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Complex Radio Emission from the X-ray Cluster Abell 2256

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Summary. A sensitive map has been made of the powerful X-ray cluster Abell 2256 (=3 *U* 1706+78) at 610 MHz with a resolution of 55″. Five discrete radio sources, three of which appear to have head-tail structure, have been identified with cluster galaxies. There are also two extended emission regions near the cluster centre which have linear sizes $\gtrsim 1$ Mpc. The faintest and most diffuse of these extended regions may be the steep-spectrum decametric source detected previously in Abell 2256. Localisation of the soft X-ray source to the region of this diffuse emission would provide strong support for the inverse-Compton model of the origin of the X-ray luminosity.

Key words: clusters of galaxies — extragalactic X-ray sources — head-tail radio sources — optical identifications

Introduction

The extended soft X-ray sources in rich clusters of galaxies (e.g. Kellogg and Murray, 1974) are often accompanied by decametric radio sources with unusually steep spectra (e.g. Bridle and Feldman, 1972; Costain et al., 1972; Harris and Romanishin, 1974). With plausible assumptions about physical conditions in the intergalactic medium in the clusters, this correlation can be explained on either an inverse-Compton or a thermal bremsstrahlung model of the origin of the X-rays (Bridle and Feldman, 1972; Baldwin and Scott, 1973). The observed X-ray spectra of the cluster sources cannot convincingly decide between the competing models, as bremsstrahlung from a nonuniform plasma could have a power-law spectrum, and inverse Compton radiation from a nonuniform ensemble of relativistic particles and magnetic fields need not have a power-law spectrum. Studies of the radio and X-ray structures of the cluster sources may therefore offer a more useful approach to understanding the physical conditions within the X-ray clusters.

In this paper we report sensitive observations of the X-ray cluster Abell 2256 (=3 *U* 1706+78) at 610 and 2695 MHz which show an unusual complex of radio emission on the scale of the visible cluster and of the soft X-ray source. Several active galaxies and unusual large-scale emission regions have been detected in the cluster.

I. The Radio Maps

Abell 2256 is one of six rich clusters of galaxies for which a definite X-ray size ($16' \pm 9'$) was assigned by Kellogg and Murray (1974) and is one of the more powerful extragalactic X-ray sources presently known. We initially used the NRAO 300-ft telescope at 1400 MHz as described by Bridle et al. (1972) to map an area 45′ in right ascension by 35′ in declination around the steep-spectrum decametric source found in Abell 2256 by Costain et al. (1972). These preliminary observations revealed a total flux density of 1.07 ± 0.11 Jy in a region $\sim 15'$ in diameter centred on the 1950.0 position $\alpha = 17^h06^m19^s$, $\delta = +78°45'50''$, whereas earlier interferometric observations at 1445 MHz by Fomalont and Rogstad (1966) had found only 0.66 Jy in a source about 6′ in extent. The apparent discrepancy suggested that both large and small-scale radio structures might exist in Abell 2256. We therefore mapped the region at 610 MHz with the Westerbork Synthesis Radio Telescope and observed the more compact features of the cluster emission at 2695 and 8085 MHz with the NRAO 3-element interferometer.

The 610-MHz map was derived from two 12-h observations providing all 36-m antenna spacings out to 1512 m. This configuration provided a beam 53″.6 in right ascension by 55″.3 in declination with nearly circular grating rings at approximately 47′, 94′, etc. The map centre was chosen at 1950.0 position

