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GASEOUS HALOS: IMPLICATIONS FOR CLUSTER, GALAXY, AND RADIO-SOURCE EVOLUTION

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ABSTRACT

Substantial amounts of enriched gas produced during the early stages of galactic evolution can be stably contained within massive extended halos and released into the intracluster medium by galaxy collisions at a relatively late epoch. If most of the intracluster gas in rich clusters originates in this manner, the onset of ram-pressure stripping can be delayed until $z \lesssim 0.5$. Prior to this, such clusters contain many spiral and gas-rich elliptical galaxies, thereby accounting for the unusually large proportion of blue galaxies found in distant clusters. Implications are drawn for X-ray observations of rich clusters, and for the morphology of extended extragalactic radio sources.

Subject headings: galaxies: clusters of — galaxies: intergalactic medium — radio sources: extended

I. INTRODUCTION

The discovery of diffuse, enriched hot gas in many rich galaxy clusters provides important constraints on models of early galactic evolution. The lack of a substantial primordial component of the intracluster gas is suggested by its near-solar abundance of iron (Mushotzky *et al.* 1978), which requires a galactic origin for much, if not all, of the intracluster gas (Silk 1978*a*). We propose here that many galaxies initially possess massive extended halos that provide a reservoir for gas shed by stars during the early stages of galactic evolution. Whether or not the enriched gas can be retained by the galaxies has been a controversial issue (cf. Larson 1974; Schwarz, Ostriker, and Yahil 1975; De Young 1978). In fact, although we believe that retention is more likely, whether the gas collects in a static gaseous halo or forms a slowly expanding shell around the galaxy is not crucial to our argument. The important point is that the hot, tenuous outer regions of these gaseous halos are likely to be stable against cooling and infall. Only at relatively late epochs will collisions between galaxies in rich clusters release the enriched gas into the intracluster medium. We argue that the intracluster gas therefore originates at $z \lesssim 0.5$, and that this leads to a delayed onset of ram-pressure stripping of gas-rich spirals and ensuing S0 formation. This model enables us to account for the high fraction of blue galaxies observed in rich clusters at $z \sim 0.5$ and for several aspects of radio source morphology. Finally, we note two important implications. Many rich clusters at $z \gtrsim 0.5$ should not be strong, hard ($\sim$10 keV) X-ray sources, although weak, soft X-ray emission ($\lesssim$1 keV) from enriched gaseous halos may be detectable. A considerable number of the most luminous galaxies should still be undergoing substantial accretion ($\sim 1\ M_\odot\ \mathrm{yr}^{-1}$) from extended gaseous halos, possibly leading to enhanced circumgalactic X-ray emission and to activity in their nuclei.

II. HALO STRUCTURE AND MAINTENANCE

In order to account for the $\sim 10^{14}\ M_\odot$ of enriched gas found in a cluster such as Coma (dynamical mass $\sim 2 \times 10^{15}\ M_\odot$), we require the initial mass fraction of enriched gas to amount to $\sim$5–10% of the mass in galaxy halos. It is also attractive (although not necessary) to associate its origin with the formation of high M/L ($\gtrsim 1000$) remnants. Galactic evolution models are consistent with these requirements. For example, Ostriker and Thuan (1975) find that the total ejected mass of gas produced by the halo population (normalized to the *present* luminosity) is of order $100\ M_\odot\ \mathrm{yr}^{-1}\ (10^{10}\ L_\odot)^{-1}$. The requirement of a massive stellar halo source for the enriched gas implies a dynamical time scale of $\sim 10^9$ yr and a mass of enriched gas, produced by several generations of star formation with an initial mass function more highly peaked toward massive stars than the current mass function, of order $10^{11}\ M_\odot$ in a galaxy of total mass $10^{12}\ M_\odot$. With a total luminosity in the Coma cluster of $\sim 10^{13}\ L_\odot$ (adopting $H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$), we can produce $\sim 10^{14}\ M_\odot$ of enriched gas over $\sim 10^9$ yr. This model requires most of the intracluster matter in Coma to have originated from halos around the relatively luminous galaxies ($L \sim 3 \times 10^{10}\ L_\odot$) near the peak of the luminosity function (Schechter 1976). In support of this contention, we note that the contribution to the total mass from the less luminous galaxies is proportional to $L^{5/4}$ (if we use the mass-to-luminosity ratio scaling in the cores of ellipticals derived by Faber and Jackson 1976). Also, the luminous galaxies are likely to provide a greater source of enriched matter per unit luminosity, since they are systematically redder and more enriched than less luminous systems, indicative of either a higher efficiency of star formation or a greater initial reservoir of enriched gas.

