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THE HALO RADIO SOURCE COMA C AND THE ORIGIN OF HALO SOURCES

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ABSTRACT

We present in this paper the first high-resolution spectral index map of the halo source Coma C, which was obtained combining WSRT data at 326 MHz and DRAO + VLA data at 1.4 GHz. The spectral index distribution shows a central region, of $\sim 8'$ radius, where the spectral index is almost constant (~ 0.8), surrounded by a region where the spectrum steepens to $\alpha \sim 1.8$. In addition, we present new observations of Coma C obtained with the WSRT at 608.5 MHz. The spectral index information and high-resolution maps are used to derive the physical conditions in Coma C and understand the processes which lead to the formation of halo sources in clusters. It is suggested that the origin of relativistic particles of Coma C is the large head-tail radio galaxy NGC 4869, orbiting at the Coma cluster center. The spectral index distribution implies that the electrons left behind from the galaxy's motion are continually reaccelerated in situ, through the weak shocks in the intracluster medium produced by galaxy wakes. According to our suggestion on the origin of radiating electrons in Coma C, we explain the rarity of radio halos as due to the difficulty of finding tailed radio galaxies orbiting at the cluster centers.

Subject headings: galaxies: clustering — radiation mechanisms: miscellaneous — radio continuum: galaxies — techniques: interferometric

1. INTRODUCTION

The probing of the gaseous medium in galaxy clusters through the study of the radio emission of "halo sources" is revealing important information on physical processes in clusters. Of particular interest is the origin of both the relativistic particles and the associated magnetic field, which are required to generate the observed diffuse synchrotron emission. Complementary information about the hot, nonrelativistic gas can be derived from X-ray and optical emission-line data. When all these data are combined, a much clearer picture should emerge of the particle acceleration and diffusion in the intracluster medium, the relation to the galaxy dynamics, the role played by the magnetic fields, and the global evolution of galaxy clusters. Unfortunately, the typically low surface brightness of cluster radio halos makes it difficult to image them accurately. Further, at lower resolution, where beam averaging enhances the detectability of extended radio emission, true diffusion emission is sometimes difficult to distinguish from a blend of weak, discrete radio sources. Ideally, one wants high sensitivity on *all* angular scales. Thus, relatively few clusters have unambiguously detected halo emission (e.g., Coma C [Willson 1970], A2255 [Harris, Kapahi, & Ekers 1980], A2256 [Bridle & Fomalont 1976], and A2319 [Harris & Miley 1978]). On the other hand, several other clusters have shown *no* significant halo emission (see Jaffe and Rudnick 1979; Hanisch 1982a; Waldthausen 1980; Andernach et al. 1988 and references therein). Different models for halo source formation and evolution have been proposed (see Hanisch 1982b for a review); however, their origin is not yet fully understood, nor it is understood why only a minority of clusters have significant nonthermal halo emission.

The best-imaged radio halo is that of the Coma cluster of galaxies (A1656) which, at $z = 0.0235$ (Sarazin, Rood, & Struble 1982) is "nearby," and whose intergalactic diffuse emission (the halo "Coma C") has a relatively high surface brightness. This paper analyses recent high-resolution maps of Coma C at 1.4 GHz, a combination of interferometer synthesis maps (Kim et al. 1990) obtained with observations at the Very Large Array (VLA)[5] and at the Dominion Radio Astronomy Observatory (DRAO), and at 326 MHz with the Westerbork Synthesis Radio Telescope (WSRT)[6] (Venturi, Giovannini, & Ferretti 1990). In addition, we present new observations of Coma C obtained with the WSRT at 608.5 MHz with a resolution of $35'' \times 63''$. These combined data provide the first opportunity to measure the halo's spectral index distribution with high resolution and accuracy. The latter is due to the high image quality at both 0.3 and 1.4 GHz, and the large frequency "baseline." We use these "state-of-the-art" images to extend the investigation of the physical properties of Coma C. In particular, we discuss the origin of the cosmic-ray gas and the physical conditions which cause halo sources. Throughout the paper we adopt a value of $H_0 = 100$ km s^{-1} Mpc^{-1} for the Hubble constant, which gives a scale of 0.35 kpc arcsec^{-1} for the Coma cluster.

2. RADIO MAPS

2.1. 1.4 GHz *VLA + DRAO Data*

Kim et al. (1990) published a detailed image of Coma C (HPBW $71''.6 \times 60''.0$) at 1.4 GHz made using the DRAO and VLA. They also estimated an equipartition-independent value of the magnetic field of Coma C based on the Faraday rotation of polarized emission from background radio sources. This is $(1.7 \pm 0.9) \times 10^{-6}$ G. Kim et al. (1990) suggested also that the

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magnetic field should be tangled on angular scales between 21″ and 1′ (corresponding to 7–20 kpc) and that the extent of the halo emission and the degree of field tangling indicate that in situ reacceleration of relativistic particles must be present.

2.2. 326 MHz *WSRT Data*

Venturi et al. (1990), obtained a WSRT high-sensitivity map at 326 MHz with a resolution of 55″ × 125″. These observations, thanks to the good sampling at the short baselines, reveal the faintest peripheral regions of Coma C, which merges into a bridge of radio emission in the direction of the extended source 1253+275 (Giovannini et al. 1989; Kim et al. 1989).

