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ENERGETIC PROTON HEATING OF GAS IN THE CORE OF THE PERSEUS CLUSTER

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ABSTRACT

Gas in the inner cores of rich clusters that contain central radio sources may be permeated by a high flux of energetic protons. Heating by these protons is likely to play a significant role in the thermal balance of the gas, thereby reducing the inferred cooling and mass accretion rates. This is shown to be the case in the radio halo region of NGC 1275 in the Perseus cluster.

Subject headings: acceleration of particles — galaxies: clusters: individual (Perseus) — galaxies: individual (NGC 1275) — intergalactic medium

1. INTRODUCTION

Gas in the inner cores of some rich clusters of galaxies is sufficiently dense that radiative energy losses may be substantial over a few billion years. One would then reasonably question the maintenance of hydrostatic equilibrium over timescales longer than the cooling time in the gas. Indeed it has been claimed that gas in the inner cores of clusters cools and flows inward, usually accreting onto a dominant, central galaxy (Fabian, Nulsen, & Canizares 1991). A typical example for such a cooling flow may exist in the Perseus cluster where mass accretion rates of up to several hundred $M_\odot$ yr^{-1} have been inferred. In more remote clusters, cooling flows in excess of 1000 $M_\odot$ yr^{-1} may have been detected.

Observational evidence for cooling flows (see references in the above review) is based on excess X-ray surface brightness in many cluster cores relative to equilibrium isothermal models, and on interpretations of X-ray spectral measurements which indicate that the gas temperature decreases toward the cluster center (in the case of Perseus, see, e.g., Canizares, Markert & Donahue 1988; Schwarz et al. 1992; Arnaud et al. 1992). The high rate of mass deposition in the cluster center, and the fact that there is little evidence for a large accreted mass of cold gas in the center, have motivated various proposed alternatives to the cooling flow model. It is the large scale *flow* inference which is usually questioned. For example, Sparks (1992) has proposed that the cooler gas seen in some clusters may be a result of recent galactic mergers, with the gas actually evaporating outward due to heat conduction from the ambient hot gas. According to Fabian, Canizares, & Bohringer (1994), however, this model assumes unacceptable geometry and boundary conditions, and is untenable.

In the central regions of many clusters (e.g., Coma, Perseus, Virgo), there are powerful radio sources, and in some clusters there is also diffuse radio emission over a region comparable to or larger than the cluster core. Cluster cooling flows are generally associated with powerful central radio sources (Jones & Forman 1984). The emission line gas found in the cores of cooling flow clusters is often attributed to the cooling flow, there being an approximate coincidence between the inferred gas flow rates if the X-ray emitting gas and Hα emitting filaments are indeed assumed to be in a flow. However, the emission nebulosity is cospatial with the radio emission and correlated in emission line width with radio luminosity (Heckman et al. 1989). The radio sources in these clusters have a compact morphology, indicative of interaction with the ambient gas pressure, while the large measured optical line widths are equally attributable to turbulence or to infall.

Radio sources may indirectly play an important role in heating the gas. The directly implied presence of relativistic electrons yields indirect evidence for the presence of relativistic protons. While a GeV electron loses energy radiatively, mildly relativistic protons interact and transfer energy to the gas through Coulomb scattering. It has already been shown (Rephaeli 1987) that if the proton to electron ratio at GeV energies is as high as in the Galaxy (where a nominal value of 100 is usually taken), then proton heating may well balance radiative losses in the hot intracluster (IC) gas. (Soker & Sarazin 1988 have proposed magnetic reconnection energy as a heating source of gas within the inner ~10 kpc cooling flow region.)

In this paper we estimate the energy deposition rate of energetic protons emanating from the powerful radio galaxy NGC 1275 into the gas in the inner core of the Perseus cluster. The possibility that proton heating is significant in this cluster is clear from previous estimates (Rephaeli 1987), and was also mentioned by Pedlar et all. (1990). Here we estimate the heating rate by calculating the proton energy input rate assuming only minimal Coulomb coupling between the protons and gas.

