THE CONTRIBUTION OF POPULATION III TO THE ENRICHMENT AND PREHEATING OF THE INTRACLUSTER MEDIUM

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ABSTRACT

Intracluster medium (ICM) abundances are higher than expected assuming enrichment by supernovae with progenitors belonging to the simple stellar population (SSP) observed in cluster galaxies if stars formed with a standard initial mass function (IMF). Moreover, new results on ICM oxygen abundances imply that nucleosynthesis occurred with nonstandard yields. The hypothesis that hypernovae in general, and hypernovae associated with Population III (Pop III) stars in particular, may significantly contribute to ICM enrichment is presented and evaluated. The observed abundance anomalies can be explained by a hypernova-producing subpopulation of the SSP, but only if the subpopulation accounts for half of all supernova explosions and if Type Ia supernova rates are very low. Also, the implied energy release may be excessive. However, an independent Pop III contribution—in the form of metal-free, very massive stars that evolve into hypernovae—can also account for all of the observed abundances while avoiding these drawbacks and accommodating a normal IMF in subsequent stellar generations. The required number of Pop III stars provides sufficient energy injection (at high redshift) to explain the ICM “entropy floor.” Pop III hypernovae preenrich the intergalactic medium and can produce a significant fraction of the metals observed in the Ly forest. Several testable predictions for ICM and intergalactic medium observations are made.

Subject headings: galaxies: clusters: general — galaxies: formation — intergalactic medium — stars: abundances

1. INTRODUCTION

Because rich clusters of galaxies are the largest virialized structures in the universe, their demographics are useful discriminants of fundamental cosmological parameters and theories of large-scale structure formation. They also comprise an astrophysical laboratory for studying physical processes involved in galaxy formation and evolution: the depths of their dark matter potential wells imply that, unlike individual galaxies and perhaps even groups and poor clusters, they are good approximations to “closed boxes” and thus ideal sites for investigating the star formation history and chemical evolution imprinted in the properties of the accumulated baryonic matter component. The hot intracluster medium (ICM) is particularly suitable for such investigations because of the relatively straightforward measurement of its thermal and chemical properties via X-ray imaging spectroscopy. This is especially true now, following the launch of the new generation of X-ray observatories that includes Chandra and XMM-Newton.

The ICM constitutes a vast reservoir of mass ($\sim 10^{14} M_\odot$) and thermal energy ($\sim 3 \times 10^{63}$ ergs). Yet even though stars constitute only about a tenth of the baryonic mass, signatures of the influence of star formation on the ICM are apparent. First, the ICM is enriched to a significant fraction of solar metallicity (e.g., White 2000). The measured amount of metals cannot be explained as originating in a simple (coeval, homogeneous) stellar population (SSP) that includes the stars observed today if the stellar initial mass function (IMF) was similar to that in the solar neighborhood and if standard nucleosynthetic yields are assumed (Loewenstein & Mushotzky 1996, § 2). Second, significant heating of the ICM is evident in departures in the (X-ray) luminosity-temperature, (total) mass-temperature, and (central ICM) entropy-temperature relations from predictions of self-similar (no heating) scaling (e.g., Loewenstein 2000). Moreover, by some accounts, the required heating ($>1$ keV particle$^{-1}$; Wu, Fabian, & Nulsen 2000) exceeds even that associated with the number of supernovae needed to enrich the ICM to its observed metal abundance, assuming a reasonable energy conversion efficiency. Metallicities and line widths of Ly clouds demonstrate that the entire intergalactic medium (IGM) has been profoundly affected by physical processes associated with star formation (Cen & Ostriker 1999; Ellison et al. 2000; Aguirre et al. 2001; Cen & Bryan 2001).

