A COMPARISON OF METAL ENRICHMENT HISTORIES IN RICH CLUSTERS AND INDIVIDUAL LUMINOUS ELLIPtical GALAXIES

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ABSTRACT

The large spatial extent of hot, X-ray emitting gaseous halos around massive elliptical galaxies indicates that most of this gas has not been generated by stellar mass loss. Instead, much of this gas results from an intergalactic gaseous inflow toward the overdensity from which giant ellipticals and their associated galaxy groups formed. Since these hot gaseous halos are old, they contain important information about the star formation history of elliptical galaxies. In this paper we show that the enrichment history of this hot gas is closely linked to its gas dynamical history; supernovae provide both energy and metal enrichment. We find that Type II supernovae based on a Salpeter IMF, plus a small number of additional Type Ia supernovae, can explain the density, temperature and abundance profiles currently observed in gaseous halos around massive ellipticals. Within the central, optically bright region of luminous ellipticals, approximately half of the interstellar iron is produced by Type Ia supernovae and half by mass lost from evolving stars which were originally enriched in iron by Type II supernovae. However, iron and silicon abundances in the intracluster gas within rich clusters suggest enrichment by a larger number of supernovae per unit optical light than we require for massive ellipticals. The additional supernovae implied by cluster data cannot be reconciled with our models for individual massive ellipticals. Evidently, rich clusters cannot be constructed by simply combining ellipticals and their associated groups since the enrichment history of clusters and massive ellipticals appears to be fundamentally different. Neither currently discussed resolution of this discrepancy – increased number of Type II supernovae (flat IMF) or strong Type Ia enrichment in clusters – is attractive. Although the global hot gas iron abundance is similar in all large galaxy clusters, silicon is enhanced in hotter, richer clusters. This Si/Fe variation implies that E and S0 galaxies are not the only sources of cluster gas enrichment; perhaps spirals or low mass galaxies are also important.

Subject headings: galaxies: elliptical and lenticular – galaxies: formation – galaxies: evolution – galaxies: cooling flows – x-rays: galaxies

1. INTRODUCTION

Luminous elliptical galaxies are the astronomical analog of tree rings or geological core samples – within the hot gas in these massive galaxies resides important information about the earliest stages of galaxy formation and the enrichment of the cosmos with heavy elements from the first generations of stars. The
stellar density profile and low rotation of bright ellipticals indicate that they were assembled from smaller galactic objects containing stars. The most likely sites for the formation of giant elliptical galaxies are small groups of galaxies where mutual tidal interactions are strong and the likelihood of galactic merging is enhanced. In an idealized version of this formation hypothesis, the merging process within the group comes to completion after a few dynamical times when the massive central elliptical has consumed the dark and luminous matter of many original group galaxies of moderate mass. When this happens, the merging process shuts down and the elliptical evolves passively as a group-dominant elliptical in the field or enters a large cluster. While there is clear evidence that some massive ellipticals contain younger stars and must have suffered significant mergers since the epoch of most intense galaxy formation, there is also evidence that other more venerable ellipticals have survived until the present time, relatively undisturbed by events that have occurred since their formation at early times. The hot interstellar gas in these old galaxies is most interesting since it still contains information about the earliest stages of star formation, including the heating and enrichment of the gas by supernovae.

In this paper we investigate the production of iron and silicon by Type Ia and Type II supernovae (SNIa and SNII respectively) and follow the dynamical redistribution of these metals in the hot interstellar and intragroup gas until the present time. Gas enrichment and dynamical evolution are linked since the collective energy released by Type II supernovae can expel metal-enriched gas from elliptical galaxies in a wind. The energetics of Type II supernovae during early star formation can be constrained by comparing heavy metal abundances expected from evolutionary gas dynamical calculations with abundances provided by X-ray observations of individual massive ellipticals. In a similar fashion, metal abundances observed in rich clusters of galaxies provide global enrichment constraints on early type galaxies which are generally regarded as the principal source of metals in the intracluster gas. Rich clusters are thought to have retained all of the products of supernova enrichment either within galactic stars or in the hot intrachuster medium. In this sense rich clusters are closed boxes. From an observational standpoint individual massive elliptical galaxies are certainly not closed boxes since most of the metals produced by supernovae have been carried out by supernova-driven winds. Much of these metals now resides in low density gas at large distances from the optical galaxy where detection is difficult or where the metal enriched gas has been tidally or dynamically removed. From the standpoint of our gas dynamical models, however, individual ellipticals are closed boxes since we can accurately follow the products of supernova enrichment into distant regions of very low density.

Thermal X-ray emission from hot circumgalactic gas surrounding many bright ellipticals often extends far beyond the optical image of the galaxy (Mathews & Brighenti 1998a). The large mass and extended spatial distribution of this gas cannot be understood only from normal evolutionary stellar mass loss. Our dynamical models indicate that the most distant gas in these galactic halos has accumulated by secondary infall into the perturbation that initially led to the formation of the group and its dominant elliptical (Brighenti & Mathews 1998a, 1998b; Mathews & Brighenti 1998b).

The objective of our recent gas dynamical calculations has been to follow the evolution of the hot gas within and around massive elliptical galaxies since the time of galaxy formation. A successful model can reproduce the radial density and temperature distributions as determined from X-ray observations. In our recent models we begin with an overdensity perturbation in a simple flat cosmology. As dark matter accumulates in the core of the growing perturbation, we assume that a stationary NFW dark matter halo is formed (Navarro, Frenk and White 1996). Exterior to this stationary halo the dark matter inflow is identical to the cosmic similarity flow of Bertschinger (1985). The baryonic gas evolves in this time-dependent potential: flowing inward, shocking at some radius and radiatively cooling near the center. At some early
time, $t_*$, when enough baryons have accumulated in the perturbation, we form the de Vaucouleurs profile of the large elliptical observed today. By this means we circumvent the complex merging processes that occurred at very early times. Nevertheless, our calculation globally conserves dark and baryonic mass and treats the gas dynamics in full detail from $t_*$ to the present time. In these simple models we release the Type II supernova energy at the same time $t_*$ that the stellar system is formed but the Type Ia energy is released from $t_*$ to the present according to some assumed variable rate.

However, there is a degeneracy in our successful solutions. We find that the hot gas density and temperature profiles typical of massive ellipticals, $n(r)$ and $T(r)$, can be reproduced with different combinations of the fundamental model parameters: the time of star formation $t_*$, the total SNII energy released $E_{II}$, and the universal baryon mass fraction $\Omega_b \approx 0.05 \pm 0.01$ as determined by big bang nucleosynthesis (Walker et al. 1991). For example, solutions with $\Omega_b$ decreased by $\sim 0.01$ are similar to those with $E_{II}$ increased by $\sim 2$ or with $t_*$ decreased by $\sim 1$ Gyr.

Much of the degeneracy involving these uncertain parameters can in principle be removed by considering the abundance and of iron and other elements produced in supernovae. The total mass of heavy elements in stars and gas today is directly related to the total number of supernovae of each type that have occurred. Unfortunately, many of the essential supernova-related parameters are poorly known: the average amount of iron or silicon created in each supernova event, the total mass of these elements locked into stars today, the initial mass function (IMF), etc.

While we cannot attempt here a definitive theoretical resolution of the enrichment history of early type galaxies, we can make progress within the limitations of current theory and observational data. In view of the uncertainties involved, however, a highly detailed gas dynamical calculation including the effects of metal enrichment seems unwarranted. The approximate results we present here can be regarded as the first step in an iterative procedure that will become better defined in the future.

Nevertheless, the metal enrichment history of elliptical galaxies that we describe here is sufficient to rule out several scenarios that have been widely discussed. One of our motivations for beginning this project is the apparent dissimilarity of iron abundance and gas fraction between galaxy groups and rich clusters which led David (1997) and Renzini (1997) to remark that present-day, rich clusters cannot be assembled from present-day groups. For example, most (50% - 80%) of the mass of heavy metals in rich clusters resides in the intracluster gas where the iron mass per unit of stellar light $M_{Fe}/L_B$ consistently exceeds that in small groups or individual massive ellipticals. Moreover, the lower fraction of gas mass in galaxy groups relative to clusters indicates that much of the metal-enriched gas produced in groups or individual ellipticals has been expelled into the environment by the release of supernova energy (Arnoud, et al. 1992; David, Jones, & Forman 1995). Perhaps, therefore, the gas and iron formerly within large ellipticals and galaxy groups has been expelled by supernova-driven winds into the low density environment where it escapes X-ray detection. However, this low density, metal-enriched gas can be followed in our gas-dynamical models. In successful models the metal rich gas remaining within the galaxy must agree with the gas abundance and abundance gradients observed in these bright galaxies.

Our results reported here indicate, however, that the mass of metals that has flowed out of luminous ellipticals into their low density environment is insufficient to account for the larger mass of metals observed in rich clusters. We are therefore faced with a fundamental inconsistency: parameters that allow the intracluster gas to be enriched by galactic winds from massive ellipticals are inconsistent with detailed X-ray observations of the metal content within individual ellipticals.

The relative importance of SNII and SNIa in creating the metals observed in cluster gas has been
widely debated. The total iron abundance in rich clusters is too large to be produced by SNII with a standard Salpeter IMF. Many authors have suggested that SNIa produce enough iron to account for the additional iron required (e.g. Ishimaru & Arimoto 1997; Renzini 1997; Wyse 1997). This solution is appealing since approximately $\frac{3}{4}$ of the iron in our Galaxy is produced by Type Ia supernovae (Renzini 1997). However, we show here that the total silicon produced by both types of supernova, when considered along with additional gas dynamical constraints, indicates that SNIa produce at most only a few percent of the total iron in massive ellipticals. By contrast, if SNII are the primary source of metal enrichment in rich clusters then the IMF must be flatter than Salpeter; this solution to the iron problem has been suggested by David (1997) and Gibson, Loewenstein & Mushotzky (1997). However, the iron abundance and its radial gradient observed in massive ellipticals cannot be fit with our gas-dynamical models if the number of SNII exceeds the Salpeter value. It would appear therefore that massive ellipticals may not be the primary source of enrichment of the intracluster gas.

We begin our discussion with a review and reanalysis of the observed iron and silicon abundances in rich clusters and discuss the implications of these abundances for clusters and individual early type galaxies.

