THE ASTROPHYSICAL JOURNAL, 419:52–65, 1993 December 10
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PRODUCTION AND CIRCULATION OF IRON IN ELLIPTICAL GALAXIES AND CLUSTERS OF GALAXIES

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Received 1993 April 1; accepted 1993 June 17

ABSTRACT

We introduce the concept of cluster *iron mass-to-light ratio* (IMLR) and estimate its value for both the intracluster medium and the stars, finding the amount of iron to be nearly the same in the two cluster components. We discuss under which conditions the past supernova activity can account for the observed IMLR and provide evidence that either the past average rate of Type Ia supernovae was at least a factor of ~ 10 higher than the present rate in ellipticals, or massive stars in clusters formed with a very flat initial mass function (IMF). A solution in which $\sim \frac{1}{4}$ of the observed iron in clusters of galaxies was contributed by Type II supernovae, and $\sim \frac{3}{4}$ by Type Ia supernovae, presents several advantages, as it would allow to preserve the current scenario for the establishment of element abundance ratios in the Galactic halo, bulge, and disk and would leave open the possibility of a universal IMF.

We consider the iron abundance in the gas flow of individual elliptical galaxies, emphasize a macroscopic discrepancy that has recently emerged between the predicted iron abundance in the flow and that derived from X-ray observations, and discuss possible solutions of the discrepancy. We argue that the iron in the intracluster medium (ICM) of rich clusters was ejected from individual galaxies by internal forces generated by supernovae or active galactic nuclei (AGNs), rather than stripped by external forces such as ram pressure. We go further in considering the supernova heating and the presupernova light production which are implied by the observed IMLR and discuss their implications for elliptical galaxy formation. We suggest a possible test for the proposed scenarios, based on the predicted difference in elemental ratios between the ICM and cluster elliptical galaxies, with α-elements to iron ratio being below solar in the ICM and above solar in the stellar component of galaxies.

Subject headings: galaxies: abundances — galaxies: clustering — galaxies: elliptical and lenticular, cD — galaxies: evolution — intergalactic medium — supernovae: general

1. INTRODUCTION

Supernovae (SNs) make metals, and, in particular, they make iron, an element that nonexploding stars are unable to synthesize. Thus, the total amount of iron in a portion of the universe today—such as a cluster of galaxies—keeps the record of the overall SN activity in the past, provided that any major loss of mass has not occurred. But SNs do not make only iron. Each SN injects kinetic energy into the interstellar medium (ISM), and each SN progenitor burns nuclear fuel and radiates the corresponding amount of photons. There is, therefore, a direct link between the total amount of iron and the integrated, past SN heating and stellar light production. In this paper we follow these connections in some detail, with no recourse to elaborate modeling, but rather attempting in a most direct and transparent way to keep track of the implications of our assumptions once coupled to the observed amount of iron in clusters. In doing so we use much less algebra—but not necessarily less physics—than, e.g., chemical and dynamical models of galaxy formation and evolution.

It will progressively appear through the paper that an uncommon variety of astrophysical issues converges on the quest for iron in clusters, from the formation and evolution of elliptical galaxies and clusters of galaxies to supernova physics and astrophysics and from nucleosynthesis and chemical evolution in the halo and disk of our Galaxy to the evolution of gas flows and X-ray properties of elliptical galaxies, with topics such as star formation, dark matter, active galactic nucleus (AGN) activity, galaxy interactions with the environment, and many others coming into play. Therefore, in addressing the iron problem we expect eventually to learn more about each of the topics involved, while the ultimate aim of our approach is to gather direct information and useful constraints on the formation processes of galaxies—especially of elliptical galaxies and bulges—and on their subsequent evolution. The role of SN activity in galaxy formation has been widely entertained in recent years (e.g., Ostriker & Cowie 1981; Ikeuchi & Ostriker 1986; Dekel & Silk 1986; White 1989; Heckman, Armus, & Miley 1990; Ikeuchi & Norman 1991; Djorgovski 1992). Here we provide an additional quantitative basis concerning this specific aspect of the formation process.

In § 2 we introduce the concept of iron-mass-to-light ratio (IMLR) and report about its value in clusters of galaxies, as it

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can be inferred from existing X-ray and optical observations. In § 3 we deal with the iron production by SNs of both types and with the constraints set by the observed IMLR on the overall past SN activity. In § 4 we compare expected and observed iron abundances in galactic flows, emphasize the need to identify the origin of a macroscopic discrepancy between them, and discuss the question of how and when the bulk of iron was transferred from individual galaxies to the intracluster medium (ICM). In § 5 we compare the past SN heating in elliptical galaxies—as implied by the observed IMLR—to the binding energy of galaxies. In § 6 we estimate the total amount of light that forming elliptical galaxies must have emitted, as implied by the present IMLR. In § 7 we formulate a prediction of the standard model for iron and intermediate-mass elements production, according to which a *chemical asymmetry* in elemental proportions should exist between the stellar component of cluster galaxies and the ICM. We also discuss possible alternatives to the standard model. Our conclusions are summarized in § 8.

2. THE IRON MASS-TO-LIGHT RATIO IN CLUSTERS OF GALAXIES

In clusters of galaxies iron is partly dispersed in the intracluster medium (ICM) and is partly locked into the stellar component of galaxies. The ISM of individual galaxies also contains some iron, but its total amount is negligible compared to the two former contributions.

The amount of iron in the various components of a cluster can be expressed in several ways, the most traditional being the abundance, i.e., the mass fraction of iron in either the ICM or in stars. For our purposes, this is not the most useful way of describing the iron content of clusters. For example, in the case of the ICM, iron abundances depend not only on the total amount of iron produced, but also on its dilution with unpredictable amounts of pristine gas, an effect that we know to exist (e.g., Matteucci & Vettolani 1988; Ciotti et al. 1991, hereafter Paper I). A better alternative is represented by the iron mass to stellar mass ratio used, e.g., by Arnaud et al. (1992): here the total iron mass in the ICM is divided by the total mass in stars present in the cluster. Operationally, the latter quantity comes from the observed total luminosity of the cluster and from an assumed stellar mass-to-light ratio for individual galaxies. However, the relation between iron production and mass of the stellar component is rather indirect. For example, two stellar populations differing only in the lower mass cutoff of the initial mass function (IMF) have the same number of massive stars and then produce the same amount of iron but would have different mass and mass-to-light ratios. Moreover, the observed stellar mass-to-light ratio comes from dynamical arguments and from the central velocity dispersion of galaxies, and it may therefore be contaminated by unknown amounts of dark matter. To avoid these assumptions and complications, in Paper I we introduced the concept of IMLR (see also Ciotti et al. 1992), defined as the ratio of the iron mass (either in a specific cluster component, or total) to the total light of the cluster, i.e.:

$$\frac{M_{\rm Fe}}{L_B} = \frac{M_{\rm Fe}}{\Sigma_i L_B^i}, \quad \left(\frac{M_\odot}{L_\odot}\right), \tag{1}$$

where the L_B^i's are the (blue) luminosities of the individual galaxies of the cluster. The IMLR is expressed in terms of quantities whose link with real observables is most direct and presents several other advantages that will become apparent in the following sections.

2.1. *The ICM IMLR*

2.1.1. *Clusters of Galaxies*

The presence of vast amounts of iron in the ICM was theoretically anticipated by Larson & Dinerstein (1975), shortly before its actual discovery via the iron line emission in the X-ray spectra of galaxy clusters (Mitchell et al. 1976; Serlemitsos et al. 1977). From literature data, in Paper I we have estimated $M_{\rm Fe}^{\rm ICM}/L_B$ values in the range $(0.7\text{–}1.6) \times 10^{-2}$ $M_\odot/L_\odot$ for the nearby clusters Virgo, Coma, and Perseus. These values are confirmed by the more extended compilations of Tsuru et al. (1992) and Arnaud et al. (1992), from which we derive the IMLR of the ICM of clusters:

$$\frac{M_{\rm Fe}^{\rm ICM}}{L_B} = 0.01\text{–}0.02 \quad \left(\frac{M_\odot}{L_\odot}\right), \tag{2}$$

with no appreciable trend with cluster richness. Thus, the ICM contains 0.01–0.02 $M_\odot$ of iron for every $L_\odot$ of the galaxy (star) population of the cluster, and, e.g., a cluster such as Perseus with a total luminosity $L_B \simeq 10^{13}$ $L_\odot$ contains $\sim 0.015 \times 10^{13} = 1.5 \times 10^{11}$ $M_\odot$ of iron in its ICM (Paper I).

One caveat is, however, in order: this value of the IMLR follows from the assumption of a chemically homogeneous ICM, but iron may be more concentrated towards the cluster center (Ponman et al. 1990; Koyama, Takano, & Tawara 1991; but for a different conclusion see Hughes et al. 1993). If this is the case, then relation (2) would overestimate the cluster IMLR. On the other hand, especially in the early phases, iron may escape from the cluster, a process that if present would introduce the opposite bias. Evidence for iron actually escaping from small galaxy groups is briefly discussed next.

2.1.2. *Small Galaxy Groups*

Mulchaey et al. (1993) have recently reported *ROSAT* observations of the small group around the giant elliptical NGC 2300. They determine an extremely low iron abundance in the ICM, only ~ 0.06 solar, 5 to 10 times less than in rich clusters. Combined with the estimated mass of the ICM ($\sim 5 \times 10^{11}$ $M_\odot$), this gives $\sim 6 \times 10^7$ $M_\odot$ of iron and an IMLR of only $\sim 4.5 \times 10^{-4}$ when dividing by the total luminosity of the group ($\sim 1.34 \times 10^{11}$ $L_\odot$, using the luminosities adopted by Mulchaey et al.). This is more than 30 times smaller than the IMLR estimated for rich clusters in the previous section and indicates that most of the iron not locked into stars has been lost by the group, probably at an early stage of evolution. The very low IMLR of the NGC 2300 group indicates that small groups, and perhaps poor clusters as well, are subject to major gas exchanges with their surroundings, ejecting at early times most of the iron lost by individual galaxies and reaccreting at later times gas whose primordial composition has been only modestly contaminated by stellar nucleosynthesis products. An early mass loss from the group is certainly not surprising, when one considers that the escape velocity from the group is very close to that from the main individual galaxies, and thus matter having managed to escape from a galaxy may well continue its flow all the way out of the group. We shall return to this point in § 4.4.