a) Outflow

What is the fate of this enriched matter? Larson (1974) has argued that supernova remnants will undergo strong radiative cooling, and the interstellar gas will largely be retained in giant ellipticals. On the other hand, Schwarz, Ostriker, and Yahil (1975) and De Young (1978) have asserted that supernova-driven outflow will predominate. To attempt to clarify this situation, we note that the total energy output in supernovae ejecta (assuming that all stars greater than 8 $M_\odot$ yield 10^{51} ergs per supernova) is 10^{51} ergs per present visual solar luminosity for an initial stellar-mass function $dN/dm \propto m^{-1-\kappa}$, with $\kappa = 1.35$. This yields a ratio of supernovae ejecta energy input to galaxy binding energy of $5[100(M/L)^{-1}]$, where we have normalized to a present total mass-luminosity ratio of 100 in solar units.

However, only a fraction $\chi \equiv t_{\text{cool}}/t_*$ of this energy is available for driving a net gas outflow, if $t_*(\sim 10^8$–10^9 yr) is the time scale over which the bulk of the supernova energy is released and t_{cool} (assumed $< t_*$) is the mean time scale for the supernova remnants to radiate their entire interior energy. Even in the absence of a significant abundance of heavy elements,

$$t_{\text{cool}} = 1.2 \times 10^6 E_{51}{}^{1/8} n_a{}^{-3/4} \text{ yr} ,$$

where E_{51} is the initial energy of the remnant in units of 10^{51} ergs and n_a (cm^{-3}) is the mean ambient hydrogen density (Shull and Silk 1979). Thus it seems inevitable that $\chi \ll 1$, and radiative cooling losses are likely to account for most of the energy injected by supernova remnants.

This conclusion does assume that the individual remnants enter the shell-formation phase and undergo strong cooling prior to the occurrence of shell intersections. Failure to satisfy this condition enables continuing energy injection to occur that can overcome the cooling losses for a sufficiently great supernova rate and drive a wind. Specifically, the requirement that supernova remnants must not intersect until they reach the cooling phase imposes an upper limit to the supernova rate (cf. Larson 1974; McKee and Ostriker 1977):

$$S_{\text{crit}} = 10^{-9.34} Q^{-1} E_{51}{}^{-1.15} n_a{}^{1.76} \text{ pc}^{-3} \text{ yr}^{-1} ,$$

where the volume filling factor for remnants that have just reached the cooling phase is $1 - e^{-Q}$. This shows explicitly the importance of the assumed dependence of the supernova rate (S) (or, equivalently, star-formation rate) on density. For example, if $S \propto n_a{}^2$, then $S/S_{\text{crit}} \propto n_a{}^{0.14}$, and is insensitive to density. Larson (1974) has computed detailed models for this ratio, and finds that in particular, if the supernova rate is 1 per 100 $M_\odot$ of stars formed and we assume that a wind will occur only when the supernova-injected energy per gram of gas exceeds the escape velocity, then for a 10^{11} $M_\odot$ galaxy, a wind will not develop until $\sim$90% of the initial mass has formed into stars. For more massive galaxies, the percentage is correspondingly higher. Hence for galaxies more massive than $\sim 10^{11}$ $M_\odot$, there is insufficient energy input to remove the gaseous halos if these halos are to contain a mass fraction in gas of $\sim$10%. The above conclusions are actually conservative, since recent models for elliptical galaxy formation, based on numerical simulations of mergers (Norman and Silk 1979), suggest that star formation may actually be spread out over $\sim 10^9$–10^{10} yr, thereby substantially lowering the early supernova rate and removing any possibility of supernova ejecta driving a galactic wind in giant ellipticals at early epochs.