2. SUPERNOVA ENRICHMENT IN RICH CLUSTERS

The mean iron abundance observed in the hot gas in rich clusters is about 0.40 in solar units with a cosmic scatter (0.3 - 0.65) that exceeds the errors of measurement (Mushotzky 1998). These values are somewhat greater than the iron abundances quoted in the X-ray literature, most of which are based on the “photospheric” solar iron abundance (by mass) $z_{Fe,\odot}^{(ph)} = 2.66 \times 10^{-3}$ since we assume here the lower, “meteoritic”, solar iron abundance $z_{Fe,\odot} = 1.83 \times 10^{-3}$. This distinction between “meteoritic” and “photospheric” solar iron abundance was made in the review by Anders & Grevesse (1989). However, recent atmospheric models of the sun indicate that the iron abundance in the solar photosphere is similar to the so-called “meteoritic” value of Anders & Grevesse (Holweger et al. 1991; Biemont et al. 1991; McWilliam 1997). The implications of the lower $z_{Fe,\odot}$ for X-ray abundances has been discussed by Ishimaru & Arimoto (1997) and Gibson, Loewenstein, & Mushotzky (1997).

Arnaud et al. (1992) have shown that the total gas mass in the hot intracluster medium (ICM) of rich clusters $M_g$ and the mass of iron in that gas are proportional to the total optical luminosity $L_B$ of all early type galaxies in the cluster. Arnaud et al. find that $M_g$ is uncorrelated with the total $L_{B,sp}$ from spiral galaxies in these clusters. Based on these findings, it is generally assumed that early type galaxies dominate the cluster gas enrichment.

The relative contributions of Type II and Type Ia supernovae (SNII and SNIa) to the ICM metal enrichment has been widely discussed. The total mass of a particular heavy element in the ICM can be determined from the mass of that element produced by supernovae and the total number of supernova events in the past. The number of SNII events can be inferred from the total spheroidal stellar mass in the cluster, together with an assumed initial mass function (IMF) to determine the fraction of stars that become Type II supernovae. For SNIa the currently observed rate for ellipticals is poorly known and almost nothing is known about the SNIa rate at earlier times. The SNIa rate is thought to depend on mass exchange between binary stars and theory provides no unambiguous way to estimate orbital parameters and binary mass ratios. The yields of heavy metals in SNIa are thought to be known reasonably well from theoretical models while those from SNII are uncertain because of complexities in the pre-explosion evolution, uncertain reaction rates, and the unknown amount of processed material that falls back on the
stellar remnant (Woosley & Weaver 1995; Gibson, Loewenstein & Mushotzky 1997).

In view of these difficulties, the relative influence of SNII and SNIa in enriching elliptical galaxies and rich clusters must be determined largely from observations of the metal abundance in stars and gas. The enrichment history of individual ellipticals and associated groups of galaxies is difficult to access since the total energy released in all SNII is sufficient to expel a significant fraction of metal-rich gas from these systems. However, rich clusters of galaxies are massive enough to have retained all of the material processed in supernovae over cosmic time. The “closed box” nature of rich clusters is supported by the relative constancy of the ratio of baryonic to total mass for cluster masses $> 5 \times 10^{13} \, M_\odot$ (David 1997). The data assembled by Renzini (1997) indicates that metal enrichment by supernovae in rich clusters remains confined within the cluster potential; $M_g/L_B$ and the total iron mass per unit optical light $M_{Fe,g}/L_B$ are nearly constant for cluster masses $> 5 \times 10^{13} \, M_\odot$. Clusters and galaxy groups with masses less than this have lower gas to stellar mass ratios, suggesting gaseous outflow.

In determining the past history of supernova enrichment, the silicon abundance is more useful than the iron abundance. The silicon abundance has been observed in the ICM of many rich clusters and is based on a well-understood K-line emission feature so that translation into abundances should be reliable. In addition, silicon yields from SNII and possibly SNIa may be better determined from theoretical supernova models than those of iron. While the iron yield from SNII $y_{Fe,II}(m)$ increases monotonically with the pre-supernova stellar mass $m$, the silicon yield $y_{Si,II}(m)$ has a pronounced maximum at $m \sim 22 \, M_\odot$ provided the energy released by the supernova is not too large (A and B models of Woosley & Weaver 1995). Because of this maximum, the IMF-averaged yield $\langle y_{Si,II} \rangle$ is very insensitive to the choice of parameters for power law IMFs provided the upper mass limit $m_u > 22$.

Assuming that silicon is a reliable tracer of past supernova activity in rich clusters, we wish to construct an expression for the observed ratio of the total mass of silicon in the hot cluster gas (ICM) to the total optical luminosity of spheroidal system stars in the cluster,

$$\Upsilon_{Si,g} = \frac{M_{Si,g}}{L_B}.$$  

The present mass of silicon in the ICM is determined by the total mass of silicon produced by SNII and SNIa less the amount of silicon currently within stars:

$$\Upsilon_{Si,g} = \frac{M_{Si,II} + M_{Si,Ia} - M_{Si,\ast}}{L_B}. \quad (1)$$

Another important observed quantity is the currently observed silicon to iron ratio in the ICM,

$$R \equiv \left( \frac{z_{Si}}{z_{Fe}} \right)_g = \frac{M_{Si}}{M_{Fe}} = \frac{M_{Si,II} + M_{Si,Ia} - M_{Si,\ast}}{M_{Fe,II} + M_{Fe,Ia} - M_{Fe,\ast}}. \quad (2)$$

Note that $R$ is the ratio of silicon to iron masses in absolute units and is not normalized with the solar ratio. We now seek expressions for $\Upsilon_{Si,g}$ and $R$ in terms of the expected number of supernovae and the average silicon and iron yields for each supernova event.

If we assume that all stars more massive than $8 \, M_\odot$ produce SNII, the number of SNII per $M_\odot$ of stars formed, $\eta_{II}$, can be found for any assumed IMF. For a power law IMF $\phi(m)dm = \phi_0 m^{-(1+x)}dm$ the number of SNII is equal to the total number of stars more massive than $m_8 = 8 \, M_\odot$, therefore

$$\eta_{II} = \frac{N_{II}}{M_*} = \frac{x - 1}{x} m_8^{-x} - m_u^{-x}. \quad \frac{x}{m_8^{-x} - m_u^{-x}}.$$
For example, $\eta_{II} = 6.81 \times 10^{-3}$ SNII per $M_\odot$ for a Salpeter IMF (slope $x = 1.35$) having upper and lower masses of $m_u = 100 \ M_\odot$ and $m_l = 0.08 \ M_\odot$ respectively. In recent discussions of the metal enrichment of early type galaxies and galaxy clusters it has been fashionable to consider only single power law IMFs (e.g. Loewenstein & Mushotzky 1996; Ishimaru & Arimoto 1997; Gibson, Loewenstein & Mushotzky 1997) with the Salpeter slope regarded as “normal.” However, many lines of evidence in our own Galaxy suggest that the normal IMF has some curvature, becoming flatter at subsolar masses (Leitherer 1998). Scalo (1998) suggests the following triple power law approximation for a universal IMF:

$$\phi(m)dm = \phi_i m^{-(1+x_i)} dm \quad i = 1, 2, 3$$

with

$$x_1 = 0.2 \pm 0.3 \quad \text{for} \quad 0.1 < m < 1 \ M_\odot$$
$$x_2 = 1.7 \pm 0.5 \quad \text{for} \quad 1.0 < m < 10 \ M_\odot$$
$$x_3 = 1.3 \pm 0.5 \quad \text{for} \quad 10 < m < 100 \ M_\odot$$

Evaluating the specific SNII frequency for this IMF we find $\eta_{II} = 7.81 \times 10^{-3}$ which differs by less than 15 percent from the single-slope Salpeter value. In view of the many larger uncertainties involved in other parameters, we shall continue to use simple power law IMFs in this paper to determine the number of SNII, mean Type II supernova yields and the stellar mass loss rate.

The total number of SNII explosions during the entire history of rich cluster stars is $N_{II} = \eta_{II} \mathcal{M}_o$ where $\mathcal{M}_o$ is the total initial stellar mass in cluster E + S0 galaxies. The current mass of all early type galaxies in a rich cluster can be estimated from the total B-band luminosity of all cluster galaxies, $\mathcal{M}_* = (M/L_B) \mathcal{L}_B$, where $M/L_B \approx 7$ is an average mass to light ratio for bright cluster ellipticals. Assuming that star formation in ellipticals can be approximated with a single burst at time $t_*$, the stellar mass at that time was $\mathcal{M}_o = \mathcal{M}_*/(1 - \beta)$ where $\beta$ is the fraction of the initial mass that has been lost from the stars between $t_*$ and the present time $t_n$. For example, if stars form with a Salpeter IMF at time $t_* = 2$ Gyrs and $t_n = 13$ Gyrs is the present time, then $\beta = 0.3$.

Since galactic stars in rich clusters are observed to be enriched by SNII ejecta, it is clear that the single burst approximation is only an approximation. However, if most of the stars are formed in several bursts concentrated near time $t_*$, the long term stellar evolution will be little altered although the single-burst value of $\beta$ will be overestimated if some supernova-processed gas is formed into stars in nearly simultaneous multi-bursts. If a fraction $f_*$ of SNII-produced metals formed into stars at time $t_*$, then a fraction $F_* = f_*(1 - \beta)$ is still locked in stars today. The total mass of SNII-produced silicon still remaining in the intracluster gas phase today is therefore

$$(1 - \beta)^{-1} (M/L_B) \mathcal{L}_B \eta_{II} \langle y_{Si,II} \rangle (1 - F_*)$$

where the mean silicon yield $\langle y_{Si,II} \rangle$ is the IMF-averaged mass of silicon (in solar masses) generated per SNII event. The total mass of iron in the ICM from SNII is given by the same expression with $\langle y_{Si,II} \rangle$ replaced with $\langle y_{Fe,II} \rangle$. By using the single burst assumption, modified by allowing some of the SNII ejecta to form stars, we are neglecting higher order details such as second generation SNII formed from stellar ejecta.

The total amount of silicon produced in SNIa is the product of the total number of Type Ia supernovae and the silicon yield, $N_{Ia} y_{Si,1a}$. Since the past rate of SNIa explosions in ellipticals is poorly known, we represent our ignorance with a power law:

$$\frac{dN_{Ia}}{dt} = \frac{\mathcal{L}_B}{10^{10} \text{ 100yrs SNu}(t)} \text{ SNIa yr}^{-1}$$
where $L_B$ is in units of $L_{B,\odot}$ and

$$\text{SNU}(t) = \text{SNU}(t_0)(t/t_0)^{-p}$$

is the SNIa rate in SNU units (supernovae per $10^{10} L_B$ per 100 years). The total number of SNIa since $t_*$ is therefore

$$N_{Ia} = L_B \frac{SNU(t_0)}{10^{10} 100} t_0 \int_{t_*/t_0}^{t} (t/t_0)^{-p} dt/t_0 \equiv L_B N_{Ia}$$

where $n_{Ia}$ is the number of SNIa per unit $L_B$. The important parameter that governs the SNIa contribution to the observed ratios $R$ and $Y_{Si,g}$ is $n_{Ia}$ although we shall occasionally use the current SNIa rate $\text{SNU}(t_0)$ to characterize $n_{Ia}$, assuming particular values of $p$ and $t_*$. If a fraction $g_*$ of the enriched SNIa ejecta was incorporated into stars at time $t_*$, then a fraction $G_* = g_* (1 - \beta)$ remains in stars at the present time.

