Models for the lithium abundances of multiple populations in globular clusters and the possible role of the Big Bang lithium

Francesca D’Antona¹, Annibale D’Ercole², Roberta Carini¹,³, Enrico Vesperini⁴, & Paolo Ventura² *

¹ INAF, Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monteporzio Catone (Roma), Italy.
² INAF- Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 BOLOGNA (Italy).
³ Department of Physics, Università di Roma “La Sapienza”, Roma, Italy
⁴ Department of Physics, Drexel University, Philadelphia, PA 19104, USA

ABSTRACT

Globular cluster stars show chemical abundance patterns typical of hot–CNO processing and photometric evidence for the presence of multiple populations. Lithium is easily destroyed by proton capture in stellar environments, so determining its abundance may be crucial to discriminate among different models proposed to account for the origin of the gas from which the multiple populations form. In order to reproduce the observed O–Na anticorrelation and other patterns typical of multiple populations, the formation of second generation stars must occur from the clearly processed stellar ejecta, responsible of the chemical anomalies, diluted with pristine gas having the composition of first generation stars. This gas is either a remnant of the first phases of star formation, or it has been re-accreted on the cluster core after the end of the SN II explosions. As a consequence, the lithium abundance in the unprocessed gas—which is very likely to be equal to the lithium abundance emerging from the Big Bang—affects the lithium chemical patterns among the cluster stars. This paper focuses on a scenario in which processed gas is provided by asymptotic giant branch (AGB) stars. We examine the predictions of this scenario for the lithium abundances of multiple populations. We study the role of the non–negligible lithium abundance in the ejecta of massive AGB (A(Li)∼2), and, at the same time, we explore how our models can constrain the extremely large —and very model dependent— lithium yields predicted by recent super–AGB models. We show that the super–AGB yields may be tested by examining the lithium abundances in a large set of blue main sequence stars in ω Cen and/or NGC 2808. In addition, we examine the different model results obtained by assuming for the pristine gas either the Big Bang abundance predicted by the standard models (A(Li)=2.6–2.7), or the abundance detected at the surface of population II stars (A(Li)=2.2–2.3), and we show that, once a chemical model is well constrained by a comparison with the observations, the O–Li distribution could perhaps be used to shed light on the primordial lithium abundance.

Key words: stars: Population II; stars: abundances; stars: AGB and post-AGB; globular clusters: general.

1 INTRODUCTION

The spread of light elements abundances in globular clusters is larger than in field stars of similar metallicity and requires the presence of a population of stars formed from matter processed through the hot CNO cycle and by other proton–capture reactions on light nuclei (hereafter we will refer to this population as second generation, SG). The site of processing of this matter in the first generation (FG) stars of the proto-cluster is a subject of intensive investigation. The two main scenarios are: the “AGB scenario”, in which the site of processing are the hot bottom burning
envelopes of massive asymptotic giant branch (AGB) stars (Ventura et al. 2001, D’Antona & Caloi 2004, Karakas et al. 2004), and the “fast rotating massive stars (FRMS) scenario” (Prantzos & Charbonnel 2004, Meynet et al. 2004, Decressin et al. 2007a), in which the site is the interior of fast rotating massive stars.

Problems are present in both scenarios (see, e.g., Renzini 2008, for a critical review). In all the scenarios proposed so far, the composition of SG stars is, in most cases, best explained by dilution of the polluting ejecta with pristine gas (see, e.g., D’Ercole et al. 2011). One possible discriminant between the two scenarios is the comparison between the abundance of lithium in FG and SG stars. In fact, massive stars destroy lithium, while massive AGB produce it at the beginning of the HBB (Ventura et al. 2002), so possibly the prediction of the two models differ. Also for other scenarios lithium can be a powerful discriminant: the polluting matter is Li–free also if it comes from runaway collision between massive stars (Sills & Glebbeek 2010), or non–conservative evolution of massive binaries (de Mink et al. 2009), while the diluting gas may be Li–free, if it comes from mass loss from FG stars by winds (Gratton & Carretta 2010), and also if it is made up by the matter in non conservative evolution of interacting close binaries (Vanbeveren et al. 2012) or stripped during close encounters in the cluster core (Carini et al. 2012).

Self–consistent models to study the chemical evolution of lithium in multiple–population GCs are still lacking, while some sets of observational data are already available. Decressin et al. (2007a) show that the anticorrelation Li–Na in the data of NGC 6752 (Pasquini et al. 2005) are fully compatible with a simple dilution model, but Shen et al. (2010) present new data Li–O, probably not compatible with dilution with Li–free matter. In other clusters, like NGC 6397 (Lind et al. 2009), M 4 (D’Orazi & Marino 2010; Monaco et al. 2012), 47 Tuc (D’Orazi et al. 2010) the FG and SG stars have very similar lithium content, and Li–depleted stars may be attributed to convective dilution. Naively, the similar abundances in these clusters seems in better agreement with the AGB scenario.

In this paper, we study the lithium abundance patterns resulting from the chemical evolution models presented by D’Ercole et al. (2010) (Paper I) and D’Ercole et al. (2012) (Paper II). The models are based on the AGB scenario, and on the hydrodynamical computations by D’Ercole et al. (2008), and can reproduce the chemical patterns both in clusters having an extended O–Na anticorrelation, like NGC 2808, and in clusters showing a mild anticorrelation, like M 4.

The outline of the paper is the following. In Sect. 2 we briefly summarize the model, describe the lithium yields of the AGB and super–AGB models. As there is a still debated discrepancy between the predictions for primordial lithium from the standard Big Bang nucleosynthesis and the abundance observed in the atmospheres of population II stars, an additional hypothesis must be made, concerning the choice of the initial lithium abundance in the diluting pristine gas. Sect. 3 compares the data by Monaco et al. (2012) for M 4 with the models that account for the O–Na anticorrelation.

