

# The large-scale structure of the diffuse radio halo of the Coma cluster at 1.4 GHz

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**Abstract.** We present new measurements of the diffuse radio emission from the Coma cluster of galaxies at 1.4 GHz using the Effelsberg 100-m-telescope. Even at that high frequency, the halo source Coma C has an extent down to noise of  $\sim 80'$  corresponding to 3 Mpc ( $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) in Coma. The radio map reveals clear similarities with images of the extended X-ray halo of the Coma cluster. However, the radio halo appears to be displaced from the X-ray halo by  $\sim 3 - 4$  arcmin. After subtracting the contributions from point sources we obtained an integrated diffuse flux density of  $S_{1.4\text{GHz}} = 640 \pm 35$  mJy from Coma C.

We derive relations between the various observationally determined spectral indices and the spectral index of the synchrotron emissivity, which allow one to achieve a rough estimate concerning the consistency of the presently available data at different frequencies and to place constraints on the emissivity index distribution. In the halo's core region, the inferred emissivity index between 0.3 GHz and 1.4 GHz appears to be in the range 0.4 - 0.75 implying that there must be some very effective mechanism for particle acceleration operating in the intracluster medium. We discuss implications of our measurements and of the spectral index information on current theories for radio halo formation. We stress the importance of having more measurements of Coma C at frequencies above 1.4 GHz, in order to be able to derive constraints on the physics of the formation process of the radio halo.

**Key words:** clusters: individual: Coma clusters – intergalactic medium – radio continuum: galaxies – acceleration of particles – diffusion

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## 1. Introduction

Diffuse cluster-wide radio emission not associated with individual galaxies defines a separate class of extragalactic ra-

dio sources: the diffuse radio halos of galaxy clusters. Radio halo sources are observed in the richest and most X-ray luminous clusters of galaxies. However, one of their most enigmatic properties appears to be their obvious rarity. At present, only a few clusters are definitely known to have an extended radio halo: e.g., A754 (Waldthausen 1980), A2255 (Harris et al. 1980), A2256 (Bridle & Fomalont 1976), A2319 (Harris & Miley 1978). The best studied example, however, is the Coma cluster (A1656) with its extended, diffuse halo source Coma C (e.g., Hanisch 1980; Hanisch & Erickson 1980; Waldthausen 1980; Cordey 1985; Schlickeiser et al. 1987; Henning 1989; Venturi et al. 1990; Kim et al. 1990; Giovannini et al. 1993).

At lower frequencies diffuse radio emission from Coma C has been observed up to an angular distance of  $\sim 35'$  from the cluster center [e.g., Henning (1989) at 30.9 MHz], which corresponds to a radius of 1.5 Mpc in Coma ( $z = 0.0235$ ; Sarazin et al. 1982). (We adopt  $H_0 = 50 \text{ km s}^{-1}$  for the Hubble constant throughout the paper; i.e.,  $1' \hat{=} 40$  kpc). This implies the existence of a cluster-wide presence of relativistic electrons as well as of a magnetic field.

Kim et al. (1990) published a detailed image of Coma C at 1.4 GHz using a synthesis aperture telescope (Dominion Radio Astrophysical Observatory, DRAO). Applying a Gaussian fit, they inferred a  $\text{FWHM}_{1.4\text{GHz}}$  of the radio halo of  $18.7 \times 13.7$  which is significantly smaller than the value of the FWHM obtained at lower frequencies, e.g., at 326 MHz (Venturi et al. 1990). From these observations Giovannini et al. (1993) concluded that the spectral index of the diffuse radio emission strongly steepens with increasing radius. The DRAO radio map of Kim et al. (1990) reveals a halo diameter down to noise level of  $< 25'$ . However, emission from larger structures could be attenuated due to the synthesis aperture technique. This has implications for the determination of the spectral index distribution (Giovannini et al. 1993) as well as of the integrated flux at 1.4 GHz. In order to obtain informations on the large scale characteristics of the halo at high frequencies, we observed Coma C at 1.4 GHz with the Effelsberg single-dish 100-m-telescope.

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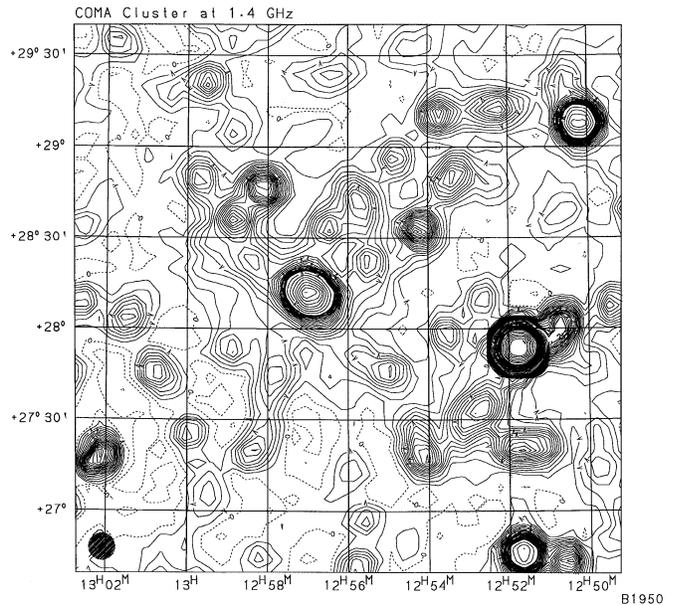
The exact shape of the diffuse radio emission spectrum of Coma C is yet unclear. Schlickeiser et al. (1987) claimed that the integrated flux density spectrum strongly steepens at high frequencies ( $\nu > 1$  GHz). We discuss the consistency of their measurements to our observations, and we discuss some implications of our new measurements on current models for radio halo formation which have been proposed in the literature (e.g. Hanisch 1982, Tribble 1993).