Finally, the current stellar iron abundance is given by

$$z_{Fe,*} = 1.4 \frac{M_{Fe,*}}{M_*}$$

(3)

where $z_{Fe,*}$ is the abundance of iron by mass in stars relative to hydrogen and $z_{Fe,*}/1.4$ is the ratio of iron mass to total mass including helium.

Following the notation introduced above, Equations (1) - (3) can be written as

$$Y_{Si,g} = \frac{M_{Si,g}}{L_B} = (1 - \beta)^{-1} (M/L_B) \eta_{II} (y_{Si,II})(1 - F_*) + n_{Ia} y_{Si,Ia}(1 - G_*),$$

(4)

$$R = \left( \frac{M_{Si}}{M_{Fe}} \right)_g = \left( \frac{1 - \beta}{1 - \beta} \right)^{-1} (M/L_B) \eta_{II} (y_{Fe,II})(1 - F_*) + n_{Ia} y_{Fe,Ia}(1 - G_*),$$

(5)

and

$$z_{Fe,*} = 1.4[(1 - \beta)^{-1} \eta_{II} (y_{Fe,II}) F_*(1 - G_*) + (M/L_B)^{-1} n_{Ia} y_{Fe,Ia} G_*].$$

(6)

If SNIa do not contribute to the enrichment of the stars, then the ratio of stellar silicon and iron must be in proportion to SNI yields, $z_{Fe,*} = z_{Si,*} (y_{Fe,II})/(y_{Si,II})$; equation (6) reduces to this simple expression when $n_{Ia} = 0$ or $G_* = 0$. With the total number of SNIa regarded as a parameter, we shall solve the three equations above for the most uncertain remaining parameters: the specific number of SNIa, $\eta_{II}$, the mean iron yield from SNIII $\langle y_{Fe,II} \rangle$, and the fraction $f_*$ of SNIII ejecta that has formed into stars.

Values for the many additional parameters in the last three equations must be determined from theoretical supernova calculations or from observation. IMF-averaged theoretical supernova yields for iron and silicon have been collected and discussed by Loewenstein & Mushotzky (1996) and Gibson, Loewenstein & Mushotzky (1997). Following these authors we take SNIa silicon and iron yields from Model W7 of Thielemann, Nomoto & Hashimoto (1993): $y_{Si,Ia} = 0.158$ and $y_{Fe,Ia} = 0.744$, both in $M_\odot$. Yields for SNI collected by Loewenstein & Mushotzky (1996), mostly based on Woosley & Weaver (1995), have a large range for different models: $\langle y_{Si,II} \rangle = 0.08 - 0.32$ and $\langle y_{Fe,II} \rangle = 0.11 - 0.34$ while yields for the less extreme SNI models discussed by Gibson, Loewenstein & Mushotzky (1997) have a more limited range: $\langle y_{Si,II} \rangle = 0.104 - 0.143$ and $\langle y_{Fe,II} \rangle = 0.073 - 0.141$ both evaluated with a Salpeter IMF. Gibson, Loewenstein & Mushotzky (1997) discuss the uncertainties in theoretical SNIII yields in detail. As discussed previously, because of the maximum in the silicon yield near progenitor mass $22 M_\odot$, the mean silicon yield $\langle y_{Si,II} \rangle \approx 0.133 M_\odot$ appears to be more securely known than $\langle y_{Fe,II} \rangle$ which we regard as an unknown to be determined by solving the equations above.
The stellar mass to light ratio in early type galaxies is a slowly increasing function of galactic luminosity, \(M/L_B \propto L_B^{-0.2}\) (Faber et al. 1984), and depends somewhat on the cluster luminosity function. For a representative value we choose \(M/L_B = 7\) (in solar units), characteristic of typical bright ellipticals.

Values of \(\Upsilon_{Si,g}\) and \(R\) in Equations (4) and (5) must be supplied from X-ray observations. For three rich clusters (A 2199, A 496, and AWM 7) observed with ASCA Mushotzky et al. (1996) find an average silicon mass to light ratio \(\Upsilon_{Si,g} = 0.0305 \pm 0.008\) in solar units. More extensive observational data indicates that there is a significant cosmic variation in the abundances of Si and Fe among rich clusters (Mushotzky & Loewenstein 1997; Mushotzky 1998). If real, this variation of galaxy-averaged values suggests that the IMF, star formation efficiency, supernova frequency or other supernova properties may vary dramatically among cluster galaxies. Nevertheless, for our purposes here we simply use average abundances from all of the clusters observed. ASCA observations indicate a silicon to iron ratio of \(Si/Fe = 2.2 \pm 0.25\) (Mushotzky 1998) in solar units. But this abundance ratio, based on the so-called “photospheric” solar iron abundance, becomes \(Si/Fe = 2.2(1.83/2.66) = 1.51\) in units of the “meteoritic” solar ratio \((Si/Fe)_\odot = 0.550\) adopted here. The corresponding absolute Si/Fe abundance ratio in equation (5) is therefore \(R = 0.83\).

Equations (4) - (6) for \(\Upsilon_{II}, \langle y_{Fe,II} \rangle\), and \(f_*\) are shown in Figure 1 as functions of the total number of SNIa events \(N_{Ia}\) and the current Type Ia supernova rate \(SNu(t_n)\) evaluated with \(p = 1, t_n = 13\) Gyrs, and \(t_* = 2\) Gyrs. Two representative solutions are illustrated: (i) with no enrichment of stars by SNIa ejecta \(g_* = 0\) and (ii) with a significant SNIa enrichment \(g_* = 0.5\). The plotted solutions are based on a mass return parameter appropriate for a single burst Salpeter IMF \(\beta = 0.3\).

Type Ia supernova rates observed in elliptical galaxies favor low values of \(SNu(t_n)\) where \(\Upsilon_{II}, f_*\) and \(\langle y_{Fe,II} \rangle\) in Figure 1 are almost independent of \(SNu(t_n)\) and \(N_{Ia} \ll N_{II}\). In a recent study of the observed frequency of SNIa in ellipticals, Cappellaro et al. (1997) find a low current SNIa rate \(SNu(t_n) = 0.058(H/50)^2\) in SNu units. The current SNIa rate is also restricted by our gas dynamical models for the evolution of hot gas in large elliptical galaxies. The computed radial variation of gas density and temperature agree with those observed only when \(SNu(t_n) \lesssim 0.25\) (with \(p = 1\), again suggesting low values for \(N_{Ia}\). However, when silicon and iron abundances are included in these hydrodynamical evolution, as discussed below, low values of \(SNu(t_n)\) and \(N_{Ia}\) are essential. In this low-\(SNu(t_n)\) range of Figure 1, solutions for the three parameters \(\Upsilon_{II}, \langle y_{Fe,II} \rangle\), and \(f_*\) approach the limit of no SNIa enrichment, \(N_{Ia} \rightarrow 0\). In this limit solutions to Equations (4) - (6) for \(\Upsilon_{Si,g}\), \(R\), and \(z_{Fe} f_*\) simplify to

\[
\langle y_{Fe,II} \rangle = \langle y_{Si,II} \rangle / R = 0.16, \tag{7}
\]

\[
\Upsilon_{II} = \frac{\Upsilon_{Si,g} + R(z_{Fe,*}/1.4)(M/L_B)}{(M/L_B)\langle y_{Si,II} \rangle (1 - \beta)^{-1}} = 0.026, \tag{8}
\]

and

\[
f_* = \frac{R(z_{Fe,*}/1.4)}{\Upsilon_{II} \langle y_{Si,II} \rangle} = 0.16. \tag{9}
\]

These numerical evaluations are based on \(\Upsilon_{Si,g} = 0.0305\), \(R = 0.83\), \(z_{Fe,*} = 0.5z_{Fe,\odot}\), \(M/L_B = 7\), \(\langle y_{Si,II} \rangle = 0.133\), and \(\beta = 0.3\). Since \(\Upsilon_{Si,g}\) dominates the numerator of Equation (8), the value of \(\Upsilon_{II}\) is essentially unchanged if the mean stellar iron abundance is taken to be solar, \(z_{Fe,*} = z_{Fe,\odot}\).

The value of \(\langle y_{Fe,II} \rangle\) in Equation (7) is within the range of possible SNIll iron yields calculated by Woosley & Weaver (1995); this provides some confidence in the veracity of other parameters determined from the equations above. However, the specific supernova rate \(\eta_{II} = 0.026\) is almost four times the time expected for a Salpeter IMF, \(\eta_{std} = 0.00681 (x = 1.35, m_u = 100 \, M_\odot \text{ and } m_f = 0.08 \, M_\odot\). Values of \(\Upsilon_{II}\)
computed with single power law IMFs are sensitive to both the slope $x$ of the IMF and the mass limits $m_u$ and $m_t$. The variation of $\eta_{II}$ and $\beta$ with $x$, $m_u$ and $m_t$ for several power law IMFs is illustrated in Figure 2.

It is difficult to assign errors to the quantities evaluated in Equations (7) - (9) because of the many uncertainties involved and the possibility of systematic errors. If all the quantities in Equation (8) are skewed to their limits of uncertainty in an effort to minimize $\eta_{II}$, it is possible to achieve a close agreement with a Salpeter IMF. For example, if $T_{S,i,q} = 0.225$, $R = 0.92$, $M/L_B = 9$, $\langle y_{S,i,I} \rangle = 0.32$ (model WW1ex from Loewenstein & Mushotzky 1996), and $\beta = 0.3$ then $\eta_{II} = 0.0068$, close to the Salpeter value. Of course it is most unlikely that Nature would conspire in this manner.

