CNO in Low- and Zero-Metallicity AGB Stars

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Abstract. The oldest stars hide information about the chemical evolution of the early universe. In this context new models of the AGB stellar evolution phase at very low and zero metallicity are presented. Due to the deficiency or absence of CNO catalytic material hydrogen burning operates at significantly higher temperatures than in stars of higher metallicity. As a result convective mixing plays a very important role since the nuclear burning shells are not well separated by an entropy barrier. These stars can host flash-like burning events induced by mixing of $^{12}\text{C}$ and protons at the core-envelope interface. Three different mixing events with proton-capture nucleosynthesis can be encountered. One of them, the hot dredge-up, is reported here for the first time. All these specific modes of nucleosynthesis are relevant for the production of CNO material in the first intermediate mass stars.

1. Introduction

The first nuclear processing of pristine Big Bang matter has left a signature in today’s most metal poor low mass stars. There is some debate whether both low mass and massive stars contributed to this processing (Nakamura & Umemura, 2002) or whether the first stars were exclusively very massive (e.g. Abel et al., 2002). The recently discovered low mass star HE0107-5240 has [Fe/H]=-5.3 (Christlieb et al., 2002). This may indicate that the Pop. III IMF has a low mass component. The large nitrogen overabundance in this object could mean that intermediate mass stars are involved in the contamination of this star.

This is much more obvious for stars like HE0024-2523 (Lucatello et al., 2003), a very metal poor main sequence star with [Fe/H]=-2.7, an s-process abundance signature, large C and N overabundances as well as radial velocity variations. It has been suggested that this star and related objects have been polluted by an intermediate mass binary companion. The carbon and s-process abundance could – in principle – be understood with the dredge-up and s-process mechanisms known from AGB stars of solar-like metallicity (e.g. Gallino et al., 1998). The nitrogen overabundance could result from partial envelope CNO cycling (hot bottom burning, HBB). Siess et al. (2002) predict that both carbon as well as nitrogen may be significantly enhanced due to dredge-up and HBB in Z=0 AGB stars. Their 3(2)M☉ model predicts at the last thermal pulse (TP) $\frac{C}{H}\sim -0.9(0.0)$, $\frac{N}{H}\sim +0.4(-2.2)$ and $C/O= 5(53)$. HE0024-2523 has $\frac{C}{H}= -0.1$, $\frac{N}{H}= -0.6$ and $C/O= 100$. A $\frac{C}{N}$ ratio of a few tenth of a dex is also found in other similar stars (e.g. CS 22948, Aoki et al., 2002). It is
even more extreme in HE0107-5240. This puts some limit on the role HBB can play because efficient HBB may too quickly decrease the C/N ratio below unity.

The role of intermediate mass stars as a source of primary nitrogen in the early chemical evolution has recently been revisited on the basis of the N abundances in Damped Lyman-α Absorbers (Pettini et al., 2002, and Henry & Proschaska, this volume). Meynet & Maeder (2002) have shown that in intermediate mass stars of very low metallicity rotationally induced mixing can lead to significant $^{14}$N enrichment of the outer layers even before the first TP occurs. In these models the C/N ratio is much smaller than unity and would not reproduce the abundance patterns of stars like HE0024-2523. Clearly, the envelope abundances are modified in the subsequent TP AGB phase.

In very low and zero metallicity stars the convection zone driven by the He-flash may reach into the proton rich unprocessed outer layers. As protons enter the He-shell environment they initiate a vigorous non-equilibrium nuclear burning, mainly of proton captures on $^{12}$C. This may happen in the case of
Figure 2. Evolution of the mass coordinate of the H-free core $M_H$ and the H-burning luminosity $L_H$ during the end of the second dredge-up ($t < 7500\,\text{yr}$) and the first two AGB TPs of the $Z=0.0001$ sequence with $M=5M_\odot$.

In this paper I present first results on stellar evolution calculations that consider convective nucleosynthesis in a numerically consistent way and also allow for soft convective boundaries with respect to mixing. Models of the proton ingestion induced H-flash during TPs of $Z=0$ AGB stars of $2M_\odot$ and $5M_\odot$ are described. In addition I report on a new process of carbon and nitrogen enrichment uniquely present in very low metallicity stars which is a combination of HBB and third dredge-up.

2. Stellar evolution code and physical model

The 1D hydrostatic stellar evolution code EVOL has been previously used for extensive calculations of the TP AGB phase (Herwig, 2000). The models contain a parametric hydrodynamic overshooting at all convective boundaries. The efficiency $f$ is expressed as the e-folding distance of the decay of the turbulent velocity field in the stable layer. This scheme has been adopted from 2D RHD simulations. In AGB models the efficiency can be constrained by careful analysis of the $s$-process nucleosynthesis, and comparison with both stellar observations and measurements of pre-solar meteoritic grains. In particular certain temperature dependent branchings provide valuable constraints on mixing processes in low mass TP AGB stars (Lugaro et al., 2002; Herwig et al., 2002).
Figure 3. Temperature and abundance profile during the hot dredge-up phase after the first TP of the $5M_\odot$, $Z=0.0001$ evolution sequence.

