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ON THE DISTRIBUTION OF RADIO EMISSION IN THE X-RAY CLUSTER OF GALAXIES ABELL 401

JACK O. BURNS

National Radio Astronomy Observatory,[a] VLA Program, Socorro, New Mexico 87801

M. P. ULMER

Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60201

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ABSTRACT

We report 4885-MHz VLA observations of four galaxies in the rich cluster Abell 401. We produced ~2-arcsec-resolution maps of the fields near the sources 4C13.17A, 4C13.17B, and 14W12, as well as the cD in A401. 4C13.17A (total flux ≅ 120 mJy) has an ~20-arcsec structure aligned along the minor axis of its associated optical galaxy. A portion of this radio structure is very highly polarized—48±4%. The apparent location of high polarization (near the nucleus of the radio galaxy) is probably due to projection effects. Along with 4C13.17B, we find that thermal or ram pressure confinement models of the source structures are consistent with x-ray observations that require a hot intracluster gas ($T \sim 10^8$ K, $n \sim 5 \times 10^{-4}$ particles/cm^3). 4C13.17B (total flux ~40 mJy) has a U-shaped "twin-tailed" structure quite similar in size, shape, and brightness to NGC 1265. We found that 14W12 was point-like (~0.5″ size) with total flux density 32.6±1 mJy and centered on its associated optical galaxy. We also observed the cD galaxy but failed to detect it down to a 1σ limit of ≈300 μJy. We discuss this lack of radio emission within the context of the accretion model of Mathews and Bregman (1978).

I. INTRODUCTION

The rich cluster of galaxies Abell 401 has many diverse and unusual characteristics which distinguish it from other clusters. The optical brightness distribution is strongly dominated by a cD galaxy which lies near the cluster center (Bahcall 1974). Dressler (1978) has noted that A401 has an unusual luminosity function which rises steeply at the bright end and is flatter than most other clusters at the faint end. Strom and Strom (1979) find a strong gradient of elliptical galaxy sizes from the center to the outer regions of the cluster with the small lenticulars found most often in the center (with the exception of the cD directly at the center). Both studies suggest that strong tidal stripping of galaxies near the center may be occurring. The redshift for this cluster is $z = 0.0746$ (Hintzen *et al.* 1977), which corresponds to a luminosity distance of ~300 Mpc for $H_0 = 75$ km s^{-1}Mpc^{-1}. At an angular distance of only 0°.7 from A401, a second rich cluster with a cD galaxy (A399) can be found; its redshift is $z = 0.071$ (Hutchings 1978). Based on recent observations (Ulmer and Cruddace 1980; Ulmer *et al.* 1979), the x-ray emission in this region is observed to be diffuse, extended, and centered near the cD galaxies in A401 and A399. Ulmer *et al.* (1979) suggested that the A401/A399 system might be a gravitationally bound binary system, and the redshifts of A401 and A399 are consistent with this hypothesis.

At radio frequencies, there are several strong sources in the cluster field. Slingo (1974), McHardy (1978), Simon (1979), and Harris *et al.* (1980a) have mapped 4C13.17A, a tailed radio source located about 6′.4 (0.4 Abell radius) from the cluster center and associated with a 16^m.2 galaxy (Harris *et al.* 1980a). The length of the tail at 408 MHz (7′ or 0.5 Mpc) prompted Hintzen *et al.* and Simon to suggest the need for *in situ* particle reacceleration to generate the observed radio emission. 4C13.17B, which is located about 9′ from the center of A401, is identified with a 16^m.8 cluster galaxy (Harris *et al.* 1980a). A very slight extension was seen to the north of the centroid in the Westerbork map (Harris *et al.* 1980a). A third source, labeled 14W12 by Harris *et al.* (1980a), was found about 21 arcmin to the north of the cD in A401 in the Westerbork survey. Although located very far from the cluster center (0.8 Abell radii or 1.6 Mpc), it has an apparent wide-angle radio tail morphology and a galaxy magnitude (16^m.3, Harris *et al.* 1980a) consistent with cluster membership. No emission has been detected from the cD galaxy in A401. The distribution of these galaxies is shown on the enlargement of the PSS field in Fig. 1.