2.3. 608.5 MHz *WSRT Data*

To produce a Coma C map at this third frequency, we used two 12 hr syntheses obtained in 1988 August in a survey of the Coma cluster (Giovannini et al. 1993). The pointing position was on the cD galaxy NGC 4874 at the cluster center; the baseline coverages were $36 + n \times 72$ m and $72 + n \times 72$ m with $n = 0$–37. The data were reduced with the AIPS package. The two visibility data sets were first edited and self-calibrated separately. After combination of the two data sets, more iterations with self-calibration routines were applied. In our observations the shortest baseline is 73λ. Due to its large angular extent, Coma C was detected only by the shortest baseline interferometer which was also affected by solar interferences during part of the observation run. The derived maps at full resolution (HPBW = 35″ × 62″, P.A. = 90°) and with a HPBW = 70″ are displayed in Figures 1*a*–1*b*. The noise in the final map is 0.5 mJy beam^{-1}. The estimated uncertainty in the Coma C flux density is determined by the very low number of UV points at which it is detected. We estimated a total flux of 1.2 ± 0.3 Jy, in agreement with Valentijn (1978). An estimate of the total flux from the visibility amplitudes is problematic due to solar interference. For all these reasons we were not able to produce reliable spectral index maps between 326 and 608.5 MHz or between 608.5 and 1380 MHz. Despite of these uncertainties, the 608.5 MHz map is the highest resolution map yet produced of Coma C and allows us to look for possible substructures in the central regions of the cluster.

3. MORPHOLOGICAL AND PHYSICAL PROPERTIES

3.1. *Radio Morphology*

We refer to Venturi et al. (1990) for the Coma C radio map at 326 MHz and to Kim et al. (1990) for the 1.4 GHz map. The map at 608.5 MHz is given in Figures 1*a*–1*b*. One outstanding characteristic of this radio halo is that the surface brightness is smooth and featureless. There is no structure visible in the radio halo implying no structures resembling relic radio tails even at the 608.5 MHz resolution (~10 × 20 kpc), which is nearly the scale of an optical galaxy.

No significant morphological differences are seen between the maps at the three different frequencies. The baricenter of the brightness distribution is located near NGC 4874 and the brightness distribution is nearly symmetric with a faint extension in the direction of the peripheral cD galaxy NGC 4839 (at R.A. = $12^h54^m59^s.4$, Decl. = 27°46′02″) where a bridge of radio emission was detected at 326 MHz (see § 2.2). In this region a second, extended X-ray feature was found in the *ROSAT* all sky survey data (Briel, Henry, & Boehringer 1992), suggesting that the cluster could be in the process of merging. Except for the faint bridge radio emission, our maps show no peculiar radio emission in the region where the X-ray map shows evidence of interaction between the Coma cluster and the NGC 4839 subgroup.

The deconvolved size of the halo at 326 MHz, derived by fitting the brightness distribution with a two-dimensional Gaussian, is 28′ × 20′ in P.A. ~90° (HPBW). This value is significantly larger than the size derived by Kim et al. (1990) at 1.4 GHz (18′.7 × 13′.7) and is in agreement with previous low-frequency measurements (see Jaffe 1977 and ref. therein). This implies that the external regions of the halo have a steep spectrum.

3.2. *Integrated Spectrum of Coma C*

Schlickeiser, Sievers, & Thiemann (1987) published a 2.7 GHz map of Coma C, obtained with the 100 m Effelsberg single dish and studied the integrated spectral index with data at nine different frequencies. They found that the spectrum steepens considerably at high frequencies and that the best fit to these points is given by the in situ acceleration model, which they favored over both the primary and the secondary electron models (see also Kim et al. 1990). The in situ acceleration model predicts a power-law spectrum with a high-frequency cutoff for the total radio luminosity. With a low frequency spectral index = 0.52 and a frequency cutoff $\nu_c = 0.15$ GHz, the in situ acceleration model gives a remakably good fit to the data (Schlickeiser et al. 1987). Formal uncertainties in the low-frequency spectral index are large: it can be in the range 0.0–0.9 at the 68% confidence level. However, taking into account the physical and spectral index properties of extended radio sources, a very flat spectrum should be ruled out, so we will consider in this paper a spectral index uncertainty from 0.4 to 0.9 with the corresponding ν_c ranging from 0.1 to 0.4 GHz, respectively (see Fig. 10 in Schlickeiser et al. 1987 for more details). The turbulent magnetic fields necessary for the in situ acceleration can be provided by the wakes of galaxies (Jaffe 1977; Roland 1981; Roland et al. 1981). Since new measurements of the integrated flux density of Coma C at various frequencies have been published in the past few years, we added these new points to the data set used by Schlickeiser et al. 1987 (see Table 1 and Fig. 2); we have omitted the data from Willson 1970; Hanisch 1980; Valentijn 1978 in view of the more recent and more reliable data at the same frequencies which are now available. In fact the better signal-to-noise ratio and the more accurate and reliable "pointlike" source subtrac-

TABLE 1

COMA C FLUX DENSITIES

Frequency (MHz)	Flux (Jy)	Error (Jy)	References
30.9	49	10	1
43	51	13	2
73.8	17	12	2
151	7.2	0.8	3
326	3.18	0.03	4
408	2.0	0.2	5
608.5	1.2	0.3	6
1380	0.53	0.05	7
2700	0.08	0.02	8
4850	< 0.052	...	8

REFERENCES.—(1) Henning 1989; (2) Hanisch & Erickson 1980; (3) Cordey 1985; (4) Venturi et al. 1990; (5) Kim et al. 1990; (6) present paper; (7) Kim et al 1990; (8) Schlickeiser et al. 1987.