Although more detailed models incorporating both galactic evolution and radiative dissipation by supernova remnants are needed in order to ascertain more precisely the conditions under which the halo gas can be retained, it seems clear that massive galaxies will be able to retain their primordial gaseous halos.

b) Halo Survival

Once the initial burst of star formation is over, supernova heating can no longer provide a significant energy input into the halo. For conventional supernova rates ~ 0.5 (100 yr)$^{-1}$ (10^{11} $L_\odot$)$^{-1}$ (Tamman 1977) and adopting $E_{51} = 1$, the specific heating rate is

$$\sim 2.5 \times 10^{14} \text{ ergs g}^{-1} (10^{10} \text{ yr})^{-1} (10^{10} L_\odot)^{-1} \quad \text{per } 10^{11} M_\odot \text{ of gas} .$$

Thus it takes at least a Hubble time to heat the halo to escape temperature. It is the huge thermal capacity of the extensive ($\sim$100 kpc) gaseous halo that makes this result differ from the Mathews-Baker (1971) steady wind models. In general we conclude that *massive galaxies* ($\sim 10^{12}$ $M_\odot$) *can retain enriched gaseous halos at all phases of their evolution* (see also Bregman 1978).

It should be noted that our conclusions about the persistence of (and infall from) an extensive gaseous halo embedded in a massive dark halo are qualitatively similar to those reached by Mathews (1978) in his model for the extended X-ray source in M87. The halos that we require, however, are some two orders of magnitude less massive in both total mass and gaseous mass content than that postulated by Mathews for this exceptional galaxy.

c) Halo Structure

We now examine the structure of the resulting gaseous halos, adopting for the outer mass distribution of the halo a density $n_* = n_{*c} [1 + (r/r_c)^2]^{-m}$. If the gas (density n, pressure p) satisfies a polytropic equation of state $p \propto n^\gamma$ with index γ, then the gas distribution outside the core region (where $r \leq r_c$, $n \approx n_c$) satisfies

$$n(r)/n_c = [1 - \beta\gamma(\gamma - 1) \ln (r/r_c)]^{1/\gamma - 1} , \quad (m = 1) ,$$

where $\beta = GM_{*c}r_c^{-1}v_{sc}^{-2}$, $M_{*c} = \xi_m r_c^3 n_{*c}$, and $v_{sc}^2 = [dp/d\rho]$. For $m = 1$ (appropriate for an isothermal sphere at $r \gg r_c$), $\xi_1 = 2.7$. In the isothermal gas limit ($\gamma = 1$), $n(r)/n_c = (r/r_c)^{-\beta}$, ($m = 1$). A fundamental property of our model is that the halo gas is injected from halo stars and therefore, at least in the outer regions where cooling is unimportant, the gaseous and stellar components must have a similar radial dependence. We shall show below that thermal conduction maintains isothermality in the outer regions. Moreover, the requirement of a massive halo compels us to choose $m \approx 1$; such a density law is suggested by the dynamical data (Ostriker, Peebles, and Yahil 1974). Thus we shall subsequently set $\gamma = 1$, $\beta = 2$, and $m = 1$. In this case, the halo gas mass is $M_{11} \equiv M_h/10^{11} M_\odot = 10^{-0.3} r_2^3 n_4$, and the gas mass in the halo core is $10^9 r_1^3 n_2 M_\odot$, where $r_1 \equiv (r_c/10 \text{ kpc})$, $n_2 \equiv (n_c/10^{-2} \text{ cm}^{-3})$, $n_4 \equiv (n/10^{-4} \text{ cm}^{-3})$, and the halo radius $r_2 \equiv (r_h/100 \text{ kpc})$.

