that the jets show a similar position angle to the galactic plane, and probably lie within the plane.

**OH maser emission**

The brightness temperature of the OH masers implies a column density of inverted OH molecules along the line of sight of $6 \times 10^{12}$ molecules m$^{-2}$ (Norris et al. 1984). If a few percent of the OH molecules are inverted by far infrared at 35 or 80 $\mu$m, then the total column density of OH molecules is of the same order as that of a typical molecular cloud in our own galaxy (e.g. Solomon and Sanders 1980). However, the observed widths of the OH lines demonstrate that several clouds of OH over a range of velocities contribute to the maser emission. This is consistent with the line of sight lying within the galactic plane. Thus the required column density of OH is consistent with normal galactic densities and abundances, provided that a small population inversion has been achieved, probably by far-infrared pumping at 35 or 80 $\mu$m. No detailed pumping scheme has been advanced for extragalactic masers, but a plausible scheme might be based on those developed for masers in our own galaxy (e.g. Guilloteau et al. 1981). Calculations based upon photon requirements then show that the far-infrared flux density required to produce this inversion is less than 1 Jy, which is two orders of magnitude less than the flux density measured by IRAS. Thus no special conditions are required to produce a mega-maser, other than:

(a) a compact radio source to provide the input to the maser amplifier;

(b) an edge-on galaxy to provide the optical depth for OH gas;

(c) a high far-infrared luminosity to pump the masers.

**Is IC4553 Unique?**

It has been shown that the conditions necessary to produce a mega-maser may not be uncommon. The discovery of the IC4553 mega-maser was serendipitous, and resulted from a search for OH absorption. Previous searches for extragalactic OH emission have concentrated on relatively nearby galaxies, and have not included galaxies like IC4553. It is therefore hoped that future searches will be extended to include distant active galaxies. If a class of mega-masers can be found, they will provide an important source of additional information on the processes that drive active galactic nuclei.

I am indebted to David Allen for spending a great deal of time introducing me to optical and infrared techniques. I also thank Bill Pence for obtaining a FORS spectrum of IC4553, Jeremy Walsh for help with data processing, and the Anglo-Australian Observatory for the use of their facilities.

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**Steep-Spectrum Radio Sources in Clusters of Galaxies—The Southern Sample**

O. B. Slee, *Division of Radio physics, CSIRO, Sydney*

J. E. Reynolds, *School of Physics, University of Sydney*

**Introduction**

It is well established (e.g. Slee et al. 1983) that radio galaxies near the centres of rich clusters of galaxies tend to have steeper radio spectra than field radio galaxies. The fact that the sources with the steepest spectra occur in clusters that are highly luminous X-ray emitters has generally been interpreted in terms of the confining influence of a hot ($\sim 10^8$ K), relatively dense ($10^{-2}$ to $10^{-3}$ electrons cm$^{-3}$) intra-cluster gas; the confined relativistic plasma then preferentially loses its high-energy electrons through synchrotron and inverse Compton losses, resulting in a steepening of the radio spectrum. A more detailed review of the evidence for this process is given by Robertson (1983).

Surveys of large numbers of clusters at Molonglo (408 MHz) and Culgoora (80 and 160 MHz) have identified a number of sources with unusually steep spectral indices $\alpha < -1.5$ (where the flux density $S(\nu)$ at frequency $\nu$ is described by the power law $S(\nu) \propto \nu^\alpha$). When one considers that these spectral indices were averaged over the extent of unresolved sources it is clear that one may find considerably steeper spectra in some parts of these sources. In order to clarify the distribution of spectral index in such sources and to compare their radio, optical and X-ray morphologies we selected 11 very-steep-spectrum sources from the cluster sample for detailed observation with the VLA at 1.465 and 4.885 GHz. Six of these sources south of declination $-10^\circ$ were also satisfactory observable with the Molonglo Observatory synthesis telescope (MOST) at 0.843 GHz. This
Table 1
The Steep-Spectrum Sample of Radio Sources