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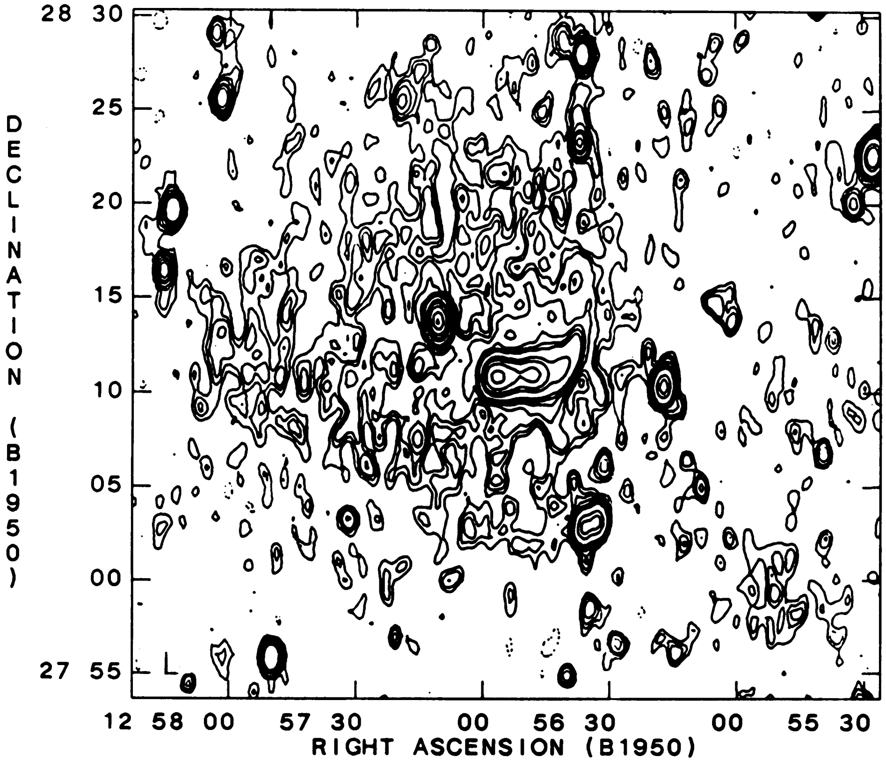

FIG. 1*a*

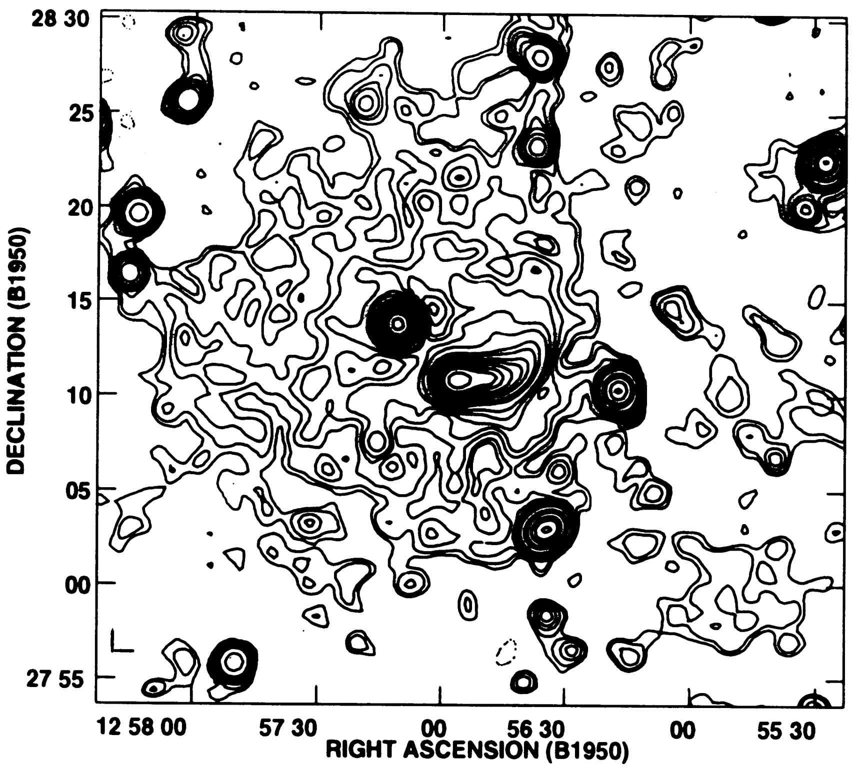

FIG. 1*b*

FIG. 1.—(*a*) Isocontour map of Coma C from WSRT observations at 608.5 MHz. The L-shaped sign in the lower left-hand corner is the HPBW (63″ × 35″ in P.A. 0°). The rms level is 0.5 mJy beam^{-1}. Contours are −1, 1, 1.5, 2, 3, 5, 7, 10, 30, 50, 100, 200, 300, mJy beam^{-1} The map peak flux is 369 mJy beam^{-1}. (*b*) Same as (*a*), but at a resolution of 70″ × 70″. The rms level is 0.7 mJy beam^{-1}. Contour levels are −1.5, 1.5, 2, 3, 4, 5, 7, 10, 20, 30, 50, 70, 100, 150, 200, 300, 400 mJy beam^{-1}. The map peak flux is 474 mJy beam^{-1}.

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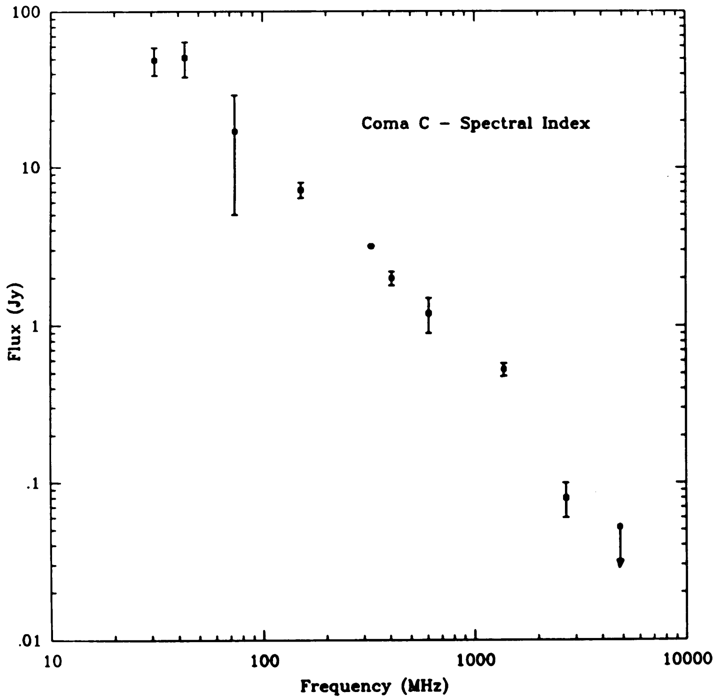