Also shown in Figure 1 are the fraction of all iron created by SNIa:

$$F_{Ia} = \frac{n_{Ia}y_{Fe,Ia}}{n_{Ia}y_{Fe,Ia} + (1 - \beta)^{-1}(M/L_B)\eta_{II}(y_{Fe,Ia})}$$

and the fraction of all iron in the hot ICM gas that originated in SNIa:

$$F_{Ia,g} = \frac{n_{Ia}y_{Fe,Ia}(1 - G_s)}{n_{Ia}y_{Fe,Ia}(1 - G_s) + (1 - \beta)^{-1}(M/L_B)\eta_{II}(y_{Fe,Ia})(1 - F_s)}.$$ 

Provided $\text{SNIa}(t_n)$ is limited to values of interest, $\log[\text{SNIa}(t_n)] < -1$, Type Ia supernovae can contribute to the stellar enrichment without substantially changing $\eta_{II}$ or $\langle y_{Fe,Ia} \rangle$.

Renzini et al. (1993), Ishimaru & Arimoto (1997), Renzini (1997) and Wyse (1997) have discussed the X-ray data for rich clusters in detail. These authors prefer models in which the overabundance of iron relative to that expected with a normal Salpeter IMF is due to a large additional iron contribution from Type Ia supernovae, corresponding to $F_{Ia} \approx 0.5$ in Figure 1. Such a model would be very similar to the enrichment history of our own Galaxy. In particular, Renzini et al. (1993) suggest a model for rich cluster enrichment in which $\sim \frac{3}{4}$ of the iron is produced by SNIa with the remaining $\sim \frac{1}{4}$ coming from SNIIf. If only half of the iron in rich clusters has originated in SNIa, then the number of SNIa per $L_B$ is $n_{II} = N_{II}/L_B \approx 0.25$. But such a large number of SNIa is incompatible with iron and silicon abundances in our calculated model of a single large elliptical, discussed below, where we find $n_{II} = N_{II}/L_B \lesssim 0.001$. For the simple power law model for SNIa(t) we adopt in Figure 1 ($p = 1$, $t_s = 2$ Gyr, $t_n = 13$ Gyr), the current SNIa rate would need to be very large, SNIa(t_n) $\gtrsim 0.6$, for Type Ia supernova to supply half of the iron. This is about ten times greater than the SNIa rate estimated from observations of bright ellipticals.

An alternative explanation of the iron excess in rich clusters relative that produced by a Salpeter IMF ($x = 1.35$, $m_u = 100$, 0.08) is to invoke a flatter IMF having a larger fraction of massive stars and associated SNIIf. This is the interpretation preferred by David (1997) and Gibson, Loewenstein & Mushotzky (1997). For consistency both $\beta$ and $\eta_{II}$ must be adjusted when the IMF slope is changed; the value of the mass return fraction $\beta = 0.3$ used in Equation (8) is based on the Salpeter IMF. Logically compatible parameters can be found by simultaneously solving Equation (8) for $\eta_{II}(\beta)$ with the parametric variations $\eta_{II}(x)$ and $\beta(x)$ plotted in Figure 2. The result of this joint solution is that Equation (8) now gives $\eta_{II} = 0.016$ with $\beta = 0.55$ for ($x$, $m_u$, $m_t = 1.00$, 100, 0.08) or $\eta_{II} = 0.018$ with $\beta = 0.51$ for ($x$, $m_u$, $m_t = 0.94$, 40, 0.08). (Such large values of the mass return $\beta$ from evolving stars may be unrealistic since several generations of stars must have formed near time $t_s$, each consuming some of the metal-enriched gas ejected from previous generations of stars.) With these flat IMFs almost all of the iron in rich clusters originates in SNIIf and the low SNIa rates are consistent with those observed in massive ellipticals. IMFs flatter than Salpeter are also supported by the large mass of oxygen in rich clusters; Gibson, Loewenstein & Mushotzky (1997) claim that the observed O/Si ratio can be produced by SNIIf alone with little or no contribution from SNIa.
When silicon and iron abundances in the ICM are considered together with abundance constraints set by individual massive ellipticals, as we have done here, the metal enrichment of rich clusters by early type galaxies is shown to be almost exclusively due to Type II supernovae with a negligible contribution from Type Ia supernovae. Evidently, star formation conditions in rich clusters are quite unlike those that prevail in our own Galaxy.

The controversy concerning the relative enrichment from Type II and Type Ia supernovae in rich clusters is further confounded by the gas dynamical solutions we discuss below. We describe a variety of supernova enrichment histories for massive elliptical galaxies in which the hot interstellar gas is constrained to evolve toward the radial distribution of gas density, temperature and metal abundance observed today. In particular we show that the production of SNII using a Salpeter IMF is sufficient to achieve simultaneous agreement with \( n(r) \), \( T(r) \) and \( z_{Fe}(r) \) indicated by X-ray observations of massive ellipticals. Gas dynamic solutions based on IMFs flatter than Salpeter are generally incompatible with the observed abundance variation \( z_{Fe}(r) \). The SNIa rate must also be low. If more supernovae of either type are involved, as indicated by the large \( \eta_{II} \) for rich clusters (Equation 8), the iron and silicon abundances in the models greatly exceed those observed in massive elliptical galaxies.

3. IRON AND SILICON IN NGC 4472

3.1. Gas Dynamical Models for NGC 4472

In a recent paper (Brighenti & Mathews 1998b) we discuss in detail the basic assumptions and equations used in our gas dynamical models that simulate the evolution of hot interstellar gas in elliptical galaxies. Since the models we discuss here are very similar to those in that paper, we provide only a brief summary.

Our 1D spherical calculations begin with an overdensity perturbation in a flat cosmology having an amplitude designed to produce a mass concentration similar to that of NGC 4472 after a few gigayears. The flow of dark and baryonic matter far from the center of the perturbation follows the self-similar solution described by Bertschinger (1985). An outward moving turn-around radius defines the instantaneous locus where the cosmic flow velocity vanishes. The “secondary infall” occurs within the turn-around radius, allowing baryonic and dark matter to collect near the origin. The central accumulation of dark matter grows from the inside out; although the collisionless dark fluid interpenetrates, after passing through the origin it continues to oscillate, spending most of its time at large radii. The net effect is that a quasi-stationary core of dark matter grows outward from the origin and is matched to the outer Bertschinger inflow in a manner that preserves the total mass of dark matter. However, we replace the inner power law core of the self-similar Bertschinger solution with a (less peaked) dark halo having an NFW profile as determined by Navarro et al. (1996) with full three-dimensional N-body calculations. The dark matter mass of NGC 4472 inferred by X-ray data can be fit reasonably well with an NFW dark halo of mass \( M_h = 4 \times 10^{13} \, M_\odot \) within the current virial radius assuming \( D = 17 \, \text{Mpc} \) for the distance to NGC 4472. The cold baryonic gas also participates in the Bertschinger flow, but deep within the turnaround radius it passes through an accretion shock, compresses and is heated to approximately the virial temperature of the galactic dark halo. At time \( t_* \) when enough baryonic matter has collected within the shock, some of which has radiatively cooled, we form the de Vaucouleurs stellar configuration having a total mass \( M_* = 7.26 \times 10^{11} \, M_\odot \) appropriate to NGC 4472 and corresponding to a stellar mass to light ratio \( M_*/L_B = 9.20 \) (van der Marel 1991). The stellar galaxy is constructed by removing a baryonic mass equal to \( M_* \) from gas within the accretion shock.
\( r_{sh}(t_*) \) to form the stars. The gas density in the remaining gas is reduced in proportion to its density just before \( t_* \).

We assume the SNII energy is released immediately at time \( t_* \). After gas has been removed to form the stars, the SNII energy is assumed to be evenly deposited (masswise) to remaining gas within the accretion radius or within some other specified radius. Removing gas interior to \( r_{sh}(t_*) \) and heating the remaining gas introduces a transient in the flow, but after \( \sim 1 \) Gyr gas moving within \( r_{sh} \) becomes subsonic and approaches hydrostatic equilibrium. The subsequent time dependent gas dynamics within and around the galaxy are followed in full detail. The potential of the dark matter continues to evolve according to the NFW-Bertschinger prescription and the baryonic shock grows in radius. The flow of these two fluids is solved simultaneously using 1D Eulerian hydrodynamics on a logarithmic grid. The equations that describe this flow are described in detail in our recent papers (e.g. Brighenti & Mathews 1998b). Inside the de Vaucouleurs core new gas is provided by mass loss from stars as they evolve off the main sequence.

The total energy released by SNII explosions at time \( t_* \) is \( E_{\text{II}} = \epsilon_{\text{sn}} \eta_{\text{II}} M_\odot E_{\text{sn}} \) where \( E_{\text{sn}} = 10^{51} \text{ergs} \), \( \eta_{\text{II}} \) is the total number of SNII produced and \( \epsilon_{\text{sn}} \) is the efficiency that SNII energy is converted to thermal energy in the ambient gas, the rest is lost to radiation. For a reference value of \( \eta_{\text{II}} \) we use the value computed with a Salpeter IMF \((x, m_u, m_\odot = 1.35, 100, 0.08) \), \( \eta_{\text{sal}} = 6.81 \times 10^{-5} \). For simplicity, the stellar mass in these relations (and in establishing the fixed stellar potential) is set to the current value \( M_\ast = M_\ast(t_\ast) \) rather than its value at \( t_* \), \( M_\ast/(1-\beta) \). In view of the uncertainties involved in all these parameters, in the gas dynamical models we evaluate \( E_{\text{II}} = \eta_{\text{II}} M_\odot(t_\ast) {\text{ergs}} \) as if \( \epsilon_{\text{sn}} = 1 \) and vary \( \eta_{\text{II}} \), seeking results that best match current observations. Each \( E_{\text{II}} \) determined in this way corresponds to a range of \( M_\ast(t_\ast) E_{\text{sn}} \) for each assumed gas heating efficiency \( \epsilon_{\text{sn}} = E_{\text{II}}/\eta_{\text{II}} M_\ast(t_\ast) E_{\text{sn}} \leq 1 \). Metal enrichment by SNII accompanies the energy deposition within the accretion shock radius at \( t_* \). Altogether \( \langle \gamma_{\text{Fe,II}} \rangle \eta_{\text{II}} M_\odot \) solar masses of iron are available for enriching stars and gas within \( r_{sh}(t_*) \). If \( z_{\text{Fe,II}} \) is the assumed stellar iron abundance, a mass \( z_{\text{Fe,II}} M_\odot/1.4 \) of iron produced by SNII is allocated to the newly formed stellar system at time \( t_* \) and the remainder is introduced into the gas within the shock radius in proportion to the local gas density.

In summary, the important galactic parameters that determine the early star formation and SNII enrichment in rich clusters and individual massive ellipticals are (i) the total energy released in SNII
explosions $E_{II}$, (ii) the number of SNII per solar mass $\eta_{II}$, and (iii) the time of star formation $t_\ast$.

