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# AGB evolution: the key rôle of the C/O ratio

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**Abstract.** The evolution of AGB stars is reviewed as a function of a crucial parameter: the photospheric C/O ratio.

**Key words.** Stars: abundances – Stars: AGB and Post-AGB – Stars: evolution – Stars: atmospheres – Stars: abundances

## 1. Introduction

The photospheric C/O ratio of AGB stars drives sharp dichotomies in many of their observed properties, e.g. spectra, colors, effective temperatures, dust chemistry, etc., depending on whether the surface chemical composition is O-rich (C/O $< 1$) or C-rich (C/O $> 1$). Such dichotomies have become more prominent with the recent near-IR photometry provided by wide-area surveys (DENIS, 2MASS), and the mid-IR spectroscopic and photometric data being provided by the Spitzer satellite.

As a matter of fact, distinctive signatures of either O-rich or C-rich compositions are seen not only in the spectra of resolved AGB stars, but they can be detected also in integrated galaxy spectra. For instance, the SiO emission from early-type galaxies in the Virgo cluster is currently interpreted as due to the presence of mass-losing O-rich AGB stars (Bressan et al. 2006), while the new discovery of near-IR CN bands arising from the nuclear spectra of AGNs should be ascribed to C-rich stars belonging to an intermediate-age stellar population (Riffel et al. 2007).

On the theoretical side it is generally believed that the photospheric C/O ratio in (single, not belonging to binary systems) AGB stars is the result of the rich nucleosynthesis and convective mixing (i.e. the third dredge-up and hot-bottom burning) that characterize this evolutionary phase. Stellar models predict that the C/O ratio is strongly dependent on both stellar mass (hence age) and metallicity. Consequently, its knowledge is of paramount importance to a number of issues, such as: i) evaluating the role of low- and intermediate-mass stars in the chemical enrichment of the interstellar medium, ii) possibly inferring the star formation history in (un)resolved galaxies trough the detection or not of C-star features; ii) determining the mass of high-redshift galaxies (SED fitting technique).

## 2. Observed dichotomies between O-rich and C-rich AGB stars

It has been already known for a long time that in near-IR color-magnitude (e.g. $(J-K)$ vs $K$) diagrams and color-color (e.g. $J-H$ vs. $(H-K)$) diagrams AGB stars display a clear separation between M stars and C stars (e.g.

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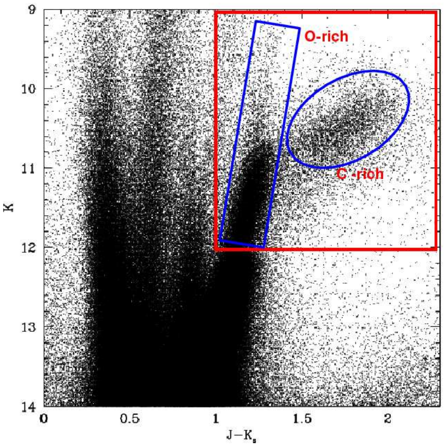

**Fig. 1.** Near-IR colour-magnitude diagram towards the LMC provided by 2MASS survey. Note the well-developed red tail populated by C stars.

Frogel et al. 1990). These latter exhibit systematically redder colors compared to those of M stars of the same luminosity. The dichotomy between the two spectral classes is so sharp that such diagrams are often used diagnostic tools to identify carbon star candidates from observed samples.

Recent wide-area near-IR (2MASS, DENIS) and mid-IR surveys (Spitzer satellite) towards the Magellanic Clouds (MCs) have confirmed these findings. By providing photometric data for the complete AGB population of both irregular galaxies, they have revealed the presence of a red plume of C-stars in a striking way (DENIS: Cioni et al. 1999; 2MASS: Nikolaev & Weinberg 2000; SAGE: Blum et al. 2006; S$^3$MC: Bolatto et al. 2006). In particular, the Spitzer SAGE and S$^3$MC surveys provide also a complete census of the extreme dusty stars characterized by very red IR colours, which are currently interpreted as AGB stars evolving through the last evolutionary phases with strong mass loss.

