

On Dwarf Galaxies as the Source of Intracluster Gas

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ABSTRACT

Recent observational evidence for steep dwarf galaxy luminosity functions in several rich clusters has led to speculation that their precursors may be the source of the majority of gas and metals inferred from intracluster medium (ICM) x-ray observations. Their deposition into the ICM is presumed to occur through early supernovae-driven winds, the resultant systems reflecting the photometric and chemical properties of the low luminosity dwarf spheroidals and ellipticals we observe locally. We consider this scenario, utilising a self-consistent model for spheroidal photo-chemical evolution and gas ejection via galactic superwinds. Insisting that post-wind dwarfs obey the observed colour-luminosity-metallicity relations, we conclude that the bulk of the ICM gas and metals does not originate within their precursors.

1. Introduction

The existence of a hot, metal-enriched (e.g. for iron, $\sim 1/2$ solar), gaseous component in the intracluster medium (ICM) of clusters of galaxies has been a well-established fact for over two decades (see the seminal review of Sarazin 1986). With upwards of a third of a given cluster’s total gravitational mass locked up in this gas (White et al. 1993), understanding the origin of this massive component has been of the utmost importance.

That the ICM metals are the byproduct of gas that has been processed in galaxies, and subsequently ejected, is now widely accepted – indeed, Larson & Dinerstein (1975) predicted that observations of metal-enriched gas in the ICM would be a natural consequence of Larson (1974) supernovae-driven wind model for elliptical galaxies. Galactic winds are certainly the current favoured mechanism for ejecting heavy elements (e.g. Matteucci & Vettolani 1988; David et al. 1991; Ciotti et al. 1991; Mihara & Takahara 1994; Matteucci & Gibson 1995), although it should be noted that ram pressure stripping of the enriched interstellar media (ISMs) during the initial phase of star formation may also play a role (e.g. Sarazin 1979, although for persuasive arguments against the “stripping” scenario, the reader is directed to White 1991 and Renzini et al. 1993).

Matteucci & Vettolani (1988) illustrated that by integrating the mass of metals ejected from ellipticals of different initial masses over a Schechter (1976) luminosity function (assuming some mass-to-luminosity ratio) with faint-end slope $\alpha = -1.25$, one could account for the mass of iron observed in cluster ICMs as a function of cluster richness. One drawback to their early work was that it overproduced iron in relation to α -elements, such as Mg, Si, and O. This appears to be at odds with x-ray observations of the hot gas which show $[O/Fe] \gtrsim +0.2$ and $[Si/Fe] \gtrsim +0.15$ (Mushotzky 1994). Subsequent work by David et al. (1991) and Matteucci & Gibson (1995) alleviates this discrepancy somewhat by allowing for a flatter than Salpeter (1955) initial mass function slope, by mass, of $x \approx 1$. A more

exotic mechanism for ejecting the observed mass of metals in their appropriate abundance ratios is the bimodal star formation scenario of Arnaud et al. (1992) and Elbaz et al. (1995), although a recent photometric analysis of their model Gibson (1996b) highlights its shortcomings, at least in its present form.

While Matteucci & Vettolani (1988) recovered the total ICM *iron* mass, one of their primary conclusions was that the winds could only contribute at most 10 → 20% to the total *gas* mass – the bulk of the gas was necessarily of primordial origin.

The past few years have seen substantial advancements made, observationally, in determining the nature of the faint end slope of cluster luminosity functions. The gathering evidence seems to indicate that while the bright and intermediate luminosity regime is consistent with a uniform α of -1.25 to -1.45 (e.g. Ferguson & Sandage 1991), the faint end (i.e. $M_B \gtrsim -15$) dwarf spheroidal slope (at least in rich clusters) is significantly steeper, with values of $\alpha \approx -1.8 \rightarrow -2.2$ being favoured (e.g. Driver et al. 1994; De Propris et al. 1995; Bernstein et al. 1995; De Propris et al. 1995).

In a most interesting recent paper, Trentham (1994) speculates that the precursors to these dwarfs which currently populate the steep faint-end luminosity functions may in fact be the originating source for $\sim 100\%$ of the x-ray ICM gas. Trentham (1994) argues that if the faint-end dwarf slope is indeed $\alpha \approx -1.9$, and the precursors eject $\sim 8 \rightarrow 33\%$ of their initial *total* (i.e. “initial total” equals initial gas plus dark matter) mass in the form of gas (i.e. $\gamma \approx 0.08 \rightarrow 0.33$), after an initial burst of star formation, then these “dwarf precursors” can account for most of the present-day ICM gas, at odds with the earlier studies which favoured a primordial origin.

Following Trentham’s (1994) suggestion, Nath & Chiba (1995) derived analytical expressions for the amount of mass which can be lost by dwarf galaxies as a function of galactic mass. They showed that the Trentham (1994) idea was difficult to support if their

more realistic γ values were considered, but they also did not adopt self-consistent models of galaxy evolution.

In light of the aforementioned observations, and subsequent work of Trentham (1994) and Nath & Chiba (1995), we plan to re-examine the potential role played by dwarf galaxies in the enrichment of gas and metals in the ICM of galaxy clusters. To this end, we have constructed a self-consistent, coupled photo-chemical evolution package suitable for the study of spheroidal star systems in the context of a supernovae-driven wind framework. This is the first time, to our knowledge, that ICM enrichment models have been generated in conjunction with the photometric evolution of the underlying galactic population. Details regarding the mechanics of the population synthesis and chemical evolution implementation are given in Gibson (1995a,b). Earlier versions of the code were demonstrated in Gibson (1994a,b).

We begin Section 2 with a review of the observational constraints for the problem at hand. Following this, we shall introduce our favoured “template spheroidal models”, which in turn form the basis for the subsequent analysis of the ICM abundances and gas mass. The discussion of our results, and summary, can be found in Sections **3** and **4**, respectively.

2. Analysis

2.1. Observational constraints

Previous models which use supernovae-driven winds from ellipticals to enrich the ICM have had at least one major drawback – no self-consistency check on the implied photometric properties of resultant galaxies (e.g. Matteucci & Vettolani 1988; Pastor et al. 1989; David et al. 1991; Ciotti et al. 1991; Arnaud et al. 1992; Okazaki et al. 1993; Mihara & Takahara 1994; Elbaz et al. 1995; Matteucci & Gibson 1995). It is all very well to adjust

various input ingredients to the models in order to maximise the mass of ejecta and/or favour specific abundance ratios, but it is imperative to test that this has not been done at the expense of replicating the observed colour-luminosity-metallicity relationships.