In this paper we report new observations of the three

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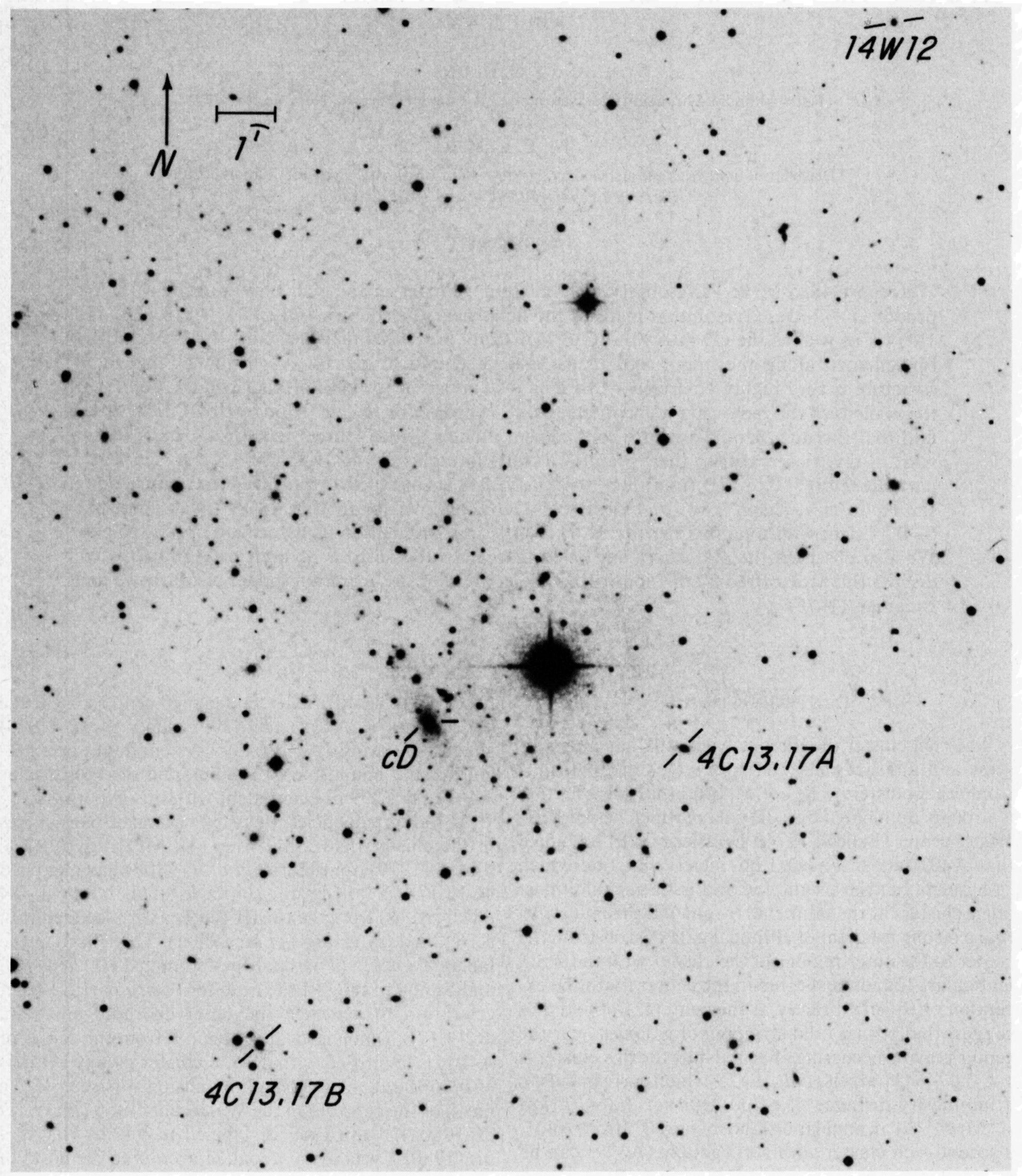

