The Chemical Evolution of Helium in Globular Clusters: Implications for the Self-Pollution Scenario

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ABSTRACT

We investigate the suggestion that there are stellar populations in some globular clusters with enhanced helium (\(Y \sim 0.28\) to 0.40) compared to the primordial value. We assume that a previous generation of massive Asymptotic Giant Branch (AGB) stars have polluted the cluster. Two independent sets of AGB yields are used to follow the evolution of helium and CNO using a Salpeter initial mass function (IMF) and two top-heavy IMFs. In no case are we able to produce the postulated large \(Y \sim 0.35\) without violating the observational constraint that the CNO content is nearly constant.

Subject headings: stars: AGB and post-AGB stars: chemically peculiar stars: abundances Galaxy: globular clusters: general

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1H. G. Thode Fellow at the Origins Institute
1. Introduction

Star-to-star abundance variations of the light elements C, N, O, Na, Mg and Al have been observed in every well studied globular cluster (GC) to date (Kraft 1994; Gratton et al. 2004, and references therein) but are not found in field stars of the same metallicity (Gratton et al. 2000). Hence these abundance anomalies are somehow the result of the cluster environment. The variations of the elements follow a common pattern: C-N, O-Na and Mg-Al are all anti-correlated (Shetrone 1996; Kraft et al. 1997; Cannon et al. 1998; Gratton et al. 2001; Cohen & Meléndez 2005; Cohen et al. 2005). The abundances of iron-peak, s and r-process elements do not show the same star-to-star scatter nor do they vary with the light elements (Gratton et al. 2004; James et al. 2004; Yong et al. 2006), although new observations by Wylie et al. (2006) suggest that there is real star-to-star scatter amongst heavy element abundances in stars in the metal-rich cluster 47 Tucanae. The other important exception is the massive cluster ω Centauri, whose age and metallicity spread, along with a rise in s-element abundance with increasing [Fe/H], suggests that it evolved very differently from other GCs and may even have an extragalactic origin (Smith et al. 2000). The key points are that O has been destroyed in some stars by up to one dex, the C+N+O abundances remain almost constant and there is no evidence for large-scale variation of the neutron-capture elements.

Two hypotheses had been proposed to explain these observed abundances. The first was deep mixing, where the abundance anomalies are produced by internal mixing during the ascent of the giant branch, after the first dredge-up (Sweigart & Mengel 1979; Pinsonneault 1997; Charbonnel 1994). However, star-to-star abundance variations in C, N, O and Na were subsequently observed in stars at or near the main-sequence turn-off (Gratton et al. 2001; Ramírez & Cohen 2003; James et al. 2004; Cohen & Meléndez 2005; Cohen et al. 2005). These observations support the self-pollution scenario, first proposed by Cottrell & Da Costa (1981). Here a previous generation of stars polluted the atmospheres of stars we observe today or provided part of the material from which those stars formed. Because [Fe/H] is roughly constant in stars in a given GC it has been assumed that polluters were intermediate-mass AGB stars with initial masses between ∼3 to 8M⊙ rather than supernovae, which produce Fe. The hot bottom burning experienced by these stars provides the hydrogen burning environment (at least qualitatively) that can alter the abundances of the light elements. One consequence is the production of a significant quantity of helium (Y, 4He; Lattanzio et al. 2004). The mass lost via the slow winds of AGB stars could, in principle, have been retained by the cluster from which new stars may have been born (Thoul et al. 2002). Detailed AGB models have so far mostly failed to match the observed abundance trends (Denissenkov & Herwig 2003; Fenner et al. 2004; Campbell et al. 2004; Cohen et al. 2005), but major uncertainties that affect the models undermine the reliability of the predictions.
and leave room for an AGB solution (Ventura & D’Antona 2005a,b).