Figure 1 shows the metallicity versus V-band luminosity relation for dwarf through giant ellipticals. Our model curves will be discussed in Section 2.2. The absolute magnitudes for the Virgo cluster ellipticals were derived assuming $H_0 = 85$ km/s/Mpc, and indeed this value of the Hubble constant is assumed throughout the remainder of the paper. The metallicities from the Terlevich et al. (1981) and Sil’chenko (1994) samples were derived from Mg_2 line index measurements, whereas the lower mass dwarf spheroidals (taken from Smith 1985 compilation) are typically estimated from giant branch locations in the spheroid’s colour-magnitude diagram (Smith 1985, and references therein). As an aside, the dominant elemental components of “Z” for these dwarfs are the α -elements, whereas both iron and α -elements contribute to the more massive systems (Matteucci 1994). Ideally one would, for example, like to compare synthetic Mg_2 indices for our model giant ellipticals against those shown in the figure, but as this is outside the scope of our current analysis, we settle for a compromise comparison with the global metallicity Z. In order to estimate the value of Z for those galaxies whose abundances were determined with the Mg_2 line, (i.e. all those points which lie above $[Z]=-0.6$), we adopt the $[Mg/Fe]=+0.25$, Mg_2 -Z calibration of Barbuy (1994). In light of the measurements of Mg overabundances relative to Fe, of this order, in giant ellipticals (Worthey et al. 1992), we felt that this was justified. Our results do not change substantially if we were to adopt the older $[Mg/Fe]=+0.00$ calibration.

EDITOR: PLACE FIGURE 1 HERE.

Figure 2 shows the second of our primary observational constraints – the colour-luminosity relation. We will be restricting the discussion which follows to the

optical-infrared V-K colour, although it should be understood that others, including B-V, have been considered. The reason we concentrate on V-K is that it provides a more valuable constraint than say B-V. Over the range of luminosities considered in our study, B-V does not vary by more than ~ 0.2 magnitudes, whereas the V-K versus M_V relation is flatter and spans $\gtrsim 1$ magnitude. The near vertical distribution of ellipticals in the B-V versus M_V plane (e.g. Figure 7b of Arimoto & Yoshii 1987) makes this colour, by itself, a poor constraint.

The sample of giant ellipticals in Figure 2 is taken from Bower et al. (1992), and, following their prescription, we shift the Coma data to the Virgo scale using $\Delta(V - M_V) = 3.58$ and $H_0 = 85$ km/s/Mpc. The local dwarf colours are from Thuan (1985). Using the local dwarfs as a constraint can be dangerous, as it is apparent that some have suffered complicated star formation histories (e.g. Phoenix, Leo I, Fornax, Carina ... Ferguson & Binggeli 1994), whereas others (e.g. Sextans, Sculptor, Draco, Ursa Minor) show little or no signs of star formation besides the initial burst. We feel reasonably safe in ensuring our model colours trace the lower envelope of the distribution, and simply note that subsequent strong star formation epochs will scatter the colours redward in this figure (due to the fact that the later bursts will be taking place in pre-enriched material from the dying stars in previous bursts, so despite being younger, their colours will almost certainly be redder ... see, for example, Table 5A of Worthey 1994).

EDITOR: PLACE FIGURE 2 HERE.

We mention in passing one final constraint pertaining to the properties of the elliptical galaxies themselves. As Worthey et al. (1992) have shown, and alluded to earlier, giant ellipticals seem to possess a magnesium to iron overabundance, as compared to the solar ratio, with values between $[Mg/Fe] \approx +0.2 \rightarrow +0.3$, albeit with a large scatter. This is

almost certainly due to the chemical enrichment history of said systems being dominated by Type II SNe, as opposed to Type Ia.

Another clue to the importance of Type II SNe, not only for the role they play in driving the stellar $[\text{Mg}/\text{Fe}]$ to super-solar values, but also for the one they play in the ICM itself, comes from x-ray observations of α -element abundances in the hot gas. Early observational work only allowed detection of the strongest Fe lines (Mitchell et al. 1976), but it has become clear over the past few years, and especially with the results from the ASCA satellite, that there is also an α -element overabundance with respect to iron, compared with solar ratios, in the ICM gas, with $[\text{O}/\text{Fe}] \approx +0.2 \rightarrow +0.6$ and $[\text{Si}/\text{Fe}] \approx +0.1 \rightarrow +0.5$ (Mushotzky 1994) Again, these ratios are indicative of Type II SNe dominated origin, as opposed to SNe Type Ia.

The combination of the α -element to iron ratios in both the ICM and the cluster ellipticals both strongly implicate early Type II-driven winds.

As to the absolute masses of both iron and gas implied by the x-ray observations, we refer attention to Figures 3 and 4. Arnaud et al. (1992) have demonstrated that a correlation exists between the total luminosity originating in a given cluster's elliptical+lenticular population and the measured mass of iron residing in the hot ICM gas. The shaded region of Figure 3 encompasses the observed scatter in the iron-cluster luminosity relation, as reported in Arnaud (1994). Again, a reasonable amount of scatter exists, but the trend does appear to be real. For comparison, we note the location of Virgo and Abell 2199, poor and rich clusters, respectively. Figure 4 shows the parallel correlation, but this time for ICM gas mass, as opposed to iron mass. The gas masses are claimed to be accurate to within a factor of two by Arnaud et al. (1992), and that is reflected in the width of the scatter at a given luminosity.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

In summary, the primary observational constraints that we must honour in a study of this nature are: the colour-luminosity-metallicity relations highlighted in Figures 1 and 2, the $[\text{Mg}/\text{Fe}] \approx +0.2 \rightarrow +0.3$ overabundance in the stellar populations of giant ellipticals, the correlation between ICM iron mass and cluster luminosity as seen in Figure 3, and finally, the $[\text{O}/\text{Fe}] \approx +0.2 \rightarrow +0.6$ overabundance in the ICM. As this is the first study to couple ICM abundances with the photo-chemical evolution of the underlying stellar population, we will demonstrate that previous work has suffered due to their restricting of constraints to the chemical properties alone.

2.2. Photo-chemical evolution models

We utilise the **Metallicity Evolution with Galactic Winds** chemical evolution package, **MEGAW** (Gibson 1996a), which is similar in spirit to that of Matteucci & Tornambè (1987), but adopts the more aesthetically pleasing (at least in the opinion of the first author!) “mass in/mass out” formalism, similar to that of Timmes et al. (1995), as opposed to the matrix form of Talbot & Arnett (1973). Diffuse dark matter halos, and their influence upon the system’s global and gaseous gravitational binding energy, are included, following Bertin et al. (1992). As in Matteucci (1992), we adopt initial dark-to-luminous masses, and radial extents, of 10. This means that the dark matter halos, although heavy, are very diffused and their effect on the potential well is not important, as shown by Matteucci (1992). Therefore, we are in a situation of almost minimal binding energy for the galaxies. As a consequence, the amounts of matter restored by galaxies into the ICM are close to the

maximum ones. Moreover, the assumed constancy of the ratio between dark and luminous matter from galaxy to galaxy is leading to a situation where the dwarfs can contribute to a maximum amount of matter. In fact, there are suggestions (Kormendy 1990) that the percentage of dark matter in dwarf is likely to be higher than in giant galaxies. We do not make any assumption concerning the nature of dark matter which could be either baryonic, non-baryonic or a mixture of both. In any case, the nature of dark matter is not relevant to the results of this paper.