2. PROTON DENSITY AND HEATING RATE

A detailed study of radio emission from the central region of the Perseus cluster was conducted by Pedlar et al. (1990). Radio emission from this cluster is mainly from NGC 1275 and its environment; the emission has a very complex structure. Most of the emission comes from a compact core, but about a fourth of the total flux is from an extended region with a few components with sizes ranging from a few kpc to (roughly) a

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hundred kpc. Conditions (magnetic fields, radiation energy densities, and the gas density) in the core of this galaxy make it impossible for relativistic electrons and protons escaping from the compact core to reach distances of even a few kpc before they lose their energies. Therefore, of interest to us here is the extended emission over scales of at least a few kpc, well beyond the galactic core.

Parameters of the extended radio emission in and around NGC 1275 are not very well determined; the following values are adopted from the work of Pedlar et al. (1990): the total emission at 1380 MHz is estimated to be ~5 Jy, out of which ~1.3 Jy is from a "halo" region of ~75 kpc radius. The (poorly determined) spectral index in this region is $\alpha \sim 1.2$. Pedlar et al. estimated the equipartition magnetic field in the halo to be 8 μG, but this is a substantially uncertain value which has, at best, a very limited meaning. (Uncertainties in the values of α and B will be accounted for in our estimated proton heating rate.)

A full calculation of the relativistic particle densities requires knowledge of the various source and energy loss terms in the kinetic equation for $n(\gamma, t)$, the particle density per unit (Lorentz factor) γ, at time t. This is not warranted, given the scant observational data. Rather, we infer a suitably time-averaged electron density $n(\gamma)$ directly from the observed synchrotron radio flux. In effect, this amounts to assuming that steady state conditions prevail, under which the ejection of electrons and protons from the main, active parts of the source is at a rate which just balances the total energy-loss rate. Alternatively, taking the particle density to be constant is reasonable over a timescale comparable to the dominant energy-loss time, if the source (NGC 1275) has been active for at least that long. (We will discuss this assumption below.)

Radio emission from the halo is by electrons originating in the lobe of NGC 1275—the source region—where they are accelerated. Our (partial) knowledge of the relation between the electron and proton densities, by inference from the Galaxy, is for conditions within the source. Thus, we have to relate the electron density in the halo, which is deduced from the radio emission there, to the electron density in the source region. We can then deduce the proton density in the source from the electron density there. Finally, the proton density in the halo is determined from consideration of the energy loss incurred by protons in the halo, similarly to what had already been done by Rephaeli (1987).

Suppose that the electron *source* spectrum is a power-law $n_e(\gamma) \propto \gamma^{-p}$, so that after they have sustained synchrotron losses in the halo magnetic field B, and Compton losses off the CMB radiation at a combined rate

$$b_e = (d\gamma/dt)_e = b_{e,o}\gamma^2 = 1.3 \times 10^{-13}(1 + 10^{11}B^2)\gamma^2 \text{ s}^{-1} , \quad (1)$$

the electron density changes to

$$n_e(\gamma) = n_{e,o}\gamma^{-(p+1)} , \quad (2)$$

for $\gamma \geq \gamma_{e,m}$. The synchrotron radio flux from a region of radius R at a distance d is

$$F_s(\nu) = \frac{a_2(p)n_{e,o}R^3B^{(p+2)/2}\nu^{-(p/2)}}{3d^2} , \quad (3)$$

where the function $a_2(p)$ is defined in Rephaeli (1979). Let the observed flux be

$$F_o(\nu) = A\nu^{-\alpha} , \quad (4)$$

then $p = 2\alpha$, and

$$n_{e,o} = \frac{3Ad^2}{R^3a_2(p)B^{(p+2)/2}} . \quad (5)$$

In the Galaxy, the proton-to-electron density ratio is usually inferred from a comparison between the cosmic ray proton flux and the cosmic ray electron flux at an energy of about 1 GeV. The power-law indices of these fluxes are roughly equal, and a value of ~100 is usually taken for this flux ratio, k, as is observed locally. Similarly, we can relate the proton density to that of the electrons within the *source* region of NGC 1275. As mentioned, to find the proton density in the halo we have to take account of the very different energy loss mechanisms of electrons and protons.

