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WHERE HAVE ALL THE CLUSTER HALOS GONE?

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ABSTRACT

A new low-frequency (330 MHz) VLA image of the Perseus cluster confirms the presence of a mini–radio halo with diameter ∼430 kpc ($H_0 = 75$ km s^{-1} Mpc^{-1}) surrounding 3C 84. A careful comparison with the Coma cluster shows that there is no evidence for a similar, very extended halo in Perseus despite the large number of cluster radio galaxies which could power such a halo. These two clusters represent two classes of radio halos which differ by the absence (Coma) or presence (Perseus) of cooling inflows. We argue that smaller halos as in Perseus result from insufficient cluster-wide magnetic fields. A simple model is presented which suggests that cooling flows can suppress the diffusion of turbulently amplified B-fields outward from the cluster core. Such a suppression leads to the development of minihalos which are confined to the cores of cooling flow clusters.

Subject headings: galaxies: clustering — intergalactic medium — magnetic fields — polarization — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

Large-scale radio halos remain one of the most enigmatic and poorly understood phenomena in clusters of galaxies. The Coma cluster ($z = 0.0232$) contains the prototype halo source (Hanisch 1980; Schlickeiser, Sievers, & Thiemann 1987; Kim et al. 1990) which has a diameter of >2 Mpc and a steep radio spectrum ($\alpha = 1.34$, where $S_\nu \propto \nu^{-\alpha}$). Hanisch (1982) notes that there are only 10 known examples of halos reported in the literature. He finds that halos tend to occur in clusters without cD galaxies but with high velocity dispersions and low spiral fractions.

In an effort to further investigate the cluster halo phenomenon, we have produced a new, deep VLA image of the Perseus cluster at 330 MHz. Perseus is ideally suited for such an observation because of its proximity ($z = 0.0179$) and the large number of radio galaxies in the cluster (Gisler & Miley 1979) which provide a pool of electrons for a potential halo. Furthermore, because of the steep spectra of cluster halos, the 330 MHz system using the VLA C and D configurations has an excellent combination of resolution (50″–170″) and sensitivity to image large scale cluster emission. The 90 cm VLA data were taken in the spectral line mode to allow removal of RFI and to eliminate the effects of bandwidth smearing. Standard mapping, cleaning, and self-calibration (see e.g., Perley, Schwab, & Bridle 1989) using AIPS were performed on the data bases. In addition, special software (Cornwell & Perley 1991) was used to correct the maps for aberrations caused by the "depth" (three-dimensional effect) of the array.

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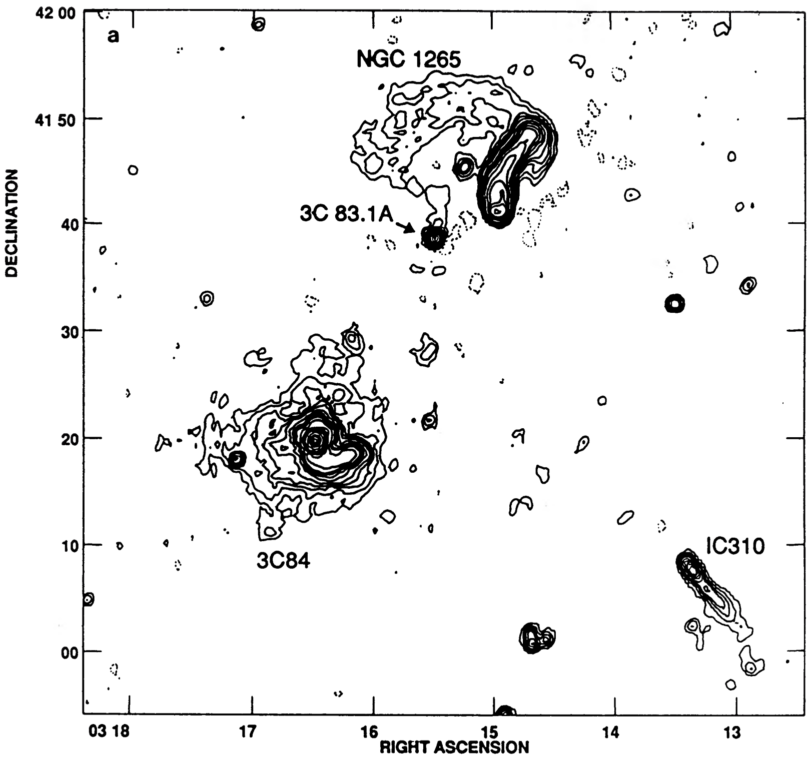
Our maps in Figure 1 reveal several extended cluster sources. These sources include the prototype head-tail galaxy NGC 1265 which has a remarkable curvature in the extended tail shown here for the first time. Also, the Perseus cluster has a "minihalo" centered on the well-known peculiar radio galaxy 3C 84/NGC 1275 (e.g., Miley & Perola 1975; Noordham & de Bruyn 1982). Its maximum diameter on the map in Figure 1*b* is ∼20′ or ∼430 kpc to a brightness level of 13 mJy per beam (24 mJy arcmin^{-2}).

