The formation of multiple populations in the globular cluster 47 Tuc

P. Ventura, M. Di Criscienzo, F. D’Antona, E. Vesperini, M. Tailo, F. Dell’Agli and A. D’Ercole

1INAF–Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monte Porzio Catone, Italy
2INAF–Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131 Napoli, Italy
3Department of Astronomy, Indiana University, Bloomington, IN 47405-7105, USA
4Dipartimento di Fisica, Università di Roma ‘La Sapienza’, Piazzale Aldo Moro 5, I-00185 Rome, Italy
5INAF–Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy

Accepted 2013 October 31. Received 2013 October 29; in original form 2013 September 24

ABSTRACT

We use the combination of photometric and spectroscopic data of 47 Tuc stars to reconstruct the possible formation of a second generation of stars in the central regions of the cluster, from matter ejected by massive asymptotic giant branch (AGB) stars diluted with pristine gas. The yields from massive AGB stars with the appropriate metallicity (Z = 0.004, i.e. [Fe/H] = −0.75) are compatible with the observations in terms of extension and slope of the patterns observed, involving oxygen, nitrogen, sodium and aluminium. Based on the constraints on the maximum helium of 47 Tuc stars provided by photometric investigations and on the helium content of the ejecta, we estimate that the gas out of which second-generation stars formed was composed of about one-third of gas from intermediate-mass stars, with M ≥ 5 M⊙ and about two-thirds of pristine gas. We tentatively identify the few stars whose Na, Al and O abundances resemble the undiluted AGB yields with the small fraction of 47 Tuc stars populating the faint subgiant branch. From the relative fraction of first- and second-generation stars currently observed, we estimate that the initial first-generation population in 47 Tuc was about 7.5 times more massive than the cluster current total mass.

Key words: stars: abundances – stars: AGB and post-AGB – globular clusters: general.

1 INTRODUCTION

The traditional paradigm that stars in globular clusters (GCs) are an example of a coeval and chemically homogeneous population was challenged by photometric and spectroscopic results, which highlighted the presence of at least two generations of stars: a first generation (FG), with the chemistry of the cloud from which the cluster formed, and an additional component (second generation, hereinafter SG), with a composition showing the signature of proton-capture nucleosynthesis. The surface abundances of stars belonging to the SG define abundance patterns, where sodium is correlated to aluminium and anticorrelated to magnesium and oxygen. The extension and the slope of these trends change from cluster to cluster, but it is interesting that they have been detected within each GC investigated so far (Gratton, Sneden & Carretta 2004; Gratton, Carretta & Bragaglia 2012). These chemical anomalies involve only ‘light’ elements, up to silicon, whereas no spread is observed in the iron content.⁰

On the photometric side, the hypothesis that the morphology of the horizontal branch (HB) of some GCs could be explained by the presence of two or more populations, differing in their original content of helium, came from the seminal paper by D’Antona et al. (2002), and subsequently extended to NGC 2808 (D’Antona & Caloi 2004), M3 and M13 (Caloi & D’Antona 2005) and NGC 6441 (Caloi & D’Antona 2007).

These early speculations were later confirmed by detailed photometric analysis of the main sequence (MS) of the cluster NGC 2808, which was shown to be split in three components, differing in their helium content (D’Antona et al. 2005; Piotto et al. 2007). Subsequent investigations detected a splitting in the MS of NGC 6752 (Milone et al. 2010) and in the subgiant branches (SGBs) of NGC 1851, NGC 6656, 47 Tuc and other five GCs (Milone et al. 2008; Anderson et al. 2009; Marino et al. 2009; Piotto et al. 2012).

There are indeed a few clusters in which an iron variation is present, such as ω Cen (e.g. Norris, Freeman & Mighell 1996) and M22 (e.g. Marino et al. 2009). Their chemical evolution must have been more complex than in standard mono-metallic clusters.

⁰E-mail: paolo.ventura@oa-roma.inaf.it
This impressive set of evidence indicates that in most (if not all) GCs a self-enrichment mechanism must have produced gas contaminated by p-capture nucleosynthesis, such that one or more additional generations of stars formed, and are currently co-existing with the original population.

According to the most complete scenario suggested so far, a crucial role as polluters of the intracluster medium was played by stars of intermediate mass during the asymptotic giant branch (AGB) phase (Ventura et al. 2001). The paper by D’Ercole et al. (2008) set the theoretical framework to describe the formation of SG stars in GCs, by gas ejected by AGBs possibly mixed with pristine gas, survived to the epoch of supernovae explosions. This approach allowed us to reconstruct the formation of multiple populations in M4 (an example of a cluster showing mild anomalies) and NGC 2808 (an example of a cluster hosting, in addition, an extremely helium-rich population; D’Ercole et al. 2010, 2012).

As we will show in this paper to reproduce the observed abundance patterns processed gas provided only by AGB stars with masses between about 5 and 8 $M_{\odot}$ can be used along with some pristine gas. As already discussed in several of the papers cited above, the amount of gas available for SG formation in this scenario (as well in other competing scenarios for which a detailed study of the resulting abundance patterns have been investigated; see e.g. Bekki et al. 2007; Decressin, Charbonnel & Meynet 2007; D’Ercole et al. 2008; Renzini 2008; Carretta et al. 2009; Bekki 2011) implies that the FG cluster must have initially been more massive. We discuss the specific implications of the model presented here in Section 4.