The main energy loss of mildly relativistic protons is by Coulomb collisions with the gas particles through the excitation of plasma oscillations, a process called electronic excitation (also known as ionization loss). The loss rate, $(d\gamma/dt)_p = b_p(\gamma)$, in a gas of density n is (e.g., Gould 1972)

$$b_p(\gamma) = \frac{4\pi mcr_o^2 n}{\beta M}\left[\ln\left(\frac{2\gamma mc^2\beta^2}{\hbar\omega_p}\right) - \frac{\beta^2}{2}\right] , \quad (6)$$

where β is the proton velocity in units of c, $r_o = e^2/mc^2$ is the classical electron radius, and $\omega_p = 5.63 \times 10^4 n^{1/2}$ is the plasma frequency. The characteristic (*kinetic*) energy loss time is

$$\tau_p(\gamma) = \frac{(\gamma - 1)}{b_p(\gamma)} , \quad (7)$$

which is as short as $\sim 2 \times 10^8 (n/0.01)^{-1}$ yr for a 100 MeV proton.

Due to the effectiveness of energy losses of energetic protons, their energy spectrum in the halo is also modified from the original $n_p(\gamma) \propto \gamma^{-p}$ for values of γ in the range $[\gamma_{p,m}, \gamma_{p,M}]$ to

$$n_p(\gamma) = \left(\frac{M}{m}\right)^{1-p} kn_{e,o}b_{e,o}\begin{cases} \dfrac{\gamma^{-(p-1)}}{b_p(\gamma)} & \gamma_{p,m} < \gamma \leq \gamma_{p,m} \\[2ex] \dfrac{\gamma_{p,m}^{-(p-1)}}{b_p(\gamma)} & \gamma \leq \gamma_{p,m} \end{cases} , \quad (8)$$

where M is the proton mass. Because of the significant losses by protons with initial energies well below 100 MeV, we will take $\gamma_{p,m} = 1.1$, and since in the halo this loss rate is ineffective above a few GeV, $\gamma_{p,M} = 3 - 4$, although its particular value is not very important here.

The gas heating rate per unit volume is just the energy input by the protons:

$$\Gamma_h = Mc^2\int_1^{\gamma_{p,M}}\left(\frac{d\gamma}{dt}\right)_p n_p(\gamma)d\gamma$$

$$= \frac{3kMc^2(M/m)^{1-p}Ab_e d^2 g(p, \gamma_{p,m}, \gamma_{p,M})}{R^3a_2(p)B^{(p+2)/2}} , \quad (9)$$

where

$$g(p, \gamma_{p,m}, \gamma_{p,M}) = \frac{(p-1)\gamma_{p,m}^{2-p}}{p-2} - \gamma_{p,m}^{1-p} - \frac{\gamma_{p,M}^{2-p}}{(p-2)} . \quad (10)$$

The energy density in protons with energies in the interval $[\gamma_{p,m}, \gamma_{p,M}]$ is

$$\rho_p = Mc^2\int_1^{\gamma_{p,M}}(\gamma - 1)n_p(\gamma)d\gamma . \quad (11)$$

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Similarly, the electron ($\gamma \gg 1$) energy density is

$$\rho_e = mc^2 \int_{\gamma_{e,m}}^{\gamma_{e,M}} \gamma n_e(\gamma) d\gamma = \frac{mc^2 n_{e,o}(\gamma_{e,m}^{1-p} - \gamma_{e,M}^{1-p})}{p-1} . \quad (12)$$

