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Is the surface brightness spectrum of the Coma Cluster radio halo inverted?

Brian Dennison[1,2,★]

[1] Onsala Space Observatory, Chalmers University of Technology, S-43900 Onsala, Sweden
[2] Department of Physics, Virginia Polytechnic Institute and State University, Blackburg, VA 24061, USA

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Summary. Comparison of published maps of the Coma Cluster radio halo at 430 and 1400 MHz (Hanisch, 1980) reveals that the spectrum of the surface brightness is inverted or flat over most of the extent of the 1400 MHz diffuse emission. This is very unusual for a highly extended source thought to emit via the synchrotron mechanism. Various explanations are considered, including a relatively flat electron-energy spectrum, free-free emission, emission by numerous compact sources, as well as instrumental effects. Constraints provided by searches for the Sunyaev-Zel'dovich effect tend to disqualify explanations (including free-free emission) in which the flat surface brightness spectrum continues to microwave frequencies. Verification of the high surface brightness at 1400 MHz is required.

Key words: clusters: of galaxies – galaxies: radio – radiation mechanisms: synchrotron radiation – radio sources: general

1. Introduction

Diffuse radio emission has been detected in various clusters of galaxies, with the Coma Cluster being the best documented case (Willson, 1970; Donivan et al., 1974; Jaffe et al., 1976; Hanisch et al., 1979; Hanisch, 1980). In Coma, the emission is highly extended (~ 1 Mpc), fairly symmetric about the approximate (optical) cluster center, and evidently occurs in the intracluster medium, and is not a superposition of individual radio galaxies. Cluster halos, such as the one in Coma, are of considerable interest because of questions concerning the origin and transport of the relativistic electrons responsible (Jaffe, 1977; Holman et al., 1979). Also, it has been suggested that the relativistic electrons can significantly heat the intracluster gas through collective interactions (Scott et al., 1980).

Clearly, the analysis of these problems requires observational data on the spatial extent and structure of the Coma halo, particularly at different frequencies, giving information on the distribution of electrons at varying energies. Until 1980, the observational data available (at frequencies below 1 GHz) indicated that the halo size depended only weakly upon frequency, if at all (Jaffe, 1977). However, Hanisch (1980) has extended the observations to 1400 MHz, and reports that the diffuse halo is much smaller at that frequency ($9' \times 14'$ to the noise level, versus $72' \times 63'$ to the noise level at 430 MHz). Remarkably, the integrated halo spectrum remains straight up to 1400 MHz. Although, Hanisch sensibly advises caution in comparing sizes derived from the noise level limit (which is frequency dependent), it is highly significant that the spectral index of the halo surface brightness, derived from comparing his maps at 430 and 1400 MHz, is inverted over much of the extent of the 1400 MHz emission. Such an observation appears to be a radical departure from the spectral properties normally attributed to highly extended synchrotron sources, on both theoretical grounds and observational experience.

In Sect. 2, I briefly describe Hanisch's observations, and compare the surface brightness at 430 and 1400 MHz. [For complete details of the observations, the reader is referred to Hanisch (1980)]. Some possible explanations for the inverted brightness spectrum are discussed in Sect. 3.

2. The spectral index of the diffuse surface brightness

The observations at 430 and 1400 MHz (Hanisch, 1980) were, of course, sensitive to both individual radio galaxies in the cluster, as well as diffuse halo emission. Hence, the maps were corrected (Hanisch, 1980) for the presence of unresolved sources through a subtraction procedure, in which interferometric fluxes of catalogued discrete sources (Willson, 1970) in the field were used. Comparison of these subtracted maps, given in Hanisch (1980), (which are a claimed representation of the diffuse emission only) results in a flat or inverted surface brightness spectral index over most of the region where a diffuse component is present at 1400 MHz. This conclusion is not significantly changed by first smoothing the 1400 MHz brightness distribution to the resolution used at 430 MHz (see Fig. 1). It is, of course, consistent with the published sizes and integrated fluxes given by Hanisch. Extrapolation of the 430 MHz surface brightness in proportion to $\sim \nu^{-1}$ (which seems to apply at frequencies below 600 MHz), would suggest a very faint halo at 1400 MHz, with peak surface brightness ~ 7 mJy/(1400 MHz beam area). As this is below the noise level (10 mJy/beam area) in the 1400 MHz map, it would appear that a canonical (steep-spectrum) halo would be undetectable at 1400 MHz in these observations. It may also be significant that just outside the diffuse 1400 MHz emission, the limits on the surface brightness spectral index are quite positive, typically

