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Hot CNO and p-capture nucleosynthesis in intermediate-mass AGB stars

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Abstract. When the judgement on the reliability of models for "multiple" populations in globular clusters is based on the nucleosynthesis needed to produce the anomalous abundances of light elements, the asymptotic giant branch scenario remains the only game in town. We discuss this evidence, together with the difficulties that this model too has to face in dealing with the direct comparison between the observed abundances and predicted yields. We show that a reduction of the cross section of the ^{23}Na(p,α)^{20}Ne reaction at T$\sim$100MK is the main requirement that could allow to ease or fully solve the problems.

Key words. Stars: abundances – Stars: Population II – Galaxy: globular clusters –

1. Introduction

The structure of asymptotic giant branch stars evolving above a critical luminosity changes in a dramatic way: the convective boundary touches the H-burning shell, so that "hot bottom burning" (HBB) occurs, and the products, which depend on the temperature T_{HBB}, are spread from the envelope up to the atmosphere. As these luminous giants lose mass, the products of nucleosynthesis are recycled into the interstellar medium, and have an important role in the galactic chemical evolution. This seems to have occurred also at the epoch of the formation of the old globular clusters of our Galaxy, where ubiquitous "multiple populations" show, inter alia, chemical anomalies due to hot CNO and other p-capture reactions. Are these anomalies due to pollution by massive AGBs (Ventura et al. 2001; D'Ercole et al. 2008), or by other stars subject to advanced nucleosynthesis during the H–burning stage such as fast rotating massive stars (FRMS, e.g. Decressin et al. 2007), or massive interacting binaries (MIB, de Mink et al. 2009)? In this contribution we recall and emphasize that the AGB scenario is the only one that *in principle* can account for the whole spectrum of abundance variations found in globular clusters, a well known and settled result. Thus, we claim that it is the only game in town for the formation of multiple populations. Despite the *qualitative* picture is in favour of this model, the abundances obtained in the most favorable computations of yields of massive AGBs (our own) show *quantitative* discrepancies with respect to the observed anomalies. Directions along which further research can deal with these discrepancies are discussed.

2. The problem of abundance patterns in globular clusters

It is now fully acknowledged that globular clusters (GCs) host multiple populations, with variations in the abundances of He and