3. RESULTS

We have calculated values of Γ_h, ρ_p, and ρ_e for the following choice of parameters: $k = 100$, $R = 75$ kpc, $B = 8$ μG, $n = 1 \times 10^{-2}$ cm^{-3} (adopting the $r^{-3/2}$ density profile which presumably is an adequate fit to the X-ray data from the inner core of Perseus—Mushotzky et al. 1981), $\gamma_{e,m} = 200$, and with a halo flux of 1.3 Jy at 1380 MHz. The relevant range of values of p is 2.2–2.6, and that of $\gamma_{p,m}$ is 1.1–2.0 (i.e., protons with kinetic energies between 100 MeV and 1 GeV). For these values of p and $\gamma_{p,m}$, we have

$$\Gamma_h = (4 - 7) \times 10^{-28} \left(\frac{B}{8\ \mu\mathrm{G}}\right)^{-(p+2)/2} \times \left(\frac{k}{100}\right)\left(\frac{R}{75\ \mathrm{kpc}}\right)^{-3} \mathrm{ergs\ cm^{-3}\ s^{-1}} . \quad (13)$$

The proton heating rate should be compared with radiative losses from the gas. In the temperature and density ranges of interest here, the total cooling rate is $\Gamma_c \sim 2 \times 10^{-23} n^2$ ergs cm^{-3} s^{-1} (e.g., Raymond, Cox, & Smith 1976), i.e., 2×10^{-27} ergs cm^{-3} s^{-1} for $n = 1 \times 10^{-2}$ cm^{-3}. Comparison of the above heating rate with the radiative cooling rate indicates that for reasonable values of the relevant parameters, proton heating of IC gas (in the inner core of Perseus) can be significant. Of the relevant quantities upon which the heating rate depends, the most uncertain are B and k, with $\Gamma_h \propto B^{-(p+2)/2}$.

For the above range of p and $\gamma_{p,m}$, the proton pressure is

$$P_p \simeq (0.5 - 1) \times 10^{-11} \left(\frac{B}{8\ \mu\mathrm{G}}\right)^{-(p+2)/2} \left(\frac{k}{100}\right) \times \left(\frac{R}{75\ \mathrm{kpc}}\right)^{-3} \left(\frac{n}{0.01\ \mathrm{cm^{-3}}}\right)^{-1} \mathrm{ergs\ cm^{-3}} . \quad (14)$$

The gas temperature (determined recently from BBXRT measurements; Arnaud et al. 1992) in the core of the Perseus cluster is ~ 4 keV, so that the thermal pressure is

$$P_g \simeq 6 \times 10^{-11} \left(\frac{n}{0.01\ \mathrm{cm^{-3}}}\right) \mathrm{ergs\ cm^{-3}} . \quad (15)$$

These estimates clearly indicate that proton heating is appreciable even if $P_p \leq P_g$, and that even if proton heating were to exactly balance radiative losses, the required proton pressure would still not exceed the gas pressure.

The electron energy density is much lower than that of the protons, but because electrons radiate much more efficiently, it is interesting to compute the X-ray flux expected from Compton scattering of the electrons off the CMB (temperature T_o). The expression for the Compton (energy) flux can be conveniently written in terms of the observed radio flux (Rephaeli 1979)

$$F_c(\epsilon) = a_3(p) A (k_\mathrm{B} T)^{(p+6)/2} B^{-(p+2)/2} \epsilon^{-(p/2)} . \quad (16)$$

For $p = 2.4$, the predicted photon flux at $\epsilon = 1$ keV is

$$f_c(1\ \mathrm{keV}) \sim 5 \times 10^{-6} \left(\frac{B}{8\ \mu\mathrm{G}}\right)^{-2.2} \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}} , \quad (17)$$

about four orders of magnitude lower than the thermal flux from (the central region of) the Perseus cluster. At 70 keV, the predicted flux is also about four orders of magnitude lower than the recently reported (Osako et al. 1994) OSSE upper limit. Thus, unless $B \ll 1$ μG, the contribution of electrons *in the halo* of NGC 1275 to the soft X-ray flux is negligible. Obviously, most of the hard X-ray emission is produced in the compact core; this emission (unlike that coming from the extended halo) is expected to show time variability.