<table>
<thead>
<tr>
<th>Radio Source</th>
<th>Spectral Index</th>
<th>Cluster Name</th>
<th>Redshift†</th>
<th>Distance</th>
<th>Richness</th>
<th>B-M class</th>
<th>r/R_A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0010-197</td>
<td>-1.56</td>
<td>A13</td>
<td>0.104</td>
<td>5</td>
<td>2</td>
<td>II</td>
<td>0.15</td>
</tr>
<tr>
<td>0038-096</td>
<td>-1.60</td>
<td>A85</td>
<td>0.067</td>
<td>4</td>
<td>1</td>
<td>I</td>
<td>0.06</td>
</tr>
<tr>
<td>0100-221</td>
<td>-1.63</td>
<td>A133</td>
<td>0.074</td>
<td>4</td>
<td>0</td>
<td>I</td>
<td>0.16</td>
</tr>
<tr>
<td>1251-289</td>
<td>-1.46</td>
<td>SC1251-288</td>
<td>0.056</td>
<td>3</td>
<td>1</td>
<td>I</td>
<td>0.20</td>
</tr>
<tr>
<td>1346-252</td>
<td>-1.25</td>
<td>A1791</td>
<td>0.126</td>
<td>5</td>
<td>1</td>
<td>(II)</td>
<td>0.03</td>
</tr>
<tr>
<td>2345-284</td>
<td>-2.38</td>
<td>SC2345-283</td>
<td>0.027</td>
<td>1</td>
<td>2</td>
<td>II</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Data from Slee and Siegman (1983) except the bracketed B-M class for A1791, which is an estimate by the present authors.

†Calculated from the magnitude of the tenth brightest galaxy in the cluster.

Table 2
Summary of Observing Dates and VLA Arrays

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Cluster Name</th>
<th>Date*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100-197</td>
<td>A13</td>
<td>Aug. 81† May 83</td>
</tr>
<tr>
<td>0038-096</td>
<td>A85</td>
<td>Aug. 81† May 83† June 83</td>
</tr>
<tr>
<td>0100-221</td>
<td>A133</td>
<td>Aug. 81 May 83</td>
</tr>
<tr>
<td>1251-289</td>
<td>SC1251-288</td>
<td>Aug. 81 May 83</td>
</tr>
<tr>
<td>1346-252</td>
<td>A1791</td>
<td>Aug. 81 May 83</td>
</tr>
<tr>
<td>2345-284</td>
<td>SC2345-283</td>
<td>Aug. 81† May 83 June 83</td>
</tr>
</tbody>
</table>

*Observations by scaled arrays are joined by horizontal lines.
†Source was not detected.

The Observations
Some useful information about the six southern clusters (from Slee and Seigman 1983) is presented in Table 1. The headings on Table 1 are self-evident, except perhaps for the last column, in which r, the angular distance from the cluster centre to the source centroid, is expressed as a fraction of the Abell radius of the cluster, R_A. It is clear that the sources are close to the cluster centres and that the clusters are comparatively rich in galaxies. Five clusters have been classified according to Bautz-Morgan criteria for dominance or otherwise of a single galaxy; in all cases the cluster is dominated by either a single cD or by two or three bright ellipticals of comparable luminosity. We estimate that A1791 should be classified B-M II. All clusters except the distance 5 members of the sample have been detected in X-ray sky surveys by the Uhuru, Ariel V and HEO-I satellites. One of us (OBS) conducted two observational sessions on these sources with the VLA; the details are listed in Table 2. An attempt was made to observe each source at 1.465 and 4.885...
GHz with the scale B and C arrays (FHPW at the zenith ~ 4" arc). Sources that could not be detected at 1.465 GHz with the B array were reobserved with the scaled C and D arrays (FHPW at the zenith ~ 12''). The VLA was not able to detect three sources (0010-197, 0038-096 and 2345-284) at 4.885 GHz; the MOST maps at 0.843 GHz of these three sources supply our only reasonably high-resolution data at a different frequency for spectral index determination.

