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On the origin of the helium-rich population in ω Centauri

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ABSTRACT

To study the possible origin of the huge helium enrichment attributed to the stars on the blue main sequence of ω Centauri, we make use of a chemical evolution model that has proven able to reproduce other major observed properties of the cluster, namely its stellar metallicity distribution function, age–metallicity relation and trends of several abundance ratios with metallicity. In this framework, the key condition to satisfy all the available observational constraints is that a galactic-scale outflow develops in a much more massive parent system, as a consequence of multiple supernova explosions in a shallow potential well. This galactic wind must carry out preferentially the metals produced by explosive nucleosynthesis in supernovae, whereas elements restored to the interstellar medium through low-energy stellar winds by both asymptotic giant branch (AGB) stars and massive stars must be mostly retained. Assuming that helium is ejected through slow winds by both AGB stars and fast-rotating massive stars, the interstellar medium of ω Centauri's parent galaxy gets naturally enriched in helium in the course of its evolution.

Key words: stars: AGB and post-AGB – stars: mass-loss – globular clusters: general – globular clusters: individual: ω Cen – galaxies: evolution – galaxies: star clusters.

1 INTRODUCTION

Once referred to as 'simple stellar populations', globular clusters (GCs) are not simple at all, in that they display significant and peculiar star-to-star abundance variations (see Gratton, Sneden & Carretta 2004 for a review). These are most likely the records of a complex star formation history. Indeed, the C–N, Na–O, Al–O and Al–Mg anticorrelations seen among both evolved and unevolved stars of individual clusters cannot be reconciled with a simple deep mixing scenario (Gratton et al. 2001; Cohen, Briley & Stetson 2002). Rather, they are naturally explained if one or more successive stellar generations form out of the ejecta from first-generation stars that have undergone nuclear processing through proton capture reactions at high temperatures (Sneden et al. 2004; Carretta et al. 2006 and references therein). This evolutive picture is supported by the presence of multiple main sequences (MSs) in two massive Galactic GCs, ω Cen and NGC 2808 (Bedin et al. 2004; Piotto et al. 2007). The bluer MSs are – surprisingly – more metal-rich than the red ones, or have the same iron content. This, at present, can be understood only in terms of an extreme helium enhancement in the blue population (Norris 2004; D'Antona et al. 2005; Piotto et al. 2005). Further evidence in favour of the existence of very helium-rich subpopulations in massive clusters comes from the peculiar morphology of the horizontal branches in some of them (Busso et al. 2007; Caloi & D'Antona 2007; Yoon et al. 2008; but see also Catelan et al. 2009). The excess in the far-ultraviolet flux detected for most of the massive clusters observed in M 87 by Kaviraj et al. (2007) can also be interpreted as a signature of extreme helium enrichment and would demonstrate that this phenomenon is not limited to our Galaxy.

It is common wisdom that the key to understanding the origin of extreme helium populations is the identification of extreme helium polluters. Though massive (approximately 5–10 $M_{\odot}$) asymptotic giant branch (AGB) stars have been suggested as likely 'culprits' for the chemical 'anomalies' observed in GC stars since the work by Cottrell & Da Costa (1981), only recently detailed stellar modelling has provided yields compatible with the observations over a significant range of initial stellar masses (Pumo, D'Antona & Ventura 2008; Ventura & D'Antona 2008a,b). In Ventura & D'Antona's models, convection is modelled efficiently and a very fast AGB evolution is obtained, which results in a relatively low number of thermal pulses and third dredge-up (TDU) episodes. This leads to a lower production of carbon and nitrogen and no appreciable increase of the overall CNO abundance in the envelope, an important point of view of the fact that in ω Cen and other globulars the [C+N+O/Fe][1] ratio is constant within a factor of

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[1] Unless otherwise stated, chemical abundances throughout this paper are by number, except for Y and Z, that indicate the mass fraction of helium and total metals, respectively. As usual, $\log \varepsilon(\mathrm{X}) \equiv 12 + \log(\mathrm{X/H})$, while square brackets indicate logarithmic ratios relative to solar, $[\mathrm{A/B}] \equiv \log(\mathrm{A/B}) - \log(\mathrm{A/B})_{\odot}$.

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about 2 (Norris & Da Costa 1995; Smith et al. 1996; Ivans et al. 1999; Carretta et al. 2005; Cohen & Meléndez 2005; but see Yong et al. 2009).

Up to now, chemical evolution models aimed at explaining the large helium abundance implied by the blue MS of ω Cen with the ejecta of AGB stars have predicted an enormous increase in the total C+N+O content of the cluster, contrary to observations (e.g. Karakas et al. 2006). This failure has spurred the quest for alternative solutions. Decressin et al. (2007a) and Decressin, Charbonnel & Meynet (2007b) have proposed a scenario where the H-processed material lost by first-generation fast-rotating massive stars (FRMSs) through slow mechanical equatorial winds is retained in the cluster potential well, where it enters the formation of second-generation stars. Matter expelled through fast polar winds and supernova (SN) explosions leaves the cluster instead. A major drawback with this scenario is that it cannot estimate from first principles the efficiency of meridional circulation to mix helium (and other chemicals) into the stellar envelope, or the rate of mass loss through the outflowing disc (Renzini 2008). Furthermore, the helium-rich stars would form in very 'hostile' surroundings, their birth being shortly followed by – or even concomitant to – multiple SN explosions.