d) Thermal Stability and Infall

Can such a halo structure, once established, remain stable? To investigate this, we note that the cooling time over the temperature range 1×10^5–4×10^7 K, assuming a solar abundance of heavy elements, can be expressed as (McKee and Cowie 1977) $t_{\rm cool} = 10^{18.02} T_7^{1.6} n_4^{-1}$ s, and the conductive energy flow time scale $t_{\rm cond} = (4\pi R^3 \times 3nkT)/(4\pi R\kappa T) = 10^{16.4} r_2^2 n_4 T_7^{-5/2}$ s, where κ is the thermal conductivity coefficient, and we have set $T/\nabla T = r$, $T_7 \equiv T/10^7$ K, and evaluated the thermal energy content for an isothermal atmosphere.

It is apparent that outside the halo core, where $n \lesssim 0.01 \text{ cm}^{-3}$, we have $t_{\rm cond} \lesssim t_{\rm cool}$. Thus conductive transport of energy from the hot outer regions, where the cooling time exceeds a Hubble time, effectively inhibits cooling throughout this region with $n < 0.01 \text{ cm}^{-3}$. The reservoir of thermal energy stored in the outermost halo can maintain almost all of the halo gas at $T \sim 10^7$ K. Only within the core where $n \gtrsim 0.01 \text{ cm}^{-3}$ does thermal conductivity become unimportant, and cooling will result in continued infall and severe depletion of the gas. If the entire halo were to collapse in a free-fall time, rapid depletion would occur: this does not happen, however, because of the huge thermal reservoir in the outer halo which is too hot to fall in. Only the core can collapse, because it will not stay hot. But the total amount of gas stored in this core region is $\sim 10^9 M_\odot$ and the cooling time $\sim 10^9$ years. Thus, we infer that the effect on the outermost halo of cooling is negligible, less than 10% of the halo mass being removed even within a Hubble time. The corresponding accretion rate into the inner regions of the galaxy amounts to $\sim 1 M_\odot \text{ yr}^{-1}$. This suffices to have interesting implications for nuclear activity and optical emission lines

Our model, in which most of the enriched gas shed by halo stars stays hot, provides an alternative to the fate of the gas that was envisaged by Ostriker and Thuan (1975) in their massive halo models of galactic evolution. However, if conductive heating is suppressed (for example, by magnetic fields), a massive gaseous halo will be unstable, and it seems likely that infall would result in formation of a stellar disk. Indeed, disk formation would be inevitable after a Hubble time has elapsed for isolated systems that have retained their gas. One might speculate that these two limiting cases could in fact represent the evolution of elliptical and spiral galaxies.

III. GALAXY COLLISIONS AND RAM-PRESSURE STRIPPING

We shall now argue that the halo gas liberated in galaxy collisions constitutes most of the present intracluster gas. This result, however, is sensitive to the radial distribution of galaxies between 1 and 10 cluster core radii.

To demonstrate this, let the galaxy density vary with cluster radial distance R as $N_g = N_{gc}(R_c/R)^{2+\mu}$, where R_c is the cluster isothermal core radius and μ must be observationally determined. Between 1 and 10 core radii from the center of the Coma cluster, μ may vary between 0 (Yahil 1974) and 0.6 (Bahcall 1977). If V_g denotes the rms velocity dispersion, the galaxy-galaxy collision time at radius R is $t_c(R) = t_{c0}(R/R_c)^{2+\mu}$, where $t_{c0} = [N_{gc}\pi(r_h/2)^2 2^{1/2} V_{gc}]^{-1} = 5 \times 10^7$ ($10^3 \text{ Mpc}^{-3}/N_{gc}$) $\times$ $(r_h/100 \text{ kpc})^2$ ($2000 \text{ km s}^{-1}/V_g$) yr. The number of halos stripped at time t is $N_g(t/t_c)(1 + t/t_c)^{-1}$, and the total mass of gas produced within radius R (assuming equal halo masses are stripped per collision and $\mu = 0$) is given by