The I, Q and U Stokes parameters were individually mapped and cleaned to produce maps of the total and linearly polarized flux and its position angle. The inner quarters of 512 × 512 pixel dirty maps were cleaned with up to 5000 beam subtractions; in some fields we were able to achieve a higher dynamic range by self-calibration of the U-V data. A similar treatment of a variety of unpolarized calibrator sources showed that the instrumental polarization was ≲2% at both 1.465 and 4.885 GHz.
GHz. The polarized calibrator 3C 286 was used to calibrate the position angle of the electric vector. Polarization in these fields was considered to be significant if it exceeded 4σ; as a precaution against showing spurious instrumental polarization, the fractional polarization vectors were only plotted on the I-map if they exceeded 5% of the beam brightness. These rather conservative selection criteria resulted in our detecting significant linear polarization in only two of the six steep-spectrum fields.

MOST observations of the six southern sources were made between September 1981 and December 1982. Each source was well-detected despite the reduced sensitivity of the instrument north of δ = -30° caused by foreshortening of the aperture at large hour angles. The half-power beamsize is approximately 40" x 40" cosec δ for δ ≤ -30° but rises to about 40" x 55" cosec δ at δ = -10°, owing to restricted hour-angle coverage.

Maps of each field were synthesized and cleaned on the University of Sydney's Cyber 170 system—see Reynolds and Harnett (1983). Integrated flux densities were determined both
from the cleaning operation and from measurements of source volume on the cleaned maps. The uncertainty in these measurements is estimated to be 10% to 15%.

The Radio Maps

(i) 0010-197 (Abell 13) The relevant maps and the spectra of integrated fluxes are shown in Figure 1; the spectral indices of the integrated fluxes are listed in Table 3. The 4σ upper limit for linear polarization at the brightest portion of the 1.465 GHz map is −24%.

It is clear from the spectral plots and Table 3 that both components of 0010-197 possess abnormally steep spectra but the slope of −4.3 for component 2 is probably the steepest ever measured in an extragalactic sources. It is apparent however that the spectrum is markedly curved, with the slope of the summed spectrum varying from ~ −1.0 at 160 MHz to −3.5 at 1 GHz.

Table 3

<table>
<thead>
<tr>
<th>Source</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A11†</td>
</tr>
<tr>
<td>0010-197</td>
<td>−2.09</td>
</tr>
<tr>
<td>0038-096</td>
<td>−2.37</td>
</tr>
<tr>
<td>0100-221</td>
<td>−1.99</td>
</tr>
<tr>
<td>1251-289</td>
<td>−1.22</td>
</tr>
<tr>
<td>1346-252</td>
<td>−1.28</td>
</tr>
<tr>
<td>2545-284</td>
<td>−1.98</td>
</tr>
</tbody>
</table>

*Power law spectrum of best fit between 80 MHz and 4.885 GHz.
†Power law spectrum of best fit between 0.845 and 4.885 GHz. See contour maps for identification of components.

The optical morphology in Figure 1(c) is rather complex. We have used the AAT to measure the redshifts of four of the five galaxies within and just outside the radio isophotes; the average redshift of z = 0.0945 ± 0.0047 ensures their membership of A13. The first- and second-ranked cluster ellipticals are located on the eastern edge of radio component 1 and one of the less bright ellipticals is 28" arc from the centroid of 2. The radio-optical morphology of component 2 is suggestive of a tailed radio galaxy with the elliptical at its head but its abnormally steep spectrum would not support this interpretation—the many known examples of tailed radio galaxies in northern clusters do not have integrated spectral indices steeper than α = 1.5.

We prefer to interpret both radio components 1 and 2 as ancient ejecta from one or both of the dominant cluster galaxies to the east, with component 2 being the earlier. There is as yet no X-ray detection of this cluster—the X-ray morphology would be particularly valuable in defining the regions of high thermal plasma density and temperature necessary to confine the radio sources for the required long time intervals.

(ii) 0038-096 (Abell 85) The relevant maps and the spectrum of integrated flux are shown in Figure 2; the spectral index of the integrated flux is listed in Table 3. The 4σ upper limit for linear polarization at the brightest portion of the 1.465 GHz map is ~7%.

It is clear from Figure 2(a) that 0038-096 has three components, but owing to the lower declination resolution of the MOST we are unable to derive their individual spectral indices. The power-law spectral index of their integrated fluxes between 80 MHz and 1.465 GHz is α = −2.37, but Figure 2(d) shows pronounced curvature, with the slope decreasing from ~ −3.0 at 1 GHz to −2.0 at 160 MHz. Low-resolution measurement at 29.9 MHz by Finlay and Jones (1973) confirms this flattening of the spectrum, with the slope between 29.9 and 80.0 MHz decreasing to ~ −1.1.

