

How many low-mass stars do destroy ^3He ?

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Abstract. We recall the current status of the long-standing ^3He problem, and its possible connection with chemical anomalies on the red giant branch. In this context, we collect in the literature all the available observations of the carbon isotopic ratio in field and cluster giant stars. Using the HIPPARCOS parallaxes, we get constraints on the evolutionary status of the field stars of the sample. This allows us to identify the stars that have passed the luminosity function bump and present $^{12}\text{C}/^{13}\text{C}$ ratios in disagreement with the standard predictions of stellar evolutionary models. We determine statistically what fraction of low mass stars experience an extra-mixing process on the red giant branch, and are then expected to destroy their ^3He at this evolutionary phase. The high number we get satisfies the galactic requirements for the evolution of the ^3He abundance.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: interiors – stars: rotation

1. The ^3He problem

The evolution of ^3He in the Galaxy has first been considered to be straightforward, dominated by the net production of this light element by low mass stars (i.e., with masses lower than $2 M_{\odot}$). In these objects, initial D is processed to ^3He during the pre-main sequence phase. Then, as described by Iben (1967), an ^3He peak builds up due to pp-reactions on the main sequence, and is engulfed in the stellar convective envelope during the first dredge-up on the lower red giant branch (RGB). Standard theory predicts that, once in the convective layers of the evolved star, ^3He cannot be destroyed because of the too cool temperature in these regions. It is finally ejected in the interstellar medium (ISM) in the latest stages of stellar evolution. In this standard view, the abundance of ^3He must increase in the Galaxy as soon as low-mass stars begin to pollute the ISM (Rood et al. 1976). One expects then to have constraints on the cosmological abundance of ^3He (Yang et al. 1984).

Recent observations of a few planetary nebulae (PN; Rood et al. 1992, Balser et al. 1997) led to the measurement of ^3He in

one object, NGC 3242¹. This PN, whose estimated initial mass is $1.2 \pm 0.2 M_{\odot}$ (Galli et al. 1997, hereafter GSTP97), presents a value of $^3\text{He}/\text{H} = (7.3 \pm 1.4) \times 10^{-4}$, in very good agreement with standard predictions (Vassiliadis & Wood 1993, Charbonnel 1995, Dearborn et al. 1996, Weiss et al. 1996 for the most recent computations). This value however differs by almost two orders of magnitude with the ^3He abundance in the proto-solar nebula, $^3\text{He}/\text{H} = (1.5 \pm 0.3) \times 10^{-5}$ (Geiss 1993), in the local interstellar cloud, $^3\text{He}/\text{H} = (2.2 \pm 0.2) \times 10^{-5}$ (Gloeckler & Geiss 1996), and in galactic HII regions, $^3\text{He}/\text{H} = (1 \text{ to } 5) \times 10^{-5}$ (Balser et al. 1994).

These low values are in clear contradiction with the conventional scenario for galactic evolution of the ^3He abundance, and cannot be explained if all low mass stars, such as NGC 3242, happen to return all their ^3He to the ISM. GSTP97 showed that, in order to fit the galactic constraints, ^3He should be destroyed in at least 70% of low-mass stars before they become PN.

2. Constraints on the destruction of ^3He in low-mass stars

Rood et al. (1984) suggested that the destruction of ^3He could be related to chemical anomalies such as the very low carbon isotopic ratios observed in low-mass red giants. Indeed, while standard models predict post-dredge up values of the $^{12}\text{C}/^{13}\text{C}$ ratio between 20 and 30 (depending on the stellar mass and metallicity; see Charbonnel 1994), Pop II field and globular cluster giants present $^{12}\text{C}/^{13}\text{C}$ ratios lower than 10, even down to the near-equilibrium value of 4 in many cases. This discrepancy also exists, but to a lower extent, in evolved stars belonging to open clusters with turnoff masses lower than $2 M_{\odot}$ (see Charbonnel et al. 1998, hereafter CBW98, for references).

The $^{12}\text{C}/^{13}\text{C}$ data point out the existence of an extra-mixing process that becomes efficient in low mass RGB stars as soon as they reach the so-called luminosity function bump (Gilroy & Brown 1991, hereafter GB91; Charbonnel 1994; Pilachowski et al 1997; CBW98). Different groups have simulated extra-mixing between the base of the convective envelope and the hydrogen-burning shell in order to reproduce the chemical anomalies in RGB stars. These non-standard models predict

¹ Balser et al. (1997) got no definitive detection of ^3He in any of the other five PN they observed; however detection of ^3He is probable in two of their objects

that the mechanism which is responsible for the low $^{12}\text{C}/^{13}\text{C}$ ratios on the RGB must also lead to the destruction of ^3He by a large factor in the bulk of the envelope material (Charbonnel 1995, Wasserburg et al. 1995, Weiss et al. 1996), and confirm the estimation of Hogan (1995).