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[★] Current address: E.O. Hulburt Center for Space Research, Naval Research Laboratory, Code 4131 D, Washington, DC 20375-5000, USA

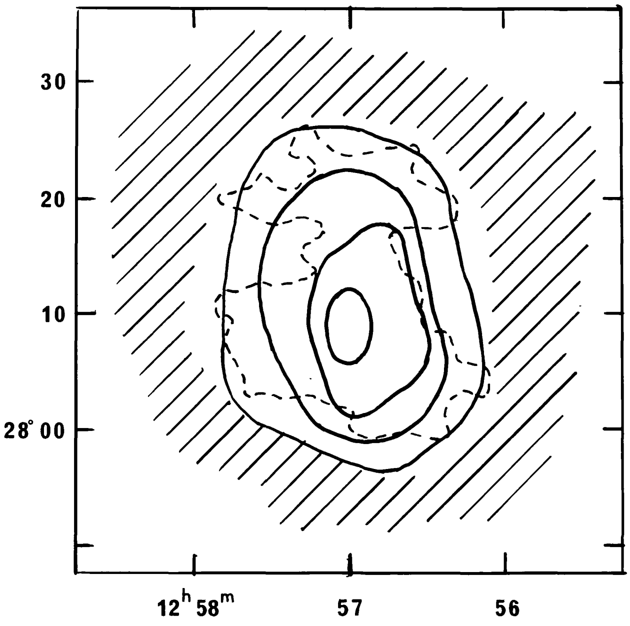

Fig. 1. Spectral index map of the inner coma cluster halo. The brightness distribution at 1400 MHz (Hanisch, 1980) has been first smoothed to correspond with the resolution at 430 MMHz (9′). Dashed lines indicate the extent of the halo at 1400 MHz prior to smoothing. After smoothing the brightest inner portion of the halo retains its apparent inverted spectrum ($\alpha < 0$). Cross hatching indicates region in which only lower limits to α can be established, due to an absence of measurable surface brightness at 1400 MHz (after smoothing). Over most of this region $\alpha > 1$. Contour levels (inward) are 1.0, 0.4, 0.0, -0.2

$\alpha \gtrsim 1.0$, (where surface brightness $\propto \nu^{-\alpha}$), and thus it would appear that the surface brightness of the "anomalous halo" at 1400 MHz cannot be extrapolated from the 430 MHz surface brightness using a single, spatially homogeneous value for α.

Additional constraints can be obtained from published searches (Rudnick, 1978; Lake and Partridge, 1980; Birkenshaw et al., 1981) for the Sunyaev-Zel'dovich effect in Coma, in which a reduction of about 0.6 mK in the temperature of the microwave background radiation was sought. Because these observers did not report strong microwave excesses, limits can be set to the surface brightness at high frequencies (see Sect. 3).

3. Some possible explanations

Possible explanations for the anomalous halo are either astronomical in nature, or involve instrumental effects or data reduction procedures. The astronomical explanations will be considered first, as they illustrate the remarkable nature of these results.

3.1. Astronomical explanations

3.1.1. Flat electron spectrum

If the emission is due to synchrotron radiation, and diffuse on scales $\sim 10^5$ pc, then the optical depth must be negligible for any reasonable value of the magnetic field. In the inner halo where $\alpha \gtrsim 0$, the electron energy spectrum must then the quite flat, i.e. $\Gamma \lesssim 1$, (where $N(E) \propto E^{-\Gamma}$). Such a situation might arise under unusual conditions of injection and/or particle diffusion. Wilson (1975) has produced general solutions to the diffusion equation in which electrons are injected near the source center with spectrum $Q(E) \propto E^{-\gamma}$, and diffuse with coefficient, $D \propto E^p$. A flat electron spectrum ($\Gamma \lesssim 1$) near the center, where radiative losses should be small, requires $\gamma + p = \Gamma \lesssim 1$. If the injection is like that typically found in extended extragalactic sources ($\gamma \simeq 2.5$), then $p \lesssim -1.5$. On the other hand, energy-independent diffusion would require a relatively flat injection spectrum ($\gamma \lesssim 1$).