The reproduction of the CCD image in Figure 2(c) shows no bright galaxies within the 1.465 GHz contours. The 19 mag galaxy near the brightest contour on the eastern component was too faint to yield a measurable redshift with the AAT, but it is unlikely that the galaxy is a member of the cluster. The dominant cluster member of Abell 85 (not shown in Fig. 2c) is a cD (which is also the centroid of the X-ray emission) ~ 6.5 arc to the north-east of 0038-096. We are reluctant to reject an association between the steep-spectrum source and the cluster: on statistical grounds (Slee et al. 1983) very-steep-spectrum sources are preferentially seen in the directions of cluster centres. We suggest that the steep-spectrum source is either an ancient plasmoid ejected from the cD now ~ 540 kpc to the north-east or the radio remnant of a galaxy swept up by the cD.

(iii) 0100-221 (Abell 133) The relevant maps and the spectra of integrated flux densities are given in Figures 3, 4 and 5; the spectral indices of the integrated fluxes are listed in Table 3. The 4σ upper limits for linear polarization on the scaled array maps at their brightest regions are 2% at 1.465 GHz and 12% at 4.885 GHz.

Figure 4 shows that components 2 and 3 have the steepest integrated spectra and dominate the total flux below 1 GHz. Reference to the spectral index map (Fig. 3c) from the scaled array observations (spectra of beam brightness) shows that the extended component 3 has one of the steepest radio spectra known, with a slope of −3.5 between 1.465 and 4.885 GHz. Component 2 is also steep with a slope of ~ −2.0, but its contribution to the total flux at 80 MHz would be small compared with 3. Although there is not a very pronounced curvature in the total spectrum of Figure 4, some flattening must occur at the low-frequency end, since an extrapolation of components (2 + 3) to 80 MHz predicts a higher flux than is measured. A low-resolution measurement at 29.9 MHz by Finlay and Jones (1973) shows a very pronounced flattening of the spectrum below 80 MHz, with a slope of ~ −0.4. Figure 3(d) shows that 2 and 3 are not connected at a brightness level of 10% of the peak brightness of 2.

The optical morphology in Figure 5 is relatively simple in that the dominant cluster member (a cD with a measured AAT redshift of z = 0.0570) coincides with the centroid of radio component 2; a faint galaxy (probably not a cluster galaxy) coincides with the centroid of 1. A blue stellar image is located close to the peak of 4, whose flat spectrum suggests that it is a QSO.

The diffuse component 3 appears almost certainly detached...
Figure 3 Contour maps and spectral index map for 0100-221 (Abell 133). (a) 4.885 GHz contours (D array) at 0.11, 0.22, 0.33, 0.54, 0.87, 1.31, 1.85, 2.51, 3.27, 4.14, 5.12 mJy per beam with a peak of 5.45 mJy per beam. (b) 1.465 GHz contours (C array) at 0.74, 1.49, 2.23, 3.72, 5.95, 8.92, 12.6, 17.1, 22.3, 28.2, 34.9 mJy per beam with a peak of 37.2 mJy per beam. (c) Spectral index map from the scaled C/D arrays: blank area, $|\alpha| < 1$; right-hatched, $1 < |\alpha| < 2$; left-hatched, $2 < |\alpha| < 3$; stippled, $3 < |\alpha| < 4$. (d) 1.465 GHz contours (B array) of the steep-spectrum components 2 and 3 in (b); levels at 0.98, 1.95, 2.93, 4.88, 6.84, 8.79 mJy per beam with a peak of 9.11 mJy per beam.
Figure 4 Radio spectra of the components and total flux of 0100-221 (Abell 133). The components are identified in (b). The error bars on the low-frequency points are about the sizes of the filled circles.

from the cD and we suggest that it is a fossil radio source that has not been replenished with fresh electrons. It may originate in one of the following ways: (i) an ejected plasmoid from the cD rising away from the cluster centre in the denser intra-cluster gas (the cluster is a known luminous X-ray source); (ii) the remnant of a radio galaxy that has been accreted in the past by the central cD.