## 2. Radio continuum observations

We have made radio continuum observations at 1.4 GHz with the Effelsberg 100-m telescope in April 1993. At this frequency the telescope has an angular resolution (HPBW) of  $9'.35$ . A field of  $3^\circ \times 3^\circ$  centered on the Coma cluster has been mapped twice in orthogonal directions. We used a two channel receiver with cooled HEMT amplifiers. A bandwidth of 20 MHz was centered on 1.4 GHz. The data have been processed using standard procedures for continuum mapping observations with the Effelsberg 100-m telescope (e.g. Reich et al., 1990). The data from both channels have been averaged and the two coverages have been combined using the method described by Emerson and Gräve (1988). The final map is limited by confusion and has an rms-noise of about 7 mJy (or 14.4 mK Tb). We displayed our result in the form of a contour plot in Fig. 1. The map shows numerous compact radio sources, most of them associated with Coma cluster galaxies, superimposed on a weak large scale diffuse emission component.

In order to separate the diffuse extended emission from the contribution of individual sources, we have used the master list of radio sources from the Coma cluster as compiled by Kim (1994). The data for 298 sources are from various observations made with synthesis telescopes and therefore include sources as weak as a few mJy not directly accessible by us due to our larger beam width and resulting higher confusion limit. We have used the spectral fits by Kim et al. (1994) to calculate the flux density of all sources at 1.4 GHz and subtracted these contributions assuming a Gaussian source shape at the listed positions. We have in addition subtracted a few sources fitted by a Gaussian at the edge areas of our field which are outside the region where Kim (1994) has listed radio sources. The result of this procedure is shown in Fig. 2 where a weak diffuse radio component is left which is centered on the Coma cluster.

The east-west angular extent of the diffuse radio source is more than  $80'$ . The bridge-like extension of the diffuse radio emission to the south-west is related to the galaxy group associated with the bright galaxy NGC 4839. In order to obtain the integrated flux density of the diffuse radio emission at 1.4 GHz from Coma C, we integrated the diffuse flux (Fig. 2) over a circular area of radius  $40'$  centered at  $\alpha = 12^h 57^m 10.7$ ,  $\delta = 28^\circ 12' 16''$  (1950), but where we subtracted contributions from the region around NGC 4839 and from the narrow halo extension to the north. The latter might be related to the radio source 5C4.109.



**Fig. 1.** 1.4 GHz map of the Coma cluster from Effelsberg 100-m telescope observations. The rms noise is 7 mJy/beam. Contours are 10 mJy/beam apart (dashed contour: 0.0 mJy/beam). The HPBW ( $9'.35$ ) is indicated in the lower left-hand corner

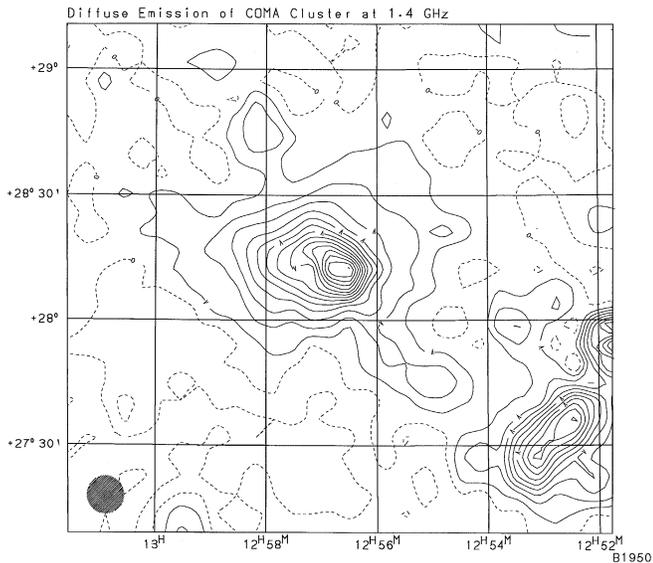
## 3. Results

### 3.1. Morphological structure of the radio halo

At 1.4 GHz, the diffuse radio halo Coma C reveals a butterfly-like shape with an angular extent down to noise of more than  $80'$  along the east-west direction and of about  $45'$  in north-south direction, corresponding to  $3.2 \text{ Mpc} \times 1.8 \text{ Mpc}$  respectively. The 1.4 GHz aperture synthesis map of Coma C recently obtained by Kim et al. (1990) shows an angular size of the radio halo down to noise of only  $22'$ , due to the low sensitivity to the very large scale radio emission.

An even more striking feature is the close resemblance of the spatial structure of the halo source at 1.4 GHz and the smooth, extended X-ray halo of Coma (Briel et al. 1992; White et al. 1993). The X-ray emission is thermal bremsstrahlung originating from the hot ( $T \sim 10^8$  K) intracluster gas (Sarazin 1988). Both the X-ray halo and the 1.4 GHz radio halo are elongated approximately east-west. Both the ROSAT PSPC X-ray image (White et al. 1993) and our 1.4 GHz halo map (Fig. 2) reveal a narrow extension towards the galaxy group associated with NGC 4839 south-west of the Coma cluster. Our radio map actually shows that this extended structure represents a narrow, low-brightness bridge of diffuse radio emission connecting the radio source Coma C with the peripheral extended complex of radio emission, Coma A. This bridge was also detected at 326 MHz by Venturi et al. (1990).

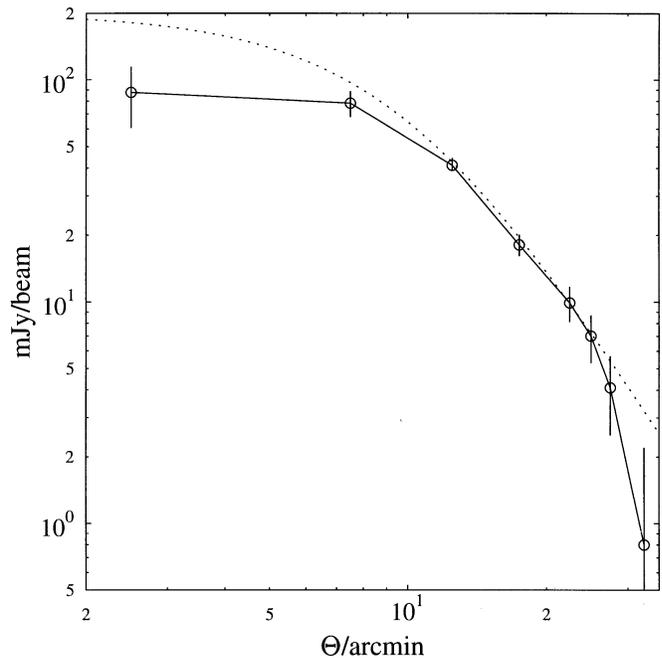
Fig. 3 shows the azimuthally averaged surface brightness distribution of the 1.4 GHz map of the halo centered at  $\alpha = 12^h 57^m 10.7$ ,  $\delta = 28^\circ 12' 16''$  (1950). For comparison, we plotted the model function (normalized to 200 mJy) given by Briel et al. (1992) which fits the azimuthally averaged surface bright-



