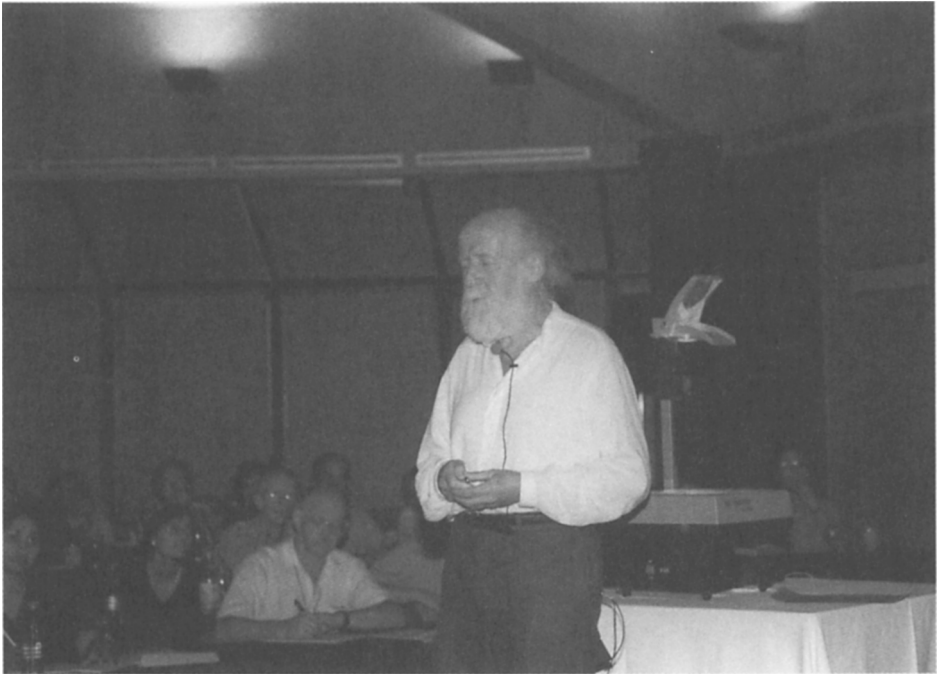# EVOLUTION OF THE LIGHT ELEMENTS

Hubert Reeves presenting his conclusions.

Evolution of D and ^{3}He in the Galaxy

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Abstract. The predictions of Galactic chemical evolution models for D and ^{3}He are described in connection with those on the other Galactic quantities for which observational constraints are available.

Models in agreement with the largest set of data predict deuterium depletions from the Big Bang to the present epoch smaller than a factor of 3 and do not allow for D/H primordial abundances larger than $\sim 4 \times 10^{-5}$. Models predicting higher D consumption do not reproduce other observed features of our Galaxy.

If both the primordial D and ^{3}He are low, models assuming that 90% of low-mass stars experience an extra-mixing during the red giant phase reproduce all the ^{3}He observed abundances. The same percentage allows to fit also the observed carbon isotopic ratios, thus supporting the self-consistency of the extra-mixing mechanism.

1. Introduction

In this review, I will try to describe what Galactic chemical evolution models tell us about the evolution and the primordial abundances of D and ^{3}He, and what, in turn, D and ^{3}He may tell us about stellar and Galactic evolution. In particular, I wish to emphasize that the light elements should not be treated separately, but should always be considered together with the other more diffuse elements, to better constrain their evolution.

The reason why Galactic chemical evolution models are required to derive the primordial D and ^{3}He abundances from the observed ones is that all the objects where the two elements are measurable are relatively young (the oldest being the sun with an age of 4.5 Gyr) and have therefore formed, with the only exception of high-redshift clouds, from an ISM whose chemical composition had been modified by the previous stellar generations. To infer the primordial abundances from these measurements, it is thus necessary to take into account the effects of the various cycles of gas astration and gas return, and the variations of the ISM chemical composition due to stellar nucleosynthesis and gas flows occurring up to the time when the observed objects have formed. This is accomplished by chemical evolution models.