A Schmidt (1959) star formation law (i.e. one in which ψ varies with some power of the gas mass) of the form

$$\psi(t) = \nu M_g^k, \tag{1}$$

with $k = 1$, is assumed for the pre-wind (i.e. $t \leq t_{\text{GW}}$) phase, whereas $\psi(t) = 0$ for $t > t_{\text{GW}}$. The star formation time-scale ν is used as a free parameter in order to ensure the colour-metallicity-luminosity relations are recovered, as will be shown in Section 3. This is similar to the procedure followed by Arimoto & Yoshii (1987) and Yoshii & Arimoto (1987). Generally though, ν is found to increase with decreasing mass in a manner reminiscent of models whose initial time-scale for star formation is set by the mean collision time of star-forming fragments in the proto-galaxy (Arimoto & Yoshii 1987).

MEGaW has the flexibility to use any number of input ingredient sources. For the purposes of this work, we have chosen a universal stellar initial mass function (IMF) of slope $x = 0.95$, consistent with the value implicated by our earlier work (Matteucci & Gibson 1995), with corresponding lower and upper limits of $0.2 M_\odot$ (Paresce et al. 1995) and $65 M_\odot$, respectively. The main sequence lifetimes come from Schaller et al. (1992), and the remnant masses are based upon the analytical expressions of Prantzos et al. (1993).

For the nucleosynthesis yields, we use the most recent metallicity-dependent tables of Woosley & Weaver (1995) for masses $m \geq 10 M_\odot$ (i.e. Type II SNe). The classic models of

Renzini & Voli (1981) are adopted for single low and intermediate mass stars (i.e. $m \leq 8 M_{\odot}$). Following Iwamoto et al. (1994), we assume that stars in the initial mass range $8 \leq m \leq 10 M_{\odot}$ undergo core collapse, as opposed to thermonuclear explosion, thereby trapping their newly synthesised metals in the resultant remnant (i.e. they only enrich the ISM via pre-collapse stellar winds). The binary Type Ia SNe model of Whelan & Iben (1973) has been included, following Greggio & Renzini (1983). For their yields, we use the updated Model W7 of Thielemann et al. (1993). We have ensured that the present-day rate of Type Ia SNe is consistent with the observed rate in giant ellipticals ($R_{\text{Ia}} = 0.07 \rightarrow 0.23$ SNU, for $H_0 = 85$ km/s/Mpc Turatto et al. 1994), by choosing, *a posteriori*, that $\sim 3\%$ of the mass in the range $3 \rightarrow 16 M_{\odot}$ of the IMF gets locked into Type Ia-progenitor binary systems (Greggio & Renzini 1983). An average value for R_{Ia} of ~ 0.12 SNU for the present-day rate in our giant elliptical models was found.

For gas to be expelled from a galaxy we require the thermal energy of the gas heated by supernovae and stellar winds to exceed its gravitational binding energy (Larson 1974). The stellar wind energy, while not important for giant ellipticals, can contribute non-negligibly for low mass (i.e. $M \lesssim 10^9 M_{\odot}$) systems (Gibson 1994a). We use the energy formalism outlined in that paper for its inclusion.

Supernovae remnant interior thermal energy (i.e. the energy assumed to be available for driving the wind) evolution follows that of Model B₃' of Gibson (1994b), which draws heavily upon the work Cioffi et al. (1988). Unlike the older Cox (1972) and Chevalier (1974) equations, which have been used exclusively to date, Cioffi et al. (1988) include a sophisticated treatment of radiative cooling in the SNR interior, as well as the effects of metallicity upon their evolution. Also, virtually all previous galactic wind models have assumed that SNRs evolve in isolation (see Model A₀ of Gibson 1994b – in particular, that after the initial adiabatic expansion phase a radiative cooling phase is entered and the

energy ε cools as $\varepsilon(t) \propto t^{-0.62}$, *ad infinitum*. This is clearly not the case, as shells either come into pressure equilibrium with the local ISM, thereby halting the expansion cooling term, or, more importantly, come into contact and overlap with neighbouring expanding shells, further cooling thereafter being negligible. This was noted in Larson’s (1974) original paper, but the “evolution in isolation” formalism still stood (and still does in most wind models) until the recent work of Babul & Rees (1992) and Gibson (1994b). As we shall see, the wind epochs favoured by Model B₃’ are significantly earlier than those predicted by Model A₀. Again, further details can be found in Gibson (1994b,1995a).

The post- t_{GW} energetics situation is somewhat more problematic. Scenarios in which continuous Type Ia-driven SNe winds ensue until the present, temporarily driven winds, or even no post- t_{GW} wind whatsoever, are all feasible. Of great significance in determining this outcome is the amount of residual thermal energy which is left in the system after the bulk of the gas has been ejected in the global wind at t_{GW} . This has been demonstrated quite graphically by Arimoto (1989) and Ferrini & Poggianti (1993). We do not wish to belabour this point, and as such, we present three different scenarios for the post- t_{GW} thermal evolution. A *minimal* model in which the only gas ejected is that due to the global expulsion at t_{GW} ; a *maximal* model in which all post- t_{GW} ejecta from lower mass stars is continuously swept out of the system due to the continued heating from Type Ia SNe; and, a *standard* model, which incorporates Arimoto’s (1989) assumption that the fraction of residual thermal energy remaining after t_{GW} compared with that before is $\lesssim 0.01$. These latter models usually lead to temporary winds of duration $\lesssim 0.5$ Gyr for massive systems, while for low mass systems they coincide with the *maximal* models.

In order to calculate the coupled photometric properties of our spheroids, we have developed a simple population synthesis package (Gibson 1996b) which, for the work described here, used the metallicity-sensitive isochrones of Worthey (1994). This compilation

spans ~ 2.5 dex in $[Z]$, and covers the primary evolutionary stages from the zero age main sequence to the onset of the post-asymptotic giant branch (or carbon ignition, depending upon the initial mass in question). Luminosity weighted (V-band) metallicities $[< Z >]_V$, $[\text{Mg}/\text{Fe}]$, colours and luminosities, and final mass-to-luminosity ratios were all generated as described in Gibson (1996b).