FIG. 2.—Coma C spectral index distribution. Data are from Table 1. Discrete sources have been subtracted.

tion in these more recent observations provide a much better separation of the *halo* emission. The new data set is in very good agreement with the one used by Schlickeiser et al. (1987) and thus supports their results and conclusions. In particular, the new measure at 30.9 MHz (Henning 1989) confirms the low-frequency agreement between the in situ model and the data.

3.3. *Spectral Index Distribution*

The radio data used to derive the spectral index of Coma C were obtained at 1.4 GHz with the VLA + DRAO and at 326 MHz with the WSRT (see references above). We produced new maps with the same UV range, gridding, and resolution in each waveband to derive the spectral index map between 1.4 GHz and 326 MHz. We did not subtract the extended or pointlike discrete radio sources, to avoid errors which might be introduced by the residuals of the subtraction. A comparison of total flux densities with single-dish data measurements shows very good agreement and confirms that our interferometric data at 326 MHz and 1.4 GHz have short enough baselines to properly map the large scale emission in both images.

In Figure 3 we present a gray-scale map of the spectral index distribution at a resolution of 130″ × 80″ (P.A. 0°); in Figure 4 slices with four different rotation angles are also given. Extended or pointlike discrete radio sources have not been subtracted to avoid unpredictable errors or fluctuations due to the subtraction procedure. The region contaminated by the presence of discrete sources (e.g., the extended radio galaxy NGC 4869) is well separated from the halo region.

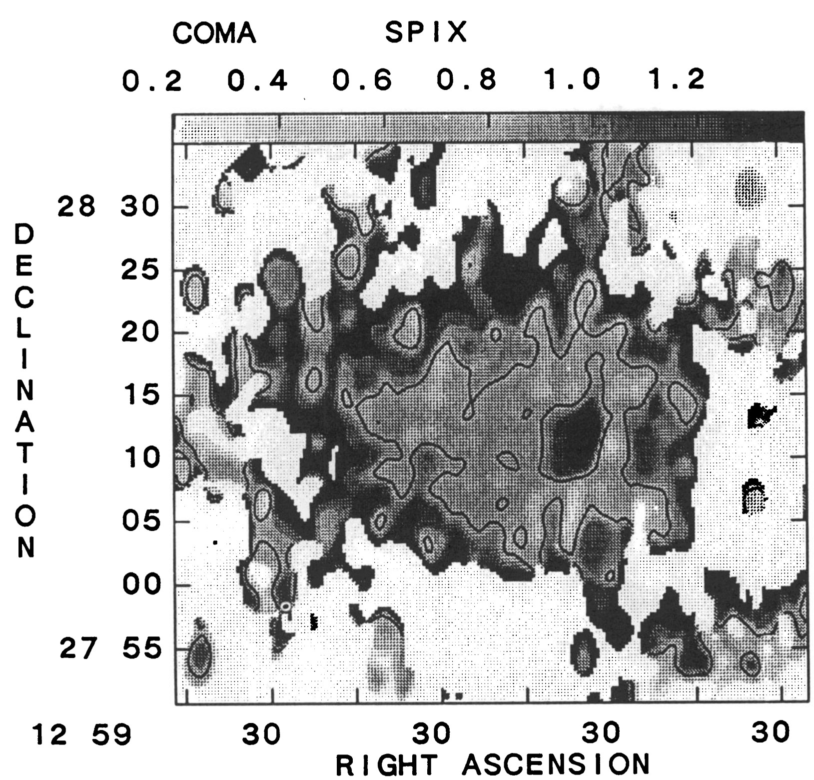

FIG. 3.—Gray level map of the Coma C spectral index distribution between 326 and 1380 MHz. The HPBW is 130″ × 80″ in P.A. 0°. The gray-scale flux range is 0.2–1.4 as displayed in the top of the figure; the contour level is at $\alpha = 0.8$.

