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WSRT and VLA observations of very steep spectrum radio galaxies in clusters

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Summary. A sample of very steep spectrum radio sources in rich clusters of galaxies has been observed at 20.5 cm with the VLA and at 49 cm with the WSRT. They are typical of sources which are confined by the intergalactic medium and they represent a late stage of evolution of radio sources in which synchrotron losses dominate and expansion losses no longer occur. Their spectra are in agreement with theoretical models of evolution governed on one hand by input of energy from the nucleus of the galaxy and on the other hand by synchrotron losses (Kardashev, 1962). One important consequence can be derived from the properties of these sources. The diffusion of relativistic electrons from the radio lobes in the intergalactic medium is not the primary mode of losses during the evolution of such confined radio sources.

Key words: radio sources

1. Introduction

A small fraction of all extragalactic radio sources have a spectral index α [defined in the sense: flux density $\propto$(frequency)$^{-\alpha}$] exceeding 1.3. Many of these steep spectrum radio sources are low luminosity sources associated with nearby X-ray clusters of galaxies (Baldwin and Scott, 1973; Slingo, 1974a, b; Roland et al., 1976; Véron, 1977). Most of them are relaxed sources showing evidence of confinement by the intergalactic medium, and are associated with one galaxy of the cluster. Typical sources of this kind are 3C 318.1, 3C 338, and 3C 317 which are associated with the X-ray clusters of galaxies MKW-3s, A 2199, and A 2052, respectively. Others are of the Coma C radio halo type associated with A 1656 (see Hanisch, 1982, for a review of these sources). A fraction of the steep spectrum radio sources have larger radio luminosities, a compact double radio structure, and are associated with high redshift galaxies (Roland et al., 1982). In this article, we are interested in the relaxed steep spectrum radio galaxies associated with clusters of galaxies. The study of these unusual sources is necessary to understand the evolution of radio sources. Thus, we selected from the literature a sample of these sources and observed them with the Very Large Array at 20.5 cm and with the Westerbork Synthesis Radio Telescope at 49 cm. We present here the results of these observations and discuss the common properties of these sources.

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2. Observations

2.1. VLA observations

Roland et al. (1976) provided a list of the steep spectrum sources ($\alpha \geqq 1.3$) then known; we have added to this list 3C 317 which, with $\alpha = 1.27$, had been excluded, and NB 78.26 F (Bridle et al., 1979), which was not yet known at the time.

Three sources had been previously observed with the VLA by others: 4C 63.10 by Harris et al. (1982), 3C 338 by Burns et al. (1983), and 3C 318.1 (Fomalont, unpublished). Within the allocated time we were able to observe the eight steep spectrum sources located in clusters listed in Table 1. The observations were done in July 1982 with the VLA in configuration *B* at 20.5 cm (1465 MHz, bandwidth 50 MHz). The half-power beam width is about 2″.6. Each source was observed for 2 times 20 min, with phase calibrations done every 30 min. Flux densities were calibrated with reference to 3C 48 and 3C 286 and on the scale of Baars et al. (1977). The maps were produced using the AIPS reduction system. The fluxes of the most extended sources were obtained by degrading the resolution of the observations.

2.2. WSRT observations

Three of the most interesting sources (B2 1028+35, 4C 38.39, and 4C 20.57) were also observed in January and March 1983 at 49 cm with the WSRT (608 MHz, bandwidth 2.5 MHz). Each source was observed for a total of 2 h in seven short integrations distributed over the largest possible range of hour angles in order to get good (u, v) coverage. The half-power beam width is about $30 \times (30/\sin\delta)$ arc s. The flux calibration sources used were 3C 147 and 3C 286. The maps were obtained using the standard reduction system.

2.3. Optical identifications

We have attempted to identify the observed sources on the Palomar Sky Survey plates. The optical positions were measured with respect to SAO reference stars with the Optronics XY measuring machine at ESO. The accuracy is better than or equal to one arc s in both coordinates.

3. Results

A summary of the results of the radio observations and optical identifications is given in Table 1 and in Fig. 7. Below we give more detailed notes on individual sources.

Table 1. The observed sources

Source name		α (1950) δ	Flux density	α	Cluster	Optical identification
4C 01.06		02 59 03.4 +01 43 29	$S_{1.4}=0.355$	1.85	Zw Cl	cD galaxy
	I	02 59 18.1 +01 42 15	$S_{1.4}=0.038$	?		Faint galaxy
B2 1028+35		10 28 52.6 +35 17 10	$S_{1.4}=0.029$*	>1.3	A 1033	Galaxy at 7″
		10 28 52.3 +35 17 14	$S_{0.6}=0.220$			
	I	10 28 50.1 +35 18 04	$S_{1.4}=0.046$	0.95		Galaxy in A 1033
			$S_{0.6}=0.100$			
	II	10 29 09.5 +35 18 21	$S_{1.4}=0.031$	1.25		Galaxy in A 1033
		10 29 08.7 +35 18 17	$S_{0.6}=0.090$			
B2 1045+31		10 45 25.0 +31 44 14	$S_{1.4}=0.048$	1.5	A 1097	EF
B2 1342+38B		13 42 49.1 +38 24 18	$S_{1.4}=?$	?	A 1785	Galaxy in A 1785
4C 38.39		14 24 03.1 +38 02 27	$S_{1.4}=0.014$*	2.3	A 1914	Galaxy at 15″
		14 24 03.0 +38 02 30	$S_{0.6}=0.284$			
	I	14 23 37.7 +37 59 16	$S_{1.4}=0.050$	1.0		QSO
		14 23 37.7 +37 59 16	$S_{0.6}=0.098$			
	II	14 23 47.1 +37 58 35	$S_{1.4}=0.006$	<0		EF
			$S_{0.6}<0.005$			
	III	14 23 50.3 +38 01 33	$S_{1.4}\sim0.003$	1.7		Galaxy in A 1914
		14 23 50.3 +38 01 30	$S_{0.6}=0.015$			
	IV	14 23 55.2 +37 57 28	$S_{1.4}=0.004$	0.8		Very faint galaxy or EF
		14 23 55.1 +37 57 19	$S_{0.6}=0.008$			
	V	14 24 03.2 +38 04 09	$S_{1.4}=0.003$	<0.6		EF or very faint galaxy
			$S_{0.6}<0.005$			
3C 317		15 14 17.0 +07 12 17	$S_{1.4}=5.46$	1.3	A 2052	cD galaxy
NB 78.26 F	I	17 08 28.5 +78 41 43	$S_{1.4}=0.003$*	?	A 2256	Galaxy cluster ~20″
	II	17 09 08.1 +78 43 21	$S_{1.4}=0.009$*	?		Galaxy cluster ~20″
	III	17 09 46.8 +78 44 56	$S_{1.4}=0.003$*	?		Galaxy cluster ~5″
4C 20.57		23 33 59.3 +20 52 11	$S_{1.4}=0.028$*	2.2	A 2626	cD galaxy
		23 33 59.2 +20 52 09	$S_{0.6}=0.371$			
	I	23 33 34.4 +20 45 10	$S_{1.4}=0.031$	0.8		Very faint galaxy
		23 33 34.5 +20 45 11	$S_{0.6}=0.056$			
	II	23 33 45.3 +20 49 38	$S_{1.4}=0.021$	<0		EF
			$S_{0.6}<0.005$			

Column 1: The name of the source. The first line is the name of the source responsible for the low frequency radio emission of the cluster. The other sources in the field are denoted I, II…
Column 2: The 1950 radio position. (First line is the VLA position and second line is the WSRT position)
Column 3: First line: the VLA (1465 MHz) flux (Jy). An asterisk (*) means that the VLA flux is underestimated, due to the existence of extended components in the source.
Second line: the WSRT (608.5 MHz) flux (Jy)
Column 4: The spectral index of the source (see also Table 2 and Fig. 1)
Column 5: The name of the cluster of galaxies
Column 6: The optical identification of the source (see also Fig. 7)

4C 01.06: The steep spectrum radio source, 4C 01.06, is associated with the cD galaxy of the cluster Zw 02589+0142 (Clarke et al., 1966), the position of which is 02 59 02.9, +01 43 26. Thus, the position of the radio peak is different from the position of the center of the galaxy by 7″.5 (Fig. 1). The spectral index below 408 MHz is ≃1.2 and becomes equal to 1.85 at frequencies greater than 600 MHz.