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2.2. *The Stellar Iron Mass-to-Light Ratio*

The IMLR of individual galaxies (i.e., of their stellar component) is given by

$$\frac{M^*_{\rm Fe}}{L_B} = \langle Z^{\rm Fe}_* \rangle \frac{M_*}{L_B}, \tag{3}$$

where $\langle Z^{\rm Fe}_* \rangle$ is the average iron abundance (by mass) in the stellar component. The iron abundance ranges over a wide interval within galaxies, and from one galaxy to another. Within individual galaxies, metallicities span from $\sim\frac{1}{100}$ solar for the extreme Population II component to several times solar in the central regions of galactic bulges and in the core of giant elliptical galaxies. Since we are dealing with rich clusters of galaxies, we make the simplifying assumption that clusters contain only early-type galaxies, which is a reasonable approximation. Early-type galaxies span *average* metallicities (iron abundances) from $\sim\frac{1}{3}$ solar for dwarf ellipticals such as M32 (Freedman 1989) to a few times solar for giant ellipticals (O'Connell 1986). Thus, we assume the general average iron abundance for all the stars in a cluster of galaxies to be nearly solar, an estimate that cannot be off by more than a factor of ~ 2, either way. We therefore adopt $\langle Z^{\rm Fe}_* \rangle \simeq Z^{\rm Fe}_\odot$ in equation (3), with $Z^{\rm Fe}_\odot \simeq 0.002$ (Anders & Grevesse 1989). Thus, for stellar mass-to-light ratios in the range $M_*/L_B = 5$–10, one gets:

$$\frac{M^*_{\rm Fe}}{L_B} = 0.01\text{–}0.02 \quad \left(\frac{M_\odot}{L_\odot}\right). \tag{4}$$

Comparing this estimate to equation (2) we conclude that *in rich clusters of galaxies there is nearly an equal amount of iron dispersed in the ICM as there is locked into the stars within individual galaxies.* We believe that this *50/50 condition* provides an important constraint for theories of galaxy formation and evolution. Combining equations (2) and (4) we get the *total* cluster IMLR:

$$\frac{M_{\rm Fe}}{L_B} = \frac{M^*_{\rm Fe} + M^{\rm ICM}_{\rm Fe}}{L_B} \simeq 0.03 \pm 0.01 \quad \left(\frac{M_\odot}{L_\odot}\right), \tag{5}$$

i.e., for each $L_\odot$ of cluster blue light there are $\sim 0.03\ M_\odot$ of iron, nearly evenly shared between stars and the ICM.

3. IRON PRODUCTION BY SUPERNOVAE

In this section we discuss the amount of iron that SNs of the various types can have produced in clusters of galaxies and their relative role in establishing the observed IMLR. In doing so, we take the view that elliptical galaxies in rich clusters are dominated by an old stellar population of age close to one Hubble time. Strong evidence supporting this assumption has been most recently provided by Bower, Lucey, & Ellis (1992; see also Ellis 1992). This allows us to use the single-burst approximation for the whole stellar content of a cluster of galaxies, and we shall do so throughout the present investigation. However, a fraction ($\lesssim 20\%$) of the total cluster light is undoubtedly produced by younger stellar populations, present primarily in the spiral fraction of the galaxy content of clusters. It is therefore worth commenting on the limitations of our single-burst approximation. In this connection, we note that most of iron is released rather promptly past a burst of star formation, while the total luminosity of the resulting stellar population secularly decreases. It follows that the corresponding IMLR is an *increasing* function of time, and, therefore, our adopted approximation sets a *lower* limit to the past SN activity needed to reproduce the observed IMLR.

3.1. *Type Ia Supernovae*

The total amount of iron produced by Type Ia supernovae (SN Ia's) over one Hubble time (~ 15 Gyr) is given by the total number of SN Ia's which have exploded times the mass of iron produced by each SN Ia. So far there has been a general consensus that a typical SN Ia produces ~ 0.5–$0.7\ M_\odot$ of iron (after the ^{56}Ni decay). This has been a consequence of the fair success with which the "W7" carbon deflagration model of Nomoto, Thielemann, & Yokoi (1984) accounts for both the light curve (e.g., Nomoto & Shigeyama 1991) and the spectrum (Branch et al. 1985; Harkness & Wheeler 1990) of SN Ia's. Alternative explosion models of Chandrasekhar mass C-O white dwarfs (e.g., carbon detonations) give quite the same or even larger amounts of iron (Shigeyama et al. 1992; Kholkhlov, Müller, & Höflich 1993). We correspondingly adopt $M^{\rm Ia}_{\rm Fe} = 0.7\ M_\odot$ for the iron yield of each SN Ia (but see § 4.3.2), while the yield for other abundant species (e.g., O, Mg, and Si) is negligible compared to the Type II supernova (SN II) production.

Much less definite is the situation concerning the total number of SN Ia's. Up to now, observations tell only about the *present* rate, while for its time evolution over the previous Hubble time no direct evidence is available. The present rate in elliptical galaxies is estimated to be 0.88 h^2 SNU (Tammann 1982; see also van den Bergh & Tammann 1991), where $h = H_0/100$ and 1 SNU $= 10^{-12}\ L_B$ SNs yr^{-1}, and L_B is the blue luminosity of the parent stellar population (e.g., of one galaxy, or a cluster of galaxies, etc.). We adopt $h = \frac{1}{2}$, and the present rate becomes 0.22 SNU, or $2.2 \times 10^{-13}\ L_B$ SNs yr^{-1}. Cappellaro et al. (1993) give a value 4 times lower than that favored by van den Bergh & Tammann, which illustrates the present range of uncertainty.

In absence of direct observational evidence, the past evolution of the SN Ia rate in ellipticals—and, more generally, its evolution following a burst of star formation—remains highly conjectural. This is so for two main reasons: (1) there is no general consensus on whether the single degenerate (SD) or the double degenerate (DD) model for the SN Ia precursors applies (Munari & Renzini 1992), and (2) in either model the evolution of the rate is controlled by an unknown distribution function describing either the mass distribution of the secondary binary components (SD model), or the distribution of the initial separation of the two white dwarfs (DD model; see Paper I). Still, for both models the *qualitative* behavior of the rate is similar: the first SN Ia explodes at least $\sim 3 \times 10^7$ yr after the burst of star formation, then the rate climbs rather quickly to a maximum in $\sim 10^8$–10^9 yr, and then it declines reaching the present value one Hubble time after the burst. The precise run of the SN Ia rate is, however, highly model-dependent; examples of plausible evolutions of such rate are offered by Greggio & Renzini (1983a) for the SD model and Tornambè (1989) for the DD model. Given these uncertainties, following our assumptions in Paper I, we adopt a convenient parameterization for the rate:

$$R_{\rm SNIa}(t) = 2.2 \times 10^{-13} \vartheta_{\rm SN} L_B t_{15}^{-s}\ {\rm yr}^{-1}, \tag{6}$$

for $t_{15} > t_{15,0}$, where t_{15} is time in units of 15 Gyr. Thus, for $\vartheta_{\rm SN} = 1$ and $t_{15} = 1$, the *standard* Type I supernova (SN I) rate in ellipticals is recovered, i.e., 0.22 SNU. Given the current uncertainty, we consider values of $\vartheta_{\rm SN}$ in the range $0.25 \lesssim$

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$\vartheta_{SN} \lesssim 1$ to be consistent with observations. For $t_{15} < t_{15,0}$ we assume the rate to increase linearly with time in such a way to join the value given by equation (6) at $t_{15} = t_{15,0}$, i.e.,

$$R_{SNIa}(t) = 2.2 \times 10^{-13} \vartheta_{SN} L_B t_{15,0}^{-(s+1)} t_{15} \text{ yr}^{-1} . \quad (7)$$

In the frame of the adopted parameterization, the time $t_{15,0}$ represents the *rise time* of the SN Ia rate, from zero to its maximum, and we shall explore values in the range between 1.5×10^8 and 1.5×10^9 yr, or $t_{15,0} = 0.01$–0.1.

The total number N_{Ia} of SNs that have exploded over a time interval of 15 Gyr is given by the integral of the rate, and from equations (6) and (7) one obtains

$$N_{Ia} = 1.5 \times 10^{10} \int_0^1 R_{SNIa}(t_{15}) dt_{15} = 3.3 \times 10^{-3} \vartheta_{SN} L_B f(s, t_{15,0}) , \quad (8)$$

where

$$f(s, t_{15,0}) = \frac{1}{2} t_{15,0}^{1-s} + \frac{t_{15,0}^{1-s} - 1}{s - 1} . \quad (9)$$

The contribution of SN Ia's to the IMLR follows naturally from equation (8):

$$\left(\frac{M_{Fe}}{L_B}\right)_{SNIa} = \frac{N_{Ia} M_{Fe}^{Ia}}{L_B} = 2.3 \times 10^{-3} \vartheta_{SN} f . \quad (10)$$

For a past SN Ia rate constant in time, one has $s = 0, t_{15,0} = 0$, and thus $f = 1$. With $\vartheta_{SN} = 1$, the corresponding IMLR is more than a factor of 10 smaller than the observed value: *had their rate been constant in the past, SN Ia's would have contributed $\lesssim 10\%$ of the observed iron in clusters of galaxies* (Paper I). Since it is very unlikely that the present rate has been underestimated by such a large factor, we conclude that the past rate had to be significantly higher if SN Ia's ought to contribute a fair fraction of the observed iron, i.e. for $\vartheta_{SN} = 1$ a value of $f \simeq 10$ is required. Formally, the SN Ia contribution to the IMLR in equation (10) depends on three parameters, of which only one (ϑ_{SN}) is directly determined by the observations. The function $f(s, t_{15,0})$—which contains the other two parameters—is tabulated in Table 1 for *reasonable* values of s and $t_{15,0}$. It appears that values of the exponent s in excess of ~ 1.3 are to be preferred if one wants SN Ia's to play a major role in iron production (Paper I). In this frame, the lower the present SN rate, the higher it had to be in the past in order to keep $\vartheta_{SN} f \gtrsim 10$. Thus, for e.g., $\vartheta = 0.25$ a very steep evolution of the rate is required, with $s \gtrsim 1.6$–1.7, along with a rather short rise time.