**Fig. 2.** 1.4 GHz map of the Coma cluster as in Fig. 1 but with compact sources subtracted. Contours are 10 mJy/beam apart (dashed contour: 0.0 mJy/beam). The HPBW (9'35'') is indicated in the lower left-hand corner

ness distribution of the X-ray halo observed with ROSAT. As a model function, Briel et al. (1992) adopted a modified isothermal King profile (King 1966)  $I(\Theta)/I_0 = (1 + (\Theta/a)^2)^{-(3\beta-1/2)}$ , where  $\Theta$  denotes the projected radius,  $a$  is the core radius,  $\beta$  is the density slope parameter, and  $I_0$  is the central surface brightness. The radial profile of the X-ray surface brightness distribution is fitted best adopting a  $\beta = 0.75 \pm 0.03$  and a core radius  $a = 10'5 \pm 0'6$  (Briel et al. 1992). The galaxy distribution of the cluster is more centrally concentrated having a core radius of 6-8 arcmin (Sarazin 1988, and references therein). The FWHM of the X-ray halo is  $\text{FWHM}_{\text{X-ray}} = 14'6$ , while one infers a  $\text{FWHM}_{1.4\text{GHz}} = 15'2$  from the azimuthally averaged, deconvolved brightness distribution at 1.4 GHz. This shows that the scale size of the diffuse radio halo source at 1.4 GHz is similar to that of the X-ray halo. However, the radio emission declines more rapidly in the outer regions of the cluster.

As has already been noted by Kim et al. (1990), the positions of the two sources are significantly displaced. On the largest scale, we find the radio source to be about 3-4 arcmin west of the X-ray source. The location of the peak surface brightness in our map (Fig. 2) seems to be even more displaced. This must not be taken too seriously, considering i) the low angular resolution of the observation, and ii) the sensitivity of the result of the removal procedure concerning the proper positioning of the strong radio sources 5C4.85 and 5C4.81 in the center region of the cluster. Inspecting the 2.7 GHz map of the diffuse radio halo obtained by Schlickeiser et al. (1987), one finds that also at this high frequency the halo source reveals a positional offset of 2-3 arcmin to the west relative to the X-ray source. From the existence of the positional offset between radio halo and X-ray halo, Kim et al. (1990) concluded that the relativistic particles in the radio halo may not be directly responsible for the heating



**Fig. 3.** Azimuthally averaged surface brightness distribution of the diffuse radio halo of the Coma cluster at 1.4 GHz (dots). The measurement points are connected by straight solid lines, in order to have a better impression about the radial profile. Dashed curve: Best fitting King model of the radial profile of the X-ray halo (Briel et al. 1992)

of the X-ray emitting gas. Since, if the relativistic particles were the main heating source of the hot gas, the two sources should be precisely coextensive. Nevertheless, the close morphological correspondence between thermal X-ray bremsstrahlung and non-thermal synchrotron radiation suggests that the existence of the diffuse radio emission is based on the physical condition of the hot thermal gas.

### 3.2. Integrated diffuse flux from Coma C

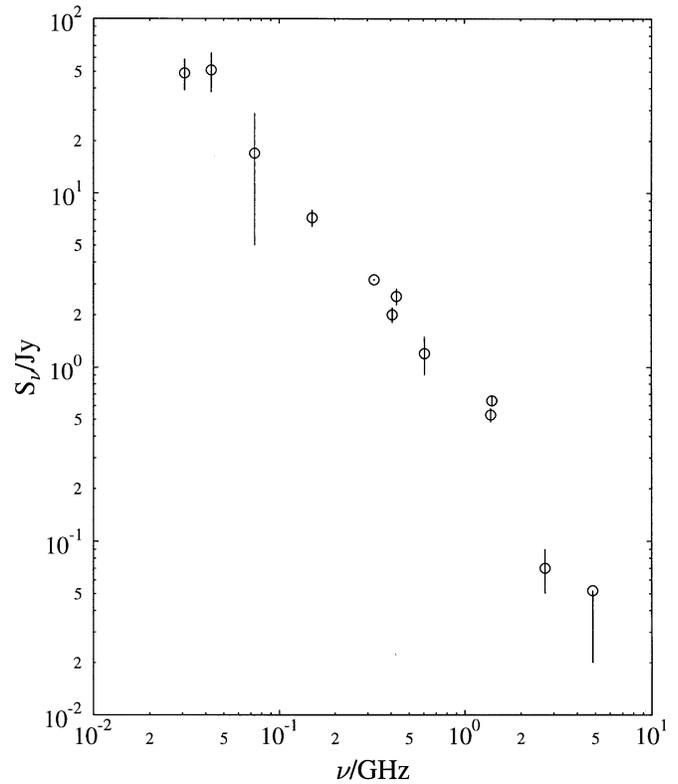
Performing the procedure described in Sect. 2 we obtained an integrated diffuse flux density from Coma C of  $S_{1.4\text{GHz}} = 640 \pm 35$  mJy. Kim et al. (1990) derived an integrated diffuse flux of  $530 \pm 50$  mJy at 1380 MHz using the DRAO Synthesis Telescope and the NRAO Very Large Array. Our single-dish observation, however, indicates that the radio halo at 1.4 GHz is much more extended than it is suggested by the DRAO image, which accounts for the increased integrated flux at that frequency. Fig. 4 shows the integrated diffuse flux from Coma C at various frequencies. The data set used (see Table 1) comprises our measurement together with data used by Schlickeiser et al. (1987) and by Giovannini et al. (1993). Our measurement seems to fit rather neatly a power law extrapolation from lower frequencies. The data points in the frequency range  $\leq 1.4$  GHz may be fitted by a power law with index  $\alpha = 1.16 \pm 0.03$ . If we take all data into account a power-law fit gives  $\alpha = 1.36 \pm 0.03$ .