The photometric segregation between O-rich and C-rich stars is just the reflection of their spectral dichotomy, mainly due to strong vibrational-rotational absorption bands and electronic systems produced by different molecules in the visual and near-IR. M- and S-type spectra are dominated by the bands of VO, TiO, ZrO, $H_2O$, while C-type spectra exhibit strong bands of $C_2$, CN, HCN, $C_2$, $H_2$ (see left panel of Fig. 2). A prominent spectral dichotomy is detected also at mid- and far-IR wavelengths where the observed features are explained as produced by dusty circumstellar envelopes with different chemical compositions, typically: silicates in M-type spectra, and silicon carbide and graphite in C-type spectra (see right panel of Fig. 2).

The C/O ratio does not determine only the spectral features of AGB stars, but is expected to have a large impact also on the efficiency of mass loss. In the framework of radiation-driven winds for AGB stars (e.g. Elitzur & Ivezić 2001), the main radiation absorbers are the dust grains that condensate in the circumstellar envelopes with an efficiency $Q^{\rm star}$ that varies significantly with the type of dust ($Q^{\rm star}$(amorphouscarbon) $\approx 5\ Q^{\rm star}$(silicates)). Moreover, current hydrodynamical AGB wind models indicate that there should be a critical C/O ratio ($\simeq 1.2 - 1.4$, depending on metallicity) to produce a dusty wind in C-rich stars (Wachter et al. 2002; Mattsson et al. 2007), while dust opacity is found insufficient to drive an outflow in O-rich models (Woitke 2006).

The influence of the C/O ratio on the properties of AGB stars is demonstrated by another striking fact: there is a correlation between the morphology of planetary nebulae (PNe) and their chemical composition. As shown by Stanghellini et al. (2004) most round PNe have C/O$>1$, while most elliptical PN have C/O$<1$ and larger N/O. This morphological and chemical segregation should be ascribed to the different dynamical and nucleosynthetic evolution of the ejecta produced by AGB stars with different initial masses.

## 3. Molecules and opacity

The key to understand the profound differences between O-rich and C-rich giants resides in the properties of molecules that form abundantly in the cool atmospheres of these stars. As firstly demonstrated by Russell (1934), on the basis of molecular equilibrium calcula-

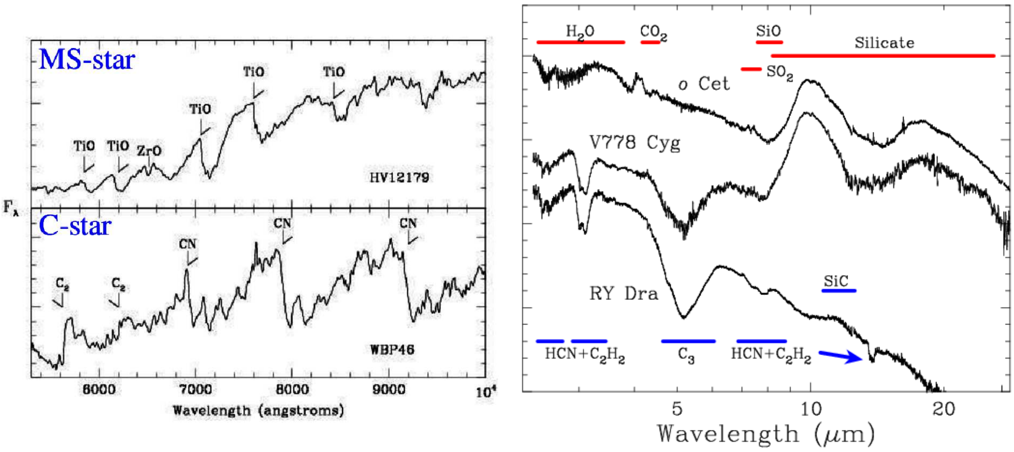

**Fig. 2. Left panel**: Optical spectra of an MS star (top panel) and a C star (bottom panel) belonging to the Large Magellanic Cloud. A few strong molecular bands are indicated. Figure adapted from Lattanzio & Wood (2003). **Right panel**: ISO SWS spectra of an M star (*o* Ceti, upper), and of a C star (RY Dra, bottom). The spectrum of V778 Cyg (middle) is a peculiar case showing features of both O-rich and C-rich chemistry. Figure from Yamamura et al. (1999).