The surface brightness profile of the 3C 84 halo, constructed from circular annuli using the image in Figure 1*b*, is shown in Figure 2*b*. We note that the outer structure of 3C 84 has both a lower surface brightness and a significantly smaller diameter than the Coma halo. If the Coma halo observed by Kim et al. with the VLA was within Perseus, and was observed at 330 MHz with the same beam as in Figure 1*a* (50″ FWHM), its average brightness should be about 20 mJy per beam (29 mJy arcmin^{-2}) at a radius of 6′.5 from the core. We measure a factor of ≈2 less brightness at this point in the Perseus halo. Also, such a halo's FWHM size should be ≈52′ (i.e., it should fill the entire image in Fig. 1*a*). Furthermore, Hanisch (1980) reported that the Coma halo extends even farther outward to a diameter of >2 Mpc (down to the map noise level) at 430 MHz using Arecibo. We estimate that such a halo, if it were present in Perseus, would have an $S_{330} \sim 24$ mJy per beam (3 mJy arcmin^{-2}) at 15′ from the core using the beam (170″ FWHM) in Figure 1*b*. This is 2.4 times the rms noise (per beam) observed in this region of our map. We further tapered the visibility function, weighting down the longer baselines in favor of the shorter, and made a map with a clean beam of 300″ FWHM (not shown). On this map, a Coma-like halo should have been detected at a level of 75 mJy per beam, more than 6



