THE ASTROPHYSICAL JOURNAL, 453:L41–L44, 1995 November 1

A CONSISTENT EXPLANATION FOR ^{12}C/^{13}C, ^{7}Li, AND ^{3}He ANOMALIES IN RED GIANT STARS

C. CHARBONNEL
Observatoire Midi-Pyrénées, LAT–CNRS URA 285, 14 Avenue Edouard Belin, 31400 Toulouse, France
Received 1995 July 28; accepted 1995 August 24

ABSTRACT

The observations of carbon isotopic ratios in evolved stars suggest that nonstandard mixing is acting in low-mass stars as they are ascending the red giant branch. We propose a simple consistent mechanism, based on the most recent developments in the description of rotation-induced mixing reported by Zahn in 1992, which simultaneously accounts for the low ^{12}C/^{13}C ratios in globular cluster and field Population II giants and for the lithium abundances in metal-poor giant stars. It also leads to the destruction of ^{3}He produced on the main sequence in low-mass stars. This should both naturally account for the recent measurements of ^{3}He/H in Galactic H II regions and allow for high values of ^{3}He observed in some planetary nebulae.

Subject headings: diffusion — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: interiors

1. EVIDENCE FOR NONSTANDARD MIXING ON THE RGB FROM ^{12}C/^{13}C, ^{7}Li, AND ^{3}He OBSERVATIONS

At the beginning of the red giant branch (RGB), stars experience the first dredge-up. The deepening convective envelope brings up to the surface internal matter, which had undergone nuclear processing during the main-sequence evolution. The dredge-up induces in particular a decrease of the carbon isotopic ratio and of the ^{7}Li abundance and an increase of the ^{3}He abundance. According to the standard scenario, the surface abundances then stay unaltered as the convective envelope slowly withdraws during the end of the RGB ascent. However, comparisons of standard stellar evolutionary predictions with observed abundances of different elements reveal that some nonstandard mixing mechanism is acting in low-mass stars as they are ascending the RGB.

The main evidence for this mixing comes from the behavior of the surface carbon isotopic ratio. In most giants with masses lower than 2 $M_{\odot}$, its value is lower than predicted by standard evolutionary calculations (see Sneden 1991 for a review of the problem). Observations of evolved stars in globular and galactic clusters indicate that the ^{12}C/^{13}C ratio continues to decrease after the completion of the theoretical first dredge-up (Gilroy 1989; Smith & Suntzeff 1989; Brown & Wallerstein 1989; Bell, Briley, & Smith 1990; Gilroy & Brown 1991). This is confirmed by observations in field Population II giant stars (Sneden, Pilachowski & VandenBerg 1986). Observational data along the subgiant and giant branches of M67 (Gilroy & Brown 1991) provide the major evidence that nonstandard mixing is occuring above the luminosity at which the hydrogen-burning shell crosses the chemical discontinuity created by the convective envelope during the dredge-up (Charbonnel 1994, hereafter C94).

Observations of ^{7}Li in evolved stars confirm the occurrence of an extra-mixing mechanism in low-mass stars on the RGB. In a large sample of evolved halo stars, Pilachowski, Sneden & Booth (1993) have shown that the lithium abundance continues to decrease after the theoretical completion of the first dredge-up (cf. Fig. 2). This further decline indicates that some mechanism transports lithium from the convective envelope down to the region where it is destroyed by proton capture after the end of the dilution phase.

A related problem involves ^{3}He. When the ^{3}He peak produced on the main sequence is engulfed in the convective envelope of low-mass stars during the first dredge-up, the surface abundance of ^{3}He increases (cf. Fig. 1). In standard stellar models, ^{3}He then survives during the following phases of evolution (Vassiliadis & Wood 1993) and is injected in the ISM by stellar winds and planetary nebulae (PN) ejection. In this standard view, stars of masses lower than 2 $M_{\odot}$ produce large amounts of ^{3}He (Rood, Steigman, & Tinsley 1976). ^{3}He/H is thus predicted to increase with time in the regions where stellar processing occurs. Chemical evolutionary models including the production of ^{3}He by low-mass stars (Vangioni-Flam & Cassé 1995; Olive et al. 1995; Galli et al. 1995) indeed predict an overproduction of ^{3}He (by factors between 5 and 20) compared to recent measurements of ^{3}He/H in Galactic H II regions and in the local ISM (Rood et al. 1995). Currently observed values essentially leave no room for important production of ^{3}He in the Galaxy and seem to indicate that actually low-mass stars do not produce this element. Hogan (1995) noticed that a mixing process capable of reducing the ^{12}C/^{13}C ratios in low-mass stars would also destroy ^{3}He. As we shall see, the mechanism we propose should only be efficient in low-mass stars, and it allows the high value of ^{3}He/H observed in the PN NGC 3242 (Rood, Bania & Wilson 1992) if the initial mass of this object was higher than 2 $M_{\odot}$.