The globular cluster NGC 104, better known as 47 Tuc, is a valuable test to understand the formation process of multiple populations in globular clusters. Until a few years ago it was considered as the prototype of a single stellar population, based on the photometric morphology of the MS and the HB. The first challenge to this belief came from the analysis based on the Hubble Space Telescope archival data by Anderson et al. (2009), showing the splitting of the SGB in two components, separated in magnitude. Di Criscienzo et al. (2010) then showed that the morphology of the HB of 47 Tuc is consistent with the presence of two populations, differing in helium content up to a maximum of $\Delta Y \sim 0.03$. Such interpretation was recently confirmed by the detailed photometric analysis published in Milone et al. (2012a), who explained the complexity of the observed colours of MS stars with a couple of populations, one with the primeval composition and another with a small helium enhancement, which, in agreement with Di Criscienzo et al. (2010), is within $\Delta Y = 0.03$.

From a spectroscopic point of view, a bimodal distribution of CN band strengths among giant stars belonging to 47 Tuc was found by Briley (1997). The following analyses by Cannon et al. (1998) and Harbeck, Smith & Grebel (2003) showed that this bimodality still exists. 2.5 mag below the turnoff, suggesting the presence of the MS and the HB. The first challenge to this belief came from the analysis based on the Hubble Space Telescope archival data by Anderson et al. (2009), showing the splitting of the SGB in two components, separated in magnitude. Di Criscienzo et al. (2010) then showed that the morphology of the HB of 47 Tuc is consistent with the presence of two populations, differing in helium content up to a maximum of $\Delta Y \sim 0.03$. Such interpretation was recently confirmed by the detailed photometric analysis published in Milone et al. (2012a), who explained the complexity of the observed colours of MS stars with a couple of populations, one with the primeval composition and another with a small helium enhancement, which, in agreement with Di Criscienzo et al. (2010), is within $\Delta Y = 0.03$.

A range of masses involved is $1 M_{\odot} \leq M \leq 8 M_{\odot}$. Models of smaller mass hardly experience the AGB phase, and are however not of interest for the scope of this paper. Stars of mass exceeding $8 M_{\odot}$ are expected to undergo core-collapse, thus skipping the AGB phase. For each mass, we followed the evolution from the pre-MS up to the almost complete loss of the convective envelope. Models of mass below $2 M_{\odot}$ experience the helium flash at the tip of their red giant phase. The evolutionary sequences for these masses were re-started from the HB, where He burning takes place in the non-degenerate core resulting from the flash.

Stars of mass above $6.5 M_{\odot}$ undergo carbon ignition in a degenerate layer above the core: these models develop a core made up of oxygen and neon and experience a series of TPPs as their lower mass counterparts (Garcia Berro, Ritossa & Iben 1997; Ritossa, Garcia Berro & Iben 1996, 1999; Siess 2006, 2007, 2010). Their evolution is known as Super Asymptotic Giant Branch (SAGB).

The initial composition in terms of metal and helium abundance is $Z = 0.004$ and $Y = 0.26$. This chemistry is similar to the models presented in Ventura & D’Antona (2008a), based on the mass fractions of the individual species given by Grevesse & Sauval (1998); the difference is that in the present investigation the mixture is assumed to be $\alpha$-enhanced, with $[\alpha/Fe] = +0.2$ (in Ventura & D’Antona 2008a, we used $[\alpha/Fe] = +0.4$). These choices, assuming a solar metallicity $Z_{\odot} = 0.017$, correspond to an iron content $[Fe/H] = -0.75$, the same measured in 47 Tuc stars (Carretta et al. 2009).
In addition to the Ventura & D’Antona (2008a) paper, we calculated the SAGB evolution of stars with mass $M > 6.5 \, M_\odot$.

### 2.2 AGB evolution and stellar yields

Following the pioneering investigations by Schwarzschild & Harm (1965, 1967), we know that stars of intermediate mass, after the end of core helium burning, experience a series of TPs in the evolutionary phase known as AGB. An updated, exhaustive description of the main features of the AGB evolution can be found, e.g. in Herwig (2005) and Karakas (2011).

The composition of the gas ejected by AGBs depends on the interface between the two mechanisms able to alter the surface chemistry: (a) third dredge-up (TDU), i.e. the inwards penetration of the convective envelope down to layers previously touched by 3$\alpha$ activity and (b) hot bottom burning (HBB), with the activation of p-capture nucleosynthesis at the bottom of the surface convective layer (Renzini & Voli 1981; Blöcker & Schönberner 1991). TDU favours the increase of the surface carbon and is the dominant mechanism in low-mass AGBs, with $M \leq 3 \, M_\odot$. More massive stars may experience HBB, provided that the temperature at the base of their envelope exceeds $\sim 40 \, MK$.

The efficiency of both mechanisms is unfortunately sensitive to the macro-physics description used. The extent of TDU depends on the treatment of convective borders, particularly to the extra-mixing from the base of the convective envelope and the boundaries of the convective shell which forms after each TP.

The strength of HBB is extremely sensitive to the convective model adopted (Ventura & D’Antona 2005). Models calculated with the FST description of the convective regions are found to experience a much stronger HBB in comparisons with models of same mass and metallicity calculated by means of the traditional mixing length theory of turbulent convection.

Table 1 summarizes the main physical and chemical results for the models investigated. For each mass, we show the evolutionary timescale, the core mass at the beginning of the AGB phase, the maximum temperature achieved at the bottom of the convective envelope and the average composition of the ejecta. For the $i$th element, we indicate the quantity $[i/Fe] = \log(X_i/\text{X(Fe)}\odot) - \log(X_i/\text{X(Fe)}\odot)_{\odot}$. For helium and lithium we show, respectively, the average mass fraction in the ejecta ($Y$) and the quantity $\log(e(Li)) = \log(n(\text{Li})/n(H)) + 12$.