The component I is associated with a faint galaxy (02 59 18.1, +01 42 14).

B2 1028+35: The situation for this cluster is rather complicated. The component I is a head-tail radio source associated with a bright galaxy of the cluster (10 28 50.0, +35 18 08). Its mean spectral index is ≃0.95.

The source B2 1028+35 is extended by about 2′.5 in the $E-W$ direction (Fig. 2a), so that the 20.5 cm flux is underestimated. The Texas interferometer indicates a 365 MHz flux density of 0.38 Jy at 10 28 53.8, +35 17 13 (Wills, 1983). This flux is in agreement with the 408 MHz flux of Bologna if we subtract the 408 MHz contribution of component I. The spectral index of B2 1028+35 is ≃1.15 at frequencies lower than 408 MHz and probably becomes steeper at higher frequencies. Further observations at 20.5 cm with VLA (configuration *C*) are necessary to see if the spectrum of this source is similar to the spectrum of 4C 01.06.

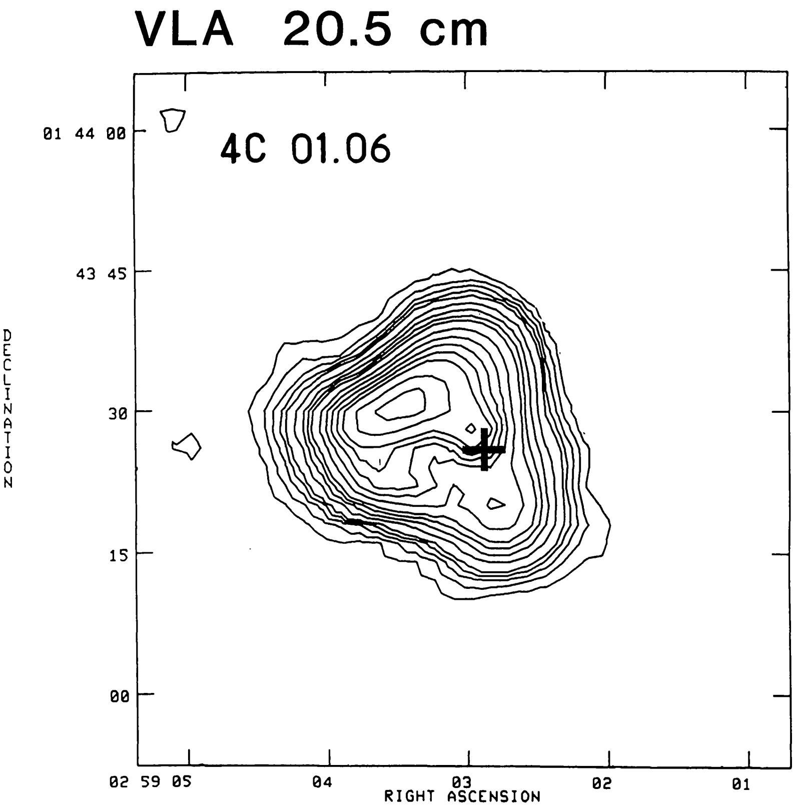

Fig. 1. 20.5 cm VLA map of 4C 01.06. Contour levels are: 0.6 mJy/beam × (1, 2, 3, 4, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, and 60). The cross indicates the position of the associated galaxy

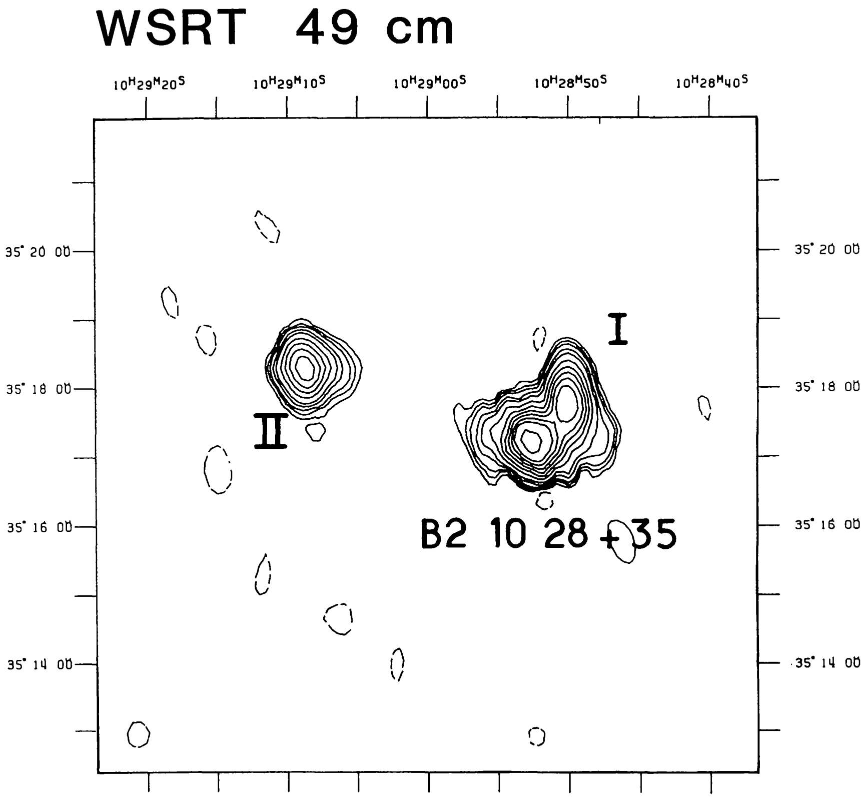

Fig. 2a. 49 cm WSRT map of B2 1028+35. Contour levels are: 5 mJy/beam × (−0.5, 1, 1.5, 2, 3, 4, 6, 8, 10, 12, 14, 16, 20, and 30)