(iv) 1251-289 (SC 1251-288) The relevant maps and the spectrum of integrated flux density are shown in Figures 6 and 8; the spectral index of the integrated flux is listed in Table 3.

In this case the angular resolution of the VLA scaled arrays was not sufficient to completely resolve the components and obtain their separate integrated fluxes. The spectrum of flux density integrated over the whole source in Figure 7 is not so steep, with a slope of $-1.22$; the low-resolution measurement at 29.9 MHz by Finlay and Jones (1973) indicates a sudden flattening, with a slope $-0.1$ between 80 and 29.9 MHz. The spectral index map in Figure 6(d) from the beam brightness values of the scaled arrays shows clearly that the extensions to the north-west and south-east are the regions of steepest spectra, which have power law exponents between 1.465 and 4.885 GHz of $-1.5$ to $-2.5$; the central high-brightness region has a normal index of $-0.8$. Fractional polarization vectors plotted on the 4.885 GHz contours in Figure 6(c) show that the north-west extension is highly polarized at between 9% and 48%; the field direction is generally transverse to the lobe elongation, but in the northern extension the field direction is longitudinal. The polarization map at 1.465 GHz could not be constructed owing to the loss of the U-V data.

The optical morphology in Figure 8 is simple in that a bright elliptical galaxy of redshift $z = 0.0573$ (Vidal 1975) lies within a few seconds of arc of the nuclear source and there are no other galaxies within or close to the radio contours. We assume that the extensions to the north-west and south-east are the ejecta from the elliptical galaxy, perhaps forming a wide-angle tailed source which lies at a large angle to the plane of the sky. The
Figure 6 Contour maps, polarization vectors and spectral index map for 1251-289 (SC1251-288). (a) 4.885 GHz contours (C array) at 0.46, 0.91, 1.83, 2.74, 4.56, 6.39, 10.0, 17.3, 26.5, 44.7, 63.0, 77.6 mJy per beam with a peak of 91.3 mJy per beam. (b) 1.465 GHz contours (B array) at 3.78, 7.56, 13.2, 18.9, 28.3, 37.8, 56.7, 75.6, 94.5, 132, 170 mJy per beam with a peak of 189 mJy per beam. (c) Electric vectors of the polarized 4.885 GHz flux superposed on the 4.885 GHz contours; the highest polarization of 48% occurs in the north-west corner, and the smallest vector corresponds to 9% linear polarization. (d) Spectral index map from the scaled B/C arrays: blank area, $|a| < 0.5$; right-hatched area, $1.0 < |a| < 1.5$; cross-hatched area, $1.5 < |a| < 2.0$; stippled area $2.0 < |a| < 2.5$. 
Figure 7 Radio spectrum of the total flux of 1251-289 (SC1251-288)
The error bars on the low-frequency points are about the size of the filled circles.

unusually steep spectra of the lobes, especially near their extremities, suggest that there has been no reinjection or reacceleration of particles for many years. The cluster is a luminous X-ray emitter of $1.2 \times 10^{45}$ erg s$^{-1}$ (Jones and Forman 1978), although we are not aware of the publication of Einstein results giving the location and extent of the X-ray source.

(v) 1346-252 (Abell 1791) The relevant maps and spectra are shown in Figures 9, 10 and 11; the spectral indices for the integrated fluxes of the components are listed in Table 3.

The scaled-array contours at 4.885 and 1.465 GHz in Figures 9(a) and 9(b) resemble slightly the morphology of a wide-angle tailed galaxy but the other observational evidence does not strongly support this interpretation. The spectra of the integrated fluxes in the eastern and western lobes between 0.843 and 4.885 GHz shown in Figure 10 are quite different, with slopes of $-1.7$ and $-1.1$ respectively; the ‘nuclear’ source, component 2, itself has a steep spectrum and is located much closer to the western lobe. In addition, the structures of the lobes are quite different, with an interesting 45° kink in the eastern lobe. The total spectrum is dominated by component 1 at the low-frequency end, but it must flatten considerably, because an extrapolation of its spectrum to 80 MHz predicts a higher flux than is actually observed. The low-resolution 29.9 MHz measurement of Finlay and Jones (1973) does not continue the flattening trend, but there are two other sources within their 48’ arc beam that probably contribute to their high flux density.

