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STRIPPED INTERSTELLAR GAS IN CLUSTER COOLING FLOWS

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ABSTRACT

We suggest that nonlinear perturbations which lead to thermal instabilities in cooling flows might start as blobs of interstellar gas which are stripped out of cluster galaxies. Assuming that most of the gas produced by stellar mass loss in cluster galaxies is stripped from the galaxies, the total rate of such stripping is roughly $\dot{M}_{\rm ISM} \sim 100\ M_{\odot}\ {\rm yr}^{-1}$, which is similar to the rates of cooling in cluster cooling flows. It is possible that a substantial portion of the cooling gas originates as blobs of interstellar gas stripped from galaxies. The magnetic fields within and outside of the low-entropy perturbations may help to maintain their identities by suppressing both thermal conduction and Kelvin-Helmholtz instabilities. These density fluctuations may disrupt the propagation of radio jets through the intracluster gas, which may be one mechanism for producing wide-angle-tail radio galaxies.

Subject headings: galaxies: clustering — galaxies: interactions — galaxies: interstellar matter

1. INTRODUCTION

One of the key questions concerning cooling flows in clusters of galaxies is the formation, evolution, and fate of the cooling gas. In typical cases, on the order of $\dot{M} \sim 10^2\ M_{\odot}\ {\rm yr}^{-1}$ of gas is inferred to be cooling (Stewart et al. 1984; Fabian, Nulsen, & Canizares 1984; Arnaud & Fabian 1989). The primary evidence for hot gas cooling at and flowing into the centers of clusters of galaxies comes from X-ray surface brightness measurements of the clusters (see the reviews by Fabian, Nulsen, & Canizares 1984 and Sarazin 1986). In cooling flow clusters, the X-ray surface brightness is very strongly centrally peaked, and the deconvolved central gas densities imply cooling times much less than the Hubble time (Stewart et al. 1984). In a few cases, stronger evidence comes from the detection of soft X-ray line emission from low-ionization stages produced at temperatures of $T_g \approx 10^6$–10^7 K, coming from the cluster center (Canizares, Markert, & Donahue 1988; Mushotzky 1989). In every case observed so far, a central dominant cluster galaxy is found at the center of the cooling flow (Jones & Forman 1984). The final repository for the cooling gas is unknown. However, it is widely believed that most of the gas cools to form low-mass stars, as was originally suggested by Fabian, Nulsen, & Canizares (1982) and Sarazin & O'Connell (1983). A small fraction of the gas may form higher mass stars in some cases (McNamara & O'Connell 1989).

As problematic as the question of the final fate of the cooling gas is the question of the formation of cool condensations in the cooling flow. Analyses of the X-ray surface brightness profiles of cluster cooling flows suggest that the mass flow rate decreases toward the center of the cluster (Thomas, Fabian, & Nulsen 1987). It is often argued that this decrease results from thermal instabilities, in which denser blobs of gas cool rapidly and drop below X-ray emitting temperatures. Since linear perturbations cannot cool fast enough to explain the rate at which mass appears to be dropping out of the cooling flows (e.g., Balbus & Soker 1989; Malagoli, Rosner, & Bodo 1987), these perturbations must enter the flow already in the nonlinear regime. A. C. Fabian (private communication) has suggested that relic nonlinear perturbations from subclusters merger are the seeds for the unstable cooling blobs.

In this paper, we suggest that nonlinear perturbations might start as blobs of interstellar gas which are stripped out of cluster galaxies. Cowie & Binney (1977) suggested that the source of cooling flow gas might be current stellar mass loss from cluster galaxies. Our suggestion is somewhat different than theirs, in that Cowie & Binney suggested that *all* of the cluster gas is currently being stripped from galaxies and that all of the intracluster gas is cooling. While it is difficult to produce all of the intracluster medium in this fashion, one can generate the amount of gas in the cooling flow region. There is a large body of evidence suggesting that much of the interstellar gas associated with galaxies in rich clusters is stripped from them, possibly by ram pressure ablation (e.g., Forman et al. 1979; Haynes, Giovanelli, & Chincarini 1984; Giovanelli & Haynes 1985). Numerical hydrodynamical simulations have demonstrated the efficiency of stripping (e.g., Takeda, Nulsen, & Fabian 1984; Gaetz, Salpeter, & Shaviv 1987). The stripped interstellar gas starts with a much lower specific entropy than the ambient intracluster gas (Gaetz et al. 1987) and will remain cooler than the ambient gas unless thermal conduction is effective. In § 2, we point to the approximate equality of the typical cooling rate in cluster cooling flows and the typical total stellar mass-loss rate in the cluster's galaxies. In § 3, we show that stripping inside the cooling radius by itself cannot explain the observations regarding mass dropping out of the flow. The relation between the cluster's properties and the efficiency of stripping is studied in § 4, and in § 5, we discuss the evolution of the stripped ISM emphasizing the importance of an interior magnetic field. In § 6, we summarize and comment on the observational implications of the suggested scenario.

