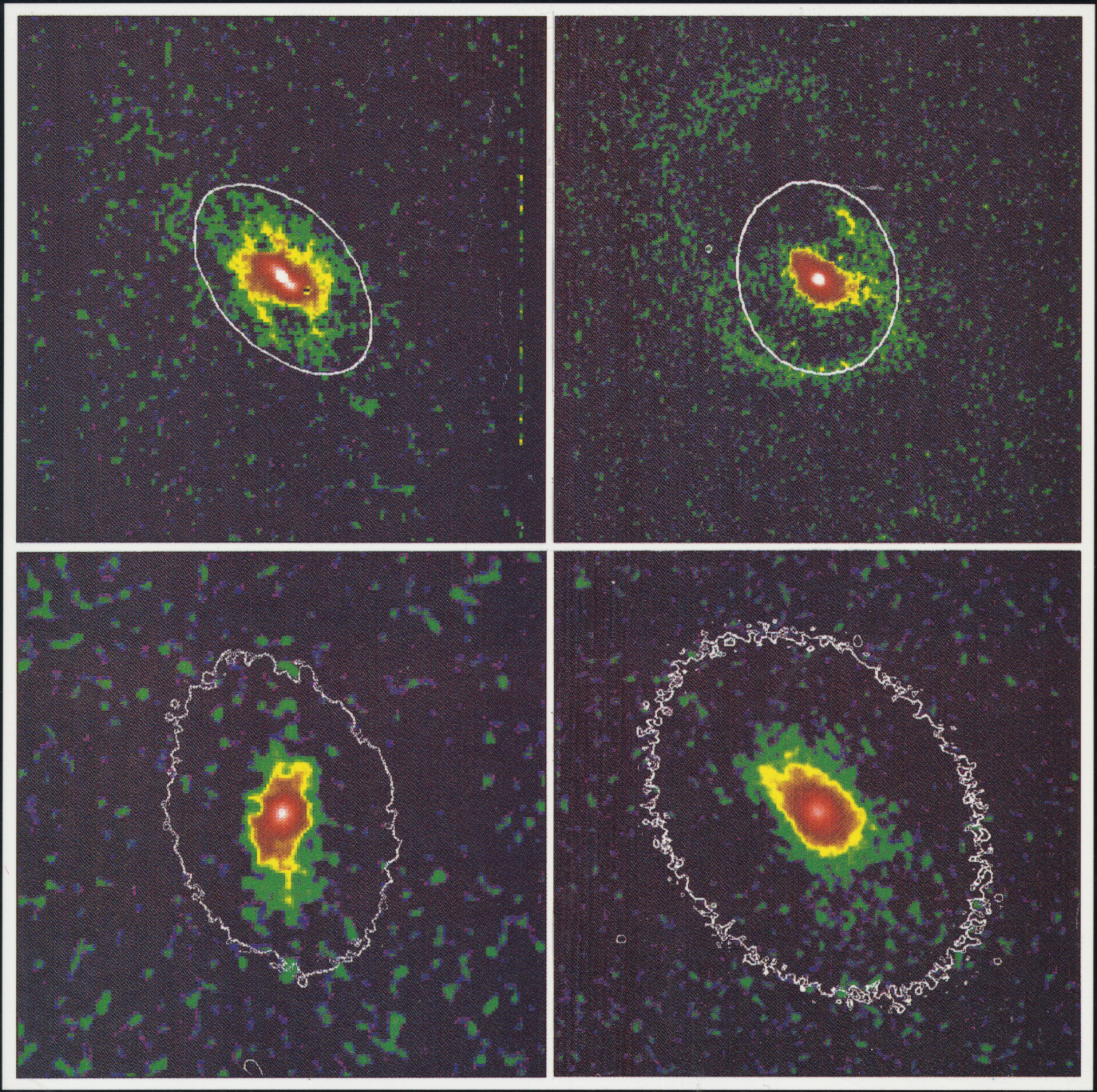
ESO/EIPC WORKSHOP

STRUCTURE, DYNAMICS AND CHEMICAL EVOLUTION OF ELLIPTICAL GALAXIES

Marciana Marina, Isola d'Elba, 25–30 May 1992



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PRODUCTION AND DISTRIBUTION OF IRON IN ELLIPTICAL GALAXIES AND CLUSTERS OF GALAXIES

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ABSTRACT. We introduce the concept of cluster *iron mass to light ratio*, and discuss under which conditions the past supernova activity can account for its observed value. We provide evidence that either the past average rate of type Ia supernovae was a fator of ~ 10 higher than the present rate in ellipticals, or massive stars in clusters formed with a very flat IMF. We favor a solution in which 1/4 of the observed iron in clusters of galaxies was contributed by type II supernovae, and 3/4 by type I supernovae, as this is their relative role in establishing solar elemental ratios, thus leaving open the possibility of a universal IMF. We go further in considering the supernova heating and the presupernova light production which are implied by the observed iron mass to light ratio, and discuss their implications for elliptical galaxy formation. We suggest a possible test for our proposed scenario, based on the predicted difference in elemental ratios between the intracluster medium and cluster elliptical galaxies.

1. INTRODUCTION

In ancient times the Elba island has been the main iron source first of Etruscans and then of Romans, and thus a paper about the iron production and distribution seemed to us particularly topical for this meeting on the "Chemical and Dynamical Evolution of Galaxies". Supernovae make metals, and in particular make iron, an element that non-exploding stars are unable to synthetize. Thus, the total amount of iron in a portion of the universe today (e.g., a cluster of galaxies) keeps the record of the overall SN activity in the past, provided it has evolved as a *closed box*, at least in the sense of having not suffered any loss of mass. But SN's don't make only iron. For example each SN injects a sizable amount of kinetic energy into the ISM, and each SN progenitor burns a definite amount of 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 in some detail these connections, but we do so with no recourse at all to elaborate modelling, and we rather attempt to keep track in a most direct and transparent way of the implications of our assumption and of 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 evolutionary models.