To reproduce the correct ratio of first generation-to-second generation stars in both the massive star pollution scenario and the AGB pollution scenario, either a highly anomalous initial mass function (IMF) for first-generation stars or a strong evaporation of low-mass stars with 'normal' chemical enrichment have to be assumed (Decressin et al. 2007b; D'Ercole et al. 2008). While, in general, the first condition is difficult to justify both theoretically and observationally, in the case of ω Cen there are fairly clear indications that the second generation of stars could have formed from the ejecta of surrounding field stellar populations in an initially much more massive system. The kinematical, dynamical and chemical properties of this cluster, in fact, are better understood if it is the surviving nucleus of an ancient dwarf galaxy captured and disrupted by the gravitational field of the Galaxy many Gyr ago (see e.g. Dinescu, Girard & van Altena 1999; Gnedin et al. 2002; Bekki & Norris 2006; Romano et al. 2007; Bellazzini et al. 2008). Recent N-body simulations of the dynamical evolution of two-population clusters show that a rapid loss of first-generation stars should be expected early on in the cluster evolution as a consequence of cluster expansion in response to the dynamical heating from SN explosions (D'Ercole et al. 2008; see also Decressin, Baumgardt & Kroupa 2008). Early phases of violent relaxation also sensibly reduce the initial cluster's mass (Meylan & Heggie 1997 and references therein). ω Cen, however, must have followed a different evolutionary path, with its putative progenitor galaxy shedding stars in trails while its orbit was degrading by approaching the Milky Way plane (Meza et al. 2005). The debris of this disruption process has been possibly identified through the kinematical feature imprinted in a sample of local, metal-poor halo stars (Dinescu 2002; Mizutani, Chiba & Sakamoto 2003).

In this paper, we deal with the chemical evolution of the system that once was/contained ω Cen. In particular, in Section 2 we propose an explanation for the origin of its helium-rich population, in the context of a model that has already proven able to reproduce the majority of the observational constraints available for its whole, complex stellar population. For the sake of completeness, in Section 2 we also examine, in our framework, the two alternative scenarios of He being overenriched either only by AGBs or by FRMSs. Our conclusions are presented in Section 3, together with a discussion of the results.

2 THE CHEMICAL EVOLUTION OF ω CENTAURI'S PROGENITOR SYSTEM

2.1 The chemical evolution model

In this paper, we adopt an updated version of the chemical evolution model developed by Romano et al. (2007) for a dwarf spheroidal galaxy whose dense central regions become ω Cen after accretion and stripping by the Milky Way. Here, we simply recall the overall evolutionary scenario, while a detailed description of the model basic assumptions and equations is given in the Appendix.

We start our computation with $\mathscr{M}_{\rm gas}(t = 0) = \mathscr{M}_{\rm bar} = 10^9\,{\rm M}_\odot$ of gas of primordial chemical composition available for accretion, embedded in a 10 times more massive dark matter halo. The system accretes gas and forms stars for 3 Gyr. About 200 Myr after the onset of star formation, as a consequence of energy injection by multiple SN explosions, a galactic wind develops and gradually cleans up the cluster of its gas. Star formation may proceed if the SN ejecta are vented out along preferential directions, leaving part of the pristine gas unperturbed (e.g. Recchi, Matteucci & D'Ercole 2001), and we assume that this is the case. Feeding the system by continuous infall of gas from the outskirts contrasts the cleaning action of the wind. At the end of the computation, we are left with $\mathscr{M}_{\rm stars}(t = 3\ {\rm Gyr}) \simeq 10^8\,{\rm M}_\odot$. According to the computations by Bekki & Freeman (2003), this is exactly what is needed to leave behind a compact remnant of mass $\mathscr{M}_{\omega\,{\rm Cen}} \simeq 10^6\,{\rm M}_\odot$ after long-term tidal interactions with the Milky Way. During the time (from $t = 0.6$ to 1 Gyr in our model) the metallicity of ω Cen's parent galaxy is growing from [Fe/H] $\simeq -1.3$ to $\simeq -1.1$ (i.e. the metallicity range where He-rich stars are observed), the system is forming stars at an average rate of $0.1\,{\rm M}_\odot\ {\rm yr}^{-1}$. Therefore, according to the assumed IMF (Salpeter 1955, extrapolated to the 0.1–100 ${\rm M}_\odot$ stellar mass range; see the Appendix), in principle up to $2 \times 10^7\,{\rm M}_\odot$ of stars (20 per cent of the overall population) can form in the range 0.1–0.8 ${\rm M}_\odot$ (i.e. they are still alive today) out of gas enriched in He at a level comparable to that required by the blue MS stars. The percentage of He-rich stars could be even higher, should the processed gas gradually collect into the galaxy's innermost regions, where the newborn stellar generations are likely to be less severely affected by the subsequent interactions with the Milky Way.

The problem we left unsettled in our previous work is how to reach the high level of He enhancement required by the blue MS stars. We tackle this subject in the present study.

2.2 Nucleosynthesis prescriptions

In this work, we adopt the following sets of metallicity-dependent yields for single stars.

(i) Model A: yields from van den Hoek & Groenewegen (1997) for low- and intermediate-mass stars (LIMSs) and Woosley & Weaver (1995) for massive stars.

(ii) Model B: yields from Marigo (2001) for LIMSs, Portinari, Chiosi & Bressan (1998) for quasi-massive stars and Kobayashi et al. (2006) for massive stars, except for He and CNO production, for which the pre-SN yields from the Geneva group[2] are adopted.

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[2] Meynet & Maeder (2002a) for $Z_{\rm ini} = 10^{-5}$ and 0.004, Hirschi, Meynet & Maeder (2005) for solar initial metallicity, Hirschi (2007) for $Z_{\rm ini} = 10^{-8}$ and Ekström et al. (2008) for zero-metallicity stars.

(iii) Model C: yields from Karakas & Lattanzio (2007) for LIMSs and Kobayashi et al. (2006) for massive stars, except for He and CNO production, for which the pre-SN yields from the Geneva group are adopted.

A thorough discussion of the adopted yields can be found in the source papers.

We also run models adopting the yields by Ventura & D'Antona (2008a,b; see Section 2.3.2) and Decressin et al. (2007a; see Section 2.3.3). Ventura & D'Antona's yields are computed for a reduced grid of stellar masses (only stars with initial masses between 3 and 6.3 $M_\odot$ are considered). Thus, below 3 $M_\odot$ we couple them with those from other studies (Karakas & Lattanzio 2007). Decressin et al. (2007a) provide the abundances of Na in the slow winds of FRMSs, but only for stars with initial metallicity [Fe/H] = −1.5. The adoption of metallicity-dependent yields of Na from FRMSs is expected to change both *qualitatively* and *quantitatively* the model predictions presented in this paper, as discussed in Section 2.3.3.