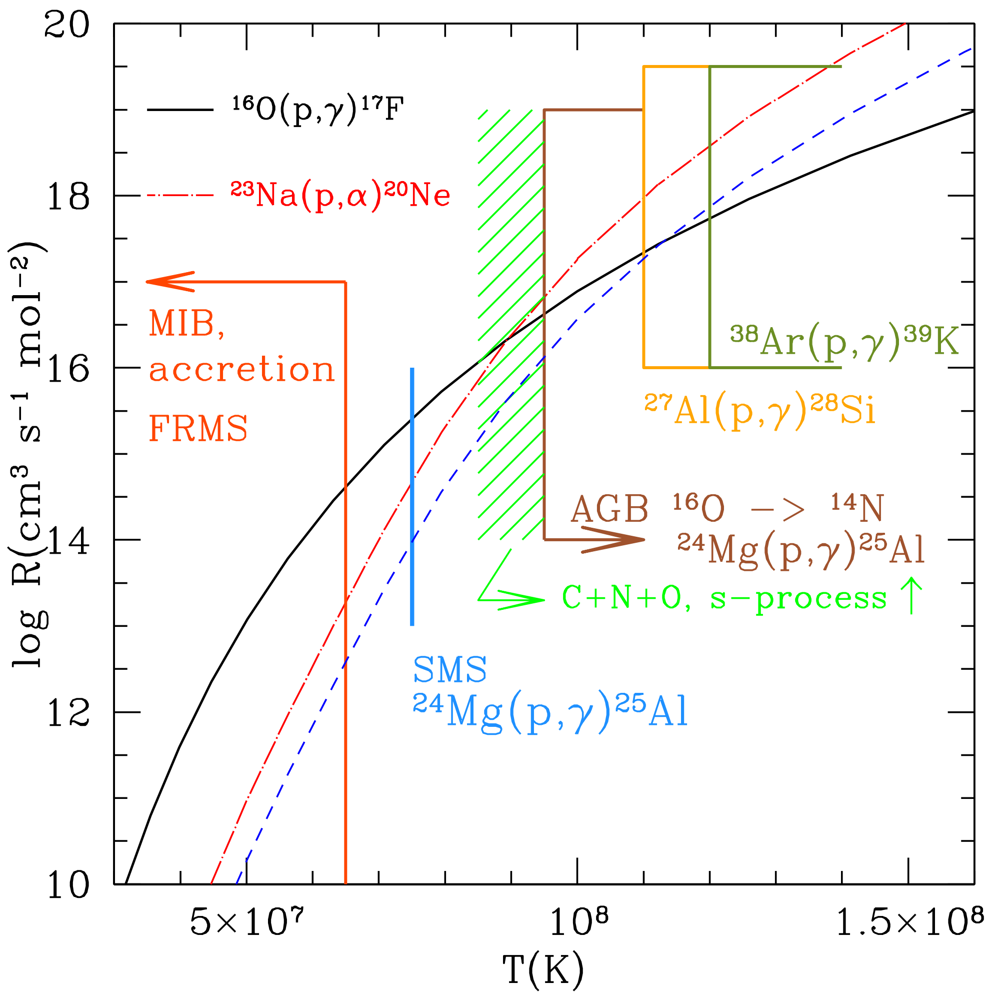

Fig. 1. The rates of the two reactions which mainly determine the O/Na ratios in AGB stars as a function of the temperature. The rate of oxygen burning by proton captures is from the NACRE compilation (Angulo et al. 1999), while the rate of the ^{23}Na burning (red line) is the lower limit allowed by the Hale et al. (2004) determination, ~ 25% below the recommended rate. The blue dashed line corresponds to a further reduction by a factor of 5. The temperature boundaries of models for different scenarios proposed to explain the multiple populations (supermassive stars –SMSs–, FRMSs, MIBs and AGB stars) are marked as well as the temperatures above which the indicated reactions start to efficiently operate in AGB stars (see text). The green shaded temperature range corresponds to the range of temperature in AGB models which have longer evolutionary times, and in which the total content of C+N+O and the s–process abundances increase due to the third dredge-up (Ventura et al. 2013).

light elements (C, N, O, F, K, Na, Mg, Al, Si). In a growing number of clusters, also Fe and/or s-process elements appear to vary. Additionally, high precision color-magnitude diagrams (CMD) show that most GCs display complex features, with splits and/or spreads in the main sequence, red-giant branch, etc. A number of (qualitative) theories have been put forward to explain the observed anomalies, but none of them is able to entirely reproduce the observed properties in GCs. Indeed, the origin of multiple populations is still disputed and many question remain unanswered.

The most important of these questions is probably the so called "mass budget" problem: the polluting material forming the second-generation (SG) stars is processed in stars of the first generation (FG), and is necessarily a small fraction of the total mass of the cluster. In most clusters, anyway, the SG stars are at least as numerous as the FG ones (e.g. Carretta et al. 2010), so a large fraction of the FG —about 90%, or even more in some cases— should have been lost from the cluster (e.g. D'Ercole et al. 2008). The halo mass in our own Galaxy contains enough mass to justify such a huge mass loss. In addition, the composition of halo stars looks like the FG composition, while a few percent of them show SG-like abundance patterns (Carretta et al. 2010; Martell et al. 2011). This observed ratio is well predicted by two-generation GC formation models (Vesperini et al. 2010). On the other hand, problems may be present in the dwarf galaxy Fornax, according to Larsen et al. (2012), but see also Bate et al. (2015).

A problem may be posed by the evidence that all the attempts to find signatures of second-generation star formation in young massive clusters (YMC), which in principle could represent snapshots of old globular clusters, have been unfruitful, casting doubts on *all* models proposed so far, in particular on the AGB scenario (Bastian et al. 2013; Cabrera-Ziri et al. 2014; Longmore 2015) and on the FRMS scenario (Bastian et al. 2014). We remark, anyway, that this lack of evidence can simply mean that old globular clusters indeed formed in an environment so different from the present one (Kruijssen 2015; Trenti et al. 2015).