Several seemingly unrelated recent astrophysical developments may shed some light on these puzzles, and they motivate the present work: (1) Spectral analysis of XMM-Newton data reveals relative O abundances well below predictions of standard enrichment theory (Tamura et al. 2001; Kaastra et al. 2001; Peterson et al. 2001; Böhringer et al. 2001). (2) Interestingly, calculations of nucleosynthesis in hypernovae, where explosion energies are $10^{50}$ times greater than in standard supernovae, yield more extensive oxygen-burning zones and hence depleted O abundances (Nakamura et al. 2001). (3) Furthermore, theoretical arguments now suggest that (a) the first metal-free generation of stars, Population III (Pop III), may be predominantly supermassive (Bromm, Coppi, & Larson 1999, 2001; Abel, Bryan, & Norman 2000; Larson 2001); (b) such stars may be structurally stable over some mass range (Baraffe, Heger, & Woosley 2001); and (c) these stars may end up exploding as hypernovae with prodigious production of metals in substantially different relative proportions than in supernovae with Population I or II progenitors (Heger et al. 2001). In the following sections, I evaluate the feasibility and implications of a substantial contribution to the enrichment and

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heating of the ICM by hypernovae in general and Pop III hypernovae in particular. I adopt the following cosmological parameters: $\Omega_{\text{matter}} = 0.3$, $\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. THE ENRICHMENT PARADOX

The baryon fraction in a rich cluster of galaxies is $f_{\text{baryon}} = 0.155(1 + \mu)$, where 0.155 is the measured gas fraction (Loewenstein 2000) and $\mu$ the mass ratio of stars (including remnants of evolved stars) to gas. Values of $f_{\text{baryon}} = 0.16$–0.20 for $\mu$ ≤ 0.3 can be compared to 0.12–0.15 obtained using $\Omega_{\text{baryon}}$ inferred from fitting big bang nucleosynthesis (BBN) models to measured high-redshift Ly-absorber deuterium abundances (Burles, Nollett, & Turner 2001). Consider chemical enrichment by an SSP, as is appropriate if dominated by early-type galaxies or their progenitors: most of the stellar mass in rich clusters resides in elliptical galaxies (Arnaud et al. 1992). For the broken power-law stellar IMF that characterizes a consensus of local IMF (LIMF) estimates (Kroupa 2001), the number of Type II supernova (SN II) explosions per mass of stars formed is $\approx 0.011 M_\odot^{-1}$, assuming all stars more massive than $8 M_\odot$ result in SNe II. However, for a coeval stellar population of age comparable to that of the universe, $\approx 40\%$ of the original mass will have been shed by stars more massive than the main-sequence turnoff during the course of their evolution (adopting remnant masses from Ferreras & Silk 2000). Thus, the number of SN II explosions per solar mass of present-day main-sequence stars plus remnants, the specific SN II rate $\eta_{\text{II}} \approx 0.019 M_\odot^{-1}$, a value insensitive to assumptions about the exact turnoff mass (0.87 $M_\odot$) or upper (100 $M_\odot$) and lower (0.1 $M_\odot$) IMF cutoff masses. For IMF's with single slopes of 1.3, 2.0, and 0.7, $\eta_{\text{II}} = 0.013, 0.0084,$ and $0.067 M_\odot^{-1}$, respectively.

To illuminate the enrichment paradox, it is sufficient to consider the elements O, Si, and Fe. Adopted solar mass fractions $f_{\text{O}}$ (Anders & Grevesse 1989) and yields for Type II and Type Ia (SN Ia) supernovae ($\langle \gamma_{\text{H}} \rangle$ and $\gamma_{\text{H}}$, respectively; see Gibson, Loewenstein, & Mushotzky 1997) are displayed in Table 1. I parameterize the contribution of SN Ia explosions by the fraction of cluster baryonic (ICM plus stellar) Fe originating in SNe Ia, $f_{\text{Fe}}$(Fe), which is estimated to be $\approx 0.5$ in the Galaxy (Timmes, Woosley, & Weaver 1996). The SN Ia/SN II ratio, $0.135 f_{\text{Fe}}$(Fe)/$[1 - f_{\text{Fe}}$(Fe)], and O/Fe and Si/Fe abundance ratios as functions of $f_{\text{Fe}}$(Fe) are displayed in Table 2 (see also Fig. 1). Also shown are the values of $\eta_{\text{II}}$ needed to reproduce a typical rich cluster ICM Fe abundance of 0.4 solar, the Fe abundance corresponding