In the range from 6–8 $M_\odot$ (depending on stellar models) to 11–12 $M_\odot$, detailed stellar yields are not available. Hence, we interpolate among the yields for LIMSs and massive stars listed above. The chemical imprint of stars in this mass range, the so-called super-AGB stars, should mainly affect the model predictions regarding ^{4}He (Pumo et al. 2008) ^{13}C, ^{14}N, ^{25}Mg, ^{26}Al and ^{23}Na evolution (Siess 2007). However, in the absence of detailed nucleosynthesis computations, it can hardly be said which effects must be expected.

For SNeIa, we adopt the yields from Iwamoto et al. (1999).

2.3 Model results

In previous work (Romano & Matteucci 2007; Romano et al. 2007), we presented a chemical evolution model able to reproduce the main chemical properties of the complex stellar population of ω Cen, namely its stellar metallicity distribution function, age–metallicity relation and the trends of several abundance ratios with metallicity. A key assumption of the model was that the cluster is the compact remnant of a dwarf galaxy that self-enriched over a period of about 3 Gyr, before being captured and partly disrupted by the Milky Way. However, the issue of the extreme helium enhancement of the stars on the blue MS was unsolved. In fact, our homogeneous chemical evolution model, adopting a standard IMF and standard stellar yields, could not predict any significant helium enrichment during the evolution of the cluster (see fig. 7 of Romano et al. 2007 and discussion therein).

Here, we propose an explanation for the origin of the helium-rich population in ω Cen in the framework of our chemical evolution model. We separately examine three key scenarios in the following sections.

2.3.1 Differential wind with helium retention

In Fig. 1 (top panel), we show how the relative He enrichment (assuming $Y_P = 0.248$ for the primordial He abundance) proceeds in the interstellar medium (ISM) of our model as a function of metallicity, according to different nucleosynthesis prescriptions (solid line: Model A; short-dashed line: Model B; long-dashed line: Model C; see Section 2.2). The efficiency of He ejection through the outflow is set to a low value, $w_{\rm He} \simeq 3\nu$, about three times the star formation efficiency, in order to reproduce the high He content of the blue MS stars (box in Fig. 1). It can be seen that changing the nucleosynthesis prescriptions does not alter much the model predictions.

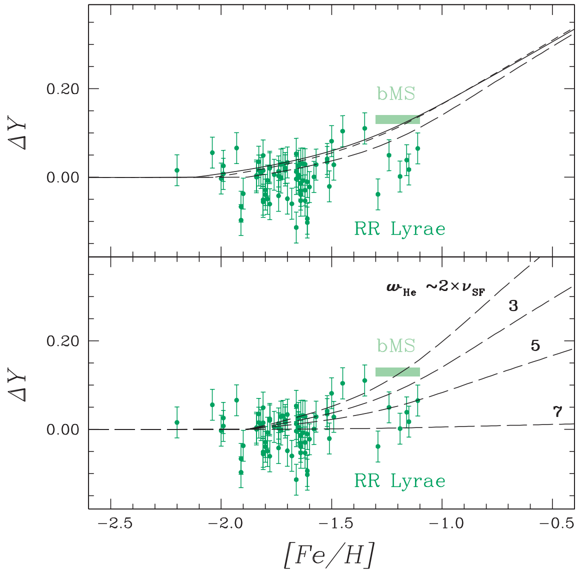

Figure 1. The He enhancement as a function of metallicity predicted by different models for ω Cen is compared to the estimates of relative He abundances from RR Lyræ (small filled circles; Sollima et al. 2006) and blue MS stars (box; Norris 2004; Piotto et al. 2005). Top panel: theoretical predictions from Model A (solid line), Model B (short-dashed line) and Model C (long-dashed line), adopting different nucleosynthesis prescriptions. Bottom panel: theoretical predictions from Model C for different choices of the efficiency of He entrainment in the galactic outflow, as labelled (see the text for discussion).

On the other hand, any modification in the efficiency of He removal from the system dramatically affects the results. In Fig. 1 (bottom panel), we show the behaviour of the relative He enrichment for Model C (but the results would be qualitatively the same for Models A and B), with four different choices for the efficiency of He entrainment in the galactic wind. It is worth noting that if different zones of the protocluster lose their He with varying strength in the outflow, a spread in the abundance of He results. This could explain the coexistence of populations with 'normal' and 'enhanced' He abundances at the same metallicity, as seems to be required by observations of RR Lyræ stars (Sollima et al. 2006; small filled circles in Fig. 1).

Thus, lowering the efficiency of He ejection through the outflow is a promising way to get He-enhanced stellar populations. However, it is mandatory to test the proposed scenario against other observed quantities. In particular, the consistency between model predictions and observations has to be obtained for other species produced in lockstep with He, which should share the same fate.

Sodium is produced by stars across the whole mass range, like He. It is synthesized partly during hydrostatic carbon burning, but mostly during hydrogen burning (through the NeNa cycle) in the envelopes of AGB stars and in the cores of massive stars. According to Decressin et al. (2007a), in massive fast rotators rotational mixing efficiently transports elements from the convective cores to the surfaces. If the initial rotational velocities are high, the stars reach the breakup early on the MS and eject important quantities of material loaded with H-burning products. Therefore, the fraction of Na produced by massive fast rotators is restored to the ISM by low-energy stellar winds, rather than through SNII explosions, and, thus, follows the same conditions as He for the entrainment in the galactic wind. In Fig. 2, we show the predictions on the [Na/Fe] versus [Fe/H] trend in ω Cen obtained with different nucleosynthesis