D and ^{3}He are obviously related to each other, since all the D which enters a star is immediately burnt into ^{3}He (Reeves et al. 1973). However, the problems faced when studying their Galactic evolution are quite different, and I will thus treat them separately in this paper.
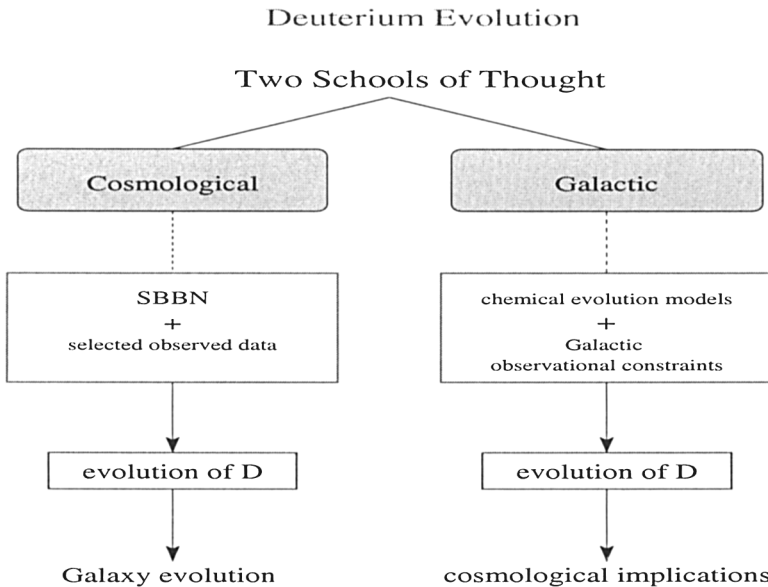
Figure 1.   Sketch of the two main approaches to study the evolution of D.

2.   D evolution

Since D is completely destroyed inside stars already in pre-main sequence phase, if we consider the Big Bang nucleosynthesis as the only source of D, the amount of D which can be present in any galactic region and at any place is that contained in gas which has never been through stars. In other words, the fraction of primordial D surviving at any epoch and in any region is equal to the fraction of virgin gas there. Hence, in principle, to infer the primordial abundance of D from its present one it would be sufficient to know the current fraction of gas which has not entered a star yet (Steigman & Tosi 1995). Unfortunately, we do not know the fraction of pristine gas even in the most local medium and we must therefore rely on Galactic chemical evolution models to derive the D evolution.

   Historically, there are two schools of thought on how to proceed in studying the D evolution, as sketched in Fig.1. The first one, in chronological order, can be referred to as the *Cosmological School*. The approach of this school is to start from standard Big Bang nucleosynthesis (SBBN) prescriptions, select the observational constraints on D which can be considered reliable, and infer from these sets of data what the D evolution must have been in the Galaxy. They then build models of Galaxy evolution able to reproduce the inferred trend of D vs time, and the predictions of such models on the other Galactic quantities are a by-product.