Column 5 of Table 1 shows that the ejecta of AGBs are helium rich, as a consequence of the two dredge-up episodes following the core H- and He-burning phases, and, for the models experiencing HBB, of the p-capture nucleosynthesis at the bottom of the surface convective layer. Models with mass exceeding $5 \, M_\odot$ produce ejecta with a helium mass fraction $Y \sim 0.35$, almost 0.1 larger than the initial abundance. This prediction, unlike those regarding the other species, is rather robust, because most of the helium enrichment occurs during the second dredge-up, which makes this finding independent of the uncertainties affecting the following TPs phase (Ventura 2009).

The three panels of Fig. 1 show the average content of the gas ejected as a function of the initial mass, in terms of the mass fractions of carbon (left-hand panel), nitrogen (middle) and oxygen (right). To better understand the extent of the variation from the initial content of each species, we show the ratio between the average and the initial abundance. The present results are compared with previous findings for different metallicities published in Ventura et al. (2013) and with models of the same metallicity by Karakas (2010, hereinafter K10).

Both the present models and those by K10 show an increase in the carbon content of the ejecta in the low-mass domain, for $M \leq 3 \, M_\odot$: this is due to the repeated TDU episodes that transport to the stellar surface carbon synthesized in the $3\alpha$ burning shell. The trend of $X(^{12}\text{C})$ with mass is rather similar in the two cases, as also the maximum increase in the carbon content, found to be $\delta(C) \sim 1.5–1.6\, dex$. The results between this investigation and the work by K10 are different for $M > 3.5 \, M_\odot$ because our models experience a stronger HBB with a faster destruction of the surface carbon: while the yields by K10 are enriched in carbon for all masses, our models experiencing HBB show a carbon decrease, which reaches the asymptotic value of $\delta(C) \sim -1 \, dex$ in the SAGB domain.

The different extent of the HBB experienced is also the reason for the difference in the oxygen content of the ejecta (see right-hand panel) for $M > 3.5 \, M_\odot$: in the present compilation, the oxygen is systematically lower than in K10, with the only exception of the $6 \, M_\odot$ model, which shows the same depletion of $\delta(\text{O}) \sim -0.4 \, dex$ in the two cases.

The trend of the nitrogen abundance with mass shows an abrupt increase around $\sim 3 \, M_\odot$, because in that range of mass the carbon

### Table 1. Relevant properties of $Z = 4 \times 10^{-3}$ AGB and SAGB models.

| $M/M_\odot$ | $\tau_{\text{evol}}$ | $M_*/M_\odot$ | $\tau_{\text{max bce}}$ | $Y$ | Li | [C/Fe] | [N/Fe] | [O/Fe] | [Na/Fe] | [Mg/Fe] | [Al/Fe] |
|-------------|---------------------|---------------|-------------------------|-----|----|--------|--------|--------|--------|--------|--------|
| 1.0         | 6.4e9               | 0.53          | 2.4e6                   | 0.283 | -1.66 | 0.62   | 0.04   | 0.22   | 0.02   | 0.20   | 0.00   |
| 1.25        | 3.1e9               | 0.54          | 3.1e6                   | 0.283 | -1.93 | 0.81   | 0.03   | 0.23   | 0.04   | 0.20   | 0.00   |
| 1.5         | 2.0e9               | 0.55          | 3.8e6                   | 0.287 | -1.90 | 1.04   | 0.04   | 0.26   | 0.08   | 0.20   | 0.00   |
| 2.0         | 1.1e9               | 0.50          | 4.1e6                   | 0.270 | 1.49  | 1.47   | 0.45   | 0.56   | 0.43   | 0.25   | 0.20   |
| 2.5         | 5.7e8               | 0.57          | 5.5e6                   | 0.296 | 1.40  | 1.63   | 0.54   | 0.76   | 0.64   | 0.47   | 0.73   |
| 3.0         | 3.4e8               | 0.70          | 2.3e7                   | 0.283 | 1.90  | 1.24   | 0.47   | 0.42   | 0.33   | 0.31   | 0.55   |
| 3.5         | 2.3e8               | 0.79          | 8.1e7                   | 0.283 | 2.80  | 0.04   | 1.37   | 0.19   | 1.01   | 0.22   | 0.20   |
| 4.0         | 1.7e8               | 0.82          | 8.7e7                   | 0.304 | 2.34  | -0.11  | 1.37   | 0.08   | 0.93   | 0.21   | 0.27   |
| 4.5         | 1.3e8               | 0.85          | 9.2e7                   | 0.324 | 2.42  | -0.20  | 1.30   | -0.06  | 0.97   | 0.20   | 0.40   |
| 5.0         | 1.0e8               | 0.89          | 9.6e7                   | 0.339 | 2.33  | -0.24  | 1.23   | -0.13  | 0.70   | 0.18   | 0.49   |
| 5.5         | 8.4e7               | 0.96          | 1.0e8                   | 0.347 | 2.35  | -1.00  | 1.01   | -0.18  | 0.57   | 0.17   | 0.52   |
| 6.0         | 6.7e7               | 1.01          | 1.0e8                   | 0.357 | 2.44  | -1.04  | 1.08   | -0.19  | 0.54   | 0.17   | 0.50   |
| 6.5         | 5.9e7               | 1.07          | 1.0e8                   | 0.356 | 2.45  | -1.06  | 1.05   | -0.18  | 0.52   | 0.16   | 0.48   |
| 7.0         | 5.1e7               | 1.18          | 1.1e8                   | 0.361 | 2.49  | -1.06  | 1.03   | -0.15  | 0.53   | 0.16   | 0.46   |
| 7.5         | 4.4e7               | 1.27          | 1.1e8                   | 0.367 | 2.74  | -1.07  | 1.02   | -0.13  | 0.54   | 0.17   | 0.44   |
| 8.0         | 4.0e7               | 1.33          | 1.2e8                   | 0.375 | 3.24  | -1.05  | 1.01   | -0.12  | 0.57   | 0.17   | 0.43   |
Multiple populations in 47 Tuc