In the present Letter we propose a consistent model based on a realistic physical process, which simultaneously accounts for observed behavior of ^{12}C/^{13}C and ^{7}Li in evolved low-mass stars and leads to low ^{3}He.

2. SPECULATIONS ON THE NATURE OF THE EXTRA-MIXING PROCESS

Different mixing processes were proposed to explain the abundance anomalies in evolved stars. Sweigart & Mengel (1979) suggested that meridional circulation on the RGB could lead to the low ^{12}C/^{13}C ratios observed in field giants. More recently, Denissenkov & Weiss (1995) and Wasserburg, Boothroyd, & Sackmann (1995) reconsidered this idea in order to explain the carbon and oxygen isotope problems on the RGB and the asymptotic giant branch (AGB).

However, when invoking meridional circulation, one has to

1995ApJ...453L..41C

consider the interaction between meridional circulation and turbulence induced by rotation in stars and has to take into account recent progress in the description of the transport of chemicals and angular momentum in stellar interiors. For this purpose, Zahn (1992) developed a consistent theory for the mixing of chemicals induced by rotation, in which he took the feedback effect due to angular momentum transport into account. He showed that the global effect of advection moderated by horizontal turbulence can be treated as a diffusion process. In our context, two important points must be noted (see Zahn 1992): (1) The resulting mixing of chemicals in stellar radiative regions is mainly determined by the loss of angular momentum via a stellar wind. (2) Additional mixing is expected near nuclear-burning shells. Since both conditions are fulfilled on the RGB, we suggest that this process is responsible for the extra-mixing acting during the RGB evolution of low-mass stars. In the present Letter, we estimate how this rotation-induced mixing can modify the surface values of $^{12}C/^{13}C$ ratios and of the abundances of ^{7}Li and ^{3}He.

3. MODELS

Stellar models (0.8 and 1 $M_\odot$ for $Z = 10^{-4}$ and $Z = 10^{-3}$) are computed from the zero-age main sequence up to the top of the RGB. We use the Geneva stellar evolutionary code in which we have introduced the numerical method described in Charbonnel, Vauclair, & Zahn (1992) to solve the diffusion equation. Observations of $^{12}C/^{13}C$ ratios in M67 evolved stars (Gilroy & Brown 1991) strongly suggest that the extra-mixing process is efficient only when the hydrogen-burning shell has crossed the discontinuity in molecular weight built by the convective envelope during the first dredge-up (C94). Before this evolutionary point, the mean molecular weight gradient probably acts as a barrier to the mixing in the radiative zone. Above this point, no gradient of molecular weight exists any more above the hydrogen-burning shell, and extra-mixing is free to act. In our computations, we thus engage the extra-mixing on the RGB at this evolutionary point (see C94, Fig. 9). Then at each numerical step we take into account both nuclear reactions and diffusion to compute the evolution of the chemicals. We simultaneously treat hydrogen, lithium, and the isotopes of carbon, nitrogen, oxygen, neon, and magnesium. The implicit method we use is extensively described in Charbonnel et al. (1992).

Let us stress that for stars with masses higher than 2 $M_\odot$ (i.e., stars which do not undergo the helium flash), the hydrogen-burning shell does not have time to reach the chemically homogeneous region during the stars short ascent of the RGB. Thus, extra-mixing should naturally not occur in these more massive objects. This crucial point is confirmed by observations in open cluster giants (Gilroy 1989).

For the present approach, we restrict our study to the case in which the stars undergo a moderate wind on the RGB. We make the assumption that an asymptotic regime is reached. The induced diffusion process can then be treated with an effective coefficient of the form (see Zahn 1992): $D \simeq (3c_h/80\pi)|(dj/dt)|(1/\alpha\rho\Omega r^3)$, where $\alpha = (1/2)(d \ln r^2\Omega / d \ln r)$, Ω is the angular velocity, dJ/dt is the variation of angular momentum, and $c_h \leq 1$. Here we take $c_h = 1$. At each evolutionary step, D is computed in each radiative shell of the star in order to consider its spatial and temporal evolution. We assume a depth-independent angular rotation velocity in the region in which diffusion can happen, i.e., between the base of the deep convective envelope and the top of the hydrogen-burning shell. For all our models, we consider a constant rotation velocity of 1 km s^{-1} on the RGB. This value is typical at this evolutionary phase for the stellar masses we consider (De Medeiros 1990).