The first and main requirement a model has to satisfy to be plausible is that it must *provide a site, for the occurrence of nucleosynthesis of light elements, able to explain all the abundance "anomalies" observed in the multiple generations*. While Renzini et al. (2015) notice that the multiple populations have characteristics of variety, discreteness, the necessity of supernovae avoidance, and others, under which scrutiny all models show to be qualitatively inadequate, and only the AGB scenario remains *barely* plausible. Here we deal only with the nucleosynthesis problem, which is mandatory. From our point of view, the interest in models which, as an example, solve the problem of the mass budget, or can deal with the lack of gas in young massive clusters, remains academic if these same models do not make correct, or *at least plausible*, predictions for the abundance patterns. We make a simple example of why the nucleosynthesis problem is the most important one. A nice model has been advanced in recent literature by Bastian et al. (2013), which in principle is able to ease the issue of the initial mass budget. These authors propose that chemical anomalies are due to massive accretion of the hot–CNO processed gas lost from massive binaries, during the first 10^7 yr of the cluster lifetime, on the *protostellar* accretion discs of low-mass stars. This would change their chemistry down to the stellar center, so that the seeds of the SG are in fact born at the same time as the FG stars of standard composition. In fact, while their model *in principle* apparently does not require an initial mass budget much larger than the present clusters' mass, it does not meet the requirements of the most basic chemical abundances needed to satisfy the observational constraints, namely the helium content in the SG, and especially in the extreme SG shown in some massive clusters (Cassisi & Salaris 2014), the abundances of lithium observed in FG and SG (Salaris & Cassisi 2014) or both of these constraints (D'Antona et al. 2014; Tognelli et al. 2015). Based on this evidence, it looks worthless to stress whether this model could satisfy other observational constraints, until it is shown how to change (dramatically) stellar evolution, to satisfy the required "chemical" constraints.

3. The role of temperature inside stars

We show in Fig. 1 (see also Renzini et al. 2015) the rates of the two reactions that mainly determine the O/Na ratios in AGB stars as a function of the temperature. The rate of the ^{23}Na burning is the red line and the rate of oxygen burning by proton capture is the black line. On the figure we draw some lines of characteristic temperatures of p–capture processes in AGBs, and boundaries for other stellar models. The first and most important one is the limit (∼65MK) of temperature reached in the core of massive stars. This limit has been discussed in the recent literature (Prantzos et al. 2007): it is the maximum temperature reached in the core of the most massive model computed (120$M_\odot$) during its final stages of burning (Decressin et al. 2007), and it is ∼10 MK smaller than the temperature needed to process ^{24}Mg by p–capture in stellar interiors. It is fundamental to realize that not much can be done to increase the temperature during the core–H burning stage of massive stars. As a direct consequence of standard physics (namely the hydrostatic equilibrium equation, perfect gas law and the mass radius relation for main sequence stars burning CNO) the central temperature has a very shallow dependence on the total mass. This means that it is not possible to attribute the magnesium depletions found in the SG of some clusters (Sneden et al. 2004; Carretta et al. 2009; Carretta 2015) to nuclear processing in the interior of massive main sequence stars. For the same reason, silicon production is also excluded. This inability to deal with some chemical processing signatures present in GC stars is enough to reject three models: FRMS, MIBs, and the accretion model already mentioned (Bastian et al. 2014) in which the polluting matter comes from interacting binaries.

The "supermassive stars" (SMS) model by Denissenkov & Hartwick (2014) resorts to supermassive stars precisely to reach internal temperatures at which magnesium can be burned (see Fig. 1). Criticism to this model comes from different considerations (Renzini et al. 2015).

In the remaining model, the AGB scenario, the p–process nucleosynthesis occurs at the bottom of the convective layers, where the densities are similar or even larger than in the cores of massive stars. Nevertheless, the evolutionary times are shorter, so larger temperatures are needed for the p–capture processes which can be related to the abundances found in SG stars. Fig. 1 shows the limits for different reactions. T∼100 MK is the temperature above which oxygen is efficiently processed back to nitrogen closing the CNO cycle (Ventura et al. 2013; Doherty et al. 2014) , ∼110 MK is necessary for synthesis of silicon from aluminum (Ventura et al. 2011), and >120 MK is needed for the proton captures on argon which may be the cause of potassium variations in NGC 2419 (Ventura et al. 2012). The AGB scenario can thus provide the correct answer to the nucleosynthesis, but it meets with a major problem, the inability to maintain a large sodium abundance in the yields of stars that are able to explain the most advanced nucleosynthesis.

4. The sodium problem

If HBB destroys efficiently oxygen mostly at $T_{HBB} > 10^8$ K, there the p–capture cross section on sodium becomes larger than the p–capture on oxygen (Fig. 1), sodium burning is more efficient, and it begins to be depleted in the envelope (Fig. 2). In those models which do not reach so high T_{HBB}, either because they have a smaller mass, or a less efficient modeling of convection (Ventura & D'Antona 2005), the luminosity is smaller, the timescale of evolution is longer, and they show a strong effect of the third dredge-up, so that their C+N+O increases, oxygen is less depleted, and sodium increases too much with respect to the observed values (Fenner et al. 2004, see also Fig. 2).