The ultimate aim of this approach is to gather direct information and useful constraint 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 extensively discuss 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 can be inferred from existing 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 relate the past SN heating in elliptical galaxies – as implied by the observed IMLR – to the binding energy of these galaxies, for galaxy luminosities following the observed $L_{\rm B} - \sigma_\star$ relation (Faber & Jackson 1976). In §5 we briefly discuss about the total amount of light that forming elliptical galaxies must have emitted, as implied by the present IMLR. The perspectives to further tighten the *iron bound* on galaxy formation are discussed in §6.

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

In clusters of galaxies iron is partly dispersed in the intra-cluster medium (ICM), partly is locked into the stellar component of galaxies. The interstellar medium (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, sometimes expressed in solar units. 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). An alternative is represented by the iron mass to stellar mass ratio introduced by Arnaud *et al.* (1992). Here the total iron mass in the ICM is devided by the total mass in stars present in the cluster. Operationally, the latter quantity comes from the observed total luminosity of the cluster, and assuming a stellar mass to light ratio for individual galaxies, for which Arnaud *et al.* adopt $M_\star/L_{\rm V} = 10$. This is better than the straight iron abundance, but it requires the assumption of a stellar mass to light ratio, and the relation between iron production and stellar mass is rather indirect. For example, two stellar populations differing only in the lower mass cutoff of the IMF would produce the same amount of iron but would have different 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 unkonwn amounts of dark matter. To avoid all these assumptions and complications, in Paper I we adopted 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.:

$$\frac{M_{\rm Fe}}{L_{\rm B}} = \frac{M_{\rm Fe}}{\Sigma_{\rm i} L_{\rm B}^{\rm i}}, \quad (M_\odot/L_\odot) \tag{1}$$

where the $L_{\rm B}^{\rm i}$'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 Iron Mass to Light Ratio

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 $M_{\rm Fe}^{\rm ICM}/L_{\rm B}$ values in the range from 0.7 to $1.6 \times 10^{-2} M_\odot/L_\odot$ for the nearby clusters Virgo, Coma, and Perseus. This value is substantially confirmed when using the relevant input data from the more extended compilations of Tsuru *et al.* (1992) and Arnaud *et al.* (1992), which indicate that the IMLR for the ICM of rich clusters is in the range:

$$\frac{M_{\rm Fe}^{\rm ICM}}{L_{\rm B}} = 0.01 - 0.02 \quad (M_\odot/L_\odot), \tag{2}$$

which means that the ICM contains $0.01 - 0.02 M_\odot$ of iron for every $L_\odot$ of the galaxy (star) population of the cluster. For example, a cluster such as Perseus has a total luminosity $L_{\rm B} \simeq 10^{13} L_\odot$, and its ICM contains $\sim 0.015 \times 10^{13} = 1.5 \times 10^{11} M_\odot$ of iron (Paper I).

One caveat is however in order: this value follows from the assumption of a chemically homogeneous ICM, an assumption which has been recently questioned by Ponman *et al.* (1990) and Koyama, Takano, & Tawara (1991) who argued for a gradient in the ICM iron abundance, with iron being concentrated in the central regions (but see Hughes *et al.* 1992, for a different conclusion).

2.2. The Stellar Iron Mass to Light ratio

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

$$\frac{M_{\rm Fe}^{\star}}{L_{\rm B}} = < Z^{\rm Fe} > \frac{M_\star}{L_{\rm B}}, \tag{3}$$

where $< Z^{\rm Fe} >$ is the average iron abundance (by mass) in the stellar component. This average refers to all stars in the cluster, while the iron abundance ranges over a wide interval within galaxies, and from one galaxy to another. Within individual galaxies metallicities span from $\sim 1/100$ solar for the extreme population II component, to several times solar in the central regions of galactic bulges and in 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 certainly a reasonable approximation. In practice, this is equivalent to ignore spiral disks and dwarf irregulars. Early-type galaxies span *average* metallicities (iron abundances) from $\sim 1/3$ solar for dwarf ellipticals such as M32 (see Freedman 1989) to a few times solar for giant ellipticals (O'Connell 1986, and references therein). We assume the general average iron abundance for all the stars in a cluster of galaxies to be nearly *solar*, a reasonable estimate that cannot be off by more than a factor of ~ 2, either way. We therefore adopt $< Z^{\rm Fe} > \simeq Z_\odot^{\rm Fe} \simeq 0.002$ (Anders & Grevesse 1989) in equation (3). For the stellar mass to light ratio we adopt typical values for early type galaxies and bulges, i.e., $M_\star/L_B = 5-10$, and from equation (3) we conclude:

$$\frac{M^\star_{Fe}}{L_B} = 0.01 - 0.02 \quad (M_\odot/L_\odot). \tag{4}$$

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 this to be an important constraint for any theory of galaxy formation. Combining equations (2) and (4) we get the *total* cluster IMLR:

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

which means that 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. SUPERNOVA TYPE Ia vs. TYPE II IRON PRODUCTION

In this section we discuss the amount of iron that SN's of type Ia and type II can produce in cluster 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. Compelling 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.

3.1. Type Ia Supernovae

The total amount of iron produced by SNIa's over one Hubble time (for which we adopt 15 Gyr) is given by the total number of SNIa's which have exploded times the mass of iron produced by each SNIa. There is general consensus that a typical SNIa produces $\sim 0.7 M_\odot$ of iron (after the ^{56}Ni decay). This follows from the 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 SNIa's. We correspondingly adopt $M^{I}_{Fe} = 0.7 M_\odot$ for the amount of iron yield of each SNIa, while the yield for other abundant species (e.g., O, Mg, and Si) is negligible.

