity function

I. Introduction

The two Abell clusters A 2151 (Hercules) and A 2147 are inside the cluster $n°7$ in field 108 of the catalogue by Zwicky and Herzog (1963). Extensive redshift measurements (Burbidge and Burbidge, 1959; Bautz, 1972; Tarenghi, 1977; Tarenghi et al., 1977) have proven that the two Abell clusters, which appear on the sky at an angular separation of less than 2°, are approximately at the same distance from us, and that the Zwicky cluster can be considered a "supercluster" with a mean recession velocity of about 11,000 km s^{-1}. The central regions ($R \leqq 0\overset{\circ}{.}6$) of A2151 and A2147 have been surveyed with the Westerbork radio telescope in the continuum at 1415 MHz (Jaffe and Perola, 1975, Pap. I in this series), and the 9 bright cluster galaxies identified with a radio source were used (Jaffe and Perola, 1976, Pap. II) to estimate the radio luminosity function of the two clusters, separately for the elliptical and SO (E+SO) and for the spiral and irregular (S+I) galaxies. In Pap. II it was shown that, while the (E+SO)'s have a radio luminosity function which agrees with both that of the other clusters surveyed at 1415 MHz (Coma, A 2197, A 2199), and with the galaxies in the general field, the (S+I)'s seem to be weaker radio-emitters with respect both to the Coma cluster, and to a nearby sample of galaxies of the same type.

Like the Coma Cluster (Jaffe et al., 1976, Pap. III), these two clusters have been re-observed at 610 MHz, where the wider extent of the area surveyed in a full synthesis ($R \leqq 1\overset{\circ}{.}6$) allows to include a larger number of galaxies and therefore increase the statistical weight of the results. These observations have been fully reduced, and in this paper we present the data on the sources identified with galaxies brighter than about $m_p = 17.5$. The main purpose of this paper is to derive from these data the radio luminosity functions. In Sect. VI comments are given on the properties of two strong sources, which have been suggested by Mills and Hoskins (1977) to be the components of a double identifiable with a member of A 2147, but could well be unrelated to each other.

For all the galaxies surveyed which are in the catalogue by Zwicky and Herzog (1963; called ZH hereafter) we have adopted a morphological classification based on plates taken with the Mayall 4 m telescope and a cluster membership based on redshift measurements (Tarenghi et al., 1978).

The distance to the Hercules supercluster used in this paper is 110 Mpc ($H_0 = 100$ km s^{-1} Mpc^{-1}).

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II. Observations and Data Reduction

The general procedures followed in these observations and in their reduction are identical to those described in the earlier papers of this series, and in particular we refer to Paps. II and III. The specification of the observations at 610 MHz are given in Table 1, and the list of calibration sources in Table 2.

The three full syntheses (4×12^h) at 610 MHz are centered the first on A 2151, the second on A 2147 and the third in between. The last one served to map the wide angle tail source associated with NGC 6034 and described in Valentijn and Perola (1978). The position of the three radio fields is shown in Fig. 1, which is a reproduction of the distribution of galaxies brighter than m_p $=15.7$, from ZH. The purpose of this figure is to show the coverage of the two clusters. The useful field of a full synthesis is limited to a circle with $1\overset{\circ}{.}6$ radius, due to the primary beam attenuation (its pattern is given in Pap. III). At that distance from the radio field centre the attenuation is a factor of 56. In Fig. 1 are also drawn the circles where the attenuation is a factor of 3, which show that A 2147, whose galaxies are spread over a larger area than in A 2151, and was therefore not properly surveyed at 1415 MHz (Paps. I and II), is well covered by the present work.

The synthesized beam has a FWHM of 53″ in R.A. and 53″ cosec δ in Dec. The first two sidelobes have heights -5% and $+3\%$ of the central peak, and are located 1.5 and 2.5 beamwidths away from it. The increments of 18 m in baseline result in a strong elliptical grating ring with semiaxis $1\overset{\circ}{.}56$ in R.A.

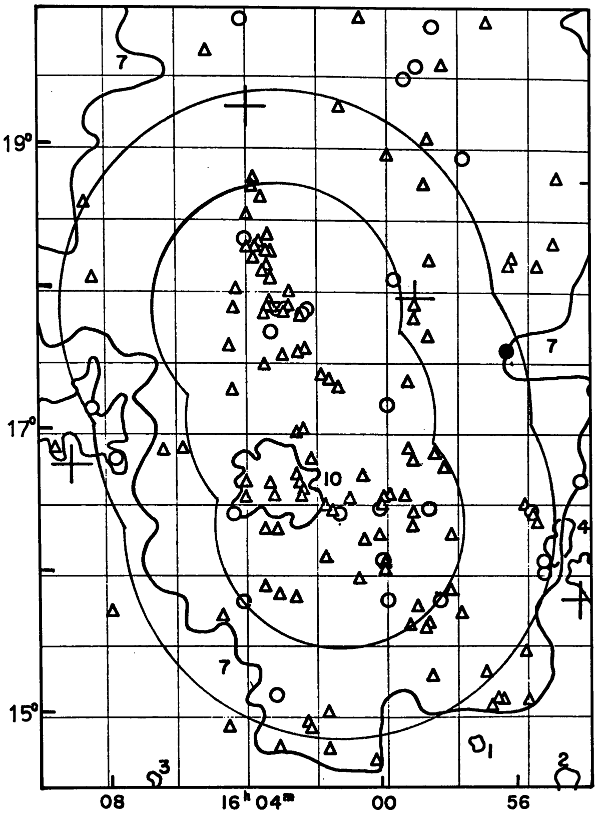


Fig. 1. Radio coverage at 610 MHz of A 2147 and A 2151. The distribution of the galaxies brighter than $m_p = 15.7$ is reproduced from ZH. The outer line represents the maximum coverage obtained combining the three full syntheses. The inner line corresponds to an attenuation factor of 3 with respect to the radio field centres

Table 1. Observation specifications

Frequency (MHz)	Field centre (1950.0)	Obs. dates (year + sidereal day)	Shortest/ incremental spacing (m)
610	$16^h02^m52\overset{s}{.}0$ +17°53′ 00″.0	75321 75332 76210 76270	38/18
1415	idem	75225 75227 75236 75241 75254 75256	54/18
610	$16^h02^m03\overset{s}{.}0$ +17°05′ 24″.0	73233 73239 73246 73250 73263 73319	54/18
610	$16^h01^m13\overset{s}{.}5$ +16°17′ 48″.0	75334 76014 76015 76032 76034 76220 76223 76224	36/18

Table 2. Calibration sources

Source name	R.A. (1950.0)	Dec (1950.0)	S_{610} (Jy)
3C 48	$01^h34^m49\overset{s}{.}827$	+32°54′20″.63	—
3C 147	05 38 43.503	49 49 42.87	37.78
3C 390.1	14 58 56.664	71 52 11.17	—

The effective noise σ in the three maps after the cleaning procedure turned out to be 1 mJy per beam area. The search of the sources was stopped at the 4σ level, which should be considered our completeness limit for "point" sources.

The measurement of the 4 Stokes parameters allowed the production of polarization maps, which however could not be used properly because of bad interference and of contamination by structures in the galactic background.

To exploit the improved system noise of the WSRT at 1415 MHz, we also obtained a further 4×12^h observation at this frequency of A 2151, with the field centre coincident with the observation described in Pap. I. However, because of dynamic range limits and errors in calibration the improvement was marginal. Of the new 1415 sources the two identified with bright galaxies are detected also at 610 MHz. For these sources (20W9 and 20W2) we give in Table 4 the 1415 MHz positions, which are supposed to be more precise than those at 610 MHz.