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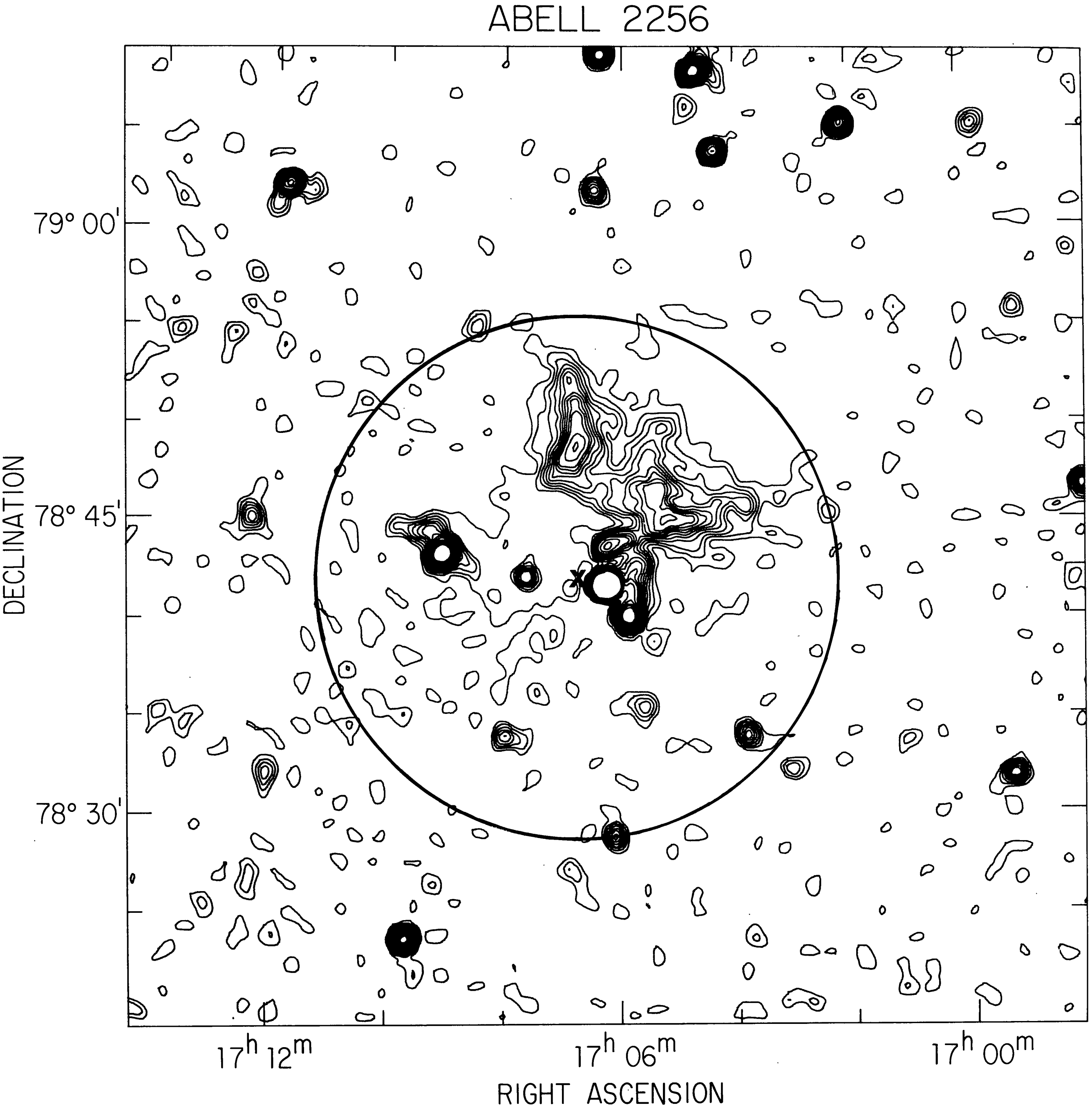

Fig. 1. Contours of the 610-MHz radio emission observed in the vicinity of Abell 2256 at 55″ resolution with the Westerbork Synthesis Radio Telescope. The lowest contour is at 2 mJy/beam. Many higher contours have been omitted for clarity. The *X* marks the centre of Abell 2256 as determined by Bahcall (1974). The circle indicates the radius at which the projected galaxy density in Abell 2256 falls to 1/20 of its value near the centre, according to Bahcall

$\alpha = 17^h06^m22\overset{s}{.}3$, $\delta = +78°45'48''$ so that the first grating response to sources near the field centre would lie well beyond the expected boundary of emission associated with the cluster. Grating responses to sources outside the cluster were removed by subtracting the contributions of strong discrete sources from the amplitude-phase data and by the "CLEAN" deconvolution procedure (Högbom, 1974) for weaker sources, down to a limit of 0.009 Jy. The zero-level of the map was established by inspection of the distribution of intensities in the map at positions away from strong discrete sources over a field of approximately one square degree around (but not including) the cluster. The final map of the 0°75 by 0°75 field around the map centre, corrected for the primary beam of the individual antennas, is shown in Figure 1, which also indicates the cluster centre and size to 5% projected galaxy density as determined by Bahcall (1975).