Horizontal branch (HB) and main-sequence color-magnitude diagrams (CMD) (Norris 2004; D’Antona & Caloi 2004; Lee et al. 2005; Piotto et al. 2005) provide increasing evidence for helium enrichment in some GC stars. The unusual HB morphology of NGC 2808, which exhibits an extended blue tail and a gap separating the red and blue clumps (Bedin et al. 2000), can be most easily explained if the blue stars have a higher helium content ($Y \sim 0.32$) compared to those in the red clump which presumably have primordial $Y \approx 0.24$ (D’Antona & Caloi 2004). Furthermore, NGC 2808 also has a peculiar main sequence (D’Antona et al. 2005) where the bluer stars are inferred to have $Y \sim 0.4$ from fitting theoretical isochrones to the observed data. To reproduce the CMD, D’Antona et al. (2005) note the absolute necessity of including a small population ($\sim 20\%$) of stars with $Y = 0.40$ and assume a spread of $Y$ between 0.24 – 0.29 to fit the main fraction ($\sim 80\%$). While the exact maximum value of $Y$ required to reproduce the CMD is dependent on the color-$T_{\text{eff}}$ transformations used in the analysis and therefore rather uncertain, it seems that the most plausible explanation is that the bluest stars have enhanced amounts of helium with $Y \gtrsim 0.35$. Observations by Piotto et al. (2005) show that the blue main-sequence of ω Centauri is more metal-rich than the red sequence, contrary to what is expected from stellar models and Norris (2004) showed that isochrones with $Y = 0.40$ best fit the bluest stars. Until a better explanation for these intriguing observations is found, we take them as motivation to study the AGB self-pollution scenario from a global perspective.

In this paper, we use the Fenner et al. (2004) GC chemical evolution model to follow the evolution of helium in the intracluster gas. We probe AGB model uncertainties by using two independent sets of yields, including those used in the previous study which were tailor made for NGC 6752 (with a metallicity $[\text{Fe/H}] \approx -1.4$). The evolution of C, N and O is also followed since they impose important empirical constraints, i.e. $C+N+O \approx$ constant, that must be met by the model.

### 2. Helium Production in AGB Stars

Prior to the AGB both the first and second dredge-up (SDU) mix helium to the surface from regions that have undergone some H burning. During the thermally-pulsing-AGB phase, partial He-burning results in an abundance of $Y \sim 0.75$ in the intershell region, and each third dredge-up (TDU) episode increases the $^4\text{He}$ abundance of the envelope. Hot

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1Slightly more metal-rich than the average of $[\text{Fe/H}] \sim -1.6$ for NGC 6752, M13, M3 and ω Cen with metallicities from Harris (1996); NGC 2808 has $[\text{Fe/H}] \sim -1.15$. 
bottom burning (HBB) also produces $^4$He via the CNO cycle. For massive AGB stars the most important mixing phase is the SDU which results in an increase of $\Delta Y \lesssim 0.1$. The first dredge-up is inefficient in low-Z stars over $3M_\odot$ (see Fig. 2 in Boothroyd & Sackmann (1999)), and efficient TDU and HBB result in small increases of at most $\Delta Y \approx 0.03$, depending on the time spent on the AGB and the temperature at the base of the convective envelope.

The helium yields from the AGB models with $Z = 0.0017$ used by Fenner et al. (2004) are shown in Table 1 as the average mass fraction of $Y$ in the winds and the total mass of helium expelled into the intracluster medium by each model. We hereafter refer to the Campbell et al. models as “our” models. We also show the $Z = 0.001$ yields from Ventura et al. (2002) for comparison and note that the yields agree to within $\sim 30\%$. Our yields (and average $Y$) are systematically larger for $m > 3.5M_\odot$, reflecting the different input physics used in the two computations. Ventura et al. (2002) use a different convective model (Full Spectrum of Turbulence instead of the mixing-length theory) and mass-loss rate, and observe shallower dredge-up. In Table 1 an important result can be seen – the average $Y$ from our models does not monotonically increase with increasing stellar mass but instead peaks at $5M_\odot$. We observe efficient TDU and HBB plus our models spend longer on the AGB thanks to the Vassiliadis & Wood (1993) mass-loss rate (see discussion in Karakas et al. 2006b). On the other hand, the models of Ventura et al. (2002) have more efficient envelope convection resulting in larger luminosities and shorter AGB lifetimes, owing to their choice of a luminosity-driven mass-loss rate (Ventura & D’Antona 2005a). This results in smaller helium yields and consequently less helium in the cluster gas for the Ventura et al. yields. This difference has important consequences for the chemical evolution model, discussed further in §4.

