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Helium enhancements in globular cluster stars from AGB star pollution

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Abstract. Using a chemical evolution model we investigate the intriguing suggestion that there are populations of stars in some globular clusters (e.g. NGC 2808, ω Centauri) with enhanced levels of helium ($Y \sim 0.28$ to 0.40) compared to the majority of the population that presumably have a primordial helium abundance. We assume that a previous generation of massive low-metallicity Asymptotic Giant Branch (AGB) stars has polluted the cluster gas via a slow stellar wind. We use two independent sets of AGB yields computed from detailed models to follow the evolution of helium, carbon, nitrogen and oxygen in the cluster gas using a Salpeter initial mass function (IMF) and a number of top-heavy IMFs. In no case were we able to fit the observational constraints, $Y > 0.30$ and C+N+O $\approx$ constant. Depending on the shape of the IMF and the yields, we either obtained $Y \gtrsim 0.30$ and large increases in C+N+O or $Y < 0.30$ and C+N+O $\approx$ constant. These results suggest that either AGB stars alone are not responsible for the large helium enrichment or that any dredge-up from this generation of stars was less than predicted by standard models.

Key words. Galaxy: globular clusters – stars: abundances: chemically peculiar – stars: AGB and post-AGB

1. Introduction

Understanding the history and evolution of galactic globular cluster (GC) stars poses one of the greatest challenges to astrophysics. The star-to-star abundance variations of the light elements C, N, O, Na, Mg and Al observed in every well studied cluster to date (Kraft, 1994; Gratton et al., 2004, and references therein) 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 from cluster to cluster: C-N, O-Na and Mg-Al are all negatively 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 as the light elements nor do these

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elements vary *with* the light elements (Gratton et al., 2004; James et al., 2004; Yong et al., 2005). The key points are that O has been destroyed in some stars by up to one order of magnitude, the C+N+O and Mg+Al abundances remain almost constant regardless of the absolute spread and there is no evidence for large-scale variation of neutron-capture elements, except in the case of ω Cen (Smith et al., 2000).

The self-pollution scenario, first proposed by Cottrell & Da Costa (1981), is the most promising to explain these abundance trends. This is because the star-to-star abundance variations in C, N, O and Na are observed in stars at or near the main-sequence turn-off in addition to stars along the giant branch (Gratton et al., 2001; Ramírez & Cohen, 2003; James et al., 2004; Cohen & Meléndez, 2005; Cohen et al., 2005). The other scenario, deep mixing, is still required to operate in low-mass giants to convert some C to N after the luminosity bump (Charbonnel, 1994). Owing to the constant [Fe/H] of stars in a given GC it has been assumed that the source of the pollution was intermediate-mass Asymptotic Giant Branch (AGB) stars with initial masses between ~3 to 8$M_\odot$ rather than supernovae. The hot bottom burning experienced by these objects provides an environment (at least qualitatively) to produce helium, convert C and O to N, Ne to Na and Mg to Al (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).

There is an increasing amount of evidence for helium enrichment from horizontal branch (HB) morphology and main-sequence colour-magnitude diagrams (Norris, 2004; D'Antona & Caloi, 2004; Lee et al., 2005; Caloi & D'Antona, 2005; Piotto et al., 2005) where the helium has been proposed to have come from a previous generation of low-metallicity intermediate-mass AGB stars. For example, 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 best explained if the blue stars have an enhanced amount of helium (up to $Y \sim 0.32$) compared to those in the red HB clump with a primordial $Y \approx 0.24$ (D'Antona & Caloi, 2004). Further evidence for an enrichment in helium in NGC 2808 comes from the peculiar main sequence (D'Antona et al., 2005), where the bluer stars are inferred to have $Y \approx 0.40$. Observations by Piotto et al. (2005) showed that the blue main-sequence of ω Centauri is more metal-rich than the red sequence, contrary to what is expected from stellar evolution, and Norris (2004) showed that isochrones with $Y = 0.40$ fit the bluest stars. These intriguing pieces of observational evidence have motivated us to study the AGB self-pollution scenario from a global perspective.