The spectral index map in Figure 9(c) from the beam brightness values of the scaled arrays shows that the spectral index has a pronounced and curious gradient across the smaller dimension of component 1; it changes systematically from $-0.8$ near the eastern and southern edges to $-2.5$ near the western and northern edges. Component 3 has a more constant spectral index over most of the area of $-1.5$ to $-2.0$, but increases to $-2.5$ in the northern tip. The more compact nuclear source has the fairly steep index of $-1.5$.

The linear polarization at 4.885 GHz in Figure 9(d) is probably the highest ever measured in an extragalactic source. The fractional polarization averages $60\%$ along most of the high-brightness central ridge of component 1 and tends to be even higher in the northern tip and along the western edge. The polarization in component 3 is confined to the more diffuse section, where it averages 40% to 50%. The nuclear source has no linear polarization above 5%. It is clear that in both components 1 and 3 the magnetic field direction is along the axes of the lobes; the field direction follows the kink in component 1 remarkably closely. The polarization at 1.465 GHz (not shown) is measurable but lower than the 4.885 GHz values; the depolarization factor is $\sim 8$ for component 1 and $\sim 4.5$ for component 2. Depolarization may be used to estimate the quantity $N_e B_{11}$ (product of thermal electron density and longitudinal field) in the source, and this aspect will be discussed in Section 4.
The optical morphology shown in Figure 11 is relatively uncomplicated. One of the brighter cluster ellipticals (no measured redshift) and a companion in a common envelope are close to the peak of the nuclear radio source. No galaxies lie within the contours of component 1 but a moderately bright elliptical is located not far from the peak brightness in component 3. It is probable however that this galaxy is a projected radio-quiet member of the cluster, because there is no disturbance at this position to the very high spectral index seen in the remainder of 3.

Our conclusion is that both components 1 and 3 are probably the radio relics of ejecta from the bright ellipticals coinciding with the nuclear radio source; alternatively they are the relics of radio galaxies (perhaps tails) that have been accreted in the ancient past by the bright ellipticals. It must be stressed however that component 1 does not conform with present ideas of a relaxed radio relic. Its strong gradient of spectral index (which is transverse to the field direction) indicates that quite different distributions of relativistic electron energies are being maintained in different parts of the source.
Figure 10 Radio spectra of the components and total flux of 1346-252 (Abell 1791). The components are identified in Figure 9(a).

(vi) 2345-284 (SC 2345-283) The maps and spectra are shown in Figures 12 and 13 and spectral indices for the components are listed in Table 3.

The scaled-array maps of Figures 12(a) and 12(b) show clearly that component 3, the extended diffuse component on the 1.465 GHz map, is completely undetectable at 4.885 GHz. It can be clearly seen on the 0.843 GHz map as the western component of the double source.

Figure 13 shows that the integrated flux of component 3 between 0.843 and 1.465 GHz has a power law index of $-2.87$ and completely dominates the spectrum below ~1 GHz. There must however be considerable curvature in its spectrum at low frequencies, since the value of 80 MHz flux density predicted from linear extrapolation lies well above the observed value; this is confirmed by a low-resolution 29.9 MHz measurement (not shown) by Finlay and Jones (1973) giving a slope of $-0.7$ between 80 and 29.9 MHz. The $4\sigma$ upper limit for linearly polarized emission at 1.465 GHz in the region of maximum brightness of 3 is $\sim 7\%$.

The optical morphology from a UK Schmidt J-plate in Figure 12(c) shows that one of the brightest cluster members and a smaller elliptical in the same envelope are close to the centroid of radio component 1; another small elliptical is close to the centroid of 2. The redshifts of eight galaxies near the cluster centre including the brighter galaxies in Figure 12(c) have been measured by Maccacaro et al. (1977), who found a mean redshift of $z = 0.0274$. No galaxy can be seen within the contours of the steep-spectrum component 3.