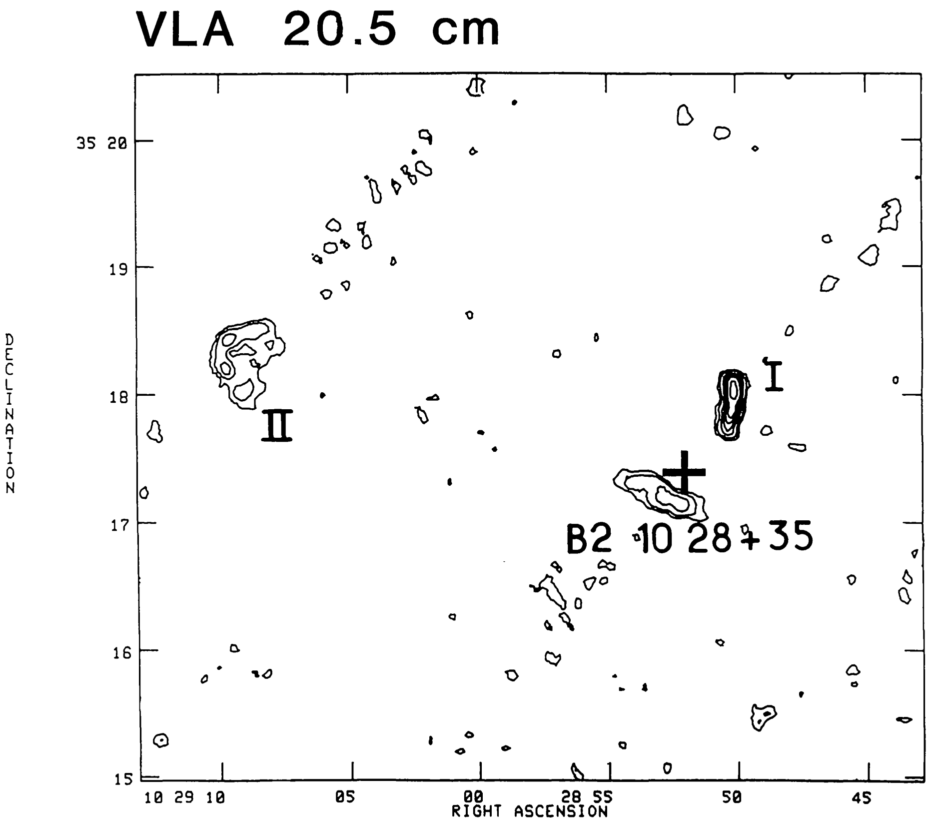

Fig. 2b. 20.5 cm VLA map of B2 1028+35. The first 3σ contour level is 1 mJy/beam. Contour levels are: 0.5 mJy/beam × (1, 2, 4, 6, 8, 10, and 15). The cross indicates the position of the associated galaxy

There is no galaxy coincident with the central radio peak. The brightest galaxy is at about 7″ (10 28 52.0, +35 17 20) from the radio peak (Fig. 2b) and is indicated by an arrow in Fig. 7. The faint galaxy located to the SW is at 10 28 53.1, +35 17 07.

Component II could be a wide angle tail with low surface brightness radio emission between the tails. It is associated with a bright galaxy of the cluster (10 29 09.9, +35 18 20). Its spectral index is $\simeq 1.25$ and its 408 MHz flux is lower than 0.25 Jy, so that it is not in the Bologna catalogue (Colla et al., 1973).

B2 1045+31: This source has been identified by Roland et al. (1976) and Harris et al. (1980) with a bright double galaxy in the cluster A 1097. However, our VLA observation indicates that the radio source is compact ($\lesssim 3''$) and that its position does not coincide with any optical object on the PSS. The positions of the two bright galaxies near B2 1045+31 are respectively 10 45 22.5, +31 44 13 and 10 45 25.1, +31 44 53. Therefore, this source is not associated with the cluster and belongs to the class of compact sources with a steep spectrum described by Roland et al. (1982). The source 1045+41 has been found to be more than 50% scintillating at 81.5 MHz with components less than 0″.7 (Readhead and Hewish, 1974). It has been associated by Readhead and Hewish with 4C 29.39 but it is in fact associated with B2 1045+31. Its 81.5 MHz flux density ($S_{81.5} = 5.5$ Jy), associated with the 408 MHz (Colla et al., 1970), the 1465 MHz (present work) and the 2700 MHz (Roland et al., 1976) flux densities, gives a spectral index $\alpha \simeq 1.5$. In such conditions, the 178 MHz flux density is expected to be lower than 2 Jy which explains why the source B2 1045+31 is not in the 4C Catalogue.

B2 1342+38 B: The 408 MHz flux is 0.26 Jy with a large error (Colla et al., 1973). The source has not been detected at 2700 MHz (Roland et al., 1976). The WSRT 21 cm flux (Harris et al., 1980) is 25 mJy and the VLA 20.5 cm flux (present work) is $\simeq 10$ mJy. The difference between the 21 cm flux densities can probably be explained by a large uncertainty in the WSRT flux and an underestimation of the VLA flux due to resolution. Although the source certainly exists, its spectral index is quite uncertain and probably not very steep. It is associated with a galaxy in the cluster A 1785 the position of which is 13 42 49.1, +38 24 17.

4C 38.39: Component I is double, with a separation of 27″. It is associated with a blue starlike object (14 23 38.2, +37 59 21).

Component II has a negative spectral index and is probably in an EF. A faint galaxy is at position: 14 23 46.1, +37 58 34.

The component III is easily detected at 49 cm, and is extended in N–W direction. It is just detected at 20.5 cm and has a spectral index of about 1.7, but does not contribute significantly to the low frequency emission of the cluster. It can be associated with a galaxy in A 1914 (14 23 50.5, +38 01 34).

Component IV might be associated with a faint galaxy (14 23 55.7, +37 57 20).

The 608.5 MHz map of 4C 38.39 (Fig. 3a) shows a maximum extension of $\simeq 2'.5$ in the N–W direction so that the 20.5 cm flux could be underestimated. Its spectral index below 178 MHz is $\simeq 1.5$, it steepens at 600 MHz with a value of 2.3. The nearest galaxy is a bright galaxy of the cluster at $\simeq 15''$ (Fig. 3b), the position of which is 14 24 03.6, +38 02 44.

Component V is a flat spectrum radio source in an EF. A very faint galaxy is at 14 24 03.2, +38 03 58.

3C 317: The structure of the source is amorphous. The position of the radio peak coincides with the optical center (Wills et al., 1973; Hunstead, 1971). The total extension is 1′ (Fig. 4). A map made at 2695 MHz with the NRAO 3-element interferometer has previously been published (Fomalont et al., 1980). The spectral index

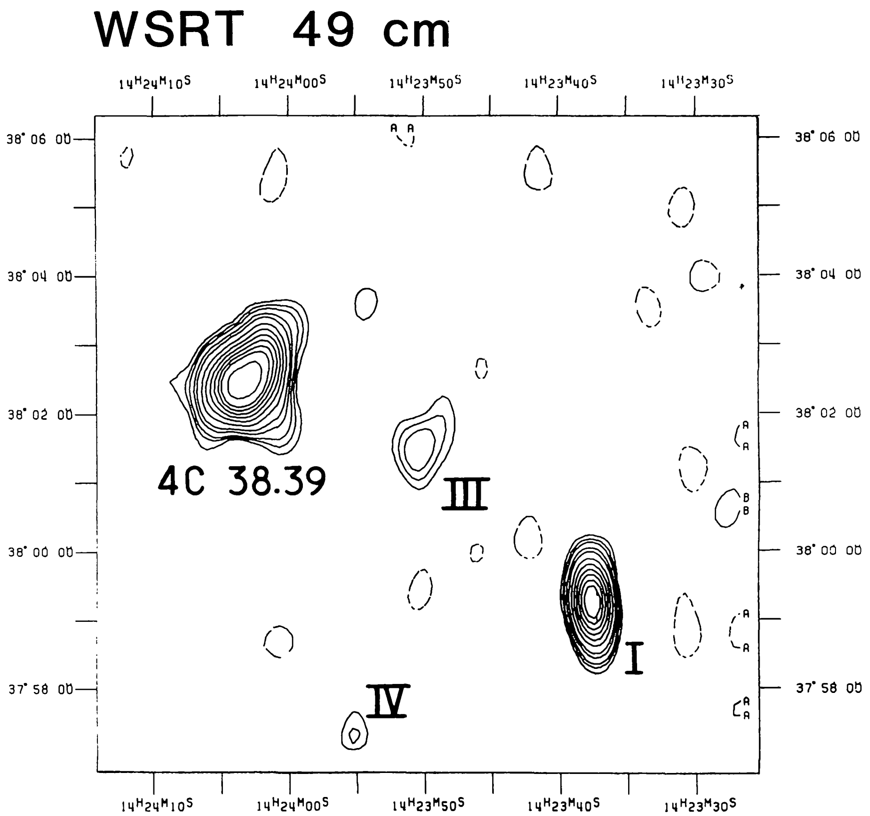

Fig. 3a. 49 cm WSRT map of 4C 38.39. Contour levels are: 5 mJy/beam × (−0.5, 1, 1.5, 2, 3, 4, 6, 8, 10, 12, 14, 16, and 20)