### 3.2. The Standard Model

In our standard or reference model for the evolution of hot interstellar gas in NGC 4472, the galaxy forms in a flat universe ($\Omega = 1$) with global baryon fraction $\Omega_b = 0.05$. The specific SNII rate is

$$\eta_{II} = \eta_{II,\text{std}} \equiv 6.81 \times 10^{-3}.$$ 

The specific stellar mass loss rate for the Salpeter IMF $\alpha_s(t) = d\log M_s/dt$ is well fit with a power law $\alpha_s(t) = 4.7 \times 10^{-20} (t/t_s)^{-1.26}$ s$^{-1}$ where $t_n = 13$ Gyrs and and $t_s = t_n - t_\ast$ is the current age of the stars. Both stars and SNII are assumed to form at time $t_\ast = 2$ Gyrs. The total number of SNII, $N_{II}$, is an integral over SNu($t$) which is assumed to vary as a simple power law parameterized with $SNu(t_n) = 0.015$ SNu and $p = 1$. Type Ia supernovae are assumed to begin at $t_\ast$ and continue until $t_n = 13$ Gyrs. Except for the slightly lower $SNu(t_n)$, all parameters are identical to the standard reference model discussed in Brighenti & Mathews (1998b). In addition, we assume for the standard model that no iron or silicon produced by SNIa is used in stellar enrichment, so the stars have abundances proportional to SNII yields.

The first requirement for an acceptable model is that the chosen parameters, when used in a gas dynamical calculation, adequately reproduce the radial variation of interstellar gas density and temperature observed in NGC 4472 today. In Figure 3 we plot with solid lines the density and temperature profiles in the hot interstellar gas for the standard model at time $t_n = 13$ Gyrs. The overall agreement with the observed gas temperature and density is satisfactory but not perfect. The excess gas density in the model in $r \lesssim r_e = 8.57$ kpc is a classical artifact of galactic cooling flow models; we believe that it can be mitigated by galactic rotation and low mass star formation but this has not yet been adequately demonstrated (see Mathews & Brighenti 1998c for a brief review). At larger radii, $r \gtrsim 10$ kpc, the computed density is slightly low. This latter discrepancy may be due to the disturbed nature of NGC 4472 at large radii where it appears to be interacting with ambient gas in the Virgo cluster (Irwin & Sarazin 1996) although the azimuth-averaged outer gas density profile in NGC 4472 is typical of the X-ray structure in other large ellipticals (Mathews & Brighenti 1998b). In any case, if $E_{II}$ is slightly lower than the Salpeter value, the standard model can be adjusted to fit the observations almost perfectly at large $r$ (Brighenti & Mathews 1998a).

For the models discussed here we assume a simple flat universe, $\Omega = 1$, but it is also possible to find satisfactory and very similar dynamical models for NGC 4472 using other cosmologies. In the Appendix we briefly describe gas dynamical models appropriate for an open universe ($\Omega = 0.3$) and a low density flat universe ($\Omega = 0.3, \Omega_\Lambda = 0.7$).

A fully successful model must also match the metal abundances and abundance gradients currently observed in NGC 4472. Unfortunately, supernova yields and observed abundances are both uncertain so there is some flexibility in making this fit. The iron abundance in NGC 4472 has been observed extensively with ROSAT and ASCA by many observers using many different data reduction procedures. Observed iron abundances expressed in solar units can be a source of some confusion if authors do not explicitly note which iron abundance they have assumed for the sun, photospheric or meteoritic. If the lower meteoritic value is more correct, as we assume here, iron abundances relative to the solar photospheric value are too low by 1.44 (Anders & Grevesse 1989). In the following discussion, we consider only observational sources for which the absolute solar abundance is specified and, if necessary, we convert observed iron abundances cited in the literature to meteoritic solar. Unfortunately, observational determinations of the iron abundance in the
hot gas also seems to depend on the data reduction procedure used. Some of the difficulty in deriving hot gas abundances arises due to the presence of additional X-ray emission unrelated to the hot interstellar gas. Harder radiation ($E \gtrsim 2$ keV) thought to be stellar in origin must be allowed for in fitting the spectrum and deriving abundances. Observational determinations of the iron abundance appear to depend on the procedure used in allowing for the hard radiation. For example, Buote and Fabian (1998) find that the iron abundance in NGC 4472 determined with a single temperature plasma increases by a factor of 4.7 when a two-temperature fit is used instead. Possible inadequacies in treating the Fe L transitions in the adopted plasma code may also influence the resulting value for the observed iron abundance.

Seeking some consistency, we consider here several published globally averaged iron abundances determined with detectors on the ASCA satellite. Using the Raymond-Smith plasma code with a hard component in the spectrum, Arimoto et al. (1997) find a Fe abundance determined with detectors on the ASCA satellite. Using the Raymond-Smith plasma code with a hard plasma code may also influence the resulting value for the observed iron abundance. Observational determinations of the iron abundance appear to depend on the procedure used in allowing for the hard radiation. For example, Buote and Fabian (1998) find that the iron abundance in NGC 4472 determined with a single temperature plasma increases by a factor of 4.7 when a two-temperature fit is used instead. Possible inadequacies in treating the Fe L transitions in the adopted plasma code may also influence the resulting value for the observed iron abundance.

Figure 4 illustrates the distribution of iron and silicon in the hot gas surrounding NGC 4472 after evolving to the present time $t_\odot = 13$ Gyr. This calculation is based on supernova parameters for the standard model – SNII ($t_\odot = 13$ Gyr) $p = 1$ and $\eta_{11} = 6.81 \times 10^{-3}$ – with supernova yields: $\langle y_{Fe,II} \rangle = 0.14$ $M_\odot$, $\langle y_{Si,II} \rangle = 0.133$ $M_\odot$, $y_{Fe,Ia} = 0.744$ $M_\odot$, and $y_{Si,Ia} = 0.158$ $M_\odot$. Following Arimoto et al. (1997), we assume a power law gradient for the stellar metal abundance

$$z_{Fe,*} = 0.675(r/r_\odot)^{-0.207}$$

which is based on the observed spatial variation of the Mg$_2$ photometric index. With this variation the mean stellar Fe/Mg ratio is half solar, $\langle z_{Fe,*} \rangle / \langle z_{Mg,*} \rangle = 0.5$, (in solar units) as suggested by Trager (1997) where $\langle z_{Mg,*} \rangle = 1.385$ solar (Arimoto et al. 1997). Since SNIa do not enrich the stars in the standard solution, the stellar silicon abundance is proportional to SNI yields, $z_{Si,*} = z_{Fe,*} \langle y_{Si,II} \rangle / \langle y_{Fe,II} \rangle$.

In the standard model all SNI enrich the stellar system as created at time $t_\odot = 2$ Gyr and the stars are enriched with enough iron and silicon from SNI to match the mean stellar abundances $\langle z_{Fe,*} \rangle$ and $\langle z_{Si,*} \rangle$. All additional iron and silicon from SNI is distributed at time $t_\odot$ to gas within the accretion shock radius $r_{sh}(t_\odot) = 200$ kpc in proportion to the local gas density. The energy released by SNI is sufficient to temporarily reverse the secondary inflow, causing the contact discontinuity that defines the enriched region within $r_{sh}(t_\odot)$ to expand to 400 kpc at the present time as shown in Figure 4. The uniformity of $z_{Fe}$ and $z_{Si}$ in the “plateau” region visible in Figure 4 between the outermost stars and the contact discontinuity, 100 - 400 kpc, is an artifact of the uniform deposition of SNI metals at time $t_\odot$. Most of the iron mass is in this plateau region as shown in the plot of $M_{Fe}(r)$ in Figure 5. At time $t_n$ the interstellar gas is slowly flowing inward within the galaxy $r \lesssim 100$ kpc, where the early SNI enrichment is diluted by new
gas contributed by stellar mass loss. But this dilution is more than compensated by additional iron and silicon contributed by SNIa and stellar mass loss within the galaxy. The total iron abundance distribution from all of these sources, shown with a solid line in Figure 4, is seen to agree reasonably well with the observations of Matsushita (1997). Emission-weighted abundances based on this standard model depend on the radius considered. For the entire region within the current accretion shock radius \( r_{sh}(t_n) = 1000 \) kpc the mean abundances in the gas (in solar units) are \( \langle z_{Fe} \rangle = 0.45 \) and \( \langle z_{Si} \rangle = 0.52 \); within the current contact discontinuity at 400 kpc the mean gas abundances are \( \langle z_{Fe} \rangle = 0.67 \) and \( \langle z_{Si} \rangle = 0.77 \); within 150 kpc the abundances are even higher, \( \langle z_{Fe} \rangle = 0.76 \) and \( \langle z_{Si} \rangle = 0.86 \). These latter values are slightly higher than the global iron and silicon abundances reported by Matsushita (1997); this excess probably arises because the gas density in our models is slightly larger and more centrally peaked than that observed in NGC 4472 (Figure 3). The approximate constancy of \( (z_{Si}/z_{Fe,\odot})/(z_{Fe}/z_{Fe,\odot}) \approx 0.6 \) with galactic radius and its value intermediate between SNII and SNIa yields \( (y_{Si,II})/(y_{Fe,II}) \approx 0.8 \) and \( y_{Si,II}/y_{Fe,II} \approx 0.2 \) respectively are both attributes of recent X-ray observations of NGC 5846 by Finoguenov et al (1998).

For any given gas dynamical solution described by \( n(r) \) and \( T(r) \) at time \( t_n \), an infinite family of interstellar abundance distributions can be generated by changing the specific number of SNII \( \eta_{II} \) (or the supernova yields) while keeping the total SNII energy \( E_{II} = \epsilon_{sn}\eta_{II}M_\odot E_{sn} \) unchanged. The constancy of \( E_{II} \) is ensured by varying the gas heating efficiency factors \( \epsilon_{sn} \) or \( E_{sn} \) to compensate for changes in \( \eta_{II} \). When following this procedure, we were surprised to discover that the iron abundance distribution shown in Figure 4 disagrees significantly with Matsushita’s observations when \( \eta_{II} \) is only varied by \( \sim 10 \) percent from that used in the standard solution. For example, if \( \eta_{II} = 1.25\eta_{II,0} \) the iron abundance in the plateau region (100 - 400 kpc) increases to \( z_{Fe}/z_{Fe,\odot} = 0.72 \) and the central value is nearly 1.1. These iron abundances are significantly higher than Matsushita’s observed values, particularly in the outer galaxy \( r \gtrsim 20 \) kpc. The sensitivity of \( z_{Fe}(r, t_n) \) to \( \eta_{II} \) can be understood because of the large amount of iron and silicon required to enrich the galactic stars. The global iron abundance in the gas just after SNII enrichment, identical to that in the plateau region, is \( z_{Fe} = (M_{Fe,II} - M_{Fe,*})/M_{gas} \) where \( M_{Fe,II} \) is the total iron produced by SNII. Since the large total mass of iron in stars \( M_{Fe,*} \) is held fixed as \( \eta_{II} \) is varied to create a family of dynamically identical enrichment models, small changes in \( \eta_{II} \) and therefore \( M_{Fe,II} \) correspond to rather large changes if \( z_{Fe} \) since \( M_{Fe,II} \) is not much larger than \( M_{Fe,*} \). In this sense our models require a high degree of regularity in \( \eta_{II} \) in order to match the negative gaseous iron abundance gradients typically observed in giant ellipticals. This sensitivity to \( \eta_{II} \) may be an indication that our model is too simple or that some additional enrichment process has been overlooked.