Such models run into difficulty in accounting for other observed properties of the halo, however. If $p \lesssim -1.5$, then the halo size, R, would be expected to be significantly larger at progressively lower frequencies (with $R \propto \nu^{(p-1)/4} \sim \nu^{-5/8}$). However, the halo size depends only weakly upon frequency between 26 MHz and 610 MHz (Jaffe, 1977; Hanisch, 1980). The observed dependence is probably no stronger than $\nu^{-1/4}$. This low-frequency saturation of the size might be understood as due to diffusion of the electrons beyond the extent of the magnetic field (Hanisch, 1980), were it not for the remarkably straight spectrum down to 10 MHz. The spectrum should flatten considerably at frequencies at which escape is important. Indeed, the spectral index of the overall source in the low-frequency limit would be just that observed for the inner halo brightness (where radiative losses are also minor), or about zero. Clearly, this is not the case between 10 MHz and 610 MHz (see Jaffe, 1977).

The alternative in which the injection is flat ($\gamma \lesssim 1$), and the diffusion roughly energy-independent ($p \approx 0$), might explain the near frequency-independence of the size at low frequencies. Even the straight, steep spectrum may be compatible under certain conditions of spatial inhomogeneity in the magnetic field and/or D (Wilson, 1975); and provided that particle escape is not important (in comparison with radiative losses), even at the lowest frequencies at which the halo has been observed (10 MHz). This implies that at some very low frequency (below 10 MHz), at which particle escape dominates radiative losses, the spectrum must flatten to an index of about zero. The major difficulty is in explaining the very small size of the halo at 1400 MHz. Of course, this could be due to instrumental limitations in which the outer halo is fainter than the noise level. However, the implication then is that some considerable portion of the flux at 1400 MHz remains undetected (particularly if the complete halo is significantly larger than the measured size at 1400 MHz), and that the true integrated spectrum flattens above 1 GHz. We are led, therefore, to postulate that either $D(E)$ or $Q(E)$ varies drastically over an energy range corresponding to $\nu \simeq 600 \rightarrow 1400$ MHz.

Essentially, the abrupt change in observed halo size between 610 and 1400 MHz implies a correspondingly abrupt change in the energy-dependence of D or Q. A complete model in this context may be required to postulate such behaviour, as well as spatial inhomogeneities in the magnetic field and/or D. Extrapolation of the high-frequency brightness would probably be consistent with existing limits (Rudnick, 1978; Lake and Partridge, 1980; Birkenshaw et al., 1981), provided the inner cluster brightness is further diminished by radiative losses, as expected.

3.1.2. Free-free emission

The very hot ($T \sim 10^8$ K), X-ray emitting gas does not have sufficient emissivity to account for the anomalous halo. However, somewhat cooler ($T \sim 10^4 - 10^7$ K) ionized gas, if present in relatively moderate amounts, might be responsible. Not surprisingly, free-free emission has been sought extensively in clusters of galaxies, including Coma (Davidson et al., 1973; Rudnick, 1978). As Tarter (1978) has shown, searches for the Sunyaev-Zel'dovich effect in clusters also provide strong limits on the amount of free-free emission. The most stringent limits available for Coma appear to be those established by Rudnick (1978) at 15 GHz, Lake and Partridge (1980) at 31.5 GHz, and Birkenshaw et al. (1981) at 10.6 GHz.

To test the free-free emission possibility, it was assumed that the anomalous halo owes 80% of its surface brightness at 1400 MHz to this mechanism, the remaining 20% due to a canonical synchrotron halo. (This partition is based upon the expected surface brightness of a canonical synchrotron halo at 1400 MHz, extrapolated in Sect. 2.) The effective brightness temperatures expected in the observations referenced above were then estimated by rescaling the surface brightness to the appropriate frequencies, and using the published primary and reference beam positions. This estimation is quite uncertain, because the reference beam frequently traces out a trajectory through the anomalous halo.