| Element | $f_{\text{O}}$ | $\gamma_{\text{H}}$ (M$_\odot$) | $\epsilon_{\text{HN}}$ | $\epsilon_{\text{HN},(100)}$ | $\epsilon_{\text{HN},(120)}$ |
|---------|----------------|-------------------------------|---------------------|------------------------|-------------------------|
| O ...... | 9.6 $\times$ 10$^{-3}$ | 0.15 | 1.7 | 0.68 | 25 | 20 |
| Si ...... | 7.1 $\times$ 10$^{-4}$ | 0.16 | 0.14 | 1.9 | 160 | 180 |
| Fe ...... | 1.3 $\times$ 10$^{-3}$ | 0.74 | 0.10 | 3.5 | 50 | 270 |

| TABLE 1
SN YIELDS AND HN ENHANCEMENT FACTORS |

| Table 2
RESULTS FOR VARIOUS SUPERNOVA COMBINATIONS |

| $f_{\text{O}}$(Fe) | $f_{\text{HN}}$ | Ia/II | O/Fe | Si/Fe | $\eta_{\text{II}}$ (M$_\odot^{-1}$) | $kT_{\text{SN}}$ (keV) | Fe | $kT_{\text{SN}}$ (keV) |
|-------------------|----------------|-------|------|-------|------------------------|--------------------|-----|---------------------|
| 0.20 $\ldots$ | 0.5 $^*$ | 0 | 0.83 | 1.6 | 0.025 | 26 | 0.31 | 20 |
| 0.20 $\ldots$ | 0.5 $^*$ | 0.92 | 0.65 | 1.3 | 0.019 | 20 | 0.4 | 20 |
| 0.59 $\ldots$ | 0.005$^*$ | 0.24 | 0.84 | 1.7 | 0.018 | 0.56 | 0.41 | 0.58 |
| 0.20 $\ldots$ | 0.005$^*$ | 0.079 | 0.84 | 1.7 | 0.019 | 0.58 | 0.4 | 0.57 |

Note.—Fe abundances and abundance ratios are relative to solar.

$^*$ Values corresponding to 0.4 solar Fe abundance.

$^*$ Values corresponding to LIMF value of $\eta_{\text{II}}$.

$^*$ HNe as in Nakamura et al. 2001.

$^*$ HNe as in Heger et al. 2001, $M_{\text{core}} = 100$.

$^*$ HNe as in Heger et al. 2001, $M_{\text{core}} = 120$. 

- The cluster data marginally favors higher values of $\Omega_{\text{matter}}$ or higher $\Omega_{\text{baryon}}$, as inferred from recent cosmic microwave background anisotropy measurements (Hu et al. 2001). Lower values of $\Omega_{\text{baryon}}$, consistent with the higher deuterium abundance of one low-redshift Ly absorber and milder lithium depletion, requires $\Omega_{\text{matter}} \lesssim 0.13$ (Olive, Steigman, & Walker 2000) for consistency with the cluster data, assuming the latter is "representative." 

- SN II yields are averaged over the IMF assuming a slope of $\approx 1.3$ for massive stars; their variation with IMF slope is a second-order effect when compared to differences in $\eta_{\text{II}}$. 

TABLE 2
RESULTS FOR VARIOUS SUPERNOVA COMBINATIONS 

| $f_{\text{O}}$(Fe) | $f_{\text{HN}}$ | Ia/II | O/Fe | Si/Fe | $\eta_{\text{II}}$ (M$_\odot^{-1}$) | $kT_{\text{SN}}$ (keV) | Fe | $kT_{\text{SN}}$ (keV) |
|-------------------|----------------|-------|------|-------|------------------------|--------------------|-----|---------------------|
| 0.20 $\ldots$ | 0.5 $^*$ | 0 | 0.83 | 1.6 | 0.025 | 26 | 0.31 | 20 |
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| 0.59 $\ldots$ | 0.005$^*$ | 0.24 | 0.84 | 1.7 | 0.018 | 0.56 | 0.41 | 0.58 |
| 0.20 $\ldots$ | 0.005$^*$ | 0.079 | 0.84 | 1.7 | 0.019 | 0.58 | 0.4 | 0.57 |
to the canonical \( \eta_H = 0.019 \, M_\odot^{-1} \), and the total supernova energy per unit gas mass, \( kT_{SN} \), for both these cases. Equal mass-averaged stellar and ICM abundances, \( 10^{51} \) ergs per (Type II or Ia) supernova, and an ICM-to-stars mass ratio of 10 (\( \mu = 0.1 \)) are assumed.