In Sect. 4 we show that the predictions for lithium in the model for NGC 2808 is relevant also for a comparison with the data by Shen et al. (2010) for NGC 6752. We will show that in this case the lithium yield of AGB stars is necessary to reproduce the observations, and a better determination of the O–Li patterns may provide an independent constraint on the lithium abundance emerging from Big Bang.

Sect. 5 shortly examines the case of dilution of nuclearly processed ejecta with lithium–free gas.

The possible constraints posed by multiple population abundance patterns on the Big–Bang lithium abundance are further discussed in Sect. 6. In Sect. 7 we summarize our conclusions.

2 INPUTS OF THE MODEL

2.1 The chemical evolution model

The chemical evolution model, described in detail in Paper I and Paper II, assumes that the proto–GC becomes completely devoid of pristine gas at the end of the SN II epoch, and begins a new star formation epoch when the low velocity winds of the super–AGB stars first, and of the massive AGB stars later on, collect in a cooling flow in the cluster core. Formation may occur directly from the super–AGB and AGB ejecta, but a phase of re–accretion of pristine gas (see e.g. D’Ercole et al. 2008, 2011) may lead to dilution of the ejecta with the original matter. This phase is characterized by an epoch of maximum accretion of pristine gas, $t_{\text{acc}}$, and a timescale of accretion $\tau_{\text{pri}}$, that in our formulation is the standard deviation of the gaussian describing the process. A third parameter, the end ($t_{\text{end}}$) of the second star formation epoch, provides a further independent timing of the process. It is also possible to accumulate and mix the ejecta for a time $t_1$ before starting star formation. Further details on the general behavior of models and on the adopted symbolism can be found in Paper I. In Paper II we introduced in the model the new yields for super–AGB models from 6.5 to $8 M_\odot$ computed by Ventura & D’Antona (2011), that complement the results by Ventura & D’Antona (2006), to revise the results presented in Paper I. In this work we explore the multiple generation lithium distribution resulting from some of the models computed in Paper II for the clusters M 4 and NGC 2808. The main parameters of the chosen models are summarized in Table 1. We then extend the model discussion to other clusters for which data of lithium abundances are available (NGC 6397, NGC 6752, ω Cen).

2.2 Lithium abundances in AGB and super–AGB ejecta

For the sake of completeness, we list in Table 2 the lithium abundances in the ejecta of AGB and super–AGB stars adopted in this work, and the evolutionary times of the corresponding masses. Notice that the assumptions on the initial lithium abundance in the gas forming the FG stars have no consequences on the yields. In fact, the initial lithium is fully depleted in the stellar envelopes, by the time the lithium production due to the Cameron–Fowler (1971) mechanism begins (Ventura et al. 2002). There are some differences between these abundances and the ones listed in Ventura & D’Antona (2010), due to recomputation of some evolutionary tracks. There is a discontinuity in the lithium
in these giants lithium is drastically reduced, both by standard
and deep mixing. The abundances in the ejecta of the masses 5–6.5
M$_\odot$ that should contribute to the SG are A(Li)$\sim$2.0. Consequently, the AGB
ejecta will be important for the final lithium content in the
SG stars only in case B of Table 3 (see Sect. 2.3), namely,
abundances as a function of the mass, that can be seen from Fig. 1 and Table 2 for increasing initial mass, the lithium abundances first decreases, reaching a minimum of A(Li)$\sim$1.9 at 5.5 M$_\odot$, then increases again. The initial de-
crease is due to the increasing temperatures at the bottom of
the convective envelopes, that imply a faster lithium pro-
duction and destruction. For the larger masses, the higher
luminosities provoke larger mass loss rate at the stage of
lithium production, and the abundance increases again. Nev-
evertheless, there is a second minimum in the abundance at a
mass of 7 M$_\odot$, that is the first mass for which the lithium
production occurs before the beginning of the thermal pulse
phase. For M=7.5 and 8 M$_\odot$ the mass loss is dominant and
huge quantities of lithium are lost to the interstellar medi-
um, finally raising the lithium in the ejecta to values such as
A(Li)$\sim$2.0. Consequently, the AGB ejecta of the 8 M$_\odot$ star. As remarked above (see also
Ventura & D’Antoni [2010]), this result is very uncertain, as
it may be due to an overestimate of the mass loss rate during
this evolution. Values of lithium abundances much smaller
both for the 8 and 7.5 M$_\odot$ stars are possible, without sig-
nificantly affecting the sodium and oxygen abundances. As
we will further discuss below, new observations will allow to
put tighter constraints on the lithium yields of these stars.

In Fig. 1 we also show the Li–Na–O abundances in the
ejecta of super–AGB and AGB stars from Table 1 in Pa-
er II. The most striking characteristic of these abun-
dances is the very large Li and Na abundances reached in
the ejecta of the 8 M$_\odot$ star. As remarked above (see also
Ventura & D’Antoni [2010]), this result is very uncertain, as
it may be due to an overestimate of the mass loss rate during
this evolution. Values of lithium abundances much smaller
both for the 8 and 7.5 M$_\odot$ stars are possible, without sig-
nificantly affecting the sodium and oxygen abundances. As
we will further discuss below, new observations will allow to
put tighter constraints on the lithium yields of these stars.

In Fig. 1 we also show the much smaller oxygen val-
ues (due to deep extra–mixing) that Paper II assumes to be
present at the surface of SG stars formed directly from the
super–AGB ejecta, and thus having very high helium
content. The values plotted refer to the abundances in the
ejecta but, obviously, the lithium abundances in giants will
be much smaller than those plotted since lithium will be
strongly diluted, both by standard and deep mixing. The
abundances in the ejecta of the masses 5–6.5 M$_\odot$ that should
cntribute to the SG are A(Li)$\sim$2.0. Consequently, the AGB
ejecta will be important for the final lithium content in the
SG stars only in case B of Table 3 (see Sect. 2.3), namely,
when the Li abundance in the diluting pristine gas is as low as that shown in the atmosphere of normal population II stars: if the initial Li is $A(\text{Li})=2.6$, it is difficult that abundances 0.6 dex smaller (a factor 4 smaller!) in the ejecta may alter the Li content of the mixture in a significant way different from ejecta with no lithium at all.