   The other school, which I will call *Galactic*, follows the opposite approach. We start from chemical evolution models of our Galaxy, select only those which are able to reproduce the largest set of observational constraints, and take the predictions on D only from these selected models. The consequences of these
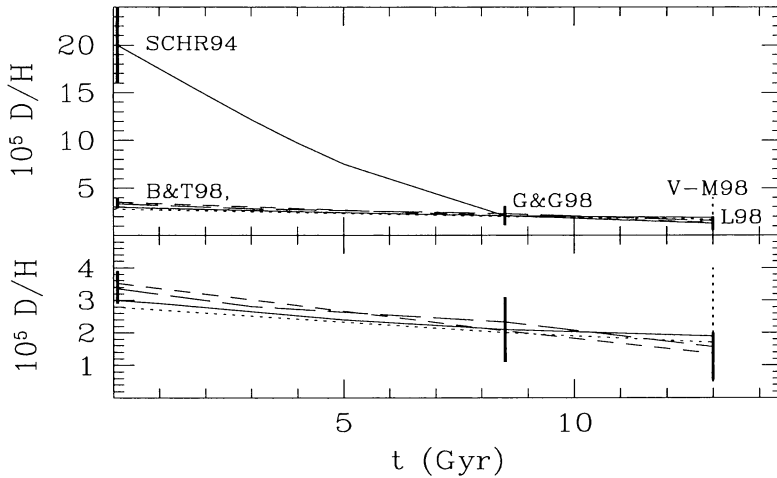
Figure 2.   Top panel: Observational abundances of D as a function
of the target formation epoch. The steep curve sketches the local evo-
lution of D as proposed by the *Cosmological School*, the other curves
show the predictions of chemical evolution models in agreement with
the largest set of observed Galaxy properties. Bottom panel: blow-up
of the lower part of the top panel. See text for details.

predictions on the primordial D abundance and on cosmology are a by-product.
Were we living in the best of all possible worlds, the two approaches should
provide the same results. Instead, their predictions are quite different from each
other.

Fig.2 shows the D abundances derived from all the available observations
and plotted as a function of the supposed epoch of formation of the observed
objects. All the error bars are 2σ. The two vertical bars at t=0 represent the
ranges of values derived by Songaila et al. (1994, hereinafter SCHR94) and
Burles & Tytler (1998, B&T98) from high-redshift, low-metallicity, absorbers
on the line of sight of distant QSO's. The bar at 8.5 Gyr represents the value of
the Protosolar Cloud inferred by Geiss & Gloeckler (1998, G&G98) from solar
system data. The solid bar at 13 Gyr shows the range of abundances derived
by Linsky (1998, L98) for the local ISM, while the length of the dotted bar
shows the possible cloud-to-cloud variations suggested by Vidal-Madjar, Ferlet
& Lemoine (1998, V-M98).

Since the *Cosmological School* was founded when the primordial ^{4}He was
definitely supposed to be low ($Y_P \simeq 0.23$ in mass fraction), and since SBBN
predicts the primordial D to be anti-correlated with Y_P, members of this school
obviously thought that the only reliable measures of D in almost primeval sys-
tems, like high-redshift, low-metallicity absorbers, were those leading to high D
abundances. They thus thought that the natural evolution of deuterium with
time is that connecting the SCHR94 value with the local ones and sketched by
the solid line in Fig.2, i.e. a D destruction by one order of magnitude from the
primordial to the present abundance.

To obtain such a high D destruction during the Galaxy evolution, one must invoke a high star formation rate (SFR), which is usually assumed to occur at the earliest epochs, because all the observational evidences are against high SFR at relatively recent times. These high SFRs (and their related metal enrichment), inevitably imply a large overproduction of the heavy elements with respect to the observed stellar abundances, unless compensated by mechanisms able to reduce the excess of metals, by diluting or removing them from the Galaxy. For this reason, models with high D destruction usually invoke infall of metal poor gas and galactic winds powered by supernovae explosions, sometimes coupled with variations in the initial mass function. There have been several attempts to find viable Galactic models with strong deuterium depletion, but no scenario consistent with all the Galactic data has been found. For instance, in their pioneering work, Vangioni-Flam & Audouze (1988) concluded that they excessively overproduced the metals, and Scully et al. (1997), in order to obtain the desired D without overproducing the metals, ended up with a present local SFR at least one order of magnitude lower than observed. Tosi et al. (1998) have tested all the possible combinations of the various parameters (SFR, infall, winds, etc.) and have always found significant inconsistencies in the models with high D destruction: metal overabundance with wrong galactocentric distribution, or metallicity distribution of the G-Dwarfs in the solar neighbourhood completely at odds with the observed one, or abundance ratios in halo or disk stars different from the observed ones (e.g. [O/Fe] vs [Fe/H]), or SFR inconsistent with the observed range. In no way have we been able to find a fairly self-consistent model with high D destruction.