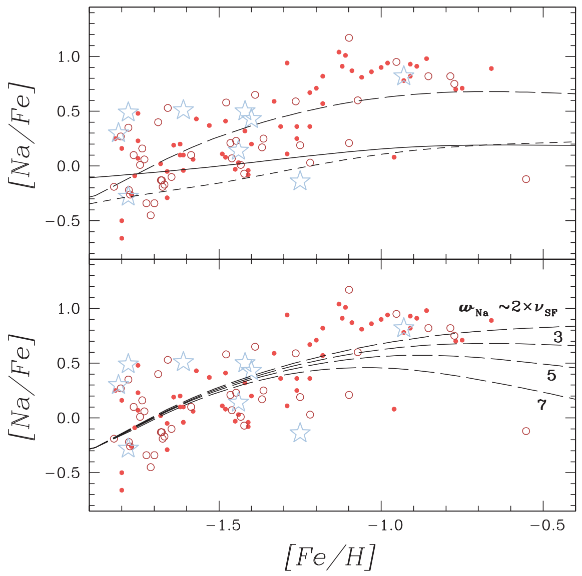

Figure 2. [Na/Fe] versus [Fe/H] in *ω* Cen. Data are from Norris & Da Costa (1995; empty circles), Smith et al. (2000; stars) and Johnson et al. (2009; small filled circles). Top panel: the solid, short-dashed and long-dashed lines are for Model A, B and C predictions, respectively. Bottom panel: Model C predictions, for different choices of the efficiency of Na ejection through the outflow (see the text).

prescriptions (top panel) and different efficiencies of Na entrainment in the galactic wind (bottom panel). Models A and B (solid and short-dashed lines, respectively) do not consider Na production from LIMSs. The differences in the model predictions are thus only due to differences in the adopted yields of Na from massive stars (Woosley & Weaver 1995 for model A and Kobayashi et al. 2006 for model B). Model C (long-dashed lines), instead, includes Na production from LIMSs, through the adoption of Karakas & Lattanzio's (2007) yields. It has been computed with four values of the efficiency of Na ejection through the outflow, $w_{\rm Na} \simeq 2$, 3, 5 and 7 times the efficiency of star formation (Fig. 2, bottom panel), the same as for He (Fig. 1, bottom panel). The theoretical predictions are compared to data from Norris & Da Costa (1995; empty circles), Smith et al. (2000; stars) and Johnson et al. (2009; small filled circles). While no attempt is made to homogenize the data, we note that Johnson et al. (2009) find negligible differences in measured [Fe/H] and [Na/Fe] ratios for seven stars they have in common with Norris & Da Costa (1995). From a comparison between model predictions and observations, we conclude the following.

(i) Model C, accounting for Na production from both LIMSs and massive stars, is able to reproduce the trend of increasing ⟨[Na/Fe]⟩ with increasing metallicity traced by the majority of the cluster stars, provided that a low efficiency of Na entrainment in the outflow is assumed. This efficiency turns out to be the same required to produce the extreme He-rich population hosted on the blue MS.

(ii) A minority of the stars in the intermediate- and high-metallicity domain have Na abundances consistent with production solely from massive stars ([Na/Fe] $\simeq$ 0.0; Fig. 2, top panel, solid and short-dashed lines). Alternatively, these stars might have formed in regions where Na was more efficiently removed from the ISM (Fig. 2, bottom panel, lower long-dashed curve); in that case, the stars should also have 'normal' He abundances (Fig. 1, bottom panel, lower long-dashed curve). Indeed, Villanova, Piotto & Gratton (2009) have recently provided the first direct measurements of the abundance of He for a sample of five stars in the Galactic GC NGC 6752. The stars likely display the original He content of the gas out of which they were born. A mean value of $\langle Y \rangle = 0.245 \pm 0.012$ is found, consistent with the primordial one. At a metallicity of [Fe/H] = −1.56 ± 0.03, all these He-normal stars are also Na-poor.

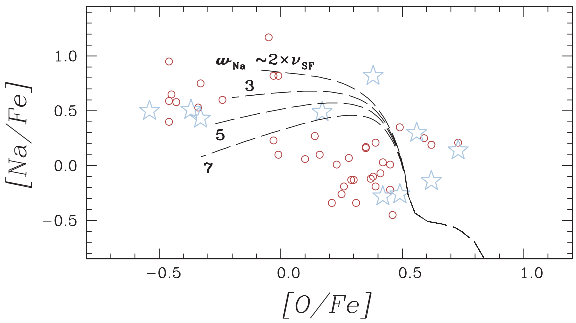

Figure 3. The Na–O anticorrelation in *ω* Cen. Data are from Norris & Da Costa (1995; empty circles) and Smith et al. (2000; stars). The predictions of Model C are also shown for four different values of the efficiency of Na entrainment in the galactic-scale outflow, as labelled. At variance with Figs 1 and 2, the time on the *x*-axis now flows from right to left.

While it is reasonable to assume that Na is restored to the ISM through slow stellar winds by both massive and AGB stars (and, hence, it is easily retained within *ω* Cen's progenitor potential well), oxygen, mostly a product of He and C burning in massive stars, is released in the ISM by fast radiatively driven winds (Decressin et al. 2007a). Thus, it is easily lost through the outflow. We assume an efficiency of O ejection through the outflow of nearly 12 times the star formation efficiency. The same value holds for all the *α*-elements. It becomes slightly higher for Fe [mostly produced by type Ia SNe (SNe Ia)] and the other Fe-peak elements: 13 times the star formation efficiency is the value which best fits both the observed stellar metallicity distribution function and several abundance ratios. This naturally leads to an Na–O anticorrelation in our model, as can be seen from Fig. 3, where we compare the trend of [Na/Fe] versus [O/Fe] predicted by Model C (for four different assumptions on the efficiency of Na entrainment in the outflow) with the available data. The temporal evolution of the system can be read on the *x*-axis from right to left. Although a large spread is present in the data, the average [O/Fe] ratio in *ω* Cen decreases with increasing metallicity, i.e. with time in our models. We expect thus O-rich, Na-poor stars in *ω* Cen to be older than O-poor, Na-rich ones. This is at variance with models for Galactic GCs by Marcolini et al. (2009), where the first stars to form are Na-rich and O-depleted and 'normal' (i.e. Na-depleted, O-rich) stars form later. We are instead in agreement with Carretta et al.'s (2009) interpretation of similar data for several Galactic globulars. Carretta et al. (2009) suggest that O-rich, Na-depleted stars form out of gas of 'primordial' chemical composition, where 'primordial' means the level of chemical enrichment determined by the first episode of star formation. The anticorrelation is then built up as long as stars of lower and lower initial mass start to die and pollute the ISM with products of H burning at high temperatures (see also Gratton et al. 2004).