4. DISCUSSION

The above estimates indicate a mean proton heating rate within the radio halo which is a factor of $\sim$3–5 times lower than the radiative loss rate in the gas. However, the heating rate can be even lower than implied by this narrow range of values which does not reflect the full uncertainty in the values of the relevant quantities. Of these, perhaps the least known is the proton-to-electron ratio, which introduces an overall scaling factor of $k/100$ in the value of the heating rate. But the rate depends sensitively on B and R which are also not known very well. Is the uncertainty in the values of these quantities large enough that a significantly higher heating rate is likely?

The mean halo field value of 8 μG adopted in our estimates was determined by Pedlar et al. (1990) by invoking equipartition between the proton and field energy densities. This is highly questionable: the field is likely to have originated from the cluster galaxies, whereas NGC 1275 is the most likely source of electrons and protons. There is no basis for equipartition between quantities which do not have a common origin in the same virialized system (whose various dynamical quantities reach a quasi-equilibrium state under which energy is equally shared). A typical value of an interstellar field is 3 μG, and since the gas in the inner core of Perseus is not denser than typical ionized interstellar gas, the frozen galactic fields in the intracluster gas are not likely to be higher than a few μG even in cluster cores. (For more on the origin and strength of cluster fields, see Goldshmidt & Rephaeli 1992). For $p = 2.4$, the proton heating rate is higher by a factor ~ 3 than estimated above if $B = 3$ μG.

We have ignored the spatial profiles of the electron and proton densities, *whereas full account was taken of the gas profile in our estimates of the cooling rate.* Obviously, a higher proton density and heating rate is expected in the region near NGC 1275. The spatial dependence of the heating rate is actually *steeper* than implied by the explicit, mere linear dependence of the energy loss (eq. [6]) on gas density, n: The proton density also depends implicitly on r, a dependence which stems from the fact that particle acceleration occurs more efficiently in the central region of the radio source. For example, a simple $1/r^2$ profile would have yielded a higher rate by a factor of a few within the inner 40 kpc region around NGC 1275. It is clear, therefore, that the full spatial dependence of the heating rate—whose exact form cannot be readily determined—is not reflected in eq. (6), and clearly not in the expression for the heating rate (eq. [9]). Thus, the likelihood of maintaining an exact *local* balance between heating and cooling, which, as we have already noted is neither realistic nor required, cannot be assessed based on a simple comparison of the different dependences of Γ_h and Γ_c on n.

Since a high heating rate is possible when the proton pressure is comparable to the gas pressure, in addition to their thermal effect the protons may also play an appreciable dynamical role. By virtue of their small Larmor radii and the small coherence scale of the field, these energetic protons act like a collisional gas, exerting an outward pressure on the thermal gas. The dynamical role of protons in the cores of clusters was studied by Bohringer & Morfill (1988). In this paper, the coupling of protons to the gas was assumed to be via excitation of hydromagnetic modes (see, e.g., Rephaeli 1977). In contrast, our estimates are based on the minimal coupling which always exists between energetic protons and gas, irrespective of whether some necessary conditions are met for the excitation of hydromagnetic modes to ensure super-Coulomb coupling. Observational evidence for the dynamical effect of energetic protons on the gas in the inner halo of Perseus was recently described by Bohringer et al. (1993). Our main result here is that if this is so, the thermal effect of the protons also has to be taken into account. Moreover, whereas the proton dynamical effect is expected in the boundary region between NGC 1275 and its radio halo, proton heating through the decay of plasma oscillations takes place throughout the halo.