### 2.3 Assumptions for the Big Bang Lithium abundance

The application of the dilution model for lithium abundances is not as straightforward as for the other elements. In fact, we do not know observationally the lithium abundance of the pristine gas. The standard Big–Bang nucleosynthesis (BBN), with the cosmological parameter $\eta=N(\text{baryons})/N(\text{photons})$ constrained by the observations of the satellite WMAP, provides $A(\text{Li})=2.64\pm0.04$ (Spergel et al. 2007), or even higher, $A(\text{Li})=2.72\pm0.05$ when updated rates are taken into account for the $^3\text{He}(\alpha, \gamma)^7\text{Li}$ reaction (Cyburt et al. 2008). The values computed from the analysis of spectra of population II dwarfs are $A(\text{Li})=2.37\pm0.06$ (Meléndez & Ramírez 2004), or $A(\text{Li})=2.23\pm0.07$ in the non–LTE analysis by Asplund et al. (2004). We have to deal with the abundances into play by considering all the possible explanations of this discrepancy (see Fields 2011, for a recent review). The possible choices are:

- **(i)** we reject the standard BBN scenario (for a review, see, e.g. Iocco et al. 2009) and assume that the abundances observed in pop. II stars (and in the FG stars of GCs) are the primordial abundances. Thus we adopt $A(\text{Li})=2.20$ or 2.30 as value for the pristine diluting gas;
- **(ii)** we accept the standard BBN, but assume that lithium has been subject to depletion before the cluster formation, by means of the reprocessing of the primordial gas in a first generation of massive, hot stars (population III) (Piau et al. 2006). As in the previous case, we adopt $A(\text{Li})=2.20$ or 2.3 in the FG stars and in the diluting FG gas.
- **(iii)** we assume that Li is depleted in the atmosphere of both FG and SG stars, as a consequence of phenomena such as diffusion, gravity waves, rotational mixing, or any combination of these. In this case, we assume $A(\text{Li})=2.60$ or 2.7—as representative of the BBN abundance—for the pristine diluting gas. We also assume that the atmospheric effect in SG stars is the same that depletes lithium in the FG stars, and reduces by $\delta A(\text{Li})=0.3$ to 0.5 dex the abundance of the mixed gas that forms the SG stars. Obviously, a depletion by 0.3 or 0.5 dex have different weight on the fit of observed data.

In order to begin exploring the range of parameters, we assume an initial $A(\text{Li})_{\text{pristine}}=2.2$, or $A(\text{Li})_{\text{pristine}}=2.7$ for M4, and $A(\text{Li})_{\text{pristine}}=2.3$, or $A(\text{Li})_{\text{pristine}}=2.6$ for the models of NGC 2808. This is also very naively motivated by the FG abundances listed by different authors for the FG stars in different clusters.

### 2.4 Reference case

Our standard case studies the SG stellar lithium abundances predicted by some of the models we presented in Paper II and that well reproduce the abundance patterns in NGC 2808 and M 4. The lithium abundances in the ejecta of super–AGB and massive AGB are taken from Table 2 while all the other abundances are listed in Table 1 of Paper II. Table 3 lists as cases A and B the two choices discussed above concerning the lithium in the pristine gas.

---

1. We quote an eye–averaged value for the data in the iron range – 2.5<$[\text{Fe}/\text{H}]<$–1.2. Actually, the Asplund et al. (2006) results show a clear trend with metallicity. The trend becomes a spread at $[\text{Fe}/\text{H}]<$2.7 (Sbordone et al. 2010).
2. The apparent lack of slope in the Spite plateau is an observational constraint that models can achieve by combining diffusion with some form of turbulence at the bottom of the atmospheric convective zone (Richard et al. 2005; Korn et al. 2006, 2007; Piau 2008; Lind et al. 2009b). The effect of turbulence is still introduced in a parametric way in the models.
Models for the lithium abundances of multiple populations in globular clusters

2.5 Other cases

We compare these “standard” results with two other different possible combinations listed in Table 3: case C in which the FG ejecta have no lithium at all (here the initial abundance of lithium in the pristine gas is irrelevant); cases D & E, in which we reduce the yield of the 7.5 and 8 $M_\odot$ to much lower values $A$(Li)$=2.0$, and finally we consider a case F, in which AGB ejecta are diluted with gas having no lithium.

3 THE CLUSTERS WITH A MILD O–NA ANTICORRELATION

3.1 M 4

In Fig. 2 we show the recent data provided by Monaco et al. (2012) for a sample of main sequence and subgiant stars in M 4, and compare them to the data for giants in the same clusters, given by D’Orazi & Marino (2010). The giants data (scale on the right) are shifted to take into account the convective dilution during the evolution. We notice that the two samples provide a slightly different Li–Na trend: the Monaco et al. (2012) sample shows a slight negative slope (the authors show that the difference in $A$(Li) between the low sodium (FG) sample and the high sodium (SG) sample is $\sim 0.1$ dex), while the D’Orazi & Marino (2010) data simply show a larger scatter in the higher sodium data. The sodium zero point also differs by $\sim 0.1$ dex between the two sets. As we will compare the models results with the Monaco et al. (2012) sample, the slight trend Li–Na is a significant ingredient of the comparison and affects considerably our interpretation.