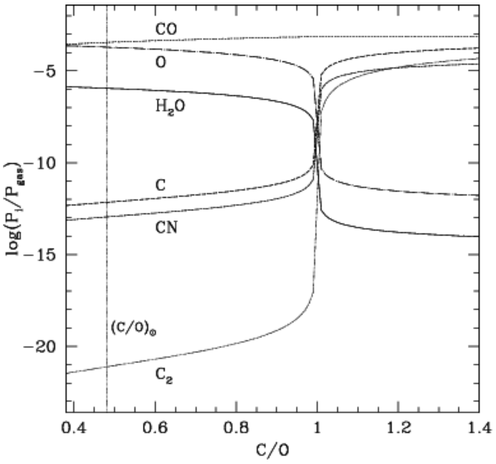

**Fig. 3.** Partial pressures of a few atomic and molecular species as a function of the C/O ratio, assuming a gas pressure $P_{\rm gas} = 10^3$ dyne cm$^{-2}$, and a temperature $T = 2500$ K. The vertical line intercepts the predicted molecular concentrations for a scaled-solar composition with C/O $\sim$ 0.48. Note the sharp dichotomy as C/O increases from below to above unity, for all species shown except the CO molecule. Figure from Marigo (2002).

tions, the binding energy of the carbon monoxide (CO molecule) is so high (11.1 eV) that almost all atoms of the least abundant element - C or O - are locked to form CO, while the excess atoms of the most abundant element are involved in the formation of the characteristic molecular bands. This fact is exemplified in Fig. 3 where an abrupt change is predicted in the atomic and molecular equilibria (involving C and O atoms) as soon as the gas mixture passes from oxygen-rich to carbon-rich.

As a consequence of the extreme sensitiveness of the molecular concentrations to the C/O ratio, dramatic changes are expected also in the gas opacities provided by molecules. Figure 4 compares the contributions of different molecules to the absorption coefficient in one oxygen-rich and one carbon-rich case. In M stars the most important opacity sources are $H_2O$, TiO and VO, while in C stars a major role is played by CN, $C_2$, HCN, $C_2H_2$ and $C_3$, with a clear correspondence with the vibration-rotation bands and electronic systems of these molecules detected in the visual and in infrared regions of the spectra.

The complex physics related to the chemistry, opacity, and radiation transfer in the