2.3. Intracluster medium implications

The work of Arnaud et al. (1992) has shown that there is a direct correlation between a cluster’s elliptical population luminosity, and the measured abundance of iron in the ICM. With knowledge of a given spheroid’s ejected mass of gas (or element i) and its V-band luminosity, we can easily integrate over the cluster’s Schechter (1976) LF, as opposed to working with the mass function and assuming *a priori* some typical mass-to-luminosity ratio. By normalising to a cluster’s E+S0 V-band luminosity $L_V^{\text{E/S0}}$, we can then write the total mass of element i ejected into the ICM by galaxies of luminosity greater than L_V^{min} as

$$M_i^{\text{ej}} = L_V^{\text{E/S0}} \int_{L_V^{\text{min}}/L_V^*}^{\infty} m_i \left(\frac{L_V}{L_V^*} \right)^\alpha e^{-L_V/L_V^*} d\left(\frac{L_V}{L_V^*} \right) / \int_{L_V^{\text{min}}/L_V^*}^{\infty} L_V \left(\frac{L_V}{L_V^*} \right)^\alpha e^{-L_V/L_V^*} d\left(\frac{L_V}{L_V^*} \right), \quad (2)$$

where m_i is the mass of element i ejected by an elliptical of luminosity L_V ¹. α is the usual faint-end slope, with canonical values ranging from -1.00 to -1.45 (e.g. Ferguson &

¹ If the function m_i can be written in the form of a power law in luminosity, then equation 2 can be written as a simple incomplete gamma function (e.g. Matteucci & Vettolani 1988; Elbaz et al. 1995). This is sufficient *provided* one restricts the fit to the high mass end of the LF (e.g. $M_g(0) \gtrsim 10^9 M_\odot$). This simple power law form does *not* extend down to the dwarf (i.e. $M_g(0) \lesssim 10^8 M_\odot$) regime. If we were to fit a power law to the high mass end

Sandage 1991, and references therein). L_V^* , for the bright-end of the LF, is chosen to be $L_V^* \equiv 1.54 \times 10^{10} L_\odot$ (i.e. $M_V^* \equiv -20.6$), again, typical for $H_0 \equiv 85$ km/s/Mpc.

The recent years have led to a revolution of sorts in our picture of the faint-end of the cluster and field LF, and in particular, the realisation that the faint-end is not well-described by a single slope α . The ten low and medium redshift clusters in the survey of Phillips et al. (1996) show a surprising uniformity in that the faint-end slope brighter than $M_V \approx -17.3$ is consistent with $\alpha \approx -1$, whereas fainter than this, a clear up-turn, with a power law slope $\alpha \approx -1.5 \rightarrow -1.8$, is seen. The deep, very faint, LFs, from the cores of four rich clusters, presented by De Propris et al. (1995), are even more extreme with a faint-end slope $\alpha \approx -2.2$. The models of Babul & Ferguson (1996) also predict a similarly steep slope below $M_V \approx -17.3$. In Section **3**, we consider a number of LFs including both the canonical single-slope faint-end, and, what appears to be, the more appropriate two-component form, consistent with the aforementioned observations.

One last point which should be made regarding equation 2 is the adopted lower limit on the intergals, M_V^{\min} . In general, or at least for all models in which the faint-end LF slope is $\alpha \gtrsim -1.45$, the results of Section **3** do not depend sensitively upon M_V^{\min} , and thus we typically assume the luminosity associated with the lowest mass dwarf in our study (i.e. $M_g(0) = 10^4 M_\odot$). As we shall see, though, for some scenarios in which the faint-end slope

of our standard models in Section **3**, and then blindly extrapolate to the low mass end, we would overestimate the predicted masses of ejected gas and metals from these dwarfs by factors of two to three. Indeed, the predicted ejected gas mass would actually exceed the mass of gas initially present! For “normal” $\alpha \gtrsim -1.45$ LFs, this unphysical situation may not be numerically significant, but as we are interested in exploring the relevance of very steep ($\alpha \approx -1.9 \rightarrow -2.2$) faint-end slopes, we feel it prudent to integrate over the Schechter function properly.

of the LF is very steep, we have to resort to more subtle means in order to set M_V^{\min} . The reason for doing so is that as Melnick et al. (1977) and Thuan & Kormendy (1977) have demonstrated, the *maximum* fraction of a cluster’s luminosity that is tied-up in the LF, *below* $M_V \approx -17$, is $\sim 1/4$, based upon cluster diffuse-light constraints. Occasionally, a lower integration limit in excess of the “default” must be enforced in order to ensure that we do not exceed this $\sim 1/4$ dwarf luminosity fraction. At some level, this should not be surprising, as one need only refer back to equation (22) of Schechter’s (1976) seminal paper to see that for $\alpha \leq -2$, a regime we are exploring in this paper, the integrated cluster luminosity diverges.

3. Discussion

We now present the results for our so-called “template models”, the input ingredients for which are described in Section 2.2. Table 1 lists the output for the three post- t_{GW} wind scenarios: the extrema (continuous Type Ia SNe-driven winds to the present and suppression of all Ia-driven winds) and the standard model (temporary winds which die at after $\sim 0.2 \rightarrow 0.5$ Gyr). For each model we list – column (1): the initial luminous mass in gas (in M_\odot) – column (2): the star formation astration parameter of equation 1 (in Gyr^{-1}) – column (3): the time of the global galactic wind (in Gyrs) – columns (4)-(6): the total mass of gas, oxygen, and iron expelled by the system until the present epoch ($t_G = 12$ Gyr) – columns (7)-(9): the present-day photometric properties of interest for this paper – column (10): the V-band luminosity-weighted metallicity – column (11): present-day mass in luminous matter (star+remnants+gas) – column (12): the total present-day mass (luminous plus dark, assuming initial dark to luminous mass ratio of ten) to luminosity ratio – column (13): the mass fraction of gas expelled by the system over its lifetime (relative to the total initial mass) – column (14): the final system’s gas mass fraction (relative to the

final luminous mass).

EDITOR: PLACE TABLE 1 HERE.

Recall that the flatter $x = 0.95$ IMF was chosen for consistency with our earlier work (Matteucci & Gibson 1995), which used predominantly the code of Matteucci & Tornambè (1987), with the Matteucci (1992) extensions. Our “minimal” models in the table above are similar to our earlier work, although we note that the later wind times found in our earlier work is due mostly to our using the classic Model A₀ evolution for the SNe energy, as opposed to Model B₃′ (Gibson 1994b). Figures 1 and 2 illustrate that our template is successful at reproducing the mean of the colour-luminosity-metallicity relations observed in present-day ellipticals and dwarfs, over ~ 16 magnitudes in V. As in Yoshii & Arimoto (1987), the astration parameter is treated as a free parameter in order to recover the observations. For masses $M_g \gtrsim 10^7 M_\odot$, $\nu \propto M_g^{-0.1}$, which is the expected behaviour if the initial time-scale for star formation is set by the mean collision time of fragments in the collapsing proto-galaxy (Arimoto & Yoshii 1987; Matteucci 1994).