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2. ISM STRIPPING AND COOLING

We begin by calling attention to an interesting and possibly significant numerical coincidence. In a typical cooling flow cluster, the inferred cooling rate is the same order of magnitude as the expected total stellar mass-loss rate from all of the cluster galaxies. One measure of the number of galaxies in a cluster is the Abell richness N_A defined as the number of galaxies with magnitudes between m_3 and $m_3 + 2$, where m_3 is the magnitude of the third brightest galaxy (Abell, Corwin, & Olowin 1989). For a Schechter (1976) luminosity function with $\alpha \approx 5/4$ and moderate richness, the Abell richness and the total optical luminosity of the cluster are related by $L_{\rm opt} \approx 1.5 N_A L^*$, where L^* is the characteristic Schechter luminosity. The absolute magnitude corresponding to L^* is roughly $M_V^* \approx -21.9$ (Schechter 1976). Using standard values for the rate of stellar mass loss from ellipticals (Renzini & Buzzoni 1986), the rate of mass loss from an L^* galaxy is $\sim 0.6\ M_\odot\ {\rm yr}^{-1}$. Then the total rate of stellar mass loss from the galaxies in a cluster with an Abell richness of N_A is

$$\dot{M}_* \approx 100\left(\frac{N_A}{100}\right) M_\odot\ {\rm yr}^{-1} . \quad (1)$$

Since spiral galaxies have higher mass-loss rates than ellipticals, the rate might be somewhat higher.

If we assume that all of the gas from cluster galaxies is stripped (see § 4), then equation (1) gives the rate of deposition of interstellar gas in the intracluster medium. This rate is too small to significantly affect the total amount of intracluster gas in a Hubble time (by about two orders of magnitude). Yet it is comparable to the cooling rates inferred at centers of cooling flow clusters, which are typically (Arnaud 1988)

$$\dot{M}_{\rm cool} \approx 100\ M_\odot\ {\rm yr}^{-1} . \quad (2)$$

Thus, it is possible that a substantial portion of the cooling gas originated recently as stripped interstellar gas, which may have never been fully mixed with the ambient intracluster gas or heated to the temperature of this gas. Such a scenario predicts that the cooling rate and richness of clusters be proportional to one another. One problem with this picture is that there exist a large number of rich clusters which show no evidence for cooling flows (the Coma cluster being one example). Possible resolutions to this problem might be (1) that a recent merger of subclusters has heated the gas and disrupted the cooling flow (Fabian, Nulsen, & Canizares 1984; McGlynn & Fabian 1984; Stewart et al. 1984), (2) that the cluster is irregular and lacks a single center to focus the infalling stripped gas, and/or (3) that stripping requires high-density ICM that may be found mainly in cooling flow clusters (see § 4).

3. STRIPPING WITHIN THE COOLING FLOW

In the previous section, we considered the total rate of stripping of gas from galaxies located throughout the cluster. In order to participate in a central cooling flow, gas stripped from galaxies in the outer portions of a cluster would have to fall into the center of the cluster before either cooling, or being heated by thermal conduction, or mixing with the intracluster gas. Before considering the motion of the stripped gas from the outer regions of the cluster, we consider whether the gas stripped from galaxies within the cooling flow region might provide an important source of cooling gas. Assuming that the galaxies in the cluster are distributed with a King law distribution with a core radius $a \sim 0.25$ Mpc, at any given time the number of galaxies within the radius of the cooling flow $r_c < a$ is roughly

$$N_{\rm cool} \approx 0.15 N_A\left(\frac{r_c}{a}\right)^3 . \quad (3)$$

If these galaxies are stripped of interstellar gas at the same rate that it is produced (the stellar mass-loss rate), then the amount of stripping within the cooling radius is

$$\dot{M}_*(\le r_c) \approx 1\left(\frac{N_A}{100}\right)\left(\frac{r_c}{100\ {\rm kpc}}\right)^3\left(\frac{a}{250\ {\rm kpc}}\right)^{-3} M_\odot\ {\rm yr}^{-1} . \quad (4)$$