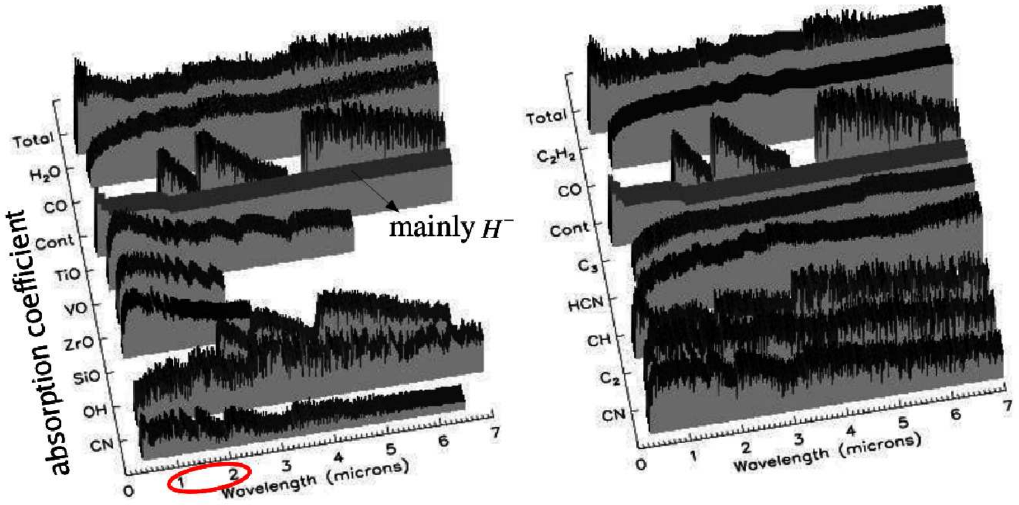

**Fig. 4.** Contributions to the opacity (mass absorption coefficient, logarithmic scale) in two model atmospheres with $T_{\rm eff}$ = 3000 K, $M = 1\,M_\odot$, $\log g = 0.0$, and C/O=C/O$_\odot$ (left panel); $T_{\rm eff}$ = 2800 K, $M = 1\,M_\odot$, $\log g = 0.0$, and C/O= 1.1 (right panel). Figure from Gustafsson & Höfner (2004).

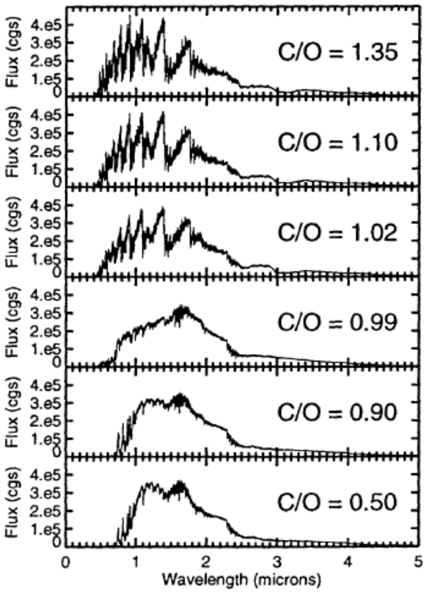

**Fig. 5.** Sequence of synthetic spectra at varying C/O ratio. All model atmospheres are computed with $T_{\rm eff}$ = 3000 K, $M = 1\,M_\odot$, and $\log g$ = 0.0. Figure from Gustafsson et al. (2003).

outermost layers of cool giants is included in present (static or dynamical) model atmospheres (e.g. MARCS models for C stars: Gautschy-Loidl et al. 2004), which are able to account for the spectral evolution as a function of the C/O ratio, in agreement As an example, Fig. 5 shows the predicted strong effect of the chemical composition on the resulting spectra: a sharp change of spectral features is expected just at C/O∼ 1, in full agreement with observations.

## 4. Evolutionary AGB models

In the following I will briefly recall a few important theoretical aspects dealing with the main processes that are predicted to alter the surface C/O ratio of AGB stars, namely: the third dredge-up and hot-bottom burning. Detailed reviews on these topics can be found in e.g. Busso et al. (1999) and Lattanzio & Wood (2004).

The third dredge-up This process, commonly invoked to explain the existence of N-type carbon stars, may take place during the power-down phase of thermal pulses. The base

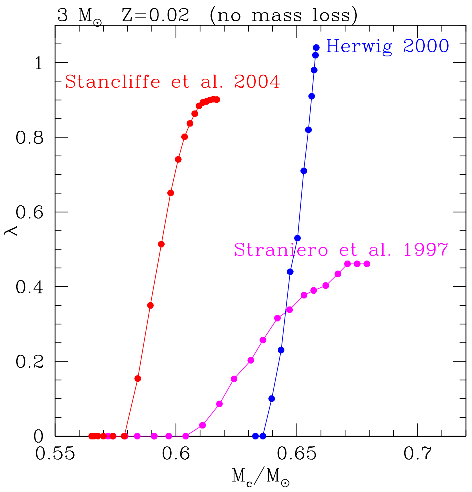

**Fig. 6.** Predicted efficiency of the third dredge-up as a function of the core mass in a model with $M = 3\,M_{\odot}$ and $Z0.02$, according to various authors as indicated. The parameter $\lambda = \Delta M_{\rm dred}/\Delta M_{\rm c}$ is defined as the fraction of the core mass growth during an inter-pulse period that is dredged up to the surface at the next thermal pulse.