We mention in passing that the two dwarf ellipticals in Figure 1 for which the model apparently overestimates the metallicity (NGCs 205 and 147) may themselves only be lower limits. Yoshii & Arimoto (1987) speculate that this is due to that fact that they were based upon individual red giants in the galaxies outer halos, and as such, may not be representative of the overall metallicity of the system, and in particular, the cores of the galaxies.

Our predicted M_t/L_V , for the standard model, is proportional to $L_V^{-0.07}$, which is flatter than the $M_t/L_V \propto L_V^{-0.13 \rightarrow -0.31}$ observational constraint from the studies of dark matter scaling laws (Kormendy 1990). It’s important to stress that we have not attempted any “fine-tuning” of the input dark matter distribution in order to recover the apparently

steeper observational relation. A global input ratio of 10:1, both in mass and radius (dark to luminous), naturally led to the -0.07 slope. It is certainly easy to recover the steeper value by systematically increasing/decreasing the dark-to-luminous initial mass ratio as one moves to smaller/higher initial masses, but for this work we have avoided any tinkering in that direction, especially because we wanted to be in the best situation for having the maximum mass ejection from dwarf galaxies and also because of the uncertainties relative to the amount of dark matter in galaxies. It is gratifying to note, at least, that the ratio does increase with decreasing luminosity, contrary, for example, to what was found in the earlier models of Yoshii & Arimoto (1987), which admittedly did not include any dark matter halos (see their Figure 6). Finally, our M_{lum}/L_V ratios for giant ellipticals are all consistent with the observed values of $\sim 10 \pm 5$ ($H_0 = 85$ km/s/Mpc)- observational values of the M/L ratios refer to the internal parts of ellipticals where the dark matter is not evident- and increase slightly with L_V ($M_{lum}/L_V \propto L_V^{0.1}$). This behaviour is observed in real elliptical galaxies although the exponent is ~ 0.2 (Bender et al. 1992). A variation of the IMF from galaxy to galaxy could steepen the predicted relation (Matteucci 1994), without any remarkable consequence on the amount of ejected matter from galaxies. On the other hand, the trend of the mass to light ratio could be due to an increasing amount and/or concentration of dark matter with galactic mass (Renzini & Ciotti 1993).

We re-iterate the point made in Section 2.1 regarding the scatter in the colours for the dwarfs shown in Figure 2. Our models trace the lower envelope of the dwarfs. We recognise that many of these systems show signs of intermediate age populations (Ferguson & Binggeli 1994), indicative more complex star formation histories than we are capable of modelling with the existing version of our code. The lower envelope represents the predicted colours for those systems which have the simple single early burst of star formation. Those which have subsequent phases of star formation will scatter redward in the plot as despite being younger, they will occur in gas that has been pre-enriched by previous generations of

dying stars.

We have not tabulated the $[\text{Mg}/\text{Fe}]$ in the underlying stellar populations, but we state here that the giant ellipticals have a luminosity-weighted $[\text{Mg}/\text{Fe}] \approx +0.35$, consistent with the mean observed values from Worthey et al. (1992). Our $[\text{Mg}/\text{Fe}]$ values are almost constant across the luminosity range covered in their sample, whereas their data implies a gentle increase in the value as a function of increasing luminosity, albeit with a great deal of scatter. This increase in the magnesium overabundance with respect to iron has been addressed recently by Matteucci (1994).

We have also not shown the fraction of the thermal energy at t_{GW} which is due to thermalised kinetic energy from pre-SN stellar winds in massive stars versus that due to thermalised SNe ejecta. For giant ellipticals this “wind” contribution is $\lesssim 5\%$, and for low mass dwarf spheroidals, $\sim 10 \rightarrow 20\%$. This only corresponds to an $\lesssim 3\%$ reduction in t_{GW} for giant ellipticals ($\lesssim 10\%$ for dwarfs) when compared with models run with no energy input from stellar winds. Adjusting ν by a few percent from the values listed in column (2) of Table 1 would compensate easily for any minor difference in wind epochs (and hence the resultant photo-chemical properties) for models run with and without stellar winds, further illustrating the point made in Gibson (1994a,1996c) that stellar winds do not play an important role in driving the galactic wind in models of this ilk.

One last input ingredient we wish to touch upon further is the initial mass function. Arimoto & Yoshii (1987), David et al. (1991), and Matteucci & Gibson (1995), amongst others, have all put forth persuasive arguments for a “flatter than Salpeter (1955)” IMF in elliptical galaxies. Some arguments are based upon ICM abundances (e.g. the latter two references), some upon the implications for the underlying ellipticals’ photometric properties (e.g. the first reference). The situation is discussed further in Gibson (1996a), but we wish to at least draw attention to some interesting aspects of the IMF selection.

In Table 2 we show a comparison of our template $x = 0.95$ IMF with that of the steeper, canonical $x = 1.35$ IMF of Salpeter (1955), each with the same upper and lower mass limits, as before. We only show one initial mass ($M_g(0) = 10^{12} M_\odot$), and one post- t_{GW} model - the “minimal” model - for succinctness. The astration parameter ν has once again been tuned to reproduce present-day ellipticals which follow the observations of Figures 1 and 2. Similarly, the binary parameter A has been chosen *a posteriori* to ensure consistency with the average present-day SNe Ia rates mentioned in Section 2.2 (specifically, $R_{\text{Ia}} \equiv 0.12$ SNU), although the slight difference in the binary parameter A (0.030 versus 0.045) is not important to the results. Column (1): the IMF slope, by mass, x – column (2): the astration parameter ν – column (3): binary mass fraction ($3 \rightarrow 16 M_\odot$) – column (4): the galactic wind time – columns (5)-(7): the masses of gas, iron, and its [O/Fe] abundance, ejected at t_{GW} – column (8): the mass fraction of gas expelled at t_{GW} – column (9): [Mg/Fe] in the underlying stellar population.

EDITOR: PLACE TABLE 2 HERE.

The key thing to note from Table 2 is that selecting a steeper IMF, but retaining the same astration parameter as for a flatter slope, leads to colours which are significantly bluer (~ 0.4 magnitudes in V-K for this example), and metallicities which are significantly lower (~ 0.3 dex), than those observed. A more “gentle” star formation scenario (the third line in the table) is required in order to allow the enrichment to proceed to such a level as to match the observations. This results in a factor of ~ 4 decrease in the absolute quantity of gas mass and oxygen mass ejected at t_{GW} , and a factor of ~ 2 decrease in the iron mass ejected. Perhaps, more importantly, the stellar [Mg/Fe] with this “template” $x = 1.35$ IMF is inevitably driven down to the solar ratio, no longer in agreement with the Worthey et al. (1992) observations of $\sim +0.2 \rightarrow +0.3$. In a related vein, the [O/Fe] ratio in the ejected gas is also only the solar ratio. Since this model is only marginally greater

than an L_* galaxy, and we have not included any post- t_{GW} Ia-driven contribution (which could only drive this ratio further downward), it would not bode well for any attempt at reproducing the oxygen-to-iron overabundance seen in the x-ray observations of the ICM gas. It is supporting evidence such as these last points which leads us to conclude that an IMF somewhat biased towards high mass stars (i.e. a slope of $x \approx 1$) is a necessity in the wind models adopted to date, in agreement with our earlier study, which was based upon the chemical properties alone (Matteucci & Gibson 1995).