Much less definite is the situation concerning the total number of SNIa's, which in turn is given by the time integral of the SN rate. Up to now, observations tell only about the *present* rate, while for its time evolution over the preceding Hubble time no direct evidence is available. The present rate in ellipticals is estimated to be $0.88\,h^2$ SNU (Tammann 1982, see also van den Bergh & Tammann 1991), where $h = H_\circ/100$ and 1 SNU $= 10^{-12} L_B$ SN's yr^{-1}, and L_B is the blue luminosity of the parent stellar population (e.g., of one galaxy, of a cluster of galaxies, etc.). We adopt $h = 1/2$ and correspondingly the present rate becomes 0.22 SNU, or $2.2 \times 10^{-13} L_B$ SN's yr^{-1}, a value whose observational uncertainty is estimated to be of the order of a factor of 2.

In absence of direct observational evidence, on purely theoretical grounds the past evolution of the SNIa rate in ellipticals – and more generally its evolution following a burst of star formation – both remain highly conjectural. This is so for two main reasons: 1) because there is no general consensus on whether the single degenerate (SD) or the double degenerate (DD) model for the SNIa precursors applies (Munari & Renzini 1992), and 2) because in either model the evolution of the rate is controlled by an unkwnown 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 in the DD model (see Paper I for an extensive discussion). Still, for both models the *qualitative* behavior of the rate is similar: it departs from zero at least $\sim 3 \times 10^7$ yr after the burst of star formation, climbs rather quickly to a maximum in $\sim 10^8 - 10^9$ yr, and then declines reaching the present value (0.22 SNU) one Hubble time after the burst. The precise run of the SNIa rate is however highly model dependent; examples of plausible evolutions of such rate are offered by the models of 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:

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

for $t_{15} > t_{15,\circ}$, where t_{15} is time in units of 15 Gyr, in such a way that for the parameter $\vartheta_{\rm SN} = 1$ and $t_{15} = 1$ the standard SN I rate in ellipticals is recovered, i.e., 0.22 SNU. For $t_{15} < t_{15,\circ}$ we assume the rate to increase linearly with time in such a way to join the value given by equation (6) at $t_{15} = t_{15,\circ}$, i.e.:

$$R_{\rm SNIa}(t) = 2.2 \times 10^{-13} \vartheta_{\rm SN} L_{\rm B} t_{15,\circ}^{-(s+1)} t_{15} \qquad ({\rm yr}^{-1}). \tag{7}$$

In the frame of the adopted parameterization, the time $t_{15,\circ}$ is the *rise time* of the SNIa 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 $t_{15,\circ} = 0.01 - 0.1$.

The total number $N_{\rm Ia}$ of SN's 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:

$$N_{\rm Ia} = \int_0^1 R_{\rm SNIa}(t_{15}) dt_{15} = 3.3 \times 10^{-3} \vartheta_{\rm SN} L_{\rm B}\, f(s, t_{15,\circ}), \tag{8}$$

where

$$f(s, t_{15,\circ}) = \frac{1}{2} t_{15,\circ}^{1-s} + \frac{t_{15,\circ}^{1-s} - 1}{s - 1}, \tag{9}$$

and where the first term corresponds to the number of SNIa's exploded during the rate rise time, and the second term refers to the subsequent power-law decline. The contribution of SNIa's to the IMLR follows naturally from equation (8):

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

For a past SNIa rate constant in time one has $s = 0$, $t_{15,\circ} = 0$, and so $f = 1$. With $\vartheta_{\rm SN} = 1$ the corresponding IMLR is more than a factor of 10 smaller than the observed value: *had their*

TABLE 1

VALUES OF THE FUNCTION $f(s, t_{15,\circ})$

$t_{15,\circ}$	$s = 1.3$	$s = 1.4$	$s = 1.5$
0.01	11.9	16.4	23.0
0.05	6.1	7.4	9.2
0.10	4.3	5.0	5.9

rate been constant in the past, SNIa's would have contributed $\lesssim$*10% of the observed iron in clusters of galaxies* (Paper I). Since it is 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 SNIa's ought to contribute a fair fraction of the observed iron, i.e., for $\vartheta_{\rm SN} = 1$ a value of $f \simeq 10$ is required. Formally, the SNIa contribution to the IMLR in equation (10) depends on three parameters, of which only one ($\vartheta_{\rm SN}$) is directly determined by the observations. The function $f(s, t_{15,\circ})$ – which contains the other two parameters – is tabulated in Table 1 for reasonable values of s and $t_{15,\circ}$. It appears that the exponent s plays the main role, and that values in excess of ~ 1.3 are to be preferred if one wants SNIa's to play a major role in iron production (see Paper I). Before pushing further this discussion we need to introduce the other potential producers of iron in the universe, i.e., massive stars exploding as type II SN's.

3.2. Type II Supernovae

In the case of SNIa'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 theory unable to predict the corresponding evolution of the SN rate. The case of type II SN's is quite the opposite. In fact, we believe to have a perfect understanding of what are the progenitors (i.e., stars more massive than $\sim 8M_\odot$), while a great uncertainty affects the amount of iron $M_{\rm Fe}^{\rm II}(M)$ produced by each SNII 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 SNII event being crucially dependent on the precise position of the *mass cut* between the neutron star remnant and the ejecta, an extremely model dependent quantity (e.g., Woosley & Weaver 1986). Figure 1 shows three options for $M_{\rm Fe}^{\rm II}(M)$. Not by chance all the three options coincide for $M = 20M_\odot$, the progenitor mass of SN1987A, for which the amount of iron produced – $0.07M_\odot$ – comes from the very precise determination obtained from fitting the exponential decline of the light curve of this SN (Woosley 1988; Shigeyama, Nomoto, and Hashimoto 1988).