Obviously, this is much smaller than the cooling rate within the same region (eq. [2]). However, it is possible that the stripped gas mixes with part of the intracluster gas, so that the stripped gas only forms the "seeds" for high-density, low-entropy perturbations. To estimate the size of the density perturbations produced by this mixing, we assume that the density of the stripped ISM is much higher than that of the ICM. Under these assumptions, the average density perturbation is

$$\frac{\delta\rho}{\rho} \approx \frac{\dot{M}_*(\le r_c)}{\dot{M}_{\rm cool}} \approx 0.01\left(\frac{N_A}{100}\right)\left(\frac{r_c}{100\ {\rm kpc}}\right)^3\left(\frac{a}{250\ {\rm kpc}}\right)^{-3}\left(\frac{\dot{M}_c}{100\ M_\odot\ {\rm yr}^{-1}}\right)^{-1} . \quad (5)$$

The size of the density perturbations given by equation (5) is rather small.

Alternatively, the stripped ISM may only mix with a portion of the ambient gas. In order to estimate the effect this would have, we assume that all of the stripped gas mixes instantaneously with a portion of the ICM, which then immediately cools and drops out of the flow. The amount of stripped gas in a spherical shell with an inner radius r and an outer radius $r + dr$ is

$$\frac{d\dot{M}_*}{dr}\, dr \approx 3\left(\frac{N_A}{100}\right)\left(\frac{r}{100\ {\rm kpc}}\right)^2\left(\frac{dr}{100\ {\rm kpc}}\right)\left(\frac{a}{250\ {\rm kpc}}\right)^{-3} M_\odot\ {\rm yr}^{-1} , \quad (6)$$

Assuming $dr \ll r$. X-ray observations suggest a linear dependence of the cooling rate on radius (Thomas, Fabian, & Nulsen 1987).

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Thus, the cooling rate in the same spherical shell is

$$\frac{d\dot{M}_{\rm cool}}{dr}\,dr = \dot{M}_{\rm cool}\,\frac{dr}{r_c}\,. \tag{7}$$

Under these assumptions, the average density perturbation at radius r is

$$\frac{\delta\rho}{\rho} \approx 0.03\left(\frac{r}{r_c}\right)^2\left(\frac{N_{\rm A}}{100}\right)\left(\frac{r_c}{100\ {\rm kpc}}\right)^3\left(\frac{a}{250\ {\rm kpc}}\right)^{-3}\left(\frac{\dot{M}_c}{100\ M_\odot\ {\rm yr}^{-1}}\right)^{-1}\,. \tag{8}$$

In this limit of instantaneous cooling of the stripped gas, the size of the density perturbations decreases very rapidly as the flow moves inward.

It is now well-established that linear perturbations cannot cool fast enough to explain the rate at which mass appears to be dropping out of cooling flows (e.g., Balbus & Soker 1989; Malagoli, Rosner, & Bodo 1987). From equations (5) and (8), the perturbations produced by gas stripped from galaxies within the cooling radius in steady state are too small to explain the observed cooling. Thus, if stripped interstellar gas contributes significantly to the mass or the density fluctuations in cooling flows, much of this gas must originate in galaxies which are generally located outside the cooling radius. The dense gas stripped from galaxies beyond the cooling radius may fall into the central region of the cluster. Alternatively, if many galaxies have radial orbits, they would pass through the inner region of the cluster where the ambient density is high and stripping is efficient.