Besides the total amount of iron production, also astrophysically important is the rate at which iron is delivered, and the typical timescale of such delivery τ_{SNIa}. The definition of this timescale is unavoidably ambiguous, given the particular shape of the SN Ia rate past a burst of star formation. Following an analogy with radioactive decay, we define τ_{SNIa} as the time after the burst when $\frac{1}{2} N_{Ia}(t = 15 \text{ Gyr})$ SN Ia's have exploded. In our adopted parameterization, τ_{SNIa} is a function of the risetime $t_{15,0}$ and of the slope s:

$$\tau_{SNIa} = 15 \left(\frac{1}{2} + \frac{s+1}{4} t_{15,0}^{1-s}\right)^{1/(1-s)} \text{ Gyr} , \quad (11)$$

and representative values are reported in Table 1. Worth noting is that for values of the parameters giving an important SN Ia iron production ($f \gtrsim 10$), one-half of the iron is necessarily delivered on a rather short timescale ($\lesssim 0.5$ Gyr). Before pushing this discussion further, we need to introduce the other potential producers of iron in the universe, i.e., massive stars exploding either as Type II or Type Ib/Ic SNs.

TABLE 1

VALUES OF $f(s, t_{15,0})$ AND τ_{SNIa} (GYr)

$t_{15,0}$	$s = 1.3$	$s = 1.5$	$s = 1.7$
0.01	11.9	23.0	47.0
	0.49	0.33	0.25
0.05	6.1	9.2	14.3
	1.73	1.38	1.16
0.10	4.3	5.9	8.24
	2.84	2.44	2.16

3.2. *Type II Supernovae*

In the case of SN Ia's we believe to have a fairly precise knowledge of the amount of iron released by each event, while the ambiguities affecting the progenitors make the theory unable to predict the corresponding evolution of the SN rate. The case of SN II's is quite the opposite. In fact, one believes to have unambiguously identified the progenitors (stars more massive than $\sim 8\ M_\odot$), while a great uncertainty affects the amount of iron $M_{Fe}^{II}(M)$ produced by each SN II event as a function of the initial mass of the progenitor. This is a result of the current uncertainty in SN theory, with the iron delivered by a SN II event being crucially dependent on the precise position of the *mass cut* between the neutron star remnant and the ejecta, and extremely model-dependent quantity (e.g., Woosley & Weaver 1986). Figure 1 shows three options for $M_{Fe}^{II}(M)$. Not by chance, all the three options coincide for $M = 20\ M_\odot$, the progenitor mass of SN 1987A, for which the amount of iron produced ($0.07\ M_\odot$) comes from the very precise determination obtained by fitting the light curve of this SN (Woosley 1988; Shigeyama, Nomoto, & Hashimoto 1988). A recent compilation of SN II light curves shows that after ~ 300 days from explosion, all the examined light curves tend to converge to nearly the same exponential decline, with rather small scatter

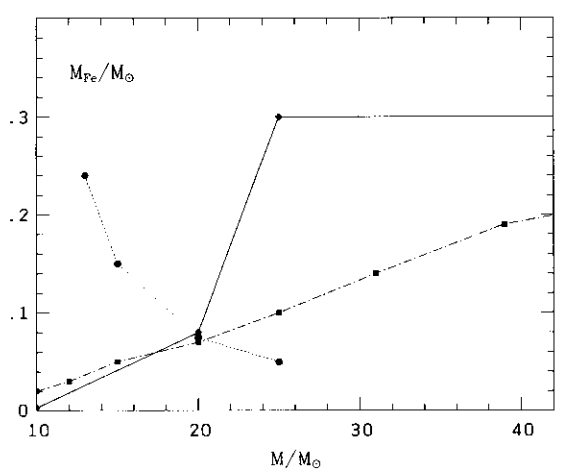

FIG. 1.—The iron yield of massive stars in $M_\odot$ units is displayed as a function of the initial mass, from three different sources: (*dotted line*) Thielemann et al. (1992); (*solid line*); Woosley (1989, referred to by White 1991); (*dash-dot line*) Arnett (1991).

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(Barbon et al. 1993). This finding supports the notion of a small SN II to SN II variation in the iron yield.

The total amount of iron produced by SN II's is obtained integrating the yield per star $M_{\rm Fe}^{\rm II}(M)$ over the stellar IMF or, equivalently, by the product of the mass-weighted average of the yield per star times the total number of SN II's. As usual, for the stellar IMF we assume a power law,

$$\psi(M) = AM^{-(1+x)} = 2.9L_B M^{-(1+x)}, \qquad (12)$$

where we have adopted the normalization $A = 2.9\ L_B$ introduced in Paper I, with L_B—as elsewhere in this paper—being the luminosity of the stellar population at the conventional age of elliptical galaxies, i.e., 15 Gyr. For all the options shown in Figure 1, we find $\langle M_{\rm Fe}^{\rm II}\rangle \simeq 0.07\ M_\odot$, fairly insensitive to the slope x of the IMF. Correspondingly, the SN II contribution to the IMLR becomes

$$\left(\frac{M_{\rm Fe}}{L_B}\right)_{\rm SNII} = \langle M_{\rm Fe}^{\rm II}\rangle 2.9 \int_8^{100} M^{-(1+x)}\,dM \simeq 0.2\left(\frac{8^{-x}}{x}\right)\frac{M_\odot}{L_\odot}. \qquad (13)$$

Clearly, the flatter the IMF slope the larger the number of massive stars per unit present luminosity, the larger the number of SN II's, and, therefore, the larger the implied IMLR. Thus, from equation (13) we get:

$$\left(\frac{M_{\rm Fe}}{L_B}\right)_{\rm SNII} \simeq \begin{cases} 0.003 & \text{for } x = 1.7\,, \\ 0.009 & \text{for } x = 1.35\,, \\ 0.035 & \text{for } x = 0.9\,. \end{cases}$$

We conclude that if the Galactic IMF slope ($x = 1.7$; Scalo 1986) applies also to elliptical galaxies in rich clusters, then SN II's underproduce iron by about a factor of 10 compared to what is demanded by equation (5). Instead, making all the observed iron by SN II's would require a very flat IMF ($x \simeq 1.0$).

3.3. *Type Ib and Ic Supernovae*

Massive stars having lost their hydrogen-rich envelope—such as in either single or binary Wolf-Rayet stars—should be characterized by hydrogen-free spectra and then classified as some kind of SN I's (Renzini 1978), a notion now widely accepted for SNs of Type Ib and Ic (SN Ib and SN Ic) (Wheeler & Levreault 1985). Membership in a binary system may affect the iron yield as a function of the initial stellar mass, either because the absence of a confining envelope may lead to a deeper mass cut (S. Woosley, private communication) or because rotationally induced mixing could increase the mass of ejected ^{56}Ni (Tutukov & Chugai 1992). Since SN Ib's and SN Ic's are almost as frequent as SN II's in star-forming galaxies (Muller et al. 1992; Cappellaro et al. 1993), it follows that these SN types should be taken into account when estimating the iron yield of stellar generations. Here we do so indirectly by counting them among massive stars, i.e., including them among SN II's in equation (13). This is equivalent to assuming the same iron yield–initial mass relation as for SN II's, which cannot be too far from reality (the Thielemann et al. 1992 relation in Fig. 1 was actually meant to apply to SN Ib's and SN Ic's).

3.4. *The Solar Supernova Proportion*

Before discussing recipes for the production of the observed IMLR, we need to consider the evidence about the relative role of the SN types in Galactic nucleosynthesis. While there is no guarantee that one can safely apply the same scheme to elliptical galaxies, we feel it worthwhile to explore the possibility of accounting for the cluster IMLR without appealing to exotic nucleosynthetic scenarios or to an ad hoc IMF, which would inevitably introduce extra adjustable parameters.

It is well known that the O/Fe ratio in the Population II stars of the Galactic halo is 3–4 times solar (Sneden, Lambert, & Whitaker 1979; Gratton & Ortolani 1986; Barbuy 1992). The most popular interpretation of the Galactic trend of [O/Fe] versus [Fe/H] appeals to the different nucleosynthesis roles of SN Ia's and SN II's: the enrichment of the halo was sufficiently rapid to sample almost exclusively the prompt release of SN II products (α-elements such as oxygen, r-process elements, but little iron), while it would take a longer time for SN Ia's to release the bulk of their iron (e.g., Sneden et al. 1979; Greggio & Renzini 1983a, b; Matteucci & Greggio 1986; Abia, Canal, & Isern 1991; Nomoto et al. 1992; Matteucci & François 1992). Correspondingly, in this scenario SN II's produce almost 100% of the iron in extreme Population II stars and $\sim\frac{1}{4}$ of the iron present in the sun, while the residual $\sim\frac{3}{4}$ come from SN Ia's. The same $\frac{1}{4}$–$\frac{3}{4}$ proportion—that hereafter we call the *solar SN proportion*—would be expected for any system old enough to have already experienced the bulk of SN Ia iron release, provided the IMF and the frequency of SN Ia precursors are the same of the solar neighborhood. Rich clusters of galaxies are likely to meet the first requirement: the bulk of their stellar content is very old, and, therefore, most of SN Ia's should have already exploded by now. The likelihood of the second requirement is further discussed in the next sections. Since this relative role of SN Ia's and SN II's in establishing the solar abundances has been widely entertained in recent years, for short we refer to it as the *standard chemical model*. It is worth noting that in star-forming (spiral) galaxies the SN Ia's rate is about $\frac{1}{3}$ the rate of all other types together (Cappellaro et al. 1993). If each SN Ia produces 10 times more iron than other SNs, then the present iron production in spiral galaxies is indeed dominated 3 to 1 by SN Ia's, in just the solar SN proportion.

3.5. *Producing the Observed IMLR*

We now discuss three alternatives for the production of the cluster IMLR.

1. Making all the iron with SN Ia's requires a strong evolution of the SN rate, with $f \gtrsim 15$ in equation (10) if $\vartheta_{\rm SN} \lesssim 1$. From Table 1 we see that large values of the exponent s and short rise times $t_{15,0}$ are favored. Such values are consistent with $s \gtrsim 1.3$ as demanded by the evolutionary scenario for gas flows in ellipticals in which the SN Ia rate secularly declines and galactic flows evolve from an early supersonic wind to a subsonic outflow and to, eventually, an inflow regime (Paper I). Such early winds also help to establish the observed even share of iron between stars and the ICM (see § 2). However, no doubt some iron is also contributed by SN II's.