In this paper, we use the observations of $^{12}\text{C}/^{13}\text{C}$ in evolved stars to determine statistically what fraction of low-mass stars experience this extra-mixing on the RGB, and are then expected to destroy their ^3He .

3. The data sample

3.1. Giants with measured $^{12}\text{C}/^{13}\text{C}$ ratios

We collected in the literature all the available observations of $^{12}\text{C}/^{13}\text{C}$ ratios in stars of luminosity classes III and IV-III in the spectral ranges F to K. The whole sample contains 191 stars, with $[\text{Fe}/\text{H}]$ values between -2.8 and 0.3. Our 85 field stars have been observed by Lambert & Ries (1981), Cottrell & Sneden (1986), Sneden et al. (1986), Shetrone et al. (1993), Shetrone (1996), CBW98. The data for galactic cluster giants are from GB91 for NGC 2682 (M67) and Gilroy (1989) for NGC 752, NGC 2360, IC 4756. For globular clusters, we use the data from Brown & Wallerstein (1989) for NGC 104, NGC 5139, NGC 6121 (M4), NGC 6656 (M22), from Smith & Suntzeff (1989) for NGC 6121 and NGC 6656, from Suntzeff & Smith (1991) for NGC 6121 and NGC 6752, from Shetrone (1996) for NGC 6205 (M13), from Briley et al. (1997) for NGC 6838, and from CBW98 for 47 Tuc. When different values of the $^{12}\text{C}/^{13}\text{C}$ ratio are given by different authors for the same star, we take the most recent determination. We use the $[\text{Fe}/\text{H}]$ values quoted in the respective papers.

3.2. Evolutionary status of our sample stars

The determination of the $^{12}\text{C}/^{13}\text{C}$ ratio in our sample is not homogeneous. This is however not a problem for our statistical study: We consider that a star has undergone extra-mixing when its $^{12}\text{C}/^{13}\text{C}$ is smaller than 15, i.e., well below the minimum standard post dredge-up prediction.

It is crucial however to have secure constraints on the evolutionary state of our sample stars. Indeed, as shown by GB91 and CBW98, the extra-mixing becomes efficient on the RGB only after the luminosity function bump. Our statistics must thus be done only for stars that have already passed this evolutionary state. The luminosity of the bump slightly depends on the initial metallicity. In the $[\text{Fe}/\text{H}]$ range we consider, M_V^{bump} is higher than ~ -0.2 (Fusi Pecci et al. 1990).

For the field stars, we use the m_V and the parallaxes given in the HIPPARCOS catalogue to get M_V . For the globular cluster stars, we take the M_V values given in the respective papers quoted above. Precise absolute magnitudes depend on the cluster distance modulus, which is probably still uncertain. However, it matters only here to be sure that the cluster stars that we take into account in our final statistics are more luminous than the bump.

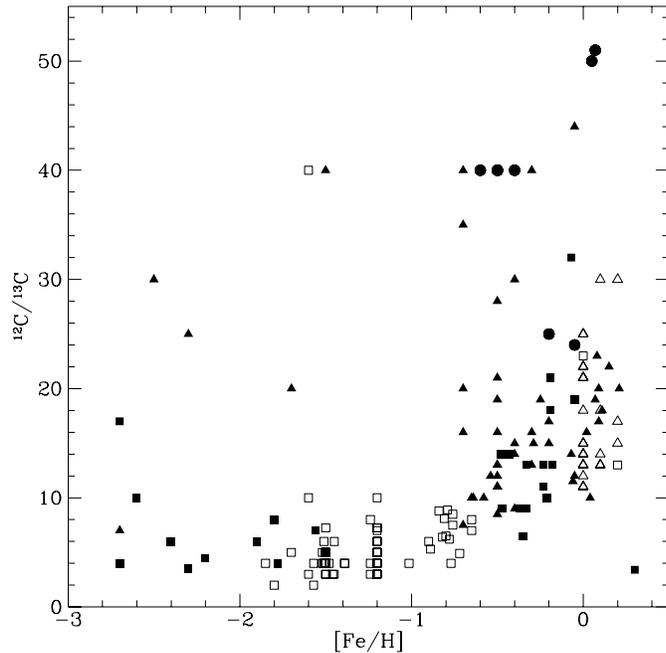


Fig. 1. Carbon isotopic ratio as a function of $[\text{Fe}/\text{H}]$ for our whole sample. The circles correspond to stars with M_V higher than 2, the triangles to stars with M_V between 0 and 2, and the squares to the brightest stars with M_V lower than 0. Black and white symbols relate respectively to field and cluster giants