4. STRIPPING RATES FOR ELLIPTICALS

Gas may be stripped from cluster galaxies in a steady fashion. However, galaxies with elliptical orbits or falling into the cluster for the first time may be stripped suddenly when they encounter sufficiently dense intercluster gas (Takeda, Nulsen, & Fabian 1984). Although the latter case is likely to be quite important, it requires detailed knowledge of the orbits of galaxies in clusters. In this treatment, we will assume that the stripping occurs in a steady manner. We will consider the stripping of elliptical galaxies, since these form a major portion of the galactic population in clusters. We use the results of the steady state numerical simulations of Gaetz, Salpeter, & Shaviv (1987). They find that the stripping efficiency depends on a single parameter

$$\xi = \nu\omega^{0.7}\,, \tag{9}$$

where ν is the ratio of the mass flux of intracluster gas to the average mass flux within the galaxy generated by stellar mass loss, and ω is the square of the ratio of the velocity of the galaxy v to its average escape velocity. Substituting numerical values, the stripping parameter becomes

$$\xi = 9\left(\frac{n_p}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{v}{10^3\ {\rm km\ s}^{-1}}\right)^{2.4}\left(\frac{R_{\rm gal}}{10\ {\rm kpc}}\right)^2\left(\frac{\dot{M}}{1\ M_\odot\ {\rm yr}^{-1}}\right)^{-1}\left(\frac{\sigma_*}{300\ {\rm km\ s}^{-1}}\right)^{-1.4}\,, \tag{10}$$

where n_p is the proton number density in the ICM, $R_{\rm gal}$ is the effective radius of the galaxy, $\dot{M}$ is the stellar mass-loss rate for the galaxy, and σ_* is the central, one-dimensional velocity dispersion of stars within the galaxy. For the stellar population in elliptical galaxies, $(\dot{M}/L_B) \approx 1.5 \times 10^{-11}(M_\odot\ {\rm yr}^{-1}/L_\odot)$ (Faber & Gallagher 1976; Renzini & Buzzoni 1986), where L_B is the blue optical luminosity of the galaxy.

For elliptical galaxies, there are correlations between $R_{\rm gal}$, σ_*, and L_B. Davies et al. (1983) find

$$\sigma \approx 260\ {\rm km\ s}^{-1}\left(\frac{L_B}{10^{11}\ L_\odot}\right)^{0.255}\,, \tag{11}$$

$$R_{\rm gal} \approx 7.3\ {\rm kpc}\left(\frac{L_B}{10^{11}\ L_\odot}\right)^{0.575}\,. \tag{12}$$

Using these correlations, equation (10) becomes

$$\xi \approx 4\left(\frac{n_p}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{v}{10^3\ {\rm km\ s}^{-1}}\right)^{2.4}\left(\frac{L_B}{10^{11}\ L_\odot}\right)^{-0.2}\,. \tag{13}$$

Gaetz, Salpeter, & Shaviv (1987) find that most of the gas is stripped from the galaxy if $\xi \gtrsim 0.5$. Thus, the condition for stripping becomes

$$\left(\frac{n_p}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{v}{10^3\ {\rm km\ s}^{-1}}\right)^{2.4} \gtrsim 0.1\left(\frac{L_B}{10^{11}\ L_\odot}\right)^{0.2}\,. \tag{14}$$

Note that the stripping condition is rather insensitive to the luminosity of the galaxy involved. Although larger galaxies produce more interstellar gas, it is spread over a larger area. The rate of stellar mass loss per unit area is proportional to the surface brightness of the galaxy, and larger ellipticals actually have slightly lower surface brightnesses than fainter galaxies. Their deeper potential wells more than make up for this, but the result is that the steady state stripping of ellipticals is nearly independent of the luminosity of the galaxy.

Within the cooling flow, the cooling time is less than the age of the galaxy. The outer boundary of the cooling flow (the cooling radius r_c) is usually taken to be the point at which the cooling time equals the age. Assuming isochoric cooling and taking the age to

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be 10^{10} yr, the proton density at the cooling radius is

$$\left(\frac{n_c}{10^{-3}\ \mathrm{cm}^{-3}}\right) \approx 4.7\left(\frac{T_g}{7\times 10^7\ \mathrm{K}}\right)^{1/2}, \quad (15)$$

where T_g is the gas temperature at the cooling radius. In the outer parts of clusters, the gas density usually falls off roughly as r^{-2} (Jones & Forman 1984). For simplicity, we assume that the gas density profile in the cluster is

$$n_p = n_c\left(\frac{r}{r_c}\right)^{-2} \quad (16)$$

outside of the cooling radius. Then the galaxies in a cluster with a cooling flow will be stripped out to a radius r_s, where

$$r_s \approx 1.3\left(\frac{\sigma}{10^3\ \mathrm{km\ s}^{-1}}\right)^{1.7}\left(\frac{r_c}{100\ \mathrm{kpc}}\right)\mathrm{Mp}, \quad (17)$$

