New clues on non-standard mixing on the RGB

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1. Chemical anomalies in low mass red giants

It has been known for a long time that low mass red giants (i.e., with initial mass lower than \(\sim 2\,M_\odot\)) present chemical anomalies which are not predicted by the standard evolution theory. In particular, the models which neglect the transport of chemicals in the stellar radiative regions can not explain the observed behavior of the carbon isotopic ratio both in Pop I and II stars on the red giant branch (RGB), of the lithium and carbon abundances (respectively in halo and globular cluster giants) after the completion of the first dredge-up, neither the evidences of O versus N anticorrelation and Na and Al versus N correlation seen in a large number of globular cluster giants (see Charbonnel, Brown & Wallerstein 1998, hereafter CBW98, for references). These observations suggest that low mass stars undergo a non-standard mixing process which adds to the first dredge-up and modifies the surface abundances.

2. When does the extra-mixing occur?

To throw a new light on the problem of the onset of the extra-mixing, and of its possible metallicity dependance, we assembled accurate abundance observations for the \(^{12}\text{C}/^{13}\text{C}\) ratio as well as for Li, C, and N for five field giants with \([\text{Fe/H}] \simeq -0.6\) and two stars in the globular cluster 47 Tuc. Using the HIPPARCOS parallaxes, we could constrain the evolutionary status of the sample stars.

Our data can be viewed as an evolutionary sequence, as shown in Fig.1 where the \(^{12}\text{C}/^{13}\text{C}\) ratio is plotted against \(M_{\text{bol}}\) and where the position of the luminosity function bump of 47 Tuc (at \(M_{\text{bol}} = +1.05 \pm 0.2\)) is indicated. Along this sequence, the behavior of the \(^{12}\text{C}/^{13}\text{C}\) ratio is very similar to the one observed at solar metallicity in the open cluster M67 (Gilroy & Brown 1991) : Below the bump, the observations are in agreement with standard predictions for dilution (\(\sim 20\)). Then between \(M_{\text{bol}} = +1\) and \(+0.5\), the \(^{12}\text{C}/^{13}\text{C}\) ratios
drop from $\sim 20$ to near $7$, i.e., well below the standard predicted ratio (at the same time, Li disappears and the $^{12}\text{C}/^{14}\text{N}$ ratio diminishes by $0.2$ to $0.4$ dex$^3$). Finally, there is no further change in the $^{12}\text{C}/^{13}\text{C}$ ratio from $M_{\text{bol}} = +0.4$ to $-2$.

Figure 1. The ratio of $^{12}\text{C}/^{13}\text{C}$ is plotted against the bolometric magnitude of our stars with moderate metal deficiency. The absolute magnitudes are derived from the HIPPARCOS parallaxes. The horizontal line indicates the position of the bump in the luminosity function of 47 Tuc (King et al. 1985).

These results show that the extra-mixing process which leads to very low $^{12}\text{C}/^{13}\text{C}$ ratios in metal-deficient low-mass evolved stars becomes efficient exactly after the luminosity function bump, i.e., the evolutionary point where the hydrogen-burning shell crosses the chemical discontinuity created by the outward moving convective envelope. This confirms the inhibiting effect of molecular weight (or $\mu$) barriers against the development of the extra-mixing (see Sweigart & Mengel 1979; Charbonnel 1994, 1995). Since stars more massive than $\sim 1.7$ - $2.2 M_\odot$ do not reach the bump, they are not expected to experience this extra-mixing on the RGB (this is confirmed by the observations in open clusters; Gilroy 1989).

3. How many low mass stars do undergo the extra-mixing on the RGB?

To answer this question, we collected in the literature all the observations of the carbon isotopic ratio in field and cluster giant stars (see Charbonnel & Dias 1998). For the whole sample stars, $M_V$ values were determined thanks to the

$^3$see Tables 1 and 2 in CBW98
HIPPARCOS parallaxes. In the [Fe/H] range we consider, $M_V^{\text{bump}}$ is higher than $\sim -0.2$.

Above the bump (squares in Fig. 2), i.e., the evolutionary point where the extra-mixing can occur, the disagreement between the post dredge-up standard predictions ($^{12}\text{C}/^{13}\text{C}$ around 20-30) and the observations appears in 96% of the low mass giants. This high value for the fraction of low mass stars that experience an extra-mixing process on the RGB and are thus expected to destroy their $^3\text{He}$ at this evolutionary phase (Hogan 1995, Charbonnel 1995) satisfies the galactic requirements for the evolution of the $^3\text{He}$ abundance (see Galli et al. 1997 and Charbonnel & Dias 1998).

4. Critical $\mu$-gradient

As can be seen in Fig. 2, the final $^{12}\text{C}/^{13}\text{C}$ ratios are lower in the more metal-poor stars. The observations at various metallicities provide precise clues on the extension of the extra-mixed region, and on the $\mu$-barriers that may shield the central regions of a star from extra-mixing.

From evolutionary models of stars with various masses and metallicities, we showed that, in order to account for the $^{12}\text{C}/^{13}\text{C}$ ratios observed in stars of different metallicities, the extra-mixing must extend from the base of the external convection zone down to a region where the gradient of molecular weight is equal to $\sim 1.5 \times 10^{-13}$. This value for the “observational” critical $\mu$-gradient, $(\nabla \ln \mu)_{c,\text{obs}}$, which appears to shield the central regions of the star from extra-
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mixing agrees with the one which is expected to stabilize meridional circulation. This result indicates that the extra-mixing on the RGB could be related to rotation-induced processes. If we assume that such a $\mu$-barrier can not be penetrated, then the energy production in the hydrogen-burning shell should not be affected.

Let us note that, on the main sequence, $\nabla \ln \mu$ becomes higher than $(\nabla \ln \mu)_{c,obs}$ in the very external part of the low mass stars, and no extra-mixing is expected to occur in the stellar region of energy production. This explains the perfect agreement between standard theoretical dilution and observations of $^{12}\text{C}/^{13}\text{C}$ for stars that have not yet reached the bump. This is also in agreement with the best solar models (for what concerns helioseismological comparison and agreement with Li and Be observations; Richard et al. 1996) that include both element segregation and rotation-induced mixing which is cut-off when the $\mu$-gradient becomes $\geq 1.5 - 4 \times 10^{-13}$.

5. Conclusions

The physics of the extra-mixing process in low mass stars has to be better understood. Detailed simulations, with a consistent treatment of the transport of matter and angular momentum, have to be carried out for different stellar masses and metallicities, and various mass loss and rotation histories. The impact of this process on the behavior of various elements in RGB stars ($\mathrm{C} \nearrow$, $\mathrm{Na} \nearrow$, $\mathrm{O} \nearrow$, $\mathrm{Al} \nearrow$, $\mathrm{Mg} \nearrow$) and on the precise yields of $^3\text{He}$ has to be investigated in details. Consequences for the energy production in the HBS and for the HB morphology may not be neglected.

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