III. The Cluster Galaxies Already Detected at 1415 MHz

In Paper II the galaxies brighter than $m_p \simeq 17$ detected in the 1415 MHz survey are listed with their measured redshift. All but one (1601+16W3) are cluster members, and these are listed again in Table 3 along with the radio parameters at 610 MHz. In Col. 2 the map flux, that is the flux uncorrected for the attenuation, is given. For the extended sources a numerical map was produced and the flux determined by integration over this map. The sky flux is given in Col. 3, along with the uncertainty. This was obtained by combining the estimated error in the map flux and the error in the attenuation factor, which was taken to be $10R\%$, where R is the distance from the field centre in degrees. A probable error of 5% in the absolute flux density scale should be added to the uncertainty reported here. In Col. 4 the spectral index α between 610 and 1415 MHz and its uncertainty are given. For the resolved sources the maximum extension, and its position angle when the source is elongated in one direction, are reproduced in Col. 5. In A 2151 two sources are well resolved, namely 1601+17W1 and 1604+18W1. They are of the wide angle tail type: a multifrequency analysis of the first is published in Valentijn and Perola (1978), a similar analysis for the second will be published later (but see the 610 MHz map in Fig. 3). The structure at 1415 and 5000 MHz of the strongest source in this cluster, 1602+17W4, is discussed in Jaffe and Perola (1974). At 610 MHz

Table 3. 610 MHz parameters of Cluster radio galaxies detected at 1415 MHz

Source name	S_{map} (mJy)	S_{sky} (mJy)	α_{610}^{1415}	θ_m,PA	IC	Galaxy name	Gal. type	m_p	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
A2151									
1601+17W1	915	1190 ±15	0.61 ±.03	510",-	II	N6034	E	15.2	Wide angle tail source, see Valentijn and Perola (1978)
1602+17W1	111.5	114.2 2.0	−0.18 .03		II	N6040B	SO	15.7*	In double system with spiral
1602+17W2	15.9	16.1 1.0	0.86 .14		I	N6041A	E	15.3*	In double system with an SO∿16ᵐ–16ᵐ.5. Radio source could be either galaxy
1602+17W4	1349	1349 25	0.63 .03	60":,90°	II	N6047	E	15.4	4C17.66, see Jaffe and Perola (1974)
1603+17W2	8.7	8.9 1.5	0.86 .30		I	IC1182	SOp	15.2	Slightly confused by nearby weak sources
1603+17W3	13.5	13.8 1.0	0.53 .14		III	IC1185	Sa	15.1	Classified E in Pap.II
1604+18W1	392.8	673 41	0.49 .08	500",-	II	N6061	E	15.0	Wide angle tail source (see map). New flux at 1415 MHz: 446±8 mJy
A2147									
1559+16W1	8.5	10 –	–		I	Anon	E	16.5*	Confused by nearby source, flux very uncertain
1559+16W2	35	42 10	0.3 .4	60",10°	II	Zw108-73	E	14.9	Slightly confused by nearby source. The double structure is evident at 1415MHz, see Pap.I
1600+16W10	22.5	24.3 1.1	0.88 .14		I	Zw108-82	E	15.5	
1601+15W1	160.4	192 6	0.66 .07	85",90°	III	Anon	E+E	16.5*	Double radio source, see Pap.I for the map at 1415 MHz

the beam is slightly broadened in a way consistent with the size and structure of this source as determined at 5000 MHz. The two extended sources in A2147 (1559+16W2 and 1601+15W1) are close doubles at 1415 MHz, and the extension measured at 610 MHz is consistent with the one determined at the higher frequency.

The identification class in Col. 6 (as defined in Paper I) is the one determined at 1415 MHz, where the positional accuracy is better. The position of 1603+17W3 determined at 1415 MHz with the new observations confirms that its identification with IC 1185 is rather improbable (IC III).

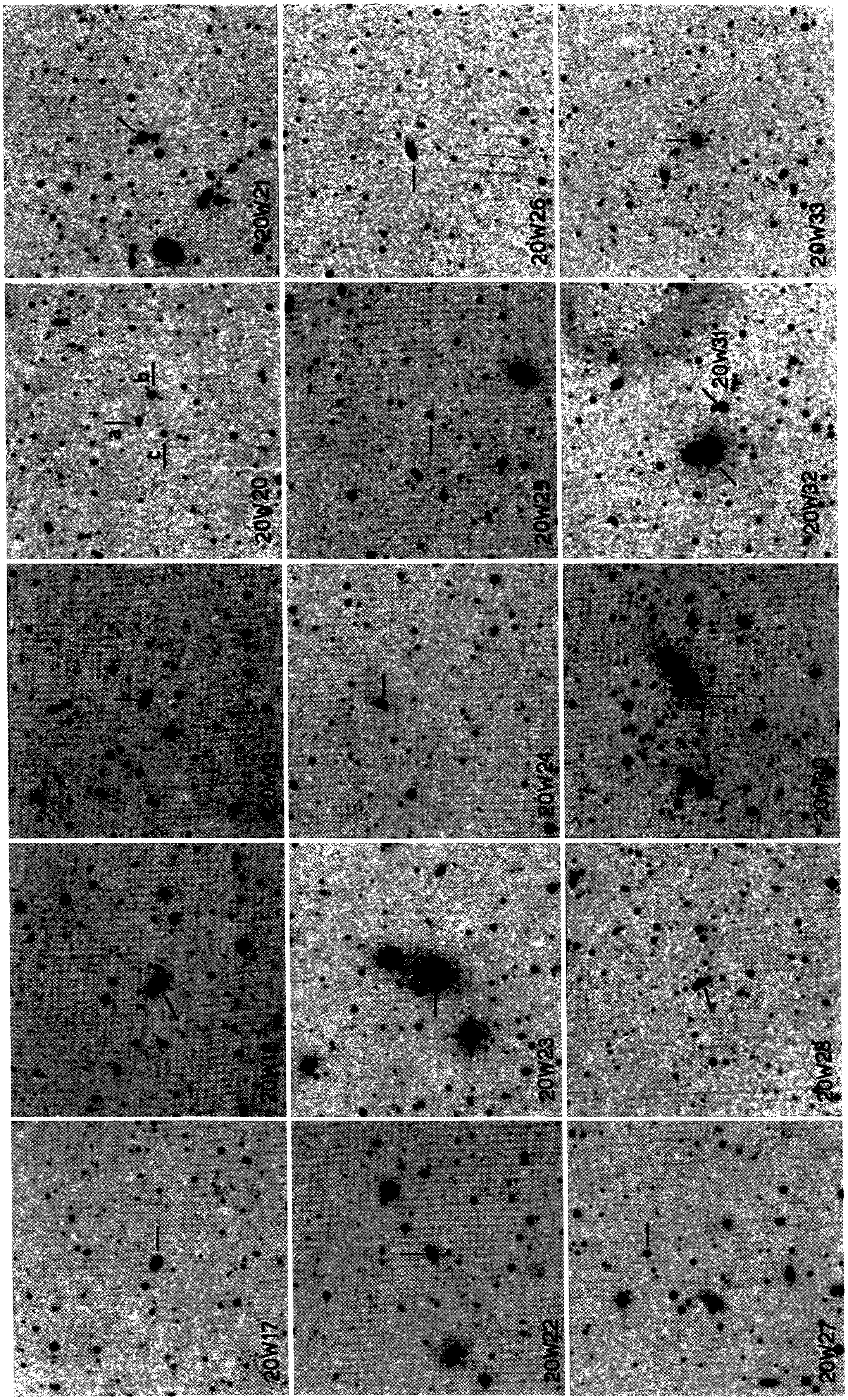
The NGC and IC catalogue numbers in Col. 7 are assigned according to Corwin (1971). The ZH galaxies not in those catalogues have been assigned the sequential number in ZH field number 108. The morphological classification (Col. 8) of the ZH galaxies is somewhat different from that given in Paper II. The only change that could matter for the construction of the Radio Luminosity Function (RLF) concerns IC 1185, from E to Sa; this galaxy however was not and is not used for that purpose because of its IC III. The photographic magnitudes m_p in Col. 9 are either from ZH, or have been estimated by us on the blue print of the Palomar Sky Survey (see Paper I; these magnitudes are indicated by an asterisk, and are affected by an uncertainty of $\pm 0^m.5$). Two ZH galaxies (N 6040 B and N 6041 A) are in a double system, and therefore we had to subtract from the ZH magnitude the estimated contribution of their companion. Note that the SO companion of N 6041 A could also be identified with the same radio source, on the basis of the positional error at 1415 MHz, and that we have chosen the brighter component of the double for the construction of the RLF.