Are conditions such that $P_p \geq P_g$ likely in cluster cores, even if there is a strong radio galaxy near the center? It is indeed possible that in the immediate vicinity of the radio source the particle pressure exceeds the gas pressure because the activity of the radio galaxy is not directly related to the processes by which the gas pressure builds up within the core. However, the attainment of (fine-tuned) balance between these two very different pressures is unlikely unless full steady state is reached. This, in turn, requires that the radio source is active at least until such time that the inner core is filled up with particles (propagating outward at the Alfvén velocity?).

Specifically, consider the spectrally (and spatially) averaged proton density, $n_p(t)$, and let τ_p be a characteristic energy-loss time (assumed to be shorter than the escape time from the inner core). If protons populate the inner core at a mean rate (per unit volume) q_o, then the proton density at a time t after the beginning of the process is

$$n_p(t) = q_o \tau_p[1 - \exp(-t/\tau_p)] . \tag{18}$$

Steady state, $n_s \sim q_o \tau_p$, is reached after a time $t > \tau_p$. Under the above conditions, the energy loss time of a 100 MeV proton is only $\sim 2 \times 10^8$ yr, which is also comparable to (or shorter than) the synchrotron loss time, τ_s, of a GeV electron in the halo. The period of activity of NGC 1275 is likely to be longer than this characteristic proton loss time. Otherwise, if protons (and electrons) had been escaping to the inner core over a shorter period ($<2 \times 10^8$ yr), then $n_p \sim n_s t/\tau_p$. However, because the proton density was deduced from the electron density, which was in turn normalized to the observed radio flux, any reduction in the proton density by a factor t/τ_p (and in the electron density by a factor t/τ_s) would have to be compensated for by an implied higher value of q_o. Thus, even if steady state had not been attained in the halo, the normalization of the proton density there in terms of the observationally deduced electron density assures, at least qualitatively, the validity of our treatment and resulting estimates.

The existence of a rough pressure equality in the inner core has a closely related implication on the energetics in the same region. Such an equality does not imply a *global* energy criterion, as is sometimes stated. The total X-ray luminosity of the core has little to do with the amount of heating required to prevent cooling within the inner core. (If it did, one could have also argued that the internal energy of the outer intracluster gas is available for heating of the inner core.) Rather, if a bolometric luminosity comparison is nonetheless desired (disregarding the uncertainties introduced by the need to integrate over spectra, and in the choice of radial extent of the emitting region), the total X-ray emissivity from the radio halo region should be compared with the halo radio luminosity. But since these luminosities are directly linked to the cooling and heating rates as calculated above, such a rough luminosity equality follows automatically in our treatment (based as it is on normalization of the proton density on the radio flux through the ratio k).

Consider, for example, the following luminosity comparison: Pedlar et al. (1990) estimate a particle luminosity of 10^{43} ergs s^{-1} from the radio halo, whereas—according to Bohringer et al.—the total X-ray luminosity from the same region is about 10 times higher. Even though these estimates, given the inherent uncertainties, are really roughly consistent with our estimated discrepancy of a factor of 3–5 (mentioned in the beginning of this section) between the heating and cooling rates, one should remember that the particle luminosity is based on the value $B = 8\ \mu$G. If, as we argued above, a value of $B = 3\ \mu$G, is taken, the particle luminosity increases by about an order of magnitude, echoing also our estimate that the heating rate would then be quite comparable to the cooling rate.

In order to gain further insight on the thermal state of a gas which is permeated by a high flux of protons whose pressure is comparable to the gas pressure, we write $\Gamma_h = P_p b_p \eta$; for the above parameter range, $\eta \sim 1$. Now $b_p = b_o n$, and the radiative cooling rate is $\Gamma_c = \lambda n^2 T^{1/2}$, with $\lambda \simeq 4 \times 10^{-27}$ in cgs units. From these relations it easily follows that

$$\frac{P_g}{P_p} = \left(\frac{T}{T_c}\right)^{1/2} \frac{\Gamma_c}{\Gamma_h} , \tag{19}$$