In Paper I we provided a “standard” model to describe
the huge lithium abundances in the 7.5 and 8 M\textsubscript{\odot} giant branch stars in M4 (open pentagons with error bars) are compared with the results of the simulation M4-0 (from Table 2 by D’Ercole et al. (2012)). Blue triangles are the first generation points, black squares are the SG points. The left panel shows case B (A(Li)=2.2 in the pristine diluting gas), the right panel represents case A (A(Li)=2.7). The red line in both panels represents the gas composition along the evolution. The initial part of the curve (at large lithium and sodium abundances) is scarcely populated due to the fast evolution of the gas composition and to the low star formation rate assumed (see Table 1).

Figure 3. The sample by Monaco et al. (2011) for turnoff - subgiant branch stars in M4 (open pentagons with error bars) are compared with the results of the simulation M4-0 (from Table 2 by D’Ercole et al. (2012)). Blue triangles are the first generation points, black squares are the SG points. The left panel shows case B (A(Li)=2.2 in the pristine diluting gas), the right panel represents case A (A(Li)=2.7). The red line in both panels represents the gas composition along the evolution. The initial part of the curve (at large lithium and sodium abundances) is scarcely populated due to the fast evolution of the gas composition and to the low star formation rate assumed (see Table 1).

The “short” O–Na anticorrelation of clusters like M 4, but in Paper II we have shown another class of viable models in which SG stars are formed from super–AGB ejecta strongly diluted with pristine matter. Fig. 3 shows the results of the standard simulation (M4-0) of Paper II, in which the bulk of accretion of pristine matter and star formation of the SG stars occurs during the evolution of the masses from \(\sim 6.5\) to \(\sim 5\, M\textsubscript{\odot}\). In this figure and in the following ones, we display as (blue) triangles the FG stars, and as (black) squares the SG stars. A stochastic error in the range 0–0.1 dex, comparable to the observational errors, is introduced, scattering the position of the stars, either with respect to the assumed FG abundances \([\text{O/Fe}]=0.4, \,[\text{Na/Fe}]=0, \,\text{A(Li)}=2.2\) for the triangles, or with respect to the red line, representing the path of the gas composition during the SG formation, starting from top right and ending to the bottom left. The lithium abundance of the SG stars is very similar to that of the FG stars, if we are dealing with case B (A(Li)=2.2 or 2.3), because the lithium in the ejecta is very similar to what we assume to be the abundance in the pristine gas. On the contrary, if we deal with case A (A(Li)=2.6 or 2.7), the abundances in the ejecta are on average smaller than the pristine gas abundance, and the SG shows a slightly reduced lithium abundance, in full agreement with the data.  

In Fig. 4 we show instead the results of the simulations made in Paper II, in which the super–AGB have a dominant role for the formation of the SG. It is evident that the huge lithium abundances in the 7.5 and 8 M\textsubscript{\odot} ejecta have led to an increase in the average SG star lithium abundance. In the leftmost column of Fig. 4 we show case B for cases M4-2, 3, 4 and 5 (from top to bottom). The average lithium in the SG is \(\sim 0.15-0.2\) dex larger than the FG abundance, while the observations show that it is \(\sim 0.1\) dex lower: this full factor two difference rules out case B. The second column from left shows case A: here the situation is more ambiguous, and these models can not be excluded (see in particular case M4-2). In the third and fourth columns, we show respectively case E and case D – where we reduce the yield from the 7.5 M\textsubscript{\odot} and 8 M\textsubscript{\odot} to A(Li)=2.0: both cases are acceptable, apart from the model M4–5 in the last row. Finally, the rightmost column shows the results obtained if we assume that the ejecta have no lithium, but maintain the sodium abundance of AGB–super AGB ejecta in the polluting matter (case C). It is obvious that, in this case, assuming different Big Bang initial lithium is irrelevant. The results show a very good agreement with the observations in all cases.

We see then that the M 4 data do not allow to discriminate between the AGB scenario and other scenarios in which the polluting matter is very sodium rich, but Li–free like in the FRMS model. Some models of the AGB scenario reproduce well the M 4 Li–Na patterns, but the Li in the super–AGB ejecta is not a necessary ingredient.

Fig. 3 and 4 also show that the models predict the presence of a few stars with very large lithium abundance (see Sect. III for a discussion of the difference in maximum lithium between case A and B). In M 4, Monaco et al. (2012) find that the star 37934 has A(Li)=2.9 ad relatively high sodium \([\text{Na/Fe}]=0.37\). Could it be born in the minute subsample of cluster stars formed directly from the super–AGB ejecta, just before the strong dilution with pristine gas that gave birth to most of the SG? Actually, we notice that the abundance of sodium predicted by the simulations is too large \([\text{Na/Fe}]\sim 1\), but a further exploration of the parameter space could be worth. We also remark two consequences of this interpretation: 1) this star should be very helium rich. Its location at the left border of the main sequence turnoff stars (Figure 1 in Monaco et al. 2012) leaves this possibility open; 2) the HB of M 4 should include a few hot blue tail stars, representing the HB phase of these few very helium rich stars.

Another cluster, NGC 6397 presents a case of a super–Li rich turnoff star (Koch et al. 2011). Here A(Li)\sim 4, close to our extreme predictions for the 8 M\textsubscript{\odot} super–AGB uncertain evolution. According to our models, this super–Li rich star should also be characterized by a huge sodium abundance, but a preliminary study of its spectrum (private communication by K. Lind) appears to indicate a normal sodium abundance.

3 In the standard case for M4 in Paper II we assume that the sodium yields for M4 are a factor two larger than those listed in Table 1 of that paper. This is done because neon is overabundant in the stars of this cluster, so that we should expect that also the sodium yield is larger (see the discussion in Paper I). For this reason, the two stars with very high lithium in this simulation have sodium as large as \([\text{Na/Fe}]\sim 1.3\), a factor two larger than the abundance provided by the maximum super–AGB mass 8 M\textsubscript{\odot} \([\text{Na/Fe}]\sim 1\).