Figure 1. The average mass fractions of carbon (left), nitrogen (middle) and oxygen (right) in the ejecta of AGB and SAGB stars as a function of the initial mass. The ordinate shows the ratio of the abundance of the elements to the initial mass fraction. The results presented here, with metallicity $Z = 0.004$, are indicated with black, full squares and are connected with solid lines. The blue triangles indicate the results by K10 and are connected with a dotted curve. Red, open points and green asterisks show, respectively, results for metallicities $Z = 3 \times 10^{-4}$ and $Z = 8 \times 10^{-3}$ by Ventura et al. (2013).

Dredged-up to the surface is converted into nitrogen during the following interpulse phase. Note that in the $M \geq 3.5 M_\odot$ domain, our nitrogen yields are lower than K10, because the stronger HBB experienced by our models limits the number of TPs, and thus the amount of carbon available.

An important consequence of the strong HBB in the envelope of massive AGB models calculated with the FST description of convection is that TDU is scarcely efficient in modifying the surface chemistry: as discussed previously, the star loses the whole envelope after a limited number of TPs before TDU becomes efficient (Ventura & D’Antona 2008b). This, in turn, implies that the overall C+N+O content of the ejecta of massive AGBs (with $M > 5 M_\odot$) and SAGBs is practically unchanged with respect to the initial abundance, as expected from a pure p-capture nucleosynthesis (Ventura & D’Antona 2009).

The differences between models with different chemistry are due to the different impact of TDU and HBB in models with different metallicities. In the low-mass domain, where the yields are dominated by TDU, the percentage increase in the surface carbon is larger for models with lower $Z$, because the same amount of carbon transported to the surface produces a larger increase in the surface abundance. The lower metallicity models experience a stronger HBB (Ventura et al. 2013): this is the reason why models with $Z = 3 \times 10^{-4}$ have much smaller oxygen content than their higher $Z$ counterparts. The opposite behaviour is found in the $Z = 8 \times 10^{-3}$ case, where only a modest depletion of the surface oxygen is achieved.

We note in the right-hand panel of Fig. 1 that in the range of massive AGBs and SAGBs the low-$Z$ models are characterized by a broad range of oxygen, while the models with $Z = 4 \times 10^{-3}$ (and even more those with $Z = 8 \times 10^{-3}$) have a much smaller variation of oxygen with mass. The reason for this difference is, again, the stronger HBB experienced by massive AGBs of smaller metallicity: the fast increase in the surface luminosity favours a large increase in the mass-loss rate, such that in the models with the largest core masses the envelope is lost rapidly, before an advanced nucleosynthesis can be achieved. The trend of the oxygen content of the ejecta with mass is consequently not monotonic, the SAGB models showing up traces of a milder nuclear processing (Ventura & D’Antona 2011).

In Fig. 2, we show the sodium and aluminium content of the ejecta of the models presented here, compared to models of different metallicities published in Ventura et al. (2013). In the [Na/Fe]–[Al/Fe] plane, we only show the yields of masses experiencing HBB, with $M \geq 4 M_\odot$. For each metallicity, results for increasing mass are in the counterclockwise direction.

The interpretation of the aluminium abundances is straightforward. Lower metallicity models undergo stronger HBB, thus the Mg–Al nucleosynthesis proceeds faster. This can be clearly seen in the right-hand panel of Fig. 3, showing the variation of the surface Al abundance in models of various masses and metallicities. The increase of Al with respect to the initial abundance is enhanced in low-$Z$ models, whereas it is extremely small in the $Z = 8 \times 10^{-3}$ case. In the $Z = 3 \times 10^{-4}$ models (and also in the $Z = 10^{-3}$ ones, not shown here for clarity reasons), the temperatures at the
bottom of the surface convective zone become so large that eventually an equilibrium stage is reached, such that the rates of production and destruction of aluminium balance each other (Ventura, Carini & D’Antona 2011): this is the motivation of the counterclockwise shape of the [Na/Fe]–[Al/Fe] trends in Fig. 2 for these two metallicities, with the largest masses showing a smaller Al enhancement in their ejecta.

In the $Z = 4 \times 10^{-3}$ models presented here, the temperature at the bottom of the convective envelope hardly exceeds 10 $^8$ K (see column 4 of Table 1), thus the Al-burning channel is never activated: the behaviour of the various masses involved is much more homogeneous (see right-hand panel of Fig. 3), and the extent of the increase in Al in the ejecta is approximately independent of mass, for $M \geq 5 M_\odot$: for the present mixture, massive AGBs produce winds with an average increase in the aluminium content of $\Delta$[Al/Fe] $\sim +0.5$ dex.