and σ is the cluster one-dimensional velocity dispersion. Although the stripping condition is nearly independent of galaxy luminosity, equation (17) assumes $L_B = L^*$, where L^* is the characteristic galaxy luminosity. Equation (17) also assumes that the galaxies all have the rms velocity $v = (3)^{1/2}\sigma$. In X-ray clusters, the gas temperature is found to vary in proportion to the square of the velocity dispersion, with $T_g \approx 6\times 10^7$ K $(\sigma/10^3\ \mathrm{km\ s}^{-1})^2$ (Smith, Mushotzky & Serlemitsos 1979). This relationship was also substituted into equation (15).

Thus, in clusters where the central density is high enough for a cooling flow to occur, galaxies will be stripped throughout most of the cluster. If one includes the effects of noncircular galaxy orbits, a galaxy located outside r_s is likely to be carried inside of this radius during a portion of its orbit. In a non–cooling-flow cluster, the central density can be much lower, and the stripping radius may be a small fraction of the cluster radius. This does not mean that stripping does not occur, but just that the high-density ISM is not stripped as efficiently.

5. EVOLUTION OF THE PERTURBATIONS

In this section, we study the evolution of the low-entropy blobs, emphasizing the importance of an interior magnetic field. One point should be kept in mind; for linear density perturbations in a cooling flow without a magnetic field, buoyant oscillations suppress the growth of thermal instabilities (Balbus & Soker 1989; Malagoli, Rosner, & Bodo 1987). Even without this suppression, the growth rate of the linear perturbations is too small to cause the perturbations to decouple from the main flow at the large radii at which gas appears to be leaving the flow (Nulsen 1987). For nonlinear perturbations, the amplitude of the displacement is large compared to the scale height, and this buoyant stabilizing effect may not occur (Nulsen 1986; Balbus & Soker 1989).

Nulsen (1986) treats the evolution of dense blobs undergoing infall in cooling flows. When the blobs move rapidly relative to the ambient gas, they tend to break up because of the induced interior pressure gradients (Nulsen 1986). A good fit to Nulsen's condition for the break up is $(\delta\rho/\rho_e) \gtrsim (a/r)$. Since we are interested in nonlinear perturbations with $\delta\rho/\rho \gtrsim 0.5$, all such blobs will break up according to this criterion, since $a/r \lesssim 0.5$. Eventually the blobs might become small enough for heat conduction from the ambient medium to evaporate them, even if thermal conduction is partially suppressed by the magnetic field.

Let us examine the role played by a magnetic field inside a blob by examining the evolution of the magnetic field in eddies. As a result of turbulence in the galactic wake, we assume that vortices are formed, which preserve their identities and evolve to become independent blobs. Their vorticities and interior magnetic fields help to preserve their integrity. Weiss (1966) simulates the evolution of an uniform magnetic field within a rotating fluid eddy. Three main features appear in his calculations. First, the large-scale magnetic field is expelled from the eddy, and the amplitude of the large-scale field drops essentially to zero. This is true only for the component of the magnetic field which varies on scales which are larger than the eddy size; small-scale fields within the eddy are not influenced by the rotation of the eddy relative to its surrounding. Second, the magnetic field within the eddy is concentrated at its edges, becoming azimuthal. Finally, the magnetic field within the eddy becomes almost completely disconnected from the surrounding field. The time for the field to diffuse out of the eddy is of the order of $\tau \simeq R_m^{1/3}L/v$, where R_m, L and v are the magnetic Reynolds number, eddy size, and rotation velocity, respectively. The magnetic Reynolds number in the ISM or ICM is very high, and resistive diffusion is apparently not an important process; however, turbulent diffusion of the magnetic field may be much more rapid, with the turbulent magnetic Reynolds number being $R_{tm} \sim 10$ (Parker 1979, p. 522). This means that the large-scale field (larger than the blob size) can be expelled from the eddy in a few turnover times L/v. However, the small-scale interior field is not greatly influenced by the relative rotation of the blob and the surrounding gas.