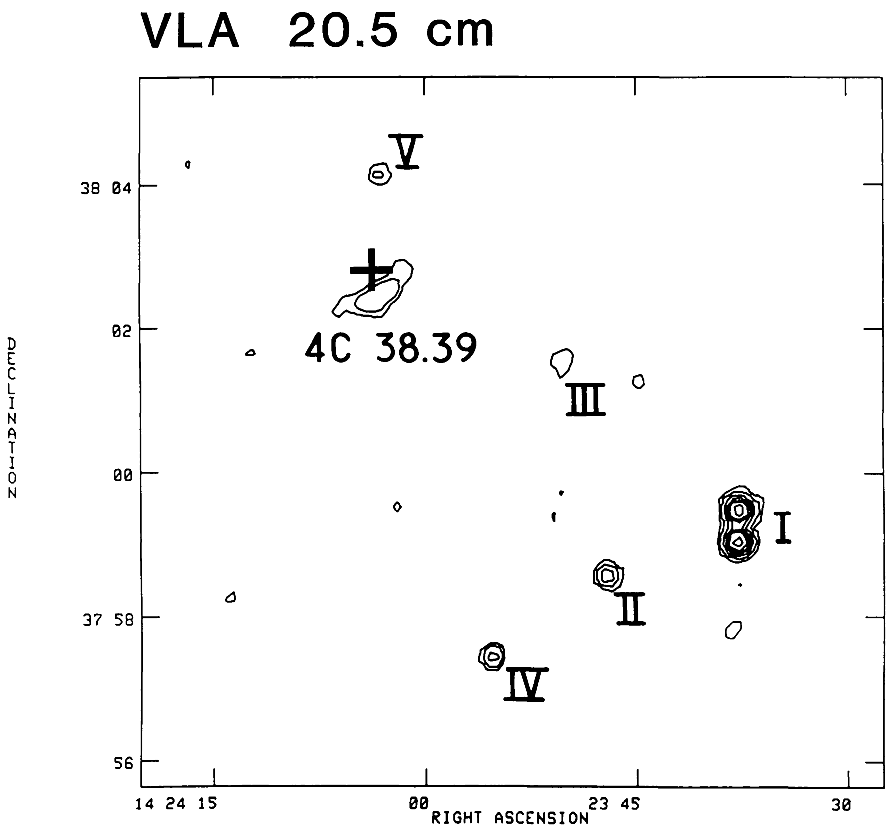

Fig. 3b. 20.5 cm VLA map of 4C 38.39. Contour levels are: 1 mJy/beam × (1, 2, 4, 6, 8, 10, and 15). The resolution of this map has been degraded by a factor 3. The cross indicates the position of the associated galaxy

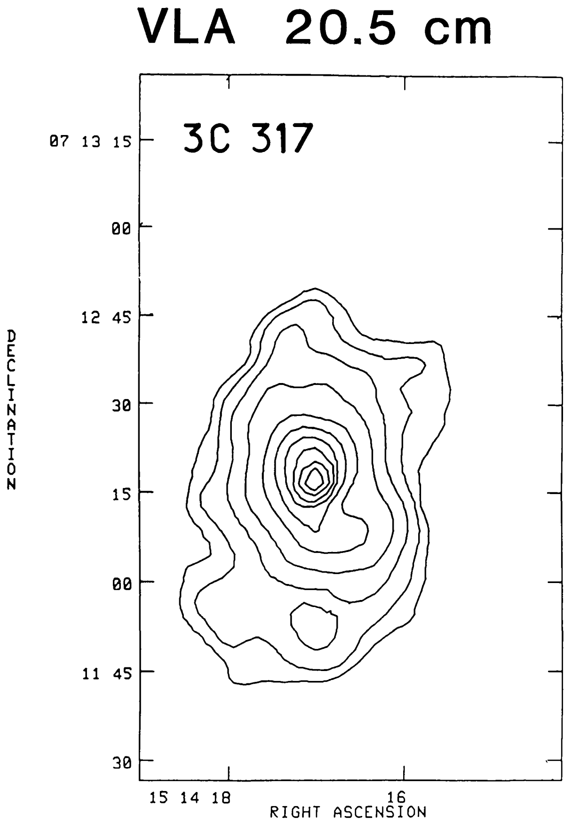

Fig. 4. 20.5 cm VLA map of 3C 317. Contour levels are: 8 mJy/beam × (1, 2, 4, 8, 16, 24, 32, 40, 50, and 60)

below 200 MHz is ≃0.8 and becomes steeper (≃1.3) at frequencies greater than 750 MHz.

NB 78.26 F: The case of NB 78.26 F is complicated. The position of component I differs from component I of Bridle et al. (1979) by about two arc min in declination. Components II and III have positions in agreement with those of Bridle et al. (1979). However, fluxes found with the VLA in configuration *B* are about 3 times smaller than those measured with the WSRT at 1415 MHz (Bridle et al., 1979). This is probably due to extended components associated with the three components which are not detected with the VLA.

The positions of the three bright galaxies which are the closest of the three components NB 78.26 F I, II, III are respectively at 17 08 30.1, +78 41 24, 17 09 11.7, +78 43 05, and 17 09 48.8, +78 44 53 (Fig. 5).

4C 20.57: Component I is associated with a very faint galaxy (23 33 34.3, +20 45 10) which is not associated with the cluster.

Component II has a negative spectral index and is in an EF. The two galaxies near 4C 20.57 II are respectively at 23 33 45.3, +20 49 46 and 23 33 46.1, +20 49 12.

The source 4C 20.57 is the very steep spectrum radio source associated with IC 5338 (Sargent, 1973, and ref. quoted). The 608.5 MHz map (Fig. 6a) shows that it is *S*-shaped and extended by ≃3′; in that case the VLA flux is underestimated. The VLA map (Fig. 6b) indicates an unresolved core (S_{1400} = 14 mJy) and two extensions in the same direction as the 608.5 MHz map. The spectral index is ≃2.2 at frequencies higher than 200 MHz and ≃1.1 at frequencies below 200 MHz.

The characteristics of the observed steep spectrum radio galaxies can be summarized as follows:

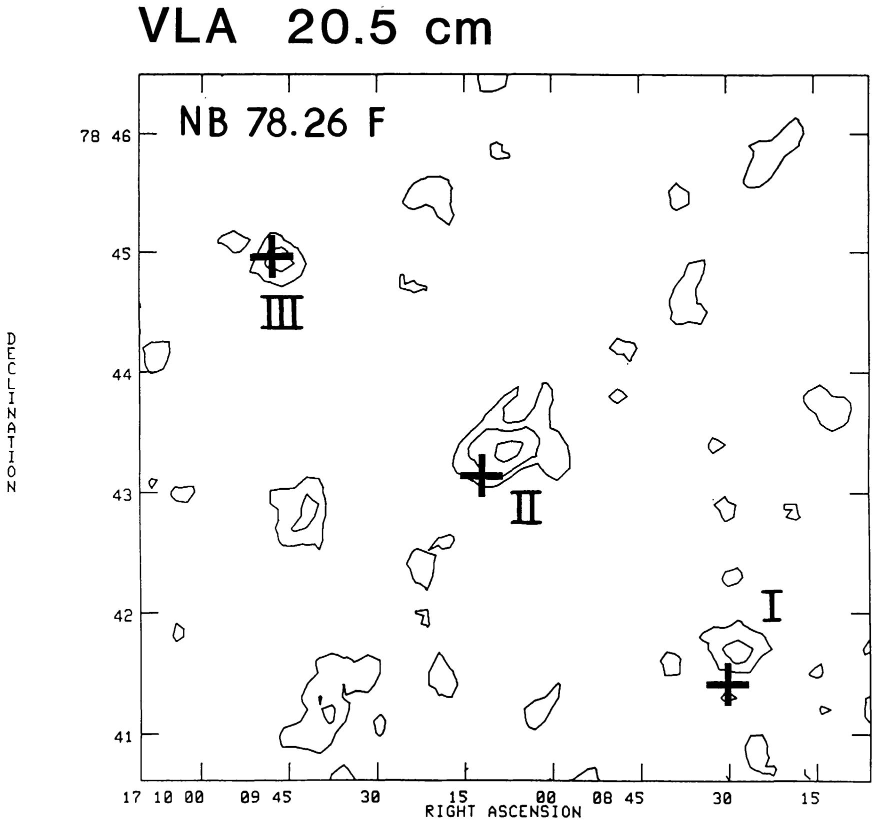

Fig. 5. 20.5 cm VLA map of NB 78.26 F. The first 3σ contour level is 1 mJy/beam. Contour levels are: 0.5 mJy/beam × (1, 2, and 4). The resolution of this map has been degraded by a factor 3. The crosses indicate the positions of the associated galaxies