The total amount of iron produced by SNII'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

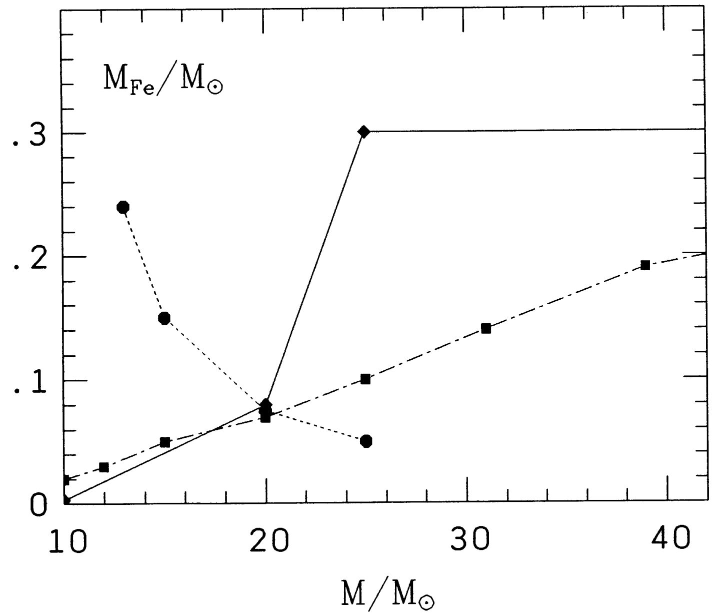

Fig. 3. The iron yield of massive stars in $M_\odot$ units is displayed as a function of the initial mass, from three different sources.
Dotted line: Thielemann & Hashimoto (1991); solid line: Woosley (1989, referred by White 1991); dot-dashed line: Arnett (1991).

of yield per star, times the total number of SNII's.[1] As usual, for the stellar IMF we assume a power law:

$$\psi(M) = A\,M^{-(1+x)} = 2.9 L_B\, M^{-(1+x)}, \tag{11}$$

where we have adopted the very useful normalization $A = 2.9\,L_B$ introduced in Paper I, with L_B – like everywhere in this paper – being the luminosity of the stellar population at the conventional age of elliptical galaxies, i.e., 15 Gyr. For the average iron production by SNII's we find $< M^{II}_{Fe} > \simeq 0.07 M_\odot$, fairly insensitive to the slope x of the IMF, and for either of the options shown in Figure 1. Correspondingly, the SNII contribution to the IMLR becomes:

$$\left(\frac{M_{Fe}}{L_B}\right)_{SNII} = < M^{II}_{Fe} > 2.9 \int_8^{100} M^{-(1+x)} dM \simeq 0.2\,(8^{-x}/x) \quad (M_\odot/L_\odot). \tag{12}$$

Clearly, the flatter the IMF slope the larger the number of massive stars per unit present luminosity, the larger the number of SNII's, and therefore the larger the implied IMLR. Thus, from equation (12) we get:

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

We conclude that if the Galactic IMF slope ($x = 1.7$, Scalo 1986) applies also to ellipticals in rich clusters then SNII's underproduce iron by about a factor of 10 compared to what demanded by equation (5). Instead, making all the observed iron by SNII's would require a very flat IMF ($x \simeq 0.9$).

[1] Here we assimilate to SNII producers also those massive stars which may have lost entirely their hydrogen envelope, and for this reason would be spectroscopically classified in SNI subtypes other than SNIa.

3.3. The Galactic Constraint

Before proposing our recipe for the production of the observed IMLR we need to consider the evidence about the relative role of the SN types in Galactic nucleosynthesis. There is certainly no *a priori* guarantee that such role was the same in elliptical galaxies, but we should not renounce to explore the possibility of accounting for the cluster IMLR without appealing to exotic nucleosynthetic scenarios, which would inevitably introduce extra adjustable parameters.

It is well known since a long time that the O/Fe ratio in the population II stars of the Galactic Halo is 3-4 times solar (Sneden, Lambert, & Whitetaker 1979; Gratton & Ortolani 1986; see Barbuy 1992, and references therein). The most popular interpretation of the Galactic trend of [O/Fe] vs. [Fe/H] appeals to the different nucleosynthesis roles of SNIa's and SNII's: the enrichment of the halo was sufficiently rapid to sample almost exclusively the prompt release of SNII products (α-elements such as oxygen, r-process elements, but little iron), while it would take a longer time for SNIa'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.* 1991; Matteucci & François 1992). Correspondingly, in this scenario SNII's produce almost 100% of the iron in extreme population II stars, and $\sim 1/4$ of the iron present in the sun, while the residual $\sim 3/4$ comes from SNIa's. The same 1/4-3/4 proportion – that hereafter we call the *solar SN proportion* – would be expected for any system old enough to have already experienced the bulk of SNIa iron release, provided the IMF and the frequency of SNIa precursors are the same of the solar neighborhood. Rich cluster of galaxies are likely to meet the first requirement: the bulk of their stellar content is very old, and therefore most of SNIa's should have already exploded by now. The likelyhood of the second requirement is further discussed in the next sections.

3.4. Producing the Observed IMLR

We now return to the question of the cluster IMLR, for which we discuss three possibilities.

1. Making all the iron with SNIa's requires a strong evolution of the SN rate, with $f \simeq 15$ in equation (10) if the canonical Tammann's rate applies to present-day ellipticals (i.e., $\vartheta_{\rm SN} = 1$). From Table 1 we see that large values of the exponent s and short rise times $t_{15,\circ}$ are favored. Such values are consistent with those demanded by the evolutionary scenario for gas flows in ellipticals presented in Paper I, in which the SNIa rate secularly declines and galactic flows evolve from an early supersonic wind, to a subsonic outflow, to eventually an inflow regime. Such early winds are instrumental in establishing the observed even share of iron between stars and the ICM (see §2). However, no doubt some iron is also contributed by SNII's.