It is clear that one cannot simultaneously reproduce the observed 0.4 solar Fe abundance and Si/Fe ratio of \( \sim 1.7 \) (Fukazawa et al. 1999) if the ICM-enriching SNe II and current stellar population derive from a single star formation epoch with the LIMF (see also Loewenstein & Mushotzky 1996). Given the observed Fe abundance, the Si abundance falls short by \( \sim 50\% \) [see the \( f_{SN}(Fe) = 0.66 \) Table 2 entry and Fig. 1] unless the number of SNe II is increased by a factor \( \approx 1.8 \) [\( f_{SN}(Fe) = 0.38 \) entry], which also increases the supernova heating by \( \sim 60\% \). An increase in the average SN II Si yield from 0.14 to 0.24 \( M_\odot \) is required to reconcile the observed abundances with the LIMF, an increase not supported by any published SN II nucleosynthesis calculations.

Current understanding of star formation is sufficiently incomplete that the top-heavy or bimodal IMF inferred for the earliest generations of stars in cluster galaxies (or protogalaxies) by the ICM observations (see also Elbaz, Arnaud, \& Vangioni-Flam 1995; Matteucci \& Gibson 1995) cannot be ruled out a priori and may even be supported by other lines of evidence (e.g., Mathews 1989). However, these scenarios are in conflict with the first precise X-ray measurements of O abundances by the detectors on the XMM-Newton observatory (Tamura et al. 2001; Kaastra et al. 2001; Peterson et al. 2001; Böhringer et al. 2001). The O/Fe ratio in the best-fit spectral models for the galaxy clusters Abell 1795, Abell 1835, Sérsic 159-03, and Virgo ranges from \( \sim 0.3 \) to 1.0 solar, with the lowest values found in the cores of the latter two systems. If the ICM in these systems—all of which are cooling flow clusters—is intrinsically chemically inhomogeneous, both elemental abundance and abundance ratio estimates based on relatively simple models may not accurately reflect the true level and pattern of enrichment (Fabian et al. 2001).

However, for the purposes of this paper, I provisionally adopt these values. Combined with ASCA measurements of supersolar Si/Fe ratios (Fukazawa et al. 1999), confirmed with XMM-Newton for Virgo (Böhringer et al. 2001), these indicate a relative underabundance of O compared to Fe and Si. The predicted O/Fe ratio is minimized for high values of \( f_{SN}(Fe) \); however, these produce unacceptably low Si/Fe ratios (Table 2). For example, \( f_{SN}(Fe) = 0.85 \) implies O/Fe \( \sim 0.5 \) but Si/Fe \( \sim 0.7 \) (and also an \( \eta_H \) less than half the LIMF value). Subsolar values of O/Fe imply Si/Fe \( < 1.3 \) solar.

It is possible that “standard” SN II O yields (Table 1) may be overestimated owing to inaccurate reaction rates, an incorrect treatment of convection, and/or preexplosion mass loss (Gibson et al. 1997). The O/Fe abundance ratio can be lowered to \( \sim 0.5 \) by reducing the assumed IMF-averaged O yield by \( \sim 40\% \); although the observed Si/Fe ratio still requires an \( \sim 80\% \) enhancement in the SN II rate per stellar mass. Here I consider a more radical alternative: significant enrichment by hypernovae. My aim is to determine whether the addition of a hypernova contribution might account for these preliminary indications of O/Fe \( \sim 0.5 \) while maintaining consistency with the observed Si/Fe ratio [for some value of \( f_{HN}(Fe) \)] and, if so, to explore the resulting implications.

3. HYPERNOVAE, POPULATION III, AND THE ICM

3.1. A Hypernova-Progenitor Subpopulation

I initially investigate the case of a unimodal IMF, where a fraction \( f_{HN} \) of the early-phase massive stellar population, perhaps corresponding to the most metal-poor supernova progenitors, results in hypernova explosions rather than conventional SNe II. The closed box approximation is used: all nucleosynthetic products from both SNe II and hypernovae are assumed to be retained in the deep cluster potential well. Nucleosynthetic yields corresponding to the most extreme explosion kinetic energy studied by Nakamura et al. (2001), \( 10^{53} \) ergs, are considered. Extended burning out to lower density regions results in relative depletion of O but enhancement of Si and Fe. For the most massive He core model they consider, the ratios of yields in the \( 10^{53} \) erg model compared to those for \( 10^{51} \) ergs are displayed in Table 1 (\( \epsilon_{HN} \)). I adopt these as scaling factors in estimating the possible contribution of such hypernovae to ICM metal enrichment.