**Table 1.** Integrated flux densities from Coma C. References: (1) Henning 1989; (2) Hanisch & Erickson 1980; (3) Cordey 1985; (4) Venturi et al. 1990; (5) Kim et al. 1990; (6) Hanisch 1980; (7) Giovannini et al. 1993; (8) present paper; (9) Schlickeiser et al. 1987; (10) Waldthausen et al. 1980

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
430	2.55	0.28	6
608.5	1.2	0.3	7
1380	0.53	0.05	5
1400	0.64	0.035	8
2700	0.070	0.020	9
4850	< 0.052	...	10

### 3.3. Scale-size-vs.-frequency relation

Our value for the FWHM of the halo at 1.4 GHz ( $15'.2$ ) is in agreement with the scale size obtained by Kim et. (1990) ( $18'.7 \times 13'.7$ ), who fitted the brightness distribution with a two-dimensional Gaussian. At 326 MHz, Venturi et al. (1990) inferred a  $\text{FWHM}_{326\text{MHz}} = 28' \times 20'$ . Henning (1989) derived the scale size of the radio halo at an even lower frequency (30.9 MHz). She found  $\text{FWHM}_{30.9\text{MHz}} = 31' \pm 5' \times 15' \pm 5'$ . In order to obtain a rough estimate of the halo's FWHM at 2.7 GHz, we azimuthally averaged the 2.7 GHz map given by Schlickeiser et al. (1987) and inferred a FWHM from that radial distribution. This yields a  $\text{FWHM}_{2.7\text{GHz}} \sim 12'.6 \pm 1'.3$  which may be regarded as an upper limit, since we did not deconvolve the original map. In any case, this is significantly smaller than the scale size of the halo at 1.4 GHz. Hence, there appear to be strong observational evidences that the scale size of the radio halo is a monotonically decreasing function of frequency. This supports the suggestion made by Giovannini et al. (1993) that in the external regions of the cluster the diffuse radio halo exhibits a steeper spectrum than in the core region. Comparing surface brightness measurements at 326 MHz and 1.4 GHz, performed with synthesis aperture telescopes, Giovannini et al. (1993) derived a spectral index distribution which shows an almost constant index of  $\sim 0.8$  within a cluster radius of  $\sim 8'$  and a strong increase of the index up to values higher than 1.8 outside this central "plateau". However, our single-dish observations indicate that at larger spatial scales there is much more diffuse radio power at 1.4 GHz than it is suggested by the synthesis aperture measurements. Thus, the increase of the spectral index may be weaker than claimed by Giovannini et al. (1993). A smaller spectral index implies a weaker net energy loss of the relativistic electrons in the peripheral region of the cluster.



**Fig. 4.** Integrated flux density spectrum of the diffuse radio halo Coma C. Data are from Table 1.

## 4. Discussion

### 4.1. Consistency of data and the spectral index distribution

The integrated diffuse flux measurements listed in Table 1 may be subjected to considerable systematic errors: for instance, an improper subtraction of contributions from point sources, a too small integration volume, or an erroneous intensity offset of the diffuse emission. Due to the very low number of data points, these (unknown) systematic errors may dominate any statistical analysis of a theoretical halo model. In that respect, it still seems to be an open question whether the strong steepening of the integrated-flux spectrum of Coma C above 1 GHz, claimed by Schlickeiser et al. (1987), is real. Our observations indicate that, at least up to 1.4 GHz, the integrated spectrum shows no tendency to steepen. If the 2.7 GHz value obtained by Schlickeiser et al. (1987) is real this implies a rather distinct cutoff of the spectrum between 1.4 GHz and 2.7 GHz. However, such a sharp spectral break can hardly be reproduced by any theoretical halo model, since, even in the case that the electron energy distribution tends to zero at some characteristic energy, the decline of the synchrotron emission spectrum is at most exponential. Hence, one may suspect that at frequencies  $> 1.4$  GHz the diffuse radio halo is much more luminous than it is suggested by the measurements by Schlickeiser et al. (1987) and Waldthausen (1980).

Using the combined data of the integrated flux densities, the surface brightness distributions and the scale-size-vs.-frequency

relation one may achieve, under some simplifying assumptions, a rough estimate concerning the consistency of the measurements at different frequencies. In addition, the considerations described in the following allow to place some constraints on the spectral index distribution of the synchrotron emission coefficient.

The FWHM at a given frequency is usually inferred from a Gaussian fit to the spatial profile of the surface brightness distribution. This appears to be reasonable, since the shape of the surface brightness distribution is more or less Gaussian. This implies that the spatial profile of the emission coefficient  $\epsilon_\nu(\mathbf{r})$  may be assumed to be Gaussian-shaped, too. Taking advantage of that allows one to derive a relation between the spectral index distribution of  $\epsilon_\nu$  and other spectral indices which can be determined by observations. For the sake of simplicity, we consider a spherically symmetric halo. At a given frequency, say  $\nu = m$ , the integrated diffuse radio flux density spectrum  $S_m$  and the surface brightness distribution  $I_m(b)$  at a projected radius  $b$  are given by

$$S_m = (\text{const}) \int_0^\infty r^2 \epsilon_m(r) dr \quad (1)$$

and

$$I_m(b) = (\text{const}) \int_0^\infty \epsilon_m(r^2 = z^2 + b^2) dz. \quad (2)$$

In Eqs. (1) and (2) we implicitly assumed a quasi-locally averaged, isotropic emission coefficient which depends only on the absolute value of the cluster radius  $r$ . This is a reasonable simplification, since the cluster magnetic field which generally introduces a directional dependence appears to be tangled on rather small scales. Feretti et al. (1995) give scale sizes for the magnetic field reversals of less than 1 kpc; this value is required to explain the dispersion of the rotation measure of the radio source NGC 4869.