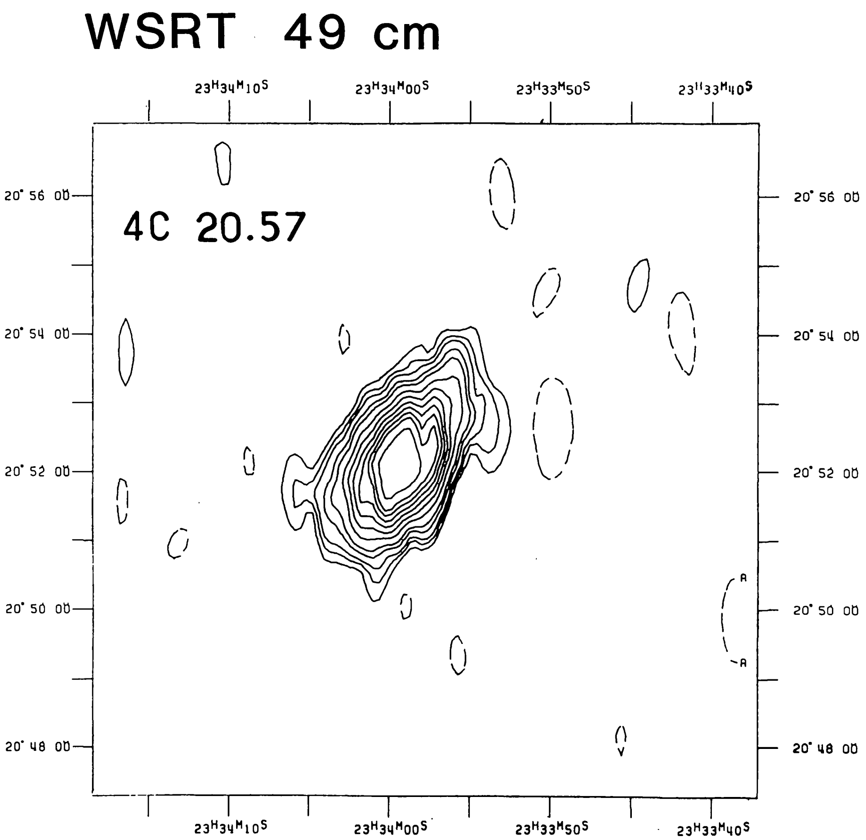

Fig. 6a. 49 cm WSRT map of 4C 20.57. Contour levels are: 5 mJy/beam × (−0.5, 1, 1.5, 2, 3, 4, 6, 8, 10, 12, 14, 16, and 20)

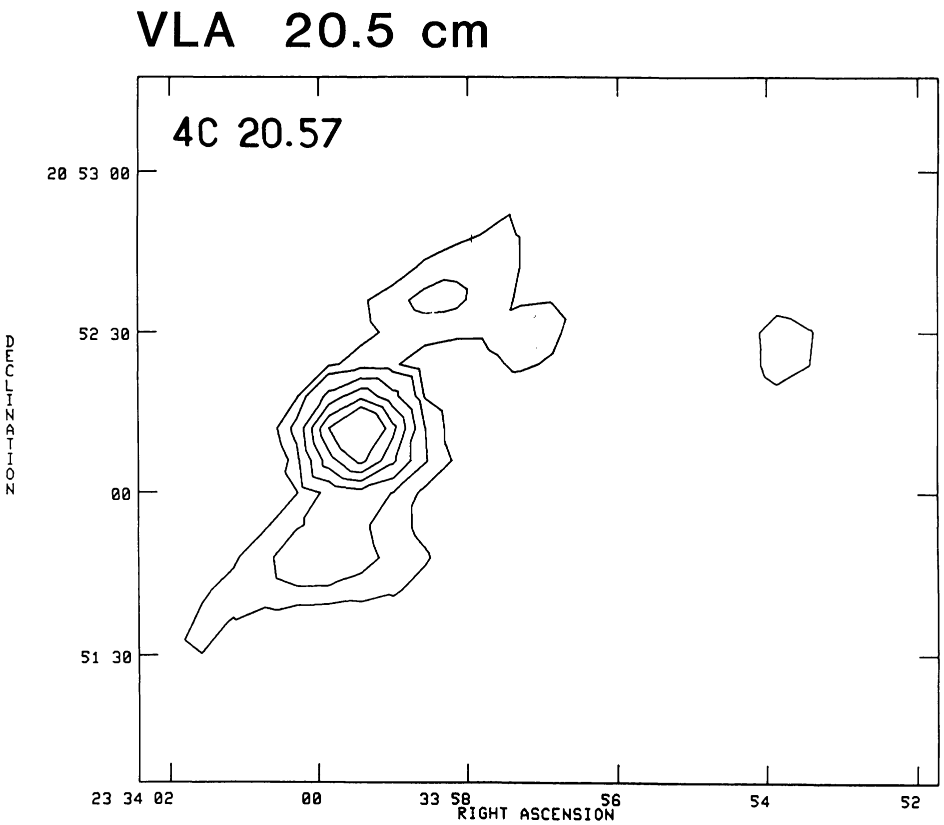

Fig. 6b. 20.5 cm VLA map of 4C 20.57. Contour levels are: 1 mJy/beam × (1, 2, 4, 6, 8, and 10). The resolution of the map has been degraded by a factor 3