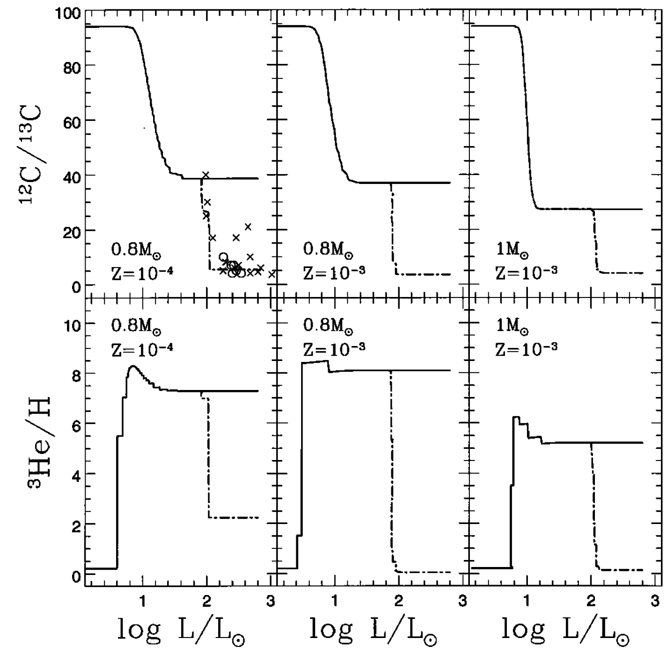

FIG. 1.—Evolution of $^{12}C/^{13}C$ (*top*) and of $^{3}He/H$ in units of 10^{-4} (*bottom*) as a function of luminosity. Theoretical results are displayed for standard evolution (*solid lines*) and for the evolution including extra-mixing (*dashed-dotted lines*). As discussed in the text, the postdilution values remain constant in the standard case and depend both on mass and metallicity. Rotation-induced mixing induces a further decrease of $^{12}C/^{13}C$ down to the values currently observed in Population II giants. The final carbon isotopic ratios are nearly identical in the three models because of their structural similarity. Observations of the carbon isotopic ratio in field Population II (*crosses*; Sneden et al. 1986) and globular cluster M4 (*circles*; Smith & Suntzeff 1989) giant stars are compared to the predictions of the 0.8 $M_\odot$, $Z = 10^{-4}$ model, which is typical for the considered stellar population. The behavior of $^{12}C/^{13}C$ is well reproduced. Rotation-induced mixing simultaneously leads to the destruction of ^{3}He produced during the main-sequence evolution. This result leads us to revise the actual contribution of low-mass stars to the production of ^{3}He in the Galaxy.

We use the OPAL radiative opacities (Iglesias, Rogers, & Wilson 1992) complemented at low temperature by the atomic and molecular opacities by Kurucz (1991). The nuclear cross sections are from Caughlan & Fowler (1988), with the exception of the $^{17}O(p, \gamma)^{18}F$ and $^{17}O(p, \alpha)^{14}N$ for which we adopt the values of Landré et al. (1990). Screening factors are considered according to the prescriptions by Graboske et al. (1973). For mass loss on the red giant branch, we use the expression of Reimers (1975). At solar metallicity, $\eta = 0.5$ is chosen (see Maeder & Meynet 1989). At nonsolar metallicity Z, we take mass-loss rates lowered by a factor of $(Z/0.02)^{0.5}$ with respect to the models at $Z = 0.020$ for the same stellar parameters.

4. RESULTS

Figure 1 shows the evolution of the surface ratio $^{12}C/^{13}C$ as a function of luminosity, both for standard computations and for computations including diffusion on the RGB. Because of dilution, $^{12}C/^{13}C$ decreases down to a value that depends of the maximal extent reached by the deepening convective envelope and which is function of both mass and metallicity (see C94).