The behaviour of sodium is more tricky, given the different sensitivity to temperature of the production and destruction channels (Ventura & D’Antona 2006). While for temperatures below $\sim$70 MK sodium is produced at the expense of neon, for larger $T'_s$ the destruction process takes over. The typical behaviour of the surface sodium during the AGB evolution (see left-hand panel of Fig. 3) shows an initial increase, followed by a depletion of the surface abundance in the latest evolutionary phases.

The higher is the temperature, the stronger is the rate at which sodium is consumed: lower metallicity models show on the average a lower content of sodium in the ejecta, as shown in Fig. 2. In low-Z SAGB models, mass-loss is so fast to prevent a great destruction of the surface sodium (Ventura & D’Antona 2011): this is the reason for the large sodium content in the ejecta of the most massive models of $Z = 3 \times 10^{-4}$ and $Z = 10^{-3}$.

At $Z = 4 \times 10^{-3}$, sodium is initially produced in massive AGBs, the surface abundance increasing by almost a factor of $\sim$10 compared to the initial mass fraction. Unlike their lower Z counterparts, the destruction process proceeds later at a very slow pace. The sodium content of the ejecta is not very sensitive to the initial mass: we find that the sodium increase in the gas lost is $\Delta$[Na/Fe] $\sim +0.5$ dex.

To summarize our findings, we conclude that massive AGBs with the chemistry examined here suffer a mild HBB. The gas ejected by these stars is expected to present the signature of p-capture burning, with the depletion of the surface content of oxygen of $\sim 0.4$ dex, and an enhancement of the surface sodium and aluminium of $\sim +0.5$ dex. The nucleosynthesis experienced is not sufficiently advanced to produce any modification of the surface silicon, whereas the overall content of magnesium is poorly reduced with respect to the initial abundance, of $\sim 0.04$ dex. The gas ejected is helium rich, with an average helium of $Y \sim 0.35$. Finally, for what concerns the overall content of CNO, the yields from models with mass above $5 M_\odot$ are found to maintain the initial C+N+O, whereas for $4 M_\odot \leq M \leq 5 M_\odot$ the increase in the total CNO ranges from 20 per cent up to almost $\sim 100$ per cent.

3 THE INTERPRETATION OF THE CHEMICAL PATTERNS TRACED BY 47 Tuc STARS

The recent investigation by Carretta et al. (2013) shows that stars in 47 Tuc trace well-defined abundance patterns, involving some of the elements touched by p-capture nucleosynthesis. Sodium is correlated to aluminium and nitrogen and anticorrelated to oxygen. The present data do not allow us to confirm possible variations in the abundances of magnesium and silicon, but the variation of these elements, if present, cannot exceed a few per cent.

In the O–Na plane, similar trends were found by the analysis focused on HB stars by Gratton et al. (2013) and by spectroscopy of unevolved stars of the same cluster (D’Orazi et al. 2010).  

The overall magnesium content is only modestly touched by the nucleosynthesis experienced. However, the internal distribution among the Mg isotopes is considerably different in comparison with the initial mixture: most of the $^{24}$Mg is lost, whereas $^{25}$Mg is increased by almost one order of magnitude.
To understand whether this set of observations can be explained on the basis of the self-enrichment mechanism by AGBs, we compare the data available with the chemistry obtained by mixing gas from massive AGBs and SAGBs with gas assumed to share the primeval chemistry of the cluster, characterizing the FG component.

The dilution of the chemistry reported in Table 1 for \( M \geq 5 \, M_\odot \) with pristine material defines an abundance pattern, for different degrees of dilution. Theoretically, all the results obtained with degrees of dilution ranging from 0 to 1 should be considered. However, the photometric analysis of the HB (Di Criscienzo et al. 2010) and of the MS of 47 Tuc (Milone et al. 2012a) indicate that the range of helium abundances of the stars in the cluster is \( \Delta Y \sim 0.03 \), which rules out the possibility that uncontaminated stars with the pure chemistry of AGBs formed: based on the values shown in Table 1, these stars should have a helium mass fraction \( Y \sim 0.35 \), which would determine a much wider spread of the MS. These arguments allow us to determine the minimum degree of dilution from which the stars in the SG formed: mixing of pristine matter with \( Y = 0.26 \) and gas from AGBs with \( Y = 0.35 \) leads to the maximum helium allowed from the photometric analysis, \( Y = 0.29 \), if we assume that the fraction of gas from AGBs used to form SG stars is one-third, the remaining being provided by pristine gas in the cluster. In the following analysis, we will allow the relative contribution from gas ejected by AGBs to range from a minimum of 0 per cent to a maximum of 35 per cent. Obviously stars formed with no AGB ejecta or with a very large fraction of pristine gas will have the chemical properties of FG stars and would not be classified as SG stars (D’Ercole, D’Antona & Vesperini 2011).

Fig. 4 shows the results from Carretta et al. (2013) on the Na–Al (left-hand panel) and Na–N (right) planes. In both axes, we report the variation with respect to the abundances observed in the stars that we assume to belong to the FG of the cluster. This choice is motivated by the offset between the solar-scaled abundances of nitrogen, aluminium and sodium used in our models and the minimum values for the same elements reported in Carretta et al. (2013).

