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EVOLUTIONARY PROPERTIES OF PRIMORDIAL STARS

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Abstract

We present the results of new computations of the evolution of primordial stars (Z=0) and focus our discussion on low- and intermediate-mass stars. The evolution has been computed from the pre-main sequence phase up to the beginning of the AGB phase. We summarize the main evolutionary features of these peculiar stars and describe how they enter the thermally pulsing AGB (TP-AGB) phase after the development of instabilities near the H-He discontinuity at the time of H burning shell reignition. We also briefly describe the nucleosynthesis and the evolution of the surface chemical composition.

1 Introduction

The first stars formed in our universe at redshifts of the order of $z = 10 - 30$. Their chemical composition is inherited from the Big Bang nucleosynthesis and is characterized by the absence of metals, and in particular of CNO nuclei. They are consequently primarily made of hydrogen (76%), helium (24%) with some traces of lithium. The initial mass function of the so-called population III stars is still largely unknown. While some groups favor the formation of massive stars (e.g. Bromm et al 1999), others argue that molecular hydrogen represents an efficient cooling factor that allows for the formation of low- and intermediate-mass stars (e.g. Palla et al 1983). In this context, it is possible that even very low-mass stars ($M \lesssim 0.8\ M_\odot$) might have survived up to now as nuclear burning stars. On the theoretical side, several works have explored the structure and evolution of primordial stars, and we refer the reader to the recent reviews by Castellani (2000) and Chiosi (2000) for a description of these previous investigations. In the next section, we summarize the structural evolution of these peculiar stars based on some recent computations (Siess et al 2001). Then we describe briefly the nucleosynthesis and surface enrichment and conclude.

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2 Structural evolution

2.1 Central H and He burning

During the pre-main sequence evolution, deuterium and lithium are burnt as the star contracts. At central H ignition, the pp chains come into play and represent the only available nuclear energy source at this stage. The lack of CNO nuclei does not affect substantially the evolution of the lower mass stars ($M \lesssim 1.2\ M_\odot$) since the energy released by the pp cycles is large enough to balance the energy loss at the surface. However, stars which usually sustain their energy requirement by the CNO cycle ($M \gtrsim 1.2\ M_\odot$) have to face an energy deficit resulting from the use of the poorly efficient pp chains. Consequently they contract, and the 3α reactions ignites when the central temperature reaches $\sim 10^8$K. Carbon is then produced, and when its central abundance (in mass fraction) approaches $X_{12\mathrm{C}} \sim 10^{-11}$, the CNO cycle finally activates and a convective core forms. At the exhaustion of hydrogen at the center, the 3α reactions are still at work and the star enters the core He burning phase without experiencing the first dredge-up. More generally, this first deep mixing event is absent in all our stellar models with $M \gtrsim 1\ M_\odot$. At the end of the central He burning phase, the convective envelope deepens and stars in the mass range $1.0 \lesssim M \lesssim 10\ M_\odot$ experience the second dredge up (in fact the first dredge up) which mainly enriches the surface in ^{4}He.

2.2 Mixing episodes and the thermally pulsing AGB phase

The occurrence of thermal pulses in zero-metal stars requires specific conditions. Fujimoto et al (1984) first pointed out the existence of a critical mass for the core ($M_\mathrm{crit} \approx 0.73\ M_\odot$) below which recurrent He shell flashes are expected to occur. They also found that for a core mass $M_\mathrm{core} \gtrsim M_\mathrm{crit}$, there exists a critical envelope CNO abundance ($X_\mathrm{CNO} \gtrsim 10^{-8}$) above which He shell flashes will be triggered. The reason for this behavior is explained as follows (Fujimoto et al 1984) : in massive stars, for which $M_\mathrm{core} \gtrsim M_\mathrm{crit}$, the lack of CNO nuclei imposes that H is burnt at very high temperatures, allowing for carbon production (by the 3α reactions) in the H burning shell (HBS). Thus, the 3α reactions are working contemporaneously in both shells and they advance in mass at similar rates. This prevents the mass growth of the intershell and thereby the occurrence of the instability. Conversely, in low-mass stars, the energy requirements are lower and the 3α reactions are not very active in the HBS. The two shells thus proceed outward at different rates - an unstable situation leading to the development of thermal pulses.