FIG. 1. Enlargement of the optical field of Abell 401 taken from the *E* print of the Palomar Sky Survey.

radio sources discussed above plus the cD galaxy in A401 using the NRAO Very Large Array (VLA) at 4885 MHz ($\lambda = 6$ cm). The high-resolution VLA maps reveal several interesting new features in the radio galaxies, e.g., 4C13.17A is unusually highly polarized near the galaxy nucleus unlike other head-tail sources, and 4C13.17B is shown for the first time to have characteristics very similar to the U-shaped source NGC 1265. From these maps, we have produced models that require the hot ICM that has been detected by x-ray observations. We

TABLE I. VLA antenna positions on 16 May 1979.

Antenna	Distance from array center (km)
	West arm (azimuth = 236°)
1	0.48
2	1.59
3	3.2
4	5.2
5	7.7
6	13.6
7	17.2
	East arm (azimuth = 115°)
8	0.09
9	0.15
10	0.48
11	0.97
12	1.95
	North arm (azimuth = 355°)
13	0.13
14	0.27
15	0.44

also couple the x-ray observations to our work by using the accretion model of Mathews and Bregman (1978). This model suggests that there should be a correlation between the radio and x-ray emissions from massive galaxies in clusters.

II. OBSERVATIONS AND REDUCTIONS

A401 was observed on 16 May 1979 with the partially completed VLA. A bandwidth of 50 MHz at a center frequency of 4885 MHz was used. A total of 15 antennas located at the stations listed in Table I was present in the array during the observations. The available baselines ranged from $\approx$60 m to $\approx$17 km, producing a maximum possible resolution of $\approx$0.8 arcsec. However, because of poor weather conditions much of the data on baselines $\gtrsim$8 km was not usable and therefore the resolution on the maps is $\gtrsim$2 arcsec.

Each antenna used two channels of opposite circular polarization. All possible baselines and polarizations were correlated. The left- and right-hand polarizations were used to produce visibilities of Stokes parameter I. The cross products of right-left and left-right were used to make maps of Stokes parameters Q and U and the polarized intensity $P \equiv (Q^2 + U^2)^{1/2}$.

All four galaxies in A401 (4C13.17A, 4C13.17B, 14W12, and the cD) were observed during a 12-hr period. In each half-hour, 4C13.17A was observed for $\approx$15 min and then the remaining sources were observed for about 5 min each. The calibrator 0316+161 ($S_{4.9}$ = 2.94 Jy) was monitored once every 15 min to determine gain and phase variations resulting from changes in the instrument and weather conditions. In addition, 3C286 ($S_{4.9}$ = 7.41 Jy) was observed several times both to connect our observations to the Baars *et al.* (1977) flux density scale and to calibrate the polarization parameters.

After data editing and calibration, the visibilities were Fourier transformed to produce a "dirty" map. In several instances described in Sec. III, the visibilities corresponding to long baselines were weighted down with a Gaussian taper for the purpose of emphasizing the more extended structure. Owing to the limited u,v coverage, strong sidelobes appeared on all of the maps. To reduce these sidelobes, the "clean" algorithm was utilized in the standard NRAO software package. The resulting maps are described in Sec. III.