EDITOR: PLACE FIGURE 5 HERE.

EDITOR: PLACE FIGURE 6 HERE.

EDITOR: PLACE FIGURE 7 HERE.

EDITOR: PLACE FIGURE 8 HERE.

Using the photo-chemical properties of the ejecta, and the resultant galaxies, shown in Table 1, we can use equation 2 to determine the predicted ICM mass of an element (or simply the gas mass) originating in the elliptical/spheroidal population of a cluster of luminosity $L_V^{\text{E/S0}}$. This is a particularly nice aspect of the formalism – specifically, the predicted ejected mass is normalised to the actual *observed* cluster luminosity, and does not need to be inferred from integrating over the mass functions, assuming some galactic mass-to-luminosity relationship (Arnaud et al. 1992).

Figure 3 shows the results of said analysis for iron for the *minimal* (i.e. no post- t_{GW} contribution to the ejecta) models of Table 1. The solid curve shows the predicted iron

ICM mass as a function of cluster luminosity, assuming the elliptical/lenticular population is well-described by a single Schechter (1976) luminosity function with $M_V^* = -20.6$ and $\alpha = -1.45$. The model is only marginally consistent with the most-metal poor observed distribution (shaded region), at a given luminosity. In general, the predicted iron mass is $\sim 1/2$ that of the mean of the observed relation.

Now, let us follow the suggestion of Trentham (1994) (and the supporting observations discussed in Section 2.1) and take the cluster dwarf spheroidal population to be represented by a separate Schechter (1976) luminosity function from that of the giant elliptical, with $M_V^* = -16.7$ and $\alpha = -1.90$. We now assume that 30% of the cluster E+S0 luminosity originates in this dwarf population, which is the upper limit set by diffuse background light measurement in rich clusters of galaxies (e.g. Melnick et al. 1977; Thuan & Kormendy 1977). The remaining 70% is associated with the giant luminosity function, with M_V^* and α as in the previous paragraph. As the global cluster luminosity does not change, we are effectively shifting the available light from one part of the luminosity function to another.

The top, heavy dotted, curve in Figure 3 shows the result of this 70/30 distribution. The predicted ICM iron mass is now only $\sim 76\%$ that of the single luminosity function result. The reason for this is as just implied – we have shifted the emphasis, somewhat, from giants, which for the minimal model, eject $\sim 0.008 M_\odot$ of iron per unit luminosity, to dwarfs, which at the low mass end, only eject $\sim 1/40$ this amount. In this 70/30 luminosity split, the dwarfs only contribute $\sim 10\%$ the absolute mass of iron that the giants do.

Figure 4 shows the corresponding prediction for gas, in the minimal model. Here we see that the single luminosity function can only account for $\sim 18\%$ of the observed ICM gas at a given cluster luminosity. The double LF is able to raise this to $\sim 23\%$, for much the same reason that it led to lower iron – specifically, the ejected gas mass per unit luminosity is ~ 5.5 times higher at the low mass end of the minimal models in Table 1, as compared

to the giant end. By shifting the luminosity distribution to favour the low mass end of the spectrum, we do end up boosting the predicted cluster ICM gas mass which originates, but not nearly to the level necessary to explain 100% of the gas.

Because there is no post- t_{GW} contribution to the winds, and the wind epochs are quite early ($\lesssim 0.1$ Gyr), it is not surprising to note that the predicted ICM gas [O/Fe] is $\sim +0.4$, consistent with a prominent Type II origin to the elements (Woosley & Weaver 1995), and easily consistent with the observed oxygen overabundance relative to iron observed by ASCA (Mushotzky 1994). Besides the slight underproduction of iron just alluded to, a more notable problem with the minimal model is the predicted final fraction of gas in the system at the present-day. From column (14) of Table 1, we can see that the ratio of gas mass to total luminous mass, at $t_{\text{G}} \equiv 12$ Gyr, ranges from ~ 0.6 (dwarfs) to ~ 0.4 (giants). This is considerably higher than the observed maximum of $\sim 10\%$ (Forman et al. 1985). Obviously then, some other mechanism has to come into play. We shall return to this point momentarily.

The parallel analysis for the maximal and standard models are shown in Figures 5 through 8. The maximal model overproduces iron by a small amount ($\sim 50\%$), but is still within the observed maximum for a given cluster luminosity. Because of the increased importance of the Type Ia SNe in the post- t_{GW} ejecta, the [O/Fe] of the ejected gas is decreased by ~ 0.3 dex, when compared with the minimal model of Figure 3. The difference between the single and double luminosity function scenarios is negligible, although the dwarfs do contribute $\sim 1/3$ of the total iron in the maximal model, as opposed to the $\sim 1/10$ we saw in the minimal case.

Of more interest for the maximal model, perhaps, is the result shown for the total gas mass, in Figure 6. Recall that for the minimal model of Figure 4, the ellipticals in a cluster could contribute $\sim 18 \rightarrow 23\%$ of the observed ICM gas. Now, considering the

maximal model, we see that for the single/double luminosity function scenario that the cluster ellipticals can contribute approximately 33/38%, of which $\sim 40\%$ derives from the “dwarfs”. This is one of the key conclusions of our work – *even assuming an extreme scenario in which all the gas returned by dying stars is ejected continuously to the ICM, neither the giant ellipticals nor the dwarf spheroidals (nor their sum, for that matter) can be responsible for all the gas observed in the ICM of galaxy clusters, provided that we insist that the resultant galaxies reflect the photo-chemical properties of present-day systems.*

Figures 7 and 8 show the results for our standard model. The iron mass predicted for our model ICMs lies along the median of the observed region, but once again, the gas mass accounted for is at most $\sim 35\%$, with a similar distribution of giant/dwarf origin as was found for the maximal model. The predicted $[O/Fe]$ of $\sim +0.2$ is consistent with the ASCA observations (Mushotzky 1994). The dwarfs are identical to the maximal models. This is not surprising as their shallow potential wells facilitate the continual expulsion of gas during the post- t_{GW} regime, a result reflected in the recent hydrodynamical simulations of Wang (1995). The giants (i.e. $M_g(0) = 5 \times 10^{10}$ and $1 \times 10^{12} M_\odot$) in this “standard” model only drove steady winds for 0.22 and 0.43 Gyrs, respectively, beyond which the binding energy of the returning gas from dying stars “catches up” with the more rapidly cooling term for the SNe-heated gas. At this point, one might be tempted to re-ignite star formation, and indeed this is exactly what Arimoto (1989) and Ferrini & Poggianti (1993) consider. As this introduces further free parameters into the picture, we decided not to pursue this option, and we simply direct the reader to their excellent studies of late-time star formation within the framework of the wind model.