of the convective envelope penetrates the C-rich region produced by the He-shell flash and newly synthesized products (mainly He, C, N, s-process elements) are brought up to the surface. In spite of its importance in determining the chemical enrichment of TP-AGB stars the modeling of the third dredge-up is still very uncertain. The main reason is the unsatisfactory description of stellar convection, which is mostly treated with local and one-dimensional analyses. Over the last years there has been much debate among AGB modelers to define a criterion for the convective boundary when a composition/opacity discontinuity is met, as in the case of the third dredge-up. Given the unstable character of the Schwarzschild border, extra-mixing beyond it must take place, which is realized with various approaches, e.g. a recursive sequence of (iteration + mixing) until stability is recovered (Karakas et al. 2000); overshooting scheme (Herwig 2000, Cristallo et al. 2007); simultaneous solution of structure and mixing equations (Stancliffe et al 2004).

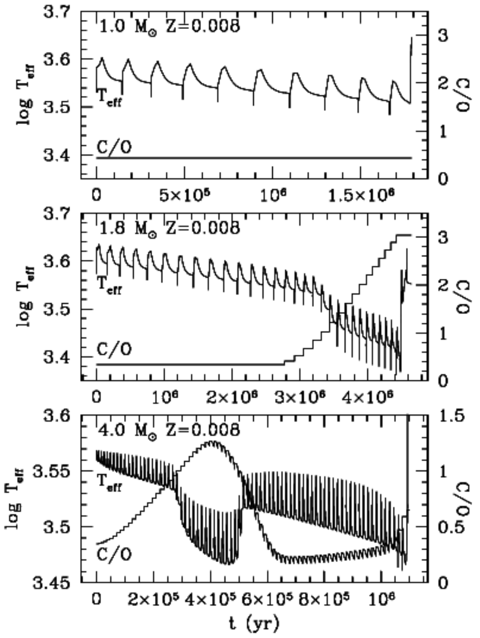

**Fig. 7.** Evolution of effective temperature and photospheric C/O ratio for a few models computed by Marigo & Girardi (2007). Note the remarkable decrease in $T_{\rm eff}$ as soon as C/O increases from below to above unity. The reverse trend, i.e. an increase in $T_{\rm eff}$, occurs instead in the 4.0 $M_{\odot}$ model due to the subsequent reconversion from C/O > 1 to C/O < 1 caused by HBB.

The main results of present AGB calculations can be summarized as follows: a few groups do predict the third dredge-up even in low mass stars (down to $M \sim 1.0 - 1.5\,M_{\odot}$ depending on metallicity; Straniero et al. 1997, Herwig 2000, Karakas et al. 2002, Stancliffe et al. 2005), apparently alleviating the long-standing difficulty to account for the faint C stars in the observed luminosity functions (Iben 1981). At large masses ($M > 3\,M_{\odot}$) convective dredge-up is expected to be very deep ($\lambda \sim 1$), thus preventing any growth of the core mass with important consequences for the initial-final mass relation. In general, however, model predictions appear to be quite heteroge-