IV. New Identifications at 610 MHz

For all radiosources found down to the search limit in the three 610 MHz syntheses an optical identification was tried on 48″ Palomar Schmidt photographs, and those which were identified with galaxies brighter than $m_p = 17.5$–18 are listed in Table 4. These sources are divided in two groups according to whether they fall in the A 2151 or in the A 2147 field. The two fields are rather arbitrarily defined as above and below Dec. = 17°.

Columns 2 and 3 give the 1950.0 position. The r.m.s. position error in R.A. σ_α is given as a function of map flux in Fig. 1 of Pap. III. Note that the error in Dec. σ_δ is larger by the factor cosec δ. The radio position error is the dominant contribution to the radio-optical combined error in Col. 8. The map and sky fluxes with the estimated uncertainty (Cols. 4 and 5) have been obtained as described in the previous section. Two sources found by the search program, but with $S_{map} < 4$ mJy (20W21 and 20W31) are included in this table because of their interesting identification, but will not be used to construct the RLF (Sect. V) because below the formal completeness limit for unresolved sources. For the resolved sources the maximum extension and its position angle are given in Col. 6. Among these there are three close couples which are tentatively considered double sources (20W7, 10, and 20). The maps of the doubles and of the well resolved sources are presented in Fig. 3. For the unresolved sources an upper limit of $100''(S_{map}/\sigma)^{-1/2}$ can be placed on the extension in R.A. (the limit in Dec. is larger by cosec δ).

The optical positions were measured partly with the XY measuring machine of the ROUB group in Bologna on a IIIaJ plate


20W21
20W26
20W33
20W20
a
b
c
20W25
20W31
20W32
20W24
20W23
20W28
20W17
20W22
20W27

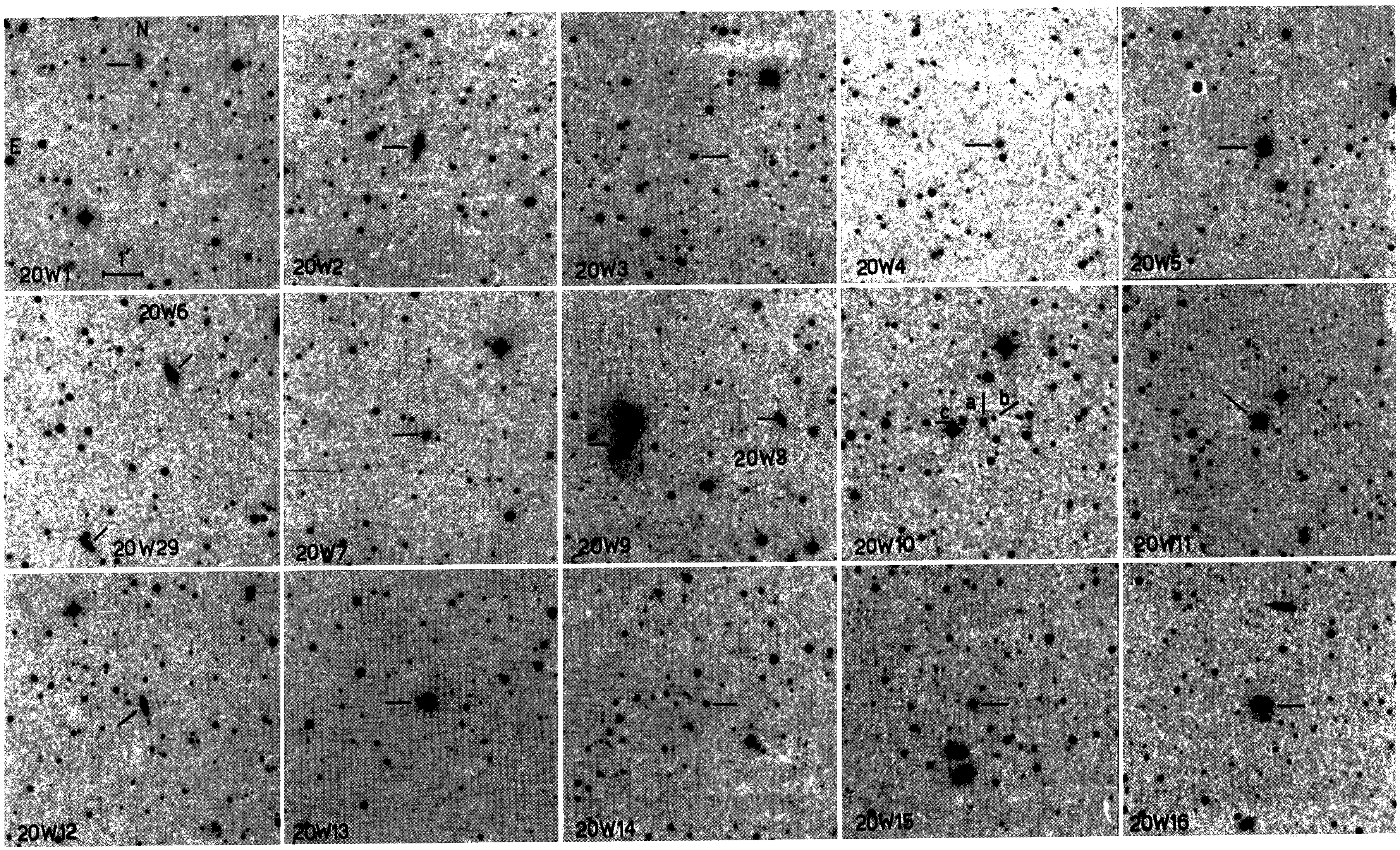


Fig. 2. Finding charts for all the identifications in Table 4. Reproductions are courtesy of Palomar Sky Survey – National Geographic Society

Table 4. 610 MHz radio sources identified with galaxies brighter than $m_p \simeq 17.5$

Field of A2151 (Dec >17°)