where $T_c = (\lambda/k_B \eta)^2$. Interestingly, for the above parameter range this critical temperature is a few keV. The qualitative equality of this theoretically derived critical temperature and the actual temperature (deduced from X-ray measurement) is certainly consistent with the importance of proton heating. When the gas and proton pressures are *comparable*, $\Gamma_h \ll \Gamma_c$ implies that cooling is very effective and, therefore, $T < T_c$. If, on the other hand, $\Gamma_h \gg \Gamma_c$, then unbalanced heating will lead to $T > T_c$. If so, the fact that $T \sim T_c$ would then indicate that there is an *approximate* balance between heating and cooling in the inner core of Perseus. (We emphasize that this reasoning only concerns the inner core region where heating may be effective.)

It is unrealistic to expect that an *exact* balance is attained between particle and gas pressures everywhere in the inner core, because of the different spatial profiles of the proton density and of the gas density and temperature. Thus it is unlikely that a simple dynamical criterion characterizes the thermal state of the gas throughout the core. Neither is it clear how such an exact pressure balance would have been attained, nor is such a dynamical state stable. It is tempting to speculate that the initiation of a cooling flow may have energized the central radio source via feeding the galactic nucleus. In this case, feedback and the ensuing self-regulation could possibly result in a rough global balance between cosmic ray pressure and gas pressure. Rayleigh-Taylor instabilities will most likely occur in cosmic-ray–supported intracluster gas (Bohringer & Morfill 1988). Instability is likely to be a desirable attribute of any model involving cosmic-ray injection and diffusion, for it allows the possibility of magnetic field amplification via dynamo activity, and may help account for the origin of the large-scale magnetic fields in clusters.

One may obviously question—especially in light of the considerations discussed in the last two paragraphs—the general relevance of proton heating to the thermal state of the gas, given that powerful radio sources have been detected in only some clusters. Even though *we are not arguing here that proton heating plays appreciable role in cluster cores in general*, it is still of interest to note that the activity of a radio galaxy strongly depends on its mean magnetic field: A field value lower by only a factor of 3 results in a radio source which is typically weaker by a factor ~ 10. Also, the proton density decreases much more slowly than the electron density in the environment of a faded radio remnant. For example, while $\tau_s \sim 10^8$ yr for an electron in a 10 μG field, $\tau_p \sim 10^9$ yr for protons (with a median—with respect to the range taken in our estimates—kinetic energy of 1 GeV).

Another consideration which would only strengthen our main result is the possibility that relativistic electrons are coupled to the gas much more strongly than inferred by Coulomb collisions. It has been suggested (Scott et al. 1980) that if the electron spatial distribution is sufficiently anisotropic, collective ion density fluctuations can be excited, resulting in an anomalous resistivity and a much higher energy deposition rate by electrons. These authors estimated that electron heating can well balance radiative losses in the Coma cluster, and also in the halo of M87 (Tucker & Rosner 1983). Although we have here completely ignored the heating effect of electrons, if anomalous resistivity is indeed as high as claimed, then this additional heating will reduce the required proton pressure for a given level of particle heating.

We conclude, therefore, that it is indeed possible that proton heating is substantial in the region around NGC 1275. A careful assessment of the net cooling rate of the gas must then include proton heating. Simplistic estimates of the mass accretion rates based on just the radiative cooling rate may be exaggerated. This radiative cooling time is $\sim(1\text{–}3) \times 10^9(n/0.01)$ yr, whereas the net cooling time is a factor $\alpha/(\alpha - 1)$ higher, where α is the ratio of the proton heating time to radiative cooling time. It is quite possible that in the inner core this ratio is sufficiently small that the effective cooling time (which, after all, is not much shorter than the age of the universe, let alone the age of the gaseous core) is appreciably longer than the radiative cooling time. The mass accretion rate in this cluster, and consequently in other clusters, may therefore be considerably smaller than previously estimated.

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