2. Making all the iron with SNII's requires star formation in cluster elliptical galaxies to have occurred with a very flat IMF ($x \simeq 0.9$), much flatter than the Galactic IMF. Equivalently, one can appeal to a *bimodal* IMF, as argued by Arnaud *et al.* (1992), who unexplicably dismiss SNIa's as major iron producers. In the bimodal IMF scenario quiescent star formation proceeds with a normal IMF while strong bursts of star formation produce only massive stars (e.g., more massive than $\sim 2M_{\odot}$). Quite obviously, in such a scenario one can generate arbitrarily large IMLR, simply because the burst component produces iron from SNII's, but no light at all after

15 Gyr as stars more massive than $2M_\odot$ stars live less than ~ 1 Gyr. Clearly, bimodal star formation can be tuned to produce the observed IMLR in rich clusters.

3. The third scenario allows for a contribution from both SN types, and does so in the *solar SN proportion*, with 1/4 of the iron in clusters coming from SNII's and 3/4 from SNIa's. In this case, indeed, we have that massive stars with a Galactic IMF ($1.35 \lesssim x \lesssim 1.7$) contribute for about 1/4 to the cluster IMLR, while with $\vartheta_{\rm SN} f \simeq 10$ SNIa's contribute the residual 3/4. In this way, with the same combination of parameters x for massive stars, and $\vartheta_{\rm SN} f$ for SNIa'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 SNII's, see Woosley & Weaver 1992). We shall further explore its implications in the following sections.

4. SUPERNOVA HEATING vs. BINDING ENERGY OF GALAXIES

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

$$N_{\rm SN} = \frac{M_{\rm Fe}}{<M_{\rm Fe}>} = \frac{0.03\,L_{\rm B}}{<M_{\rm Fe}>} = \begin{cases} 0.04 L_{\rm B} & \text{for all iron from SNIa's} \\ 0.40 L_{\rm B} & \text{for all iron from SNII's} \\ 0.14 L_{\rm B} & \text{for the \textit{solar SN proportion},} \end{cases} \tag{13}$$

respectively for the three possibilities discussed in §3.4. Correspondingly, the kinetic energy injected is given by:

$$E_{\rm SN} = 10^{51} \cdot N_{\rm SN} \ \ ({\rm erg}) = \begin{cases} 0.4 \times 10^{50} L_{\rm B} & \text{for all iron from SNIa's} \\ 4.0 \times 10^{50} L_{\rm B} & \text{for all iron from SNII's} \\ 1.4 \times 10^{50} L_{\rm B} & \text{for the \textit{solar SN proportion}.} \end{cases} \tag{14}$$

Note that in these relations $L_{\rm B}$ can be interpreted as the luminosity of a whole cluster, or of an individual galaxy. In the rest of this section we adopt this second 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 interrupting the star formation process, establishing galactic winds, and replenishing of iron the ICM. One way of figuring out how *big* is $E_{\rm SN}$ is to ask how much baryonic mass it would be able to extract from the galactic potential well. For the bright and dark matter distributions used in Paper I, the energy required to extract one $M_\odot$ from the potential well of the galaxy is given by:

$$E^{\rm LIFT}(M_\odot) \simeq 2 \times 10^{44} (0.34 + 0.09\,R) \sigma_\star^2 \quad ({\rm erg}), \tag{15}$$

TABLE 2

SN ENERGY TO GALAXY BINDING ENERGY RATIOS

$\sigma_\star$ (km s^{-1})	L_B ($L_\odot$)	$E_{SN}/E_\star^{BIN}$			
		$R=0$[1]	$R=9$[1]	$R=0$[2]	$R=9$[2]
200	2.0×10^{10}	29	9	10	3.0
300	8.5×10^{10}	13	4	5	1.3
400	2.0×10^{11}	7	2	3	0.8

[1] For all iron from SNII's

[2] For the solar SN proportion

where $R = M_{\rm DARK}/M_*$ is the galactic dark matter to star matter ratio, and $\sigma_\star$ – the galactic central velocity dispersion – is in km s^{-1} units.[2] By good fortune, in this class of models $E^{\rm LIFT}$ is fairly insensitive to the actual distribution of dark matter.

Clearly, the ratio of the available energy $E_{\rm SN}$ to the energy required to lift one $M_\odot$ gives the total mass that could be extracted from the potential well of a galaxy, provided all the available energy could be used. Thus, from equations (14) and (15) we can derive the *liftable-mass to light ratio* (LMLR):

$$\frac{M^{\rm LIFT}}{L_{\rm B}} = \frac{E_{\rm SN}}{L_{\rm B}E^{\rm LIFT}} \simeq \frac{5\times10^5 F_{\rm SN}}{(0.34+0.09\,R)\sigma_\star^2} \quad (M_\odot/L_\odot), \tag{16}$$

where the numerical factor $F_{\rm SN}$ depends on the mix of SNIa'a to SNII's, and is equal to 0.4, 4.0, and 1.4, respectively for the three cases discussed in §3.4., see also equation (14). Furthermore, the ratio of this LMLR to the usual stellar mass to light ratio gives:

$$\frac{M^{\rm LIFT}}{L_{\rm B}}\cdot\frac{L_{\rm B}}{M_*} = \frac{M^{\rm LIFT}}{M_*} \simeq \frac{E_{\rm SN}}{E_\star^{BIN}}, \tag{17}$$

which is the ratio of the SN energy to the present binding energy of the bright (sometimes called baryonic) component of galaxies. This ratio is given in Table 2 for $M_\star/L_{\rm B} = 5$, for two values of the dark to bright matter ratio R, and for the two options 1) all iron from SNII's, and 2) the solar SN proportion. We have also connected $L_{\rm B}$ to $\sigma_\star$ via the Faber-Jackson relation.

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

1. Were most of the iron in the universe manufacted by massive stars (SNII's) and were ellipticals deprived of dark matter, then the energy released by SN's would exceed by more than an order of magnitude the present binding energy of galaxies.