4 Notice that case B (and, with it, a Big Bang lithium abundance A(Li) as low as 2.2), is excluded — if these models represent a correct reproduction of the SG formation in M4— only thanks to Monaco et al. (2012) data, showing the mild anticorrelation Li–Na. It would not be excluded based on previous observations. Thus we remark here how crucial it is to get precise lithium determinations in multiple populations.
3.2 NGC 6397

The lithium abundances in the stars of NGC 6397 have been presented by Lind et al. (2009). We commented in Paper II that NGC 6397 belongs to the clusters showing a mild O–Na anticorrelation and, as such, is a good candidate for a cluster in which the SG is formed by super–AGB ejecta strongly diluted with pristine gas. Unfortunately, we do not yet have models for the super–AGBs of metallicity as low as required to discuss in more detail this cluster (in particular, we expect smaller oxygen yields), but the interpretation of its data can be very similar to that presented for M 4 in Fig. 4. A strong dilution of the sodium rich, nitrogen rich and oxygen poor super–AGB ejecta may be an important factor to explain the problem of the Be abundance in two dwarfs of this cluster, analysed by Pasquini et al. (2004). Both these stars have beryllium consistent with a spallation production of this element, a production that well describes the relation between beryllium and iron (or oxygen) in halo stars (Boesgaard et al. 1999). Nevertheless, one of these stars is also oxygen depleted. Pasquini et al. (2004) consider the possibility that this may be a SG star, and correctly notice that it should also be beryllium depleted, if the polluted matter included in its formation was hot–CNO processed. But, if strong dilution of the super–AGB ejecta with pristine gas has taken place, the beryllium abundance in this SG star may remain close to that of the pristine gas, similar to what happens for the lithium abundance.

4 THE CLUSTERS HARBORING AN EXTREME SG

In this section we focus our attention on clusters that either have an extreme O–Na anticorrelation (such as NGC 2808), or for which the presence of a blue main sequence (MS) is evidence of the presence of a population with very large helium content (such as NGC 2808 and ω Cen), or have other signs of an high-helium population, like NGC 6752. In this latter cluster, the horizontal branch shows a high-temperature tail, that puts into evidence a high-helium content in a fraction of the SG stars (D’Antona et al. 2002), and the main sequence too has some indication of splitting (Monaco et al. 2010). Although this cluster is probably not as extreme as ω Cen and NGC 2808, it also seems to harbor three MSs identified by means of UV colors (Milone et al. 2012, in preparation). In addition it has an interesting set of O-Li abundances (Shen et al. 2010) that are worth of an analysis in terms of our models.

4.1 Predictions for the extreme populations: the blue MS of NGC 2808 and ω Cen

Paper II reproduces the O–Na anticorrelation and three different helium contents of the subpopulations in NGC 2808 by a two-stage process of SG formation, the first episode taking place from the pure super–AGB ejecta, leading to the very high helium stars populating the blue main sequence, the second episode occurring from ejecta diluted with pristine gas. As discussed, different models are possible for the timing and duration of the episode of pristine gas accretion, all consistent with the observed O–Na anticorrelation. In Fig. 5 we now examine the predictions for the Li–Na and Li–O patterns for the model NGC 2808-1 of Paper II, that reasonably represents both the O–Na anticorrelation and the probable helium difference between the FG and the extreme and intermediate SG displayed by NGC 2808. The SG points are 40% of the total, following the choice made in Paper II. The number of points is proportional to the time spent along the line (as well as to the star formation rate) so that very few stars have the extreme compositions that are linked to the short phase during which the polluters are the most massive super–AGBs.

4.2 The extreme population

Large lithium abundances are found in stars formed from pure super–AGB ejecta. We notice again the interesting role played by the value assumed for the Big Bang (or pristine) lithium abundance, by comparing the left and right panels, representing case B (A(Li)_{pristine}=2.3) and case A (A(Li)_{pristine}=2.6). In fact, the maximum Li achieved (for a given model of SG formation) is larger in case B, where we assume that the pristine gas has the same lithium abundance observed in population II stars. In this case, the atmospheric abundance coincides with the initial gas abundance, as no reduction is ascribed to mechanisms that deplete it. If the pristine gas has a larger, e.g. a standard Big Bang A(Li)=2.6, we implicitly assume that depletion mechanisms are acting at the surface, to bring this value down by ~0.3 dex. Some same mechanisms will apply also if the lithium abundance in the star is the result of the super–AGB ejecta high abundance.

Thus, contrary to simple intuition, lithium in SG stars (and in particular its maximum abundances, that are directly related to star formation from pure ejecta) will be ~0.3 dex smaller if the diluting gas has a larger abundance, in the stars that form from pure ejecta. This could not be noticed in the bulk of results for M 4 (but is evident in the two stars with extreme abundance), due to the strong dilution operating in that case.

An observational confirmation of these predictions would provide strong support to the AGB scenario as described by our models. However, we point out that if observations will not find a large lithium abundance in the blue MS, this would not falsify the AGB scenario but, rather, it would simply be an indication that the mass loss rates adopted for the models of 7.5 and 8 M⊙ are too extreme (see also the discussion of the models for M 4 in section 3.1). These observations are not yet available.

It is important to notice, however, that Monaco et al. (2010) measured or derived upper limits to the lithium abundances in 91 MS or early subgiant stars in ω Cen, finding a remarkable similar value A(Li)=2.19±0.14 for the whole sample. In their data, a few stars may have A(Li) close to 2.4–2.5 (still within 3σ from the average value), but certainly none has a lithium abundance as large as predicted in Fig. 5 for the blue MS stars in NGC 2808. ω Cen too has a blue MS (Bedin et al. 2004) that is interpreted to be very helium rich MS (e.g. Norris 2004). Observations aimed at selecting specifically blue MS stars to determine their lithium abundance could result in some detections of a very large lithium content. We remark again that high helium does not necessarily mean high lithium, as we show by plotting.
Figure 5. Li–Na and Li–O simulations for a cluster like NGC 2808, harboring an extreme, very helium rich, population and an intermediate one. The parameters refer to model NGC 2808-1 in Table 3. We further have $A(\text{Li})=2.3$ (left panels) and 2.6 (right panels). Blue triangles represent the first generation population, black squares represent the SG. The red line in both panels represents the gas composition along the evolution.