2. Making all the iron with SN II's requires star formation in cluster elliptical galaxies to have occurred with a very flat IMF ($x \lesssim 1.0$), much flatter than the Galactic IMF. Equivalently, one can appeal to a *bimodal* IMF, as argued by Arnaud et al. (1992), who dismiss without justification SN Ia's as major iron producers. In the bimodal IMF scenario *quiescent* star formation proceeds with a normal IMF, while *bursts* of star formation produce only massive stars (e.g., more massive than $\sim 2\ M_\odot$). Quite obviously, in such a scenario one can generate an

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arbitrarily large IMLR, simply because the burst component produces iron from SN II's at the time of the burst but no light at all after 15 Gyr, as stars more massive than 2 $M_\odot$ live less than ~ 1 Gyr. Clearly, bimodal star formation can be tuned to produce any desired IMLR. However, the homogeneity of cluster ellipticals implied by the very small scatter about the fundamental plane (Bender, Burstein, & Faber 1992) indicates a very small scatter in the stellar M_*/L_B ratio, which, in turn, implies a very small scatter in the IMF among galaxies (Renzini 1993). Also, the narrowness of the metallicity–σ_* relation (Bender 1992) suggests that the metal production per unit present luminosity was not appreciably different from one galaxy to another. Thus, the proportion of *quiescent* to *burst* star-formation modes should be virtually universal in order for the bimodal IMF scenario to be tenable: fine tuning seems to be required.

3. The third scenario allows for a contribution from both SN types and does so in the *solar SN proportion*, with $\frac{1}{4}$ of the iron in clusters coming from SN II's and $\frac{3}{4}$ from SN Ia's. Indeed, in this case massive stars with a Galactic IMF ($1.35 \lesssim x \lesssim 1.7$) contribute about $\frac{1}{4}$ to the cluster IMLR, while with $\vartheta_{SN} f \simeq 10$, SN Ia's contribute the residual $\frac{3}{4}$. In this way, with the same combination of the parameters x for massive stars and $\vartheta_{SN} f$ for SN Ia's, one accounts for the Galactic chemical evolution as well as for the IMLR in clusters: a clear advantage for this scenario. Moreover, with this choice of parameters one satisfactorily accounts also for the present X-ray properties of elliptical galaxies, as extensively discussed in Paper I, and one preserves the early winds necessary to replenish of iron the ICM. Although very attractive, this scenario requires independent confirmation, as several ingredients are in fact rather uncertain (e.g., the iron yield from SN II's; see Woosley & Weaver 1992). We shall further explore its implications in the following sections.

4. IRON IN GALAXY FLOWS: AN EMBARRASSING DISCREPANCY

4.1. *The Predicted Iron Abundance in Galaxy Flows*

Stellar ejecta in present-day ellipticals can either flow out as a supersonic wind or a subsonic outflow or flow in towards the galaxy center. The initial iron content of stellar ejecta—which reflects the average stellar abundance—is further increased *in flight* by the SN Ia explosions. Since the rate of stellar mass loss is very well known, the iron abundance in the flow is determined by the rate of SN Ia's (see Paper I):

$$Z_{\rm flow}^{\rm Fe} = \langle Z_*^{\rm Fe} \rangle + \frac{M_{\rm Fe}^{\rm Ia} R_{\rm SNIa}}{\dot{M}_*} , \qquad (14)$$

where $\langle Z_*^{\rm Fe} \rangle$ is the mass-loss–averaged iron abundance of the stars of the galaxy and $\dot{M}_*$ is the total stellar mass loss at $t = 15$ Gyr. For our adopted values of $\langle Z_*^{\rm Fe} \rangle$ and $M_{\rm Fe}^{\rm Ia}$, equation (14) becomes:

$$\frac{Z_{\rm flow}^{\rm Fe}}{Z_\odot^{\rm Fe}} \simeq 1 + 5\vartheta_{SN} . \qquad (15)$$

Thus, for $0.25 \lesssim \vartheta_{SN} \lesssim 1$ the iron content of the flow is correspondingly expected to range from ~ 2 up to ~ 6 times solar.

The iron content of the flow is predicted to evolve rather weakly with cosmological time if the SN Ia rate evolution is close to that of stellar mass loss (i.e., for $s \simeq 1.1$–1.5), while for a constant rate ($s = 0$) it was much lower in the past. In this latter case a significant radial gradient in the iron abundance can be originated, since the gas flow time can be as long as several Gyr (Loewenstein & Mathews 1991). As pointed out in Paper I, the direct determination of the iron content in the gas flows of elliptical galaxies may provide a rather straightforward determination of the present SN Ia rate, thus complementing direct SN surveys.

4.2. *Observed Iron Abundances in X-Ray Elliptical Galaxies*

Estimates of the iron abundance in galaxy flows was first attempted using data from the *Ginga* satellite. Ohashi et al. (1990) reported an upper limit about twice solar for NGC 4472 and NGC 4636. From the upper limit to the iron line equivalent width reported by Awaki et al. (1991) for NGC 4472, Ohashi & Tsuru (1992) estimate the iron abundance in the flow to be, at most, solar. For NGC 1399—the cD galaxy in the Fornax cluster—Ikebe et al. (1992) estimate iron to be $1.1^{+1.3}_{-0.5}$ times solar. A preliminary analysis of *ROSAT* data suggest a very low iron abundance in the core of M86, i.e., ~ 0.2 times solar (Döbereiner, Böhringer, & Heidt 1993). Finally, from BBXRT observations and one-temperature fits, Serlemitsos et al. (1993) estimate the metallicity of NGC 1399 and NGC 4472 to be at 90% confidence $0.56^{0.82}_{0.38}$ and $0.20^{0.46}_{0.09}$, respectively. Taken at face value, there is a factor of ~ 10 discrepancy compared to the predicted iron abundance with $\vartheta_{SN} = 1$, and SN Ia's could really be excised from the list of important iron contributors in galaxies.

4.3. *Possible Origins of the Discrepancy*

We first address the question of the metallicity of the stellar component of NGC 1399, and concentrate the discussion on this galaxy because BBXRT data for NGC 4472 were of inferior quality. Burstein et al. (1988) give $Mg_2 = 0.357$ for the magnesium index of NGC 1399, one of the highest values among elliptical galaxies, indicating that at least the core of NGC 1399 is extremely metal-rich. Moreover, Franx, Illingworth, & Heckman (1989) find very flat U–R and B–R color gradients in this galaxy out to about one effective radius, and the central metallicity may be representative of the galaxy as a whole. Worthey, Faber, & Gonzales (1992) provide a collection of Mg_2-[Fe/H] calibrations (see their Fig. 2), which all indicate [Fe/H] $\gtrsim 0.3$, i.e., larger than twice solar for the value of Mg_2 reported above. Near solar abundance at the center—dropping to $\sim \frac{1}{3}$ solar at one effective radius—is instead obtained by Ostrov, Geisler, & Forte (1993) for NGC 1399, using surface photometry in the Washington system. So there is at least a factor of 2 discrepancy between the two optically determined metallicities. There appears to be also a similar discrepancy between the metallicity from the Mg_2-[Fe/H] calibration and the BBXRT abundances of the ISM of NGC 1399, *even assuming no ongoing enrichment at all by SN Ia's*, while there appears to be near agreement between BBXRT and Washington photometry results. Thus there might be a problem either with the BBXRT metallicity determination or with the existing Mg_2-[Fe/H] calibrations, if the bulk of the ISM is endogenous to the galaxy. We are not in the position to discuss either of these possibilities, and for the rest of this section we assume the BBXRT determination at face value (but see § 4.3.3).

4.3.1. *Is the SN Ia Rate Much Lower than "Observed"?*

Serlemitsos et al. (1993) note that their result implies $\vartheta_{SN} \lesssim 0.1$, a constraint virtually consistent with $R_{\rm SNIa} = 0$. Reducing the SN rate would certainly help ease the discrepancy between

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optical and X-ray abundance determinations, and SN rate determinations in ellipticals are so difficult that perhaps one cannot exclude the possibility that current estimates might be affected by unaccounted systematic errors. The factor of 4 discrepancy between van den Bergh & Tammann (1991) and Cappellaro et al. (1983) may point in this direction. However, a reduction by a large factor of the SN Ia rate would drastically reduce the role of SN Ia's in the chemical evolution of galaxies and would leave us without an explanation for the halo and disk abundance patterns (see § 3.4). We shall return to this point in § 7.2.

4.3.2. *Does Each SN Ia Produce Less Iron?*

Another way of reducing the iron production rate is to reduce the iron yield per SN. A reduction of the size required to ease the discrepancy while keeping a nominal SN Ia rate ($\vartheta_{SN} \simeq 1$) is highly implausible in the frame of the carbon deflagration model of a Chandrasekhar mass white dwarf. At least 0.16 $M_\odot$ need to be incinerated to ^{56}Ni just to unbound the star, and burning at least 0.4 $M_\odot$ is required to account for the velocity of the photosphere (Arnett, Branch, & Wheeler 1985). This leaves very little room for a reduction below the value adopted here (0.7 $M_\odot$).

Alternatives to the carbon deflagration model still exist and may lead to lower iron yields. Accretion onto a sub-Chandrasekhar mass C-O white dwarf can indeed lead to helium detonation in an accumulated helium envelope, which, in turn, may ignite a detonation in the C-O core (Woosley, Weaver, & Taam 1980; Nomoto 1982; Limongi & Tornambè 1991). Conditions for helium detonations are certainly easier to achieve than for carbon deflagration, since a smaller amount of mass needs to be accreted onto the white dwarf and because the star does not need to reach the Chandrasekhar limit for the explosion to occur. This makes double-detonation models quite attractive, at least on purely statistical grounds (Kenyon et al. 1993). Early explorations of helium detonation models showed that they tend to underproduce the intermediate mass elements and expand too fast to provide a good fit to SN Ia spectra (Branch & Nomoto 1986). Recently, Shigeyama et al. (1992) and especially Woosley & Weaver (1993) have explored the outcome of explosions of low-mass C-O white dwarfs, finding better agreement with SN Ia light curves and composition. The iron yield of these models ranges from a minimum of $\sim 0.27\ M_\odot$ to over 1 $M_\odot$. We conclude that a reduction by more than a factor of three of M_{Fe}^{II} compared to the assumption in equation (15) is extremely unlikely. A combination of the two effects, i.e., a lower SN rate coupled to a lower yield per SN, would obviously give iron abundances closer to the BBXRT result. For example, with $\vartheta_{SN} = 0.25$ and $M_{Fe}^{Ia} = 0.27\ M_\odot$, the iron in the flow would be $\sim 1 + 0.5 = \sim 1.5$ times solar, if stars are solar on average. But again, the standard chemical model with the $\frac{1}{4}$–$\frac{3}{4}$ solar proportion could only be maintained by appealing to a short SN Ia risetime ($\lesssim 10^8$ yr) coupled to a fast drop of the rate ($s \gtrsim 1.6$).