[2] This equation (15) comes from equation (15) in Paper I (see also Ciotti & Pellegrini 1992) where $\sigma_\star$ was expressed in cm s^{-1}. Here we have further adopted the ratio of the dark to bright matter core radii to be 10, and the ratio of the tidal to core radii to be 140.

2. Allowing for 90% of galactic mass to be in a dark matter halo reduces this figure by nearly a factor of ~ 3, with the SN energy still exceeding the binding energy of the bright matter by a factor between 3 to 9.

3. The SN to binding energy ratio is similar to the previous case if no dark matter is present, but $\sim 3/4$ of the iron in the universe is manufacted by SNIa's.

4. Only if SNIa's make $\sim 3/4$ of the iron, *and* $\sim 90\%$ of galactic mass is in a dark matter halo, then the early SN heating becomes comparable or smaller than the binding energy of the stellar component, and from these facts we can derive the following qualitative inferences.

5. 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.

6. 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 succeds in establishing a global wind.

7. The numbers in Table 2 enlight that in this class of models the detailed results must be very sensitive to the particular SNIa/SNII mix that is adopted, to the amount of dark matter assumed around protogalaxies, and especially on the treatment of radiative losses, as a major fraction of SN heating has to be radiated away. This last aspect is somewhat worrying for the ability of such models in making predictions as opposed to *fits*. Indeed, radiative losses depend on gas density squared, and a clumpy, multiphase ISM is likely to dominate within forming ellipticals: all conditions that practically prevent the evaluation of radiation losses with the accuracy that would be required to generate fully meaningful models.

8. Given these difficulties, we are just left with the rather obvious consideration that it must be easier to make galaxies the larger the share of iron made by SNIa's, the larger the amount of dark matter around protogalaxies, and the larger the ability to cool of the ISM of forming galaxies. All in all, we are left with an even stronger suspicion than before that some feedback, self-regulating mechanism must be at work during galaxy formation (see e.g., Heckman *et al.* 1990, and references therein).

5. 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 SN's.

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

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

$$E_{\rm ph}\simeq 3\times 10^{52}L_{\rm B}\quad ({\rm erg}), \tag{18}$$

for the energy radiated by SNII precursors during the formation phase of galaxies. Here, again, $L_{\rm B}$ (in solar units) can be interpreted as either the present luminosity of a whole cluster, or of one individual elliptical. For example, a today $5\,L_\star$ elliptical galaxy with $L_{\rm B}\simeq 5\times 10^{10}L_\odot$ had to radiate some 1.5×10^{63} erg during its formation. For a star formation time scale $\tau_{\rm SF}$, the corresponding bolometric luminosity was

$$L\simeq 10^{14}(\tau_{\rm SF}/10^8{\rm yr})^{-1}L_\odot. \tag{19}$$

Clearly, this figure would be a factor of 4 larger (or protogalaxies ~ 1.5 mag brighter) if most of the iron was made by SNII's, rather than in the solar SN proportion.

Here we are concerned with purely energetic arguments. 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.

6. THE GALAXY-ICM CHEMICAL ASYMMETRY

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 time scale of star formation in early elliptical galaxies in clusters.

Ratios such as [O/Fe], [Mg/Fe], and [Si/Fe] may be different in the stellar component of galaxies from what they are in the ICM, and the size of this *galaxy-ICM chemical asymmetry* would have important implications for our understanding of the galaxy formation process. Again, this follows from the fact that elements almost exclusively produced by SNII's (e.g., O, Mg, and Si) are released on a time scale $\sim \tau_{\rm SF}$, since the lifetime of SNII precursors is very short, while most of iron is released at a much slower pace following the evolution of the rate of SNIa's. So, the particular *"chemical trajectory"* traced by the stellar component of young ellipticals in e.g., the [O/Fe] vs. [Fe/H] plane depends on the relative size of $\tau_{\rm SF}$ and a typical time scale $\tau_{\rm SNIa}$ for SNIa's (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 time scales is *a priori* known, a condition which leaves them as mere adjustable (or hidden) parameters in chemical evolution models.[3]

In this scenario for the formation of elliptical galaxies, star formation ceases after $t \simeq \tau_{\rm SF}$, as gas starts flowing out of galaxies into the ICM. The composition of this gas reflects the stellar abundances, further enriched *in fly* by SNIa's. It follows that the shorter the time scale of galaxy formation, the less SNIa 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 SNIa iron would flow in 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 1/3 M_* is ejected, this mass will contain 1/3 of the whole Mg, 1/3 of the Fe from SNII's (which is $1/3\times1/4 = 1/12$ of the total), plus the whole iron from SNIa's, which is 3/4 of the total. Thus, all in all the ICM would contain 5/6 of the total iron but only 1/3 of the total magnesium, or [Mg/Fe]=–0.4. On the other hand, by construction the overall cluster Mg/Fe ratio is solar, where by overall ratio one means the total mass of iron in the ICM *and* galaxies, over the corresponding mass of magnesium.

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 (and masses) in galaxies can only come from population synthesis techniques, the raw data are already available and indeed there is a hint for Mg being enhanced compared to Fe (e.g., Davies, Sadler, & Peletier 1992). For the ICM, X-ray line observations are required, but no data for elements other than iron is presently available. The only exception we are aware of is a very uncertain estimate of O/Fe in Virgo and Perseus (Canizares *et al.* 1982, 1988), according to which O/Fe would be 3–5 times solar. Such a large ratio would definitely rule out SNIa's as important iron producers in clusters of galaxies as argued by White (1991), who makes an attempt at reproducing it with chemical evolution models. However, his solution implies an IMLR ~ 0.0003, or ~ 100 times smaller than the observed value. We conclude that within our current knowledge of stellar nucleosynthesis there is no way of reconciling a high O/Fe ratio in the ICM with the observed IMLR (and with the solar O/Fe ratio!), and we prefer to wait for future X-ray observations. Though difficults, the observational check of the predicted

[3] The definition itself of $\tau_{\rm SNIa}$ is unavoidably ambiguous, given the particular shape of the SNIa rate past a burst of star formation. For example, following an analogy with radioactive decay, $\tau_{\rm SNIa}$ could be defined as the time after the burst of star formation when half of SNIa's have exploded. In our adopted parameterization – equations (6) and (7) – $\tau_{\rm SNIa}$ is a function of $t_{15,\rm o}$ and s that can be easily evaluated.

chemical asymmetry would be of great value for our understanding of galaxy formation and evolution.