Previously (Karakas 2003) we compared the stellar yields from the Monash models with those from Forestini & Charbonnel (1997); van den Hoek & Groenewegen (1997); Marigo (2001) and Izzard et al. (2004), for varying metallicities and find agreement for $^4$He for $m \geq 5M_\odot$ at the level of $\sim 30\%$, with the exception of van den Hoek & Groenewegen (1997) who produce $\sim 90\%$ less $^4$He. Karakas (2003) also observed that the final surface abundance of $Y$ in the $Z = 0.004$ models (slightly higher but similar to the average $Y$ in the winds) did not monotonically increase with mass but peaked at both $2.5M_\odot$ (owing to efficient TDU) and $6M_\odot$ (due to hot bottom burning). We conclude that the relatively close agreement between helium yields from various studies indicates they are more robust than other species (e.g. $^{12}$C and $^{16}$O). This is partly because the net result of hydrogen fusion is helium production regardless of the rates of the various internal cycles (CNO cycle, NeNa and MgAl chains).
3. The Chemical Evolution Model

The GC chemical evolution (GCCE) model was described in detail in Fenner et al. (2004); here we summarize the main features and the changes made for this study. We assume a two-stage formation model whereby the first stage acts as a prompt initial enrichment that brings the cluster gas up to a metallicity of $[\text{Fe/H}] = -1.4$. This first stage assumes a bimodal top-heavy IMF (Nakamura & Umemura 2001) and zero-metallicity massive star yields from Chieffi & Limongi (2002) and Umeda & Nomoto (2002).

During the second stage, we assume that the GC stars form in $10^7$ years from this low-metallicity gas\(^2\). In Fenner et al. (2004), the Kroupa et al. (1993) IMF was adopted and it was assumed that the GC retained ejecta from stars with $m \leq 6.5M_\odot$; here we change to a standard Salpeter-like IMF (Salpeter 1955) and test the effect of different power-law slopes (see §3.1). Furthermore, we also run separate simulations using the AGB yields from Ventura et al. (2002) for helium and the CNO isotopes. These yields cover the mass range $3 \leq m(M_\odot) \leq 5.5$; we extrapolate these yields to $2.5M_\odot$ and $6.5M_\odot$ and substitute in yields from Fenner et al. (2004) for $m < 2.5M_\odot$. We underline here that this extrapolation to higher mass renders uncertain the results obtained in terms of the maximum $Y$ expected after $50 - 100$ Myr when using the Ventura et al. (2002) yields. Although, in this case the extrapolation should be fairly reasonable given that the yields are monotonic with mass. No contribution from Type Ia SNe was included due to the observed uniform $[\text{Fe/H}]$. We favor a scenario in which the next (third) generation of stars is assumed to form out of this polluted gas rather than this gas accreting onto their surfaces. This is because observational evidence shows that there is no dilution of the surface abundances when stars move through the first dredge-up. The first dredge-up would mix the polluted envelope material with primordial material, yet no changes to O, Na, Mg or Al abundances are observed at this stage (Gratton et al. 2001).

In the GCCE model we simply track the composition of the cluster gas as a function of time. Hence the abundance of the gas reflects the continuous addition of AGB material as stars of decreasing mass evolve and lose their envelopes via winds. We do not model the formation of the third stellar generation but we can speculate that star formation will lock up some of this gas in new stars at a rate (and efficiency) that does not use up all of the gas.

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\(^2\)The models of Ventura et al. (2002) used scaled-solar abundances whereas those of Fenner et al. (2004) used initial abundances taken from the prompt initial enrichment stage. This also accounts for the larger than expected $Z = 0.0017$ compared to $Z \approx 0.001$ that we would get if we assumed scaled-solar initial abundances. We therefore shift the $[\text{O}/\text{Fe}]$ values from Ventura et al. (2002) by a factor of 2.5 to account for this difference.
from the 6.5M⊙ stars before the 6M⊙ stars have added new material (≈ 20 Myr). This is going on star formation timescales for low-mass stars, which can be anything from ≈ 1 Myr during the proto-star phase to ≈ 10⁸ Myr to reach the zero-aged main sequence (Siess et al. 2000; White & Hillenbrand 2004).

3.1. The Initial Mass Function

The IMF is one of the most uncertain parameters of the GCCE model. Hints that the IMF is not universal (Kroupa 2001) have come from observations of carbon-enhanced s-process-rich metal-poor stars (Lucatello et al. 2005), which suggest more s-process-producing AGB stars were required at the earliest stages of Galactic formation. Observations of the present-day mass function for the Arches cluster in the Galactic center by Stolte et al. (2005) suggest a turnover mass of ≈ 6M⊙, with a possible absence of low-mass stars. D’Antona & Caloi (2004) required a factor of ≈ 10 more 4 – 7M⊙ stars than produced by a Salpeter-like IMF to return the amount of helium required to form the number of blue HB stars in NGC 2808. The lack of observational evidence for enhanced levels of s-process elements or carbon suggests that stars between 1 – 3M⊙ are either not produced in significant numbers or they are ejected from the cluster.