For two different frequencies, say  $\nu_1 = m$  and  $\nu_2 = n$ , and on the assumption that the radial distributions of  $\epsilon_m(r)$  and  $\epsilon_n(r)$  may be reasonably well fitted by Gaussians, the following relations hold:

$$\frac{S_m}{S_n} = \frac{\epsilon_m(0)}{\epsilon_n(0)} \left( \frac{\text{FWHM}_m}{\text{FWHM}_n} \right)^3 \quad (3)$$

and

$$\frac{I_m(b)}{I_n(b)} = \frac{\epsilon_m(r)}{\epsilon_n(r)} \Big|_{r=b} \frac{\text{FWHM}_n}{\text{FWHM}_m}. \quad (4)$$

As it is usually done, we characterize the ratios  $S_m/S_n$ ,  $I_m(b)/I_n(b)$  and  $\epsilon_m(r)/\epsilon_n(r)$  by spectral indices  $\alpha_{S,mn}$ ,  $\alpha_{I,mn}(b)$  and  $\alpha_{\epsilon,mn}(r)$ , respectively. In addition, we define a corresponding index  $q_{mn}$  for the size-vs.-frequency relation through the ratios

$$\frac{\text{FWHM}_m}{\text{FWHM}_n} = \left( \frac{m}{n} \right)^{-q_{mn}}. \quad (5)$$

Employing Eqs. (3) and (4) we can now relate the spectral index  $\alpha_{\epsilon,mn}(r)$  of the emission coefficient to the observationally given indices  $\alpha_{S,mn}$ ,  $\alpha_{I,mn}(b)$  and  $q_{mn}$ . We obtain

$$\alpha_{\epsilon,mn}(0) = \alpha_{S,mn} - 3q_{mn}, \quad (6)$$

$$\alpha_{\epsilon,mn}(r)|_{(r=b)} = \alpha_{I,mn}(b) - q_{mn}. \quad (7)$$

In the latter equation, the notation  $(r = b)$  means that the value of the cluster radius  $r$ , at which we would like to know the index  $\alpha_{\epsilon,mn}(r)$ , is set equal to the value of the projected radius  $b$  at which the index  $\alpha_{I,mn}(b)$  is measured.

Equations (6) and (7) imply the relation

$$\alpha_{S,mn} = \alpha_{I,mn}(0) + 2q_{mn} \quad (8)$$

which provides a check on the consistency of the observational data. It relates to each other the measurements of the integrated flux, of the central surface brightness, and of the scale size of the halo at two different frequencies. Of course, considering the employed simplifications such a relation will never be exactly fulfilled. Nevertheless, it can give a hint to whether there are considerable systematic errors, e.g., in the measurement of the integrated flux densities, as discussed above.

Since we assumed that the surface brightness distributions have Gaussian-shaped profiles, the theoretical spectral-index distribution  $\alpha_{I,mn}(b)$  is necessarily a quadratic function given by

$$\alpha_{I,mn}(b) = \alpha_{I,mn}(0) + \frac{b^2}{r_{mn}^2}, \quad (9a)$$

where  $r_{mn}$  is defined through

$$r_{mn} = (4 \ln 2)^{-1/2} \text{FWHM}_m \left[ \ln \frac{n}{m} \right]^{1/2} \left[ \left( \frac{\text{FWHM}_m}{\text{FWHM}_n} \right)^2 - 1 \right]^{-1/2} \quad (9b)$$

At the characteristic radius  $r_{mn}$  the spectral index is greater than at the cluster center by one. The comparison of the theoretical profile (9) and the observed spectral-index distribution may serve as an additional check on the consistency of the data; and it gives a hint on the degree of reliability of the Gaussian fits.

As a first example, we consider the observations at  $m = 326$  MHz (Venturi et al. 1990) and  $n = 1.38$  GHz (Kim et al. 1990) (see Table 1 and Sect. 3.3). Inserting  $\text{FWHM}_{326\text{MHz}} \simeq 24'$  and  $\text{FWHM}_{1.38\text{GHz}} \simeq 16'$  in definition (5) we obtain  $q_{mn} = 0.28$ . The spectral index of the integrated flux is  $\alpha_{S,mn} = 1.23$ . Then, for reasons of consistency, the central value of the spectral index of the surface brightness  $\alpha_{I,mn}(0)$  should be 0.67 according to relation (8). This value is slightly smaller but still in good agreement with the value measured by Giovannini et al. (1993) (0.6 - 0.8; their Fig. 4). Hence, according to (7), the spectral index of the emission coefficient at the cluster's center is  $\alpha_{\epsilon,mn}(0) \approx 0.4 - 0.5$ . From Eq. (9b) we infer a characteristic radius of the spectral-index distribution of  $r_{mn} = 15.6$ ; i.e., the spectral index (9a) increases from its central value of 0.67

to a value of 0.93 at a projected radius of  $b = 8'$  (the central "plateau" according to Giovannini et al. 1993), and it reaches 1.8 at  $b = 16.6'$ . This shows that the theoretical spectral-index distribution fits the main features of the observed one; hence, the assumption of Gaussian surface brightness profiles does not introduce artificial inconsistencies. Thus, within the frame of our simplifying assumptions, the observational data at 326 MHz and 1.38 GHz appear to be consistent.

As a second example, we consider the Effelsberg observations at  $m = 1.4$  GHz (present work) and  $n = 2.7$  GHz (Schlickeiser et al. 1987). From the measurements of the integrated flux densities one infers a value for the spectral index of  $\alpha_{S,mn} = 3.37$ . Taking  $\text{FWHM}_{1.4\text{GHz}} = 15.2$  and  $\text{FWHM}_{2.7\text{GHz}} \simeq 12'$ , we obtain  $r_{mn} = 9.5$  and  $q_{mn} = 0.36$ ; the latter implies that, according to (8), the spectral index of the surface brightness at  $b = 0$  should have a value of  $\alpha_{I,mn}(0) = 2.65$ . The peak surface brightness of the 2.7 GHz map is  $\sim 11$  mJy/beam (beamwidth 4.3). The peak surface brightness of our 1.4 GHz map (Fig. 2) is  $\sim 130$  mJy, where the beamwidth is 9.35; this would reduce roughly by a factor of  $(4.3/9.35)^2 = 0.21$  if one used a 4.3 beam. Hence, one derives a value of the surface-brightness index of  $\alpha_{I,mn}(0) \sim 1.40$  which is considerably smaller than that expected from relation (8). Our 1.4 GHz observations appear to be in accord with the measurements made by Kim et al. (1990), as has been discussed above. Hence, the disagreement between the indices strongly indicates that the 2.7 GHz data are inconsistent, in the sense that the value of the integrated diffuse flux given by Schlickeiser et al. (1987) is, most probably, too low. Since the observed surface brightness at 2.7 GHz declines rapidly in the peripheral region of the halo, an extension of the integration area, which might have been too small, would lead to an increase of the total flux of only a few percent. Another source of error, to which the integrated-flux measurement at 2.7 GHz is very sensitive due to the low surface brightness, is the determination of the correct intensity offset of the diffuse emission. For instance, one would yield an additional integrated diffuse flux of  $\sim 50$  mJy if one lowered the intensity offset by only 1 mJy/beam; however, the resulting spectral indices were still inconsistent in that case. The data would be roughly consistent, if the surface brightness at 2.7 GHz were about 2.5 mJy/beam higher than the values given in the 2.7 GHz map; the integrated diffuse flux density would then presumably amount to  $S_{2.7\text{GHz}} \sim 200$  mJy and the values of the spectral indices would be  $\alpha_{S,mn} \approx 1.8$  and  $\alpha_{I,mn}(0) \approx 1.1$ , while the FWHM would increase only slightly. In that case,  $\alpha_{\epsilon,mn}(0)$  were about 0.75 at the cluster's center.