The Galactic School works instead on chemical evolution models able to reproduce as well as possible the largest set of observed Galactic features. Thanks to the improvements both on the observational and on the theoretical sides, good chemical evolution models of the Milky Way nowadays can reproduce the average distribution of the following list of observed features (see e.g. Tosi 1996 and 2000, Boissier & Prantzos 1999 for references):
- current distribution with Galactocentric distance of the SFR,
- current distribution with Galactocentric distance of the gas and star densities,
- current distribution with Galactocentric distance of element abundances as derived from HII regions and from B-stars,
- distribution with Galactocentric distance of element abundances at slightly older epochs, as derived from PNe II,
- age-metallicity relation not only in the solar neighbourhood but also at other distances from the center,
- metallicity distribution of G-dwarfs in the solar neighbourhood,
- local Present-Day-Mass-Function (PDMF),
- relative abundance ratios (e.g. [O/Fe] vs [Fe/H]) in disk and halo stars.

When one compares with each other all the models in better agreement with these data (e.g. Tosi 1996), the striking result is that they all predict essentially the same deuterium evolution, in spite of the fact that they are computed by different people, with different assumptions on the input parameters and with different numerical codes. The bottom panel of Fig.2 shows an updated version of the comparison: the plotted models are from Galli et al. (1995a, short-dashed line), Dearborn, Steigman, & Tosi (1996, solid line), Chiappini & Matteucci
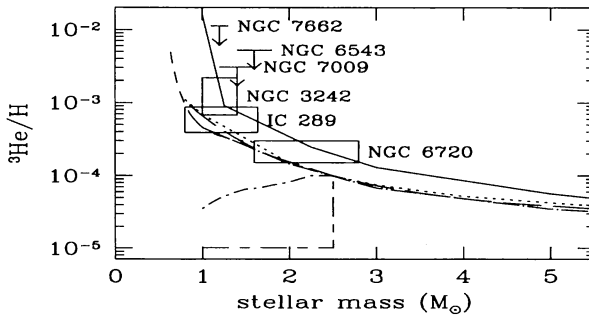
Figure 3. ^{3}He yield as a function of the stellar initial mass. The curves show various stellar nucleosynthesis predictions, the boxes and arrows the PNe with high ^{3}He (see Galli et al. 1997 for details).

(1996, long-dashed line) and Boissier & Prantzos (1999, dotted line). All the shown curves fit very well the average abundances derived for the local ISM, the pre-solar nebula and the high-redshift absorbers by B&T98. They all show a fairly moderate (a factor from 1.5 to 3, at most) D destruction during the Galaxy lifetime, and therefore suggest that the primordial D abundance should be low: $2 \leq (D/H)_P \times 10^5 \leq 4$.

This homogeneity of predictions is not a chance effect, but the consequence of the circumstance that all these models fit equally well the observational data on the present SFR, gas and mass densities, and chemical abundances, which necessarily implies that they predict similar fractions of pristine gas and, therefore, of surviving primordial deuterium.

Our current knowledge on the Galactic evolution of D can thus be summarized as follows: Models predicting high deuterium destruction cannot account for all the observed Galactic properties; models able to reproduce the largest set of Galactic properties all predict low deuterium destruction and, hence, low primordial D.