Dynamical simulations of GCs suggest that top-heavy IMFs result in larger velocity dispersions than when using a Salpeter-like IMF (Downing & Sills, in preparation), and that cluster masses grow too large if the IMF is normalized by the number of blue HB stars. Simple analytical considerations led Bekki & Norris (2006) to conclude that the top-heavy IMFs required to produce the postulated helium enrichment in ω Cen would most likely result in the disintegration of the cluster. With these points in mind, we compute separate simulations with 1) a Salpeter-like IMF and 2) a top-heavy IMF that increases the number of intermediate-mass AGBs by a factor of 10; see Figure 1. We hereafter refer to the top-heavy IMF as “IMS-enhanced” (intermediate-mass star enhanced). In Karakas et al. (2006a) we present results from simulations that employ a power-law IMF with slope of 0.3.

4. Results

Previously, Fenner et al. (2004) conservatively assumed that at the end of the simulation the intracluster gas consists of about three parts AGB ejecta to one part primordial material. If we think about this assumption in terms of $Y$, then we begin with an initial $Y = 0.23$ and after about 50 Myr the most massive AGB stars of ≈ 6.5M⊙ start losing mass and hence we
see an increase in $Y$ to some value dictated by the maximum $Y$ in the AGB ejecta and the amount of dilution with primordial gas. The shape of the IMF will also dictate when the $Y$ peak is reached, where a standard Salpeter IMF will favor the contribution from lower mass AGB stars that produce significant helium. The peak will be offset in time according to the lifetime of these stars ($\sim 4 - 5M_\odot$) and this is indeed the behavior we see in Figure 2 (a), where we show the time evolution of helium using the standard Salpeter IMF for both sets of yields. In the case with some dilution with primordial material (the top panel $a$) the helium abundance is not predicted to exceed $Y > 0.30$ at any time, where our models predict a maximum $Y \approx 0.29$ and Ventura et al.'s $Y \approx 0.26$, both lower than the inferred maximum helium ($Y \gtrsim 0.30$) in HB and blue main-sequence stars. In §2 we described that the helium abundance in our AGB models does not monotonically increase with stellar mass, but instead peaks at $\sim 5M_\odot$. On the other hand, the Ventura et al. (2002) yields are monotonic with mass so we expect a maximum $Y$ at the slightly earlier times than when using our yields. From Figure 2 we see that the maximum $Y$ is reached in just over $\sim 100$ Myr, reflecting the dominant contribution of stars with $m \sim 4 - 5M_\odot$, favored both by the Salpeter IMF and by the amount of helium they produce. The difference in maximum $Y$ between the sets of yields can be attributed to the different input physics as discussed in §2.

One of the consequences of deep TDU is the production of $^{12}$C which is quickly converted to $^{14}$N by HBB at the base of the convective envelope. In Figure 3 and 4 we show the temporal evolution of C, N, and O (on a log scale) as a function of the helium mass fraction. Using a standard Salpeter IMF (Figure 3) we see that the deep TDU observed in our models result in a $\sim 0.8$ dex increase in C+N+O with most of this in the form of $^{14}$N, again reflecting the dominant contribution of intermediate-mass AGB stars. The Ventura et al. yields show a modest increase in C+N+O of only $\sim 0.4$ dex and oxygen has been destroyed by 0.3 dex in comparison to our results where we see little or no O depletion. The large increase in CNO that the Campbell et al. yields predict is not observed in GC stars whereas the small increase from the Ventura et al. yields is probably within observational uncertainties.

The results of the simulation using the IMS-enhanced IMF are shown in Figure 4. Using our yields, we see a substantial increase in helium, $Y \approx 0.35$, similar to the value required by isochrones (D’Antona & Caloi 2004; D’Antona et al. 2005) to match the bluest HB and main-sequence stars of NGC 2808 and $\omega$ Centauri. This increase is also accompanied by a 1 dex increase in CNO although now there is a noticeable depletion of O by $\sim 0.3$ dex. The simulation using Ventura et al. yields maintains a constant CNO (to within $\sim 0.3$ dex) but in this case the maximum $Y$ does not exceed 0.30. Importantly, the substantial O depletion of $\sim 0.8$ dex in this case is similar to the maximum dispersion observed in GC stars (ignoring the case of the peculiar M13, where the most O depleted stars with [O/Fe] $\sim -1$ are likely the result of enhanced extra-mixing). If we compare with observations, the most “polluted” stars
in a number of different clusters including M5, M15, M71 and NGC 6752 have \([\text{O}/\text{Fe}] \approx -0.5\) (Ramírez & Cohen 2002) whereas “normal” stars have \([\text{O}/\text{Fe}] +0.5\), indicating significant O destruction of about 0.8 – 1 dex. The simulation with the IMS-enhanced IMF gives a higher weight to the most massive AGB stars which tend to destroy O at the base of the envelope at temperatures \(T \gtrsim 80 \times 10^6\)K.