Since the scale size of the halo appears to be a decreasing function of frequency, one expects, for reasons of consistency, an increase of the spectral index of the integrated diffuse flux density. However, the extremely sharp spectral break above 1.4 GHz, suggested by the presently available integrated-flux data, seems to be unrealistic. Nevertheless, above 1.4 GHz the spectral index of the emission coefficient seems to increase even in the core region of the cluster.

#### 4.2. Implications on theories of halo formation

In this section, we discuss some implications on theories of radio halo formation following from the considerations of the previous section and from the observed large extent of the radio halo at 1.4 GHz and its clear similarity with the X-ray halo.

The dominant energy loss processes of the relativistic electrons in the intracluster medium are synchrotron emission and inverse Compton scattering off the cosmic microwave background radiation (CMB).

The "lifetime" of an (isotropic) ensemble of relativistic electrons radiating at 1.4 GHz is given by (Pacholczyk 1970)

$$\tau_{\text{loss}} = 1.3 \cdot 10^8 \left( \frac{B}{\mu\text{G}} \right)^{1/2} \left( 1 + \frac{2}{3} \frac{B^2}{B_{\text{CMB}}^2} \right)^{-1} \text{ yr}, \quad (10)$$

where the "monochromatic approximation" is used, and where  $B_{\text{CMB}} = 3.18(1+z)^2 \mu\text{G}$  denotes the magnitude of the magnetic field equivalent to the CMB. The magnetic field strength in the intracluster medium of the Coma cluster is still a matter of debate. Kim et al. (1990) derived a magnetic field strength of  $B = 1.7 \pm 0.9 \mu\text{G}$  using excess Faraday rotation measure (RM) of polarized emission from background radio sources. Recently, however, Feretti et al. (1995) inferred a much stronger magnetic field of  $\sim 6 \pm 1 h_{50}^{1/2} \mu\text{G}$  from polarization data of the radio galaxy NGC 4869 located in the central region of the cluster. Hence, the electrons' lifetime seems to be at most  $10^8$  years.

This short lifetime and the observed large extent of the 1.4-GHz halo augment the well-known diffusion speed problem of the primary-electron model suggested by Jaffe (1977) and Rephaeli (1979): In order to reach the edge of the halo, "primary electrons" which are presumed to be ejected from central radio galaxies must propagate at a speed of at least  $v_{\text{prop}} = 1.5 \cdot 10^4 (R/1.5 \text{ Mpc}) \text{ km/s}$ . This is an order of magnitude larger than the ion sound speed  $c_{\text{ion}}$  which is on the order of 1500 km/s, and at which speed relativistic particles are expected to propagate through the hot intracluster medium (Holman et al. 1979). Hence, it seems to be more plausible that the electrons have been accelerated or, at least, reaccelerated in situ.

From the discussion of the previous section we find that, in the core region of the Coma cluster, the spectral index of the synchrotron emission coefficient between 326 MHz and 1.38 GHz is  $\alpha_{\epsilon,mn}(r \leq 9') \approx 0.4 - 0.75$  which implies an energy spectrum index of the electrons of  $x \approx 1.6 - 2.5$ . Considering only the integrated spectrum, Coma C is usually classified as a steep-spectrum radio source, i.e.  $\alpha > 0.75$  and hence  $x > 2.5$ ; obviously, this does not apply to the halo's core region. This indicates that there must be some very effective mechanism for particle acceleration operating in the ICM in the core region of the cluster: one would expect a power-law energy distribution with  $x = 2.5$  if the electrons were purely originating in a rapid leakage from radio galaxies (see, e.g., Feretti et al. 1990 for the radio tail galaxy NGC 4869); particle acceleration in strong shocks would produce a power law with  $x = 2$  (see e.g. Longair 1994 and references therein), while stochastic second order Fermi acceleration leads to an exponentially decreasing energy spectrum (Schlickeiser 1984) which, however, may be

rather flat (effective  $x < 2$ ) in the low-energy range below some characteristic energy.