It is reasonable to assume that component 3 is either the radio relic of an ejection from the cD galaxy coinciding with component 1 or the remnant of a galaxy that has been accreted by the cD galaxy. The present linear separation between the peaks of components 1 and 3 is 63 kpc ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). SC 2345-284 is a well-established X-ray emitter with a luminosity of $1.4 \times 10^{44}$ erg s$^{-1}$ (Jones and Forman 1978), but to our knowledge the accurate position and extent of the X-ray source have not yet been published.

Discussion

We can summarize the observational results of the previous section as follows:

(1) Steep-spectrum sources that were positioned near cluster centres by low-resolution radio telescopes are generally complex; in addition to containing sources with normal spectral indices they contain at least one component with an extremely steep spectrum. This component itself often shows some structure.

(2) The spectrum of the steep-spectrum component flattens out markedly below 0.1 GHz; this indicates, we believe, that these are very old sources in which synchrotron and Compton
Figure 12 Contour maps and optical/radio morphology for 2345-284 (SC2345-283). (a) 4.885 GHz contours (D array) at 0.14, 0.28, 0.42, 0.69, 1.39, 2.08, 3.47, 4.87, 6.25 mJy per beam with a peak of 6.95 mJy per beam. (b) 1.465 GHz contours (C array) at 0.93, 1.87, 2.80, 3.73, 4.66, 6.53, 9.33, 13.1, 16.8 mJy per beam with a peak of 18.7 mJy per beam. (c) 0.843 GHz contours at −7, −4, 4, 7, 10, 15, 25, 35, 50, 70, 90 mJy per beam. (d) 1.465 GHz contours overlaid on a copy of the UK Schmidt J-plate.
losses have greatly depleted the store of high-energy relativistic electrons.

(3) Four of the steep-spectrum sources (0010-197, 0038-096, 0100-221 and 2345-284) do not contain a cluster galaxy that could directly account for the radio emission, as is the case for normal classical doubles and head-tail sources.

(4) Two of the steep-spectrum sources (1251-289 and 1345-284) may be head-tail sources, but their radio morphology is not at all like that of the many northern sources in this class; it may not be a coincidence that these are the sources that show high linear polarization (up to 70%) at 4.885 GHz.

(5) Four of the six steep-spectrum sources (0038-096, 0100-221, 1251-289 and 2345-284) are in clusters with high X-ray luminosity; the other two clusters (containing 0100-197 and 1345-284) are more distant and were not detected in the general X-ray sky surveys.

Table 4 lists the median physical parameters for the six sources; these have been derived assuming Euclidean geometry and $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and that the sources are in the associated clusters. The computations of minimum energy, magnetic field strength and aging time contain the same assumptions and methods as those used by Miley (1980).

<table>
<thead>
<tr>
<th>Half-brightness dimensions</th>
<th>$75 \times 25 \text{ kpc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from nearest bright galaxy</td>
<td>76 kpc</td>
</tr>
<tr>
<td>Travel time to nearest bright galaxy at 1000 km s$^{-1}$</td>
<td>$7.4 \times 10^7 \text{ yr}$</td>
</tr>
<tr>
<td>Power emitted at 1.465 GHz</td>
<td>$4.1 \times 10^{24} \text{ W Hz}^{-1}$</td>
</tr>
<tr>
<td>Minimum energy density*</td>
<td>$2.2 \times 10^{41} \text{ erg cm}^{-3}$</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>$15.5 \times 10^{-6} \text{ G}$</td>
</tr>
<tr>
<td>Synchrotron plus Compton age†</td>
<td>$4.1 \times 10^7 \text{ yr}$</td>
</tr>
</tbody>
</table>

*Computations assume the power law spectra of column 2 in Table 3 between 0.01 and 100 GHz.
†Break in the spectra at 0.1 GHz.

It seems likely that all the steep-spectrum components that provided the data for Table 4 are associated in some way with the brightest nearby galaxies (which also happen to be the brightest members of the cluster). The spacings between the remnant centres and their associated galaxies coupled with a velocity (1000 km s$^{-1}$) that is within a factor of two of both the random velocities of galaxies in rich clusters and the sound speed in the intra-cluster gas yield transit times that are close to the aging times, due to synchrotron and Compton losses, of an isolated source. Thus we suggest that either of the two following methods of forming these relics could operate: (i) the source is a fossil relic of a radio galaxy (perhaps a tail) that has been swept up by the massive central cD or giant elliptical; (ii) the steep-spectrum component that we now see is the aged remnant of a plasmoid that was ejected from the bright central galaxy at a speed close to or somewhat higher than the sound speed in the intra-cluster gas.