III. RADIO-FREQUENCY PROPERTIES OF SOURCES IN A401

a) The Tailed Radio Galaxy 4C13.17A

A VLA total intensity contour map of 4C13.17A at 4885 MHz is shown on the right-hand side of Fig. 2. This

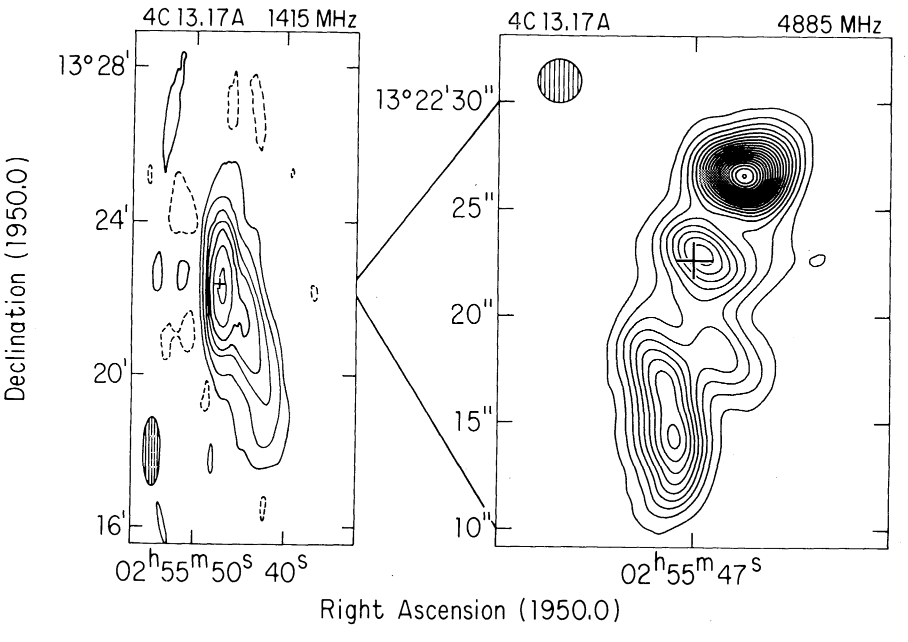

FIG. 2. Westerbork (left) and VLA (right) total intensity contour maps of 4C13.17A. Contours are in equal multiples of 1.09 mJy/clean beam area on the VLA map and at the levels −1.4, 1.4, 5.5, 16.4, 27.4, 54.8, 109.6, and 219.2 mJy/clean beam on the Westerbork map. The crosses mark the position of the optical galaxy nucleus. The shaded ellipses are the half-power contours of the clean beams.

TABLE II. Minimum pressures, associated parameters, and polarization of regions in 4C13.17A.

Component δ (1)	$S_{4.9}$ (mJy) (2)	$P_{4.9}$ (mJy) (3)	ψ (°) (4)	$F_{4.9}$ (%) (5)	Volume (arcsec³) (6)	$E_{\min P}$ (erg) (7)	$B_{\min P}$ (μG) (8)	Pressure (dyn/cm²) (9)	L (erg/s) (10)	t_{syn} (yr) (11)
13°22′27″	54.7	1.2	−29°	5	$4/3\pi(2.2)^3$	4×10^{56}	26	6×10^{-11}	2×10^{41}	2×10^{6}
13°22′23″	21.8		+18°		$4\pi(1.5)^2(1.7)$	2×10^{56}	18	3×10^{-11}	8×10^{40}	3×10^{6}
13″22′18″	17.5	1.5	+11°	48	$4\pi(1.9)^2(1.7)$	3×10^{56}	15	2×10^{-11}	6×10^{40}	4×10^{6}
13°22′14″	19.4		−12°		$4\pi(1.0)^2(1.7)$	2×10^{56}	22	4×10^{-11}	7×10^{40}	2×10^{6}

Notes

Column 1 is the component declination.

Column 2 is the flux density of the component, corrected for the fact that the source is extended in the transverse direction.

Columns 3–5 are the peak polarized intensity, polarization E-vector position angle, and fractional polarization at that declination, respectively.

Column 6 is the component volume computed as described in Burns *et al.* (1979). For the northern component the 2.2 is the deconvolved radius. For the three southern components the first term in parentheses is the deconvolved second moment of the brightness distribution measured along the minor axis and the second term is the second moment of the beam measured along the major axis.

Columns 7–11 are the minimum energy, minimum magnetic field strength, minimum pressure, luminosity, and synchrotron lifetime of the component, respectively.