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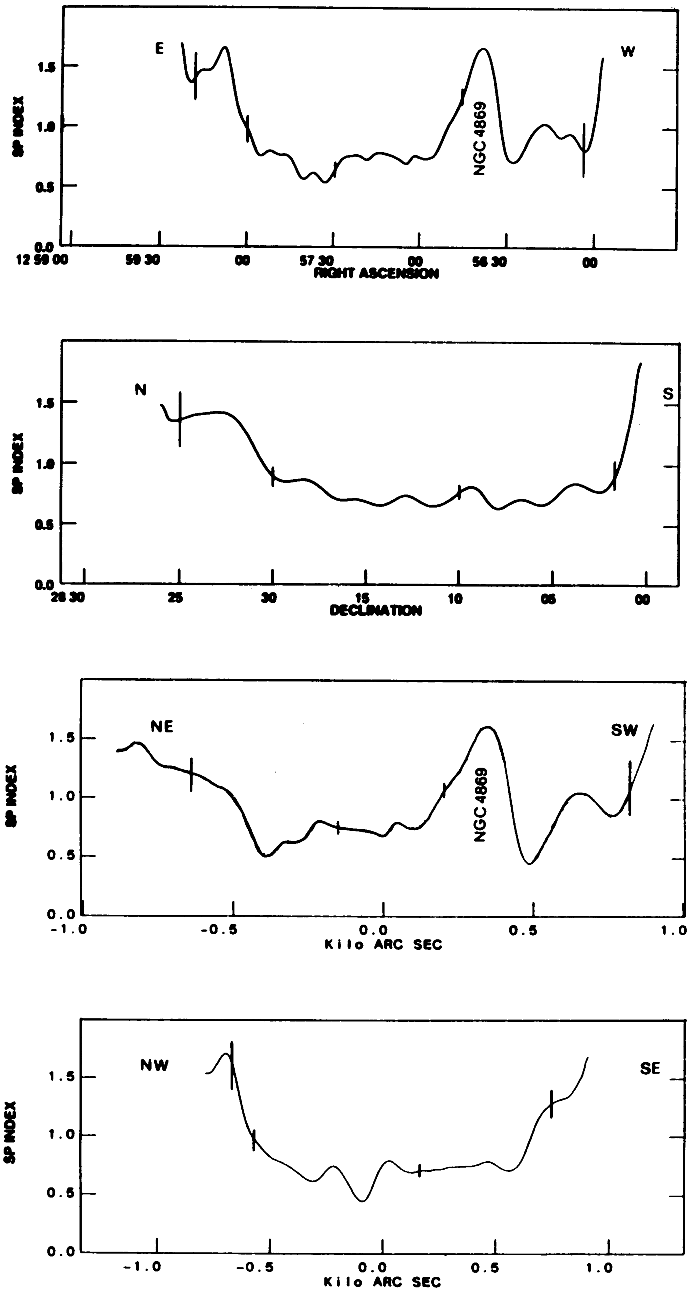

FIG. 4.—Slices of the spectral index map of Coma C crossing the halo source center. The vertical axis is the spectral index value between 326 and 1380 MHz. Along the horizontal axis we have, from top to bottom, R.A. (E-W slice), declination (N-S slice), and kiloarcsec in the other two slices, in which rotation angles are $-114°$ and $135°$, respectively. Bars represent 1 rms.

The most striking feature of the spectral index distribution is the central region, of radius $\sim 8'$ (corresponding to ~ 170 kpc), where the spectral index is almost constant with the value of ~ 0.8. Outside this central "plateau," the spectral index distribution shows a strong increase, reaching values higher than 1.8.

On the basis of the distribution obtained we can state that, at least in the low-frequency range (326 MHz–1.4 GHz), Coma C consists of two different regions: the innermost one with a size of $\sim 15'$, where $\alpha_{326\,\mathrm{MHz}}^{1380\,\mathrm{MHz}}$ has a constant value (~ 0.8) and the outer one where the spectrum strongly steepens. A decrease of the spectral index toward the center was also present in the 408–1380 MHz spectral index map obtained by Kim et al. (1986) at a much lower resolution ($7\farcm45 \times 3\farcm45$). We estimate that, at higher frequencies (> 1.4 GHz) the halo spectrum must steepen even in the central regions to be consistent with the total spectrum.

The radio galaxy NGC 4874 (Feretti & Giovannini 1985, 1987) and the extended NAT galaxy NGC 4869 (Dallacasa et al. 1989; Feretti et al. 1990) are presumably embedded in the halo source. Comparison of the spectral index of these two sources with that of the halo may give important clues on the origin of the radiating electrons and on the acceleration mechanisms. Both objects are located within the central "plateau." The spectral index of NGC 4874 is the same as that of the surrounding halo regions; along NGC 4869 instead, the spectrum steepens regularly (Dallacasa et al. 1989) reaching values as large as ~ 1.8. This steepening is clearly visible also in our spectral index map.

3.4. *Equipartition Parameters*

We derived the minimum energy density assuming energy equipartition between relativistic particles and magnetic field, a filling factor of 1, and equal energy in electrons and heavy particles (Pacholczyck 1970). To compute the equipartition parameters we integrated the total luminosity of the source between 10 MHz and 1 GHz with a spectral index $\alpha = 0.5$ (see § 3.2) and assumed a depth of ~ 400 kpc along the line of sight. The upper frequency limit approximately coincides with the value where the spectrum steepens considerably. It should be noted, however, that the estimate of the minimum energy density is very slightly affected by the assumed high-energy cutoff. The equipartition magnetic field is ~ 0.5 μG and the minimum energy density is 2.4×10^{-14} ergs cm^{-3} (see Table 2). The uncertainty on the spectral index (see § 3.2) can change the minimum energy density from 2.2 to 3.6×10^{-14} ergs cm^{-3} with the magnetic field ranging from 0.5 to 0.7×10^{-6} G. The value of the minimum energy density and consequently that of the magnetic field is about constant across the halo, owing to the fact that the lower depth expected at the halo periphery is approximately compensated by the lower brightness. The total minimum energy is $\sim 0.5 \times 10^{59}$ ergs with a volume of the radio emitting region $\sim 10^8$ kpc^3.

We have no evidence that radio sources in general and halo sources in particular are at the "equipartition" condition. However, we note that the estimated equipartition magnetic field is lower, but still in agreement with the magnetic field estimate by Kim et al. (1990) from the study of the RM of radio sources projected on the Coma cluster. Both estimates are based on uncertain assumptions, but it is important that two completely different estimates of the magnetic field give comparable results. Therefore, as in most papers discussing proper-

TABLE 2

PHYSICAL PARAMETERS

Parameter	Value
$\log P_{327\,\mathrm{MHz}}$ (W Hz^{-1})	24.28
$\log P_{610\,\mathrm{MHz}}$ (W Hz^{-1})	23.85
$\log P_{1.4\,\mathrm{GHz}}$ (W Hz^{-1})	23.50
Luminosity (ergs s^{-1})	10^{41}
H_{eq} (G)	0.5×10^{-6}
u_{min} (ergs cm^{-3})	2.4×10^{-14}
U_{tot} (ergs)	0.5×10^{59}

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ties in extended radio emitting regions, we will assume in this paper the magnetic field value corresponding to the equipartition condition.