REFERENCES

Abia, C., Canal, R., & Isern, J. 1991, ApJ, 366, 198
Anders, E., & Grevesse, N. 1989, Geochimica et Cosmochimica Acta, 53, 197
Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Arnett, D. 1991, in Frontiers od Stellar Evolution, ed. D.L. Lambert, ASP Conf. Ser. 20, 389
Barbuy, B. 1992, in The Stellas Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), p. 143
Bower, R.G., Lucey, J.R., & Ellis, R.S. 1992, MNRAS, 254, 613
Branch, D., Doggett, J.B., Nomoto, K., & Thielemann, F.-K. 1985, ApJ, 294, 619
Canizares, C.R., Clark, G.W., Jernigan, J.G., & Markert, T.H. 1982, ApJ, 262, 33
Canizares, C.R., Markert, T.H., & Donahue, M.E. 1988, in Cooling Flows in Clusters and Galaxies, ed. A. Fabian (Dordrecht: Kluwer), p. 63
Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1991, ApJ, 376, 380
————. 1992, in Frontiers of X-Ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: Universal Academy), p. 441
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Djorgovski, S. 1992, in Cosmology and Large Scale Structure in the Universe, ed. R.R. de Carvalho, ASP Conf. Ser. 24, 73
Ellis, R.S. 1992, in The Stellar Populations of Galaxies, ed B. Barbuy & A. Renzini (Dordrecht: Kluwer), p. 297
Faber, S.M., & Jackson, R.E. 1976, ApJ, 204, 668
Freedman, W. 1989, AJ, 94, 1285
Gratton, R., & Ortolani, S. 1986, A&A, 169, 201
Greggio, L., & Renzini, A. 1983a, A&A, 118, 217
————. 1983b, Mem. SAIt, 54, 311
Harkness, R.P., & Wheeler, J.C. 1990, in Supernovae, ed. A.G. Petschek (New York: Springer), p. 1
Heckman, T.M., Armus, L., & Miley, G.K. 1990, ApJS, 74, 833
Hughes, J.P., Butcher, J.A., Stewart, G.C., & Tanaka, Y. 1992, ApJ, in press
Ikeuchi, S., & Norman, C. 1991, ApJ, 375, 479
Ikeuchi, S., & Ostriker, J.P. 1986, ApJ, 301, 502
Koyama, K., Takano, S. & Tawara, Y. 1991, Nature, 350, 35
Larson, R.B. 1974, MNRAS, 166, 586
Larson, R.B., Dinerstein, H.L. 1975, PASP, 87, 511
Matteucci, F., & François, P. 1992, A&A, 262, L1
Matteucci, F., & Greggio, L. 1986, A&A, 154, 279
Matteucci, F., & Tornambè, A. 1987, A&A, 185, 51
Matteucci, F., & Vettolani, G. 1988, A&A, 202, 21
Mitchell, R.J., Culhane, J.L., Davison, P.J., & Ives, J.C. 1976, MNRAS, 175, 29p

Munari, U., & Renzini, A. 1992, ApJ, 397, L87

Nomoto, K., & Shigeyama, T. 1991, in Supernovae, ed. S.E. Woosley (New York: Springer), 572

Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644

Nomoto, K., *et al.* 1991, in Elements and the Cosmos, ed. R.J. Terlevich, B.E.J. Pagel, R. Carswell, & M. Edmunds (Cambridge Univ. Press)

O'Connell, R.W. 1986, in Stellar Populations, ed. C. Norman, A. Renzini, & M. Tosi (Cambridge Univ. Press), p. 167

Ostriker, J.P., & Cowie, L. 1981, ApJ, 243, L127

Ponman, T.J., *et al.* 1990, Nature, 347, 450.

Renzini, A. 1986, in Stellar Populations, ed. C. Norman, A. Renzini, & M. Tosi (Cambridge Univ. Press), p. 213

Scalo, J.M. 1986, Fundam. Cosmic Phys, 11, 1

Serlemitsos, P. *et al.* 1977, ApJ, 211, L63)

Shigeyama, Y., Nomoto, K., & Hashimoto, M. 1988, A&A, 196, 141

Tammann, G. 1982, in Supernovae: A Survey of Current Research, ed. M. Rees & R. Stoneham (Dordrecht: Reidel), p. 371

Thielemann, F.-K., & Hashimoto, M. 1991, in Elements and the Cosmos, ed. R.J. Terlevich, B.E.J. Pagel, R. Carswell, & M. Edmunds (Cambridge Univ. Press)

Tornambè, A. 1989, MNRAS, 239, 771

Tsuru, T. *et al.* 1992, in Frontiers of X-Ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: Universal Academy), p. 485

van den Bergh, S., & Tammann, G. 1991, ARA&A, 29, 363

White, R.E. III 1991, ApJ, 367, 69

White, S. 1989, in The Epoch of Galaxy Formation, ed. C. Frenk, *et al.* (Dordrecht: Kluwer), p. 15