Our models, despite some simplifying assumptions, account satisfactorily well for *the trends of average abundances and abundance ratios* with metallicity (see also Romano et al. 2007 and Romano & Matteucci 2007) and for observational constraints such as the Na–O anticorrelation in *ω* Cen. An important point to be stressed here is that also *the relative fractions of stars with normal and peculiar* *chemical compositions* can be reproduced (see Section 2.1). The key ingredient for the model predictions to be in agreement with the observations is the development of a strong differential outflow in a much more massive parent system. This outflow must vent out a major fraction of the metals ejected by SN explosions. In turn, elements restored to the ISM through gentle winds by both LIMSs and massive stars must be retained in the shallow potential well of the cluster progenitor.

In the following sections, we discuss the role of possible self-pollution from either AGB or massive stars.

2.3.2 *AGB star pollution scenario*

Early claims that chemically peculiar GC stars could have formed from gas processed in the envelopes of first-generation massive AGB stars (Cottrell & Da Costa 1981; Ventura et al. 2001) have recently been reconsidered and given further support by detailed hydrodynamical and *N*-body simulations (D'Ercole et al. 2008). These models assume the first stellar generation already in place and start the calculations when all the SNeII have already exploded. Since only stars in the 4–5 to 8 $M_\odot$ mass range provide abundances in the ejecta compatible with the observations (Ventura & D'Antona 2008a,b), the second-generation stars must form in a relatively short period of time – 100 Myr in D'Ercole et al.'s model – before stars with masses <4–5 $M_\odot$ can contribute to the chemical enrichment. In the most extreme scenario, second-generation stars form out of the AGB processed gas with an efficiency of 100 per cent and an IMF completely skewed towards low-mass stars (only stars in the mass range 0.1–0.8 $M_\odot$ are allowed to form). This minimizes the mass of first-generation stars which is needed in order to reproduce the fraction of chemically peculiar stars currently observed in GCs. Under these conditions, in fact, a cluster with a current mass $\mathcal{M}_{\rm GC}$ had a 10 times larger progenitor, while the mass of the progenitor must be much larger if one or both of the aforementioned hypotheses is relaxed. This is the case of our chemical evolution model for ω Cen, where gas is turned into stars with an efficiency of nearly 40 per cent and the stars distributed according to a Salpeter-like IMF over the whole stellar mass range (0.1–100 $M_\odot$; see the Appendix).

In our standard model, ω Cen's precursor is treated as a one-zone system where the ejecta from massive stars, AGB stars (if any) and SNeIa (if any) mix all together at each time. A contribution from infall of gas of primordial chemical composition is considered as well. According to equation (A4), the infall term exponentially decreases in time.

To examine the 'pure AGB' scenario, let us now assume that at a given time – or, better, time interval – the ejecta of AGB stars stop mixing with the surrounding medium and collect into the cluster core in a cooling flow (for a detailed discussion on how cooling flows develop, see D'Ercole et al. 2008). In Fig. 4 (left-hand panel), we show the cumulative ejecta of AGB stars belonging to the field stellar populations of ω Cen's parent galaxy as a function of time. The chemical composition of the ejecta as a function of time is shown in the right-hand panels (solid and dashed lines). In the top-right panel, we show the relative He enrichment, in the middle-right panel the [Na/Fe] ratio and in the bottom-right panel the [O/Fe] ratio. Also shown in the upper part of the top-right panel is the run of metallicity in the ISM of ω Cen's progenitor with time. The dashed lines refer to model predictions obtained by using the yields for AGB stars by Karakas & Lattanzio (2007), and the solid lines refer to model predictions obtained by using the Karakas & Lattanzio (2007) yields for AGB stars below 3 $M_\odot$ and the Ventura & D'Antona (2008a,b) yields for AGB stars in the range 3–6.3 $M_\odot$. The ranges of ΔY, [Na/Fe] and [O/Fe] values inferred from observations of chemically peculiar stars are indicated by the shaded areas. Two important things are immediately apparent from this figure. The first is that, in the framework of our model, AGB stars provide nearly 2×10^7 $M_\odot$ of processed material. It suffices that 10 per cent of this matter is converted into stars before any mixing with the surrounding ISM to produce (assuming a standard Salpeter IMF) about 10^6 $M_\odot$ of long-lived stars with a chemical composition typical of pure AGB ejecta. The second important thing is that AGB stars hardly produce the huge helium amount required to explain the blue MS of ω Cen (see also Karakas et al. 2006; Choi

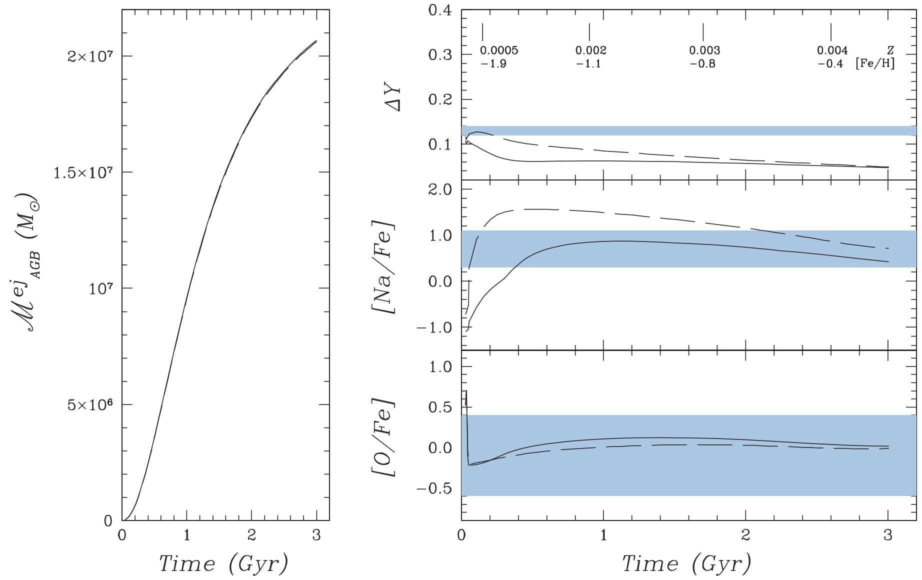

Figure 4. Left-hand panel: cumulative mass ejected by AGB stars in our model for ω Cen parent galaxy as a function of time. The chemical composition of the ejecta as a function of time is shown in the right-hand panels, for two sets of stellar yields (solid and dashed lines; see the text for details). The shaded areas in each of the right-hand panels indicate observed values for chemically peculiar stars (references in the text).