Table 2 includes two entries for \( f_{HN} = 0.5 \) that are required to produce O/Fe \( \sim 0.5 \). The second, with \( f_{HN}(Fe) = 0.23 \), is tuned to produce a 0.4 solar Fe abundance assuming the canonical \( \eta_H = 0.019 \, M_\odot^{-1} \) and yields an Si/Fe ratio about 30% lower than typically observed in rich clusters (Fig. 1). The first, with \( f_{HN}(Fe) = 0 \), simultaneously produces the correct O, Si, and Fe abundances with a modest increase of \( \eta_H \) to 0.025 \( M_\odot^{-1} \). The resulting heating is prodigious: \( \sim 25 \) keV particle \( ^{-1} \), equivalent to \( \sim 3 \times 10^{44} \, \text{ergs} \, \text{s}^{-1} \) per \( L_* \) galaxy, compared to \( \sim 10^{44} \, \text{ergs} \, \text{s}^{-1} \) per \( L_* \) galaxy for \( f_{HN} = 0 \), where the energy is released over an interval of \( 10^9 \, \text{yr} \). The hypernovae may have more modest energies of \( \sim 10^{52} \) ergs; but in that case the yield scaling factors will be closer to unity and the required value of \( f_{HN} \) correspondingly higher.

![Fig. 1.](image-url) O/Si (lower curves) and Si/Fe (upper curves) abundance ratios as a function of Fe abundance for the LIMF specific SN II rate. Solid curves, the case of no HNe; dotted curves, HeNe as in Nakamura et al. (2001); dashed curves, HNe as in Heger et al. (2001).
3.2. Hypernovae Associated with Population III

In addition to a parallel subpopulation, I consider a distinct star formation mode consisting of very massive (> 100 \( M_\odot \)) metal-free Pop III stars that ultimately produce ICM-enriching hypernovae. I do not address in detail the issue of when and how completely the products of the two star formation modes are ejected from protogalaxies; the dispersal of hypernova products may very well take place in pregalactic fragments and the SN II products via subsequent galactic winds. I also characterize these hypernovae with \( f_{HN} \), the fraction of all SN II or hypernova progenitors that result in hypernovae. The absence of metals assures structural stability up until the onset of a pair-creation instability that proceeds the hypernova explosion (Baraffe et al. 2001). He core masses \( M_{\text{core}} = 100 \) and 120 \( M_\odot \) (from progenitors of mass \( \sim 200-250 \ M_\odot \)), with corresponding explosion energies of \( 4 \times 10^{52} \) and \( 7 \times 10^{52} \) ergs and yield-enhancement factors displayed in Table 1 [as \( \epsilon_{\text{HN}}(100) \) and \( \epsilon_{\text{HN}}(120) \), respectively], are utilized (adopted from Heger et al. 2000). The resulting enrichment and preheating are shown on the final two lines of Table 2, the former illustrated in Figure 1.

Intriguingly, unlike all other scenarios described above, the observed Fe, Si, and O abundances are simultaneously reproduced for an SN II per stellar mass ratio consistent with the LIMF (Fig. 1) if \( f_{HN} = 0.005 \) and \( f_{\text{SN}}(\text{Fe}) = 0.59 \) (\( M_{\text{core}} = 100 \ M_\odot \)) or 0.20 (\( M_{\text{core}} = 120 \ M_\odot \)). Of the 0.56 \( (0.58) \) keV per ICM particle produced by SN II plus hypernovae for \( M_{\text{core}} = 100 \) (120), 0.08 (0.14) keV per particle originates in the hypernova component. This relatively modest energy, however, is released at very high redshift \( z \gtrsim 10 \), where it has maximal effect on the entropy—and hence subsequent evolution and final state—of the proto-ICM (Tozzi & Norman 2001).