In this vein though, we note that the final gas fractions for our massive model ellipticals range from $\sim 20 \rightarrow 25\%$, which is still higher than the $\lesssim 10\%$ expected from observations (Forman et al. 1985). We are not overly concerned by this apparent discrepancy, partly

because of the uncertainties in predicting the exact mass of post- t_{GW} ejecta, and partly because of the neglect of post- t_{GW} star formation. Indeed, the high final gas fractions were similarly a problem with the original models of Arimoto & Yoshii (1987), and as shown in Arimoto (1989), recurrent periods of star formation (at a much reduced level to that in the initial burst) are a natural consequence of the late-time cooling of the gas, although we re-iterate that the exact amount of both the post- t_{GW} star formation and gas ejection is highly sensitive to the assumed fraction of thermal energy in the gas immediately after t_{GW} . Arimoto (1989) alleviated his $\sim 20\%$ gas fraction “problem” without unduly altering the present-day photo-chemical properties of the galaxies, with limited post- t_{GW} star formation/gas ejection. Again, we do not consider such evolution in our models, but anticipate that such a scenario, identical to his, would similarly reduce our final gas fractions without altering our photo-chemical properties. Still, this is an obvious avenue for future research.

Column (13) of Table 1 shows the initial mass fraction which is ejected into the ICM in the form of gas. Regardless of model-type, the values range from $\gamma \approx 0.04 \rightarrow 0.08$. These compare favourably with the lowest value considered by Trentham (1994), but are not consistent with his higher value of 0.33. It is important though to recall that our values were derived from a self-consistent wind model which leads to ellipticals (giant and dwarf) with photometric and chemical properties which reflect those observed at the current epoch, whereas the values considered by Trentham (1994) were somewhat arbitrary.

4. Summary

In summary, we stress that by considering coupled photometric and chemical evolution of simple spheroidal models within the framework of a galactic wind model, the precursors to the dwarf spheroidals which we observe today in clusters do not seem capable of

providing the gas necessary to explain the mass observed in the ICM. Our standard model with a giant elliptical luminosity function contributing 70% of the cluster luminosity, and the remaining 30% originating in a low luminosity diffuse contribution, shows that the precursor dwarfs contribute at most $\sim 15\%$ of the ICM gas, with the giants responsible for $\sim 20\%$. The remaining $\sim 65\%$ is then, by definition, “primordial” in origin. This is somewhat less than the $\sim 80 \rightarrow 90\%$ first proposed by Matteucci & Vettolani (1988), so we conclude that the precursors to the dwarfs do contribute a non-negligible amount of gas to the ICM of clusters, but that this amount is nowhere near enough to explain *all* the gas. Our self-consistent treatment led to ejected initial mass fractions of $\gamma \lesssim 0.08$, allowing us to exclude the $\gamma = 0.33$ assumption of Trentham (1994). Whether this non-galactic wind-originating gas has resided in the cluster since early epochs, or supplied by later gas infall, or simply failed to completely collapse into galactic potentials is still a matter under vigorous investigation (e.g. White et al. 1993, Nath & Chiba 1995, and references therein).

We admit that the parameter space in these wind models is large, but we explored a much larger parameter space than presented in this work and found that without resorting to extraordinarily ad hoc assumptions regarding one or more of the input ingredients, we can not envision a scenario which will eject the required gas mass and still honour the underlying photo-chemical properties of the resultant galaxies and the ICM abundances. Moreover, we stress the point that our estimate for the total gas ejected from galaxies is an almost maximal one, so that any reasonable change of parameters goes in the direction of further decreasing the amount of matter which can be restored from galaxies into the ICM, thus reinforcing our conclusion.

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Table 1. Template Models^a

| $M_g(0)$ | ν | t_{GW} | m_g^{ej} | m_{O}^{ej} | $m_{\text{Fe}}^{\text{ej}}$ | M_V | B-V | V-K | $[< Z >]_V$ | M_{lum} | M_t/L_V | γ | f_{gas} |
|-----------------------|-------|-----------------|-------------------|----------------------------|-----------------------------|--------|------|------|-------------|------------------|-----------|----------|------------------|
| <i>Minimal Model</i> | | | | | | | | | | | | | |
| 1.0e6 | 73.3 | 0.006 | 6.7e5 | 2.8e2 | 1.2e1 | -7.01 | 0.68 | 2.07 | -2.45 | 3.3e5 | 191 | 0.061 | 0.62 |
| 5.0e7 | 89.9 | 0.007 | 2.9e7 | 4.1e4 | 2.1e3 | -11.56 | 0.69 | 2.10 | -1.81 | 2.1e7 | 147 | 0.053 | 0.60 |
| 1.0e9 | 59.4 | 0.014 | 5.1e8 | 6.8e6 | 2.3e5 | -14.95 | 0.76 | 2.46 | -0.68 | 4.9e8 | 129 | 0.046 | 0.55 |
| 5.0e10 | 37.9 | 0.037 | 1.9e10 | 6.6e8 | 4.4e7 | -19.38 | 0.86 | 3.16 | -0.01 | 3.1e10 | 111 | 0.035 | 0.48 |
| 1.0e12 | 32.6 | 0.068 | 2.6e11 | 1.3e10 | 9.5e8 | -22.82 | 0.92 | 3.44 | +0.30 | 7.4e11 | 95 | 0.024 | 0.43 |
| <i>Maximal Model</i> | | | | | | | | | | | | | |
| 1.0e6 | 73.3 | 0.006 | 8.7e5 | 5.5e3 | 9.0e2 | -7.01 | 0.68 | 2.07 | -2.45 | 1.3e5 | 188 | 0.079 | 0.00 |
| 5.0e7 | 89.9 | 0.007 | 4.2e7 | 4.9e5 | 6.6e4 | -11.56 | 0.69 | 2.10 | -1.81 | 8.5e6 | 143 | 0.077 | 0.00 |
| 1.0e9 | 59.4 | 0.014 | 7.8e8 | 1.9e7 | 1.6e6 | -14.95 | 0.76 | 2.46 | -0.68 | 2.2e8 | 126 | 0.071 | 0.00 |
| 5.0e10 | 37.9 | 0.037 | 3.4e10 | 1.0e9 | 1.2e8 | -19.38 | 0.86 | 3.16 | -0.01 | 1.6e10 | 108 | 0.062 | 0.00 |
| 1.0e12 | 32.6 | 0.068 | 5.8e11 | 1.9e10 | 2.8e9 | -22.82 | 0.92 | 3.44 | +0.30 | 4.2e11 | 92 | 0.053 | 0.00 |
| <i>Standard Model</i> | | | | | | | | | | | | | |
| 1.0e6 | 73.3 | 0.006 | 8.7e5 | 5.5e3 | 9.0e2 | -7.01 | 0.68 | 2.07 | -2.45 | 1.3e5 | 188 | 0.079 | 0.00 |
| 5.0e7 | 89.9 | 0.007 | 4.2e7 | 4.9e5 | 6.6e4 | -11.56 | 0.69 | 2.10 | -1.81 | 8.5e6 | 143 | 0.077 | 0.00 |
| 1.0e9 | 59.4 | 0.014 | 7.8e8 | 1.9e7 | 1.6e6 | -14.95 | 0.76 | 2.46 | -0.68 | 2.2e8 | 126 | 0.071 | 0.00 |
| 5.0e10 | 37.9 | 0.037 | 2.8e10 | 7.8e8 | 8.0e7 | -19.38 | 0.86 | 3.16 | -0.01 | 2.2e10 | 109 | 0.051 | 0.27 |
| 1.0e12 | 32.6 | 0.068 | 4.5e11 | 1.6e10 | 1.8e9 | -22.82 | 0.92 | 3.44 | +0.30 | 5.5e11 | 93 | 0.041 | 0.24 |