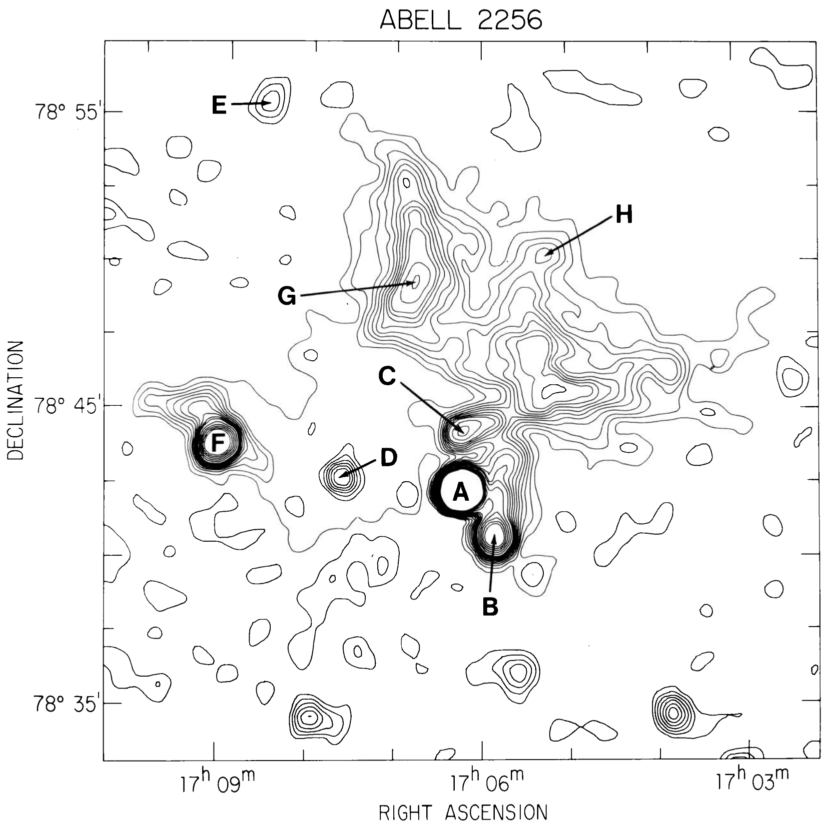

Fig. 2. The central region of Figure 1, expanded to show the cluster region more clearly. The labelling defines the alphabetical source terminology used in the text (Section II)

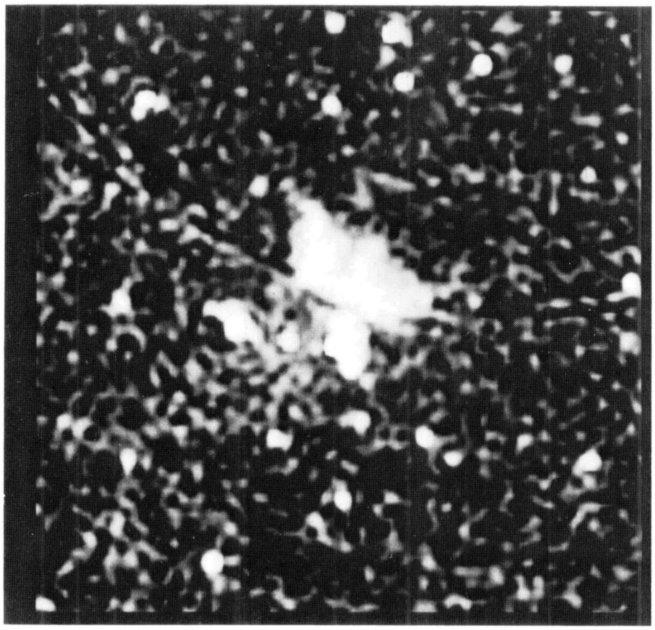

Fig. 3. A radiophotograph of the 610-MHz emission from Abell 2256, produced from the data shown in Figure 1 using the NRAO Image Recording System. A faint grating response to a bright source North-West of the cluster runs through the centre of the field. The diffuse emission around source D in the Eastern part of the cluster is clearly visible

Three aspects of the 610-MHz map are of interest. First, the field contains many discrete sources, some of which are congregated near the cluster centre; identifications of these with cluster galaxies are discussed in the next Section. Second, there is an emission complex North of the cluster centre with a largest angular size of about 15′. As the galactic latitude of the region is +32° this complex is unlikely to be a foreground galactic feature and is probably associated with Abell 2256. Third, there is low-brightness emission with an angular scale of at least 10′ in the Eastern part of the cluster, around discrete source *D* (see Figure 2 for definition of the alphabetic source nomenclature). This emission is close to the noise level of the map, but is significantly present over a large area of sky, as can be seen from the radiophotograph in Figure 3.