From the comparisons, it appears that the free-free interpretation of the anomalous halo is marginally inconsistent with the existing high-frequency limits to the surface brightness. At the positions examined by Birkenshaw et al. (1981) the expected effective brightness temperatures are typically in the range 2–5 mK, whereas the measured values tend to be somewhat smaller, usually $\lesssim 2$ mK, although at one position they report 4.5 mK. Lake and Partridge (1980) reported no excess brightness near the cluster center and at offset positions. The center positions are not expected to yield significant signal, due to significant anomalous brightness at the reference beam positions. Their "offset" positions, however, should yield about 0.5–0.7 mK of signal, since the reference beams are well outside the anomalous halo. In this case they report $T_b^{\max} = 0.04 \pm 0.23$ mK. Finally, Rudnick (1978) using a combined beam-switching and scanning method, reported that a component of width 16′, centered on Coma, has $T_b^{\max} = 0.4 \pm 0.9$ mK. This is to be compared with a free-free emitting anomalous halo, which at this frequency would appear as a component of width 8′, offset to one side of the cluster center, with $T_b^{\max} \simeq 3.8$ mK. Thus, it appears that the microwave brightness implied by the free-free interpretation tends to be quite close to the available (3σ) upper limits. Increasing the fractional contribution of synchrotron emission to the 1400 MHz surface brightness (to 40%, for example) only reduces the expected microwave brightness by 20%, while requiring significant flattening in the synchrotron spectrum between 430 and 1400 MHz. Despite the difficulties of comparison, it seems that free-free emission of an amount sufficient to account for the anomalous halo at 1400 MHz, would probably have been detected at microwave frequencies.

3.1.3. Compact emitters

If most of the 1400 MHz flux (0.52 Jy) of the anomalous halo is produced in compact sources, these might have gone undetected in the 5C4 survey if sufficiently numerous ($N \gtrsim 10^2$), in which case their aggregate emission would not have been subtracted out, and would remain in Hanish's map as diffuse flux. Synchrotron self-absorption could account for the flat spectrum between 430 and 1400 MHz, although these sources would have to be optically thin at frequencies $\gtrsim$ 5–10 GHz, to avoid a microwave excess. Hanisch (1980) estimated the expected contribution due to weak radio-sources in Coma, by extrapolating the luminosity function to very low flux levels. This was found to be negligible in comparison with the observed flux. This leaves the seemingly unlikely possibility of an aggregation of weak compact sources associated with Coma, numerically in excess (by several orders of magnitude) of the quantity expected from extrapolation of the luminosity function.

3.1.4. Coincident foreground or background source

The microwave constraints discussed above (Sect. 3.1.2) and the high galactic latitude of Coma tend to argue against a foreground H II region being responsible. An unrelated extended synchrotron source along the line of sight is of course a possibility (albeit unlikely), in which case the inherent difficulties posed by the surface brightness spectrum remain (see Sect. 3.1.1). The good alignment of the maximum of the 1400 MHz emission with the emission at lower frequencies argues against this class of explanation.

3.2. *Instrumental explanations*

3.2.1 Undersubtraction of the discrete source flux

This might occur for example if the flux scale differed significantly from that in the 5C4 survey, but seems unlikely as the total discrete source flux in the region is 0.64 Jy (Willson, 1970), whereas the diffuse flux remaining in Hanisch's subtracted map is 0.52 Jy. Also, undersubtraction should result in a fairly lumpy appearance in the subtracted map, which is not observed.

3.2.2. Sidelobe contamination by discrete sources

The integrated sensitivity of the inner sidelobes, particularly the first grating ring, is probably significant in comparison with that in the main beam, and thus a major contribution to the distributed brightness due to sidelobe contamination is to be expected. However, the subtraction procedure employed by Hanisch (1980) included the sidelobe response as mapped by observing a nearby point source. This procedure should have eliminated both the main beam and sidelobe response to known unresolved sources in the field.

4. Conclusions

The existence of the anomalous halo emission at 1400 MHz in the Coma Cluster needs to be verified. If real, this phenomenon represents a radical departure from the usual properties of extended extragalactic sources. None of the possible explanations considered in Sect. 3 appear to be completely satisfactory. Hence, other possibilities may need to be considered as well. Any viable explanation is subject to the observational constraints discussed in Sect. 3. The microwave limits require at least slight steepening of the brightness spectrum in the inner halo between 1.4 and 10 GHz ($\alpha \gtrsim 1.0$), if the emission at 1.4 GHz is real.

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