In order to investigate the origin of Coma C and to address the question of the source of the relativistic electrons, we estimated the number of relativistic particles present in the halo source. Using standard synchrotron formulae (Pacholczyk 1970), we calculated the number of relativistic electrons with energy between E_1 and E_2, radiating between $\nu_1 = 10$ MHz and $\nu_2 = 1$ GHz:

$$N = 4\pi d^2 S_0 \nu_0^{\alpha} c_1 c_2^{-1} \frac{1}{\alpha} H^{-1}(\nu_1^{-\alpha} - \nu_2^{-\alpha}) ,$$

where d is the cluster distance, S_0 is the flux density at the frequency ν_0, c_1 and c_2 are the constants given by Pacholczyk (1970), α is the spectral index [defined as $S(\nu) \propto \nu^{-\alpha}$] and H is the magnetic field. The number of relativistic particles radiating in Coma C is $\sim 1.6 \times 10^{60}$. This value becomes 1.4×10^{60} with $\alpha = 0.4$ and as large as 3×10^{60} with $\alpha = 0.9$.

4. DISCUSSION

Given that radio halos are synchrotron sources, we would like to understand the following: (1) the origin of the magnetic field; (2) the origin of the relativistic particles; (3) the mechanism by which the relativistic particles are reaccelerated. Any successful model for the formation of a radio halo should further be able to explain (4) what determines the occurrence of a radio halo in some galaxy clusters, and not in others.

4.1. *Origin of Magnetic Field*

Ruzmaikin, Sokoloff, & Shukurov (1989) showed that faint magnetic fields which are present in galaxy clusters, but too weak to cause a radio halo, can be amplified into chaotic fields by the turbulent dynamo mechanism. This mechanism originates from galaxy motion inside the clusters and is able to amplify a weak seed magnetic field up to a strength of the microgauss order. Since the physical conditions in rich galaxy clusters are very similar to those we find in the Coma cluster, we expect that the mechanism which produced the large scale magnetic field in Coma C should be able to create a large scale magnetic field in most, if not all, rich clusters. This is confirmed by Kim, Tribble, & Kronberg (1991), who find an excess of Faraday rotation from radio sources aligned with rich clusters of galaxies.

It thus appears that both recent observations and theories support the notion that the IGM in cluster of galaxies can be sufficiently magnetized to cause a cluster radio halo.

4.2. *Origin of Relativistic Particles*

Schlickeiser et al. (1987) suggested that the radio emitting particles in the halo are likely to be drawn from the thermal pool through efficient in situ acceleration. But this cannot explain the rarity of radio halos, which should be present in most if not all X-ray clusters.

Blandford & Ostriker (1978) and Blandford (1979), discussing Fermi acceleration by shock waves, show the possibility of accelerating charge particles distributed according to a power law. Low-energy relativistic electrons injected with a power-law distribution by active radio galaxies into the halo source can be reaccelerated by the weak shocks present in the cluster center. The problem with this model is that diffusion losses of relativistic electrons have to be very small compared to radiative losses, as deduced by the presence of very steep spectrum radio galaxies in clusters (Roland et al. 1985; Roland, Hanisch, & Pelletier 1990). Therefore we cannot expect that the relativistic electrons present inside Coma C are orginated simply from diffusion from active radio galaxies. It is also worth pointing out that the number of radio galaxies found in the Coma cluster and their radio luminosities are typical for cluster galaxies (Hanisch 1982a). Therefore the origin of the Coma C halo cannot be attributed to an unusual radio activity of the Coma cluster galaxies.

A noteworthy characteristic of the Coma cluster is the presence of the head-tail galaxy NGC 4869 in its central region. Since this radio galaxy is moving in the dense IGM, we may expect that a significant number of relativistic electrons are left behind. These relativistic electrons are in regions where the tail magnetic field becomes very low and are mixed with the thermal plasma (Feretti et al. 1990). Therefore we can assume that after some time they are no longer connected with NGC 4869 but move in the IGM magnetic field. The curvature of the bent tail suggests a closed orbit around NGC 4874, rather than a radial orbit crossing the center of the cluster (Jaffe, Perola, & Valentijn 1976). Feretti et al. (1990) found that an elliptical orbit with eccentricity of 0.26, semimajor axis of 120 kpc and inclination of 64° fits the tail structure. The orbital period would be 7.5×10^8 yr. The proposed orbit is *inside the central region of Coma C* and approximately coincides with the "plateau" where the spectral index is constant.

Assuming that NGC 4869 has maintained this orbit long enough, we may check if it has had time to supply the relativistic electrons present in the radio halo. The total number of relativistic electrons present in NGC 4869 is $\sim 2 \times 10^{58}$. Provided that the radio activity remained constant during the lifetime of this radio galaxy, using the age of outermost radio emitting regions of NGC 4869 ($\sim 4 \times 10^7$ yr; Feretti et al. 1990), we can estimate that the rate of production of relativistic electrons is $\sim 5 \times 10^{50} e$ yr^{-1}. Assuming that all the electrons in Coma C come from NGC 4869, we need $\sim 3 \times 10^9$ yr to have the required number of relativistic electrons. In this time NGC 4869 should have traveled ~ 4 orbits around NGC 4874. These numbers may be higher of a factor of 2 according to the uncertainties in the electron numbers discussed in § 3.4. This picture is consistent with a low spatial diffusion coefficient, since electrons are "deposited" by NGC 4869 during its orbital motion.