Source name (1)	α_R(1950.0) (2)	δ_R(1950.0) (3)	S_{map} (mJy) (4)	S_{sky} (mJy) (5)	(Θ_m,PA) (6)	$\alpha_o-\alpha_R$ (arcsec) (7)	$\delta_o-\delta_R$ (arcsec) (8)	Pos.err. (arcsec^2) (9)	IC (10)	Gal. name (11)	Gal. type (12)	m_p (13)	Membership (14)	Notes Source may be spurious
20W1	15h58m41.s5	17°13'14."2	4.0	10.7 ±2.7		13.5	-27.7	6.6x22.1	I		S	17*		
20W2	15 59 11.3	18 09 43.8	4.0	14.1 3.7		- 5.8	1.0	6.6x21.2	I		S	15.8*		
20W3	15 59 21.5	17 21 18.4	4.2	8.7 2.1		-10.8	-36.8	6.5x21.5	I		SO?	17.5*		Reddish lenticular galaxy
20W4	15 59 50.7	17 21 59.3	7.0	11.8 1.8		- 2.7	4.2	4.1x13.4	I		E?	17.5*		Reddish galaxy
20W5	16 02 30.5	17 35 20.1	4.1	4.6 0.8		- 5.8	-17.4	6.5x21.5	I	Zw108-108	Sbc	15.7	Yes	
20W6	16 02 32.0	17 00 47.5	4.4	4.6 1.0		6.3	22.0	6.1x20.5	I	Zw108-107	Sd(B)	15.7	Yes	
20W7a 20W7b	16 02 39.7 16 02 45.9	18 43 20.4 18 44 26.7	203.6	589 16	100", 50°	75.4	35.6		II		E?	17.5*		Double radio source (see map) Flux ratio of components =1.3
20W8	16 03 00.2	17 44 04.2	4.2	4.3 0.8		10.0	17.5	6.1x20.0	I		S	16.5*		
20W9	16 03 19.1	17 43 59.9	4.1	4.3 1.0		- 3.0	-18.4	2.7x7.9	I	IC1181	SO	15.7	Yes	In double with IC1178(SO). Position measured at 1415 MHz. α =1.2±.3.
20W10a 20W10b	16 03 55.4 16 04 00.5	17 02 03.5 17 02 10.1	22.9	30.6 5.0	75", 90°	20.6	- 5.1		III		E	17.5*		Double radio source (see map). Flux ratio =1.2. For alternative identification of components see caption to map.
20W11	16 04 32.4	17 37 38.0	5.3	7.3 1.0		10.4	- 4.2	5.3x17.2	I	Zw108-154	Sb	15.7	Yes	
20W12	16 04 33.0	17 46 32.1	5.5	7.0 1.0		1.4	20.9	2.9x9.5	I		S	16*		Position measured at 1415 MHz α= 0.6±.3.
20W13	16 05 25.0	18 36 32.0	5.3	20.5 3.0		- 4.4	14.2	5.3x16.5	I		SO?	16*		
Field of A2147 (Dec <17°).														
20W14	15 56 58.9	16 26 03.7	49.6	246.9 9.3		- 0.9	- 2.1	1.5x4.1	I		E?	17.5		
20W15	15 58 36.1	16 30 13.8	17.1	83.1 5.0	50", 90°	- 5.4	9.2		II		E?	18		Very red galaxy
20W16	15 58 58.9	15 46 30.5	16.4	37.9 4.6	130",170°	4.3	31.9		II	IC1161	E	15.2	Yes	Very close to 4C+15.52, of which this source could be an extension (see map)
20W17	15 59 05.8	16 21 34.4	14.7	21.6 1.1		5.9	- 8.4	2.2x7.2	I	Zw108-58	Scp(R)	15.3	Yes	
20W18	15 59 21.0	16 34 34.3	7.5	11.3 1.1	90", 20°	-11.2	-21.2		II	Zw108-64	Sc	15.6	Yes	The measured extension is very uncertain
20W19	15 59 22.4	16 27 06.2	6.8	9.4 1.0		4.2	- 7.4	4.2x14.5	I		Sab	16*		
20W20a 20W20b	15 59 23.4 15 59 29	15 34 08.9 15 32 24	24.3	71.4 3.0	115",130°	32.7	26.4		III		SO?	17*		Double source with flux ratio =1.8 (see map) For alternative identification, see caption to map
20W21	15 59 38.4	15 51 11.0	3.1	5.1 1.2		- 3.7	-29.2	8.1x29.5	I		Ir	16*		Source can be spurious. The galaxy is very blue.
20W22	15 59 45.0	16 34 31.2	7.2	9.6 0.9		1.7	- 4.9	4.1x14.1	I	Zw108-66	SO	15.7	Yes	
20W23	16 00 02.6	16 29 10.6	10.6	12.4 0.8		6.1	- 8.2	2.9x9.5	I	Zw108-75	E	14.6	Yes	
20W24	16 00 27.1	16 48 03.1	4.0	7.3 1.8		- 2.6	21.8	6.6x22.0	I		Pec	16.5*	No	
20W25	16 01 03.5	16 35 04.9	5.9	9.3 1.6		-12.2	-12.4	4.7x16.2	I		SO?	17.5*		Reddish galaxy
20W26	16 01 14.6	15 42 10.9	7.5	12.7 1.2		- 1.6	7.7	3.9x14.0	I		SO?	16*		
20W27	16 02 01.7	16 52 01.6	6.4	6.8 1.1		- 6.6	-15.0	4.4x14.8	I		E?	17.5*		Red galaxy
20W28	16 02 16.4	16 08 49	5	6 1		- 3	2	6x24	I		S?	17*		
20W29	16 02 42.7	16 56 36.1	7.8	8.3 1.1		- 2.1	7.5	3.7x12.4	I		S	16*	Yes	
20W30	16 03 13.3	16 33 51.1	72.3	124.4 7.1	50", 60°	4.5	- 1.6		II		E	18*		Very red galaxy. Map given
20W31	16 04 03.2	15 48 43.4	3.6	10 2		2.2	4.2	7x25	I		E?	17*		Star superimposed on galaxy.
20W32	16 04 09.2	15 49 03.4	5.2	15.5 2.1		-13.0 - 9.1	7.5 34.8	5.3x19.5	I	Zw108-147	E E	15.0* 15.0*	Yes Yes	Either galaxy in the "double" system can be identified with source
20W33	16 06 53.2	16 33 34.5	7.3	97 18		- 1.1	3.9	3.9x13.4	I		E	17.5*	No	Very red galaxy