Although our standard model, as illustrated in Figures 3 and 4, is successful in approximately reproducing all relevant observations of NGC 4472, the value of \( \eta_{II} \) that we have used corresponds to a normal Salpeter IMF and is therefore several times less than values required to enrich massive clusters of galaxies (Equation 8). In spite of this important difference in \( \eta_{II} \), the gaseous iron and silicon abundances in our standard model within the current accretion shock radius \( r_{sh}(t_n) = 1000 \) kpc, \( \langle z_{Fe} \rangle = 0.45 z_{Fe,\odot} \) and \( \langle z_{Si} \rangle = 0.52 z_{Fe,\odot} \), are both rather similar to typical abundances in the ICM of rich clusters, \( \sim 0.4 \) solar. The ratio of total iron mass in both stars and gas to the total baryonic mass within \( r_{sh}(t_n) \) corresponds to an iron abundance of \( \sim 0.4 \) in solar units, again very similar to cluster values. This apparent agreement is likely to be just a coincidence, however. The important distinction between our model for NGC 4472 based on a Salpeter \( \eta_{II} \) and higher values of \( \eta_{II} \) required to understand cluster ICM abundances is in the much lower total gas mass fraction currently present in galaxies as compared to clusters. Within any radius of interest out to the current accretion shock radius, the ratio of gas mass to total baryonic mass in our standard model is much lower than that found in rich clusters. If the ICM in rich clusters contains additional, unenriched primeval gas at larger radii, the enrichment of cluster gas by ellipticals similar to our
model for NGC 4472 is even more dramatically inadequate. Therefore, our models support the contention made by Renzini (1997) and David (1997) that it is impossible to build presently observed rich clusters by merging hot gas in group-dominant massive ellipticals having properties similar to our standard solution for NGC 4472.

We have made additional calculations using standard model parameters but assuming that the SNII energy and enrichment occur within radii that are not equal to $r_{sh}(t_*)$. When the enrichment region is smaller than $r_{sh}(t_*)$, the plateau region is smaller but its iron abundance is increased so that it is no longer possible to match the current negative iron abundance gradients observed in NGC 4472 and other similar massive ellipticals. To correct for this excess iron, the value of $\eta_{II}$ would need to be less than $\eta_{std}$, diverging further from typical cluster values. If the size of the enrichment radius is much larger than $r_{sh}(t_*)$, then the dynamical time for other stars spatially associated with the enriching SNII to arrive at the outer radius of the currently observed stellar system in NGC 4472 exceeds the time available $t_n - t_*$. For example, stars that form at $t_*$ beyond $r \approx 700$ kpc in the standard solution can never enter the stellar part of the galaxy ($r \lesssim 100$ kpc) by the present time $t_n = 13$ Gyrs; any SNII enrichment beyond this radius is unrelated to stars within NGC 4472. In any case, even if we use a SNII energy and enrichment radius equal to the maximum allowed size at $t_*$, the current abundances of iron and silicon are still too large if the cluster value of $\eta_{II}$ is used.

3.3. The Cluster Model

To emphasize the disparity between optimum values for the specific number of SNII in rich clusters and in single bright ellipticals, we briefly discuss a “cluster” model for NGC 4472 in which $\eta_{II}$ has a larger value appropriate for rich clusters. Following our previous discussion in §2, we assume $\eta_{II} = 2.36\eta_{std}$ with $\beta = 0.55$ and a slightly larger mean SNII iron yield, $\langle y_{Fe,II} \rangle = 0.158$. All remaining variables and the gas dynamical solution are identical to those in the standard model previously discussed. Larger $\eta_{II}$ corresponds to a lower heating efficiency $\epsilon_{sn}$, keeping $E_{II}$ and the associated gas dynamics unchanged from the standard solution.

After evolving to the current time, the iron and silicon distributions in this model, shown in Figure 6, are clearly unable to account for gas abundances observed in NGC 4472. Iron and silicon within the galaxy are dominated by the inflow of SNII-enriched gas from outside the stellar system. The total iron abundance within the optical galaxy ($r \lesssim 100$ kpc) is much higher than observed abundances and its radial gradient is positive throughout the galaxy. This model is an example of the sensitivity of $z_{Fe}(r)$ to the parameter $\eta_{II}$. Increasing $\eta_{II}$ by a factor of 2.36 causes the gas abundance in the plateau region to increase to 3.35, almost 22 times greater than the abundance in this region in the standard solution. As before most of the iron mass in the gas is contained in this distant plateau region (see Figure 5).

We explored several variants of the “cluster” model in an attempt to reconcile cluster values of $\eta_{II}$ and the enrichment history of large ellipticals. The high abundances in the “plateau” region just beyond 100 kpc can be reduced if the radius of SNII enrichment at time $t_*$ is increased or if this gas is (rather arbitrarily) mixed and diluted with primordial gas at larger radii. However, as discussed above, such models are unrealistic since the dynamical times at $\sim 700$ kpc for either of these variant models is too long. Low mass stars accompanying metal-producing SNII at these radii will not have joined the galaxy by the present time. We have also sought solutions in which the galaxy formation time $t_*$ is 3 or 4 Gyrs in an attempt to lower the abundances by mixing SNII ejecta with larger masses of unprocessed gas inside the accretion
shock at these later times, but unrealistically high iron abundances are still present.

We are faced with the unexpected result that the amount of metals required to fit abundances in rich clusters are incompatible with those observed in individual ellipticals. This is very curious since bulge dominated E and S0 galaxies are generally thought to be the primary source of metals in the ICM of rich clusters.

3.4. The Ia Model

We now explore the possibility that SNIa are important contributors to the iron abundance in rich clusters and that bulge dominated galaxies are the primary sites of these SNIa explosions. This can be accomplished with the “Ia” model for NGC4472 for which $n_{Ia} = 0.011$, corresponding to $F_{Ia} = 0.22$ and $F_{Ia,g} = 0.25$ in Figure 1. To achieve this high SNIa rate we choose $SNu(t_n) = 0.1$ and $p = 1.5$; this is the same slope as that of Ciotti et al. (1991), but our $SNu(t_n)$ is only 70% of their value. All other parameters are identical to those in the standard model.

Since the energy deposited by SNIa in this model exceeds that of the standard model, the hydrodynamic solution is also different. The gas density and temperature for this model after time $t_n = 13$ Gyrs are shown with dashed lines in Figure 3. The agreement with the observed gas density in NGC 4472 is good, but the gas temperature has a minimum near 60 kpc that is not observed. This curious feature is a long-lived relic resulting from gas flows driven by SNIa and SNII heating at times just after time $t_n$. In earlier theoretical models for the evolution of hot gas in ellipticals in which stars are assumed to be the only source of interstellar gas, such a large energy deposition by SNIa would have driven a strong galactic wind. For the model we discuss here, where the young galaxy is surrounded by cosmic gas converging toward the overdensity perturbation (secondary infall), early SNIa-driven winds are suppressed by the inertia of this ambient gas and only a modest outward redistribution of the gas occurs.

Apart from the small temperature minimum in Figure 3, the general trend in the gas temperature for this model is a reasonably good fit to gas temperatures observed in NGC 4472. However, the current iron and silicon abundances in the hot gas for this model, illustrated in Figure 7, are clearly at variance with X-ray observations. In this SNIa-dominant model the interstellar enrichment of iron and silicon is caused almost exclusively by SNIa, raising the iron abundance to $> 6$ times solar throughout the optical galaxy. The shallow positive gradient $dz_{Fe}/dr > 0$ for $r < \sim 100$ kpc is due to a small residual gaseous outflow caused by the large energy released by SNIa inside the galaxy. The global value of the iron abundance and its radial gradient are both too large. This model is rather similar to the earlier result of Loewenstein & Mathews (1991) in their study of simpler galactic cooling flows without cosmological secondary infall; they also found iron abundances far in excess of those observed when SNIa are important contributors to the overall galactic enrichment. It is also significant that the silicon abundance in this model is much higher than the global value observed in the hot interstellar gas of NGC 4472, $\langle z_{Si} \rangle = 0.5$ solar. Most of the excess iron and silicon inside the galaxy in this model comes from Type Ia supernovae with a smaller contribution from stellar mass loss. Because of the low-level, subsonic outflow driven by SNIa, iron and silicon introduced into the gas by SNII at $t_n$ are unable to enter the interstellar gas interior to $\sim 100$ kpc.

We have also explored additional high $n_{Ia}$ models in which the SNIa varies like a step function rather than a power law. By concentrating most of the SNIa energy at early times, we hoped that the large amount of metals produced then would be expelled in a powerful galactic wind. If so, the low gas abundances observed today within $\sim 100$ kpc might be made consistent with large SNIa enrichment at early times. For
example, we considered a model with \( n_{1a} = 0.05 \), with most of the SNIa exploding at very early times: \( SN_{1a} = 24.86 \) for \( 2 < t < 4 \) Gyr, and \( SN_{1a} = 0.03 \) for \( t > 4 \) Gyr. However, with this sort of model the gas dynamics were altered so that we were unable to match \( n(r) \) and \( T(r) \) currently observed in NGC 4472. The iron and silicon abundance distribution are also strange in these models at the present time, with an enormous metal enrichment occurring just outside of the stellar part of the galaxy.