The fraction of the total cluster baryonic mass originating as Pop III hypernova progenitors is

\[
\frac{M_{\text{HN}}}{M_{\text{ICM}} + M_{\text{stars}}} = 0.019 \left( \frac{f_{\text{HN}}}{0.005} \right) \left( \frac{\eta_\text{II}}{0.019 \ M_\odot^{-1}} \right) \\
\times \left( \frac{M_{\text{prog}}}{200 \ M_\odot} \right) \frac{\mu}{1 + \mu},
\]

(1)

where \( M_{\text{prog}} \) is the mean hypernova progenitor mass and \( \mu \) is the cluster ratio of stars to gas as previously defined. That is, the mass density of Pop III stars in units of the critical density,

\[
\Omega_{\text{III}} = 7.1 \times 10^{-5} \left( \Omega_{\text{baryon}} \right) c^{-1} b_1^{-1} b_2^{-1},
\]

(2)

for \( f_{\text{HN}} = 0.005 \), \( \eta_\text{II} = 0.019 \ M_\odot^{-1} \), \( M_{\text{prog}} = 200 \ M_\odot \), and \( \mu = 0.1 \). The term \( \Omega_{\text{baryon}} \) is normalized to the BBN value, \( c \) (\(< 1\)) is the fraction of Pop III stars that produce hypernovae, and \( b_1 \) and \( b_2 \) are cluster “bias” factors encompassing any over- or underconcentration of baryons and any relative Pop III stellar formation probability enhancement in clusters relative to the universal average, respectively. Ostriker & Gnedin (1996) estimated \( \Omega_{\text{III}} \) from self-consistent semianalytic modeling of the evolution of the Jeans mass through the epoch of IGM reheating. Their results imply \( b_2 \approx 17 \) (for \( c \sim 1 \), \( b_1 \sim 1 \)). A value \( b_2 \gg 1 \) is not unexpected: Pop III stars are unlikely to have formed as readily (or perhaps early or with the same IMF) outside of these regions of highest primordial overdensity. A low value of \( \Omega_{\text{baryon}} \) (as, e.g., implied by a high primordial deuterium abundance) would indicate \( b_1 > 1 \) and a correspondingly lower value of \( b_2 \).

4. DISCUSSION AND PREDICTIONS

4.1. Summary of Hypernovae ICM Enrichment

If the stars responsible for enriching the ICM and the stars observed today in cluster early-type galaxies originate in the same early star formation epoch, then the amount of Si observed in clusters cannot be explained with standard SN II yields and the solar neighborhood IMF: the number of SNe II per stellar mass must be increased by a factor of nearly 2 through invocation of a flat or bimodal IMF. However, recent observations of IC ratios of O/Si that are well below solar cast doubt on this explanation. For reasonable SN Ia/SN II ratios, Si and O are predominantly synthesized in SNe II that produce a roughly solar O/Si ratio.

Although hypernova nucleosynthesis calculations are at an early stage, depleted O abundances caused by more extensive oxygen burning are likely to persist. Thus it is worth studying their possible role in ICM enrichment, particularly in light of their potential to preheat the ICM and their possible connection to the elusive Pop III stars. I investigate two classes of hypernova contributions. First, I consider the case in which some fraction (perhaps the most metal poor) of SN II progenitors from a unimodal IMF give rise to hypernovae with increased explosion energy and nonstandard yields, as in the calculations of Nakamura et al. (2001). Their contribution can indeed lower the O/Si ratio to the observed level, but only if there are approximately equal numbers of hypernovae and conventional SNe II. Moreover, this implies an energy production of more than 20 keV per ICM particle, a sufficient energy to unbind the ICM of even the most massive clusters unless most of the \( \sim 10^{64} \) ergs of energy is radiated, as well as negligible enrichment by SN Ia.