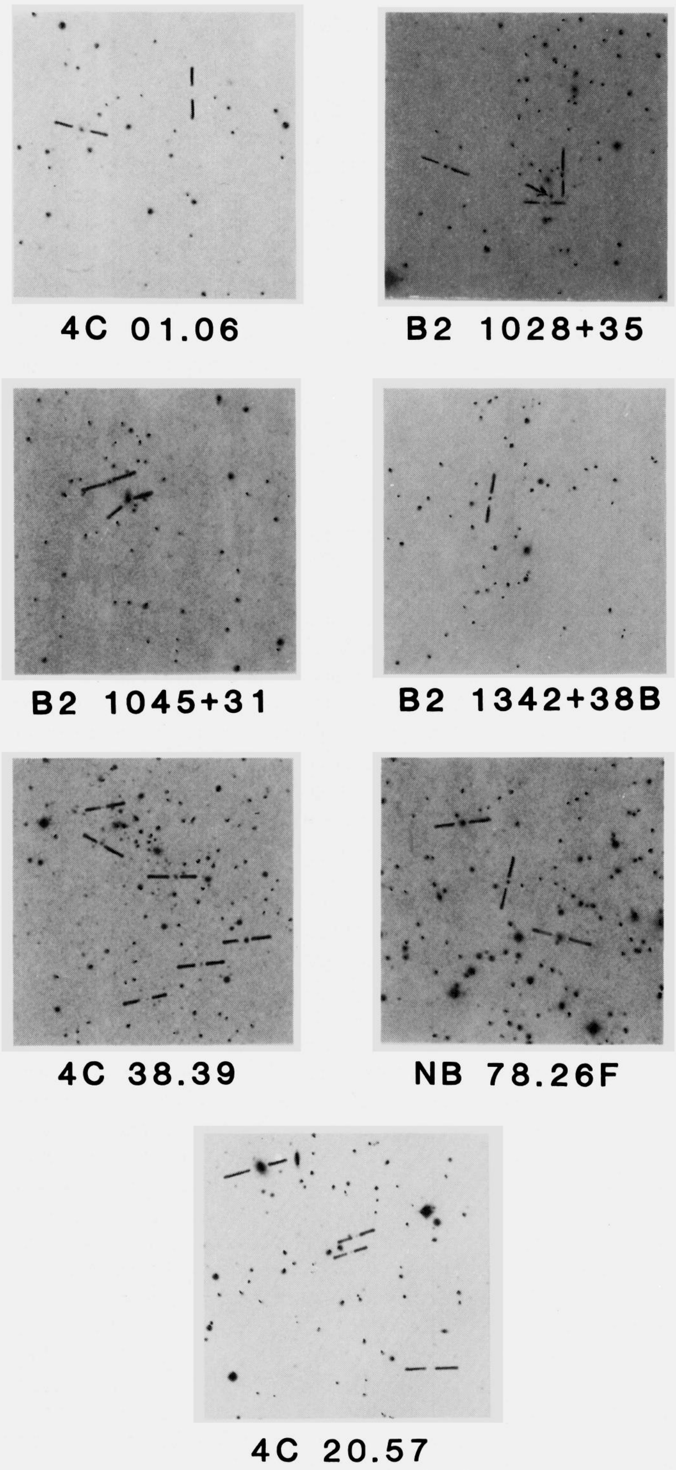

Fig. 7. Optical identifications of the fields of 4C 01.06, B2 1028+35, B2 1045+31, B2 1342+38 B, 4C 38.39, NB 78.26 F, and 4C 20.57. North is upwards and east is to the left

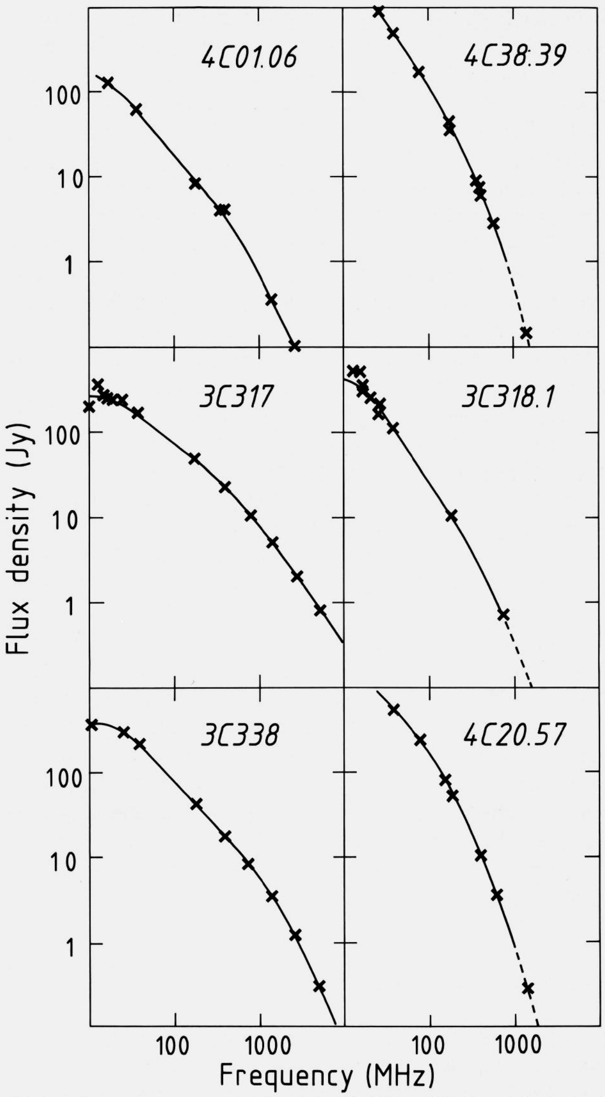

Fig. 8. The radio spectra of 4C 01.06, 4C 38.39, 3C 317, 3C 318.1, 3C 338, and 4C 20.57. The flux densities are from: Bridle and Purton (1968) (10 MHz), Braude et al. (1978, 1979) (15–25 MHz), Viner and Erickson (1975) (26 MHz), Williams et al. (1966) (38 MHz), Gower et al. (1967) and Pilkington and Scott (1964) (178 MHz), Wills (1983) (365 MHz), Slingo (1974b) (408 MHz), Colla et al. (1973) (408 MHz), Kellermann et al. (1969) (178 MHz, 750 MHz, 1400 MHz, 2700 MHz, and 5000 MHz), present work (610 MHz and 1400 MHz). The spectra of very steep spectrum sources have been studied by Baldwin and Scott (1973), Slingo (1974a, b), Jaffe and Perola (1974) for 3C 338, Harris et al. (1982) for 4C 63.10

a) The source B2 1342+38 B (A 1785) probably does not have a steep spectrum. B2 1045+31 is a compact source which is not associated with the cluster A 1097.

b) Three sources, 4C 01.06, 3C 317, and 4C 20.57, are associated with the brightest galaxy of the clusters and the peak of the radio brightness distribution coincides with the galaxy in the cases of 3C 317 and 4C 20.57.

c) The other sources (B2 1028+35, 4C 38.39, 4C 38.39 III, and NB 78.26 F I, II, III) are more complicated and are discussed in detail below.

The source 4C 38.39 III has been discovered to have a very steep spectral index ($\alpha \simeq 1.7$); therefore the cluster A 1914 contains two steep spectrum sources, although this one is very faint. The radio source coincides with a galaxy of the cluster.

The two sources B2 1028+35 (Fig. 2) and 4C 38.39 (Fig. 3) are probably associated with the clusters A 1033 and A 1914 respectively, but the galaxies which could be responsible for the radio emission are displaced 7″ and 15″ (31 and 65 kpc, assuming $H_0 = 50$ km s/Mpc) from the radio peaks. Both sources have angular extents less than 2.′5, or projected linear extents less than 650 kpc if we assume that they are associated with the clusters of galaxies.

NB 78.26 F (Fig. 5) has three components and was interpreted by Bridle et al. (1979) as an unusual curved head-tail in the cluster A 2256. The components *F* I, II might be either a segment of the tail oriented along the line of sight or a section of the tail that was produced by heightened activity of the parent galaxy at some time in the past (Bridle et al., 1979); the associated galaxy is displaced 5″ from component III. The VLA 20.5 cm observations differ significantly from previous 21 cm Westerbork observations (Bridle et al., 1979). The VLA fluxes are three times lower than the Westerbork fluxes and thus imply that the majority of the flux density must originate in quite extended components. Also the peak flux density positions of component I differ by about 2′. The interpretation of NB 78.26 F as a remnant of a head-tail seems unlikely for two reasons. First, the spectral index does not change along the tail and secondly, the projected distance on the sky between *F* I and *F* III is 5′, which corresponds to 525 kpc, so that it cannot be oriented along the line of sight. Further observations, using VLA configuration *C* are needed to know if the three components are connected. The nearest bright galaxies of components *F* I, II, and III are at 20″, 20″, and 5″ of the radio peaks, respectively. Thus, the distance of the radio peaks to the optical objects is 35, 35, and 9 kpc, respectively.