The three brightest 610-MHz sources (A, B and C) were also detected in our observations with the NRAO interferometer at 2695 and 8085 MHz using baselines from 0.1 to 2.7 km. Our map is also consistent with the 1445-MHz observations by Fomalont and Rogstad (1966). The 408 and 1407-MHz observations of Abell 2256 by Slingo (1974) failed however to detect any emission other than the brightest discrete source (A) near the cluster centre, presumably due to lack of adequate short-spacing data in his synthesis.

II. Comparison with the Optical Field

Several of the discrete radio features can be associated with individual cluster galaxies, whose optical positions and redshifts have been determined by Drs. B. and D.

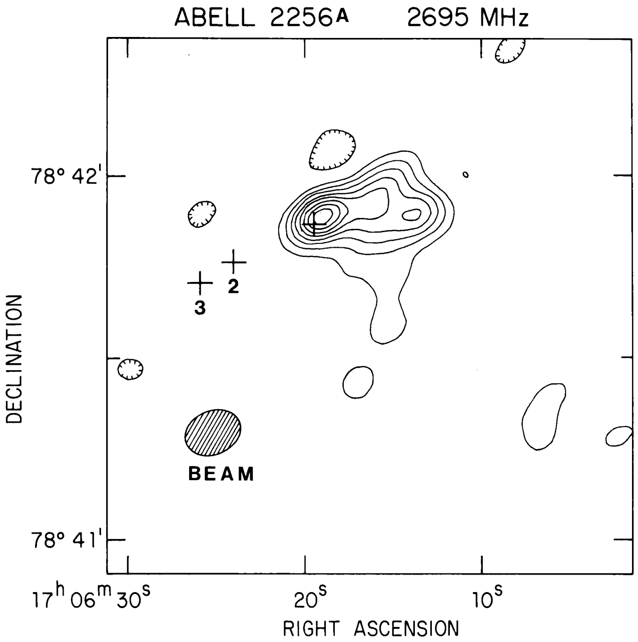

Fig. 4. The 2695-MHz map of source A obtained with the NRAO interferometer. The beamwidth (shaded ellipse) is 8".6 by 6".6, major axis in position angle −49°. The contours are in equal increments of 3.6 mJy/beam. Hatched contours are negative

Wills and are listed in Table 1. The mean redshift of these galaxies is $z = 0.0566$, corresponding to a distance of 340 Mpc (Einstein-de Sitter cosmology, $H = 50$ km s^{-1} Mpc^{-1}).

Source A *(1706+786)*. This is the brightest (0.25 Jy) source near the cluster centre at 610 MHz; at this frequency it is extended ~27 arc sec (~40 kpc) along position angle 99°. Figure 4 shows the 2695-MHz map of this source obtained with the NRAO interferometer at 8".6 by 6".6 resolution. Also shown in Figure 4 are the optical positions of the nuclei of the 15^m double galaxy NGC 6331 and its north-preceding neighbour (see Table 1 and Figure 5). The 2695-MHz peak is within 2" of the *neighbour* (image 1 in Figure 5); no emission is detected from either of the bright nuclei