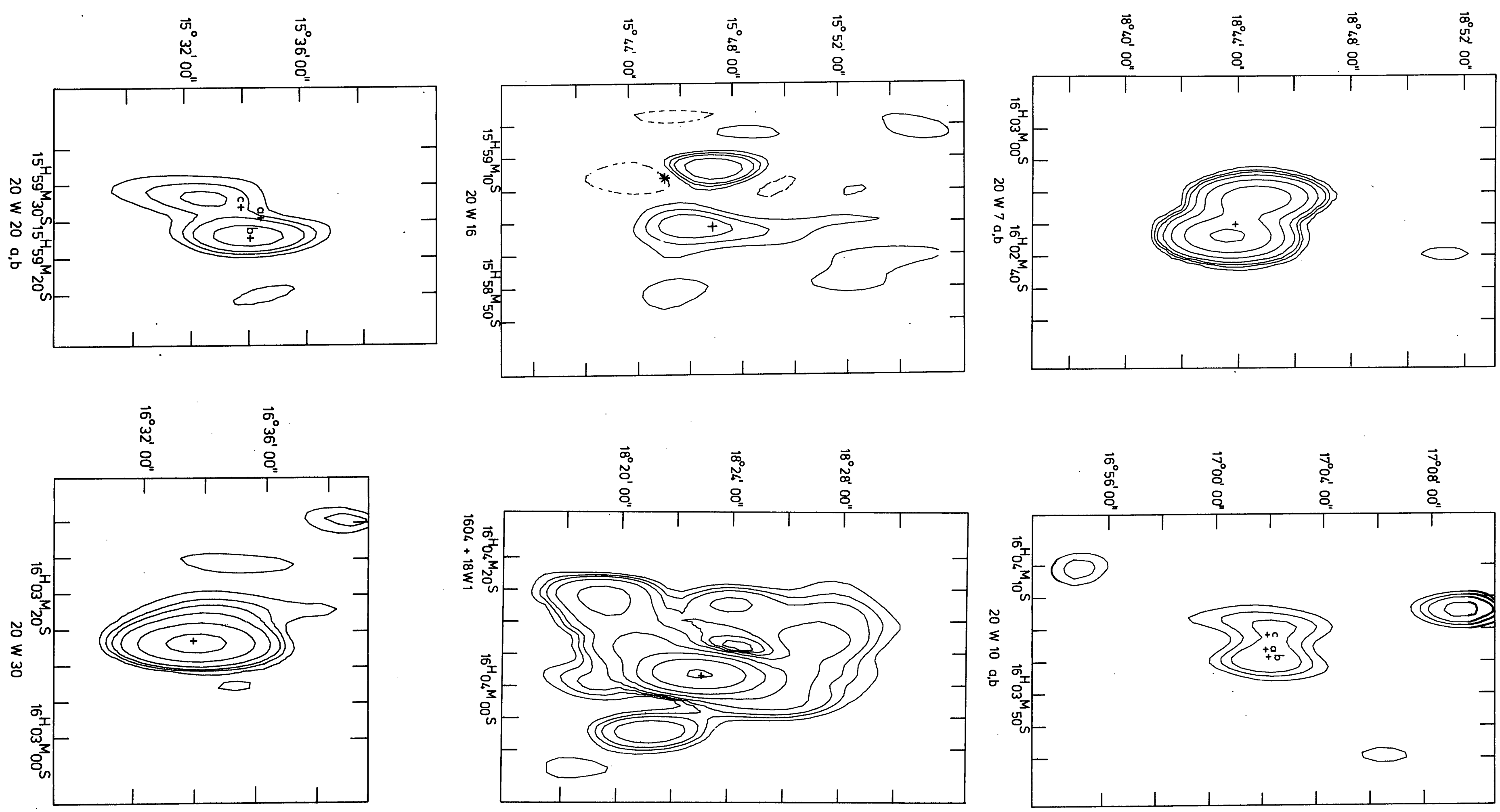


Fig. 3. The 610 MHz radio maps of the extended sources. The crosses indicate the position of the galaxy. In the map of 20W16, the asterisk indicates the position of the strong source 1559+15W1 (4C+15.52) subtracted from the map (cf. Sect. VI). Coordinates of alternative identifications in 20W10: (b) $16^h03^m55\overset{s}{.}7$, 17°02′5″.1; (c) $16^h03^m59\overset{s}{.}1$, 17°02′1″.2. 20W20: (b) $15^h59^m22\overset{s}{.}9$, 15°34′13″.2; (c) $15^h59^m27\overset{s}{.}2$, 15°33′54″.9. Contour levels 2, 4, 6, 10, 20, 40, 80, 160, 320 mJy/beam (map flux, uncorrected for attenuation). Beam area: 1.6 10^{-7} sterad

Table 5. Sources identified with E or SO cluster members and probable members with $m_p \leqq 17$* (identification classes I and II)

Source	Galaxy	log P_{610} (WHz^{-1})	M_p	$l_{r.a.}$ (kpc)	l_{max} (kpc)	Emission lines
			A 2151			
1601+17W1	N 6034	24.21	−20.1		280	NEL
1602+17W1	N 6040 B	23.19	−19.6*	< 5		EL
1602+7W2	N 6041 A	22.34	−20.0*	<14		NEL
1602+17W4	N 6047	24.26	−19.9		33:	NEL
1603+17W2	IC 1182	22.09	−20.1	<19		EL
1604+18W1	N 6061	23.97	−20.3		275	NEL
20W9	IC 1181	21.77	−19.6*	<27		NEL
20W13	Anon	21.98	−19.3*	<24		NEL
			A 2147			
1559+16W1	Anon	22.14	−18.8*	—	—	NEL
1559+16W2	Zw 108-73	22.76	−20.4		33	NEL
1600+16W10	Zw 108-82	22.52	−19.8	<11		NEL
20W16	IC 1161	22.72	−20.1		71	NEL
20W22	Zw 108-66	22.12	−19.6	<20		NEL
20W23	Zw 108-75	22.23	−20.7	<17		
20W26	Anon	22.24	−19.3*	<20		
20W31	Anon	22.14	−18.3*	<29		
20W32	Zw 108-147	22.33	−20.3*	<24		NEL

kindly lent us by F. Bertola, and partly with a similar measuring machine at the Leiden Observatory on a glass copy of the Palomar Sky Survey. The measuring errors are comparable for the two instruments, and are in the order of 1″. Cols. 7 and 8 give the difference in radio and optical position, and Col. 9 the combined radio-optical error. As in Pap. I the identifications are subdivided in three classes (Col. 10). IC I include the unresolved sources satisfying the 3σ criterion:

$$\frac{(\alpha_0-\alpha_R)^2}{\sigma_\alpha^2+\sigma_0^2}+\frac{(\delta_0-\delta_R)^2}{\sigma_\delta^2+\sigma_0^2}\leqq 9,$$

where σ_0 is the estimated error in the optical position (1″). The IC II in this table are extended sources which either have the brightness peak within 3σ of the optical position, or extend to cover the optical image. The double 20W7 is also considered IC II. These two classes contain the sources whose identification is considered certain. The uncertain cases are considered IC III. In this table there are two such cases, the "doubles" 20W10 and 20, for which alternative identifications of at least one of the components are acceptable (see captions to Fig. 3), while the proposed identifications are rather off the line joining the two peaks. For Cols. 11–13, see in Sect. III the comments on the corresponding columns in Table 3. The morphological class of the galaxies not in ZH was assigned after inspection of the red and blue glass copies of the Palomar Sky Survey and partly with the aid of more adequate photographic material (M. Tarenghi, private communication). The information based on redshift measurements about the membership to the two clusters (Col. 14) is complete for the ZH galaxies, but is limited to only four of the other galaxies (H. Tarenghi, private communication). Of those with no redshift measured we shall tentatively consider cluster members the galaxies with $m_p \leqq 17$*, and *use only these for the construction of the* RLF.

Since the identifications are based on positional coincidence, it is important to estimate the number of them in Tables 3 and 4 which could be due to chance associations. To this purpose we have proceeded as in Paper III, taking care of the non uniform distribution of the galaxies in the clusters and of the radio sources in the radio fields (the latter being due to the radial dependence of the attenuation). We have done this separately for the galaxies brighter than $m_p = 15.7$ (the ZH galaxies) and for the galaxies with $15.7 < m_p \leqq 17$* (on the basis of the counts described in the next section). We obtain for the unresolved sources (the majority) that only 0.5 galaxies with $m_p \leqq 15.7$ and 1.5 galaxies in the fainter group are expected to be included as identifications in Tables 3 and 4 because of a chance coincidence. This means that the incidence of spurious identifications is of order 10% or less, and should not influence significantly the RLF that we are going to derive.

Finding charts of all identifications in Table 4 are reproduced in Fig. 2.

V. The Radio Luminosity Functions

To test whether the galaxies in a cluster have a radio power distribution consistent or not with that in other clusters or in the field, it is convenient to construct a fractional bivariate radio luminosity function (BRLF), which represents the fraction of cluster galaxies per interval of radio power, as a function of the absolute optical magnitude (see Papers II and III, and Auriemma et al., 1977). Since ellipticals and spiral galaxies have different radio properties, we subdivide the galaxies in two groups, the ellipticals and the SO's (E+SO), the spirals and irregulars, (S+I).

The BRLF has been determined in the way described in Paper II, which requires counting the galaxies in circles of increasing radius about the radio field centres. The counts were done in two steps. The first consisted in counting the cluster galaxies in the ZH catalogue, assumed complete down to $m_p = 15.7$, which corresponds to $M_p = -19.6$, if an interstellar absorption of $0^m.1$ is included. The galaxies in double and triple systems which appear as single entries in ZH have been counted individually, and their magnitudes estimated by us. The second step was to count the galaxies in the interval $15.7 < m_p \leqq 17$* on a 4× enlargement of

Table 6. Sources identified with S or I cluster members and probable members with $m_p \leqq 17^*$ (identification classes I and II)

Source	Galaxy	log P_{610} (WHz^{-1})	M_p	$l_{r.a.}$ (kpc)	l_{max}	Optical spectrum
			A 2151			
20W1	Anon	22.17	−18.3*	<27		
20W2	Anon	22.29	−19.5*	<27		
20W5	Zw 108-108	21.80	−19.6 (−19.7)	<27		EL
20W6	Zw 108-107	21.80	−19.6 (−19.9)	<26		NEL
20W8	Anon	21.77	−18.8*	<27		
20W11	Zw 108-154	22.00	−19.6 (−19.7)	<24		NEL
20W12	Anon	21.98	−19.3*	<25		
			A 2147			
20W17	Zw 108-58	22.47	−20.0	<14		EL
20W18	Zw 108-64	22.19	−19.7 (19.8)		49:	NEL
20W19	Anon	22.11	−19.3*	<21		
20W21	Anon	21.84	−19.3*	<31		
20W28	Anon	22.10	−18.3*	<25		
20W29	Anon	22.06	−19.3*	<20		