The common properties of the steep spectrum sources B2 1028+35, 4C 38.39, and NB 78.26 F in the clusters A 1033, A 1914, and A 2256 are: a) they are associated with a galaxy which is not the dominant galaxy of the cluster, and b) the peak of radio brightness is displaced from the associated galaxy by a projected distance in the range 10–60 kpc. A galaxy with a velocity of 200 km s^{-1} would travel 60 kpc in 3 10^{8} yr, so that the projected distance found between the center of the radio source and the brightest galaxy of the cluster can easily be explained by a slow motion of the galaxy.

4. Discussion and conclusions

The very steep spectrum radio sources are interesting because they represent evolving radio sources for which either synchrotron losses are dominant and/or the nuclear activity has stopped or slowed down. Generally, expansion losses of the extended lobes, associated with a strong fading of the activity of the nucleus, lead to the disappearance of the radio source. But in the case of sources associated with clusters of galaxies the intergalactic medium stops the expansion of the radio lobes and permits the observation of the evolution of the plasma with synchrotron losses only. This static equilibrium phase is observed for tails of head-tail radio sources (Roland, 1982).

Roland et al. (1976), Véron (1977) and others (for instance Slee et al., 1982) have noted that steep spectrum radio galaxies are more frequently associated with clusters containing a cD galaxy [clusters of class I or I–II of the Bautz-Morgan classification (Bautz and Morgan, 1972)]. This can be easily understood because Bautz-Morgan I clusters are more frequently X-ray sources (Jones and Forman, 1978) and it is expected to find the steep spectrum radio galaxies in X-ray clusters (Baldwin and Scott, 1973; Slingo, 1974a, b). Indeed, it is the high pressure of the intergalactic medium in X-ray clusters which allows the steep spectrum sources to survive.

The main characteristics of the observed very steep spectrum radio sources are listed in Table 2. Examination of this table shows that:

(a) When the very steep radio galaxy is the dominant galaxy of the cluster (3C 317, 3C 338, 4C 20.57, and 4C 63.10) the position of the center of the extended component coincides with the galaxy, but in some cases (4C 01.06, 3C 318.1) the radio peak can be displaced from the center of the galaxy. In other cases (B2 1028+35, 4C 38.39, NB 78.26 F I, II, III) the central radio peak is displaced by 10–60 kpc from the nearest bright galaxy which are not located in the center of the cluster. These differences between the radio and optical positions can be due to a slow motion of the galaxy in the intergalactic medium.

(b) The extension of the radio sources 4C 63.10, 3C 317, 3C 338, and 4C 20.57, which all have about the same radio luminosity and are located at the center of the cluster and associated with the brightest galaxy, is correlated with the X-ray luminosity of the cluster: the more luminous the cluster, the smaller the extension of the radio source.

(c) Finally, the most interesting property of these sources concerns their spectral index: the mean low frequency spectral index $\bar{\alpha}_1$ is: 1.30±0.17 [using 4C 01.06, 4C 63.10, B2 1028+35, 4C 38.39, 3C 317 ($\alpha=1.4$), 3C 318.1 ($\alpha=1.5$), 3C 338, and 4C 20.57] and the mean high frequency spectral index $\bar{\alpha}_2$ is $=2.3\pm0.3$ [using 4C 01.06, 4C 63.10, 4C 38.39, 3C 318.1 ($\alpha=2.5$), 3C 338, and 4C 20.57].

All the properties of these sources can be understood if we suppose that they are confined by the intergalactic medium. The third property suggests two stages in the evolution of extended lobes confined by the intergalactic medium. The first stage is characterised by the appearance of a first break in the spectrum and a high frequency spectral index of 1.3 (3C 317 for example). The second stage is characterised by the appearance of a break in the spectrum with $\alpha=1.3$ and the formation of a second break in the spectrum, above which the spectral index increase to eventually reach the limiting value of 2.7. These two stages of evolution have been predicted by Kardashev (1962). Our results can be easily understood if we suppose that at the beginning of their evolution, extended lobes grow into the intergalactic medium with a spectral index of 0.8. Then, when the internal pressure is equal to the external pressure, expansion losses are stopped and an equilibrium is reached between synchrotron losses and the input from the nucleus with $\alpha_0=0.8$. When expansion losses and diffusion losses due to the escape of relativistic electrons from the radio lobe can be neglected compared with synchrotron losses, it has been demonstrated that in stationary conditions (injection of relativistic particles and synchrotron losses) a break appears in the radio spectrum and the high frequency spectral index is $\alpha_1=\alpha_0+0.5=1.3$; this break appears even if the inverse Compton losses are not negligible (Ginzburg, 1957; Kardashev, 1962). Later, when the injection by the nucleus stops, if the evolution is dominated by synchrotron losses only, a new break appears in the radio spectrum, the high frequency spectral index becomes $\alpha_2=\frac{4}{3}\alpha_1+1=2.7$ (Kardashev, 1962). The Kardashev solution is obtained assuming an initial isotropic distribution of the electron velocities and of the magnetic lines of force in the radio lobes. This second break appears in the radio spectrum if:

a) inverse Compton losses on the 3 K are negligible compared with synchrotron losses (this is the case if $B_\perp > 3.5\,10^{-6}$ G);

b) the typical pitch angle scattering time is larger than the synchrotron loss time (i.e. the pitch angle is assumed to be constant in the diffusion equation for the high energy electrons considered here).

Let us show that for the confined very steep spectrum radio galaxies studied here, this break may be observed. If, for example, the magnetic field in the radio lobes is $B=2\,10^{-5}$ G,

a) the typical synchrotron loss time at 1000 MHz is $\tau_{syn}=9\,10^{6}$ y. The typical isotropisation time τ_{scatt} due to scattering

Table 2. Properties of very steep spectrum radio galaxies in clusters

Source name	IAU name	Cluster name	Cluster redshift	Source extension (kpc)	Distance radio peak – bright galaxy (kpc)	Break frequency (MHz)	α_0–α_1–α_2	L_R (erg/s)	L_X (erg/s)
4C 01.06	02 59+01.7	Zw Cl	(0.15)	150	32	600	–1.2–1.8	$9.9\,10^{42}$	
4C 63.10	06 59+63.4	A 566	0.095	170	21	200	–1.4–2.7	$2.4\,10^{42}$	$1.8\,10^{44}$
B2 1028+35	10 28+35.3	A 1033	(0.146)	<650	31	?	–1.2–>1.2	$1.4\,10^{42}$	
4C 38.39	14 24+38.0	A 1914	(0.146)	<650	65	200	–1.5–2.3	$6.4\,10^{42}$	
3C 317	15 14+07.2	A 2052	0.034	180	+	600	0.8–1.4–	$3.0\,10^{42}$	$3.9\,10^{44}$
3C 318.1	15 19+07.8	MKW-3s	0.045	<120	65	500	–1.5–2.5?	$1.4\,10^{42}$	$1.0\,10^{44}$
3C 338	16 27+39.7	A 2199	0.030	110		1200	–1.1–2.0	$3.8\,10^{42}$	$2.5\,10^{44}$
4C 20.57	23 33+20.9	A 2626	0.055	340	+	200	–1.1–2.2	$4.7\,10^{42}$	$2.0\,10^{43}$

Column 1: The name of the source
Column 2: The approximate position
Column 3: The name of the cluster of galaxies
Column 4: The redshift of the cluster
Column 5: The extension of the source (kpc)
Column 6: The projected distance between the radio peak and the nearest bright galaxy of the cluster (kpc)
Column 7: The frequency of the observed break in the radio spectrum (MHz)
Column 8: The spectral index at frequencies lower and higher than the break frequency of the radio spectrum (see Sect. 4: Discussion and conclusions)
Column 9: The integrated radio luminosity between 10^7 and 10^{10} Hz (erg/s)
Column 10: The X-ray luminosity of the cluster