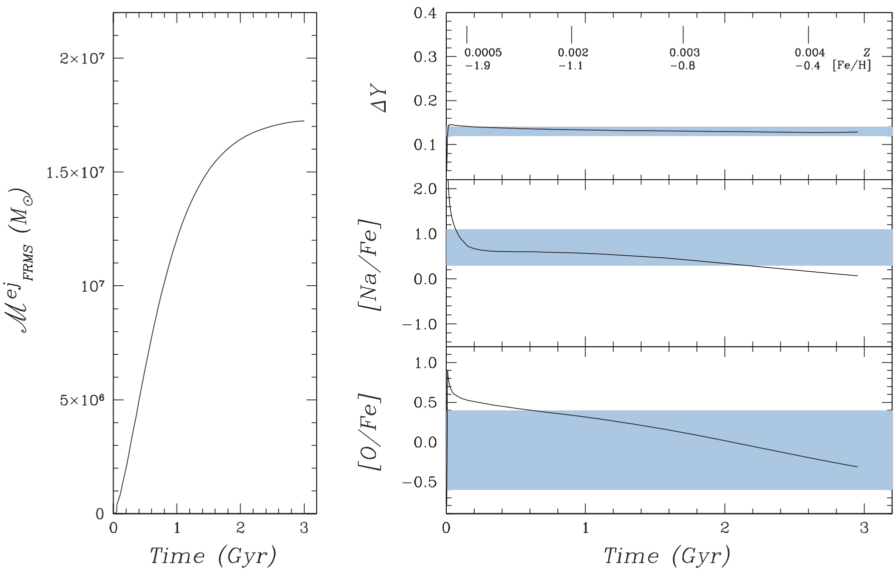

Figure 5. Left-hand panel: cumulative mass ejected in the slow winds by FRMSs in the framework of our model for ω Cen parent galaxy as a function of time. The chemical composition of the ejecta as a function of time is shown in the right-hand panels. The shaded areas in each of the right-hand panels indicate observed values for chemically peculiar stars (see the text for references). Also shown in the upper part of the top-right panel is the run of the ISM metallicity with time for the proto-ω Cen host.

& Yi 2008). The necessary helium overabundance is attained only during the very early phases of the protocluster evolution; then, as soon as stars less massive than $\simeq$5 M$_\odot$ start to die, the overall AGB ejecta start to display much more 'normal' He abundances. Values of the oxygen-to-iron ratio as low as [O/Fe] = −0.5 are never reached for the same reason, while it seems easier to get enhanced [Na/Fe] ratios.[3] In the simplified situation of two-population clusters, it may well be that only AGB stars with initial masses in the range 4–5 to 8 M$_\odot$ have contributed to the building up of second-generation stars. However, ω Cen suffered a much more complex evolutionary path (as witnessed by several indicators), and we do not have any reason to exclude low-mass AGB stars from contributing to the chemical enrichment. Rather, the exceptionally high abundances of *s*-process elements displayed by some cluster stars do suggest that low-mass polluters played a fundamental role in the protocluster enrichment (Johnson et al. 2009 and references therein).

2.3.3 Massive star pollution scenario

In an attempt to overcome the shortcomings of the AGB star pollution scenario, Decressin et al. (2007a,b) have proposed the winds of FRMSs as the source of the chemical 'anomalies' in GCs. Their study is limited to the case of two-population clusters where the first generation of stars is already in place.

Here, we analyse the implications of the winds of FRMSs scenario in the framework of our complete modelling of the chemical enrichment of the whole stellar population of ω Cen. Of course, our analysis does not correspond exactly to their case, because the original scenario strictly applies to two-population clusters, whereas we are dealing with a much more complex population in ω Cen. In Fig. 5, we show the cumulative ejecta in the winds of FRMSs during ω Cen's parent galaxy evolution (left-hand panel), as well as their chemical composition as a function of time: the He enrichment, [Na/Fe] ratio and [O/Fe] ratio are displayed in the top-right, middle-right and bottom-right panels, respectively. The solid lines are the model predictions, while the shaded areas represent the range of observed values for peculiar stars. It is seen that any star formed from the pure ejecta of the slow winds from FRMSs will have the extreme He abundance required by the location of the blue MS on the CMD of ω Cen, but the corresponding Na abundance will be too low. In this respect we note that, while the yields of He and CNO elements from FRMSs are provided for a wide grid of initial stellar metallicities (see works by Meynet & Maeder 2002a; Hirschi et al. 2005; Hirschi 2007; Ekström et al. 2008), Na yields have been computed only for stars with initial metallicity [Fe/H] = −1.5 (Decressin et al. 2007a). The adoption of metallicity-dependent yields of Na from FRMSs could, in principle, counterbalance the effect on the [Na/Fe] ratio due to the increasing Fe production from SNe Ia with increasing time in ω Cen host galaxy. Na yields from massive stars computed by Kobayashi et al. (2006) without taking stellar rotation into account increase with increasing the initial metallicity of the stars (see Kobayashi et al. 2006, their table 3). Should the inclusion of rotation preserve the trend found by Kobayashi et al. (2006), Na production from FRMSs could eventually overwhelm that of Fe from SNeIa. In this case, the O-poor stars born in the latest stages of the protocluster formation (Fig. 5, bottom-right panel) would also be Na-rich, thus producing the Na–O anticorrelation, as observed.

Note that the trend of decreasing [O/Fe] with time in the slow-wind ejecta of FRMSs simply reflects the evolution of the [O/Fe] ratio in the ISM of the host galaxy. Any O and Fe produced within the massive stars themselves, in fact, do not enter the composition of the slow-wind ejecta. Both these elements, in fact, are expelled later through fast polar winds and SN explosions (see Decressin et al. 2007a).