Woosley, S.E. 1988, ApJ, 330, 218

Woosley, S.E., & Weaver, T.A. 1986, ARA&A, 24, 205

————. 1992, preprint

2D HYDRODYNAMICS OF GAS FLOWS IN ELLIPTICAL GALAXIES INTERACTING WITH THE INTRACLUSTER MEDIUM

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Gas flows in 1D model elliptical galaxies evolve through three major evolutionary stages: from an early supersonic wind which is established shortly after galaxy formation, to a subsonic outflow which can last for even one Hubble time or more, until a central cooling catastrophe marks the transition to the inflow phase (Ciotti *et al.* 1991). The behavior of this class of models follows from the rate of type I supernovae decreasing slightly faster than the rate at which gas is shed by stars, and can satisfactorily account for the major properties of ellipticals in X-rays. In particular, most galaxies are predicted to still be in either the wind or the outflow regime at the present epoch, while only the most luminous galaxies may have already experienced the transition to the inflow phase. The large scatter in X-ray luminosity for given optical luminosity can be readly explained in this context. The physical conditions near the center of the galaxy are crucial in determining the time at which the cooling catastrophe sets in, and therefore the present apparence of the galaxy in X-rays. From a numerical point of view this means that two length scales must be described accurately at the same time: the galaxy as a whole ($r_t \sim 70$ kpc) and its central region (few hundreds of parsec). For example, degrading the central zoning from 100 to 200 pc can significantly affect the time at which the cooling catastrophe takes place (D'Ercole *et al.* 1990). In one dimension we obtained a sufficient numerical accuracy by adopting a logarithmic grid.

Real galaxies however are not isolated entities, but interact with the intracluster medium (ICM) through which they move, the flow of the hot interstellar gas is affected, and (at least) 2D simulations are needed for a realistic description. This problem has been addresses e.g., by Gaetz *et al.* (1987) for the particular case of non-evolving, steady-state cooling flows. We want instead to study how the external ram pressure affects our *evolutionary*, non-steady state models, and in particular whether the moment of the cooling catastrophe is anticipated or delayed.

Here we present a model in which the galaxy moves supersonically with a Mach number $M = 1.5$ through an ICM with $n = 4 \times 10^{-5}$ cm^{-3} and $T = 5 \times 10^7$ K. The model galaxy and the dark halo are the same as for the "KRM" model adopted by Ciotti *et al.* (1991). Figure 1 shows the flow density conturs at several times. We adopted an Eulerian rectangular grid whose zones are 2.2 kpc wide. As expected a bow shock forms, while the contact discontinuity between the ICM and the galactic ISM experiments Kelvin-Helmotz instabilities.

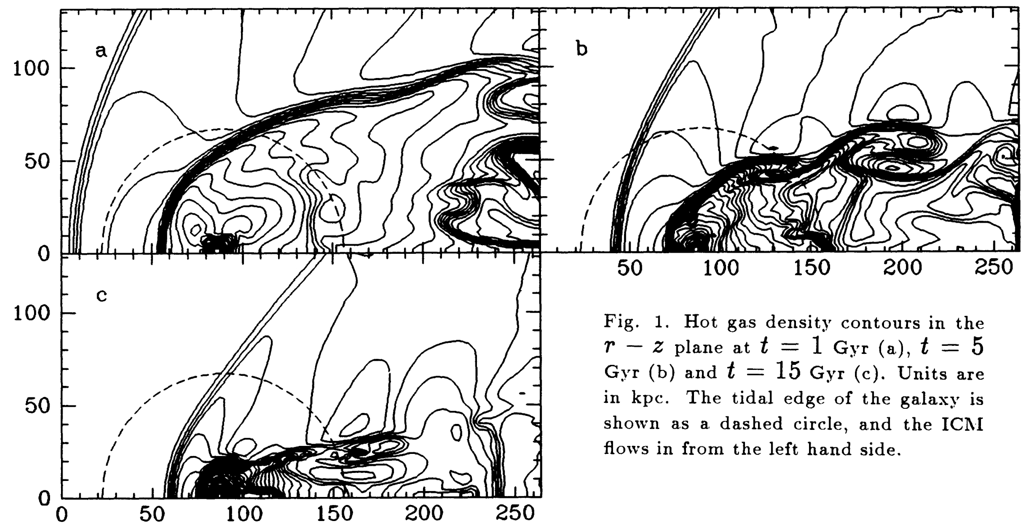

Fig. 1. Hot gas density contours in the $r - z$ plane at $t = 1$ Gyr (a), $t = 5$ Gyr (b) and $t = 15$ Gyr (c). Units are in kpc. The tidal edge of the galaxy is shown as a dashed circle, and the ICM flows in from the left hand side.

With time the global supernova luminosity and the rate of gas release from the stars decrease, and the bow shock migrates closer and closer to the galactic center. With this set of parameters, the ram pressure of the ICM proves very effective in reducing the gas content of the galaxy as well as its X-ray luminosity. Contrary to the 1D KRM model which experiments its central cooling catastrophe at $t \simeq 10$ Gyr, here no cooling catastrophe takes place at least up to 20 Gyr, and all the gas flows out of the galaxy though the whole simulation. However, as pointed out above, this result may be due at least in part to an insufficient spatial resolution of the central regions. We therefore introduced a local mesh refinement, by "nesting" a finer grid into the few inner cells, while a uniform zone refinement would have unaffordably inflated the CPU time. The time step on the coarse grid is rendered an integer multiple m of the time step on the finer grid, thus satisfying the Courant conditions. Conservation in the intergrid communication is ensured following Berger & Colella (1989). Our preliminary results for the same example discussed above, and assuming a refinement ratio 14 (i.e., a spatial resolution of 157 pc in the central region) indicate that the overall evolution of the flow does not change much, and the gas content of the galaxy remains quite low. However, a "mini inflow" appears near the center, early in the evolution of the flow.

REFERENCES

Berger, M.J., & Colella. P. 1989, JCP, 82, 64

Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1991, ApJ, 376, 380

D'Ercole, A., Ciotti, L., Pellegrini, S., & Renzini, A. 1990, in Windows on Galaxies, ed. G. Fabbiano, J.A. Gallagher, & A. Renzini (Dordrecht: Kluwer), p. 275

Gaetz, T.J., Salpeter, E.E., & Shaviv, G. 1987, ApJ, 316, 530