"cleaned" map was restored with a circular Gaussian of 2 arcsec FWHM as shown by the shaded circle. The noise on this map is ≈200 μJy per beam area. The cross marks the center of the optical galaxy as measured by Simon (1979); it coincides with a radio component of peak flux density ≈9 mJy at 4.9 GHz. The total flux density of 4C13.17A at 4.9 GHz is ≈120 mJy as determined from the sum of the clean components.

The centroid of emission in 4C13.17A is located on the optical galaxy; two streams or "lobes" of radio emission extend out along the minor axis of the galaxy (see PSS enlargement in Simon 1979). Unlike other head-tail sources the radio emission appears to peak at the extremities of the 20-arcsec linear structure. [This elongated emission on the VLA map was also the only radio structure visible in the Cambridge maps at 2.7 and 5.0 GHz (Simon 1979 and McHardy 1978, respectively).] There is no indication of the structure forming the extended tail reported by Harris *et al.* (1980a) (see Fig. 1). This is most likely due to the fact that the u,v coverages of the higher-resolution (and higher-frequency) maps from Cambridge and the VLA were considerably different from that used to construct the Westerbork map. In particular, Westerbork had a very short spacing (36-m, or 180 wavelengths at 21 cm) compared to the VLA (60-m, or 1000 wavelengths at 6 cm). If the tail is very diffuse and extended, then the VLA or Cambridge interferometers were not sensitive to such large-scale features in the configurations used for the reported observations.

Following the procedure outlined in Burns *et al.* (1979), we computed the minimum pressures, energies, and associated parameters for four regions of 4C13.17A in the VLA map. Spherical geometry was assumed for the northernmost component, and cylindrical geometry was used for the other regions. The synchrotron spectrum was taken to extend from 10 MHz to 10 GHz with a spectral index of 0.8*. The source is slightly resolved along the minor axis, averaging about 4–6 arcsec in (deconvolved) diameter. The results of this calculation are shown in Table II. The minimum internal pressures are consistent with confinement (either thermal or ram pressure) by an intracluster gas whose parameters are like those reported from x-ray observations (i.e., $n_{\rm ICM} \sim 5\times10^{-4}\ {\rm cm}^{-3}$, $T\sim10^8$ K).

A map of the polarized intensity for 4C13.17A is displayed in Fig. 3 and the values are noted at four regions in Table II. The distribution of polarization, like that of the total intensity, is unusual. The northernmost component is (5 ± 3)% linearly polarized with an E-vector position angle of ≈−30°, whereas, at the southern peak, the source has an amazingly high degree of polarization—(48 ± 4)%. This is the largest fractional polarization known near the "head" of a tailed radio source (typically $F_{\rm head} < 10\%$).

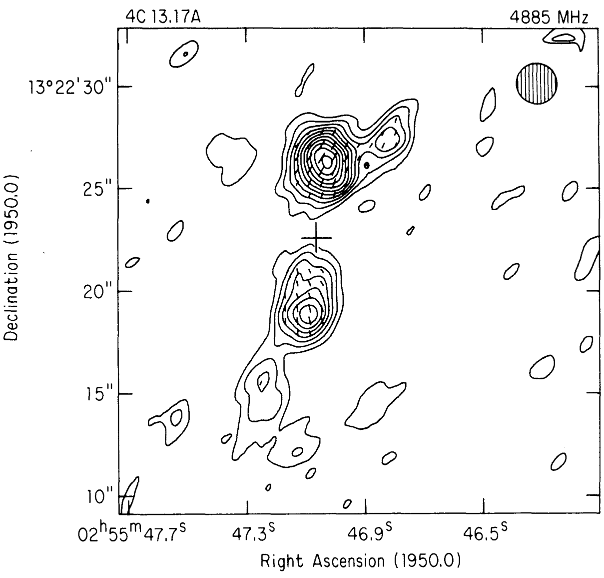

FIG. 3. VLA polarized intensity contour map. Dashed lines represent the polarization E vectors. The cross and beam are as in Fig. 2.