The AGB and SAGB yields reported in Table 1 are indicated with full, blue triangles. The white curve indicates a dilution relationship, obtained by mixing gas with the original chemistry of the cluster with matter ejected by AGBs; this analysis is particularly simple in this case owing to the little variation with mass of the chemistry of the ejecta in the massive AGBs domain, and would be harder to be applied to lower metallicity clusters, for which the composition of the ejecta is much more sensitive to the initial mass of the star. The dilution curves in Fig. 4 are limited in such a way that the contribution of AGB ejecta range from 0 per cent to a maximum of 35 per cent. As pointed out above, and previously discussed in D’Ercole et al. (2011), stars forming from a mix of gas with a large fraction of pristine gas would fall in the FG portion of the chemical patterns planes. We extend the lines to such a large fraction of pristine gas only for illustrative purposes.

We see from both panels that the observed trends, within the error bars associated to the abundances of the individual stars, are satisfactorily reproduced. In the Na–Al plane (left-hand panel), most of the stars fall within the dilution curve, with the exception of two sources, that show a chemistry similar to the pure AGB ejecta. The same holds for the Na–N pattern, the dilution curve encompassing the most extreme, nitrogen-rich stars.

Fig. 5 shows the comparison between the theoretical predictions and the observations, for what concerns the oxygen–sodium anti-correlation. Similarly to the Na–Al and Na–N patterns showed in Fig. 4, we show the (negative) variation of the surface oxygen of the individual stars, assuming that the FG has an initial oxygen [O/Fe] = +0.2.

The comparison in this case is not straightforward, given the large uncertainties associated in particular to the abundances of oxygen. The abundances of the ejecta lay in the upper-left portion of the plane, where the most contaminated objects are found. Given the arguments discussed previously, regarding the maximum degree of
contamination by AGB gas in the formation of the SG of stars, we must rule out such extreme chemistries, limiting the contribution from AGBs to 35 per cent. In this way, we obtain the dilution curve in Fig. 5. The observed points are reproduced within the error bars associated to the observations, with the exception of the three most extreme objects with the smallest abundances of oxygen. This comparison, though less meaningful than the previous analysis based on the abundances of aluminium and nitrogen, indicates that the HBB experienced by AGB models of the same chemistry as 47 Tuc stars is appropriate to provide the oxygen depletion needed to fit the observations.

A word of caution concerning the assumptions made on the chemical mixture from which the cluster formed (i.e. the composition of FG stars) is needed here. The results from the above analysis hold provided that the values used to build the models are correct and that the observed data show an offset in the measured abundances. Should the initial aluminium be that observed in the assumed FG component (a factor of ~3 higher than our assumption), the magnesium nucleosynthesis would work with the same efficiency, and thus the amount of aluminium produced \( \delta(\text{Al}) = X(\text{Al})_{\text{ejecta}} - X(\text{Al})_{\text{initial}} \) would be unchanged. This would imply a smaller percentage increase in the content of Al in the ejecta, thus a smaller difference between the abundances of SG and FG stars. This can be easily compensated by a higher content of magnesium, which we assumed to be \( [\text{Mg/Fe}] = +0.2 \), whereas data from Carretta et al. (2013) point in favour of a larger abundance of \( [\text{Mg/Fe}] = +0.4 \).

The situation is less critical for sodium, not only because the offset between our assumptions and the abundances given in Carretta et al. (2013) limited to a factor of ~2, but also because the percentage increase in the surface sodium is only marginally touched by the initial abundance: the horizontal extension of the dilution curves in both panels of Fig. 4 would be slightly shorter, but the conclusion drawn would remain unchanged.

As far as oxygen is concerned, the rate of destruction of this species scales with its abundance, which makes the percentage reduction independent on the assumed initial value.

We do not discuss here the effects of a possible offset in the nitrogen content, because the absolute values are strongly interfaced with the assumptions concerning the initial carbon in the mixture, thus containing a high degree of arbitrariness. We limit our analysis on the variations observed.

According to the models used here, no change in the silicon abundance should be detected. This seems to be in agreement with the data from Carretta et al. (2013), where no clear Si–Al trend is observed.

Magnesium is only marginally touched by the HBB experienced, the decrease in the overall Mg being below 0.05 dex (see column 11 of Table 1). The detection of a similar spread among 47 Tuc stars is behind the possibilities of the present observations, given the undetermination in the measured abundances, exceeding 0.1 dex (Carretta et al. 2013).

### 3.1 The faint turnoff in 47 Tuc

The analysis by Di Criscienzo et al. (2010) suggested the presence in 47 Tuc of a stellar component enriched in the overall C+N+O, based on the morphology of the SGB of the cluster. These faint turnoff stars should be revealed along the Red Giant Branch. We suggest that they are the few stars in the left-hand panel of Fig. 4 which are out of the dilution pattern but have high [Na/Fe] and [Al/Fe]. The stars for which we have measures of oxygen have also low [O/Fe], closer to the pure yields of our models.

Following the models by D’Ercole et al. (2012), we can think that the bulk of SG stars in 47 Tuc has been formed by dilution of pristine gas with the AGB ejecta. When the pristine gas gets consumed, the star formation may go on for a while, until Type Ia supernovae (SNe Ia) completely clean the cluster from gas. The stars formed in this phase would have the chemistry of the 5 M\(_\odot\) ejecta scarcely diluted with pristine gas. The CNO enhancement of the 5 M\(_\odot\) is 1.35 times the original CNO, and the turnoff location of these stars could resemble the faint turnoff. This small population should also be helium rich, so their HB location would be among the most brilliant HB stars of 47 Tuc.