3. ^{3}He evolution

^{3}He has a more complex evolution than D, because it is produced not only during the Big Bang but also inside stars, during the main sequence phase. This early stellar production may be however largely compensated by further nuclear processing in subsequent phases. Standard stellar nucleosynthesis studies predict that, at the end of the star life, the ^{3}He present in the initial stellar composition is significantly destroyed in massive stars, but preserved or even strongly enhanced in lower mass stars, and that the ^{3}He net yield is a steeply decreasing function of the stellar initial mass, with a large net production in stars below 2–2.5 $M_\odot$ (see e.g the monothonic curves in Fig.3). This behaviour was known since the late sixties (e.g. Iben 1967), and already in 1976 Rood, Steigman, & Tinsley noticed that it leads to overproduce the solar abundance. Only in the mid-nineties, however, with the advent of more detailed combinations of ^{3}He yields
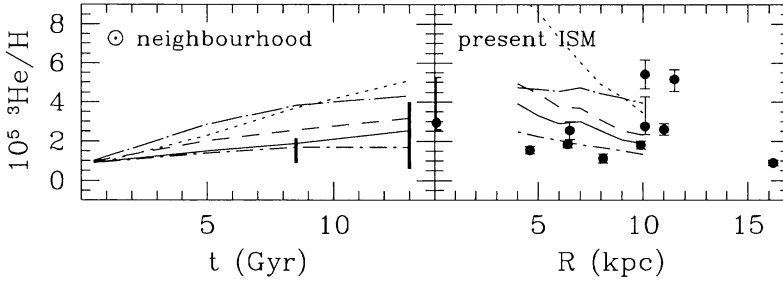
Figure 4.   Comparison between the observed abundances of ^{3}He and the predictions of model Tosi-1 with CBP in 0, 90 or 100% of low-mass stars. Left hand panel: Evolution of ^{3}He/H in the solar neighbourhood. Right hand panel: Corresponding radial distribution at the present epoch. See text for symbols and references on the observational data.

with galactic chemical evolution models (Vangioni-Flam, Olive & Prantzos 1994, Galli et al. 1995a, Dearborn, Steigman & Tosi 1996) it became apparent that the results on ^{3}He of standard nucleosynthesis studies are definitely inconsistent both with the solar and with the ISM observed abundances. This inconsistency is found with any type of Galactic evolution models, including those in agreement with all the other observational constraints (e.g. Tosi 1996) and was emphasized by several groups at the Elba meeting on the Light Element Abundances in 1994 (Cassé & Vangioni-Flam 1995, Galli et al. 1995b, Tosi, Steigman & Dearborn 1995). In that occasion, Michel Cassé concluded with what has been the most popular refrain on ^{3}He ever since: ^{3}*He delendum est*, like the city of Carthago for the ancient Roman M.P. Cato Censor.

   The most probable solution to the ^{3}He problem is less drastic than that applied to Carthago by the Romans and was proposed already in 1995 (Charbonnel 1995, Hogan 1995). It consists in the further ^{3}He processing into heavier elements favoured by an extra-mixing occurring in the red giant phase of low-mass stars (see both Charbonnel and Sackman, this volume). When low-mass stars are assumed to experience this extra-mixing and the so-called Cool Bottom Processing (CBP), Galactic evolution models do not overproduce ^{3}He anymore and fit well the observed solar and HII region abundances (Tosi 1996). The question is: in what fraction of low-mass stars CBP should occur to best fit all the data, taking into account that Bania, Rood et al. (this volume) measure in a few PNe a high ^{3}He perfectly consistent with the predictions of standard stellar nucleosynthesis (Fig.3) ? Galli et al. (1997) showed that the fraction should be larger than 80% to fit the ^{3}He abundances observed in the solar system (Geiss & Gloeckler 1998), in PNe and in HII regions (Rood et al. 1995 and this volume).

   Fig.4 shows the predictions of the best of models Tosi-1 (see Tosi 1988, Dearborn et al. 1996) when 0% (dotted line in both panels), 90% (solid lines), or 100% (short-dash-dotted lines) of stars with M $\leq$ 2.5 M$_\odot$ are assumed to follow Sackman & Boothroyd's (1999) prescriptions for CBP ^{3}He depletion. For the remaining low-mass stars, as well as for all the intermediate and high-mass ones, the ^{3}He yield is taken from Dearborn et al. (1996). The dotted, solid and

short-dash-dotted lines correspond to models assuming as initial abundances $(D/H)_p = 3 \times 10^{-5}$ and $(^3He/H)_p = 1 \times 10^{-5}$. The dashed lines show the predictions of the same model with 90% CBP, when only the initial D is changed to $(D/H)_p = 10 \times 10^{-5}$, while the long-dash-dotted lines correspond to $(D/H)_p = 20 \times 10^{-5}$.