* Spectral index defined by $S_\nu \propto \nu^{-\alpha}$.

TABLE III. Comparisons of the radio properties of 4C13.17B with NGC 1265.

	4C13.17B	NGC 1265
Overall source width	22″ (15 kpc)	60″ (20 kpc)
Integrated flux density (Jy)	0.040	3.53
Total monochromatic luminosity		
($\mathrm{W\,Hz^{-1}}$)	4.3×10^{23}	2.2×10^{24}
Hot spots in radio streams:		
$S_{4.9}$ (mJy)	<1.3	3
monochromatic luminosity		
($\mathrm{W\,Hz^{-1}}$)	$<1 \times 10^{22}$	2×10^{21}
pressure (dyn/cm^2)	$\gtrsim 10^{-11}$	$\sim 10^{-10}$
Tail lengths	$\gtrsim 1'$ (40 kpc)	$\gtrsim 8'$ (170 kpc)
Individual tail widths	<3″ (<2 kpc)	~1″ (0.3 kpc)

Projection effects probably play an important role in this source. The extreme measured radial velocity (with respect to the cluster mean) of $\gtrsim 2880$ km/s suggests that this galaxy is moving nearly along the line of sight. Such a projection effect could produce the unusual distribution of radio emission. Near the galaxy, the tail of the 4C13.17A may lie close to the line of sight and only curve into the plane of the sky at larger distances from the galaxy. The "lobe-like" structure in the VLA map, therefore, could be a summation of the emission along the inner tail plus the nuclear contribution. The probably diffuse structure seen by Harris *et al.* (1980a) would be at large distances from the galaxy; such tail emission is known to be broad in other head-tail sources not seen at such high-projection angles. It is possible, in addition, that the high polarization does not originate within the galaxy nucleus but is due to the projected tails.

b) *The Twin-Tailed Structure of 4C13.17B*

In Fig. 4, a VLA map of 4C13.17B is shown. The circular restoring beam is 6 arcsec FWHM. The individual U-shaped streams are unresolved south of $\delta = 13°16'30''$; north of this declination the signal is too weak to make a definitive statement on source sizes. 4C13.17B has a twin-tailed morphology similar to that in NGC 1265 (e.g., Miley *et al.* 1975). As in NGC 1265, a cluster galaxy lies at the leading edge of the head-tail structure. No polarization signal was detected above ≈ 300 mJy/beam.

A detailed comparison between NGC 1265 and 4C13.17B is given in Table III. The two sources are similar in luminosities of the individual streams, in overall source width, and in shape. This suggests that the plasma momentum flow and energetics in the streams near the nucleus of the two galaxies are probably comparable, since the x-ray and optical velocity data indicate that the ram pressures experienced by the galaxies in Perseus (A426) and A401 are similar. The details of the plasma flow in NGC 1265 are discussed by Jones and Owen (1979) and Begelman *et al.* (1979). The differences in total luminosities and tail lengths may be due to a difference in particle reacceleration conditions in the extended tails (see below).

A minimum pressure calculation like that performed on 4C13.17A was made for 4C13.17B. The resulting internal pressure near the leading edge is $\geq 1 \times 10^{-11}$ dyn/cm^2. For a galaxy space velocity of ~2000 km/s with respect to the cluster rest velocity, the equating of $\rho_{\rm ICM} v_{\rm gal}^2$ with the internal radio source pressure indicates that $\rho_{\rm ICM} \gtrsim 4 \times 10^{-28}$ g/cm^3 ($\sim 2 \times 10^{-4}$ cm^{-3}). Once again this is consistent with the gross estimate of $\rho_{\rm ICM}$ from HEAO-1 data and clearly indicates that a dense medium extends out to 0.6 of an Abell radius (1.2 Mpc) from the cD.