These remnants do not resemble very closely the cluster haloes that have been confirmed in the Coma cluster (Valentijn 1978) and suggested for Abell 1367 (Gavazzi 1978), Abell 2256 (Bridle et al. 1979) and Abell 2319 (Grindlay et al. 1977); according to the results of a pencil-beam survey of 32 clusters by Jaffe and Rudnick (1979), haloes of the Coma type are very rare. The remnants in the present study are an order of magnitude smaller in linear dimensions than the Coma halo, have considerable structure and are generally brighter. Our sources are more like a steep-spectrum source in Abell 566 described by Harris et al. (1982), although in their case the source is centred on the dominant galaxy in the cluster.

It is interesting to compute whether the hot intra-cluster gas can exert enough pressure on the relativistic plasma to confine it against adiabatic expansion losses for the interval needed to account for the computed ages of these relics. Abell 85 is the only cluster in our sample for which the high-resolution spatial distribution of X-ray brightness has been mapped by the Einstein satellite (Jones et al. 1979). We may estimate the central density of the thermal electrons ($N_0$) using the model of an isothermal
Afo = 8.3 x 10^{-3} \text{ cm}^{-3}. From the X-ray spectrum, the X-ray brightness at the position of the radio source is \sim 10\% of the peak, so on the isothermal model the electron density is \sim 2.6 x 10^{-3} \text{ cm}^{-3}. The pressure exerted by the hot intra-cluster gas is:

\[ p_{\text{icg}} = \frac{n_0}{k} \frac{T_e}{\mu} \text{ dyne cm}^{-2}, \]

where \( k \) is Boltzmann’s constant and \( \mu \) is the mean molecular weight (equal to 0.62 for a fully ionized gas containing 10\% He by number). Thus in this case we have \( p_{\text{icg}} = 3.5 \times 10^{11} \text{ dyne cm}^{-2} \). The pressure exerted by the relativistic gas (\( p_r \)) in the radio source is one-third of its minimum energy density computed from equipartition arguments. Thus for 0038-096, \( p_r = 2.4 \times 10^{12} \text{ dyne cm}^{-2} \), and it is clear that the source can easily be confined by the hot intra-cluster gas.

A more extreme pressure is exerted by the relativistic plasma in 1346-252, in which \( p_r = 3 \times 10^{11} \text{ dyne cm}^{-2} \); in this case however the source is nearer the cluster centre, where the thermal pressure of the intra-cluster gas is expected to be correspondingly higher. The thermal plasma in the source is expected to make some contribution to the pressure balance: using our depolarization result for 1346-252, a cylindrical model for the source (e.g. Burns et al. 1983) and the equipartition field, we compute the thermal electron density to be \sim 1 \times 10^4 \text{ cm}^{-3}. Thus even if the thermal plasma inside the radio source were at a temperature of 10^8 K its small contribution to the total pressure would not invalidate the above conclusions.

Perhaps the most interesting source for several reasons is 1346-252. First, it is not clear that the two tails are associated with the one galaxy because of their very different shapes and spectral-index distributions. Secondly, the two distinct kinks in the eastern tail imply on the accretion model that the galaxy associated with it probably changed course on two occasions during its progress toward the cluster centre; on the ejection model, the major kink seems to be in the wrong sense if buoyancy forces (Cowie and McKee 1975) directed radially away from the cluster centre are responsible. Thirdly, the remarkable gradient in spectral index across the eastern component (rather than the normal gradient along the axis) seems to imply that acceleration of relativistic electrons is still taking place along the eastern and southern edges and mixing by diffusion is prevented by the known strong uniform field in the axial direction. One method of achieving reacceleration would exist if a localized region of very low intra-cluster gas density exists; this would allow the relativistic plasma to expand rapidly, with possible consequent acceleration in strong shocks or instabilities.