As sodium and oxygen are both destroyed at each given T_{HBB}, it is impossible to obtain a sodium–oxygen "anticorrelation" directly in the yields of massive AGBs. Luckily, when a star evolves into the AGB thermal pulse phase, sodium in the envelope increases, first due to the sodium synthetised in the interior due to p–captures on ^{22}Ne and transported to the surface at the second dredge-up. A further increase follows, thanks to the HBB of the ^{22}Ne itself dredged up (Fig. 2). In the following phases, sodium is mainly destroyed by the p–capture reaction which closes the Ne–Na cycle back to neon. The amount of sodium initially dredged-up or synthesized in the envelope is an important reservoir, which can change the final yield of sodium, but it is evident that burning is unavoidable, unless mass loss is extreme and allows to lose the whole envelope at the peak of sodium abundance. In that case, however, oxygen is not depleted enough.

It is well studied that HBB efficiency depends on the convection modeling (e.g. Ventura & D'Antona 2005). W hile all models by our group (Ventura et al. 2013) always adopted very efficient convection, the FST model (Canuto & Mazzitelli 1991; Canuto et al. 1996) models adopting the MLT convection, with a moderate value of the mixing to pressure scale height length do not reach the same high T_{HBB}. In this case, luminosities are smaller, evolution is longer, and the stellar model goes through a high number of thermal pulses and episodes of third dredge-up. This is shown in Fig. 2, where we see that ^{22}Ne is dredged up at each episode, so sodium does not burn. Unfortunately, oxygen too is not depleted enough, and, in addition, the total CNO content increases.

A "simple" but unproven way to solve this problem is to ask for a reduction of the ^{23}Na(p,α)^{20}Ne rate (Ventura & D'Antona 2006). Fig. 1 shows that a reduction by a factor five would put the rate of sodium destruction below the rate of oxygen destruction in the whole range of interest for the AGB envelope p–capture processing. This would allow to reduce the mass loss rates in the models, and achieve a good quantitative agreement also in the magnesium depletion.

5. The region of C+N+O increase

A number of clusters show SG populations including C+N+O and s–process enrichment. Although only in three clusters the CNO enhancement is determined —NGC 1851 (Yong et al. 2009, 2015) and M 22 (Marino et al. 2012), plus ω Cen (Marino et al. 2012)— there are several other clusters with s–process bimodality or spread, in which the C+N+O is not yet measured. This may imply that in some cases the SG star formation is efficient also at times in which masses undergoing an important 3rd DU are evolving (green dashed regions of T_{HBB} in Fig. 1). This problem deserves a mention here, because it is a further important indication that the AGB stars are responsible for the chemical variations in multiple stellar populations, but it will be fully examined in a future paper.

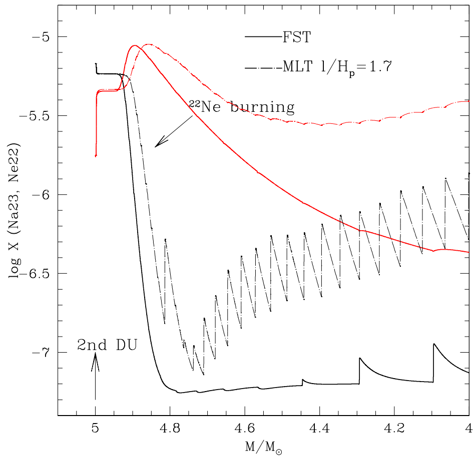

Fig. 2. Evolution of ^{23}Na (in red) and ^{22}Ne (black) as a function of the mass (decreasing due to mass loss) in the envelope of a $5M_\odot$ initial mass of metallicity mass fraction Z=0.001, when two different convection models are adopted to describe turbulence: the FST model by Canuto et al. (1996) (full lines) and the MLT model with ratio of mixing length to pressure scale height 1.7 (dashed lines). In this latter evolution, the episodes of 3rd DU are shown to increase the ^{22}Ne abundance in the envelope, following each thermal pulse, and the p–captures on ^{22}Ne increase the sodium in the envelope.

6. Conclusions

Nucleosynthesis of light elements shows that the only game in town to explain the abundance patterns of multiple populations in GCs is played by AGB models. However, the results of these models are not yet satisfactory. A plea for the re-examination of the ^{23}Na(p,α)^{20}Ne cross section in the range of temperatures of HBB is raised here.

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