The results of Weiss (1966; see also Parker 1979, § 16.6) point to an important role for the magnetic field in dense blobs in the ICM. The disconnection of the interior magnetic field from the ambient field ensures that heat conduction will be ineffective between the denser, cooler blob and the surrounding hot gas. The high magnetic pressure and surface tension at the edges of the eddy make it more robust against instabilities. Small-scale turbulence can increase the small-scale magnetic field inside the eddy. Numerical simulations of magnetized jets (Clarke, Norman, & Burns 1986; Lind et al. 1989) show that the magnetic field inside the jet makes the jet surface smoother. That is, the magnetic field can suppress Kelvin-Helmholtz instabilities (Chandrasekhar 1961), and thus reduce mixing with the ambient gas.

The pressure difference across a blob generated by its motion through the ambient gas is $\Delta P \approx \rho_e v_t^2$, where ρ_e is the ambient gas density, $v_t \approx v_K[(\delta\rho/\rho_e)(a/r)]^{1/2}$ is the terminal velocity, and v_K is the Keplerian velocity. The tension of the magnetic field is of the order of $B^2/4\pi$, and magnetic tension will be insufficient to prevent the destruction of the blob if $\Delta P \gtrsim \epsilon^2 B^2/4\pi$. This condition was derived for a cylindircal twisted magnetic flux tube by Parker (1979, § 9.8, eq. [9.115]), where he showed that the relevant magnetic field is the azimuthal component (taken here to be a fraction ϵ of the total field).

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This gives the condition for break up as

$$\left(\frac{\delta\rho}{\rho_e}\right)\left(\frac{a}{10^{-4}r}\right) \gtrsim 32\left(\frac{n_P}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{v_\mathrm{K}}{1000\ \mathrm{km\ s}^{-1}}\right)^{-2}\left(\frac{\epsilon B}{1\ \mu\mathrm{G}}\right)^{2} . \tag{18}$$

If a blob is unstable, it breaks up into smaller blobs which eventually are stable. The magnetic field will stabilize blobs if their mass is lower than the limit

$$M_\mathrm{blob} \lesssim 5000\left(\frac{r}{100\ \mathrm{kpc}}\right)^{7}\left(\frac{r_c}{100\ \mathrm{kpc}}\right)^{-4}\left(\frac{n_c}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-2}\left(\frac{\rho_i}{\rho_e}\right)\left(\frac{\delta\rho}{\rho_e}\right)^{-3}\left(\frac{v_\mathrm{K}}{1000\ \mathrm{km\ s}^{-1}}\right)^{-6}\left(\frac{\epsilon B}{1\ \mu\mathrm{G}}\right)^{6} M_\odot , \tag{19}$$

where equation (16) was used to substitute for the ambient density. Since the limiting mass of a stable blob decreases strongly with decreasing radius from the cluster center, infalling blobs will become unstable and break up at smaller radii unless the magnetic field increases with decreasing radius at least as rapidly as $r^{-7/6}$. For an isotropic, frozen-in magnetic field within a blob whose density goes as rapidly as that of the ambient gas, one expects $B \propto r^{-4/3}$. This crude estimate suggests that magnetic fields can stabilize blobs at all radii.

Consider the rate of infall of a magnetically stabilized blob. Substituting the stability limit (eq. [18]) into the expression for the terminal velocity v_t, and taking the ambient gas density profile from equation (16), the velocity of infall of a stable blob is

$$v_t \lesssim 57\left(\frac{r}{r_c}\right)\left(\frac{n_c}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1/2}\left(\frac{\epsilon B}{1\ \mu\mathrm{G}}\right) \mathrm{km\ s}^{-1} . \tag{20}$$

The total infall time from radii of r_1 to r_2 is then

$$\tau_{12} = -\int_{r_1}^{r_2}\frac{dr}{v_t} \gtrsim 1.7\times 10^{9}\left(\frac{r_c}{100\ \mathrm{kpc}}\right)\left(\frac{n_c}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{\epsilon B}{1\ \mu\mathrm{G}}\right)^{-1}\ln\left(\frac{r_1}{r_2}\right)\ \mathrm{yr} . \tag{21}$$

Although it depends on the uncertain values of ϵ and B, the infall time is on the order of the cluster age or shorter.

The mass of a surviving blob given in equation (19) depends strongly on properties of the cluster and on the magnetic field. If the stripped ISM gas has a strong, large-scale magnetic field, large blobs of low entropy will be able to survive. This might be expected if the gas is stripped from a single spiral arm of a late-type galaxy. Such massive clouds will fall rapidly into the center of the cooling flow and may form the observed optical filaments. The evolution of dense blobs inside the cooling radius was also discussed recently by Loewenstein and Fabian (1990).