4.3.3. *The 6.7 keV Iron Lines in NGC 1399*

The best-fit, single-temperature model for NGC 1399 presented by Serlemitsos et al. (1993) provides a good reproduction of the X-ray spectral energy distribution in the 0.1–10 keV (including the many iron lines around 1 keV) but fails by a very large margin to predict the observed flux in the Fe XXV Kα line at 6.7 keV. Here we explore two possibilities to account for it. Serlemitsos et al. (1993) estimate that NGC 1399 emits $\sim 5 \times 10^{39}$ ergs s^{-1} in this iron line, which becomes $\sim 1.6 \times 10^{40}$ ergs s^{-1} when adopting the distance favored by Fabbiano, Kim, & Trinchieri (1992), who give $\sim 2 \times 10^{42}$ ergs s^{-1} for the luminosity in the *Einstein* band (0.2–4 keV). Assuming the gas to be isothermal and homogeneous, the ratio of the two luminosities is given by

$$\frac{L_{6.7}}{L_{0.2-4}} = \frac{\Lambda_{6.7}(T, Z^{Fe})}{\Lambda_{0.2-4}(T, Z^{Fe})} \simeq 8 \times 10^{-3}\ , \qquad (16)$$

where the Λ's are the corresponding emissivities, and $\Lambda_{6.7}$ includes all the subordinate iron lines at ~ 6.7 keV. We now explore which combinations of T and Z^{Fe} are able to reproduce the observed value of this ratio. Figure 2 displays the run of $\Lambda_{6.7}(T, Z^{Fe})/\Lambda_{0.2-4}(T, Z^{Fe})$ as a function of iron abundance for several gas temperatures, using the Raymond & Smith (1977) thermal plasma model with solar abundances for the elements other than iron. Temperatures in excess of ~ 1.3 keV and iron abundances several times solar are required to reproduce the observed ratio. As far as the temperature is concerned, 1.3 keV is appreciably out of the 90% confidence limits given by Serlemitsos et al. (1993) (1.0–1.1 keV), but is (more) consistent with the 90% confidence limits of other determinations: 1.5–5.5 keV (Killeen & Bicknell 1988), >1.1 keV (Kim, Fabbiano, & Trinchieri 1992), 1.25–1.51 keV (Ikebe et al. 1992). Certainly with a temperature as high as 1.3 keV and iron ~ 6 times solar, the spectral fit to the BBXRT data at lower energies (around ~ 1 keV) would be worse than for the temperature and composition favored by Serlemitsos et al. (1993). On the other hand, their model falls short by a large margin to account for the strength of the 6.7 keV iron line, and one is forced to the conclusion that any isothermal, chemically homogeneous model does not fit all the BBXRT data.

We now explore the possibility that the observed 6.7 keV iron line luminosity is produced by hot bubbles generated by the SN Ia explosions (Serlemitsos et al. 1993). We assume a two-phase ISM with a dominant low-temperature and low-metallicity component and a trace high-temperature component enriched in iron by SN explosions. To get the ratio

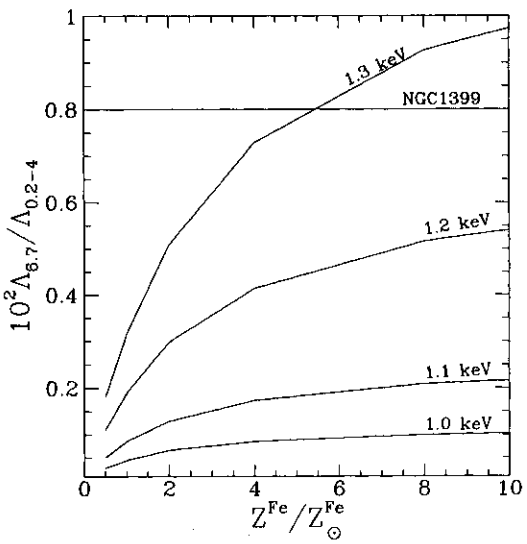

FIG. 2.—The emissivity of the Fe K lines around 6.7 keV over the continuum, plus line emission in the *Einstein* band 0.2–4 keV, as a function of iron abundance and for various temperatures in keV. For all elements other than iron, the solar abundance is adopted. The corresponding luminosity ratio observed in the galaxy NGC 1399 is also indicated.

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$L_{6.7}/L_{0.2-4}$, we assume that the bubbles have all the same temperature $T_B = 4.9$ keV, for which the emissivity in the 6.7 keV line is maximum, and are in pressure equilbrium with the surrounding ISM. Following Mathews (1990), we assume a radial trend for the stellar density and the hot ISM, respectively given by $\rho_* \propto r^{-3}$ and $n_g \propto r^{-3/2}$. The dominant phase ISM is assumed to be isothermal at the best-fit temperature given by Serlemitsos et al. ($T_g = 1.1$ keV). With these assumptions, the density inside the bubble is $n_B = n_g T_g/T_B$. Using the results of Mathews (1990), we obtain that the bubbles filling factor f_B is very low ($f_B \simeq 3.3 \times 10^{-4} \vartheta_{SN}$). With these assumptions one has

$$\frac{L_{6.7}}{L_{0.2-4}} \simeq \frac{T_g^2 \Lambda_{6.7}(T_B)}{T_B^2 \Lambda_{0.2-4}(T_g)} \frac{4\pi}{3} \frac{\nu_B \int r^2 \rho_* n_g^2 R_B^3 \, dr}{\int r^2 n_g^2 \, dr}, \quad (17)$$

where R_B is the local average radius of the bubbles, and the integrations extend over the whole galaxy volume. Here we have eliminated the density of the bubble using the pressure equilibrium condition, and the bubbles are distributed proportionally to the stellar density. The factor of proportionality ν_B is linearly related to f_B. Since $R_B \propto n_g^{-1/3}$ (Mathews 1990), one finally obtains

$$\frac{L_{6.7}}{L_{0.2-4}} \simeq \frac{T_g^2 \Lambda_{6.67}(T_B)}{T_B^2 \Lambda_{0.2-4}(T_g)} \frac{f_B \delta^{3/2}}{\log \delta} \frac{\langle Z^{Fe} \rangle_B}{Z_\odot^{Fe}}, \quad (18)$$

where δ is the ratio of the tidal to core radius and $\langle Z_{Fe} \rangle_B$ is the average iron abundance within bubbles. Adopting the mentioned temperatures for the two phases and $\delta = 180$, equation (18) becomes

$$\frac{L_{6.7}}{L_{0.2-4}} \simeq 0.17 f_B \frac{\langle Z^{Fe} \rangle_B}{Z_\odot^{Fe}} \simeq 1.9 \times 10^{-3} \vartheta_{SN}, \quad (19)$$

where we have used $\langle Z^{Fe} \rangle_B \simeq 33.5 \, Z_\odot^{Fe}$, having assumed that each bubble contains 0.7 $M_\odot$ of iron and taking the mass distribution of the bubbles from Mathews (1990). For the observed luminosity ratio (8×10^{-3}), equation (18) implies $\vartheta_{SN} \gtrsim 4$, since by relaxing the assumption $T_B = 4.9$ keV the required SN rate steeply increases as the 6.7 keV line emissivity decreases.

We conclude that neither the one-phase model nor a simple two-phase model is able to simultaneously fit the whole BBXRT spectrum of NGC 1399 with a SN Ia rate within the observed range ($0.25 \lesssim \vartheta_{SN} \lesssim 1$). Future X-ray observations should help us understand what the actual temperature and chemical structure of the X-ray gas is in this galaxy.

4.3.4. *NGC 1399: A Galactic or a Cluster Cooling Flow?*

In the frame of the evolutionary hydrodynamical models presented in Paper I, galaxies with the largest X-ray to optical luminosity ratio L_X/L_B are likely to be in the inflow regime, those with intermediate values of L_X/L_B are in the outflow phase, and those with lowest L_X/L_B values are still in the wind phase. This scenario can resist even a large reduction of the SN Ia rate over the reference value adopted in Paper I ($\vartheta_{SN} = \frac{2}{3}$), provided that the amount of dark matter is correspondingly reduced in such a way as to keep the same the rate of energy injection by SN Ia's to the power required to extract the gas from the potential well of the galaxy. For example, reducing ϑ_{SN} from $\frac{2}{3}$ to $\frac{1}{4}$ would give substantially the same kind of flow regimes, provided that the ratio of dark to stellar matter R is reduced[1] from 9 to ~ 1. Clearly, a precise determination of the SN rate is required to constrain the dark matter content by this method. Given the very high L_X/L_B of NGC 1399, its regime is likely to be an inflow, whatever the adopted SN rate.