Figure 6. Lithium versus helium content in the ejecta of super–AGB and AGB stars. The dashed area includes masses of 8, 7.5, 7, 6.5, 6, 5.5 from top to bottom: all these ejecta would populate a “blue MS”, if they are not diluted with helium–poor pristine gas before forming SG stars. Only masses from 7.5 to $8\, M_\odot$ would show an outstanding lithium content.

Figure 7. O–Li data for NGC 6752 from Shen et al. 2010. Open symbols represent upper limits. In the plot, we have shifted $[\text{O}/\text{Fe}]$ by $+0.4$ dex, as the data in Shen et al. give a standard $[\text{O}/\text{Fe}]=0$ for the FG of this cluster, contrary to the observations by Carretta et al. (2009) that indicate oxygen enhancement for the FG stars in this cluster (see text). The line connects the (red) squares that show the O–Li yields from Ventura & D’Antona 2009, 2010 and 2011.

4.3 The intermediate population

Another interesting property of the simulations for NGC 2808 are the abundances of lithium in the intermediate populations: these result from mixing of pristine gas (this latter having a lithium content chosen according to cases A or B) with the lithium of the massive AGBs. As shown in Fig. 5 the lithium abundance in the intermediate population is lower than the pristine abundance, and the cases A and B provide interestingly different results. The choice of the pristine gas abundance affects the slope of the average relation Li–Na and Li–O, that are milder in case B. (see the discussion in Sect. 4.4). In any case, the finite amount of lithium in the ejecta of massive AGBs produces slopes milder than the slope 1 predicted in the case of pure dilution of pristine gas with lithium free, sodium-rich and oxygen-poor matter.

5 According to Monaco et al. (2010), the absence of stars with high Li abundance in their $\omega$ Cen sample suggests that these were not significantly polluted by lithium produced in AGB stars. This conclusion is not consistent with the models shown here.
4.4 The case of NGC 6752

NGC 6752 is the first cluster for which the O–Na anticorrelation has been observed in unevolved stars [Gratton et al. 2001], ruling out the possibility that the abundance anomalies are generated by processes occurring inside observed stars, because of the rather low central temperatures and thin convective envelopes of stars at the turn-off of GCs. Afterwards, this finding was confirmed in other clusters, like M 71 (NGC 6838 Ramírez & Cohen [2002]) and 47 Tuc (Carretta et al. [2004]). Further data for giants of NGC 6752 have been collected in Carretta et al. [2007]. The data show a typical O–Na anticorrelation, not extremely extended in oxygen, although several upper limits to [O/Fe] are present. The sodium-poor stars (FG stars) have largely α-enhanced [O/Fe]~0.4–0.5.

Lithium in NGC 6752 was measured in nine turnoff stars by Pasquini et al. [2003], who found that its abundance was anticorrelated with sodium and nitrogen, and directly correlated with oxygen. These data formed the basis of an interpretation based on a dilution model of pristine matter with the matter processed in massive rotating stars, having no lithium and high sodium (Decressin et al. [2007]). Recently, Shen et al. [2010] examined a much larger sample (112 stars), confirming the O–Li correlation, but finding a slope of the correlation ∆A(Li)/∆[O/Fe]~0.4, much milder than the slope 1 expected if the lithium in the pristine matter were just diluted with Na-rich Li-free ejecta. Figure 7 shows the O–Li data for NGC 6752 together with our yields for super-AGB and AGB stars. Two caveats must be noticed: 1) here we plot the computed abundances, as we deal with turnoff stars, in which no kind of further deep mixing to reduce oxygen can be invoked; 2) in the comparison with simulations, we have shifted the Shen et al. [2010] [O/Fe] abundances by +0.4 dex; in fact, the “standard” [O/Fe] values in Shen et al. [2010] analysis is ~+0.0–0.1, implying some systematic shift with respect to the abundances of Carretta et al. [2007]. Our initial models have [O/Fe]=0.4, so the observational values have been adjusted.

The O–Na data for this cluster are not as good as the data for NGC 2808, and also the information of the MS are still incomplete in the literature. Therefore, we use as a guideline the simulations made for NGC 2808. In Fig. 8 we overplot the simulations of Fig. 5 to the Shen et al. [2010] data, after shifting the data by +0.4dex in [O/Fe]. We also shift A(Li) of the FG by +0.05 dex to achieve a better reproduction of the undepleted abundances in NGC 6752. We adopt the same shift in oxygen for the SG simulation, as the oxygen depletion is directly dependent on the initial abundance, but we do not shift the SG lithium upwards, because the yields in lithium are not linked to the initial abundance chosen for the models, but only to the lithium production through the Cameron Fowler mechanism during the HBB. Fig. 8 shows that the abundances in the ejecta may play a role in decreasing the slope of the [O/Fe]–A(Li) anticorrelation. There is no sign of the few very Li-rich stars predicted for the extreme second generation of NGC 2808, but we see that the “intermediate” population is broadly consistent with the data. By comparing the two panels we see that the slope of the simulated data points (excluding the super-AGB values) differs in the two cases (A & B): as expected, the slope is flatter in the case of A(Li)=2.3. We compute an average slope of the simulation by a least square fit both of the FG and SG points, after excluding the extreme lithium abundances. We obtain ∆A(Li)/∆[O/Fe]=0.27±0.05 for the case A(Li)=2.3 and ∆A(Li)/∆[O/Fe]=0.62±0.05 for the case A(Li)=2.6. Thus further observations of the lithium patterns in FG and SG stars providing a more robust determination of the [O/Fe]–A(Li) slope, along with a more detailed model in which also other chemical constraints are considered, may even result in a test of the standard BBN.