Gratton et al. (2013) show indeed that a couple of their bright star groups of 47 Tuc HB also have high [Na/Fe] and low [O/Fe]. The rest of their bright sample consists of normal FG stars, probably in an evolved phase out of the HB.

### 4 47 Tuc: HOW THE MULTIPLE POPULATIONS FORMED

The analysis carried out in the previous section shows that dilution of massive AGBs ejecta with gas pristine allows us to reproduce the observed patterns of 47 Tuc stars. This is in agreement with the scenario described by D’Ercole et al. (2008, 2010, 2011, 2012) according to which SG stars formed from a mix of AGB ejecta and pristine gas driven into the cluster central regions by a cooling flow and the SG formation process is halted after ~100 Myr by SN Ia explosions.

The chemistry with which SG stars form is therefore obtained by mixing processed matter with the chemical properties of the AGB and SAGB ejecta of stars evolving within ~100 Myr (i.e. for mass \( M \gtrsim 5 M_\odot \), see column 2 of Table 1) and pristine gas, with the same composition of FG stars. The presence of pristine gas is an essential ingredient in the self-enrichment mechanism by AGBs (as well as...
in all the other models proposed in the literature; see D’Ercole et al. 2011, for a discussion), and allows us to reproduce the O–Na anticorrelation, otherwise inhibited by the direct correlation between the oxygen and the sodium yields by massive AGBs (D’Ercole et al. 2011).

In the case of 47 Tuc, our models suggest that to reproduce the photometric and spectroscopic observations SG stars must have formed out of a mix of gas in which about one-third came from the AGB and SAGB ejecta and the rest from pristine gas. According to Carretta et al. (2013), FG stars are ~25 per cent of the total population, the remaining 75 per cent being contaminated objects belonging to the SG. The fact that the gas ejected by massive AGBs, for any realistic mass function, is only ~5 per cent of the mass of the initial FG population implies that a significant fraction of FG stars must have been lost by the cluster. According to the simulations presented in D’Ercole et al. (2008), this early loss of FG stars (and the consequent increase in the fraction of SG stars) would occur during the cluster early evolution. Memory of the initial central concentration of the SG population would be preserved during this phase and would still be present in many clusters today (Vesperini et al. 2013). Based on the analysis presented in Vesperini et al. (2013), 47 Tuc would be one of the clusters for which the SG should still be more concentrated in the inner regions than the FG population, in agreement with that found in observational studies (Milone et al. 2012a; Richer et al. 2013).

Following the calculation presented in D’Antona et al. (2013) and applying it to the chemical model presented here in which SG stars formed from a mix composed AGB ejecta (one-third) and pristine gas (two-thirds), we estimate that the total initial FG mass of 47 Tuc was about 7.5 times the current cluster mass (assuming SG stars form with masses up to about 8 M⊙ so that there are no SG SN II explosions (D’Antona et al. 2013); the initial mass required would be smaller – about 4.5 times the current cluster mass – if one assumes a range of SG stars limited to 0.8 M⊙).

5 CONCLUSIONS

In this paper, we have studied the viability of a model to explain the abundance patterns defined by stars in 47 Tuc on the basis of the self-enrichment scenario by massive AGBs.

For this purpose, we have specifically calculated a full set of AGB and SAGB models with the chemistry of 47 Tuc stars, and iron content [Fe/H] = −0.75.

AGB models in the high-mass (M ≥ 5 M⊙) domain experience a soft HBB, producing ejecta enriched in aluminium and sodium by +0.5 dex, and depleted in their oxygen content by −0.4 dex. No meaningful magnesium and silicon variations are expected. Similarly, to other metallicities, the matter ejected is helium rich, Y ~ 0.35.

Mixing of gas ejected by AGBs with pristine gas sharing the same chemistry as the stars originally present in the cluster allows us to trace abundance patterns, where sodium is correlated to nitrogen and aluminium and anticorrelated to oxygen. Based on the maximum helium enhancement allowed by the photometric analysis of the HB and the MS of the same cluster, we estimate that SG stars formed from a mix of gas composed for about one-third of AGB ejecta and two-thirds of pristine gas. Using this constrain, we can fit the extension and the slopes of the various trends observed, provided that only stars with mass M ≥ 5 M⊙ contributed to the formation of the SG. This implies that the SG population formed within ~100 Myr, before the SN Ia explosions, prevented further star formation.

Based on this analysis, and from the observed fraction of SG stars, ~75 per cent of the total stellar population, we estimate that 47 Tuc was initially about 7.5 times more massive than now (or 4.5 times for SG, star formation limited to 0.8 M⊙) and that a large fraction of its initial FG population must have been lost during the cluster early evolution.

ACKNOWLEDGEMENTS

Funding is acknowledged from PRIN INAF 2011, project ‘Multiple populations in GCs: their role in the Galaxy assembly’ (PI: E. Carretta), and from PRIN MIUR 2010-2011, project ‘The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies’ (PI: F. Matteucci), prot. 2010LY5N2T. EV was supported in part by grant NASA-NNX13AF45G. MDC was supported by the INAF fellowship 2010 grant.