Table 7. Radio luminosity function of the (E+SO) galaxies

log P_{610} (WHz^{-1})	A 2151 $-19.6<M_p\leqq-18.3$	A 2151 $-20<M_p\leqq-19.6$	A 2151 $-21<M_p\leqq-20$	A 2147 $-19.6<M_p\leqq-18.3$	A 2147 $-20<M_p\leqq-19.6$	A 2147 $-21<M_p\leqq-20$
21.76–22.10	1/ 61	1/ 9	1/9	0/ 80	0/12	0/ 7
22.10–22.50	0/ 82	0/14	1/9	2/105	1/14	2/12
22.50–22.90	0/ 95	0/14	0/9	0/125	1/15	2/12
22.90–23.30	0/110	1/16	0/9	0/130	0/16	0/14
23.30–23.70	0/110	0/18	0/9	0/130	0/18	0/15
23.70–24.10	0/110	0/18	1/9	0/130	0/18	0/15
24.10–24.50	0/110	1/18	1/9	0/130	0/18	0/15
log $P_{610}>21.76$ These clusters	0.02 ± 0.01	$0.23^{+0.12}_{-0.07}$	0.44 ± 0.22	0.02 ± 0.01	$0.14^{+0.09}_{-0.04}$	0.33 ± 0.17
Auriemma et al. (1977)	0.03	0.2	0.4			

the blue glass copy of the P.S.S.. For the magnitudes we used the scale adopted in Paper I. The background contamination was determined on the basis of 5 galaxies per square degree down to $m_p=17^*$ (cf. Oemler, 1974). The uncertainty due to our magnitude estimate and to the correction for the background can be rather serious. However we estimate that it should not exceed 50%, by comparison with the optical luminosity functions in Oemler (1974) and Krupp (1974).

We did not attempt a detailed morphological classification of the galaxies fainter than 15^{m}7, and assumed that the proportion of (E+SO) galaxies found among the ZH galaxies remains the same down to $m_p=17^*$, corresponding to $M_p=-18.3$. This proportion in our radio fields is practically identical for A 2151 and A 2147, and is equal to ~50%. We note that the proportion of bright (E+SO)'s in A 2147 is much larger in the circle $R<0\overset{\circ}{.}6$ around the field centre, which was surveyed at 1415 MHz, and close to the value of 80% adopted in Paper II.

a) The BRLF *of the* (E+SO) *Galaxies*

In Table 5 are listed the sources identified with (E+SO) cluster members and probable cluster numbers with $m_p\leqq17^*$ (IC I and II only), along with the radio power, the optical absolute magnitude, the maximum physical extent or the upper limit in R.A., and a note on the presence of emission lines in the optical spectrum (*EL*=yes; *NEL*=no). Except for 20W31, whose map flux is below the completeness limit, these sources are used to construct the BRLF, which is presented in Table 7. For each interval of radio power and of optical magnitude we give the number of detected galaxies over the number of galaxies that could have been detected if they had P_{610} in that interval. There is only one galaxy brighter than −21 (in A 2147), and this was not detected. The first two intervals of optical magnitude are very unequal, but we preferred for the sake of homogeneity to keep the ZH separated from the rest. At the bottom of the table there are the integral

Table 8. Radio luminosity function of the (S+I) galaxies

$\log P_{610}$ ($\mathrm{WHz^{-1}}$)	A 2151			A 2147		
	$-19.6<M_p\leqq-18.3$	$-20<M_p\leqq-19.6$	$-21<M_p\leqq-20$	$-19.6<M_p\leqq-18.3$	$-20<M_p\leqq-19.6$	$-21<M_p\leqq-20$
21.76–21.90	1/40	2/10	0/5	1/ 50	0/ 4	0/ 3
21.90–22.10	1/61	1/14	0/7	1/ 81	0/12	0/ 8
22.10–22.30	2/73	0/15	0/7	2/ 97	1/14	0/10
22.30–22.50	0/82	0/17	0/8	0/107	0/14	1/12
22.50–22.70	0/94	0/18	0/8	0/115	0/14	0/14
22.70–22.90	0/95	0/18	0/8	0/125	0/15	0/14
$\log P_{610}>21.76$	0.07 ± 0.03	0.27 ± 0.16	<0.2	0.05 ± 0.3	$0.07^{+0.06}_{-0.03}$	$0.08^{+0.07}_{-0.03}$

Table 9. Comparison of integral RLF's of (S+I) galaxies for $\log P_{610}>21.76$ ($\mathrm{WHz^{-1}}$)

	A 2151	A 2147	A 2151 + A 2147	Coma	Field (a)	Field (b)
$-21<M_p\leqq-20$	<0.2	$0.08^{+0.07}_{-0.03}$	$0.05^{+0.04}_{-0.03}$	$0.45^{+0.25}_{-0.10}$	0.61 ± 0.11	0.59 ± 0.16
$-20<M_p\leqq-19.6$	0.27 ± 0.16	$0.07^{+0.06}_{-0.03}$	0.22 ± 0.11			
$-20<M_p\leqq-19$				$0.49^{+0.23}_{-0.09}$	$0.06^{+0.03}_{-0.02}$	0.35 ± 0.07
$-19.6<M_p\leqq-18.3$	0.07 ± 0.03	0.05 ± 0.03	0.06 ± 0.02			
$-19 \leqq M_p\leqq-18$				0.39 ± 0.17	<0.08	<0.05

values of the BRLF above the minimum detectable power, $\log P_{610}=21.76$ (radio power in $\mathrm{WHz^{-1}}$), for the two clusters and for the (E+SO) galaxies in general (estimated from Auriemma et al., 1977). Despite of a fairly good agreement, among the three sets of integral values, we note that, while the galaxies brighter than -19.6 in A 2147 are confined in power below $\log P=23$, in A 2151 their power distribution reaches $\log P=24.5$ and this conforms better to the behaviour found for the (E+SO) in general (Auriemma et al., 1977), whose RLF is rather flat up to $\log P=24.5$. The statistical significance of this difference is however very limited, and because of the wide range of powers that elliptical galaxies can attain in their radio emitting phase(s), it can be easily attributed to a statistical fluctuation.

b) The BRLF *of the* (S+I) *Galaxies*

Table 6 contains the same information as Table 5, for the (S+I) galaxies in IC I and II. Except for 20W21, these are used to construct the BRLF. As in the previous papers of this series, we have applied to the spirals in ZH, detected and not, a correction for internal absorption, using the relationship between the correction and the apparent axial ratio given by Holmberg (1958). The axial ratios have been measured on the P.S.S. blue print. In Table 6 the corrected magnitudes are given in parenthesis. Because of the large uncertainty on the magnitudes estimated by us, this correction was not applied to the spirals not contained in ZH. This implies that some of the galaxies counted in the interval $-18.3\geqq M_p>-19.6$, including possibly 1 or 2 galaxies (in this magnitude interval) detected in radio, can be intrinsically brighter than -19.6. Therefore the estimates of the BRLF (Table 8) in this interval are also affected by this uncertainty. However this should have no consequence for the estimates in the brighter intervals, in particular the interval (-19.6, -20), because the BRLF is given in fractional form and is therefore unaffected by the incompleteness in absolute optical magnitude of the ZH sample, in that the detectability in radio of a spiral galaxy should not depend on its inclination.

By comparing the two BRLF's in Table 8, it is apparent that there are no significant differences between the two clusters. In particular they are both characterized by a low fraction of radio-emitting spirals among the bright (ZH) galaxies. This confirms the finding of Pap. II concerning A 2151 and extends its validity to the whole supercluster. In Table 9 the integral values of the BRLF of the two clusters are compared with the results obtained for the Coma Cluster (Pap. III) and for a sample of nearby "field" spirals. The "field" RLF was derived from a study by Cameron (1971a, b) in the way described in Papers II and III. We refer the reader to Paper III for the difference between entries (*a*) and (*b*), the first obtained without and the second with a magnitude correction of $0^m_.6$. The second choice is believed to be more consistent with the ZH magnitude scale.