The models presented in Paper I assume no confining pressure outside galaxies and therefore better apply to isolated objects rather than to a cD galaxy such as NGC 1399. Following a method described elsewhere (D'Ercole et al. 1990), we have constructed several evolutionary sequences, including the effect of an outer pressure so as to mimic the interaction of NGC 1399 with the ICM of the Fornax cluster. For the galaxy parameters we have adopted $L_B = 5.56 \times 10^{10} \, L_\odot$ and $\sigma_* = 370$ km s^{-1}, and we explored values of $R = 3$ and 9 and $\vartheta_{SN} = 0.1$ and $\frac{2}{3}$. For the confining pressure we have adopted 5×10^3, 10^4, and 3×10^4 K cm^{-3}, along with ICM temperatures of 1.5×10^7 K and 3×10^7 K. With $R = 9$ and $\vartheta_{SN} = \frac{2}{3}$, the galaxy is in inflow phase even with outer pressure $P = 0$, and its X-ray luminosity is $L_X \simeq 6 \times 10^{41}$ ergs s^{-1}, more than a factor of 3 less than observed (Fabbiano, Kim, & Trinchieri 1992). Models with outer pressure are considerably brighter in X-rays, a result of less degassing at early times coupled with accretion from the ICM at later times. Thus, L_X ranges from $\sim 8 \times 10^{41}$ ergs s^{-1} for $(R, \vartheta_{SN}, P) = (3, \frac{2}{3}, 10^4)$ and $(9, 0.1, 10^4)$, up to $\sim 6 \times 10^{42}$ ergs s^{-1} for $(R, \vartheta_{SN}, P) = (3, \frac{2}{3}, 3 \times 10^4)$. Correspondingly, the rate of accretion from the ICM ranges from $\sim 0.5 \, M_\odot$ yr^{-1} up to $\sim 3.6 \, M_\odot$ yr^{-1}, values to be compared to $\sim 0.8 \, M_\odot$ yr^{-1}, the rate of stellar mass loss (Paper I). It appears that NGC 1399 may accrete from the Fornax ICM more gas per unit time than lost by its stars, thus having its endogenous ISM diluted by a significant factor. Among our models, those which have the right X-ray luminosity ($L_X = 2 \times 10^{42}$ ergs s^{-1}) accrete 1.2–1.5 $M_\odot$ yr^{-1}, and, therefore, the iron content of the ISM is diluted by a factor ~ 3, since the iron abundance of the ICM is typically $\lesssim 0.5$ solar (Arnaud et al. 1992) and may be even much lower in a poor cluster such as Fornax (see § 2.1.2). We suggest that accretion is indeed required to explain the high X-ray luminosity of NGC 1399 and that the resulting dilution helps to ease the discrepancy between the expected and observed iron abundance in the ISM. Some dilution effect might also be present in NGC 4472, as this galaxy is at the center of a subcomponent of the Virgo cluster.

4.4. *Gas and Iron Flows from Galaxies to the ICM*

The mere existence of iron in the ICM demonstrates that gas is able to flow out of individual galaxies into the general potential well of the cluster. The fact that there is nearly as much iron in the ICM of rich clusters as there is locked into the stellar component of cluster galaxies (i.e., the 50/50 condition) further demonstrates that such flows have involved a main fraction of the baryonic matter once incorporated into galaxies. After these considerations, two important questions remain open: when was the iron transferred from individual galaxies to the ICM, and which was the process responsible for the transfer? Several mechanisms can be envisaged for the extraction of chemically enriched materials from individual elliptical galaxies: galactic winds and outflows powered by either SN or nuclear activity, ram pressure ablation, and

[1] See eq. (16) in Paper I. See also Fig. 9 in the same paper, which indicates that for low values of R a partial wind regime becomes more likely.

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dynamical ejection of stars, including SN Ia progenitors. Some of these processes are now briefly discussed.

4.4.1. *Wind Ejection*

Two classes of galactic wind models have been considered. They have in common an early establishment of a galactic wind powered by SN II explosions, such as in the models of Larson (1974), but differ for the role attributed to SN Ia's in the subsequent evolution of the flows. For example, David, Forman, & Jones (1990) assume a constant SN Ia rate ($s = 0$) and, therefore, as soon as a wind is established by SN II's, star formation ceases and, along with it, the SN II heating itself. Thus, SN heating reduces to that of SN Ia's, which is insufficient to maintain a wind/outflow regime, given that at such an early time stellar mass loss is more than 10 times higher than the present value (see Paper I). Correspondingly, as soon as star formation ceases, the wind tends to stall and an inflow is rapidly established. Many gigayears later a galactic wind is reestablished, since the secular decrease of stellar mass loss coupled with the assumed constant SN Ia rate implies an increasing specific heating. This kind of behavior is also exhibited by evolutionary models in which the SN Ia heating declines less steeply than stellar mass loss ($s \lesssim 1.3$), and, therefore, following formation and early wind establishment these models evolve through an inflow-outflow-wind (IOW) sequence of flow regimes.

In the other class of models (D'Ercole et al. 1989; Paper I) one adopts $s \gtrsim 1.3$, the specific SN Ia heating secularly declines, the supersonic wind evolves to a subsonic outflow, and sooner or later a central cooling catastrophe reverts the outflow to an inflow. Thus, following formation these models evolve through a wind-outflow-inflow (WOI) sequence of flow regimes.

In both models most of the iron is ejected from galaxies during the early wind phase, i.e., within the first gigayear or so, but, obviously, most iron is from SN II's in IOW models (in particular for $s = 0$) and from SN Ia's in WOI models. From Table 1 of David, Forman, & Jones (1990) we infer that their models (with $M_*/L_B = 5$) predict the resulting IMLR in the intracluster medium to range from $\sim 4 \times 10^{-5}$ to $\sim 5 \times 10^{-3}$, as the IMF slope is reduced from $x = 2$ to $x = 1$. The predicted IMLR is extremely sensitive to the adopted IMF slope, and a value of the IMF slope x somewhat less than 1 is required to fit the observed IMLR, in agreement with our conclusion in § 3.2. This is so because the flatter the IMF, the more iron is produced, *and* because the more SNs, the larger the fraction of the galactic mass which is ejected. Actually, the latter effect is quantitatively dominant in these models, which means that with a steep IMF (e.g., $x \gtrsim 1.35$) even a macroscopic increase of the iron yield per SN II does not suffice to meet the observed IMLR in the ICM.

Instead, in WOI models with a standard IMF, less mass is ejected by each galaxy, but the ejectum is highly enriched in iron by SN Ia's, especially at early times (Renzini 1989; Paper I). Yet the production of an IMLR as large as that observed in the ICM depends critically on the details of the models, especially on the efficiency with which the SN heating goes to increase the thermal energy of the ISM rather than being radiated away. For example, for $M_*/L_B = 10$ and $h = \frac{1}{2}$ the galactic wind models of Matteucci (1992) give, at most, $M_{\rm Fe}^{\rm ICM}/L_B \simeq 10^{-3}$, at least a factor of 10 too low. Again, we find that the 50/50 condition sets a strong discrimination on models of galaxy formation and evolution.

4.4.2. *AGN Ejection*

Nuclear activity powered by accretion on a massive black hole (BH) represents another obvious source of internal heating. The rate of energy production by BH accretion is roughly $L_{\rm BH} = \epsilon \dot{M} c^2$, or $\sim 6 \times 10^{44}$ ergs s^{-1} for $\dot{M} = 1\ M_\odot$ yr^{-1} and for an *efficiency* $\epsilon = 0.01$. Noting that central cooling rates as large as $\sim 10\ M_\odot$ yr^{-1} are typical at the time of a central cooling catastrophe (Paper I), it follows that $L_{\rm BH}$ may be three or more orders of magnitude higher than the cooling rate of the X-ray gas L_X. Therefore, during the power-on phases of an AGN, a strong feedback effect of $L_{\rm BH}$ on the gas flow is expected, quite possibly leading to the expulsion of most of the gas from the galaxy to the ICM. Tabor & Binney (1993) have developed a stationary semianalytical model in which a power $10^{-3}\ L_{\rm BH}$ is deposited in the inner regions of the gas flow and used to maintain a central convective zone which extends a fraction of 1 kpc around the BH itself. The assumption of a stationary condition has been relaxed by Ciotti & Ostriker (1993), who also treat in detail the Compton heating of the ISM by the hard radiation from the AGN. Their numerical one-dimensional hydrodynamical simulations show indeed that the resulting time evolution of the gas flow is highly nonstationary, with the expulsion of the bulk of galactic gas being the most likely outcome once a powerful AGN is turned on by the cooling flow feeding of the central BH.

4.4.3. *Ram Pressure Stripping*

Ram pressure stripping has been widely entertained as a mechanism for transferring materials from galaxies to the ICM. Yet this process is unlikely to have played a major role in establishing the IMLR in a cluster dominated by ellipticals from early times, although it may certainly contribute to gas removal from galaxies at the present time (e.g., D'Ercole et al. 1993). The argument proceeds as follows. The high X-ray luminosity of many ellipticals in the Virgo cluster (e.g. Fabbiano 1989) indicates that ram pressure stripping may be effective in only a fraction of cluster elliptical galaxies at the present epoch. At early times, when most of the iron was being produced, stellar mass loss was more than one order of magnitude higher and so was the energetic requirement for a steady extraction of the gas from the potential well of galaxies. Conversely, the ram pressure experienced by galaxies was either the same as now, or more likely even less, since the cosmological growth of large scale structures implies lower ICM densities and cluster dispersion velocities at early times. We conclude that—at least in poor clusters such as Virgo—ram pressure stripping was inefficient right at the time when a massive, iron-rich ISM was being produced in young ellipticals, and, therefore, without sufficient internal heating, most of the iron would have been lost in early galactic cooling flows.

Since the average ram pressure *power* scales as $n\,\sigma^3$ (n and σ being the ICM density and the cluster velocity dispersion, respectively), such power in very rich clusters may be one to two orders of magnitude higher than in Virgo, and hence the above argument may not apply to rich clusters. However, were ram pressure playing an important role in extracting iron from rich cluster ellipticals, then we would expect the IMLR to increase with cluster richness, since so does the ram pressure itself. This is not the case: as noted in § 2.1.1, there is no appreciable trend of the IMLR with the cluster richness; thus, even in rich clusters, ram pressure did not play a major role in transferring the bulk of iron from elliptical galaxies to the ICM. We conclude that the iron observed in the ICM was

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ejected from the cluster galaxies by internal forces, rather than *extracted* by forces of environmental origin. Finally, the very low IMLR in the small group around NGC 2300 does not contradict this scenario, since materials supersonically ejected by individual galaxies easily leave the group as well, and the present ICM appears to have been accreted at late times, long after most of the iron was lost to the outer space.

5. SUPERNOVA HEATING VERSUS BINDING ENERGY OF GALAXIES

Each SN injects into the ISM $\sim 10^{51}$ ergs of kinetic energy, irrespective of the SN type. Knowing how much iron is in a cluster and the average iron yield per SN, we also know how much kinetic energy has been injected into the ISM during the formation of elliptical galaxies or shortly thereafter. From equation (5) we get the number of SNs that have exploded, as the ratio of the total amount of iron in the cluster over the average iron yield of each SN:

$$N_{\rm SN} = \frac{M_{\rm Fe}}{\langle M_{\rm Fe}\rangle} = \frac{0.03 L_B}{\langle M_{\rm Fe}\rangle} = F_{\rm SN} L_B \,, \tag{20}$$

where the numerical factor $F_{\rm SN}$ depends on the mix of SN Ia's to SN II's and is equal to 0.4, 0.04, and 0.14 for the case of all iron from SN II's, all iron from SN Ia's, and the solar SN proportion, respectively. The injected kinetic energy is therefore

$$E_{\rm SN} = 10^{51} \cdot N_{\rm SN} = 10^{51} F_{\rm SN} L_B \text{ ergs} \,. \tag{21}$$

In these relations L_B can be interpreted as the luminosity of a whole cluster or of an individual galaxy. In the rest of this section we adopt this latter point of view.