5 MODELS IN WHICH THE DILUTING GAS DOES NOT CONTAIN LITHIUM

We finally shortly examine case F (Table 3), in which the diluting matter is devoid of lithium. In order to solve the problem of the source of the matter required for dilution, Gratton & Carretta (2010) proposed that it comes from mass loss from FG stars, that can quantitatively provide the gas necessary to achieve this, if we consider the main sequence stars of all masses and reasonably large mass loss rates. Consequently, this gas has no lithium, because lithium burns below the stellar surface as soon as the temperature increases above ~ 2 × 10^6 K, and the mass loss rate required in this scenario implies that layers of matter that have reached this temperature must contribute to the dilution. Another possible case is when the diluting gas comes from the mass lost by non conservative evolution of massive close binaries (Vanbeveren et al. 2012) or by close encounters of stars in the dense cores of the GCs (Carini et al. 2012). It is clear that the models for M4 in which there is a strong dilution with pristine matter (from M4-1 to M4-5) lithium in the SG will be very small, if any, in contrast with the observations. As for NGC 2808, in Fig. 8 we show the implications of a lithium-free diluting gas on the Li-O and Li-Na patterns in the model 2808-1. Contrary to the cases shown in Fig. 5, this simulation predicts much smaller lithium abundances for the intermediate population. Further observations of lithium in clusters may help to falsify this model.

6 THE BIG BANG LITHIUM ABUNDANCE

This work, first aimed at further discussing a detailed chemical evolution model for the multiple populations of GCs, has revealed an interesting implication for the Big Bang nucleosynthesis. In fact, despite the scarcity of lithium abundance determinations in GCs, these data may result to be a powerful and independent way to constrain the lithium abundance emerging from the Big Bang. The abundance of lithium in the gas forming the SG stars contains information on the abundance of lithium in the gas in which the hot-CNO processed ejecta are diluted. If we can assume (and this is very reasonable) that, at first order, the possible phenomena that deplete lithium at the surface of population II stars are independent of their being FG or SG stars, the difference in lithium between FG and SG stars will keep track of the pristine gas abundance.

In the case of M4, we have seen that the cases B (A(Li)=2.2 in the pristine gas) shown in Fig. 4 can be excluded. This could be a very interesting result, but it is subject to a confirmation of the large lithium yields shown...
Figure 8. Overplotted to the Li–O for NGC 6752 (shifted by +0.4dex, as in Fig. 7), we show the results of simulations of Fig. 5. Green squares represent the FG and green triangles the SG. The initial lithium abundance of the diluting pristine gas is $A(\text{Li}) = 2.6$ (left panel) and 2.3 (right panel). To achieve a better fit of the FG data, we have shifted $A(\text{Li})$ of the FG by +0.05 dex.

Figure 9. Li–Na and Li–O simulations for model NGC 2808-1 in Table 3. The difference with respect to Fig. 5 is in the assumption of no lithium in the diluting gas. We further have $A(\text{Li}) = 2.3$ (left panels) and 2.6 (right panels). Notice that the extreme population is similar to that shown in Fig. 5, because the SG formation occurs in the undiluted matter, while the intermediate population, where dilution is important, has much lower lithium abundances.

in Table 2 for super–AGB stars. As far as we have seen from the other observations, there is no present confirmation of those yields. Further, they are theoretically very uncertain, being linked to the choice (unconstrained by observations) of the mass loss rate adopted in these computations. A confirmation could come from observation of large lithium abundances in the blue MS stars of NGC 2808 or ω Cen. If in the end the yields of super–AGB stars will be constrained to be much smaller than those used here, case B will still be possible, and we will have to resort to different comparisons.

A very interesting information seems to come from the slope of the O–Li data in NGC 6752: Figure 8 shows the possibility of constraining the primordial lithium abundance from the data. This result is less dependent on the super–AGB yields, as it refers to the (later) phase of formation of the intermediate population. Of course, more and better data, and stronger constraints on the dilution model and on the AGB yields are necessary. We only wish to point out this rewarding possibility, to encourage further and extensive observations of lithium abundances in clusters with multiple populations.

7 DISCUSSION

In this paper we have presented the first predictions for the abundance of Lithium in first and second generation stars of GCs, based on quantitative models that can successfully reproduce the O–Na anticorrelation and the helium abundance distribution in the clusters M 4 and NGC 2808 (Paper II). Although the model is necessarily parametric, it allows us to discuss the lithium data appeared in the recent literature for several GCs: NGC 6752, M 4, NGC 6397, ω Cen. Our models are based on our recent yield predictions for massive AGB and super–AGB stars. We show that:

(i) An important ingredient in the study is the dilution of the ejecta with the pristine gas, and thus whether we interpret the surface abundance of lithium in population II stars
as the primordial abundance, or as due to in situ depletion mechanisms. A better understanding of the SG formation could perhaps help to constrain better the Big Bang abundance, although this is at present only wishful thinking.

(ii) Not all models for M 4 are consistent with the slight decline in lithium by 0.1 dex between the FG and SG. A good fit of the data is achieved also assuming zero lithium in the super–AGB matter (rightmost column panels in Fig.4), thanks to the large sodium yields of these ejecta, that require strong dilution with pristine matter. Models in which the O–Na “short” anticorrelation is the result of the rapid formation of SG stars from strongly diluted super–AGB ejecta would solve the mystery of the Be–rich, O–poor star found by Pasquini et al. (2004) in NGC 6397.

(iii) In complex clusters, in which a very He–rich extreme population is present, we should expect that this population is born from pure super–AGB ejecta, and thus is very Li–rich. Observations of lithium in the blue MS of ω Cen and NGC 2808 may verify or confute this prediction.