These are very simple assumptions, however they show that if the tail radio galaxy NGC 4869 is in a stable orbit around NGC 4874, the origin of relativistic particles in Coma C may be explained. The time needed to produce the relativistic electrons necessary to fill Coma C is long but still less than the age of the universe.

According to Feretti et al. (1990), the radiation spectrum in the outermost tail region of NGC 4869 is consistent with an electron energy distribution with power-law index $\delta = 2.5$ and shows a considerable steepening at a frequency between 800 and 1450 MHz. Assuming a magnetic field of 4×10^{-6} G, as estimated with equipartition condition (Feretti et al. 1990), the break in the radiation spectrum corresponds to an electron high-energy cutoff of 6–8 $\times 10^{-3}$ ergs. When these electrons happen to be in the lower magnetic field of Coma C ($\sim 0.5 \times 10^{-6}$ G), they radiate at a much lower frequency and the radiation spectrum shows a break frequency cutoff shifted to a value between 100 and 250 MHz. The spectral index of 0.8 found in the central halo region between 0.3 and 1.4 GHz

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implies that these electrons must gain energy through significant reacceleration.

4.3. *Reacceleration of Relativistic Particles*

Schlickeiser et al. (1987) found that the in situ acceleration model gives the best fit to the integrated spectrum of Coma C. The spectral index distribution we obtained provides strong evidence that the particle reacceleration is very effective in the central halo region. We do not expect that it is efficient for electrons confined in the tail of NGC 4869 where the equipartition magnetic field is ~ 10 times higher than that of Coma C and therefore radiation losses are very strong.

The size of the central region of Coma C, which corresponds to the "plateau," where the spectral index is ~ 0.8, is comparable in size to the Coma cluster core radius, defined as the radius at which the projected surface density of galaxies falls to one-half of its central value. Using King models, Kent & Gunn (1982) derived a core radius of $8\rlap{.}'5$–$10'$. This similarity is naturally explained if the turbulent acceleration mechanism is related to the density of optical galaxies. Outside the central region, the galaxy density drops considerably, and the effect of the in situ reacceleration is lower. Assuming that the energy spectrum of radiating electrons has an index $\delta = 2.5$ (see § 4.2), the emission spectrum in the central region of Coma C, where $\alpha_{326\,\mathrm{MHz}}^{1380\,\mathrm{MHz}}$ is ~ 0.8, must have a break at a frequency $\gg 1.4$ GHz, i.e., likely around 3 GHz, for consistency with the total integrated spectrum (see § 3.2). In the peripheral halo region, where $\alpha_{326\,\mathrm{MHz}}^{1380\,\mathrm{MHz}}$ is ~ 1.8, the break frequency is shifted to a value around 300–500 MHz (estimated according to Pacholczyk 1977).

Under the simple assumption that the spectrum break frequency corresponds to electron energies for which the synchrotron losses are equal to the energy acquired through reacceleration (Kardashev 1962), we obtain that the break frequency ν_c is roughly proportional to P/H, where P is the energy gain rate and H is the magnetic field. According to Jaffe (1980), the power dissipated by a galaxy with a characteristic radius "a" moving through the cluster medium is $P_0 \sim \rho_{\mathrm{ICM}} v_g^3 a^2$, where ρ_{ICM} is the ICM density and v_g is the galaxy velocity. So we can write that $\nu_c \propto \rho_{\mathrm{ICM}} N_{\mathrm{gal}}/H$ where N_{gal} is the number of bright galaxies.

This is fully consistent with the values of ν_c at the center and at the periphery of Coma C, given that H is almost constant and the decrease of $N_{\mathrm{gal}} \rho_{\mathrm{ICM}}$ is about a factor of 10 (the bright galaxy surface density in an inner circle with radius $= 8'$ is 2.7 times higher than in an annular ring of $r_1 = 8'$ and $r_2 = 14'$ (Kent & Gunn 1982), while the ICM density, is a factor 3–4 higher in the inner ring with respect to the outer one [Hughes 1989]).

Jaffe (1980), investigating the role of galactic wakes in supplying turbulent energy, estimated the total heating in the core of the Coma cluster in $\sim 4 \times 10^{43}$ ergs s^{-1}. The origin of this energy is the *motion* of cluster galaxies through the cluster medium. This is much higher than the power irradiated by Coma C by synchrotron emission ($\sim 10^{41}$ ergs s^{-1}). The total amount of energy provided by the galaxies' motion in 3×10^9 yr (the time necessary to "accumulate" the relativistic electrons which are estimated to be in Coma C; see § 4.2), is $\sim 4 \times 10^{60}$ ergs. Therefore, an efficiency of $\sim 1\%$ is necessary to convert this energy into the total minimum energy of Coma C ($\sim 0.5 \times 10^{59}$ ergs). A lower efficiency would result if we consider that the galaxy motion is not the only mechanism which can provide turbulent energy. The merging of subgroups in the Coma cluster has been proved by X-ray observations (Briel et al. 1992) and this interaction may produce shocks which can provide additional turbulent energy. This point will be discussed in more detail in a future work using also new data which will be soon available on the halo sources in A2255, A2256, and A2319.

4.4. *Frequency of Halo Sources*

From the previous discussion it follows that while the presence of a large-scale magnetic field and the conditions for the in situ acceleration are likely to be common in clusters of galaxies, the presence of a large enough number of relativistic electrons in a large volume is rare: one or more radio tail galaxies have to be present for long enough in the cluster center region to produce the relativistic electrons which are required to produce a visible halo source. The required time scale is related to the production rate of relativistic particles necessary to feed the halo source. To test this hypothesis we have, as a first step, verified if clusters with a halo source satisfy this requirement: a halo source is certainly present in the following clusters (see § 1): A1367, A2255, A2256, and A2319 (of course, we do not mention A1656 discussed in previous sections).