3 DISCUSSION AND CONCLUSIONS

It is common wisdom that ω Cen is the naked nucleus of a dwarf spheroidal galaxy that was ingested and partly disrupted by the

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[3] Note that the Na yields published by Karakas & Lattanzio (2007) that we use here (Fig. 4, dashed lines) are being revised downwards (Karakas, private communication). This should bring the model predictions in better agreement with the observations.

Milky Way some 10 Gyr ago (see e.g. Dinescu et al. 1999; Gnedin et al. 2002; Bekki & Norris 2006; Romano et al. 2007; Bellazzini et al. 2008). It is also customarily acknowledged that metal-enriched winds are the most straightforward explanation of the observed properties of dwarf galaxies (see the recent review by Tolstoy, Hill & Tosi 2009 and references therein).

In the case of ω Cen's progenitor, we have found, indeed, that significant outflow is needed in order to reduce the effective yield per stellar generation and explain the observed properties (the stellar metallicity distribution function, age–metallicity relation and the trends of several abundance ratios with metallicity; Romano et al. 2007; see also Ikuta & Arimoto 2000). Following the results of hydrodynamical simulations by Recchi et al. (2001), we have assumed that elements produced by SNe are lost more efficiently than others. The lowest efficiency of ejection through the outflow has been assigned to hydrogen and helium. This is a common choice when dealing with the chemical evolution of local dwarf spheroidals, and it leads to a good reproduction of several observed properties (e.g. Lanfranchi & Matteucci 2003). However, no direct measurements of He are available for local dwarf spheroidals: since they lack gas, they cannot be observed for optical/radio recombination lines. Thus, the efficiency of He entrainment in the galactic wind is, as a matter of fact, totally unconstrained. With this in mind, the challenging bet is: could ω Cen's parent galaxy *retain most of its helium,* while still *ejecting most of the heaviest species*?

Up to now, three major scenarios have been proposed for the origin of the helium-enriched populations in ω Cen, as well as in other massive GCs:

(A) accretion of helium-rich material by pre-existing stars;
(B) star formation out of the ejecta from either massive AGB stars (B1) or FRMSs (B2);
(C) pollution by Population III stars.

Recently, Renzini (2008) has reviewed them critically and concluded that only the AGB option (B1) appears to be acceptable; the others result in either a spread of helium abundances (A and B2) or a certain degree of enrichment in heavy elements as well (C). However, for the AGB option to work, AGB stars more massive than 3 $M_\odot$ must experience just a few TDU episodes and the cluster hosting the He-rich population must be the remnant of a more massive systems. Detailed stellar modelling (Ventura & D'Antona 2008a,b) shows that only AGB stars above 4–5 $M_\odot$ can actually reach the required levels of He enhancement in their atmospheres.

In this paper, we have thoroughly analysed the issue of the formation of He-rich stars in ω Cen by means of a complete model for its chemical evolution. In ω Cen, we are facing a *primary population* (about 50 per cent of the stars, with $\langle[\mathrm{Fe/H}]\rangle \simeq -1.7$ and 'normal' He) and a *secondary population* (at intermediate, $\langle[\mathrm{Fe/H}]\rangle \simeq -1.4$, and extreme, $\langle[\mathrm{Fe/H}]\rangle \simeq -0.6$, metallicities). At least part of the secondary-population stars may be He enhanced.

Although the interaction with the Milky Way is likely to have played some role in shaping the chemical properties of (at least part of) the stellar population in ω Cen, we find a good agreement between predictions from standard chemical evolution models (that do not take all the relevant dynamical processes into account) and observations of average abundances and abundance ratios by assuming that a galactic-scale outflow vented out mainly matter enriched in SN products, while mostly retaining the ejecta of slow stellar winds, irrespective of the initial mass of the stellar progenitor. Besides this ejection of enriched gaseous matter, the cluster progenitor must have lost a major fraction of stars somehow later on during its evolution. In summary, we show that, in order to explain the existence of extreme He-rich stellar populations, *what really matters is the kind of evolution the host system went through, rather than the kind of stars responsible for a 'super He production'.*

In ω Cen, because of the relatively long-lasting star formation (some 10^9 years), stars of initial mass as low as 2 $M_\odot$ had the time to contribute significantly to the chemical enrichment of the ISM. This is clearly witnessed by the high *s*-process abundances displayed by some cluster stars (e.g. Johnson et al. 2009). If cooling flows developed to collect the AGB ejecta in the innermost galactic regions where chemically peculiar stars were born, it can be hardly told which selective mechanism brought only the ejecta from 4–5 to 8 $M_\odot$ AGB stars to the cluster core, while leaving behind those from lower mass stars. Including a contribution to the chemical enrichment from super-AGB stars could help the AGB star pollution scenario to produce results in agreement with the observations (e.g. Pumo et al. 2008), but up to now no nucleosynthetic yields from this class of objects have been provided in the literature for use in chemical evolution studies.

The competing scenario of pollution from slow winds of FRMSs, while being able to reproduce, in principle, the peculiar abundances and abundance ratios required by the observations of chemically peculiar stars, is hampered by a number of assumptions about, for instance, the efficiency of meridional circulation to mix the products of core H-burning in the stellar envelope, or the rate of mass loss through the mechanical wind, or the need for the development of a large contingent of fast rotators in GCs. Since the matter expelled through the equatorial discs of FRMSs is available with the 'right' He abundance since the very beginning of the proto-ω Cen formation (see Section 2.3.3 and Fig. 5), it is not clear why an extreme He-rich population should form only later on, at metallicities around $[\mathrm{Fe/H}] \sim -1.2$ (and possibly higher).

As a last comment, it is worth stressing that abundances of He as high as that required to explain the blue MS of ω Cen have never been observed elsewhere. Although we may think about mechanisms able to originate extreme He-rich stellar populations, we must also be aware that the existence of such extremely high He abundances still awaits a confirmation from spectroscopic observations.