Certainly, part of this kinetic energy has to be dissipated and radiated away during galaxy formation, while the rest can be used to drive gas out of galaxies, thus interruptng the star formation process, establishing galactic winds, and replenishing the ICM of iron. One way to gauge how *big* $E_{\rm SN}$ is is to compare it to the binding energy of the luminous matter. For the luminous and dark matter distributions used in Paper I, such binding energy is given by

$$E_*^{\rm BIN} = -\int_0^{r_t} 4\pi r^2 \rho_* (0.5\phi_* + \phi_h) dr \simeq 1.64 \times 10^{44} M_* \times (0.17\delta_{140}^{-0.16} + 0.09\beta_{10}^{-0.14}\delta_{140}^{-0.6} R)\sigma_*^2 \text{ ergs} \,, \tag{22}$$

where $R = M_{\rm DARK}/M_*$ is the galactic dark matter to star matter ratio, M_* is in solar units, and σ_* is in km s^{-1}.[2] By good fortune, in this class of models $E_*^{\rm BIN}$ is fairly insensitive to the actual distribution of dark matter (at least for $\beta_{10} \gg 0.1$).

Clearly, the ratio of the available energy $E_{\rm SN}$ to the binding energy $E_*^{\rm BIN}$ gives approximately the fraction of the total mass that could be extracted from the potential well of a galaxy, if all the available SN energy could be used. Thus, from equations (21) and (22) we get

$$\frac{E_{\rm SN}}{E_*^{\rm BIN}} \simeq \frac{6.1 \times 10^6 F_{\rm SN}}{(M_*/L_B)(0.17 + 0.09R)\sigma_*^2} \,, \tag{23}$$

where we have adopted $\delta_{140} = \beta_{10} = 1$. This ratio is given in Table 2 for $M_*/L_B = 5$, for two values of the dark to bright matter ratio R, and for the two options (1) all iron from SN II's, and (2) the solar SN proportion. We have also connected L_B to σ_* (Faber & Jackson 1976).

TABLE 2

SN ENERGY TO GALAXY BINDING ENERGY RATIOS

σ_* (km s^{-1})	L_B ($L_\odot$)	$E_{\rm SN}/E_*^{\rm BIN}$ $R = 0^a$	$R = 9^a$	$R = 0^b$	$R = 9^b$
200	2.0×10^{10}	72	12	25	4
300	8.5×10^{10}	32	5.5	11	2
400	2.0×10^{11}	18	3	6	1

[a] For all iron from SN II's.
[b] For the solar SN proportion.

A glance at Table 2 reveals several aspects which are relevant for our understanding of galaxy formation.

1. If most of the iron in the universe is made by massive stars (SN II's) and if ellipticals have no dark matter, then the energy released by SNs exceeds by more than one order of magnitude the present binding energy of galaxies.

2. Allowing for 90% of galactic mass to be in a dark matter halo reduces this figure by nearly a factor of ~ 5, with the SN energy still exceeding the binding energy of the bright matter by a factor between 3 and 12.

3. The SN to binding energy ratio is also between ~ 3 and 12 if no dark matter is present, but $\sim \frac{3}{4}$ of the iron in the universe is manufactured by SN Ia's.

4. Only if SN Ia's make $\sim \frac{3}{4}$ of the iron *and* $\sim 90\%$ of galactic mass is in a dark matter halo, does the early SN heating become comparable to the binding energy of the stellar component. Starting from these considerations, we can proceed to the following qualitative inferences.

5. SN-driven wind models for the formation and early chemical evolution of elliptical galaxies (such as those of e.g., Larson 1974; Arimoto & Yoshii 1987; Matteucci & Tornambè 1987) may be inadequate in many details but remain the only ones able to establish (at least qualitatively) a trend of average metallicity (as measured e.g., by the Mg_2 index) with the depth of the galactic potential well (as measured by σ_*^2), as it is observed. This basically comes from the Faber-Jackson relation, which implies that matter is more tightly bound in more luminous galaxies, with star formation and chemical enrichment proceeding further in them before SN heating succeeds in establishing a global wind.

6. To make the (baryonic component of) galaxies one has to radiate away a fair fraction of the SN energy, which is at least as large as the binding energy of this component. An inspection of wind models of galaxy formation reveals that in most instances only a few percent of the galactic (baryonic) mass is ejected into the wind. This means that in such models it is implicitly assumed that all but a few percent of the total SN energy is radiated away.

7. Table 2 enlightens us as to how sensitive—in this class of models—the detailed results are to the particular SN Ia/SN II mix that is adopted, as well as to the amount of dark matter assumed around protogalaxies. It follows that the treatment of radiative losses has to play a critical role, as a major fraction of (but not all![3]) SN heating has to be radiated away. This last

[2] This relation is exact and replaces the approximation given by eq. (15) in Renzini et al. (1993). Here $\beta_{10} = r_{ch}/10 r_{c*}$ and $\delta_{140} = r_t/140 r_{c*}$.

[3] Indeed, were the whole SN energy radiated away, then no heating would be left to drive early galactic winds, star formation would proceed to completion in all ellipticals, and the observed metallicity–σ_* relation would not be established.

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aspect is somewhat worrisome for the ability of such models to make predictions as opposed to *fits*. The resulting metallicity distribution will, in fact, depend on the fraction of the SN heating which is not coverted to radiation. On the other hand, radiative losses depend on gas density squared, and a clumpy, multiphase ISM is likely to dominate within forming ellipticals—all conditions that may practically prevent the evaluation of radiation losses with the accuracy that would be desirable to generate realistic models.

8. Given these difficulties to making quantitative predictions, we are left with the qualitative consideration that it must be easier to make galaxies the larger the share of iron made by SN Ia's, the larger the amount of dark matter around protogalaxies, and the larger the ability to cool of their ISM. All in all, we are left with an even stronger suspicion than before that a feedback, self-regulating mechanism must be at work during galaxy formation.

6. THE IRON-LIGHT CONNECTION

Given the role played by the actual SN mix in galaxy formation and evolution, and in establishing the IMLR of clusters of galaxies, additional clues that may help to distinguish among the various possibilities are certainly welcome. One such clue comes from considering the total amount of light that SN precursors emit in the whole course of their evolution, before finally delivering their iron yield. There is, in fact, a dramatically different behavior in this respect between the two types of SNs.

We assume the typical SN II iron producer to be a 20 $M_\odot$ star, which delivers 0.07 $M_\odot$ of iron and exhausts hydrogen in a $\sim 6\ M_\odot$ core before exploding. Conversely, each SN Ia delivers 10 times more iron and results from the explosion of a C-O white dwarf of at most a Chandrasekhar mass, i.e., SN Ia precursors exhaust hydrogen in only a $\sim 1.4\ M_\odot$ core. In conclusion, the iron yield to light pollution ratio is some (0.7/0.07) (6/1.4) $\simeq$ 40 times higher for SN Ia's as it is for SN II's: protogalaxies would be much brighter if most of the iron was made by SN II's, rather than by SN Ia's.

We can put this argument on more quantitative grounds. Since the burning of 1 g of material with primordial composition releases $\sim 6 \times 10^{18}$ ergs, the amount of early (photon) energy release produced by SN II precursors is given by the amount of energy released by burning 6 $M_\odot$ of fuel times the number of SN II's that have contributed to the observed IMLR. For the solar SN proportion, from equation (5) we get

$$E_{\rm ph} \simeq 7 \times 10^{51} L_B \text{ ergs}\ , \tag{24}$$

for the energy radiated by SN II precursors during the formation phase of galaxies. Here, again, L_B (in solar units) can be interpreted as either the present luminosity of a whole cluster or of one individual elliptical. For example, a present 5 L_* elliptical galaxy with $L_B \simeq 5 \times 10^{10}\ L_\odot$ had to radiate some 4×10^{62} ergs during its formation. For a star formation timescale $\tau_{\rm SF}$, the corresponding bolometric luminosity was

$$L = \frac{E_{\rm ph}}{\tau_{\rm SF}} \simeq 2.5 \times 10^{13} \left(\frac{10^8 \text{ yr}}{\tau_{\rm SF}} \right) L_\odot\ . \tag{25}$$

All these figures would be a factor of 4 larger (and protogalaxies ~ 1.5 mag brighter) if most of the iron was made by SN II's, rather than in the solar SN proportion.

This is a purely energetic estimate. The actual, present spectrum of such bright protogalaxies is clearly affected by several poorly known factors: reprocessing to longer wavelengths due to gas and dust absorption within the forming galaxies themselves and redshift by an amount $z_{\rm GF}$, the redshift of galaxy formation. A discussion of these aspects goes beyond the scope of the present paper.

While SN Ia progenitors contribute only a marginal luminosity in the optical/IR band, this may not be so for the γ-ray part of the spectrum, where the radioactive decay of ^{56}CO may give a detectable contribution to the γ-ray background (The, Leising, & Clayton 1993), thus potentially placing limits on the integrated past SN Ia activity in the universe.

7. THE GALAXY-ICM CHEMICAL ASYMMETRY

7.1. *Predictions of the Standard Chemical Model*

The elemental ratios of various nuclear species in the ICM and in the stellar component offer another possibility to check whether the integrated SN activity in clusters of galaxies has—or has not—been characterized by the solar SN proportion. At the same time, such ratios may offer useful information on the typical timescale of star formation in young elliptical galaxies in clusters, with important implications for our understanding of the galaxy formation process.