In the standard case, the postdilution value of the carbon isotopic ratio stays constant for these low-mass stars and is substantially higher than observed. However, when extra-mixing begins to act, the carbon isotopic ratio drops again. It reaches the low values currently observed in globular cluster giants, i.e., it approaches the equilibrium value in the CN cycle, namely 3–8. Observations in field Population II (Sneden et al. 1986) and globular cluster M4 (Smith & Suntzeff 1989) giant stars are compared to the predictions in our 0.8 $M_\odot$, $Z = 10^{-4}$ model. The theoretical slope around $\log L/L_\odot \simeq 2$ and the final values obtained when considering rotation-induced mixing are in good agreement with observations. In a future paper, we will investigate how different rotational histories can account for the observed dispersion. We will also test our model from confrontation of its predictions with observations in Population I stars and in particular in galactic cluster giants.

Let us now consider the problem of ^{3}He. On the main sequence, the ^{3}He peak is not as deep as the ^{13}C peak. Thus, the surface mass fraction of ^{3}He begins to change earlier in luminosity than the ^{12}C/^{13}C ratio. Its value reaches a maximum before slightly decreasing when the whole peak is engulfed in the convective envelope. After the dredge-up, the temperature is too low at the base of the convective region for ^{3}He to be nuclearly processed. Then in standard models ^{3}He/H stays constant, and its final value is strongly increased compared to the initial one. However, the temperature gradient is very steep below the convective envelope: in our 0.8 $M_\odot$, $Z = 10^{-3}$ model, the temperature rises from $\log T \simeq 6.33$ to $\simeq 7.44$ in the diffusion region at the evolutionary point where extra-mixing is supposed to be free to act. Thus, when ^{3}He diffuses, it rapidly reaches the region where it is nuclearly burned by the ^{3}He(α, γ)^{7}Be reaction. This leads to a rapid decrease of the surface value of ^{3}He/H, confirming the predictions by Hogan (1995). Computations for different masses and different metallicities now have to be performed in order to estimate the actual contribution of low-mass stars to Galactic ^{3}He in the framework proposed here. Let us point out an important point concerning the high value of ^{3}He/H observed in the PN NGC 3242 (Rood et al. 1992). If confirmed, it requires that the progenitor of this object has not undergone extra-mixing. This can be explained if the initial mass of this star was higher than 2 $M_\odot$, since extra-mixing should not develop above this stellar mass, as explained before.

Observations of the lithium abundance in Population II evolved stars (Pilachowski et al. 1993) are displayed as a function of effective temperature and compared with our predictions for our models with $Z = 10^{-4}$ in Figure 2. Lithium abundances smoothly decrease with $T_{\rm eff}$ in subgiants due to dilution. Around 5000 K the dredge-up is completed, and down to this $T_{\rm eff}$ the expected lithium abundance variations reproduce the observed trend. For stars with lower $T_{\rm eff}$, the observed lithium abundance continues to drop, whereas standard models do not predict further decrease. In our models with diffusion on the RGB, lithium is rapidly transported from the convective envelope down to the region where it is burned by proton capture, and its surface abundance rapidly decreases down to the very low values observed in the halo giants. However, the problem of lithium in Population II stars has to be considered in a more general context. The present results will be discussed together with lithium variations in main-sequence halo stars in a forthcoming paper (Charbonnel & Vauclair 1995).

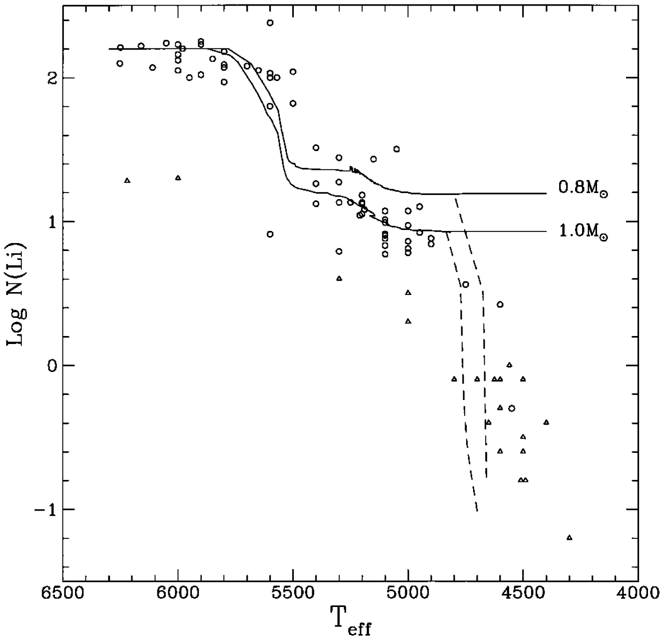

FIG. 2.—Theoretical predictions for the lithium abundance variations from the 0.8 and 1 $M_\odot$ models computed with $Z = 10^{-4}$, compared to observations of the lithium abundances in evolved halo stars from Pilachowski et al. (1993) (*open circles* for real lithium detection, *open triangles* for upper limits). The solid lines represent the lithium abundance variations due to standard dilution alone. The dashed lines correspond to the further decline of lithium due to rotation-induced mixing.