$$M_{\rm gas}(R) = \eta M_c (t/t_{c0})^{1/2} \tan^{-1} (R/R_c)(t_{c0}/t)^{1/2} ,$$

where the cluster core mass $M_c = 4\pi R_c^3 N_{gc}$ and η (~ 0.1) is the ratio of halo gas to total galactic mass. At early times, $M_{\rm gas}(R) \approx \frac{1}{2}\pi\eta M_c(t/t_{c0})^{1/2}$, and at $t \gg t_c(R)$, $M_{\rm gas}(R) \approx M_c(R/R_c)$. This result can easily be generalized to values of $\mu \neq 0$. In particular, if $\mu = 1$ there is only a logarithmic dependence of $M_{\rm gas}(R)$ on radius at times in excess of $t_c(R)$. We infer that ejection of halo gas is significant only at late times if $\mu \approx 0$. In this case, collisions therefore lead to a significant increase in $M_{\rm gas}$ at late times (after several billion years or more).

The mean intracluster gas density will rise as collisional sweeping of gaseous halos proceeds. Infall of the gas into the cluster core will result in the central gas density becoming high enough for ram-pressure stripping of the remaining gaseous halos and spiral galaxies to occur. Within $\sim 10^9$ yr galaxies within the central region ($\lesssim 10 R_c$) will be swept of gas (Lea and De Young 1977), residual gas being retained within the central bulges and the inner 20% of the disks of spiral galaxies (Tarter 1975).

The increased pressure that triggers ablation should also induce star formation in interstellar clouds, the clouds themselves being retained by the galaxies (Silk 1978*b*). Recently stripped galaxies should therefore remain blue over a period on the order of the cluster crossing time ($\sim 10^9$ yr). We suggest that the blue galaxies recently found in several rich clusters at $z \sim 0.4$ (Butcher and Oemler 1978; Spinrad 1979) are either spiral or gas-rich elliptical galaxies that have recently (within $\sim 10^9$ yr) undergone active star formation, perhaps accompanying the stripping process. Since as much as $\sim 10^9 M_\odot$ of gas would be retained in the inner disk region of a stripped Sc galaxy, the associated star formation could also result in a substantial addition to the luminosity of the resulting S0 galaxy. However, it is unlikely that most S0's, which are found outside the cores of rich clusters, are formed by ram-pressure stripping, and another formation mechanism is indicated (Norman and Silk 1979).

IV. RADIO SOURCE MORPHOLOGY

Previous evidence for the existence of massive gaseous halos (amounting to $\sim 10^{12} M_\odot$) has been based on the interpretation of extended extragalactic radio sources (van der Laan 1977). Blandford and Rees (1978) have emphasized that beam models of radio sources require a working surface where the maximum surface-brightness hot spots are observed, and suggest that this could be related to the distribution of intracluster gas. In fact, the mean linear separation for radio galaxies in the complete source sample investigated by Gavazzi and Perola (1978) is approximately 100 kpc. Moreover Lari and Perola (1978) have shown that the linear size distribution for doubles is similar both within and without Abell clusters. We therefore propose that the working surface required by beam models be identified with the extent of the massive gaseous halos rather than of the intracluster gas.

A far smaller fraction of radio doubles is found in rich clusters, as would be expected if galactic halos are mostly stripped. Primordial gaseous halos are not the only means of supplying the working surface in double sources: circumgalactic gas can also be accreted from the cluster or group environment, and double radio sources would then be associated with exceptionally massive galaxies. A higher incidence of head-tail (T) and wide-angle-tail (V) radio galaxies also appears to be present in Abell clusters. This can be understood in the context of our gaseous halo models if the V sources are due to truncated halos and the T sources are formed when the bulk of the gaseous halos have been destroyed. If the T phenomenon is indeed associated with the absence of a gaseous halo, then its occurrence need not depend on the velocity of the parent galaxy (Ulrich 1977).