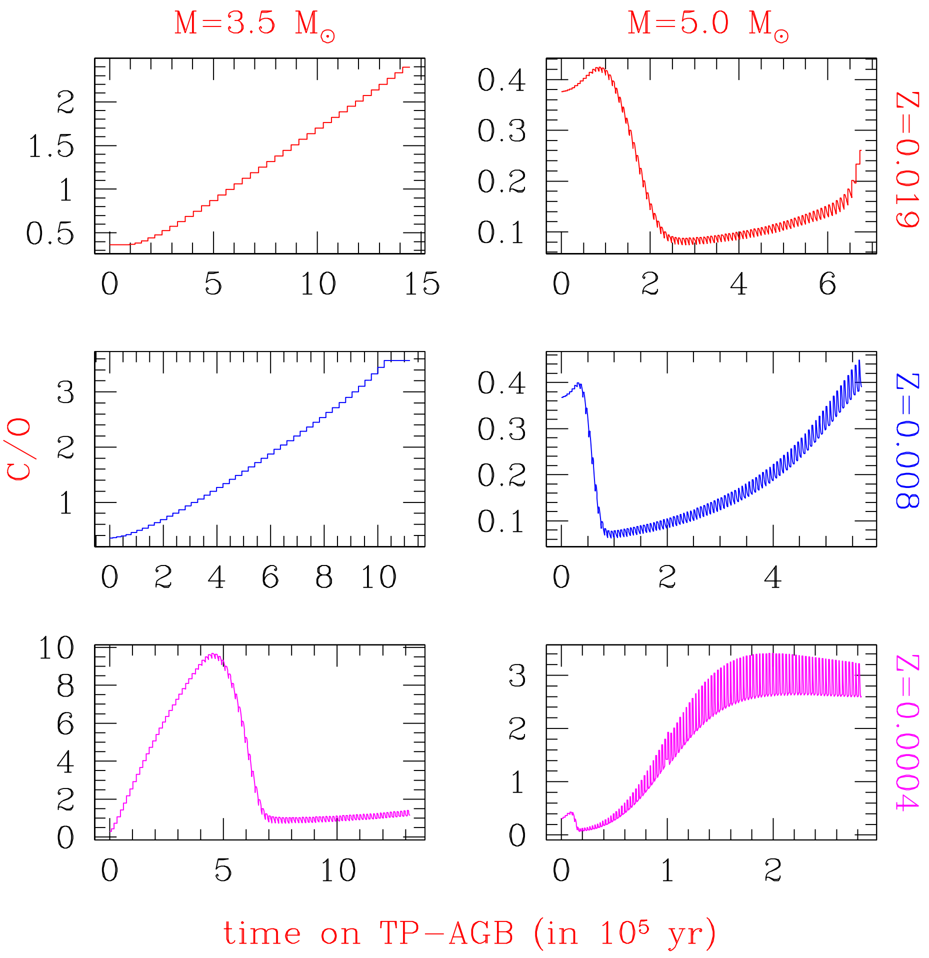

**Fig. 8.** Evolution of the surface C/O ratio during the TP-AGB evolution of a few selected models with different masses and metallicities computed by Marigo & Girardi (2007). Note that for $M = 5\,M_\odot$ HBB prevents the formation of C stars with $Z = 0.008$, while the opposite is expected at $Z = 0.0004$ due to the activation of the ON cycle. See the text for more discussion.

neous and dependent on technical details. As illustrated in Fig. 6 both the onset and efficiency of the third dredge-up in a star of given mass and metallicity are seen to vary significantly from author to author.

Another fundamental issue for evolutionary AGB models is related to the adopted low-temperature opacities ($T < 10000$ K). A still a common choice in most published TP-AGB evolutionary calculations is using opacity tables that are strictly valid for scaled-solar abundances (e.g. Ferguson et al. 2005), hence totally inadequate to produce realistic models for C stars. As already demonstrated by Marigo (2002) and Marigo et al. (2003), the adoption of proper molecular opacities, consistently coupled with the surface composition, brings a radical improvement in the treatment of carbon-star evolutionary models, leading to solve several long-lasting discrepancies between theory and observations. For instance, the red tail drawn by field carbon stars in near-infrared colour-colour diagrams of the Magellanic Clouds (e.g., DENIS, 2MASS surveys) is reproduced, as well as the low C/O and $T_{\rm eff}$ values typically found in Galactic AGB C-type stars. Illustrative examples of new TP-AGB models with variable molecular opacities are given in Fig. 7. Recent full AGB calculations with C-rich opacities are presented by Cristallo et al. (2007).

Hot-bottom burning This process is predicted to take place in the most luminous and massive AGB stars ($3.5\ M_\odot \lesssim M \leq 5{-}8\ M_\odot$, depending on metallicity and model details), and corresponds to the nuclear burning (CNO, MgAl, NeNa cycles; Cameron-Fowler mechanism for Li production) that extends from the radiative H-shell into the deepest and hottest layers of the convective envelope during the quiescent inter-pulse periods. Besides affecting their surface composition, HBB should make massive AGB more luminous than expected by the classical core-mass luminosity relation.