The preceding discussion has dealt with the dynamical stability of the blobs of stripped gas and their ability to survive into the cooling region of the cluster. It is also important to consider their thermal evolution as they drop toward the cluster center. The blobs initially will have a lower temperature and specific entropy than the surrounding gas and will maintain pressure equilibrium during infall. In order to reach the cooling radius of the cluster, the blobs must have roughly the same specific entropy as the ambient cluster gas at that radius. In detail, the specific entropy of the blobs must be slightly less than that of the ambient gas at the cooling radius if the blobs are the source of the most rapidly cooling gas within the cooling flow. If the blobs had a much lower entropy than that of the ambient gas at the cooling radius, then they would cool completely before they reach the cooling radius. If the blobs had a much higher entropy than the ambient gas at the cooling radius, the blobs would be positively buoyant and would not fall into the cooling flow region. Is it plausible that the blobs of stripped interstellar gas would have roughly the correct specific entropy?

First of all, consider the variation of the cooling time as the blobs fall into the cluster center. We assume that the blobs remain in pressure equilibrium with the ambient gas, whose pressure is $P_e(r)$. Let the cooling rate per unit volume in the blob be given by $n^2\Lambda(T)$, where T and n are the temperature and proton density of the blob, respectively. The cooling time t_cool varies as $t_\mathrm{cool} \propto (T/n\Lambda)$. The cooling function Λ can be crudely approximated as a power law, $\Lambda(T) \propto T^\alpha$ for the temperature range $10^5 \lesssim T \lesssim 10^9$, one finds that $-0.6 \lesssim \alpha \lesssim 0.5$ for a solar abundance plasma. The cooling time of a blob will then vary as $t_\mathrm{cool} \propto T^{2-\alpha}/P_e$. Let us assume for the moment that the cooling time is long, so that the blob evolves adiabatically. Then the temperature and pressure are related by $T \propto P_e^{2/5}$, and the cooling time varies with the external pressure as $t_\mathrm{cool} \propto P_e^{-(1+2\alpha)/5}$. If the blobs are not too cool ($T \gtrsim 10^{6.5}$), then the relevant value of the cooling function exponent is $\alpha > -0.5$; at high temperature ($T \gtrsim 10^{7.5}$), α reaches the thermal bremsstrahlung value of $\alpha = 0.5$. Thus, the cooling time decreases with increasing ambient pressure. Since the ambient pressure must increase toward the cluster center, the cooling time decreases as the blob falls inward. Now, if the blob has roughly the same entropy as the ambient gas at the cooling radius, then its cooling time at that radius is about the age of the cluster. Since the cooling time increases with increasing radius, the cooling time of the infalling blobs is much longer than their age everywhere outside of the cooling radius. This means that the compression of the infalling blobs will be adiabatic.

We now consider "plausible" values for the properties of the ambient gas and of the blobs. Observations of the X-ray spectra of clusters of galaxies suggest that the intracluster gas is more nearly isothermal than adiabatic (e.g., Sarazin 1986). Let us assume that the ambient gas temperature is fixed at $T_e \approx 8 \times 10^7$ K. The X-ray surface brightness profiles of clusters indicate that the gas density varies approximately as r^{-2} in the outer parts of the cluster (Jones & Forman 1984), so that the gas pressure should decrease roughly as $P_e \propto r^{-2}$. We take a typical value of the cooling radius of $r_c \approx 100$ kpc. Now consider gas which is stripped from a galaxy in the cluster at an average cluster radius of $r \sim 1$ Mpc. The pressure at this radius will be $\sim 10^2$ times smaller than the pressure at the cooling radius. Assume that the gas which is stripped initially has a temperature of 10^7 K, which is the typical temperature associated with gas in hydrostatic equilibrium in a galaxy and is the temperature of the gas observed in elliptical galaxies (Forman, Jones, & Tucker 1985). As the stripped gas falls inward and is compressed adiabatically, its temperature will vary as $T \propto P_e^{2/3}$. As

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the ambient pressure increases by $\sim 10^2$, the temperature will increase by $10^{4/5}$ to a value of $\sim 6 \times 10^7$ K, which is slightly lower than the typical value of the intracluster gas temperature. This simple argument suggests that the stripped gas will arrive at the cooling radius with an entropy which is comparable to and possibly somewhat smaller than the entropy of the ambient intracluster gas. As noted above, this is just the condition which is required so that the blobs of stripped gas can reach the cooling radius before either cooling completely or being arrested by buoyancy.