EVOL has also been used to construct model sequences of pre-white dwarf He-shell flash stars which evolve into born-again AGB stars (Herwig et al., 1999). In these stars the convection zone of the He-shell flash can reach into the thin H-rich envelope, very similar to the events reported by Fujimoto et al. (2000) in very low or zero metallicity stars. We follow the convective nucleosynthesis with a solution scheme in which nuclear rate equations and time dependent mixing equations are fully coupled. In that way the abundance profiles, in particular of hydrogen, reflect at each grid point and time step the simultaneous action of fast convective mixing and fast p-captures by $^{12}$C. Although the numerical scheme is treating the abundance evolution in this convective nucleosynthesis event correctly there is evidence that the physical model to describe convection (here the mixing length theory) may need to be adjusted (Herwig, 2001), which is done here in an approximated way.

3. Proton capture burning in the He-shell flash layer

I have computed $Z=0$ tracks for initial stellar mass of $2M_\odot$ and $5M_\odot$ from the pre-main sequence up to the TP AGB. In both cases protons are eventually entering the He-flash convection zone. The $5M_\odot$ sequence starts on the AGB with eight weak TPs with $L_{\text{He}} < 10^5L_\odot$ and a TP period of $\approx 3500\text{yr}$. The H-shell becomes convectively unstable at the time it reignites after the 9th TP. This occurrence has been previously reported by Chieffi et al. (2001) and Siess et al. (2002) as a hydrogen convective episode (HCE). The trace of any small C and N envelope abundance increase resulting from this event is lost in the following TP. As the He-flash convection zone develops it eventually reaches out into the proton rich envelope and the well known sequence of events, including the H-flash
and the splitting of the convection zone take place. A snapshot of the developing H-flash convection zone on top of the He-flash convection zone is shown in Fig. 1. In comparison to the very late TP in some pre-white dwarf models (Herwig et al., 1999) much more hydrogen is available and a large amount of $^{14}\text{N}$ is produced. The processed material is dredged-up to the surface in two subsequent phases associated with the H-flash and the He-flash respectively. The envelope $^{14}\text{N}$ mass fraction after the event is $2.5 \cdot 10^{-5}$. In the 2$M_\odot$ case the proton ingestion into the He-shell flash layer happens after 7 weak initial pulses without a previous HCE event. A peak H-luminosity of almost $10^{10}L_\odot$ is obtained and after the event both the $^{12}\text{C}$ and the $^{14}\text{N}$ abundance in the envelope amounts to about $10^{-4}$ in mass fraction with $\text{C}/\text{N} < 1$. For both masses the further evolution is equivalent to models at higher $Z$ with the same supply of CNO catalytic material.

If the models by Meynet & Maeder apply to $Z=0$ intermediate mass stars, and if these are rapid rotators, then the proton ingestion into the He-flash convection layer will not occur in TP AGB models. It is also unlikely that the HCE will occur in this case.

### 4. Hot dredge-up

In addition to the $Z=0.0$ sequences I calculated tracks for $\log Z = -5$, $-4$, and $-3$ for 2$M_\odot$ and 5$M_\odot$. In all sequences efficient dredge-up is present leading to gradual CNO enrichment at each TP. A new phenomenon was encountered in all 5$M_\odot$ cases (Fig. 2). During the dredge-up phase protons are partially mixed with the underlying $^{12}\text{C}$ in the core. In this tiny layer the $\text{H}/^{12}\text{C}$ ratio drops by orders of magnitude. At the given temperature this leads to fast proton captures and a very large H-burning luminosity. The partial mixing layer in these calculations is the immediate consequence of the hydrodynamic overshooting model. This effect is only observed in very low $Z$ models where the dredge-up layer is hotter compared to higher metallicity models. As shown in Fig. 3 a substantial $^{14}\text{N}$ pocket forms in this partial mixing layer. A $^{13}\text{C}$ pocket of the same size (not shown) is also present. The s-process can not take place in this partial mixing layer because the time scale is too short and the $^{14}\text{N}$ abundance is too high. In these models carbon is CN processed *on the fly* as it is dredged-up to the envelope. This process can be thought of as a combination of HBB and third dredge-up, and I call it *hot dredge-up*. The dredge-up with simultaneous hydrogen burning may be much deeper than usually found. This can boost the envelope enrichment with processed matter, in particular C and N. We summarize the C and N abundance features before and after the first thermal pulse with hot dredge-up in Table 1. It is tempting to compare these results with observed C and N abundances and isotopic ratios, for example Tab. 6 in Aoki et al. (2002). The isotopic ratios agree within a factor of two. However,
the combined effect of hot dredge-up, HBB, and mass loss over many thermal pulses should be taken into account before detailed comparisons are useful.

5. Conclusions

All recent calculations of the AGB phase at Z=0 agree that thermal pulses and dredge-up occur. Various processes, in particular rotationally induced mixing during the He-core burning phase, can lift the envelope abundance of catalytic material for the CNO cycle so that eventually the evolution in these objects resemble those of only mild metal deficiency. It is therefore not clear if the proton ingestion into the He-shell flash convection zone or the HCE take place in real Z=0 AGB stars should they have existed. Here a hot variant of the third dredge-up was described which may be an important ingredient in understanding both the primary production of nitrogen as well as the peculiar carbon and nitrogen overabundances observed in very metal poor stars.

Acknowledgments: I would like to thank D.A. VandenBerg for support through his Operating Grant from the Natural Science and Engineering Research Council of Canada.

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