Recently, De Young (1992) and Tribble (1993) suggested that radio halos are transient features associated with a major merger of two galaxy clusters creating turbulence and shocks in the ICM: even a small conversion efficiency should then easily accelerate high-energy particles. This model has the great advantage to offer a natural explanation for the rarity of the radio halo phenomenon: after a merger event the radio emission fades on time scales of order  $\sim 10^8$  yr due to the energy loss of the relativistic electrons, while the time between mergers is roughly  $2 - 4 \times 10^9$  yr (Edge et al. 1992). The model seems to be supported by radio observations (Bridle & Fomalont 1976) and X-ray observations (Briel et al. 1991) of the merging cluster A2256 which shows that the large diffuse radio halo is just covering the merger region of the cluster (Böhringer et al. 1992; Böhringer 1995). Regarding the Coma cluster, substructures in the X-ray map as well as in the phase space distribution of the cluster galaxies have been interpreted by White et al. (1993) and Colless & Dunn (1996) as observational evidences for an ongoing merger between the main cluster and a galaxy group dominated by NGC 4889 in the cluster's center. Such an ongoing merger may account for the rather small spectral index  $\alpha_{\epsilon, mn}$  in the center of the radio halo by just enhancing the (preexisting) turbulent velocity field in the intracluster medium (Deiss & Just 1996), leading to an amplification of the stochastic acceleration process (see below). However, it is yet unclear whether the entire extended radio halo is caused by a single major merger as suggested by Young and Tribble and whether the cluster's substructures observed by White et al. and Colless & Dunn are the remaining indications of such an event. In contrast to what is observed in the Coma cluster, one would expect that aging diffuse radio halos produced in a single burst had rather irregular and asymmetric shapes. The relaxation time scale for a merged system of galaxies is of the order of the galaxies' crossing time which is  $\sim 10^9$  years. If a major merger had happened only a few  $10^8$  years ago, which would be necessary considering the rather short fading time of the halo, one would expect a much more pronounced double-peaked phase space distribution of the galaxies of the main cluster than it is observed by Colless & Dunn (1996). Hence, even if Coma C is a transient phenomenon it can hardly be explained by a recent major merger of two galaxy clusters. An additional problem is, how, in a single merger event, electrons could be accelerated to relativistic energies out of the thermal pool throughout the whole cluster volume. According to standard particle-acceleration theory (e.g. Longair 1994), a preexisting ensemble of relativistic particles is required, in order to effectively accelerate electrons to higher energies by shock waves. That, in turn, suggests the requirement of the existence of some continuously operating reacceleration mechanism as discussed in the following.

An alternative to the cluster merger model is the "in-situ acceleration model" proposed by Jaffe (1977). In this model, the relativistic electrons are assumed to be continuously reaccelerated by some mechanism operating in the (turbulent) intracluster medium. An advantage of this model is that it provides a natural

explanation for the similarities between diffuse radio halo and X-ray halo of the Coma cluster, since one may expect a close link between the physical conditions of the relativistic particles and that of the thermal component of the intracluster medium. If the relativistic electrons, released from some central source, are continuously reaccelerated a propagation speed of  $\sim 150$  km/s is sufficient to reach the peripheral regions of the radio halo within a Hubble time. Giovannini et al. (1993) suggested that the origin of the relativistic electrons of Coma C may be the large head-tail radio galaxy NGC 4869, orbiting at the Coma cluster center.

Deiss & Just (1996) showed that, due to the gravitational drag of the randomly moving galaxies, one may expect turbulent motions  $V_{\text{turb}}$  of the intracluster medium of up to 600 km/s in the core region of the Coma cluster. This suggests that the relativistic electrons are continuously reaccelerated by a stochastic second-order Fermi process. According to the usual stochastic Fermi acceleration theory, the acceleration time scale  $\tau_{\text{acc}}$  is given by  $\tau_{\text{acc}} = 9\kappa / \langle V^2 \rangle$  (e.g. Drury 1983), where  $\kappa$  and  $V$  denote the spatial diffusion coefficient and the rms speed of the scattering centers which are presumably small-scale magnetic-field irregularities. The diffusion coefficient is proportional to the scattering mean free path of the particles, its value is expected to be on the order of  $10^{27} - 10^{29}$  cm<sup>2</sup>/s. The propagation speed of the scatterers is basically the Alfvén speed  $V_{\text{Alf}}$  which is on the order of 100 km/s relative to the background medium. However, since the magnetic field is presumably 'frozen' in the turbulent ICM, the scatterers' squared velocity amounts to  $V^2 \approx V_{\text{turb}}^2 + V_{\text{Alf}}^2$ . The correlation length  $L_{\text{corr}}$  of the excited stochastic velocity field is  $\sim 20$  kpc (Deiss & Just 1996) which is considerably larger than the 'microscopic' scattering mean free path of the particles. That means, in calculating the stochastic acceleration time scale, the usual diffusion coefficient  $\kappa$  still applies. Hence, adopting  $\kappa = 10^{29}$  cm<sup>2</sup>/s one expects a stochastic acceleration time scale of  $\tau_{\text{acc}} \sim 10^7$  years at the center of the Coma cluster. On the other hand, the more 'macroscopic' turbulent motions generate a turbulent diffusion, hence increasing the particles' propagation speed above the Alfvén speed, at least in the cluster's center. The excited turbulent motions scale like  $V_{\text{turb}}^2 \propto n_{\text{gal}}$  (Deiss & Just 1996) where  $n_{\text{gal}}$  is the number density of the galaxies; hence, at a cluster radius of  $40'$  the reacceleration time scale  $\tau_{\text{acc}}$  is on the order of  $\sim 10^9$  years. This is still fast enough to sustain an ensemble of relativistic electrons, although with a steeper energy distribution than in the cluster's center. This is in accord with the observed scale-size-vs.-frequency relation and with the steepening of the spectral index distribution with increasing cluster radius (see above).

In a simple leaky box model, the steady state energy distribution of relativistic electrons, being stochastically accelerated and losing energy via synchrotron emission and inverse Compton scattering, may be well approximated by (Schlickeiser et al. 1987)

$$N(E) \propto E^{-\Gamma} \exp\left(-\frac{E}{E_c}\right), \quad (11)$$

where the spectral index of the power law part and the characteristic energy are given by

$$\Gamma = \frac{3}{2} \left( 1 + \frac{4\tau_{\text{acc}}}{9\tau_{\text{esc}}} \right)^{1/2} - \frac{1}{2} \quad (12)$$

and

$$E_c = 12.7 \text{ GeV} \left[ \left( 1 + \frac{2}{3} \frac{B^2}{B_{\text{CMB}}^2} \right) \frac{\tau_{\text{acc}}}{10^8 \text{ yr}} \right]^{-1}, \quad (13)$$

respectively. Since the escape time  $\tau_{\text{esc}}$  is on the order of the Hubble time, we have  $\Gamma \approx 1$ . If we set  $B = 6\mu\text{G}$  (Feretti et al. 1995) and  $\tau_{\text{acc}} = 10^7$  years in Eq. (13) we derive a value of the characteristic electron energy of  $E_c = 38$  GeV. The relativistic electrons in the cluster core, radiating at 326MHz and 1.4 GHz, have energies of only  $1.8 (B/6\mu\text{G})^{1/2}$  GeV and  $3.8 (B/6\mu\text{G})^{1/2}$  GeV respectively. This implies a value of the energy spectrum index of only  $x \approx 1.1$  in that energy range. In order to match the observationally determined value of  $x$  of  $\sim 1.6$ , the efficiency for stochastic reacceleration may still be even an order of magnitude smaller than inferred above. Hence, stochastic reacceleration of the electrons amplified by turbulent gas motion, originating from galaxy motion inside the cluster, appears to be sufficiently strong to account for the rather small radio emission index in the core region of Coma C and to sustain the cluster-wide distribution of the relativistic particles in that rich cluster.