However, recent computations (Chieffi et al 2001, Siess et al 2001) have shown that the development of mixing episodes at the beginning of the double shell burning phase allows stars with $M_\mathrm{core} \gtrsim M_\mathrm{crit}$ and with initially subcritical CNO envelope abundance to reach the thermally pulsing AGB phase. This is illustrated in Fig. 1 and arises after the He shell becomes unstable and a convective zone (hereafter He convective shell, HeCS) first develops. The instability grows and reaches the tail of the H burning shell where it is stopped because of the large entropy barrier created by the HBS. As it retreats, a secondary convective zone

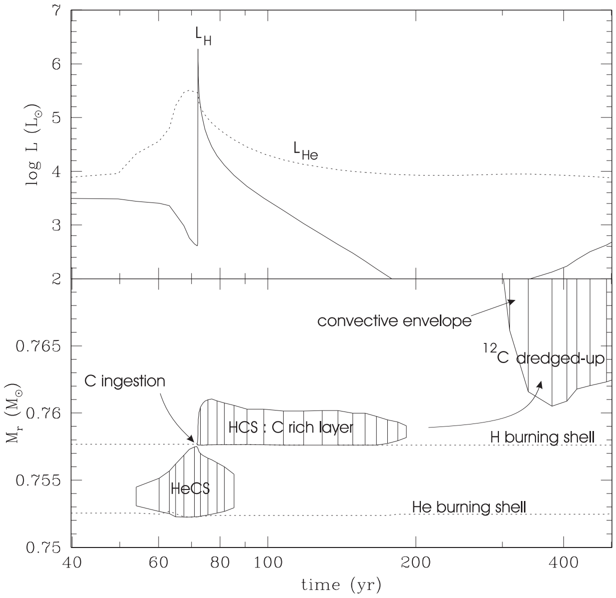

Fig. 1. Mixing episode in the 3 $M_\odot$ model at the beginning of the AGB phase (lower panel). The convective regions are hatched and the dotted lines delineate the locus of maximum energy production in the H and He burning shells. The top panel shows the evolution of the nuclear luminosities generated by H (solid) and He (dotted) burning.

forms at the H-He discontinuity (hereafter H convective shell, HCS). As the HCS expands downwards, carbon left by the receding HeCS is engulfed and a H flash occurs. The luminosity generated in the HBS (L_H) is mainly due to the CNO cycle and rapidly exceeds the one generated by the He shell (L_{He}, see Fig. 1). The energy released during the successive (He+H) flashes produces a large expansion of the overlaying layers which is followed by a deep penetration of the convective envelope. As it moves inward, the envelope reaches the region previously occupied by the HCS and dredges-up to the surface a significant amount of carbon (and nitrogen). This irreversible process enriches the envelope with CNO catalysts and allows the star to resume a "standard" thermally pulsing AGB (TP-AGB) evolution since, from now on, carbon production is no more required in the HBS. At the end of the mixing episode, the envelope mass fraction of CNO elements $> 10^{-7}$. Note that in stars with $M \gtrsim 6\ M_\odot$, the second dredge-up is able to raise the CNO abundance above the threshold value. As a consequence, these stars do not experience mixing episodes and follow a more classical evolution.

3 Chemical evolution

The development of mixing episodes allows primordial stars to enter the TP-AGB phase. Our models show that after a few He-shell flashes (pulses) the third dredge-up, i.e. the deepening of the convective envelope in the regions previously occupied by the pulse, occurs. This deep mixing leads to a substantial enrichment of the envelope in ^{12}C of course, but also of ^{16}O produced by ^{12}C(α,γ), ^{22}Ne coming from α-captures on ^{14}N and of its product ^{18}O, and of ^{25}Mg and ^{26}Mg which result from (α,n) and (α,γ) reactions on ^{22}Ne, respectively.

Primordial stars have a hotter internal structure and consequently hot bottom burning (HBB) is activated in stars with $M \gtrsim 2\ M_{\odot}$. Note that this is in distinct contrast to the standard assumption in the literature that the minimum mass for HBB is between 4 and 5 $M_{\odot}$. In addition to convert a substantial amount of ^{12}C into ^{14}N via the CNO cycle, HBB will also process ^{22}Ne into ^{23}Na, as well as the ^{25}Mg and ^{26}Mg into ^{26}Al and ^{27}Al.

Finally, if protons diffuse below the convective envelope during the third dredge up, then s-process elements can be produced *despite* the absence of iron seeds, as shown by Goriely and Siess (2001).

4 Conclusion

The main evolutionary characteristics of the first stars are : production of carbon by the 3α reaction during the main sequence in order to activate the CNO cycle, absence of first dredge up in stars with $M \gtrsim 1\ M_{\odot}$, development of mixing episodes at the beginning of the AGB phase which enrich the envelope in CNO and allow stars which do not naturally experience thermal pulses to actually enter the TP-AGB phase. As a general feature, primordial stars present higher temperatures, central densities and larger CO core masses than their more metal rich counterparts.

The evolution of the surface chemical composition results from the third dredge-up episodes and hot bottom burning. Computations indicate that primordial stars could have been strong contributors to the production of primary ^{12}C, ^{14}N, Mg and Al. Additionally, if slow transport processes (i.e. diffusion) are taking place at the bottom of the convective envelope, then s-elements can also be produced in environments originally devoid of metals.

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