Here we use the Fenner et al. (2004) GC chemical evolution model to follow the evolution of helium in the intracluster gas. We explore AGB model uncertainties by using two independent sets of AGB yields, including those used in the previous study which were tailor made for NGC 6752 with a metallicity [Fe/H] ≈ -1.4. This metallicity is slightly more metal-rich than the average metallicity of [Fe/H] ~ -1.6 for NGC 6752, ω Centauri, M3 and M13 with data taken from the catalogue of Harris (1996). The cluster NGC 2808 is more metal-rich with [Fe/H] ~ -1.15 (Harris, 1996) but we feel these AGB yields are suitable for this study because the yields would not change significantly in this [Fe/H] range. We also follow the evolution of C, N and O since they impose important empirical constraints, i.e. C+N+O $\approx$ constant that must be met by the model.

2. Helium Production in Asymptotic Giant Branch Stars

The helium yields from the AGB stars used by Fenner et al. (2004) are shown in table 1 as the total mass of ^{4}He expelled into the intracluster medium by each model. We also show the $Z = 0.001$ yields from Ventura et al. (2002) for comparison and note that they agree to within $\sim 30\%$. Our yields (Fenner et al., 2004) are systematically larger even though Ventura et al. (2002) use a different convective model and mass-loss rate and observe shallow dredge-up in their computations. The relatively good

Table 1. The mass of helium (in $M_\odot$) expelled into the intracluster medium

Model type	1.25	2.5	3.5	5.0	5.5	6.5
Fenner et al. (2004)	0.160	0.490	0.680	1.53	–	1.92
Ventura et al. (2002)	–	–	0.675	1.14	1.30	–

agreement comes about because most of the helium mixed to the surface in $m \gtrsim 3M_\odot$ models comes from the second dredge-up, not the thermally-pulsing AGB phase. Also, helium yields are more robust to reaction rate uncertainties than other species (e.g. ^{23}Na) owing to the fact that the net result of hydrogen burning is helium fusion, regardless of the internal rates of the various cycles (CNO, NeNa and MgAl).

3. The initial mass function

The globular cluster chemical evolution model was described in detail in Fenner et al. (2004). We made two main changes for this study: we used an independent set of AGB yields from Ventura et al. (2002), and we changed the shape of the initial mass function; see Karakas et al. (2006) for more details. There are other AGB yields besides those we consider here although most are from synthetic computations (e.g. Izzard et al. (2004)) and for more metal-rich populations. Herwig (2004) has low-metallicity AGB yields computed from detailed models. The results of our study would not change significantly if we were to have used these yields instead because Herwig's results are somewhere between the Ventura et al. and the Monash models. That is they have deep dredge-up but only a few (less than 20) thermal pulses, whereas the Monash models of $\sim 5M_\odot$ presented in Fenner et al. (2004) have $\sim$ 100 thermal pulses plus deep dredge-up.

In this section we focus on one crucial element of the model – the initial mass function (IMF). Most discussions in the literature point toward a universal mass function (Kroupa, 2001) although there are hints for variations at low metallicity. D'Antona & Caloi (2004) comment that to produce the amount of helium required to form the number of blue HB stars requires a factor of $\sim$ 10 more 4 to $7M_\odot$ stars than produced by a standard Salpeter IMF. Stars between 1 to $3M_\odot$ are either not produced or ejected from the cluster owing to a lack of evidence for enhanced levels of s-process elements or carbon. However, there is little physical motivation why such an unusual IMF would result from the early evolution of GCs when there is no observational evidence that such strange IMFs formed in other systems of comparable mass such as dwarf spheroidal galaxies. Although the abundance patterns observed in these systems are remarkably different from those in (most) globular clusters (Pritzl et al., 2005) there is still no evidence for a top heavy IMF.

With these considerations in mind, we compute simulations with a standard Salpeter-like IMF with a slope of 1.31, a flat Salpeter with slope of 0.30 and a top-heavy IMF that increases the number of intermediate-mass AGBs by a factor of 10, see fig. 1. We hereafter refer to the top-heavy IMF as "IMS-enhanced" (intermediate-mass star enhanced).