1. A1367 is neither luminous nor large and does not resemble the Coma halo (Hanisch 1982b). However, a diffuse emission is certainly present and in this region three peculiar irregular galaxies with extended trails of radio emission are present (Gavazzi & Jaffe 1987).
2. A2255 contains two tailed radio galaxies in the halo source region.
3. A2256 is unusual in that it contains a large number of head-tail radio galaxies (Bridle et al. 1979), many of them connected with the halo source.
4. A2319 contains at least two tailed galaxies embedded in the diffuse radio source (Harris & Miley 1978 and F. Owen, private communication).

Unfortunately there is at present no indication that these tailed galaxies follow an orbit located at the cluster center rather than being a chance projection or crossing the halo source region; better radio data may give in the future more information.

As a second step we searched in the literature for clusters with a tail radio source in the central region to see if they also have a halo source. We used the sample of 51 narrow-angle-tail (NAT) radio sources presented by O'Dea & Owen (1985) belonging to 36 clusters. As stated by the authors, the sample is not complete, but it is the largest collection of homogeneous data on galaxy clusters and covers the center of most Abell clusters. In Figure 5 we plot the number of tailed galaxies as a function of the distance from the cluster center in units of the cluster Abell radius (R_{A}). Only 15 clusters have one or more tailed sources in the inner region ($< 0.1 R_{\mathrm{A}}$). Three of them show a halo source: A1656, A2255, and A2256 (A1367 is not included since the tailed radio sources are Irr. galaxies while A2319 does not belong to the sample). The other 12 clusters are A84, A85, A119, A629, A1132, A1190, A1609, A1775, A2220, A2250, A2289, and A2572. None of them is presently known to show a halo source, but seven of them have never been observed with adequate sensitivity to low brightness extended structure. It is important to stress, however that even if all the tailed radio galaxies in these clusters are actually at the center and not simply projected onto it, the probability of detecting a radio halo in these clusters is low due to the fact that tailed radio galaxies need to be orbiting near the cluster center to fuel

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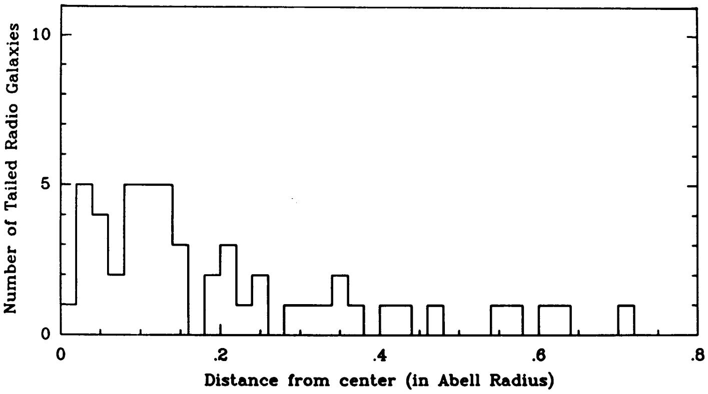

FIG. 5.—Distribution of tail radio galaxies from O'Dea & Owen (1985) vs. their distance from the cluster center in Abell radii.

a diffuse source. A statistical study of the distribution of galaxy orbits in Abell clusters (O'Dea, Sarazin, & Owen 1987) using NAT galaxies, shows that radial orbits are predominant near the cluster centers. Therefore statistically a few head-tail galaxies are expected to be present at a cluster center for a time *which is long enough to produce the number of relativistic particles necessary to fuel a radio halo.* The limited number of halo sources is therefore related to the difficulty of the electrons to diffuse from active galaxies and to the low number of head-tail galaxies orbiting around the cluster centers.

5. CONCLUSIONS

We have presented the first high-resolution spectral index map of the halo source Coma C. In addition the highest resolution image of Coma C is shown by new WSRT data at 608.5 MHz. These data show that: (1) no substructure is evident inside Coma C at a resolution of $35'' \times 63''$; (2) the spectral index is characterized by two different regions: a central one where the spectral index is constant with a value of $\sim$0.8, and a surrounding one where a strong steepening is evident, reaching values of the spectral index higher than 1.8.

The present data are consistent with the existence of a large-scale magnetic field and in situ reacceleration of relativistic particles. The reacceleration mechanism is more effective in the cluster core region where the spectral index is low (0.8) and weaker in the external regions where a strong spectrum steepening is evident. The natural explanation of these two phenomena is that the energy source originates in the turbulence caused by the motion of cluster galaxies, and therefore that it is related to the density of optical galaxies. Assuming the Jaffe (1980) model, an efficiency of $\sim$1% or less is required to convert the turbulent energy in the radiation energy of Coma C.

However, the conditions which lead to the electron reacceleration in Coma, are likely to exist in most clusters. Therefore, to explain the rarity of cluster halo sources we have investigated the possible origin of relativistic particles.

The large number of relativistic electrons necessary to fill the halo source cannot be produced by simple diffusion from active radio galaxies or efficient acceleration of electrons from the "thermal pool" because these processes are likely to be common in all clusters. We suggest that relativistic particles are deposited within the ICM volume by the *orbital motion* of the radio galaxy NGC 4869 around the cluster center. One or more tailed radio galaxies orbiting at the cluster center, appear sufficient to assure a constant supply rate of relativistic electrons on time scales long enough ($\sim 10^9$ yr) to allow the formation of a halo source. Thus we believe that the small number of radio halo clusters is related to the small number of rich clusters which have an active galaxy orbiting around the cluster center.

More detailed maps of known halo sources and of the few clusters with one or more head-tail galaxy present (or projected) into the cluster center are necessary to confirm this hypothesis.

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