6. DISCUSSION

It was demonstrated that stripping the ISM from cluster's galaxies can supply the approximate amount of low-entropy gas to explain the observed cooling rates in cluster cooling flows. Of course, the cooling of diffuse intracluster gas and of cooler blobs formed by other mechanisms may also contribute to cooling flows, and the infalling blobs may entrain intracluster gas. In any case, substantial amounts of the cooling gas can originate as stripped ISM.

What happens in clusters without cooling flows? It has been suggested that all clusters have cooling condensations, but that the cooling is not focused in the non–cD clusters (Fabian et al. 1984). Together with the less efficient stripping in a cluster where the cooling time is long (eq. [17]), we expect the X-ray emission by stripped gas to be much less prominent in the non–cooling-flow clusters. A recent merger of subclusters may also disrupt the infall of dense cooling blobs (Takeda et al. 1984).

From equation (19), we see that the blobs can be in the form of a massive condensation. Such massive blobs can disrupt and bend radio jets, especially the wide-angle–tail (WAT) radio sources associated with cD galaxies (Burns 1986). Burns et al. (1986) discussed the bending mechanisms of the WAT radio source 1919+497 associated with the cD galaxy of a rich X-ray cluster. The two jets of this radio source are bent sharply at a distance of ~ 200 kpc from the center. They suggest that each jet collides with a cloud, which must be more massive than $\sim 2 \times 10^9\ M_\odot$ with a typical radius of ~ 10 kpc. This is much more massive than the stable blob mass given by equation (19). However, the stable blob mass is very sensitive to few parameters. Moreover, WAT radio sources are found primarily in non–cooling-flow clusters (Burns 1990). We argued above that the blobs of stripped ISM exist in the inner regions of these clusters. Note that the mass limit in equation (19) increases rapidly when the ICM density is lowered. Another possibility is that the jets collide with a group of many clouds originating from the same galaxy. If these blobs have not separated significantly, they might act on the jets as a single entity.

What are the constraints on the properties of blobs of stripped galactic gas from existing observations? What new observations are needed to test this stripping scenario? The modest amount of observational data available for comparison with the stripping hypothesis lend support to this idea. The X-ray tail extending northward from NGC 4406 has been interpreted as a stripping event (Forman et al. 1979) within the Virgo cluster. Far-infrared emission (100 μm) is seen in the X-ray tail (Knapp, Guhathakurta, & Jura 1989), which suggests that cool gas and dust is also present. If a parcel of gas of the type described by equation (19) were to cool, it might be observed in neutral form. Neutral clouds of gas have been detected in 21 cm H I absorption line measurements toward radio continuum sources in the three clusters: Perseus (Jaffe 1987), 2A 0335+096, and MKW 3's (McNamara, Bregman, & O'Connell 1991). For these objects, the width of the H I absorption feature (~ 100 km s^{-1}) is considerably greater than what would be expected from a single cloud. McNamara et al. (1991) estimate that at least 40 individual clouds give rise to the absorption. If these clouds are supported by thermal pressure and are in equilibrium with their surroundings, then they must be small, with $M_{\rm cloud} \lesssim 1\ M_\odot$, and $r_{\rm cloud} \ll 1$ pc. Such clouds would have been stable when hot (according to eq. [19]) and may be evidence that the breakup into small stable units of gas did occur before the onset of radiative cooling.

The 10^4 K emission-line gas seen in clusters such as Perseus (Cowie et al. 1983) is filamentary. Such filaments could be the result of cooling wakes that have fallen into the central region of the cluster where they become ionized.

During the next decade, it should be possible to make observational tests of the stripping hypothesis. The most powerful test would to search for the presence of stripped gas that is mixing with the hot ambient medium. If a galaxy is undergoing stripping and mixing, an X-ray image will reveal a galactic wake whose temperature is below that of the ambient medium and with a correspondingly higher emission measure. Another prediction of the stripping picture is that cooled gas should exist throughout much of the cluster. It may be possible to detect this cold gas in absorption, either by using background active galactic nuclei (optical and ultraviolet absorption lines) or bright radio galaxies (21 cm absorption line) as background sources.

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