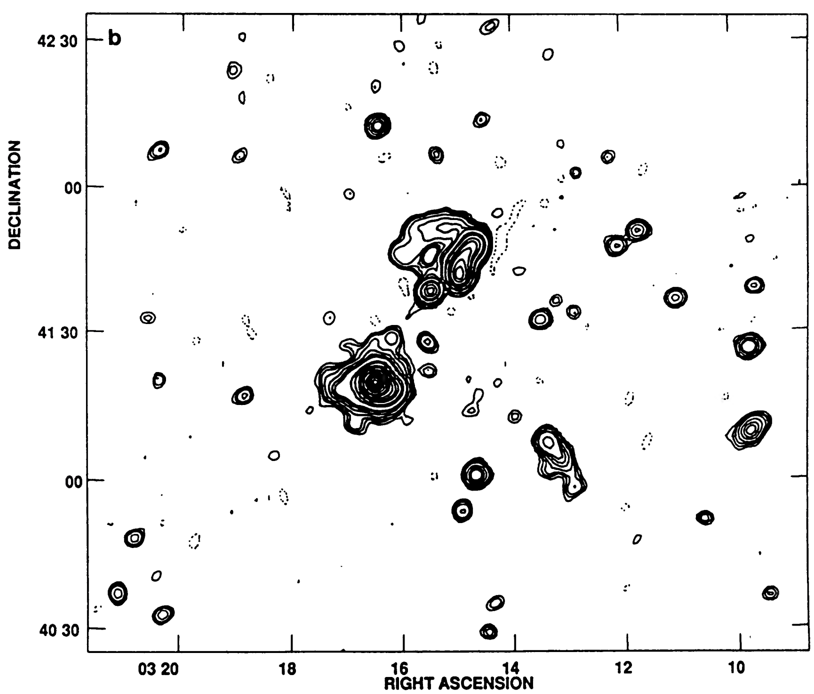


FIG. 1.—VLA images of the Perseus cluster at 330 MHz. The minihalo is centered on 3C 84/NGC 1265. Fig. 1*a* is our highest resolution map (clean beam FWHM is 50″ × 50″) made by combining VLA C and D configuration databases. Contour intervals are (−0.075, 0.075, 0.15, 0.25, 0.35, 0.5, 0.75, 1.0, 1.25, 1.5, 2, 3, 4, 5, 6, 8, 10, 20, 40, 60, 80, 100) × 0.175 Jy per clean beam. Fig. 1*b* was made from VLA D configuration data alone but is more sensitive to the largest scales of structure (clean beam FWHM is 170″ × 164″, P.A. = −70°). Contour intervals are (−0.1, 0.1, 0.15, 0.2, 0.3, 0.5, 0.75, 1, 2, 3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90) × 0.252 Jy per clean beam.

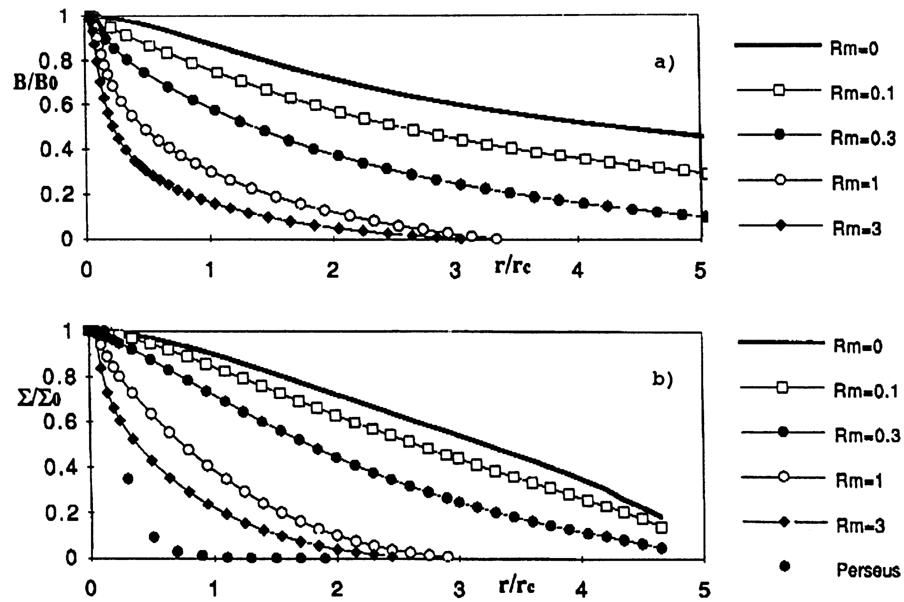


FIG. 2.—Models of cluster mini–radio halos. Fig. 2*a* contains distributions of *B*-field as a function of distance from the cluster center (in units of cluster core radius). Fig. 2*b* contains profiles of synchrotron surface brightness. Note the suppression of extended *B*-field and surface brightness as the effective Reynolds number R_m (proportional to cooling inflow velocity) increases. The filled circles represent the observed surface brightness (from circular annuli) of the Perseus minihalo from Fig. 1*b*.

times the rms noise per beam. There is simply no evidence for a large-scale radio halo, at the surface brightness of Coma, in the Perseus cluster.