^a Template Models: *Minimal* models suppress all post- t_{GW} SNe Ia-driven winds; *maximal* models eject all returning gas in said phase to the ICM; *standard* models include low mass systems which follow the maximal scenario, and high mass systems which only drive winds for $\sim 0.2 \rightarrow 0.5$ Gyrs subsequent to t_{GW} . Nucleosynthetic yield sources are Woosley & Weaver (1995) for high mass stars, Renzini & Voli (1981) for single low and intermediate mass stars, and Thielemann, Nomoto & Hashimoto (1993) for binary star supernovae Type Ia. Luminosities and colours derived from Worthey’s (1994) isochrones. Supernovae remnant thermal energy follows model B’₃ of Gibson (1994b), which is derived from Cioffi, McKee & Bertschinger (1988) and Larson (1974). A single power law initial mass function, by mass, of slope $x = 0.95$, and lower and upper mass limits of $0.2 M_{\odot}$ and $65.0 M_{\odot}$, respectively, was used. ν is the astration parameter for the star formation rate in equation (1). the galactic wind time t_{GW} is in units of Gyrs. A binary parameter $A = 0.03$ was adopted. Initial dark-to-luminous mass and radial extents of 10 were chosen. γ is the initial mass fraction ejected in the form of gas, and f_{gas} is the gaseous-to-luminous mass fraction at $t_{\text{G}} = 12$ Gyr.

Table 2. $10^{12} M_{\odot}$ Model – IMF Comparison^a

| x | ν | A | t_{GW} | m_{g}^{ej} | $m_{\text{Fe}}^{\text{ej}}$ | $[\text{O}/\text{Fe}]^{\text{ej}}$ | γ | $[\text{Mg}/\text{Fe}]_*$ | M_V | V-K | $[< Z >]_V$ |
|------|-------|-------|-----------------|----------------------------|-----------------------------|------------------------------------|----------|---------------------------|--------|------|-------------|
| 0.95 | 32.6 | 0.030 | 0.068 | 2.6e11 | 9.5e8 | +0.33 | 0.024 | +0.34 | -22.82 | 3.44 | +0.30 |
| 1.35 | 32.6 | 0.045 | 0.081 | 1.2e11 | 2.7e8 | +0.26 | 0.011 | +0.22 | -23.33 | 3.01 | +0.00 |
| 1.35 | 2.9 | 0.045 | 1.450 | 7.0e10 | 5.3e8 | +0.00 | 0.006 | +0.02 | -23.32 | 3.41 | +0.30 |

^a A comparison of the predicted ejecta composition for two different IMF slopes for an initial gas mass of $10^{12} M_{\odot}$. The $x = 0.95$ entry is identical to the template model of Table 1. A Salpeter (1955) $x = 1.35$ slope is shown for comparison – one with the identical ν as the template, one with ν set to recover the colours and metallicities shown in Figures 1 and 2. Resultant present-day SNe Ia rates are 0.11 SNU. See text and Table 1 caption for model details.

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Fig. 1.— Observed metallicity-luminosity relation for dwarf (open circles: Smith (1985)) and “normal” (open squares: Sil’chenko 1994 – filled circles: Terlevich et al. 1981) ellipticals. The $[\text{Mg}/\text{Fe}] = +0.25$, Mg_2 -Z calibration of Barbuy (1994) has been adopted for the normal/giant ellipticals. The solid curve represents our adopted template of models from Section 2.2. $H_0 = 85 \text{ km/s/Mpc}$ is assumed.

Fig. 2.— V-K colour-luminosity relation for Virgo (open circles) and Coma (filled circles) cluster ellipticals and lenticulars (Bower et al. (1992)). A Virgo distance modulus of $(V - M_V)_\circ = 31.54$ is assumed, and a shift of $\Delta(V - M_V)_\circ = 3.58$ has been applied to the Coma sample. $H_0 = 85 \text{ km/s/Mpc}$ is assumed. Data for local dwarfs has been taken from Thuan (1985). The solid curve represents our adopted template of models from Section 2.2.

Fig. 3.— Shaded region shows the observed correlation between the non-spiral-originating V-band cluster luminosity, and the observed ICM iron mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.

Fig. 4.— Shaded region shows the observed correlation between the non-spiral-originating V-band cluster luminosity, and the observed gas mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.

Fig. 5.— Shaded region shows the observed correlation between the non-spiral-originating

V-band cluster luminosity, and the observed iron mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.

Fig. 6.— Shaded region shows the observed correlation between the non-spiral-originating V-band cluster luminosity, and the observed gas mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.

Fig. 7.— Shaded region shows the observed correlation between the non-spiral-originating V-band cluster luminosity, and the observed iron mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.

Fig. 8.— Shaded region shows the observed correlation between the non-spiral-originating V-band cluster luminosity, and the observed gas mass, after Arnaud (1994). Solid curve is the single luminosity function model of slope $\alpha = -1.45$. Dotted lines are the components of the two component luminosity function model – the lower curve is the low luminosity dwarf spheroidal component with $\alpha = -1.90$. The middle one is the normal giant spheroidal population with $\alpha = -1.45$. The heavy dotted curve is their sum.