The above calculation also produced an estimate of the B field, $\gtrsim 13$ μG, which indicates that the synchrotron lifetime of the relativistic particles is $\lesssim 4 \times 10^7$ yr. The maximum tail length that could be expected if particles are accelerated only in the nucleus and are at rest in the tail with respect to the ICM is $\lesssim t_{\rm syn} v_{\rm gal} \lesssim 80$ kpc. Therefore, no additional particle reacceleration is necessary to produce the tail seen on the VLA map (tail length ~40 kpc). This differs from the case of NGC 1265, where a strong need for *in situ* reacceleration in the tails is indicated.

c) *The Westerbork Source 14W12 in the Field of A401*

On the Westerbork map of 14W12 (Harris *et al.* 1980a), the source has two distinct tails to the northwest and south of a nuclear component. This radio morphology combined with the galaxy magnitude (listed as $16^{\rm m}_{\cdot}3$ in Harris *et al.* 1980a) is what one might expect for a

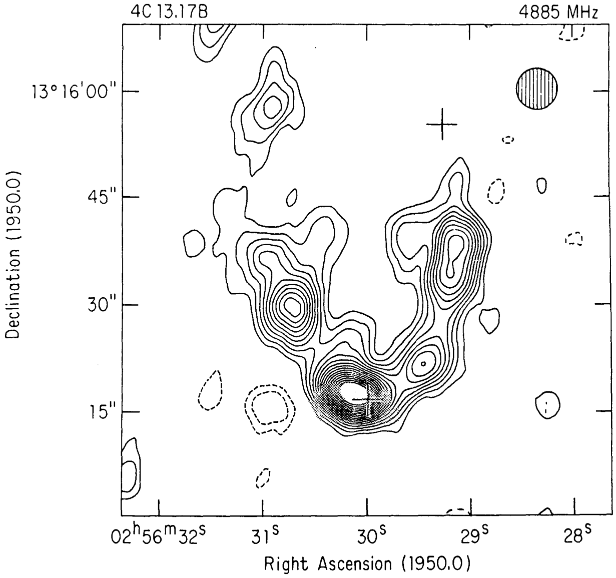

FIG. 4. Low-resolution total intensity map of 4C13.17B. Contours are in equal multiples of 0.26-mJy/clean beam area; the lowest contour is 2 × 0.26 mJy/clean beam. The crosses mark the positions of the nearest cluster galaxies. The clean beam represented by the shaded circle is FWHM = 6 arcsec.

TABLE IV. Gaussian model of 14W12.

$S_{4.9}$ (mJy) ± ΔS	α(1950) ± $\Delta\alpha$	δ(1950) ± $\Delta\delta$	Major	Minor	p.a.
32.6 ± 1.0	$02^h55^m25\overset{s}{.}284 \pm 0\overset{s}{.}001$	$13°39'54\overset{''}{.}20 \pm 0\overset{''}{.}03$	$0\overset{''}{.}7 \pm 0\overset{''}{.}2$	$0\overset{''}{.}4 \pm 0\overset{''}{.}3$	$151° \pm 0\overset{°}{.}3$

member of the A401 cluster. However, a redshift of the galaxy is needed to confirm this speculation.

The VLA map of 14W12 (not shown) at 4885 MHz revealed only the presence of a slightly resolved single component coincident with the galaxy. No tail structure was seen, even on maps restored with a large clean beam. A Gaussian model of this component is given in Table IV. As in 4C13.17A, the tails in 14W12 might be too diffuse to be seen with the VLA configuration listed in Table I.

d) *Radio Emission in cD Clusters*

A total of ~2 hr of integration time was obtained with the VLA on the cD galaxy in A401. No source was detected down to a noise value of ≈300 μJy (1σ). This implies that the radio power at 4.9 GHz of the cD is $<5 \times 10^{21}$ W Hz^{-1}.