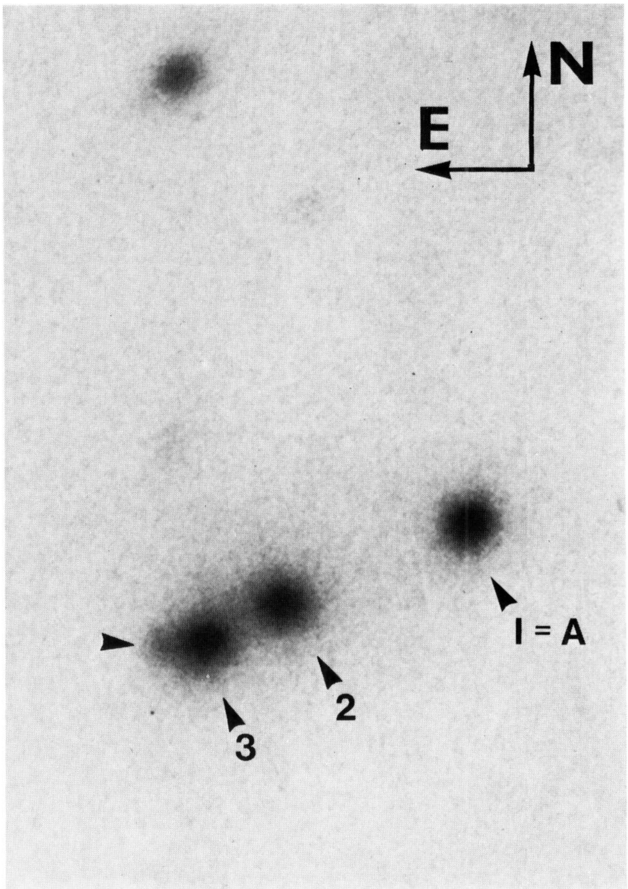

Fig. 5. NGC 6331 (images 2 and 3) and its neighbour (image 1), from a 150-min exposure on a baked IIa-O plate obtained by Harlan Smith on the MacDonald Observatory 82-inch telescope at $f/13.6$. The region shown is approximately 1' in right ascension by $1^1/_2$' in declination. Cluster radio source A is identified with galaxy No. 1 (see Fig. 4). The relationship of the faint image immediately following image 3 (unlabelled arrow) to NGC 6331 is unknown

of NGC 6331. The centroid of the radio source is displaced from $17^h06^m16^s.7$, $+78°41'55''$ at 2695 MHz to $17^h06^m15^s.2$, $+78°41'56''$ at 610 MHz, suggesting that its spectrum between these two frequencies steepens with

Table 1. Optical data on cluster galaxies

	$\alpha(1950.0)^a$	$\delta(1950.0)^a$	Red shift[b]	Absorption[c] lines used for red shift	Radio source
1.	$17^h06^m19^s.48$	$+78°41'53''.1$	0.0570 (5)	H, K, G	A
2.	17 06 24.06	78 41 45.4	0.0562 (5)	H, K, G	none – Figure 4
3.	17 06 25.96	78 41 41.9			none – Figure 4
4.	17 05 51.77	78 39 56.1	0.0561 (5)	H, K, Hδ, G, Fe	B
5.	17 06 21.09	78 43 53.2	0.0581 (4)	K, Hδ, G, Fe, Hβ	C
6.	17 07 38.81	78 42 22.7			D
7.	17 06 49.99	78 48 40.6	0.0553 (6)	H, K	near peak G
8.	17 06 49.13	78 48 16.7			near peak G

[a] Measured from the 82-inch plate (galaxies 1–3) and from the Palomar Sky Survey (galaxies 4–8) by Dr. B. Wills

[b] The number in parentheses is the internal r.m.s. error in units of 0.0001 in z