Table 1. Repartition of our sample stars in the three luminosity ranges discussed in the text, as a function of their observed $^{12}\text{C}/^{13}\text{C}$ ratio

	$^{12}\text{C}/^{13}\text{C} \leq 15$	$^{12}\text{C}/^{13}\text{C} > 15$	Total
$2 \leq M_V$	0	8	8
$0 \leq M_V < 2$	35	40	75
$M_V < 0$	101	7	108

In our sample, we may have clump or AGB stars. Among the 106 cluster giants, 10 objects have probably already reached this phase. However, their $^{12}\text{C}/^{13}\text{C}$ ratios does not differ (except in one case discussed in Sect. 4.3) from the ones of the stars that are ascending the RGB for the first time and have passed the bump. Including them in the sample does not modify the final statistics.

4. Results

4.1. How many low-mass stars do destroy ^3He ?

We show in Fig. 1 the $^{12}\text{C}/^{13}\text{C}$ ratio as a function of $[\text{Fe}/\text{H}]$ for all the stars of our sample. The evolutionary status is also indicated by the M_V values.

- Stars with $M_V \geq 2$ have not reached the bump yet, and they all present $^{12}\text{C}/^{13}\text{C}$ ratios in agreement with standard predictions for dilution. They are excluded from our final statistics, since they are not evolved enough to have undergone the RGB extra-mixing.
- For stars located in the bump region, i.e., with $0 \leq M_V < 2$, a large dispersion exists for the carbon isotopic ratio, which

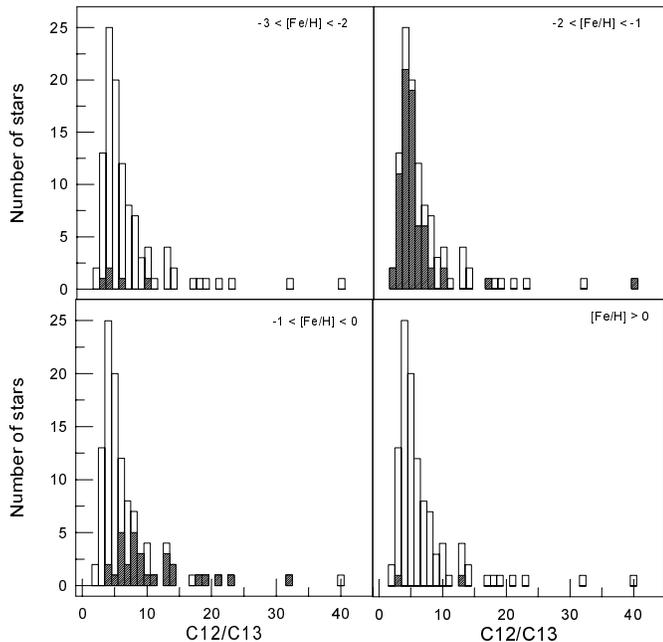


Fig. 2. Frequency distribution for the $^{12}\text{C}/^{13}\text{C}$ ratio for the stars that have already passed the luminosity bump, i.e., with M_V lower than 0. The shaded areas correspond to the different metallicity ranges indicated

already appears to be very low in many giants. We do not take either these objects into account, since they are just in the region where they may experience the extra-mixing.

- Stars with $M_V < 0$ have passed the bump, i.e., the evolutionary point where the extra-mixing can occur. The disagreement between the standard predictions and the observations appears now in most of the stars.

The distribution of our sample stars in these three luminosity ranges is indicated in Table 1. In each domain, we give the number of stars which present “normal” (i.e., higher than 15) and “low” (i.e., smaller than 15) carbon isotopic ratio.

The statistics we are interested in concern the most luminous stars. They are presented in the histograms of the Fig. 2 as a function of their metallicity. We obtain that **93% of evolved stars undergo the extra-mixing on the RGB, and are thus expected to destroy, at least partly, their ^3He** . This high number satisfies the galactic requirements, as discussed by GSTP97. Let us note that if we take -0.5 as a limit for M_V , we obtain that **96% of evolved stars show a $^{12}\text{C}/^{13}\text{C}$ ratio in disagreement with the standard predictions**.