It is interesting that even down to this low level the cD in A401 is not a radio source, but there are several prominent tailed radio galaxies in the cluster. A401 is one of a growing number of exceptions to McHardy's (1979) claim that radio-trail sources do not occur in clusters with supergiant galaxies. In fact, recent observations (e.g., Harris *et al.* 1980b; Grindlay *et al.* 1977; Schnopper *et al.* 1977) have shown that a number of Bautz-Morgan (1970) type I clusters contain head-tail sources. It is true that the cD galaxies in BM I clusters are more often radio sources than other nondominant member ellipticals and they have morphologies other than head-tails (i.e., small doubles or wide-angle tails). There is no evidence to indicate, however, that head-tail sources associated with outlying galaxies in cD clusters cannot exist.

IV. ON THE RELATIONSHIP BETWEEN CLUSTER RADIO AND X-RAY EMISSIONS IN A401

General discussions on the relationship between x-ray and radio emissions from clusters of galaxies are given by Owen (1974), Lea and Holman (1978), Erickson *et al.* (1978), Owen *et al.* (1980), and references therein. Here we specifically discuss the expected relationship between radio emission from individual galaxies and the x-ray results for A401 (Ulmer and Cruddace 1980; Ulmer *et al.* 1979; Ku 1980).

There is good agreement between our calculations of the thermal or ram pressure needed to confine the tailed radio galaxies and ICM parameters determined from x-ray observations. These radio data confirm the presence of a dense and hot ICM that is widely distributed throughout the cluster. Rapid motion through this ICM (>2000 km/s) has produced a least two prominent examples of radio tails.

In addition to the broad distribution of x rays, one may also ask on what level more localized x-ray emission near the radio sources can be expected due to the inverse-Compton effect. X rays can be produced if the photons from the 3-K blackbody background are scattered to higher energies by the relativistic electrons which produce the radio emission (see Harris and Grindlay 1979 for a recent review). Using the radio source component models for 4C13.17A and B (Secs. IIIa and IIIb and Tables II and III), we have computed that the inverse-Compton x rays would have a flux that is 100 times lower than the current x-ray upper limits ($\lesssim 3 \times 10^{41}$ erg s^{-1}, 1–3 keV; Ulmer and Cruddace 1980). If x-ray emission is detected from 4C13.17A and B at levels just below the present observational sensitivity, it could imply that the magnetic field and particle energies are not in equipartition (as assumed in Tables II and II); conversely, it could be that the x-ray flux would not be due to the inverse-Compton scattering of the 3-K background.

Turning to the cD in A401, we note that this supergiant galaxy is not a detectable radio source. Jones *et al.* (1979) and White and Burns (1980) noticed that there appear to be two components of the x-ray emission in cD clusters: (a) diffuse emission associated with the ICM and (b) concentrated emission peaked on the cD galaxy. Furthermore, in many of these clusters with peaked x-ray emission, the cD is also a radio source. It is possible that the presence of a radio source enhances the likelihood of x-ray emission near the cD, or vice versa. This apparent correlation fits well with the model of M87 and NGC 1275 by Mathews and Bregman (1978). In this model, the accretion of intracluster gas onto massive galaxies (not necessarily cD galaxies, however) directly generates galaxy. The cD in A401 is neither a strong radio nor a strong x-ray source [with HEAO-2, Ku (1980) and Ulmer and Cruddace (1980) find a diffuse component strong x-ray source [with HEAO-2, Ku(1980) and Ulmer and Cruddace (1980) find a diffuse component of x-ray emission but no point component centered on the cD]. Thus, the data are consistent with the proposed correlation between a cD radio source and peaked x-ray emission.

The cD galaxy in A401 is nearly at rest with respect to other cluster galaxies ($\Delta v \sim 40$ km/s, Hintzen *et al.* 1977). Therefore, one might expect that the cD should be accreting significant amounts of gas from the ICM and should be a radio/x-ray source. Possibly, the ICM in the cluster core has not yet achieved a sufficiently high density to produce "central cooling." Without the cooling, the gas might be too hot to be accreted by the cD galaxy. This hypothesis predicts that future x-ray work will find that A401 does not have a comparatively cooler central region, unlike the Virgo and Perseus clusters (cf. Ulmer and Jernigan 1978).

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