The dilution with primordial material only affects the smoothness of the resulting curve (\(Y\) as a function of time) and the maximum \(Y\) in the cluster gas. To check this is the case we compute two simulations with pure AGB ejecta and no dilution at all, one for each set of yields. We show the results of these models in Figure 2 (b), where we show the evolution of \(Y\), and in Figure 5, where we show evolution of the CNO species as a function of \(Y\). The behavior of \(Y\) with mass is seen more clearly in these figures, where the simulation using our yields peaks at \(Y \approx 0.36\), similar to the maximum \(Y\) in the 5M\(_{\odot}\) model. Note also that \(Y\) keeps increasing after the first initial jump from 0.23 to 0.34. The simulations using Ventura et al. yields peak very sharply at \(Y \approx 0.30\) before decreasing smoothly with time. The behavior of C+N+O is most interesting here. Our models predict a significant increase of \(\sim 1\) dex, as in the previous simulations with some dilution. The simulation using the Ventura et al. yields now also show a large spread in C+N+O, varying by \(\sim 0.8\) dex. This is because the diluted primordial gas is essentially nitrogen-free, off-setting increases from HBB.

5. Discussion

From the results presented in the previous section, it seems clear that the AGB self-pollution scenario does not successfully match the observational constraints that we have considered in this study, namely that C+N+O is roughly constant and that the maximum \(Y \gtrsim 0.30\). In no case, regardless of yields or the shape of the IMF, were we able to simultaneously match these constraints. The maximum helium abundances inferred from theoretical modeling (D’Antona & Caloi 2004; D’Antona et al. 2005) of the CMDs are quite uncertain and we should give more weight to the spectroscopic observations showing C+N+O \(\approx\) constant. We briefly consider the simulations that manage to fit this constraint.

The simulations that most closely match the observed CNO data are those employing the Ventura et al. yields, regardless of the shape of the IMF (although see Karakas et al. (2006a) for models with a flat power-law), but with a small amount of dilution of primordial gas. Note that some dilution is likely, since the star formation efficiency of low-mass stars is quite small, of the order of \(\lesssim 50\%\) (Matzner & McKee 2000). Even assuming a top-heavy IMF such as the IMS-enhanced IMF used in our study, a low-star formation efficiency and
no primordial material would make the job of producing enough polluted stars challenging.

There are many stellar model uncertainties: In particular, the extent of the TDU is far from known and shallower dredge-up, as observed in the Ventura et al. models, would help keep C+N+O constant while moderating the maximum $Y$. If this was combined with a long enough HBB lifetime, implying low AGB mass-loss rates such as those obtained when using the Vassiliadis & Wood (1993) prescription, then the required abundance patterns may be obtained by the essentially pure HBB environment. The HBB lifetime is also dependent on the convective model, and as shown by Ventura & D’Antona (2005a) more efficient convection, coupled with a luminosity-driven mass-loss rate, results in a shorter AGB lifetime.

If abundances of the bluest stars are closer to $Y \sim 0.3$, instead of $Y \sim 0.4$ then an AGB self-pollution scenario, with a top-heavy IMF, might work. How then to justify the existence of such an IMF for the first generation of GC stars? There is some observational evidence for variations in the IMF (Stolte et al. 2005) but there is ample evidence supporting a universal IMF, at least in the field (Kroupa 2001). Moreover, none of the observational evidence for variations in the IMF comes from environments similar to galactic GCs. Dwarf spheroidal galaxies have a total mass comparable to the largest clusters but supposedly did not have such strange IMFs (see for e.g. Pritzl et al. 2005). This may change as our ability to observe distant galaxies with young GCs increases, but it will be a great challenge to extract a useful mass function from these systems.