Ratios such as [O/Fe], [Mg/Fe], and [Si/Fe] are predicted to be different in the stellar component of galaxies from what they are in the ICM, and the size of this *galaxy-ICM chemical asymmetry* may tell us about the timescale of galaxy formation. Within galaxies, elements almost exclusively produced by SN II's (e.g., O, Mg, and Si) are released on a timescale $\sim \tau_{\rm SF}$, since the lifetime of SN II precursors is very short, while most of iron is released at a much slower pace following the evolution of the rate of SN Ia's. So, the particular "*chemical trajectory*" traced by the stellar component of young ellipticals in, e.g., the [O/Fe] versus [Fe/H] plane, depends on the relative size of $\tau_{\rm SF}$ and $\tau_{\rm SNIa}$ (Renzini 1986). The shorter $\tau_{\rm SF}$ relative to $\tau_{\rm SNIa}$, the higher the stellar [O/Fe], [Mg/Fe], and [Si/Fe] for given [Fe/H]. Yet neither of the two timescales is a priori known, a condition which leaves them as mere adjustable (or hidden) parameters in chemical evolution models. The ICM, instead, continues to be replenished by galactic ejecta for times longer than $\tau_{\rm SNIa}$ and therefore has a better chance of being enriched by SN Ia products such as iron.

In this scenario for the formation of elliptical galaxies, star formation ceases after a time $\tau_{\rm SF}$, as gas starts flowing out of galaxies into the ICM. The composition of this gas reflects the stellar abundances, further enriched in fly by SN Ia's. It follows that the shorter the timescale of galaxy formation, the less SN Ia iron remains locked into stars, and a larger fraction of it flows into the ICM. If the solar SN proportion applies to clusters as a whole, then we predict [O/Fe], [Mg/Fe], and [Si/Fe] ratios *above solar* in the stellar component and *below solar* in the ICM; the larger the size of this chemical asymmetry, the shorter $\tau_{\rm SF}$ with respect to $\tau_{\rm SNIa}$. In the limit $\tau_{\rm SF} \ll \tau_{\rm SNIa}$, all the SN Ia iron would flow to the ICM, and one would have [O/Fe] = [Mg/Fe] = [Si/Fe] $\simeq +0.6$ within galaxies, while the same ratios would be negative in the ICM. However, the value of [O/Fe], [Mg/Fe], and [Si/Fe] in the ICM cannot be predicted with simple arguments such as those we have developed so far, as it depends on the fraction of the original baryonic mass of the galaxy which has participated in the nucleosynthesis and which is later ejected from the galaxy. For example, if $\frac{1}{3}\ M_*$ is ejected, this mass will contain $\sim \frac{1}{3}$ of the whole Mg, $\sim \frac{1}{3}$ of the Fe from SN II's (which is $\frac{1}{3} \times \frac{1}{4} = \frac{1}{12}$ of

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the total), plus all the iron from SN Ia's, which is $\sim\frac{3}{4}$ of the total. Thus, all in all, the ICM would contain $\frac{5}{6}$ of the total iron but only $\frac{1}{3}$ of the total magnesium, or [Mg/Fe] = −0.4.[4] On the other hand, by construction the overall cluster Mg/Fe ratio is solar, where by overall ratio one means the total mass of magnesium in the ICM *and* galaxies, over the corresponding mass of iron.

The observational check of this predicted galaxy-ICM chemical asymmetry poses formidable technical problems, above all the *asymmetry* in experimental procedures with the risk of differential systematic errors. The determination of the elemental abundances in galaxies can only come from population synthesis techniques, and, indeed, there is already a hint for Mg being enhanced compared to Fe (e.g., Worthey, Faber, & Gonzales 1992; Davies, Sadler, & Peletier 1993). For the ICM, X-ray line observations are required, but only scant data are available for elements other than iron. The only examples we are aware of are a rather uncertain estimate of O/Fe 3–5 times solar in the Virgo and Perseus Clusters (Canizares *et al.* 1982, 1988) and a seemingly uncertain near-solar estimate of Si/Fe in Perseus (Mushotszky et al. 1981). Such a large O/Fe ratio definitely rule out SN Ia's as important iron produers in clusters of galaxies, as indeed argued by White (1991), who makes an attempt at reproducing this O/Fe ratio with chemical evolution models. However, his solution implies an IMLR ~ 0.0003, or ~100 times smaller than the observed value (Paper I). Within our current knowledge of stellar nucleosynthesis, we know no way of reconciling a high O/Fe ratio in the ICM with the observed IMLR and with the O/Fe ratio of the sun (see § 7.2) without appealing to ad hoc differences in the IMF and/or SN Ia productivity between cluster elliptical galaxies and the solar neighborhood. Future X-ray observations of ICM elemental abundances are therefore of prime importance. Though difficult, the observational check of the predicted chemical asymmetry would be of great value for our understanding of stellar nucleosynthesis as well as galaxy formation and evolution.

7.2. *Alternatives to the Standard Chemical Model*

The low iron content of galactic flows reported in § 4.2 and the high O/Fe ratio in the ICM discussed in the previous section are both at variance with the predictions of the standard chemical model and tend to undermine SN Ia's as major iron producers in galaxies. Were this really the case, the standard chemical model should be abandoned, thus opening the question of how to alternatively interpret the nonsolar abundance ratios in the Galactic halo and bulge and in elliptical galaxies.

A variable, metallicity-dependent IMF favoring α-elements producing stars at low metallicities might offer a solution, but the idea remains merely conjectural. The iron yield may depend only weakly on stellar mass (see § 3.2), while the α-element yields instead certainly increase with stellar mass. Thus, were the IMF flatter at low metallicities, the trend of [α/Fe] observed in the Galactic halo could be explained. However, there is presently no clear observational basis for such a metallicity dependence of the IMF.

Alternatively, the iron yield per given stellar mass could increase with increasing metallicity, as postulated by Edmunds et al. (1991). This would explain the [α/Fe] trend in the Galactic halo but would predict super–metal-rich populations in galactic bulges and elliptical galaxies to exhibit a depletion of α-elements relative to iron, just the opposite of the prediction of the standard chemical model. Edmunds et al. (1991) indeed identify in this different behavior at high metallicities the possibility of discriminating between the standard chemical model based on the time delay in the iron delivery by SN Ia's and the metallicity-enhanced iron production scenario. Though not fully conclusive, existing estimates of the [α/Fe] ratio in super–metal-rich populations such as the Galactic bulge (Barbuy 1992; Rich 1993; McWilliam & Rich 1993) and in giant elliptical galaxies (Worthey, Faber, & Gonzales 1992; Davies, Sadler, & Peletier 1993) appear to favor the standard chemical model over the alternative proposed by Edmunds et al. (1991).

[4] Note that the 50/50 condition is violated in this particular example. The solar SN proportion plus the fifty-fifty condition together also imply that $\sim\frac{1}{3}$ of the iron from SN Ia's remains locked into stars. This condition forces τ_{SNIa} to be just a few times longer than τ_{SF}.

8. CONCLUSIONS

In this paper we have discussed in detail the various perspectives to account for the observed amount of iron in clusters of galaxies, along with their implications for stellar nucleosynthesis and the formation and evolution of elliptical galaxies in clusters. The main results can be summarized as follows.

(1) Clusters of galaxies contain $\sim 0.03\ M_\odot$ of iron for each $L_\odot$ of blue light emitted by the stellar component of cluster galaxies. A nearly equal fraction of this iron is contained in the ICM and in the stellar component of galaxies. The ICM of small groups of galaxies contain ~30 times less iron per unit galaxy light, indicating that such groups suffered massive gas losses at early times.

(2) We discuss two possible explanations for the observed amount of iron in clusters. One possibility is that SN II's and SN Ia's have contributed, respectively, $\sim\frac{1}{4}$ and $\sim\frac{3}{4}$ of the total iron, as in the standard chemical model for the galactic halo and disk. This demands a substantial increase of the rate of SN Ia's toward the past and allows the IMF in elliptical galaxies to be the same as in the solar neighborhood. Alternatively, SN Ia's could have contributed a marginal fraction of the total iron if the IMF of an elliptical galaxy was considerably flatter than the Galactic one.

(3) There appears to be a major discrepancy between the expected iron abundance in elliptical galaxy flows (several times solar) and the subsolar abundance inferred from BBXRT observations of NGC 1399, the cD galaxy in the Fornax cluster. We note that no simple model is able to account at once for both the soft X-ray emission around 1.keV and for the strong iron Kα emission at ~6.7 keV. We also argue that the hot ISM of NGC 1399 may have been diluted by up to a factor ~3 by iron-poor ICM accreted by the cD galaxy through a cluster cooling flow.

(4) Arguments are presented supporting the notion that the iron now found in the ICM was ejected from individual galaxies by endogenous forces (e.g., SNs or AGNs), rather being extracted by environmental forces (ram pressure stripping).

(5) The observed amount of iron in clusters allows a rather direct determination of the amount of kinetic energy injected by SNs early in the evolution of cluster elliptical galaxies. Such kinetic energy is found to exceed the present binding energy of the stellar component of galaxies by an amount which depends on the mass of dark matter halos and on the relative role of SN Ia's and SN II's. We discuss the implications for the galaxy formation process and provide quantitative input for a better

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understanding of the self-regulating processes likely to be active during galaxy formation.

(6) The observed amount of iron in clusters also provides a fairly precise determination of the total amount of light emitted by cluster elliptical galaxies in the course of their formation. We also estimate that protogalaxies should have been about a factor of 4 brighter if most of the iron was made by SN II's rather than by SN Ia's.

(7) We argue that the standard chemical model predicts the existence of a *chemical asymmetry* between an iron-rich and α-elements–poor ICM and iron-poor and α-elements–rich galaxies, a prediction that is subject to observational verification.

(8) Finally we, argue that the standard chemical model still provides a fair account for a variety of observational facts, including the iron content of clusters, the chemical abundance ratios in the Galactic bulge, halo, and disk, and in the core of elliptical galaxies, and it does so with a minimum of adjustable parameters. Such a simplicity still does not apply to the alternatives to the standard chemical model proposed so far.

We conclude by emphasizing that future X-ray observations of elliptical galaxies and clusters of galaxies (especially by *ROSAT* and *ASCA*) may soon be able to shed full light on the iron quests concerning both kinds of objects, thus providing fundamental information on the formation and evolution of cluster elliptical galaxies.

We would like to thank Enrico Cappellaro, Doug Geisler, Michael Loewenstein, Richard Mushotzky, Reinier Peletier, Mike Rich, Massimo Turatto, and Stan Woosley for having communicated results of their research in advance of publication. We are also grateful to Michael Loewenstein, Mike Rich, and the anonymous referee for constructive comments and to John Raymond for having kindly provided his thermal X-ray emission code. This research has been supported in part by the Italian Space Agency (ASI) through contract 91-RS-86 and in part by the Italian Ministry of Research (MURST) through a "40%" research grant.

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