With respect to Coma, the spirals in the Hercules supercluster appear to be weaker radio-emitters, especially in the brightest and the faintest of the three magnitude intervals. The comparison with the field is rather tricky, mainly because of the unsatisfactory situation with regard to the homogeneity of the magnitude scales adopted. In the faintest interval there is a fairly good agreement; in the middle one the percentage in Hercules is within the uncertainties of both choice (*a*) and (*b*), although these two are rather inconsistent with each other; in the brightest interval Hercules is clearly deficient with respect to the field. Our estimate of the expected number of detections among the ZH galaxies brighter than -20 is 7.6 ± 1.4, and 7.3 ± 2.1, according to choice (*a*) and (*b*) respectively, against only 1 galaxy detected.

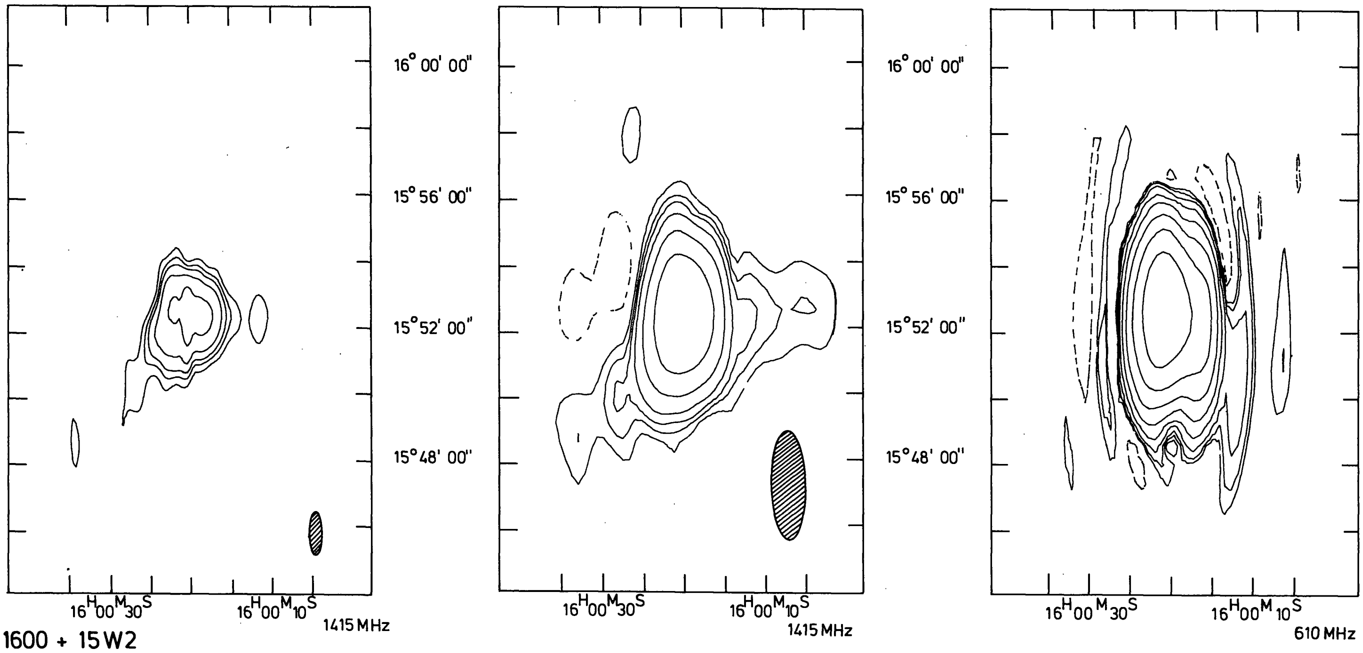


Fig. 4. Maps of 1600+15W2. To the left: 1415 MHz map; middle: 1415 MHz map convolved with the 610 MHz beam; to the right: 610 MHz map. Contour levels: 2, 4, 6, 10, 20, 40 etc mJy/beam (map flux, uncorrected for attenuation); the 2 mJy contour is left out from the 610 MHz map. Beam areas: 0.3 and 1.6 10^{-7} sterad at 1415 and 610 MHz respectively

Despite of all uncertainties, there is an indication that the deficiency in the strength of the radio-emission in the Hercules spirals (at least the very bright ones) with respect to Coma and the "field" might be due to intrinsic differences, rather than to a statistical fluctuation. Since a general discussion on the radio-optical properties of spirals in clusters is in preparation and will include also the other clusters in this survey, here we limit ourselves to the following points.

In Paper III it was stressed that 90% of the (S+I) detected in Coma have emission lines in their spectra at various degrees of intensity, compared to at most 65% of the galaxies of this type surveyed at 610 MHz. This indicates the possible existence of a correlation between the radio power and the presence of emission lines. For the Hercules supercluster a complete information on the optical spectra is not available to us, but we like to draw attention to the fact that only 2 of the 5 ZH spirals detected (see Table 6) show some evidence of emission lines. This suggests that the deficiency of radioemitting spirals might be connected with a lower proportion of emission line spectra in the (S+I) galaxies of Hercules with respect to Coma.

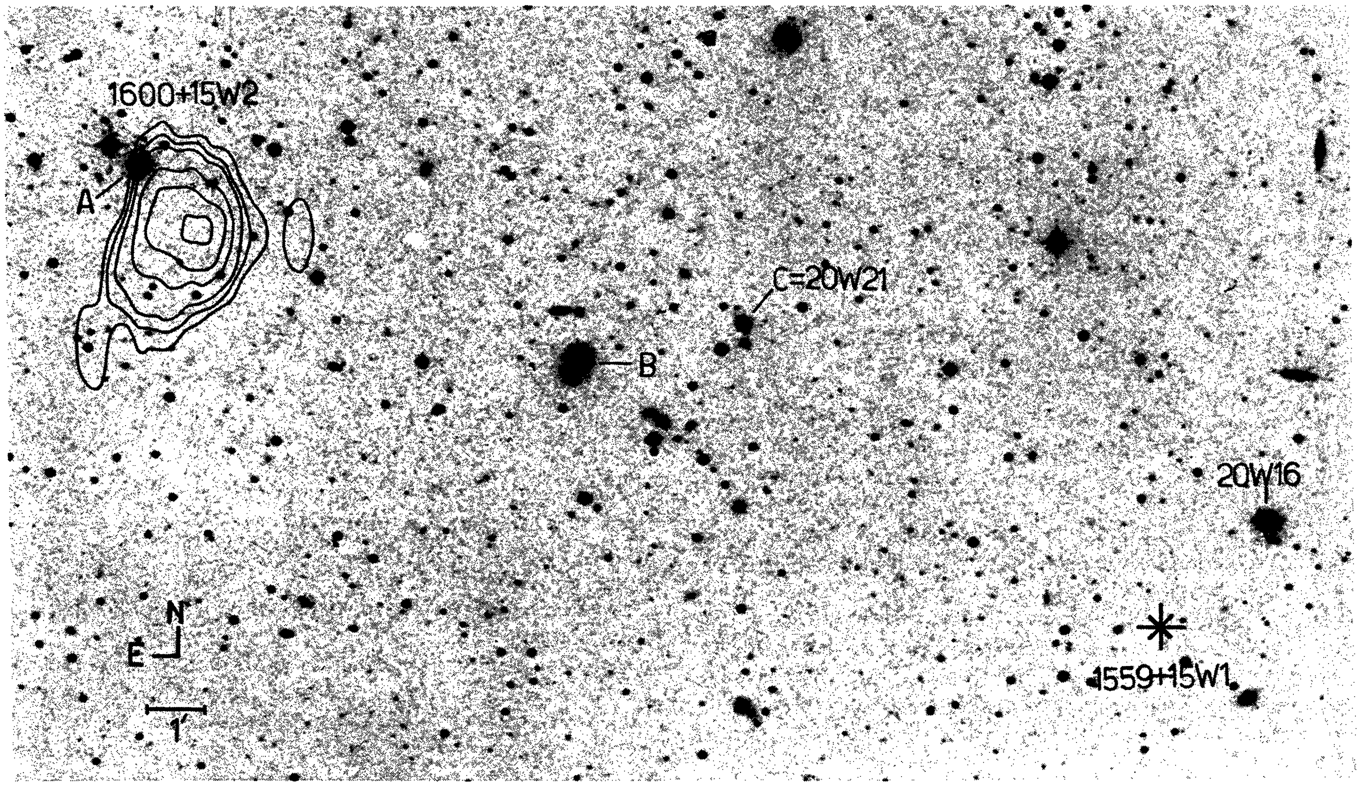
Because of the small number of detections, it is impossible to make a meaningful statistical test of whether their spatial distribution is or is not the same as that of all galaxies. We mention however the rather striking fact that none of the (S+I)'s detected in A2151, except the faint galaxy associated with 20W8, belongs to the region where the galaxy density is highest and a large fraction of the (S+I) galaxies are concentrated.