[c] There were no emission lines visible in the spectra

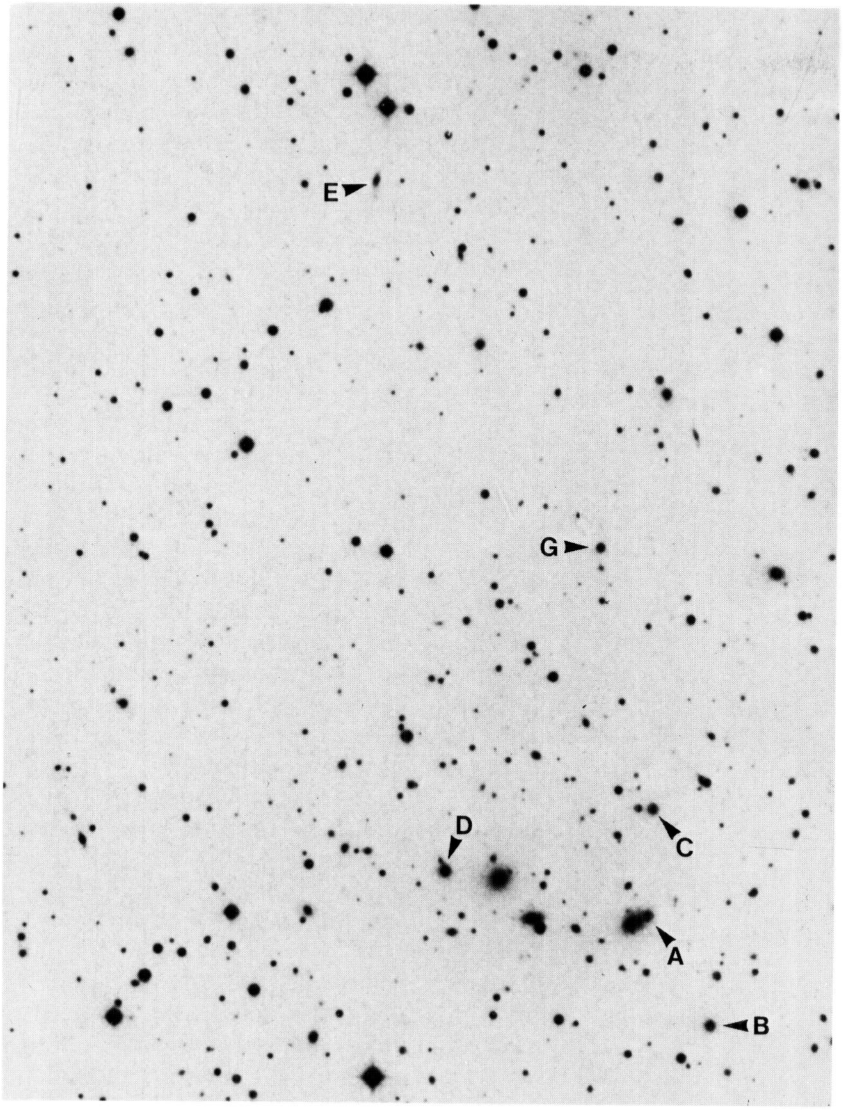

Fig. 6. Enlargement of the E print of the Palomar Sky Survey indicating the identifications proposed in this paper. The field shown is approximately 13′ in right ascension by 17′ in declination

increasing distance from the identification. This spectral variation and the configuration of the structure relative to the identification suggest that 1706+786 is a head-tail source similar to those found in other rich clusters (e.g. Miley et al., 1974) but on a small linear scale. This conclusion has also been reached by Rudnick and Owen (1976).

Source B *(1705+786)*. At 610 MHz the flux density is 97 mJy and the source is extended ~51″ (~76 kpc) along position angle 12°. It may connect with a low-brightness feature running approximately Northwards for about 3′ (~270 kpc) to comprise an extended head-tail structure (see Fig. 2). With the NRAO interferometer at 2695 MHz we find an emission peak located 23″ in position angle 27° North of the cluster galaxy marked "B" in Figure 6. The elongation of the radio structure and its offset from the galaxy suggest that this source is also a head-tail structure.

Source C *(1706+787)*. At 610 MHz the flux density is 71 mJy and the source is extended ~94″ (~140 kpc) along position angle 122°. The most likely identification is the galaxy marked "C" in Figure 6 which is 13″ in position angle 103° following the 2695-MHz peak measured with the NRAO interferometer. The asymmetry of the radio source and its displacement relative to the galaxy again suggest a head-tail structure.

Source D *(1707+787)*. The 610-MHz flux density is 30 mJy and the source lies on the galaxy pair marked "D" in Figure 6.

Source E *(1708+789)*. At 610 MHz the flux density is 7 mJy and the source appears to lie within the galaxy marked "E" in Figure 6. The galaxy has an elongated nucleus and an asymmetric envelope about 40″ in extent pointing Southwards. This source may be a normal spiral galaxy.

The remaining discrete sources in the field of Figure 1 cannot be identified with cluster galaxies. In particular the bright (0.11 Jy) source F(1709+787) has no obvious counterpart on the Sky Survey prints and may be a background object.