The vertical bars in the left hand panel represent the ranges of ^{3}He abundances (at 2σ) derived by Geiss & Gloeckler (1998) and Gloeckler & Geiss (1998) for the Protosolar and the Local Interstellar Clouds, here assumed to be representative of the local ISM, 4.5 Gyr ago and now, respectively. The data points in the right hand panel show the ^{3}He abundances derived by Rood et al. (1995) from HII region radio observations. It is apparent that the models assuming 90% and 100% of low-mass stars with CBP fit quite well all the data when the initial D is sufficiently low. The CBP depletion is however insufficient to compensate the ^{3}He overproduction if the initial D/H, subsequently turned into ^{3}He, is higher than a few 10^{-5}, in which case, first the observed protosolar abundance, and then also the local ISM one, cannot be reproduced any more. This is a further argument in favour of the low primordial deuterium resulting from the previous section and from Tytler's (this volume) discussion of the observations at high redshift.

Hence, if $(D/H)_p \simeq 3 \times 10^{-5}$, the ^{3}He problem is solved if 90% of low-mass stars burn it during the extra-mixing occurring in their red giant phase. In fact, we can simultaneously reproduce the low ^{3}He abundances of the solar region and of HII regions at any Galactocentric distance, and the high abundance of NGC 3252 and the other PNe measured by Rood et al., which would consequently be associated to the remaining fraction (10%) of stars without deep mixing.

Since the deep mixing depletes not only ^{3}He, but also the $^{12}C/^{13}C$ ratio (see Charbonnel and Sackman, this volume), it is important to check the self-consistency of the solution by comparing the model predictions with the carbon isotopic ratio. Charbonnel and do Nascimento (1998) find indeed that more than 90% of 191 field and cluster red giants present carbon ratios significantly lower than the $^{12}C/^{13}C=25$ predicted by standard nucleosynthesis. What we also want to check are the predictions of chemical evolution models. This has been done by Palla et al. (2000, hereinafter PBSTG) with a two-folding approach: a) we have compared the available observational data on the carbon isotopic ratio with the corresponding predictions of chemical evolution models assuming the deep mixing in various percentages of low-mass stars; b) we have observed ^{12}C and ^{13}C in 28 PNe in mm-waves and compared the derived ratios with those predicted by stellar nucleosynthesis.

Fig.5 shows what model Tosi-1 predicts for the carbon ratio when the ^{12}C and ^{13}C adopted yields are from Boothroyd & Sackman (1999) for low-mass stars with CBP, from Marigo (2000) for low and intermediate-mass stars without CBP, and from Limongi, Chieffi & Straniero (2000) for massive stars. Equivalent results are described by PBSTG for stellar yields from other sources. The dotted line shows that without extra-mixing in low-mass stars the $^{12}C/^{13}C$ ratio is overpredicted with respect to both the abundances observed in the sun and in molecular clouds (assumed to be representative of the present disk abundances). Vice versa a good agreement is achieved if the fraction of stars with CBP is as high as possible (recall that one cannot assume 100% because of the few
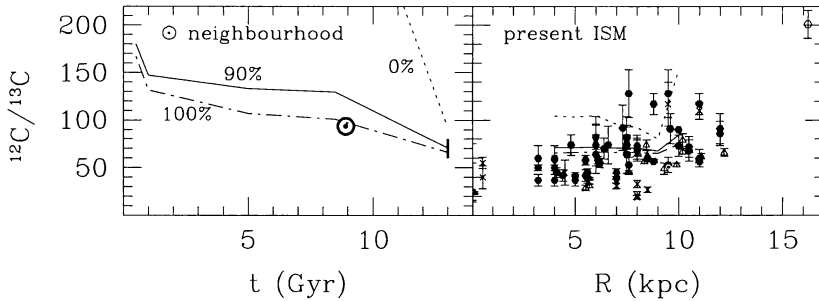
Figure 5.   Comparison between observed carbon isotopic ratios and the predictions of model Tosi-1 with CBP in the indicated fraction of low-mass stars (PBSTG). The data refer to the sun and to molecular clouds in the Galactic disk (see PBSTG for references). Left hand panel: Evolution in the solar neighbourhood. Right hand panel: Corresponding radial distribution at the present epoch.