5. SUMMARY AND OUTLOOK

The exploratory results presented here indicate that a realistic physical process, rotation-induced mixing, can simultaneously account for observed behavior of carbon isotopic ratios and lithium abundances in Population II low-mass giants and can avoid large ^{3}He production by low-mass stars in the Galaxy. In a future paper, we will develop more detailed simulations in which both the transport of matter and angular momentum will be treated simultaneously, in order to take into account the whole rotational history of the stars. Other chemical anomalies will be investigated. Theoretical predictions will also be compared to observations in galactic cluster stars. Last but not least, we will test our model efficiency in stars on the asymptotic giant branch.

REFERENCES

Bell, R. A., Briley, M. M., & Smith, G. H. 1990, AJ, 100, 187
Brown, J. A., & Wallerstein, G. 1989, AJ, 98, 1643
Caughlan, G. R., & Fowler, W. A. 1988, At. Data Nucl. Data Tables, 40, 283
Charbonnel, C. 1994, A&A, 282, 811 (C94)
Charbonnel, C., & Vauclair, S. 1995, in preparation
Charbonnel, C., Vauclair, S., & Zahn, J. P. 1992, A&A, 255, 191
Denissenkov, P. A., & Weiss, A. 1995, A&A, preprint
De Medeiros, J. R. 1990, Ph.D. thesis, Geneva Univ.
Galli, D., Palla, F., Ferrini, F., & Penco, U. 1995, ApJ, 443, 536
Gilroy, K. K. 1989, ApJ, 347, 835
Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
Graboske, H. C., de Witt, H. E., Grosman, A. S., & Cooper, M. S. 1973, ApJ, 181, 457
Hogan, C. J. 1995, ApJ, 441, L17
Iglesias, C. A., Rogers, F. J., & Wilson, B. G. 1992, ApJ, 397, 717
Kurucz, R. L. 1991, in Stellar Atmospheres: Beyond Classical Models (NATO ASI Series C, 341) ed. L. Crivellari, I. Hubeny, & D. G. Hummer (Dordrecht: Kluwer), 441

Landré, V., Prantzos, N., Aguer, P., Bogaert, G., Lefevre, A., & Thibaud, J. P. 1990, A&A, 240, 85
Maeder, A., & Meynet, G. 1989, A&A, 210, 155
Olive, K. A., Rood, R. T., Schramm, D. N., Truran, J., & Vangioni-Flam, E. 1995, ApJ, 444, 680
Pilachowski, C. A., Sneden, C., & Booth, J. 1993, ApJ, 407, 713
Reimers, D. 1975, Mem. Soc. Roy. Sci. Liège, 8, 369
Rood, R. T., Bania, T. M., & Wilson, T. L. 1992, Nature, 355, 618
Rood, R. T., Bania, T. M., Wilson, T. L., & Basler, D. S. 1995, in The Light Element Abundances, ed. P. Crane (Berlin: Springer), 201
Rood, R. T., Steigman, G., & Tinsley, B. M. 1976, ApJ, 207, L57
Smith, V. V., & Suntzeff, N. B. 1989, AJ, 97, 6
Sneden, C. 1991, in IAU Symp. 145, Evolution of Stars: The Photospheric Abundance Connection, ed. G. Michaud & A. Tutukov (Dordrecht: Kluwer), 235
Sneden, C., Pilachowski, C. A., & VandenBerg, D. A. 1986, ApJ, 311, 826
Sweigart, A. V., & Mengel, J. G. 1979, ApJ, 229, 624
Vangioni-Flam, E., & Cassé, M. 1995, ApJ, 441, 471
Vassiliadis, E., & Wood, P. R. 1993, ApJ, 413, 641
Wasserburg, G. J., Boothroyd, A. I., & Sackmann, I. J. 1995, ApJ, 447, L37
Zahn, J. P. 1992, A&A, 265, 115