VI. Comments on a Hypothetical Double Source in A 2147

The sources 1559+15W1 (4C+15.52) and 1600+15W2 (4C+15.53) are the strongest in the field of A 2147. According to Mills and Hoskins (1977) they are the components of a double identified with a bright cluster galaxy. Let us first consider them as two independent sources.

At 1415 MHz 1559+15W1 is not resolved, but because of the strong attenuation nothing can be said about its extension (see Pap. I). At 610 MHz the map after subtraction of a point source at the position of the peak is shown in Fig. 3 (map of 20W16). There is no sign of extension, unless the two weak sources to the N–W (20W16 identified with IC1161) and to the N–E are considered appendixes of the strong source itself. The peak flux at 610 MHz is 1536±39 mJy, which combined with the flux at 1415 MHz of 560±70 mJy given in Pap. I yields a spectral index $\alpha_{610}^{1415}=1.20\pm0.18$. Within 3σ of the position of the radio peak there is no optical counterpart.

The source 1600+15W2 appears very extended at 1415 MHz. The full resolution map at this frequency is given in Pap. I and is also reproduced in Figs. 4 and 5. The structure of this source is atypical, it appears as a roundish body with a brightness gradient which is steeper toward the eastern side. Low brightness extensions to the West and to the South-East appear more clearly on the convolution of this map with the 610 MHz beam in Fig. 4. A comparison with the 610 MHz map given in the same figure shows that the structure of the source is rather similar at the two frequencies. Unfortunately, on the latter map the low brightness extensions are badly affected by sidelobes. The total flux is 1617±30 mJy at 610 MHz and 887±40 mJy at 1415 MHz, and the spectral index between these two frequencies is 0.71±0.02. It should be noted however that the spectral index appears to vary across the source, and is steeper on the eastern side (0.90) than on the western side (0.60) of the main body. The optical identification is very doubtful, because there are several candidates under the radio contours, none of which is close to the radio peak. In Pap. I an IC III was assigned to the object (m_v =17.5) closest to the peak. An interesting possibility is the identification with the bright ($m_p \simeq 16$) elliptical galaxy touched by the N–E contours (object A in Fig. 5), which is probably a cluster member. One should then consider this as another example of a radio source with the main body of the radio-emission greatly



Optical field of the sources 1600+15W2 and 1559+15W1, see discussion in Sect. VI. Reproduction from Palomar Sky Survey

displaced with respect to the optical counterpart. Typical cases with a marked displacement found in clusters are the radio tails, but in these sources generally the brightness distribution indicates more clearly the connection with the galaxy, and often a component of the source appears very close to or coincident with it. Moreover the spectral index in these sources tend to increase away from the galaxy, while in this case we have an indication of the opposite. A future higher resolution observation at 5 GHz will hopefully help to clarify this association: the detection of a flat spectrum nuclear source will be an important indication in favour of the association.

The situation when these sources are, according to Mills and Hoskins (1977), considered components of a double is illustrated in Fig. 5. They propose as identification the double galaxy indicated with the letter *B*. This is the system Zw 108–67 of $m_p = 14.6$, composed of an SO (the brighter of the two) and a S galaxy. This system is well aligned with the two radio peaks, but it is twice as far away from the western component than from the eastern one. The galaxy itself is undetected, and one can place upper limits of $S_{610} = 7$ mJy and $S_{1415} = 50$ mJy. Another candidate to the identification could be galaxy C, which is detected at 610 MHz (but only at the 3σ level, source 20W21). This galaxy is closer to the radio centroid than the previous one, but is rather off the line joining the components. Moreover its optical morphology (a blue irregular) makes its association to an extended strong radio source very improbable. There is no trace on the map of radio-emission bridging the two components across a galaxy. Together with the great morphological dissimilarity between the two sources, these considerations make the hypothesis that they are related to each other and to a cluster galaxy rather doubtful. It is interesting to note that the angular separation of the two "components" is about 20′, which would correspond to a projected physical separation of 660 kpc at the distance of Hercules. This source would therefore be one of the extremely few aligned doubles of very large extent found in clusters (cf. Lari and Perola, 1977; Rudnick and Owen, 1977).

We conclude that the evidence in favour of the "double" hypothesis is very weak, and that the two sources could well be background. However, the identification of 1600+15W2 with the bright E galaxy is rather suggestive, particularly because the peculiar morphology of the source could find an explanation in the interaction with the intracluster gas.

Concerning the RLF of the (E+SO) galaxies, the inclusion of the strong source 1600+15W2 ($\log P_{610} = 24.4$) would make the power distribution in A 2147 more similar to that in A 2151, without significantly change the integral values.

VII. Conclusions

The results concerning the Radio Luminosity Function at 610 MHz of the galaxies in the Hercules supercluster (A 2151 and A 2147) confirm at a somewhat higher statistical level those obtained in Pap. II from the survey at 1415 MHz. Namely we find that:

a) The elliptical and SO galaxies have a RLF which is consistent with the one found in other clusters and in the general field. The difference in the distribution of radio power between A 2151 and A 2147 is not statistically significant, and would be reduced if the identification of 1600±15W2 with a bright elliptical (object *A* in Fig. 5) were accepted.

b) The spiral and irregular galaxies show a deficiency in their radio power with respect both to the Coma Cluster (Paper III) and to a sample of nearby galaxies. This deficiency is especially marked for the very bright galaxies ($M_p \leqq -20$). It is rather surprising that this type of galaxies are weaker radio-emitters when members of a spiral rich cluster like Hercules compared to those belonging to Coma, a spiral poor cluster.

A general discussion of the radio properties of the spirals, in connection with the morphological type of the cluster, and with their intrinsic properties, like the Hubble type, the colour and the presence of emission line in the optical spectra, is in preparation and will include the other clusters in this survey.

Acknowledgements. We wish to thank Dr M. Tarenghi and his collaborator for giving us crucial information before its publication. We thank also Prof F. Bertola for lending us a plate in an earlier phase of this work, the Bologna group, ROUB, for assistance in part of the identification work, the Westerbork Telescope Group and the Reduction Group for their work on the observation and the photographic department of the Sterrewacht Leiden for some of the figures. E.A.V. acknowledges financial support from the Netherlands Organization for Pure Research (Z.W.O.). G.C.P. acknowledges financial support from the Italian National Research Council (CNR) and the Sterrewacht Leiden for the hospitality in several occasions during this work. The Westerbork Radio Observatory and the Reduction Group are administered by the Netherlands Foundation for Radio Astronomy (S.R.Z.M.) with the financial support of Z.W.O..

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