PNe with high ^{3}He). As discussed by PBSTG, the amount of predicted ^{12}C and ^{13}C strongly depends not only on the extra-mixing assumptions but also (mostly) on the assumptions for the nucleosynthesis in intermediate-mass stars, which are the major contributors to the ISM enrichment of the carbon isotopes. However, we can safely conclude that the observed carbon ratios are always better reproduced by models adopting high percentages of low-mass stars with CBP.

This is also supported by the comparison of the ^{12}C/^{13}C derived by PBSTG for the PNe where ^{13}C was actually measurable with the carbon ratio predicted for stars right before the ejection of the PN by various nucleosynthesis studies. The left panel of Fig.6 shows that most of the data points (triangles with associated error on the progenitor mass estimate) present carbon ratios lower than those expected from standard nucleosynthesis. The right hand panel shows that the measured carbon ratios are consistent with the predictions of the CBP models at the end of the red giant phase (unfortunately, no nucleosynthesis models are available yet up to the pre-PN phase, and one cannot perform a more appropriate comparison with the PNe observed ratios).

Hence, with deep mixing in ~90% of low-mass stars one can reproduce the abundances of ^{3}He observed in the sun, in the ISM and in PNe and the ^{12}C/^{13}C measured in the sun, in red giants, in the ISM and in PNe. We can then conclude that this mechanism appears to be a very promising process, which needs to be further investigated, both to individuate its possible causes and to check its effects of later stellar evolution phases.

Our current knowledge on the Galactic evolution of ^{3}He can be summarized as follows: All its available observational abundances can be explained if a) its primordial abundance is low, $(^3\text{He/H})_p \simeq 1 \times 10^{-5}$, b) the deterium primordial abundance is also low, and c) deep mixing occurs in almost all low-mass stars.
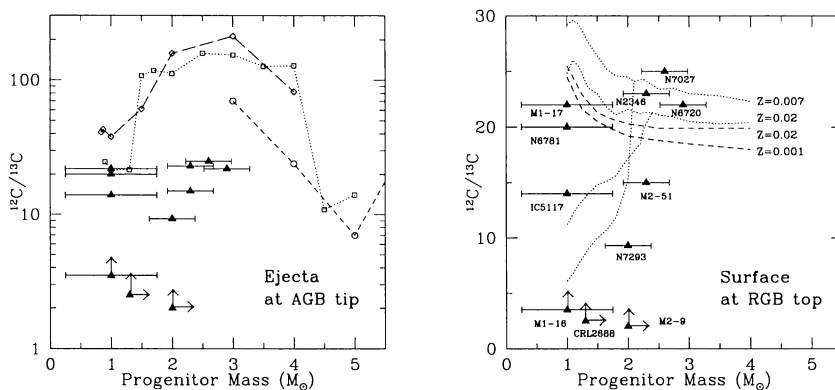
Figure 6.   Comparison between the carbon isotopic ratio measured by PBSTG in PNe and the predictions from stellar nucleosynthesis. Left hand panel: composition just before the PN ejection predicted without deep mixing by Forestini & Charbonnel (1997, short-dashed curve), van den Hoek & Groenewegen (1997, dotted curve), and Marigo (2000, long-dashed curve). Right hand panel: composition predicted with and without deep mixing at the end of the red giant phase (the dotted lines refer to Boothroyd & Sackman 1999, the short-dashed ones to Charbonnel 1994).

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