6. Conclusions

Our investigation into the chemical evolution of helium in GCs highlights the difficulty the AGB self-pollution scenario suffers in trying to explain the large postulated helium enrichment required to fit the horizontal branch of clusters like NGC 2808. With a standard Salpeter IMF, the largest predicted helium abundance in the cluster gas is $Y \approx 0.29$ but this is accompanied by a large increase in the C+N+O abundance. Using an independent set of AGB yields from Ventura et al. (2002) we find a maximum $Y \approx 0.26$ and only a modest increase of C+N+O $\approx 0.4$ dex, probably within the observational errors. We conclude that with a standard IMF it does not seem likely that the AGB self-pollution mechanism alone produced the enormous amounts of helium inferred from observations of the bluest HB and main-sequence stars of clusters like NGC 2808 and ω Centauri.

Simulations that employ the IMS-enhanced IMF show larger helium enhancements of $Y \approx 0.35$ but only when accompanied by enormous increases in the total C+N+O content of the cluster gas, in violation of observations. The Ventura et al. yields predict a maximum
$Y \approx 0.28$ and the total CNO abundance stays constant to within $\sim 0.3$ dex, although we again point out that this maximum $Y$ is made uncertain by extrapolating the yields to higher masses. Even with such an extreme IMF we have a problem fitting the observational constraints. Indeed, the use of such an IMF does not help the difficulties faced by the self-pollution scenario in matching the constraints that we have considered in this study i.e. $Y \gtrsim 0.30$ and $C+N+O \approx$ constant. Both sets of yields considered here also fail to match the observed spread of abundances between O, Na, Mg and Al, even though the quantitative predictions of the models are different. For example, the Fenner et al. models produce too much Na whereas the Ventura et al. yields destroy sodium, resulting in a O-Na correlation.

Bekki & Norris (2006) discussed the consequences of a number of top-heavy IMFs on the evolution of $\omega$ Centauri and concluded that the ones most suitable for producing the large helium enrichment would also tear the cluster apart. While $\omega$ Cen is an unusual cluster indicated by the spread in Fe, and clearly had a very different chemical enrichment history to the other lower-mass GCs, the conclusions reached about the top-heavy IMF on the cluster evolution are applicable to smaller mass, less tightly bound systems. Given the difficulties associated with the self-pollution scenario, we may need to look to other solutions such as pollution from outside the cluster. Indeed, perhaps the most unusual of all clusters, $\omega$ Cen, is actually just an extreme member and is telling us something useful about all GCs.

Acknowledgments

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FIGURE CAPTIONS

Fig. 1.— Choices of the IMF for the first generation of GC stars. We use a standard Salpeter IMF with slope $s = 1.31$ and a IMS-enhanced IMF that places about 10 times more mass in 3.5 to 6.5$M_{\odot}$ stars.

Fig. 2.— The evolution of helium ($Y$) as a function of time (Gyr) in the cluster gas. Here we assume a standard Salpeter IMF and we show the predicted helium abundance using our yields (solid line) and yields from Ventura et al. (2002) (dashed line). In (a) we show the results with some dilution with primordial material and in (b) with no dilution (i.e. using pure AGB ejecta).

Fig. 3.— The temporal evolution of the C+N+O abundance ([CNO/Fe]) in the cluster gas as a function of $Y$ for the Salpeter IMF and some dilution with primordial material, as discussed in the text. We use the standard spectroscopic notation $[X/Fe] = \log(X/Fe) - \log(X/Fe)_{\odot}$, with solar abundances from Anders & Grevesse (1989). Results using our yields are shown in (a) and results using Ventura et al. yields in (b).

Fig. 4.— Same as Figure 3 but showing results for the IMS-enhanced IMF.

Fig. 5.— The temporal evolution of the C+N+O species as a function of the helium mass fraction $Y$ using a Salpeter IMF and no dilution with primordial material.
Table 1: Yields of $^4$He expelled into the intracluster medium.

<table>
<thead>
<tr>
<th>Model</th>
<th>Initial stellar mass (M$_\odot$)</th>
<th>2.5</th>
<th>3.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campbell et al. (2004)</td>
<td>$Y$</td>
<td>0.266</td>
<td>0.255</td>
<td>0.375</td>
<td>–</td>
<td>0.349</td>
</tr>
<tr>
<td></td>
<td>mass</td>
<td>0.490</td>
<td>0.680</td>
<td>1.52</td>
<td>–</td>
<td>1.92</td>
</tr>
<tr>
<td>Ventura et al. (2002)$^a$</td>
<td>$Y$</td>
<td>–</td>
<td>0.257</td>
<td>0.289</td>
<td>0.293</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mass</td>
<td>–</td>
<td>0.675</td>
<td>1.14</td>
<td>1.30</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$Ventura et al. (2002) do not provide yields for masses less than 3M$_\odot$, or for masses above 5.5M$_\odot$. 