4. Conclusions and Final Remarks

When we began this study of the enrichment history of massive ellipticals and rich clusters, we quite mistakenly anticipated that it would be possible to find a common set of parameters that would account for evolutionary enrichment on both galactic and cluster scales. Gas phase iron abundances in bright ellipticals range from \( 0.1 \)−1 solar, with NGC 4472 lying near the upper limit of this range, but the average may not differ greatly from the mean global iron abundance in rich clusters, \( \sim 0.4 \). Rich clusters typically have higher gas fractions than massive ellipticals, but this might result in part from supernova-driven outflows from the shallower potentials of member ellipticals. Unlike the observational information available for hot gas in group-dominant ellipticals, our computational models are closed boxes since we can computationally follow gas-phase supernova enrichment products into regions of very low gas density and emissivity where observations are difficult or impossible. Perhaps, we supposed, the large number of past supernovae required to produce metal abundances in rich clusters were at one time also present in giant ellipticals but some of these metals was dispersed by galactic winds into the low density environment, escaping observational detection. If all of this were true, it might be possible to merge small elliptical-dominated groups together with their wind-enriched gaseous environments and construct rich clusters. In developing this hypothesis, we adopted the commonly held assumption that virtually all metal enrichment in rich clusters is due to the stellar spheroidal component, i.e. in E and S0 member galaxies.

As discussed in our recent paper (Brighenti & Mathews 1998b), the observed hot gas density and temperature distributions in any massive elliptical can be fit with a range of gas dynamical models having different numbers of Type II supernovae \( N_{II} \), represented here by the SNII number per unit stellar mass, \( \eta_{II} = N_{II}/M_* \), or the total energy released by all SNII, \( E_{II} = \epsilon_{sn}\eta_{II}M_*E_{sn} \). For a given set of cosmological parameters, hydrodynamical models for the evolution of hot interstellar gas are degenerate in the sense that a range of values of \( \eta_{II} \) (associated with different IMFs) and therefore \( E_{II} \) can produce similar interstellar density and temperature distributions at the present time provided the time of galaxy formation \( t_* \) is also adjusted. If the galaxy is assumed to form at a later time, more gas is available near the central overdense region and a larger value of \( E_{II} \) generates approximately the same specific thermal energy; the subsequent evolution of the gas arrives at similar \( n(r) \) and \( T(r) \) distributions at the present time. This approximate degeneracy depends only weakly on our assumption that the SNII energy is deposited within the accretion shock radius at time \( t_* \), \( r_{sh}(t_*) \). As we have discussed already, the extent of the SNII enrichment region \( r_{II} \) in massive ellipticals cannot be greatly different from \( r_{sh}(t_*) \). If \( r_{II} < r_{sh}(t_*) \), then even lower values of \( \eta_{II} \) are required to reproduce abundances observed today, increasing the disagreement with the higher cluster values for \( \eta_{II} \). If \( r_{II} > r_{sh}(t_*) \), then the dynamical time also increases and low mass stars associated with the SNII enrichment would not have enough time to enter the massive optical galaxy observed today.

The important parameters that describe our evolutionary models are (i) the total energy released by Type II supernovae, \( E_{II} = \epsilon_{sn}\eta_{II}M_*E_{sn} \) which must be adjusted to achieve agreement with \( n(r) \) and \( T(r) \) in the hot interstellar gas, (ii) \( t_* \) the time of star formation, (iii) \( \eta_{II} \) which controls most of the gas enrichment, and (iv) the SNIa rate \( SN_{1a}(t) \) that supplies much of the interstellar iron in the central galaxy,
$r \lesssim 50$ kpc. In seeking satisfactory gas dynamical models with no attention to abundances, the main parameters are $E_{II}$ and $t_\star$. We have found that models for the large elliptical NGC 4472 agree with $n(r)$ and $T(r)$ and the abundance distribution $z_{Fe}(r)$ if stars form at $t_\star = 2$ Gyrs with a Salpeter IMF for which $\eta_{II} = \eta_{\text{std}} \equiv 6.81 \times 10^{-3}$ assuming a heating efficiency $\epsilon_{sn} = 1$. If we wish to increase $\eta_{II}$ and therefore $E_{II}$ toward the global values indicated by rich cluster abundances, $\sim 2 - 3\eta_{\text{std}}$, $t_\star$ must be increased significantly. However, such an increased $t_\star$ is not possible since observations indicate that many luminous elliptical galaxies are very old: the color-magnitude diagram (Bower, Lucey, & Ellis 1992), the small scatter in the Mg$_2$ - $\sigma$ relation (Bender, Burstein, & Faber 1993), passive evolution of the fundamental plane (van Dokkum & Franx 1996), etc. With $t_\star$ constrained to values $\lesssim 2$ Gyrs, and $E_{II}$ constrained for a match currently observed $n(r)$ and $T(r)$ distributions, $\eta_{II}$ can be increased toward the cluster value ($\sim 2.6\eta_{\text{std}}$) only by decreasing the gas heating efficiency $\epsilon_{sn}$ with $E_{II}$ and $t_\star$ held fixed. This is the procedure we have considered with the “cluster” or high-$\eta_{II}$ model for NGC 4472. However, as $\eta_{II}$ is increased above the standard Salpeter value, the metal enrichment of the interstellar gas at the present time quickly rises far above abundances observed in NGC 4472. The global iron and silicon abundances and the negative radial iron gradient $dz_{Fe}/dr$ in NGC 4472 (and other large ellipticals) can be matched only with a very narrow range of $\eta_{II}$, all lower than cluster values. Similar restrictions also apply to the total number of Type Ia supernovae which we assume are also more frequent in the early universe.

We arrive at the following conclusions:

1. Type II supernova production with a Salpeter IMF is sufficient to explain all important hot gas observations in bright ellipticals: the radial distribution of density, temperature and iron abundance as well as the global iron and silicon abundances. A small additional contribution of iron and silicon from Type Ia supernovae, consistent with currently observed SNIa rates in elliptical galaxies, can also be present. Unlike the enrichment history of our Galaxy, where iron production by Type II and Type Ia supernovae have been comparable, in ellipticals the total iron and silicon enrichment by Type Ia supernovae must be much less than that from SNIa.

2. The gas dynamic and enrichment history of massive elliptical galaxies establishes upper limits on the total number of both Type II and Type Ia supernovae events. Large numbers of Type II supernovae associated for example with flat IMFs, often invoked to account for the iron observed in rich clusters, produce too much gas-phase iron and silicon in models of single massive ellipticals. If the total number of Type Ia supernovae is large enough to dynamically influence the interstellar gas in these galaxy models, the current metal enrichment greatly exceeds the gas phase iron and silicon abundances observed.

3. For fixed total SNII energy $E_{II}$, the iron and silicon enrichment is very sensitive to the specific number of Type II supernovae $\eta_{II}$ involved. This sensitivity may indicate that our galaxy enrichment model is oversimplified or it may be related to the wide spread in gas phase abundances observed in ellipticals and group-dominant ellipticals (see Fig. 6 of Renzini 1997).

4. We agree with David (1997) and Renzini (1997) that it is not possible to form presently observed rich clusters by simply combining stars and hot gas from a large number of presently observed elliptical-dominated groups.

5. In view of our model calculations for the evolution and enrichment of interstellar gas in massive ellipticals, neither of the currently-discussed explanations of cluster metal abundances is particularly attractive: (i) IMFs flatter than Salpeter, and (ii) substantial iron enrichment from Type Ia supernovae, as in our Galaxy.
These conclusions could be changed if some of the theoretical and observational parameters we have used are in error by large amounts – for example if observed metal abundances in the hot interstellar gas of ellipticals are underestimated by factors of 5 or more – but this seems unlikely.

Alternatively, the different enrichment histories of large ellipticals and rich clusters could be reconciled if the cluster gas is enriched by another source not involving massive elliptical galaxies. Arnaud et al. (1992) show that the total mass of hot gas in clusters correlates nicely with the total optical luminosity of E and S0 galaxies within 3 Mpc of the cluster centers, but there is no similar correlation with the total luminosity of the spiral galaxy component. Since global gas phase iron abundances are fairly constant among clusters, a correlation with gas mass is also a correlation with the total mass of iron, most of which is in the gas phase. Arnaud et al. (1992) therefore concluded that E and S0 galaxies are the only significant sources of metal enrichment in the hot cluster gas.

However, cluster enrichment may be more complicated than this. For example, the role of disk galaxies in ICM enrichment may be more important than is currently thought. Most low redshift rich clusters contain about twice as many S0 galaxies as ellipticals (Dressler 1980). The fractions of S0 and spiral galaxies in clusters are inversely related while the ratio of the number of S0 plus spiral galaxies to the number of ellipticals is rather constant. This suggests that S0 galaxies may be descended from spirals. This is supported by the observation that richer clusters tend to have higher S0/spiral ratios. Even more relevant, cluster observations at \( z \sim 0.5 \) reported by Dressler et al. (1997) show that the fractional content of ellipticals is similar to nearby clusters but the S0/spiral ratio is very much lower. This can be naturally explained if S0 galaxies in rich clusters were spirals in their previous lives before interacting with other cluster galaxies and the ICM. When stripped of their interstellar gas by the ICM, S0 galaxies could have enriched the ICM, perhaps with a strong SNIa abundance signature. If the ICM enrichment were due solely to this process, however, the iron abundance in the ICM should decrease systematically with redshift. Mushotzky & Loewenstein (1997) find no significant change in the global iron abundance in clusters out to redshifts \( z \sim 0.3 \), although there is considerable real scatter in the data that may have masked such a trend. While the transition of spirals into S0 galaxies is appealing as a possible explanation for the large specific supernova rates in clusters, morphological classification at large redshift is a difficult art and subject to error. In similar studies of distant clusters Stanford et al. (1997) and Andreon (1998) find no depletion of S0 galaxies at high redshift.

Another less conventional cluster enrichment possibility is that some of the cluster gas metals has come from outflows from dwarf galaxies. At least one author (Trentham 1994) has claimed that dwarf galaxies can supply all of the gas and metal enrichment observed in rich clusters. While few would agree with this extreme hypothesis, some fractional contribution from dwarf galaxies to the ICM enrichment cannot be entirely dismissed. From studies of intergalactic absorption lines in quasar spectra, Cowie & Songaila (1998) and Lu et al. (1998) find evidence of an average carbon enrichment of \( \sim 0.003 \) solar in the intergalactic medium at high redshifts \( z \sim 3 \), even in low density voids. Although this value is 100 times lower than abundances in rich clusters, it does suggest the presence of an alternative source of metal enrichment. According to Cowie & Songaila, “early generations of small galaxies might be much more efficient at ejecting heavy elements ... than has previously been thought.” Lu et al. maintain that the variation of the carbon abundance with column (and physical) density in \( \text{L}\alpha \) clouds rules out the possibility of (uniform) metal contamination of the intergalactic medium by population III objects.