Some further implications of gaseous halos may be mentioned. As the radio source reaches the edge of the halo, its morphology will change. In a number of sources with radio jets, the jets widen significantly at a distance ~ 100 kpc away from the parent galaxy (e.g., for Bo 844+31 and 3465; van Breugel 1979).

If the fueling of the central energy source in radio galaxies is due to accretion from the gaseous halo, then there are further observational consequences. For example, denser, more massive halos will lead to greater accretion rates and more powerful radio sources, and will be found most frequently outside of rich clusters. The extended components of these sources will have steeper spectra as a result of enhanced synchrotron losses (denser halos possessing correspondingly higher magnetic field strengths), and the nuclei of the galaxies should exhibit systematically stronger emission lines.

V. FURTHER IMPLICATIONS

To avoid premature ram-pressure stripping of cluster galaxies, there should be very little primordial intracluster gas; in fact, less than 10% of the current gas mass can be primordial. We therefore predict that clusters which display the Butcher-Oemler effect, and possibly many, if not all, rich clusters at $z \gtrsim 0.5$, should have a low intracluster gas content. The predicted cluster hard X-ray luminosity will be lower by ~ 100 than for similar nearby clusters. However, many galaxies will have extensive gaseous halos which individually will emit $\sim 10^{41}$–10^{42} ergs s^{-1} in soft X-rays ($\lesssim 1$ keV). Typical cluster X-ray luminosities at $z \sim 1$ will therefore be $\sim 10^{44}$ ergs s^{-1} and will cut off sharply above 1 keV.

Despite their low surface brightness, the most luminous halos may be observable: Mrk 541 is a possible example (Cash, Charles, and Bowyer 1979), as is M87. If many galaxies possess massive gaseous halos, the resulting contribution to the diffuse soft X-ray background could be significant. It would be of interest to search for such a feature: it could possess a unique signature due to line emission from the enriched halo gas. The halo gas is likely to be associated only with the more massive galaxies, with $kT \sim 1$ keV. These galaxies could possibly comprise galaxies that have an active phase. One might retain only the gaseous halos in the ellipticals, with disk formation occurring in spiral and S0 galaxies (cf. Binney and Silk 1978).Because disk formation occurs late, necessarily after cluster formation, one might expect infall also to result in substantially bluer field galaxies, even at modest redshifts. This is a speculation, of course, and further implies that substantial halo gas could still be retained in spirals. It would be of interest to search the outer regions of isolated galaxies for diffuse soft X-ray emission. The predicted emission measure could be as large as $\sim 10^{-3}\, n_4{}^2 r_2$ cm^{-6} pc, with a corresponding surface brightness $\sim 4 \times 10^{-9}\, T_7{}^{-1/2} n_4{}^2 r_2$ ergs (cm^2 s sr)$^{-1}$. Consideration of the sensitivity and field of view of *DEAO* $\frac{1}{2}$ suggests that detection is possible for galaxies at a distance $\gtrsim 30$ Mpc, where the halo subtends $\lesssim 10'$; gaseous halos around nearby spirals, such as M31, would probably be indistinguishable from the diffuse X-ray background. For our nominal parameters ($n_4 \sim 1$, $r_2 \sim 1$), a $3\,\sigma$ detection should be possible within $\sim 10^4$ s using the *HEAO 2* IPC detector. A further implication is that many ellipticals at $z \gtrsim 0.5$ should reveal evidence for optical emission. Filamentary structure may also persist in the halos from early supernova activity during the halo formation phase, where radiative dissipation in shocks in the initially high ambient density gas may lead to formation of dense filaments.

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