(iv) The O–Li observations of NGC 6752 are consistent with the intermediate population of the models discussed for NGC 2808. The slope of the correlation (milder than the slope 1 expected if the polluting matter is Li–free) is reproduced, thanks to the finite lithium content of the AGB ejecta. In this case too, a better determination of this slope might provide hints to the Big Bang Lithium abundance.

(v) In some models for the SG formation, the diluting gas comes from nuclearily unprocessed matter from FG stars, that is probably Li–free. We predict that in this case lithium in SG stars should be much smaller than in the FG.

8 ACKNOWLEDGMENTS

This work has been supported through PRIN INAF 2009 "Formation and Early Evolution of Massive Star Cluster” and PRIN INAF 2011 "Multiple populations in Globular Clusters: their role in the Galaxy assembly”. EV was supported in part by grant NASA-NNX10AD86G.

REFERENCES

Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, ApJ, 644, 229
Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R., Momany, Y., & Carraro, G. 2004, ApJ, 605, L125
Boesgaard, A. M., Deliyannis, C. P., King, J. R., et al. 1999, AJ, 117, 1549
Carini, R. et al. 2012, to be submitted
Carretta, E., Gratton, R. G., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004, A&A, 416, 925
Carretta, E., Bragaglia, A., Gratton, R. G., Lucatello, S., & Momany, Y. 2007, A&A, 464, 927
Carretta, E., et al. 2009, A&A, 505, 117
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2008, J. Cosmol. Astropart. Phys., 11, 12
D’Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69
D’Antona, F., & Caloi, V. 2004, ApJ, 611, 871
Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekström, S. 2007a, A&A, 464, 1029
Decressin, T., Charbonnel, C., & Meynet, G. 2007, A&A, 475, 859
de Mink, S. E., Pols, O. R., Langer, N., & Izzard, R. G. 2009, A&A, 507, L1
D’Ercole, A., Vesperini, E., D’Antona, F., McMillan, S. L. W., & Recchi, S. 2008, MNRAS, 391, 825
D’Ercole, A., D’Antona, F., Ventura, P., Vesperini, E., & McMillan, S. L. W. 2010, MNRAS, 407, 854
D’Ercole, A., D’Antona, F., & Vesperini, E. 2011, MNRAS, 415, 1304
D’Ercole, A., et al. 2012, MNRAS, 423, 1521 (Paper II)
D’Orazi, V., Lucatello, S., Gratton, R., Bragaglia, A., Carretta, E., Shen, Z., & Zaggia, S. 2010, ApJ, 713, L1
D’Orazi, V., & Marino, A. F. 2010, ApJ, 716, L166
Fields, B. D. 2011, Annual Review of Nuclear and Particle Science, 61, 47
Gratton, R. G., Bonifacio, P., Bragaglia, A., et al. 2001, A&A, 369, 87
Gratton, R. G., & Carretta, E. 2010, A&A, 521, A54
Iocco, F., Mangano, G., Miele, G., Pisanti, O., & Serpico, P. D. 2009, Phys. Rep., 472, 1
Karakas, A. I., Fenner, Y., Sills, A., Campbell, S. W., & Lattanzio, J. C. 2006, ApJ, 652, 1240
Koch, A., Lind, K., & Rich, R. M. 2011, ApJ, 738, L29
Lind, K., Primas, F., Charbonnel, C., Grundahl, F., & Asplund, M. 2009, A&A, 503, 545
Lind, K., Charbonnel, C., Decressin, T., Primas, F., Grundahl, F., & Asplund, M. 2011, A&A, 527, A148
Méndez, J., & Ramírez, I. 2004, ApJ, 615, L33
Meynet, G., Ekström, S., & Maeder, A. 2006, A&A, 447, 623
Milone, A. P., Piotto, G., King, I. R., et al. 2010, ApJ, 709, 1183
Monaco, L., Bonifacio, P., Sbordone, L., Villanova, S., & Pancino, E. 2010, A&A, 519, L3
Monaco, L., Villanova, S., Bonifacio, P., et al. 2012, A&A, 539, A157 (arXiv:1108.0138)
Monaco, L., Villanova, S., Bonifacio, P., et al. 2012, A&A, 539, A157
Norris, J. E. 2004, ApJ, 612, L25
Pasquini, L., Bonifacio, P., Randich, S., Galli, D., & Gratton, R. G. 2004, A&A, 426, 651
Pasquini, L., Bonifacio, P., Molaro, P., Francois, P., Spite, F., Gratton, R. G., Carretta, E., & Wolf, B. 2005, A&A, 441, 549
Piau, L., Beers, T. C., Balsara, D. S., Sivarani, T., Truran, J. W., & Ferguson, J. W. 2006, ApJ, 653, 300
Prantzos, N., & Charbonnel, C. 2006, A&A, 458, 135
Ramírez, S. V., & Cohen, J. G. 2002, AJ, 123, 3277
Renzini, A. 2008, MNRAS, 391, 354
Sbordone, L., et al. 2010, A&A, 522, A26
Shen, Z.-X., Bonifacio, P., Pasquini, L., & Zaggia, S. 2010, A&A, 524, L2
Sills, A., & Glebbeek, E. 2010, MNRAS, 407, 277
Spergel, D. N., et al. 2007, ApJS, 170, 377
Vanbeveren, D., Mennekens, N., & De Greve, J. P. 2012, A&A, in press (arXiv:1109.2713)
Ventura, P., D’Antona, F., Mazzitelli, I., & Gratton, R. 2001, ApJ, 550, L65
Ventura, P., D’Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215
Ventura P., D’Antona F., 2009, A&A, 499, 835
Ventura, P., & D’Antona, F. 2010, MNRAS, 402, L72
Ventura, P., & D’Antona, F. 2011, MNRAS, 410, 2760