In another intriguing recent observation with ASCA, Hattori, et al. (1997) have discovered an X-ray cluster at a very high red shift \( z = 0.92 \) having luminosity \( L_x = 8 \times 10^{44} \text{ erg s}^{-1} \). It is most remarkable that this cluster is optically dark. After several sensitive optical searches only the central CD galaxy has been
found at this redshift. Other cluster member galaxies of average luminosity, if present, should have been observed and were not. This cluster is similar in all respects to those at lower redshifts ($z \lesssim 0.4$) except that its mass to light ratio, $\sim 3000$, is about ten times that of less distant clusters. Given the apparent absence of prominent cluster galaxies, it is most astonishing that the iron abundance in the hot cluster gas ($kT = 8.6$ keV) is $\mathcal{Z}_{Fe} = 1.7^{+1.25}_{-0.74}$ in solar units. One possible interpretation would be that the cluster gas is enriched by a multitude of low mass galaxies which has escaped optical detection. If dwarf galaxies created some of the metals in rich clusters, it is likely that this happened at high redshifts to account for the relative constancy of the iron abundance found by Mushotzky & Loewenstein (1997) at red shifts $z \lesssim 0.3$.

Some of these alternative cluster enrichment hypotheses are subject to observational test. We have already mentioned that there is a small, but real, scatter in the global iron abundance in cluster gas (Mushotzky 1998). Since the S0/spiral ratio also varies among clusters, a weak positive correlation of this ratio with gas phase abundance excess would be expected if S0 stripping is an important contributor to cluster gas enrichment. Abundance inhomogeneities in the hot cluster gas may provide another clue to the origin of cluster metals. If only a few bright E galaxies are responsible for most of the intracluster gas enrichment, significant abundance inhomogeneities and radial gradients would be expected due to the limited previous orbital experience of these galaxies. If the cluster gas was enriched by a larger number of dwarf galaxies (most of which may no longer be visible), then abundance inhomogeneities will be much reduced. Such studies may become possible as the spatial resolution of X-ray detectors improves.

The possibility of galactic sources of cluster enrichment other than E and S0 galaxies has been considerably strengthened by recent ASCA observations of cluster iron and silicon abundances. In a study of 40 clusters Fukazawa et al. (1998) find that the ICM silicon abundance increases with cluster richness as $kT$ increases from $\sim 2$ keV to $\sim 9$ keV, but no appreciable change in the iron abundance is indicated over this range. The explanation for this behavior is unclear at present, but it very definitely requires at least two sources of ICM enrichment, otherwise the iron to silicon ratio would be the same in all clusters. For this range of cluster gas temperatures, $kT \gtrsim 2$ keV, the constancy of global gas and iron masses relative to cluster $L_B$ suggests closed box environments (Renzini 1997). However, the sense of the silicon enrichment is opposite to that expected if more spiral galaxies in richer clusters (high $kT$) convert to S0s. Nevertheless, additional sources of cluster gas metals may provide the most satisfactory resolution of the inconsistent enrichment histories of massive ellipticals and rich clusters that we have demonstrated here.

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APPENDIX

In this Appendix we briefly discuss the evolution of hot gaseous halos in NGC 4472 in the context of two different cosmologies: an open universe with $\Omega = 0.3$ and a flat, low density universe with $\Omega = 0.3$ and $\Omega_\Lambda = 0.7$. When $\Omega \neq 1$ the evolution of the dark matter can no longer be described by the self-similar solutions of Bertschinger (1985). Instead, we adopt a simple top hat overdensity perturbation at some early time designed to concentrate the dark mass of NGC 4472 by the current time. The dark matter is followed as a separate zero pressure fluid which builds a stationary NFW core that grows with time, conserving total dark mass. For simplicity we assume the NFW profile for NGC 4472 is identical to that in the flat universe described in the main text.

A. Halo and ISM Evolution in an $\Omega = 0.3$ Universe

Since all matter in an open universe is unbound, the initial perturbation must be large and non-linear in our simple model of galaxy formation. For the $\Omega = 0.3$ universe we introduced a top hat perturbation of overdensity $(1 + \delta)\rho(t_i)$ with $\delta = 5$ extending to $R_i = 43.5$ kpc at time $t_i = 10^8$ yrs. Baryons with mass density $\Omega_b = 0.05$ also participate in this top hat perturbation and by time $t* = 1.5$ Gyrs enough gas is concentrated to form the stars in NGC 4472 in the usual way described in the main text. We chose $\eta_{II} = 0.3 \eta_{\text{std}}$ for the SNII number (taking $\epsilon_{sn} = 1$) and the Type Ia supernova rate is specified with parameters $\text{SNu}(t_n) = 0.03$ and $p = 1$. In Figure 8 we show with a solid line the gas density and temperature distributions after time $t_n = 13$ Gyrs. Although the agreement is not perfect, it is adequate to illustrate that the global evolution of extended hot halos in ellipticals in an open universe is quite similar to the solution for the flat $\Omega = 1$ universe discussed in the main text.

At 13 Gyrs the transition from the stationary NFW dark halo core to the secondary infall occurs at $\sim 200$ kpc, which is just beyond the outermost observations of the X-ray image of NGC 4472. Since the potential has a strong slope change at this radius, this feature at the outer dark core might be visible in the outer X-ray images of some massive ellipticals if the universe were open. For open universe parameters, $t*$ cannot be much larger than $\sim 1.5$ Gyr otherwise too much cold gas gathers in the perturbation potential. In the open cosmology the total baryon fraction is higher at large radii $\sim 0.16$, similar to rich clusters; although the final gas density is necessarily similar to that in the flat universe solution, the dark matter fraction is lower.

We also computed the radial iron and silicon abundances in the gas at time $t_n = 13$ Gyrs and find a general agreement with observed abundances, although the fit could be improved with a slightly lower $\eta_{II}$. Successful solutions for NGC 4472 in the context of an open universe are incompatible with large $\eta_{II} \approx 2.6 \eta_{\text{std}}$ required for global cluster enrichment.

B. Halo and ISM Evolution in an $\Omega = 0.3$, $\Omega_\Lambda = 0.7$ Universe

Galaxy evolution in this cosmology was initiated with a top hat perturbation of radius $R_i = 3$ kpc and relative overdensity $\delta = 0.59$ at time $t_i = 10^6$ yrs. For the supernova rates we take $\eta_{II} = \eta_{\text{std}}$ and $\text{SNu}(t_n) = 0.03$ with $p = 1$. The stars in NGC 4472 are assumed to form at $t* = 3$ Gyrs. After 13 Gyrs the gas density and temperature profiles are shown with dashed lines in Figure 8. The gas density profile is slightly too peaked but is otherwise similar to the observed variation. The gas temperature exhibits a
curious undulation near \( r = 90 \) kpc that is not apparent in the observations. Nevertheless, the computed temperature profile for this model agrees with observed temperatures far better than profiles computed without secondary infall (see Brighenti & Mathews 1998b).

Our purpose in illustrating these results with alternate cosmologies is not to achieve the best possible fits to the current density and temperature distributions by careful adjustment of the parameters. We only wish to demonstrate that such models are feasible and that the principal conclusions reached in this paper do not depend on the simple flat cosmology that we adopt.

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Fig. 1.— Solutions of Equations (4) - (6) for cluster enrichment parameters in terms of the number of Type Ia supernovae per unit $L_B$, $n_{Ia}$ (bottom x-axis) and the current Type Ia rate SNu($t_n$) in SNu units (top x-axis). 

Upper left: Number of Type II supernovae per stellar mass $\eta_{II}$; Upper right: IMF-averaged iron yield for Type II supernovae ($g_{Fe, II}$); Lower left: Fraction of metals from Type II supernovae in stars $f_\ast$; Solid lines: correspond to no stellar enrichment by SNIa ($g_\ast = 0$); Dashed lines correspond to enrichment by half of the SNIa ejecta ($g_\ast = 0.5$). Lower right: Total fraction of iron produced by SNIa $F_{Ia}$ (dot-dashed line) and the total fraction of iron in the gas phase produced by SNIa $F_{Ia,g}$ (dotted line) when $g_\ast = 0.5$. $F_{Ia}$ and $F_{Ia,g}$ for the $g_\ast = 0$ case (solid line).

Fig. 2.— Upper panel: Variation of the number of Type II supernova per stellar mass $\eta_{II}(x)$ with IMF slope $x$ for three pairs of upper and lower mass cutoffs: solid line: $(m_u, m_l) = (100, 0.08)$; long dashed line: $(m_u, m_l) = (40, 0.08)$; short dashed line: $(m_u, m_l) = (40, 0.3)$. Lower panel: Variation of $\beta$, the fraction of initial stellar mass expelled 11 Gyrs after a single burst of star formation. The IMF notation is identical to that in the upper panel.

Fig. 3.— Upper panel: Current gas density profile of the standard model (solid line) and the cluster model (dashed line) compared with observations of NGC 4472. Filled circles are NGC 4472 gas densities observed with Einstein HRI (Trinchieri, Fabbianno & Canizares 1986) and open circles are densities determined with ROSAT HRI and PSPC (Irwin & Sarazin 1996). Lower panel: Current gas temperature profile of the standard model (solid line) and the cluster model (dashed line) compared with ROSAT gas temperature observations of NGC 4472 (Irwin & Sarazin 1996) shown with errorbars.

Fig. 4.— Radial variation of iron (upper panel) and silicon (lower panel) abundances for the standard model. The ASCA iron observations (from Matsushita 1997) are with the SIS detector (filled circles) and the GIS detector (open circles). Solid lines: total abundances; Long dashed lines: abundance contribution from SNII; Short dashed lines: abundance contribution from SNIa; Dotted lines: abundance contribution from stellar outflow.

Fig. 5.— Cumulative mass of iron in the hot interstellar gas at time $t_n = 13$ Gyrs as a function of galactic radius for the standard model (solid line), the cluster model (dashed line), and the Ia model (dotted line).

Fig. 6.— Radial variation of iron (upper panel) and silicon (lower panel) abundances for the “cluster” model. Notation is identical to that in Figure 4.

Fig. 7.— Radial variation of iron (upper panel) and silicon (lower panel) abundances for the “Ia” model. Notation is identical to that in Figure 4.

Fig. 8.— Current gas density (upper panel) and temperature (lower panel) profiles for the open universe ($\Omega = 0.3$) (solid lines) and the low density flat universe ($\Omega = 0.3, \Omega_\Lambda = 0.7$) (dashed lines) plotted against observations of NGC 4472 described in Figure 3.