REFERENCES

Anderson J., Piotto G., King I. R., Bedin L. R., Guhathakurta P., 2009, ApJ, 697, L58
Bekki K., 2011, MNRAS, 412, 2241
Bekki K., Campbell S. W., Lattanzio J. C., Norris J. E., 2007, MNRAS, 377, 335
Blöcker T., Schönberner D., 1991, A&A, 244, L43
Briley M., 1997, AJ, 114, 1051
Caloi V., D’Antona F., 2005, A&AS, 143, 987
Caloi V., D’Antona F., 2007, A&AS, 146, 949
Cannon R. D., Croke B. F. W., Bell R. A., Hesser J. E., Statkhis R. A., 1998, MNRAS, 298, 601
Canuto V. M. C., Mazzitelli I., 1991, ApJ, 370, 295
Carretta E., Gratton R. G., Bragaglia A., Bonifacio P., Pasquini L., 2004, A&A, 416, 925
Carretta E. et al., 2009, A&A, 505, 117
Carretta E., Gratton R., Bragaglia A., D’Orazi V., Lucatello S., 2013, A&A, 550, A34
Cloutmann L., Eoll J. G., 1976, ApJ, 206, 548
D’Antona F., Caloi V., 2004, A&A, ApJ, 871
D’Antona F., Caloi V., Montalban J., Ventura P., Gratton R., 2002, A&A, 395, 69
D’Antona F., Bellazzini M., Caloi V., Fusi Pecci F., Galleti S., Rood R. T., 2005, ApJ, 631, 868
D’Antona F., Caloi V., D’Ercole A., TAILO M., Vesperini E., Ventura P., Di Criscienzo M., 2013, MNRAS, 434, 1138
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., D’Antona F., Carini R., Vesperini E., Ventura P., 2012, MNRAS, 423, 1521
D’Orazi V., Lucatello S., Gratton R., Bragaglia A., Carretta E., Shen Z., Zaggia S., 2010, ApJ, 71, L1
Decressin T., Charbonnel C., Meynet G., 2007, A&A, 475, 859
Di Criscienzo M., Ventura P., D’Antona F., Milone A., Piotto G., 2010, MNRAS, 408, 999
García Beroro E., Ritossa C., Iben I. J., 1997, ApJ, 485, 765
Gratton R., Sneden C., Carretta E., 2004, A&AA, 42, 385
Gratton R., Carretta E., Bragaglia A., 2012, A&AR, 20, 50
Gratton R. G. et al., 2013, A&AA, 549, 41
Grevesse N., Sauval A. J., 1998, Space Sci. Rev., 85, 161
Harbeck D., Smith G. H., Grebel E. K., 2003, AJ, 125, 197
Herwig F., 2005, ARA&A, 43, 435
Karakas A. I., 2010, MNRAS, 403, 1413 (K10)
Karakas A. I., 2011, in Kerschbaum F., Lebzelter T., Wing R. F., eds, ASP Conf. Ser. Vol. 445, Why Galaxies Care about AGB Stars II: Shining

Multiple populations in 47 Tuc 3281

Downloaded from https://academic.oup.com/mnras/article-abstract/437/4/3274/1002366 on 26 July 2018 by guest
Examples and Common Inhabitants. Astron. Soc. Pac., San Francisco, p. 3
Marigo P., Girardi L., 2007, A&A, 469, 239
Marino A. F., Milone A. P., Piotto G., Villanova S., Bedin L. R., Bellini A.,
Renzini A., 2009, A&A, 505, 1099
Milone A. P. et al., 2008, ApJ, 673, 241
Milone A. P. et al., 2010, ApJ, 709, 1183
Milone A. P. et al., 2012a, ApJ, 744, 58
Norris J. E., Freeman K. C., Mighell K. J., 1996, ApJ, 462, 241
Piotto G. et al., 2007, ApJ, 661, L53
Piotto G. et al., 2012, ApJ, 760, 39
Renzini A., 2008, MNRAS, 391, 354
Renzini A., Voli M., 1981, A&A, 94, 175
Richer H. B., Heyl J., Anderson J., Kalirai J. S., Shara M. M., Dotter A.,
Fahlman G. G., Rich M., 2013, ApJ, 771, L15
Ritossa C., Garcia Berro E., Iben I. J., 1996, ApJ, 460, 489
Ritossa C., Garcia Berro E., Iben I. J., 1999, ApJ, 515, 381
Schwarzschild M., Harm R., 1965, ApJ, 142, 855
Schwarzschild M., Harm R., 1967, ApJ, 145, 496
Siess L., 2006, A&A, 448, 717
Siess L., 2007, A&A, 476, 893
Siess L., 2010, A&A, 512, A10
Ventura P., 2009, in Charbonnel C., Tosi M., Primas F., Chiappini C., eds,
Proc. IAU Symp. 268, Light Elements in the Universe. Cambridge Univ.
Press, Cambridge, p. 147
Ventura P., D’Antona F., 2005, A&A, 341, 279
Ventura P., D’Antona F., 2006, A&A, 457, 995
Ventura P., D’Antona F., 2008a, A&A, 385, 2034
Ventura P., D’Antona F., 2008b, A&A, 805, 816
Ventura P., D’Antona F., 2009, A&A, 499, 835
Ventura P., D’Antona F., 2011, MNRAS, 410, 2760
Ventura P., Zeppieri A., Mazzitelli I., D’Antona F., 1998, A&A, 334, 953
Ventura P., D’Antona F., Mazzitelli I., Gratton R., 2001, ApJ, 550, L65
Ventura P., Carini R., D’Antona F., 2011, MNRAS, 415, 3865
Ventura P., Di Criscienzo M., Carini R., D’Antona F., 2013, MNRAS, 431, 3642
Vesperini E., McMillan S. L. W., D’Antona F., D’Ercole A., 2013, MNRAS,
429, 1913

This paper has been typeset from a TEX/LATEX file prepared by the author.