In Fig. 3, where we present the carbon isotopic ratios as a function of M_V only for field stars, we underline the binary population among our sample. Clearly, binaries and single stars have the same behavior.

4.2. Need for consistent yields

The present non-standard models that attempt to explain the low $^{12}\text{C}/^{13}\text{C}$ ratios all predict a severe destruction of ^3He on the RGB. However, the task for stellar evolution theory is now to

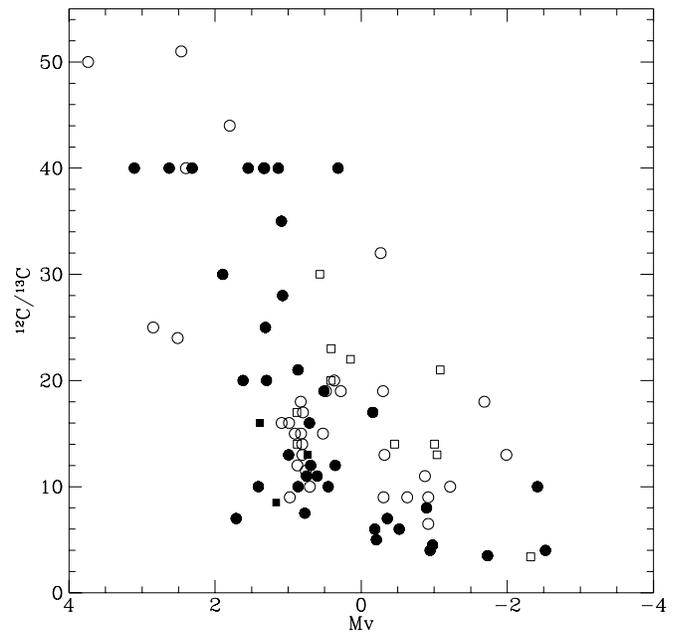


Fig. 3. Carbon isotopic ratio as a function of M_V for field stars. The circles relate to single stars and the squares to binaries. Black and white symbols correspond to $[\text{Fe}/\text{H}] \leq -0.5$ and $[\text{Fe}/\text{H}] > -0.5$ respectively

propose a physical process that explains consistently the various chemical anomalies observed in low mass red giant stars. Indeed, in addition to the $^{12}\text{C}/^{13}\text{C}$ problem, the behaviour of C, O, N, Al and Na on the RGB remains unexplained in many cases (see CBW98 for references). On the other hand, the extra-mixing process on the RGB has to destroy ^3He in more than 90% of the low-mass stars, and preserve it in the others, for the high (and standard) ^3He abundance observed in NGC 3242 to be explained. Stars with different histories (different rotation, mass loss, ...) could suffer different mixing efficiency and thus display different chemical anomalies. It is only when all these constraints will be explained that ^3He yields by low mass stars will be reliable.

4.3. The “deviant” stars

In this context, one has to raise the question of the statistical significance of Balser’s et al. sample. As discussed by the authors, this source sample is indeed highly biased, due to selection criteria. The PN showing high ^3He abundance should belong to the $\sim 7\%$ of low-mass stars which do not suffer from extra-mixing on the red giant branch. They should also show “normal” carbon isotopic ratios.

This crucial test has already been verified for one PN of Balser’s et al. sample for which ^3He detection is probable: NGC 6720 shows a $^{12}\text{C}/^{13}\text{C}$ ratio of 23 (Bachiller et al. 1997), in agreement with the “standard” predictions. One has however to be cautious with this star for which the estimated initial mass is $2.2 \pm 0.6 M_{\odot}$ (GSTP97). This PN could have indeed been too massive to have reached the bump before igniting helium and thus to have experienced the extra-mixing on the RGB. This

Table 2. Characteristics of the “deviant” stars

Name	[Fe/H]	M_V	T_{eff}	$^{12}\text{C}/^{13}\text{C}$
V8 (NGC 6656)	-1.6	-5.62	4361	40
HD 95689	-0.19	-1.08	4680	22
HD 112989	-0.44 to +0.3	-2.32	4840	3.4

is not the case for NGC 3242, which estimated initial mass is $1.2 \pm 0.2 M_{\odot}$. Observations of $^{12}\text{C}/^{13}\text{C}$ in this PN are now necessary.

Let us focus on the stars of the present sample that have passed the bump and do not behave as the majority. If we consider the objects with M_V lower than -0.5, only 3 stars appear to be really “deviant” (see Table 2).