4. Results

In fig. 2 we show the temporal evolution of the C+N+O isotopes (on a log scale) as a function of the helium mass fraction assuming the flat Salpeter IMF. Using our yields we see a substantial increase in helium with a maximum abundance of $Y \approx 0.33$, similar to (but smaller than) 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. The maximum helium abundance is reached in under 200 Myr reflecting the dominant contribution of intermediate-mass AGB stars with lifetimes $\lesssim$ 120 Myr. The increase in helium is also ac-

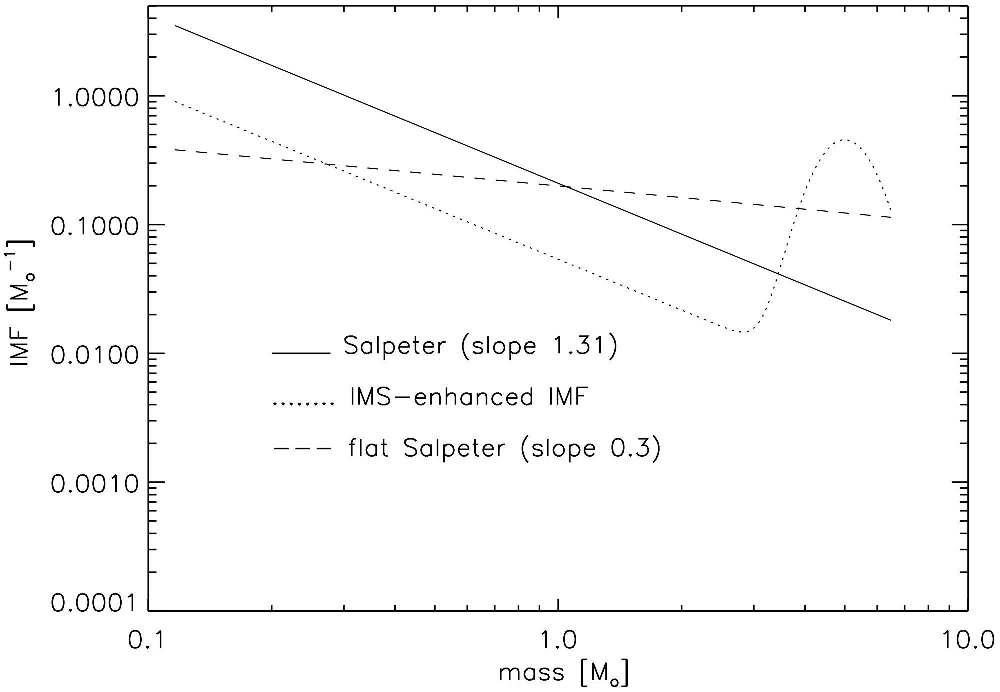

Fig. 1. Possible initial mass functions for the first generation of globular cluster stars. We consider three possible choices for the IMF including a Salpeter with slope s = 1.31, a flat Salpeter with s = 0.30 and an IMF the IMS-enhanced IMF places about 10 times more mass in 3.5 to 6.5M$_\odot$ stars.

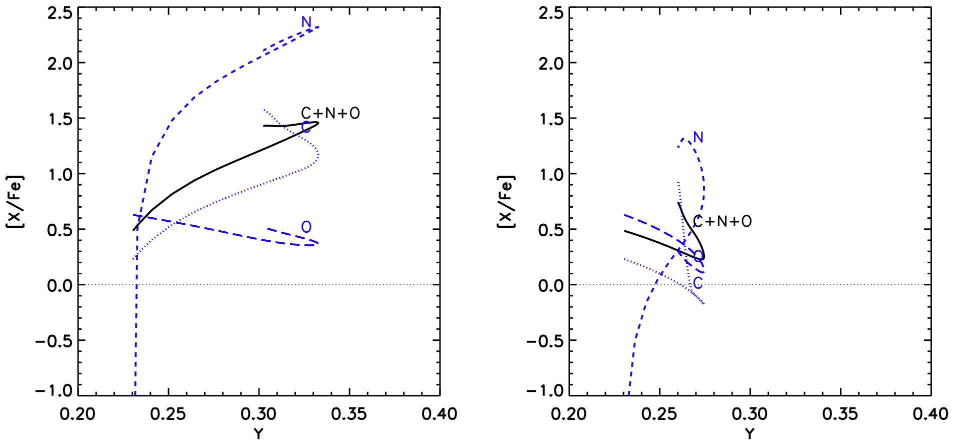

Fig. 2. The temporal evolution of the C+N+O abundance ([CNO/Fe]) in the cluster gas as a function of Y assuming a flat Salpeter IMF with slope = 0.30. In the (*left*) panel we show results using yields from Fenner et al. (2004) and in the (*right*) panel yields from Ventura et al. (2002).

companied by a $\sim$ 1 dex increase in C+N+O although there is some depletion of O by $\sim$ 0.3 dex.