Upon reexamining the table of cluster halos in Hanisch (1982), we noticed a previously unrecognized division between the clusters which may help explain the differences between Coma and Perseus. There appear to be two classes of radio halos. The first, characterized by Coma, is a Mpc or more in size and is associated with a cluster that does *not* have an X-ray cooling inflow (e.g., Fabian 1988). Other members of this class include A2255. The second, characterized by Perseus, is 1%–20% the size of Coma, is associated with a cooling core (Mushotzky et al. 1981), and is centered on a strong radio galaxy. Other recently recognized examples of such minihalos include 3C 317 (Burns 1990) and PKS 0745−191 (Baum & O'Dea 1991). It appears, therefore, that both an extensive ICM and a central cluster inflow have crucial roles to play in the evolution of cluster radio halos.

In this *Letter*, we explore one possible idea that might explain the influence of cooling inflows on radio halos. At first glance, such a connection seems tenuous since cooling inflows are significant only within the cluster core (typical cooling core radius is <100 kpc), whereas the halos are generally much larger. We speculate in the following section that it is the absence of cluster-wide magnetic fields rather than fast electrons that inhibits a large-scale halo in Perseus. We argue that, in general, cluster magnetic fields are amplified by strong turbulence within the ICM. If the turbulence energy density follows the cluster kinetic energy density, the *B*-field strength will be highest at the cluster center. Furthermore, if the magnetic Reynolds number is sufficiently small, the core *B*-fields will diffuse *outward* to fill the cluster and produce a large-scale radio halo as in Coma. However, if a central cooling inflow is present, this inflow will impede the diffusion of magnetic fields from the core to the outer parts of the cluster and produce a minihalo as in Perseus.

2. A MODEL FOR CLUSTER MINI RADIO HALOS

Our model connecting radio halos and cooling inflows hinges on the evolution of magnetic fields in clusters. So, let us first consider the structure of the magnetic field within a galaxy cluster. Near the center of a cluster, the larger number of galaxies there should fill the cluster core with plasma turbulence that has a typical velocity of $\simeq 400$ km s^{-1} (Jaffe 1980; Rosner & Tucker 1989; Ruzmaikin, Sokoloff, & Shukurov 1989), possibly caused by galaxy wakes (e.g., Goldman & Rephaeli 1991). ICM turbulence may also arise from the motion of underlying dark matter produced by subcluster merging or by convection (e.g., Eilek 1991). Initial cluster magnetic fields (e.g., Rephaeli 1988) can be amplified into a chaotic field with μG strength (Kim, Tribble, & Kronberg 1991; Tribble 1991) by dynamo action of the turbulent plasma (e.g., De Young 1980). Calculations of such a dynamo have demonstrated that a tangled *B*-field may be established within the cluster core in a relatively short time (Ruzmaikin et al. 1989). The field can then diffuse to fill the cluster (see below).

An important additional effect that needs to be considered in a cooling flow cluster is that of large-scale (generally laminar) plasma inflows on the evolution and distribution of such dynamo-formed cluster magnetic fields. We shall not describe in detail the field generation, but rather we will employ a simple averaging of the magnetic induction equation. This leads to a modified diffusion equation, containing the effects of field generation and cooling inflows. Because we do not specifically model the turbulent dynamo *B*-field amplification, we cannot predict the magnitude of the field but we do predict the relative *B*-field and synchrotron surface brightness profiles.

We begin with a simple description of the cluster magnetic field. The evolution of $\boldsymbol{B}$ is governed by the induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B} , \tag{1}$$

where v is the plasma velocity, which we take to be *nonrandom*, and η is the magnetic diffusivity (or anomalous resistivity), which we assume to be constant. For the case of a steady state magnetic field within a spherical cluster, it can be shown that the above equation can be rewritten allowing us to predict the field magnitude $B(r)$ such that

$$r^{-2} \frac{d}{dr}\left(r^2 \frac{dB}{dr}\right) + \eta^{-1}\left(\frac{2}{3}\frac{B}{r^2}\frac{d}{dr}(r^2 u) + u\frac{dB}{dr}\right) = S(r) , \quad (2)$$

where $S(r)$ is the source for the B-field and $v = -u(r)\hat{r}$. The first term on the left-hand side of equation (2) represents the diffusion of field generated by the source S, while the term proportional to η^{-1} represents the effect of inflow on the field structure. The relative importance of this term is governed by a magnetic Reynolds number, given by $R_m \equiv uL/\eta$, where $L = B/(dB/dt)$. Significant modification to the B-field profile of a static cluster will occur if $R_m \geq 1$.