V8 (NGC6656). As can be seen in Figs. 1 and 2, as soon as they are more luminous than the bump, almost all the stars with [Fe/H] lower than -0.5 present carbon isotopic ratios lower than 10. Only one star shows a $^{12}\text{C}/^{13}\text{C}$ ratio higher than the standard predictions: V8 in NGC 6656 (M22). This star presents enhanced SrII and BaII lines (Mallia 1976) and is probably a star enriched in ^{12}C and s-elements.

HD 95689 (α Uma). The relatively high Li abundance ($\log N(\text{Li}) = 1.26$, Lambert et al. 1980) observed in this spectroscopic binary is another indication that this star did not suffer any extra-mixing on the RGB. It corresponds to the expected post-dilution Li for a star more massive than $1.7\text{--}2M_{\odot}$ (see Charbonnel & Vauclair 1992). This is consistent with the observed $^{12}\text{C}/^{13}\text{C}$ ratio and with the stellar M_{bol} value we obtain with the HIPPARCOS data. For such an initial stellar mass, the extra-mixing is not expected to occur on the RGB, and this star should be excluded from the present statistics.

HD 112989. When [Fe/H] is higher than -0.5, the lower envelope of the $^{12}\text{C}/^{13}\text{C}$ ratio lies around 12. One star however, HD 112989, lies well below this limit. For this binary star, important differences appear in the various estimations of [Fe/H] available in the literature (-0.44, Yamashita 1964; +0.3, Lambert & Ries 1981; +0.14, McWilliam 1990; -0.05, Drake & Lambert 1994). A smaller value of [Fe/H] would replace this star in the “normality”.

On the other hand, this weak-G band star presents a $V_{\text{sin}i}$ value of $11 \text{ km} \cdot \text{sec}^{-1}$, which is much higher than the mean rotational velocity for giants with the same spectral type (De Medeiros 1990, 1998). Among the stars of our sample for which rotational velocity has been measured with the CORAVEL spectrometer, this star is the fastest rotator, all the others having $V_{\text{sin}i}$ lower than $5 \text{ km} \cdot \text{sec}^{-1}$ (see Fig. 4).

5. Conclusions

We have assembled all the observations of the $^{12}\text{C}/^{13}\text{C}$ ratio in field and cluster giants available in the literature. Using the HIPPARCOS parallaxes, we get constraints on the evolutionary status of our sample stars. We determine that 96% of low-mass stars do experience an extra-mixing process on the RGB and are then expected to destroy their ^3He . While consistent “non-standard” stellar models are needed to explain the various chem-

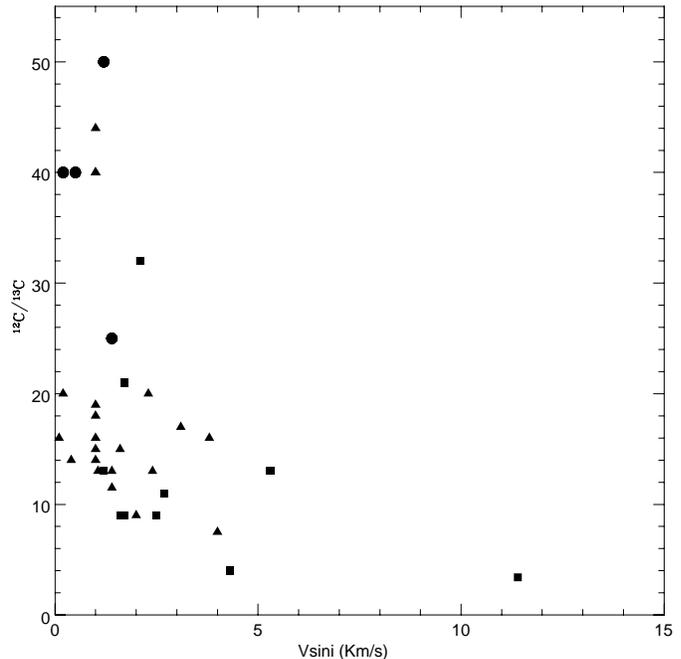


Fig. 4. Carbon isotopic ratio as a function of rotational velocity for field stars. The circles correspond to stars with M_V higher than 2, the triangles to stars with M_V between 0 and 2, and the squares to brightest stars with M_V lower than 0. HD112989 is the star with the highest $V_{\text{sin}i}$

ical anomalies in low-mass RGB stars in order to obtain reliable ^3He yields, we can already conclude that the very high percentage we get satisfies the galactic requirements for the evolution of the ^3He abundance.

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