Remarks and references for Table 2

The sources 4C 63.10 and 3C 338 have been studied respectively by Harris et al. (1982) and Burns et al. (1983). The source NB 78.26 F has been excluded because it needs more observations

References for the redshifts

The redshifts of Zw 0259+01, A 1033, and A 1914 are estimated using the magnitude of the 10th brightest galaxy (Corwin, 1974). The redshifts of A 566, A 2052, A 2199, and A 2626 are given by Corwin (1974). More information for A 566, A 2052, and A 2199 are given by Harris et al. (1982), Melnick et al. (1977), and Tifft (1974) respectively. The redshift of MKW-3s is given by Schild and Davis (1979)

References for the X-ray observations

See Harris et al. (1982) for A 566, Heinz et al. (1974) for A 2052, Kriss et al. (1980) for MKW-3s, Jones and Forman (1978) for A 2199 and Boynton et al. (1982) for A 2626

on Alfvén waves is difficult to estimate in the absence of knowledge on the structure of the magnetic field and of the level of turbulence. If we assume that the spectrum of Alfvén waves is $\propto \omega^{-2}$,

$$\tau_{\rm scatt} = \frac{L}{c\eta_{\rm turb}}, \qquad \text{(Melrose, 1980)} \quad (1)$$

where L is the typical scale length of the magnetic field and $\eta_{\rm turb}$ the fraction of the magnetic energy in turbulent form. With $L \sim 10$ kpc, and $\eta_{\rm turb} \sim 10^{-3}$ (a reasonable value as in such old radio lobes without input of energy from the nucleus, there is no source of turbulence) we obtain:

$$\tau_{\rm scatt} \simeq 3\,10^7 \text{ y} > \tau_{\rm syn},$$

b) although inverse Compton losses dominate for small pitch angle, synchrotron losses are 30 times larger for pitch angle $\sim 90°$, and the anisotropy of the electron velocity distribution corresponding to the spectral index α_2 spreads out.

Let us remark that the presence of inverse Compton losses limits the range of frequencies in which the Kardashev solution α_2 can be observed; indeed at frequencies higher than $\nu_{\rm max} = \nu_2 \left(\frac{B}{3.5\,10^{-6}}\right)^3$, the radio spectrum suffers an exponential break (ν_2 is the frequency at which a break appears in the spectrum with spectral index α_1) (van der Laan and Perola, 1969). This frequency $\nu_{\rm max}$ is obtained by writing that the typical time for synchrotron losses at frequency ν_2 is equal to the typical time for inverse Compton losses at frequency $\nu_{\rm max}$.

The anisotropy of the electron velocity distribution is the source of Alfvén waves by resonant interactions and the induced turbulence produces a diffusion of the resonant electrons such that the distribution function becomes isotropic again (quasi-linear theory); however the time scale of the development of this turbulence is very large. If the energy distribution of the relativistic electrons is $\varrho(E) = KE^{-\eta}$, there is a frequency ν_* such that, if $\nu > \nu_*$

$$\gamma(\nu)\tau_{\rm syn}(\nu) \leqq 1, \qquad (2)$$

where $\gamma(\nu)$ is the growth rate of the turbulence given by:

$$\gamma(\nu) = \frac{\pi}{2}\frac{\eta - 1}{\eta}\frac{n_r}{n}\omega_{cp}\left(\frac{E_{\rm min}}{E_\nu}\right)^{\eta - 1}, \qquad \text{(Melrose, 1980)} \quad (3)$$

where n_r and n are respectively the densities of the relativistic electrons and of the thermal ones; ω_{cp} is the proton cyclotron frequency; $E_{\min}$ and E_ν are respectively the low frequency cut-off and the energy corresponding to the radiating frequency ν of the relativistic electrons.

Using the definition of n_r, Eq. (3) can be written:

$$\gamma(\nu) \simeq \frac{n_r(\nu)}{n} \omega_{cp}, \quad (4)$$

where $n_r(\nu)$ is the density of relativistic electrons radiating at frequencies greater than ν.

Writing $S(\nu) = S_0 \nu^{-\alpha}$, we have:

$$\gamma(\nu)\tau_{\rm syn}(\nu) = A(\eta) \frac{S_0 D^2}{nV} \nu^{-(\alpha+0.5)} B^{-1.5}, \quad (5)$$

where $A(\eta)$ is a function obtained from the classical synchrotron theory (Ginzburg, 1978), D the distance of the radio source and V the volume of the lobe.

Using the most recent data published for 3C 338 (Burns et al., 1983), we are going to show that there is a frequency $\nu_k > \nu_2$ such that, for $\alpha = \alpha_2$,

$$\gamma(\nu_k)\tau_{\rm syn}(\nu_k) = 1. \quad (6)$$

If this is the case, the spectral index will steepen from α_1 to $\alpha_2 = \frac{4}{3}\alpha_1 + 1$ between ν_2 and ν_k and remains equal to α_2 between ν_k and $\nu_{\max}$; at frequencies greater than $\nu_{\max}$, the radio spectrum steepens exponentially.

The distance of 3C 338 is $D = 180$ Mpc; the volume of the radio lobes is $V = 1.7\,10^{69}\,{\rm cm}^3$ (without correction for any possible projection effects). The 5000 MHz flux density is $S_{5000} = 0.3$ Jy, thus $S_0 = 450$; the thermal density is taken to be $n = 5\,10^{-4}\,e^{-1}/{\rm cm}^3$ and Eq. (6) becomes:

$$4.5\,10^{35} \frac{S_0 D^2}{nV} \nu_k^{-3.2} B^{-1.5} = 1 \quad (7)$$

and therefore $\nu_k = 20{,}000$ MHz.

We come to the following conclusions: during the evolution of extended radio sources in X-ray clusters of galaxies, when the internal pressure within the radio lobes becomes equal to the external pressure due to the intergalactic medium, the evolution of the radio source is governed by synchrotron losses and the input of energy from the nucleus; in such conditions, a first break appears in the radio spectrum and the high frequency spectral index is $\alpha_1 = \alpha_0 + 0.5$. When the activity of the nucleus stops, if $B_\perp$ in the radio lobes is greater than $3.5\,10^{-6}$ G, synchrotron losses dominate over inverse Compton losses, and an anisotropy of the velocity distribution of relativistic electrons starts to develop; a new break appears in the radio spectrum of slope α_1, and a new spectral index $\alpha_2 = \frac{4}{3}\alpha_1 + 1 = 2.7$ is reached at a frequency ν_k given by Eq. (7); between frequencies ν_k and $\nu_{\max}$, the spectral index is equal to 2.7 and at frequencies higher than $\nu_{\max}$, inverse Compton losses combined with synchrotron losses result in an exponential break in the radio spectrum.

For these very steep spectrum radio galaxies in clusters (especially 3C 318.1, 4C 63.10, 4C 20.57, and 4C 38.39), the Kardashev theory is in good agreement with the observations.

Let us remark that the search of the three spectral indices: $\alpha_0 = 0.8$, $\alpha_1 = 1.3$, and $\alpha_2 = 2.7$ in extended radio lobes, has already been made by Dent and Haddock (1966).

The Kardashev's result has been applied to radio sources by Kellerman (1966); but his model contained two difficulties: a) for radio sources which are not in X-ray clusters, expansion losses cannot be neglected and the Kardashev result cannot be applied, b) the initial spectral index for extended radio lobes is $\alpha_0 = 0.8$ and not $\alpha_0 = 0.25$.

One interesting consequence can be derived from these observations. The diffusion losses due to the escape of the relativistic electrons from the radio lobe have to be neglected in the kinetic equation to find the Kardashev solution. Thus diffusion losses into the intergalactic medium which confines the radio lobe have to be very small compared to synchrotron losses.

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