ICM abundances are more naturally explained with a substantial contribution from Pop III hypernovae originating in an earlier, independent star formation mode. An absence of metals reduces cooling and leads to a very large Jeans mass: Pop III stars are likely to form with an extremely top-heavy IMF (Larson 2001). A hybrid scenario is also possible if the Pop III IMF is itself bimodal; Nakamura & Umemura (2001.) Very massive metal-free stars naturally give rise to hypernovae with enhanced yields and skewed abundance ratios compared to ordinary SNe II. Utilizing a pair of representative cases from Heger et al. (2001), I find that if one such hypernova contributes to ICM enrichment for every 200 SNe II, the observed proportions of Fe, Si, and O are simultaneously explained. Also, the additional contribution from ordinary SNe II required to explain the amount of these elements is consistent with the LIMF, in keeping with evidence for a universal IMF (Wyse 1997); this is not true of an alternative scenario for simultaneously explaining the relative amounts of O, Si, and Fe by reducing SN II O yields. Finally, the associated preheating of \( \sim 0.1 \) keV per particle is sufficient to account for the observed cluster “entropy floor” (e.g., Lloyd-Davies, Ponman, & Cannon 2000) since it is deposited at \( z \gtrsim 10 \) when the more diffuse ICM was especially susceptible to a shift to a high adiabat (Tozzi & Norman 2001).
In this scenario, cluster O primarily (90%) originates from SNe II, while comparable contributions from SNe II and hypernovae account for Si. About one-third of the ICM Fe originates from SNe II, with hypernovae contributing some amount less than one-half (this is uncertain because of the steep dependence of hypernova Fe yields on progenitor core mass) and SNe Ia contributing the rest. The partial decoupling of the origins of these elements has implications for expectations of future accurate X-ray measurements of ICM abundances in addition to the prediction that subsolar O/Si ratios will be confirmed and found to be common. Correlations of the mass in each of these metals versus optical light may have offset zero points relative to the case where all metals share a monolithic origin. Cluster-to-cluster variations in metal mass/optical light ratio may display an elemental dependence with, e.g., $M_{O}/L$ displaying a greater scatter than $M_{Si}/L$. Si abundances are predicted to be substantial even at very high redshift and evolve more slowly than O abundances.

4.2. Implications for the Enrichment of the IGM

In current models for the chemical evolution of the IGM, the enrichment is dominated by SNe associated with early-epoch Pop II star formation. Yields of $\sim 2-5$ times the solar mass fraction of metals for each solar mass of star formation are typically required to match the C abundances measured in Ly$\alpha$ forest clouds (Gnedin 1998; Cen & Ostriker 1999; Aguirre et al. 2001; Cen & Bryan 2001). Pop III stars have been proposed as providing the radiation that reionizes the universe (Ostriker & Gnedin 1996; Tumlinson & Shull 2000) while simultaneously preenriching the IGM to modest levels lower than $10^{-3}$ solar (Ostriker & Gnedin 1996; Wasserburg & Qian 2000). However, if hypernovae are produced by Pop III, as suggested here in order to explain ICM abundances, the implied preenrichment may be significantly enhanced. For the value of $Q_{OIII}$ calculated by Ostriker & Gnedin (1996) (corresponding to a Pop III stellar mass per baryon ratio 17 times less than proposed here for the ICM), the Heger et al. (2001) hypernova yields imply IGM preenrichment to as much as $2.5 \times 10^{-3}$ solar metallicity with very nonsolar abundance ratios. While O (and elements of lesser atomic weight) are synthesized in amounts small compared to those observed in Ly$\alpha$ forest clouds, Si attains greater than $10^{-2}$ solar abundance at $z \sim 10$. Since subsequent Pop II enrichment must then be invoked to produce $10^{-2}$ solar C abundances, an Si/C ratio about two times solar is expected. This is consistent with measured UV line ratios (Giroux & Shull 1997; Songaila 1998) in the clouds. Thus a contribution to IGM enrichment from Pop III hypernovae can alleviate the requirement of excessive Pop II yields while explaining a likely observed overabundance of Si. Similar overabundances of, e.g., S and Ca—but not N or O—relative to C are predicted, the former being produced in roughly equal amounts by Populations II and III, the latter primarily by Pop II.

5. CONCLUDING REMARKS

Signatures of hypernova explosions of very massive Population III stars are found in the number and abundance pattern of low-metallicity Milky Way stars (Hernandez & Ferrara 2001; Umeda & Nomoto 2001) and in the population of black holes more massive than 100 $M_{O}$ (Madau & Rees 2001). I have demonstrated that these extreme primordial events also leave a thermal and chemical imprint on the IGM and ICM. Direct observation of hypernova explosions and/or their progenitors with the Next Generation Space Telescope, in concert with advances in calculations of hypernova yields, could provide direct confirmation of the important role of Pop III in enriching both the IGM and ICM. Population III hypernovae may constitute an important feedback mechanism during the earliest galaxy formation era and ought to be considered in semianalytic galaxy formation calculations.

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