A comment on the magnetic Reynolds number is in order before we proceed further. It is well known that R_m is very large in astrophysical plasmas if one uses the standard Spitzer (1962) value for the plasma resistivity. However, flows at such enormous Reynolds numbers are unstable to the development of strong turbulence at all scales (e.g., Scott et al. 1980). This turbulence, in turn, gives rise to an anomalous effective resistivity which greatly reduces R_m. If cluster magnetic fields result from diffusion from a dynamo source, then R_m is of necessity fairly small. The diffusion time, $\tau = r_H R_m/u$, is $\approx 10\%$ of the Hubble time for a halo radius (r_H) of 1 Mpc, $R_m \approx 1$, and $u = 500$ km s^{-1}. From equation (2), we conclude that extended cluster B-fields (and halos) cannot exist in any cluster with a cooling flow unless the effective R_m is small. Thus, the resistivity plays two important roles here. First it makes a dynamo possible, breaking and reconnecting field lines so that a little bit of bulk kinetic energy can be transformed into magnetic and particle energy. Second, it allows fields to diffuse. In our model, magnetic field energy generated by some form of dynamo is acted upon by a bulk plasma flow, namely a cooling inflow. The nature of the flow is such as to localize the field in the cluster center relative to the field in the rest of the cluster.

For $S(r)$, we assume that the turbulent energy density, which gives rise to the amplified B-fields, is proportional to the ICM kinetic energy density. If the cluster gas density profile is represented by an isothermal King model, then $S(r) \propto \rho \propto [1 + (r/r_c)^2]^{-3/2}$, where r_c is the cluster core radius. We have solved equation (2) using this profile for $S(r)$ and an adaptive Runge-Kutta scheme with the integration running from $r = 0.05r_c$ to $5r_c$. We have also assumed that $u(r) \propto r^{-1}$ which is predicted for steady state, subsonic cooling inflows (e.g., Sulkanen, Burns, & Norman 1989). The resulting B-field profiles are shown in Figure 2*a* for different values of the effective Reynolds number (now, $R_m = u_0 r_c/\eta$). We see that weak inflow (i.e., small R_m values) produces a magnetic halo which is not significantly different from that corresponding to the dynamo action in a static King model, while stronger inflow (i.e., larger R_m values) results in strong suppression of the halo B-field up to $R_m \sim 3$.

To obtain the synchrotron surface brightness, we assumed that the energetic electrons are distributed as a spherical King model and that they have a power-law energy distribution $\propto E^{-2}$. We then integrated the synchrotron power along lines of sight to produce the surface brightness profiles shown in Figure 2*b*. Also in Figure 2*b*, we show the observed surface brightness distribution for 3C 84. Our model is clearly too simple in that it does not consider the effects of a single strong radio galaxy at the center of the cluster on the formation of a halo like that in 3C 84. However, the plot does show that the model can readily suppress radio emission on scales larger than the observed emission in Perseus.

3. CONCLUSIONS

New VLA data at 330 MHz show that the Perseus cluster does not have a large Mpc-sized radio halo as in the Coma cluster. We suggest that Perseus is one example of a class of X-ray cooling core clusters which have smaller "minihalos."

We presented a model which shows how a cooling inflow at the core of a cluster can suppress the formation of a large-scale halo beyond the core. Turbulence-induced magnetic field amplification is more effective in the cluster core where the galaxy density is highest. For a static ICM as in Coma, the field diffuses outward from the core to fill the cluster and produces a large halo. If the cluster has a cooling core, however, this plasma flow can significantly reduce the spread of B-field to the outer parts of the cluster producing minihalos as in Perseus. Thus, it would appear that the growth and evolution of radio halos depends upon the distribution of cluster radio galaxies, the level of turbulence in the ICM (which may be related to recent cluster history), and the presence or absence of cooling inflows.

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