Table 2. Radio spectral data (mJy units)

Source	Frequency (MHz) 610	778	1410	2695	8085	Spectral Index[g] α
A. 1706+786	248[a]		120[b]	72[c]	>16[c]	−0.83
B. 1705+786	97[a]			34[c]		−0.71
C. 1706+787	71[a]			16[c]		−1.0
ABC region	570[a]					
Eastern arc	450[a]					
Western arc	650[a]					
Diffuse Emission around D	100[a]					
Entire cluster region	2050[a]	1600[d]	1070[e]	570[f]		−0.85

[a] This paper, Westerbork data
[b] Slingo (1974)
[c] This paper, NRAO interferometer data
[d] Owen (private communication), NRAO 300-foot data
[e] This paper, NRAO 300-foot data
[f] Owen (1975), NRAO 300-foot data
[g] $S(\nu)=S_0\nu^{\alpha}$

The complex emission North of the cluster centre has no obvious relationship to cluster galaxies. The peak (G) of the Eastern arc of this emission region lies near the bright cluster galaxy marked "G" in Figure 6 (galaxy number 7 in Table 1). This Eastern arc may therefore be similar to the C-shaped structures found in some other rich clusters, e.g. 3 C 66 and 3 C 465 (Macdonald et al., 1968) but at the resolution of our 610-MHz map it is not clear that it can meaningfully be separated from the other complex emission or that it contains fine structure which would support identification with a single galaxy. The Western arc of the complex is mainly in an area of sky devoid of cluster members. Its configuration with respect to sources B and C suggests that it could contain a superposition of extended "tails" associated with these sources. Higher resolution observations with comparable sensitivity to our 610-MHz map should clarify this possibility and are in progress. The most northerly feature (H) on the Western arc coincides with a compact group of faint galaxies, and one or two bright galaxies lie near the arc, but there is no good basis for an identification at present. Observations of this region at 1420 MHz with the NRAO interferometer (F. N. Owen, private communication) indicate that it contains no discrete sources brighter than 5 mJy at this frequency.

III. Discussion

The radio emission from Abell 2256 is remarkably complex, and suggests that the region around the cluster centre contains an unusual concentration of active galaxies, which do not however have strong optical spectroscopic peculiarities (see Table 1). The presence of three head-tail sources near the centre of the same cluster provides an excellent opportunity for studies of the dynamics of such structures (and thus indirectly of the intracluster medium) from observations of their spectral-index and polarization distributions and of their configuration with respect to the cluster galaxies. If observations at higher angular resolution show the Western arc to be related to the tails of sources B and C, as is suggested by the present observations, these tails may be extreme cases of extension of the phenomenon to great distances (>1 Mpc) from the parent galaxies.

Costain et al. (1972) found the spectral index of Abell 2256 between 22.25 and 81.5 MHz to be −1.9. This contrasts with the index we find for the integrated emission from the cluster between 610 and 2695 MHz, which is −0.85 (Table 2), and implies that Abell 2256 contains a steep-spectrum radio component or components which would contribute a total of ~100 mJy at 610 MHz. The three discrete sources (A, B and C) near the cluster centre do not have unusually steep spectra and cannot by themselves contribute significantly to the observed decametric flux densities. The lack of ionospheric scintillation of the cluster at 22.25 MHz (Costain and Roger, private communication) further suggests that the angular extent of the low-frequency emission exceeds 10′. The steep spectrum and large low-frequency size encourage the suggestion of Bridle and Feldman (1972) that the decametric cluster sources are long-lived accumulations of relativistic particles that have escaped from radio galaxies into weak intergalactic magnetic fields, where they produce X-rays by Compton-scattering the microwave background photons. Of the extended features in the cluster, only the diffuse emission ~1 Mpc or more in extent around source D has the appropriate 610-MHz flux density *and* angular size to account for this low-frequency emission, although there is as yet no evidence that it has a high spectral index. The inverse-Compton interpretation of the Abell 2256 X-ray emission would be greatly strengthened if the X-ray source is located in the region around source D, and if this region has a steep radio spectrum.

The proposal of Baldwin and Scott (1973) would require the decametric source to be a radio galaxy or galaxies subjected to prolonged confinement by a hot dense circumgalactic medium whose thermal bremsstrahlung produces the observed X-rays. While our observations lend no specific support to this model, it cannot yet be excluded on the basis of radio observations of Abell 2256.

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