It has been invoked to explain a number of observations, namely the (almost) lack of visible luminous C-stars ($M_{\rm bol} < -6$) and the concomitant deficiency of luminous M-stars in the Magellanic Clouds (e.g. Costa & Frogel 1996); the existence among these stars of objects ( $-6 > M_{\rm bol} > -7$) with marked enhancement of surface lithium abundance (e.g. Smith et al. 1995); the overabundance of nitrogen and helium typical of type I Planetary Nebulae and some AGB stars (e.g. Peimbert & Torres-Peimbert 1983; Smith & Lambert 1990); the low value of the $^{12}$C/$^{13}$C ratio, close to the nuclear equilibrium value, characterizing the group of luminous J-type carbon stars (e.g. Lambert et al. 1986); the Na-O and Mg-Al anti-correlations exhibited by the stars of galactic globular clusters in the framework of the primordial scenario (Gratton et al. 2001); the high isotopic ratios $^{26}$Al/$^{27}$Al displayed by some meteoritic oxide grains of pre-solar origin (Mowlavi & Meynet 2000).

Several evolutionary models of massive AGB stars with HBB have been calculated in recent years (Forestini & Charbonnel 1997; Frost et al. 1998; Karakas & Lattanzio 2003; Herwig 2004; Ventura & D'Antona 2005a,b; Marigo & Girardi 2007). Compared to earlier studies, these calculations are improved in many aspects, like for instance the adoption of larger nuclear networks including many elemental and isotopic species, a more detailed description of convective turbulence and mixing, introduction of stellar rotation, and extensive calculations over wider ranges of initial stellar masses and metallicities.

However, as in the case of the third dredge-up, the results are again critically dependent on the adopted treatment of convection, mass loss (Ventura et al 2005a,b), and input physics, e.g. nuclear rates, opacities (e.g. Marigo 2007). so that quantitative results are often quite heterogeneous. However, general trends as a function of $M$ and $Z$ can be summarized with the aid of Fig. 8 as follows: a) HBB is more efficient at lower metallicities and larger stellar masses; b) it delays or even prevents the formation of very luminous C stars with $Z > 0.001$; c) conversely it may even favour the formation of massive and luminous C stars at low metallicities $Z < 0.001$, due to the activation of the ON cycle which burns oxygen in favour of nitrogen.

## 5. The domain of C stars

Collecting the present predictions of stellar evolution models the mass-metallicity domain of intrinsic C-rich stars (evolved from single stars, not belonging to binary systems) may be schematically represented as in Fig. 9. Here we have considered the contributions of three processes, namely: (A) the third dredge-up and (B) HBB during the TP-AGB phase (already discussed in Sect. 4), and (C) the possible surface enrichment of CN-rich material during the core He-flash in low-metallicity RGB stars (Fujimoto et al. 2000; Schlattl et al. 2001). On one hand, the minimum mass for a star to become a carbon star as a consequence of (A) de-

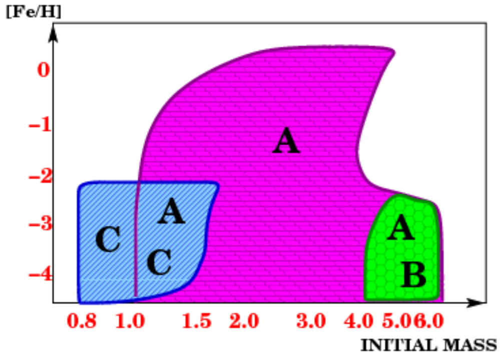

**Fig. 9.** Initial metallicity - initial mass domain of single C-stars. See the text from more explanation.

creases with the metallicity down to $\sim 1\,M_\odot$, because of the earlier onset of the third dredge-up. For [Fe/H]$\lesssim\ -2$ the minimum mass becomes as low as $\approx\ 0.8\,M_\odot$ because of (C). On the other hand, the maximum for a star to become a carbon star first decreases with the metallicity, because of the stronger competing effect due to HBB (converting C into N), then for [Fe/H]$\lesssim -2$ the formation of more massive C stars could be favoured by the destruction of O into N (operated by the ON cycle during HBB).

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