In order to explain the rarity of the radio halo phenomenon, Giovannini et al. suggested that, while the conditions for the in-situ acceleration and the presence of a cluster-wide magnetic field (e.g. Kronberg 1994, and references therein) are likely to be common in rich clusters, one or more radio tail galaxies have to be present to produce the required number of relativistic electrons. However, there may be another constraint, namely that of a high enough efficiency of the reacceleration mechanism which may depend on some details in a cluster's structure; diffuse radio halos of otherwise globally similar clusters would then have a rather dissimilar appearance. For instance, for the core region of the Perseus cluster, Deiss & Just (1996) inferred a turbulent velocity of the ICM of  $\sim 200$  km/s, i.e., three times smaller than in Coma, which implies a ten times longer acceleration time than in the Coma cluster; if, in addition, the magnetic field is  $\sim 20\mu\text{G}$  like in other cooling flow clusters, i.e. about three times stronger than in Coma, the inferred characteristic energy  $E_c$  of the electron distribution in the core region of the Perseus cluster is two orders of magnitudes smaller than in the Coma cluster. Obviously, such an electron distribution is not able to produce an extended radio halo at the GHz-range, although it may account for the observed 'minihalo' at 330 Mhz (Burns et al. 1992). This suggests that, while a cluster-wide distribution of relativistic electrons is likely to be common, in only a few clusters the conditions are such that the electrons gain enough energy to produce an extended halo observable at some hundred Megahertz. We suspect that there are far more galaxy clusters having a diffuse radio halo than have been observed so far;

though these halos would be observable only at rather low frequencies (well below 100 MHz), at which a systematic survey has yet to be done. In that picture of radio halo formation, the role of a merger is that of an amplifier of the preexisting overall stochastic reacceleration mechanism, and not that of the prime cause of the halo formation.

The origin of the intracluster magnetic field still remains unclear. Of course, it appears to be an attractive idea that galaxy motion may also drive a turbulent dynamo by which faint seed fields could be amplified to (chaotic) microgauss fields. This suggestion has been explored by Jaffe (1980), Roland (1981), and Ruzmaikin et al. (1989). More recently, however, De Young (1992) has shown that it is in general very difficult for this mechanism to produce microgauss fields on 10 kpc scales: In order to drive a turbulent dynamo on such scales, more energetic processes, like subcluster merging, must be invoked. Hence, it appears that, while reaccelerating relativistic electrons via galaxy motion may work, creating the intracluster magnetic field via galaxy motion probably does not.

## 5. Summary and conclusions

We presented new measurements of the diffuse radio emission from the Coma cluster at 1.4 GHz using the Effelsberg single-dish telescope. After subtracting contributions from 298 point sources we obtained a radio map exhibiting the large scale characteristics of the diffuse radio halo source Coma C. From the large angular extent down to noise of  $\sim 80'$ , one concludes that the radio halo in Coma is a cluster-wide phenomenon which is not restricted to only the cluster core region. This implies the presence of relativistic electrons as well as of a magnetic field throughout a spatial volume with a diameter of  $\sim 3$  Mpc.

The integrated diffuse flux from Coma C is  $640 \pm 35$  mJy at 1.4 GHz. This value fits neatly a power-law extrapolation from lower frequencies, showing that a possible steepening of the integrated spectrum may appear only above 1.4 GHz.

We derived, under some simplifying assumptions, mutual relations between the observationally determined spectral indices of the integrated diffuse flux density, the surface brightness and the halo's scale size, and the spectral index of the synchrotron emission coefficient. These relations allow one i) to achieve a rough estimate concerning the consistency of the presently available data at different frequencies and ii) to place constraints on the emissivity index distribution: i) We conclude that the 2.7 GHz measurements by Schlickeiser et al. (1987) are not consistent to our measurements. We suspect that the value of the integrated flux given by these authors is much too low, which implies that the claimed strong steepening of the spectrum above 1.4 GHz is not real. This has implications on current theories of radio halo formation. Hence, in order to be able to derive constraints on the physics of the formation process of the Coma radio halo, one needs more and improved measurements at frequencies above 1.4 GHz. ii) In the core region of the halo, the emissivity index between 0.3 GHz and 1.4 GHz appears to be in the range 0.4 - 0.75 which implies an energy spectrum index of the electrons of  $x \approx 1.6 - 2.5$ . From that we conclude

that there must be some very effective mechanism for particle acceleration operating in the intracluster medium.

We argued that the observed large extent of Coma C, its regular shape as well as its clear similarity with the X-ray halo support an in-situ acceleration model for radio halo formation, since one may expect a close link between the physical conditions of the relativistic particles and that of the thermal component of the intracluster medium. We showed that in the Coma cluster stochastic reacceleration of the electrons, amplified by turbulent gas motion originating from galaxy motion inside the cluster (Deiss & Just 1996), appears to be sufficiently strong to account for the inferred rather small radio emission index in the core region of Coma C and to sustain a cluster-wide distribution of relativistic particles in that rich cluster.

We suggested that the rarity of the radio halo phenomenon has its origin in that the efficiency of the stochastic reacceleration mechanism may depend on some details of the clusters' structure: diffuse radio halos of otherwise globally similar clusters may have a rather dissimilar appearance. That means, while a cluster-wide distribution of relativistic electrons is likely to be common in rich clusters, in only a few of them the conditions are such that the electrons gain enough energy to produce an extended halo observable at some hundred Megahertz. However, we suspect that at low frequencies (well below 100 MHz) diffuse radio halos of galaxy clusters are much more common than it is suggested by the presently available data.

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