The simulation using the Ventura et al. yields has a moderate increase in the total C+N+O of $\sim$ 0.5 dex but this is probably within observational errors. The maximum Y in this case does not exceed 0.27, well below the inferred value of the bluest main sequence and HB stars. However, the substantial O depletion of $\sim$ 0.5 dex in this case is similar to (but still smaller than) the maximum dispersion observed in GC stars. If we compare to observations, the most "polluted" stars in M13 have [O/Fe] ≈ -0.8 (Kraft et al., 1997) whereas "normal" stars have [O/Fe] +0.4, indicating significant O destruction of more than one order of magnitude. The simulation with the flat Salpeter produces many more stars with $m > 1\mathrm{M}_{\odot}$ compared to a standard Salpeter (see fig. 1) resulting in more carbon along with helium injected into the intracluster medium. Indeed, this IMF produces results quite different to the IMS-enhanced IMF which gives higher weight to the most massive AGB stars which have more efficient HBB and a lower weight to stars with $1 \lesssim M(\mathrm{M}_{\odot}) \lesssim 3$. The results using the standard Salpeter and the IMS-enhanced IMF are presented in Karakas et al. (2006) and are also not consistent with the observational constraints we have considered in this study.

5. Discussion & Conclusions

Our investigation into the chemical evolution of helium in globular clusters has shown the difficulty the AGB self-pollution scenario suffers when trying to explain the large helium enrichment ($Y \gtrsim 0.30$) hypothesized to fit the horizontal branch morphology of clusters like NGC 2808. We utilize a chemical evolution model and two independent sets of AGB yields to follow the evolution of the intracluster medium for a typical cluster with [Fe/H] $= -1.4$. We have tested three different IMFs for the first generation of GC stars including a standard Salpeter, a flat Salpeter and one IMF that boosts the number of intermediate-mass AGB stars by a factor of 10. The flat Salpeter produces maximum helium mass fractions in-between those found when using the standard Salpeter (with much lower Y values) and the IMS-enhanced IMF with slightly larger Y abundances (Karakas et al., 2006). The behaviour of the C, N and O elements is however quite different, owing to the overall increased number of 1 to 6.5$\mathrm{M}_{\odot}$ stars which produce C as well as helium.

Simulations assuming a flat Salpeter with a slope of 0.30 show helium mass fractions as large as $Y \sim 0.33$ but only with 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 $Y \approx 0.27$ with the total C+N+O abundance increasing by $\sim$ 0.5 dex. Assuming that such an IMF is realistic we still have a problem fitting all of 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. We note that the previous study by Fenner et al. (2004) suffered similar difficulties when trying to match the observed abundances of the Na, Mg and Al isotopes in the cluster NGC 6752.

There are many model uncertainties and in particular the extent of the dredge-up is far from known and shallower dredge-up, as observed in the Ventura et al. models, would help keep C+N+O constant. The nucleosynthesis associated with hot bottom burning is also dependent on the convective model (or the mixing-length parameter α for MLT models) and varying this will impact the yields (Ventura & D'Antona, 2005). However, more efficient convection leads to larger luminosities which would likely drive mass loss, leading to shorter AGB lifetimes and possibly smaller helium yields.

Thus far we have assumed that the large helium abundances inferred from theoretical isochrones are accurate. These determinations are model dependent and suffer from many of the same uncertainties that afflict AGB models (e.g. convection) and hence it is hard to gauge just how reliable these helium determinations are. Even if they are overestimates with the largest Y closer to 0.30 instead of 0.40, we still have a problem fitting the observational constraints with the current set of AGB models. Perhaps given the difficulties associated with the self-pollution scenario we need to look to other solutions including pollution from outside the cluster, as discussed in the case of ω Centauri by Bekki & Norris (2006).

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