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APPENDIX A: MODEL BASIC ASSUMPTIONS AND EQUATIONS

The chemical evolution model is one zone, with instantaneous and complete mixing of gas inside it. The instantaneous recycling approximation is relaxed, i.e. the stellar lifetimes are taken into account in detail. We follow the evolution of several stable chemical species and their isotopes (H, D, He, Li, C, N, O, F, Na, Mg, Al, Si, S, K, Ca, Sc, Ti, V, Cr, Mn, Co, Fe, Ni, Cu, Zn) by means of integro-differential equations taking the form

$$\begin{aligned}\frac{\mathrm{d}\mathcal{G}_i(t)}{\mathrm{d}t} &= -X_i(t)\psi(t)\\ &+ \int_{m_l}^{m_{B_m}} \psi(t-\tau_m)\mathcal{Q}_{mi}(t-\tau_m)\varphi(m)\mathrm{d}m\\ &+ A\int_{m_{B_m}}^{m_{B_M}} \varphi(m_B)\\ &\times \int_{\mu_{\min}}^{0.5} f(\mu)\psi(t-\tau_{m_2})\mathcal{Q}_{m_1 i}(t-\tau_{m_2})\mathrm{d}\mu\mathrm{d}m_B\\ &+ (1-A)\int_{m_{B_m}}^{m_{B_M}} \psi(t-\tau_m)\mathcal{Q}_{mi}(t-\tau_m)\varphi(m)\mathrm{d}m\\ &+ \int_{m_{B_M}}^{m_u} \psi(t-\tau_m)\mathcal{Q}_{mi}(t-\tau_m)\varphi(m)\mathrm{d}m\\ &+ \frac{\mathrm{d}\mathcal{G}_i^{\mathrm{in}}(t)}{\mathrm{d}t} - \frac{\mathrm{d}\mathcal{G}_i^{\mathrm{out}}(t)}{\mathrm{d}t}. \qquad \text{(A1)}\end{aligned}$$

Equation (A1) shows that the abundance of a given element i changes with time because of the processes of star formation, mass return from dying stars and infall (outflow) of gas towards (from) the system.

In particular, $\mathcal{G}_i(t)$ is the gaseous mass in form of element i at a given time t normalized to a baryonic mass $\mathcal{M}_{\mathrm{bar}} = 10^9\ \mathrm{M}_\odot$ (see Section 2.1), $X_i(t)$ is the abundance by mass of element i at the time t, $\psi(t)$ is the star formation rate (SFR) at the time t, τ_m is the lifetime of stars with initial mass m and $\varphi(m)$ is the IMF.

The SFR is expressed as

$$\psi(t) = \nu\mathcal{G}^k(t), \qquad \text{(A2)}$$

where $\nu = 0.35$ Gyr^{-1} is the star formation efficiency, $\mathscr{G}(t) = \mathscr{M}_{\rm gas}(t)/\mathscr{M}_{\rm bar}$ is the normalized gaseous mass at the time t and $k = 1$.

At variance with Galactic field populations, current observational evidence seems to favour a Salpeter-like IMF in both dwarf spheroidals and Galactic globulars (Wyse 2005 and references therein). Hence, we assume a Salpeter (1955) IMF, extrapolated and normalized to unity over the 0.1–100 M$_\odot$ stellar mass range. However, the current mass function of ω Centauri is better reproduced by a broken power law, with indices $\alpha = -2.3$ for $m > 0.5$ M$_\odot$ and $\alpha = -0.8$ for $m < 0.5$ M$_\odot$ (Sollima, Ferraro & Bellazzini 2007). We have checked that the results presented in this paper are not affected by our choice of the IMF, because the low-mass stars act just as an extra sink of matter in chemical evolution models.

The integrals on the right-hand side of equation (A1) represent the rate at which element i is restored to the ISM by dying stars. We adopt the production matrix formalism (Talbot & Arnett 1973) and compute the quantities

$$\mathscr{Q}_{mi}(t - \tau_m) = \mathscr{Q}_m X_i(t - \tau_m), \qquad \text{(A3)}$$

i.e. the fractional mass of the star of initial mass m that is restored to the ISM as element i when the star dies, according to different nucleosynthesis prescriptions. The dependence on time is driven by the dependence of the yields on metallicity. The integration limits m_l and m_u refer to the lowest (0.8 M$_\odot$) and highest (100 M$_\odot$) mass contributing to galactic enrichment, while $m_{B_m} = 3$ M$_\odot$ and $m_{B_M} = 16$ M$_\odot$ are the lower and upper limits for the total mass of binary systems leading to SNIa explosions (Matteucci & Greggio 1986). The first, third and fourth integrals refer to the contributions from single stars; the second one takes into account the chemical enrichment by SNeIa: m_B is the total mass of the system giving rise to an SNIa explosion; m_1 and m_2 are the masses of the primary and secondary stars, respectively, and $f(\mu)$ is the distribution function for the mass fraction of the secondary (after Matteucci & Greggio 1986, to which we refer the reader for more details). A is a free parameter, constant in time and space. It gives the fraction of mass per stellar generation that ends up in SNIa precursors. It is fixed by the SNIa rates observed in galaxies of different morphological type.

The last two terms on the right-hand side of equation (A1) represent the positive contribution from infall of pristine matter and the negative one of any outflow of gas from the system. They read as

$$\frac{\mathrm{d}\mathscr{G}_i^{\rm in}(t)}{\mathrm{d}t} = \frac{X_i^{\rm in}\exp(-t/\tau)}{\tau[1 - \exp(-t_{\rm now}/\tau)]} \qquad \text{(A4)}$$

and

$$\frac{\mathrm{d}\mathscr{G}_i^{\rm out}(t)}{\mathrm{d}t} = w_i X_i(t)\mathscr{G}(t), \qquad \text{(A5)}$$

respectively, where $\tau = 0.5$ Gyr is the time-scale for infall, $X_i^{\rm in}$ are the abundances of the infalling gas (set to their primordial values; see Romano et al. 2003), $t_{\rm now} = 13.7$ Gyr (Tegmark et al. 2006) is the age of the universe now and w_i (in units of Gyr^{-1}) is a free parameter that describes the efficiency of the galactic wind (it takes different values for different elements; in particular, it takes into account the results of dynamical studies that SN ejecta leave the galaxy more easily than the unperturbed ISM – see e.g. Recchi et al. 2001 and references therein). The time of the onset of the galactic wind is self-consistently computed (see Romano et al. 2007 and references therein).

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