Episodic lithium production by extra-mixing in red giants

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Abstract. The recent discovery of low-mass red giants with enhanced atmospherical Li abundance in galactic low-metallicity stellar clusters adds to the mysterious phenomenon of the Li-rich giants. We propose a combined scenario for the Li-enrichment: engulfing a giant planet (or brown dwarf) by a red giant (external source) activates inside the giant the "^{7}Be-mechanism" producing Li internally. This episodical Li-production can happen at any time on the red giant branch and is naturally followed by Li-depletion as is observed. Limitations of our scenario are discussed as well.

Key words: stars: chemically peculiar – stars: evolution – stars: interiors – stars: late-type – stars: rotation

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1. Introduction

In low-mass red giants ($M \leq 2.5\,M_{\odot}$) the excursion of the base of the convective envelope (BCE) into the radiative zone separating it from the hydrogen-burning shell (HBS) initiates the first dredge-up episode during which the surface composition experiences modest changes. The best indicators of the 1st dredge-up are the ratio ^{12}C/^{13}C and the Li abundance, both decreasing. A decrease of the C and an increase of N are also predicted (Boothroyd & Sackmann 1999). In the overwhelming majority of the field red giants (K giants) the surface Li abundance is low. However, there are several percent of K giants which possess surprisingly high Li abundances, sometimes exceeding the initial value of $\log\varepsilon(^7\mathrm{Li}) \approx 3$ for Pop. I stars (Wallerstein & Sneden 1982; Hanni 1984; Brown et al. 1989; Berdyugina & Savanov 1994; Da Silva et al. 1995; De la Reza et al. 1996, 1997). It was not until recently when the evolutionary status of these Li-rich giants (LIRGs) became clearer. Owing to the more accurate luminosities estimated through the Hipparcos parallaxes Jasniewicz et al. (1999) have concluded that most of the LIRGs are past the 1st dredge-up red giant branch (RGB) stars (the low ^{12}C/^{13}C ratios observed in the LIRGs support this) and hence the initial abundance of Li in their atmospheres could not have been preserved.

De la Reza et al. (1997), Jasniewicz (1999) and other researchers argue convincingly for an internal mechanism of Li production in LIRGs. In both papers quoted the "^{7}Be-transport" mechanism (Cameron & Fowler 1971) is considered as the most promising internal source of Li. This internal mechanism has recently received new support: Castilho et al. (1999) have reported that Be – as predicted – is very depleted (about 10 times) in both LIRGs they studied. In this *Letter* we propose a combined scenario of Li-enrichment: a giant planet (or brown dwarf) is engulfed by a red giant; this external source or event activates inside the giant the "^{7}Be-mechanism" producing then Li internally. Before presenting our model in Sect. 3, we will discuss existing evidence for extra-mixing in red giants (Sect. 2), because this is crucial for scrutinizing any scenario. Sect. 4 concludes the paper.

2. Extra-mixing in red giants

The 1st dredge-up episode ends when the BCE stops its excursion into the star and begins to retreat. According to the standard theory, after this moment the surface composition is not expected to change further on the RGB. However, this expectation is not supported by observations. It appears that in low-mass field red giants the surface abundances of C, N, and Li as well as the ^{12}C/^{13}C ratio, and in globular cluster red giants even O, Na, Mg and Al, do continue to change up to the RGB tip. This discrepancy has been quite satisfactorily explained by red giants models with extra-mixing placed between the HBS and the BCE (see Denissenkov & Tout 2000, and references therein). Such extra-mixing is commonly believed to work only in radiative regions with a nearly uniform composition. Therefore, it is expected to come into play after the HBS, moving outwards in mass, will have erased the H-discontinuity left behind by the retreating BCE. Standard model calculations show that the HBS arrives at the H-discontinuity while the star is still on the RGB only in low-mass stars, which is well confirmed by observations (Charbonnel 1994).

Quite recently Gratton et al. (1999) have determined Li, C, N, O and Na abundances and ^{12}C/^{13}C ratios for a large sample of field stars with accurate luminosity estimates in the metallicity range $-2 \leq$ [Fe/H] ≤ -1. In Fig. 1 we compare $\log\varepsilon(^7\mathrm{Li})$, [C/Fe] ([A/B] means $\log[n(\mathrm{A})/n(\mathrm{B})]_{\mathrm{star}} - \log[n(\mathrm{A})/n(\mathrm{B})]_{\odot}$), $\log$ ^{12}C/^{13}C and [N/Fe] for these stars with results of calculations obtained with the method and code of Denissenkov & Weiss (1996) in which extra-mixing is modeled by diffusion in a post-processing approach, which uses full stellar evolution models as background models for the parameterized diffusion and nucleosynthesis. One can see that the behaviour of the plotted abundances on the upper-RGB ($\log L/L_{\odot} > 2$, following the nomenclature of Gratton et al. 1999) is quite well reproduced by the diffusive mixing with a depth $\delta m_{\mathrm{mix}} = 0.12$ (δm is a

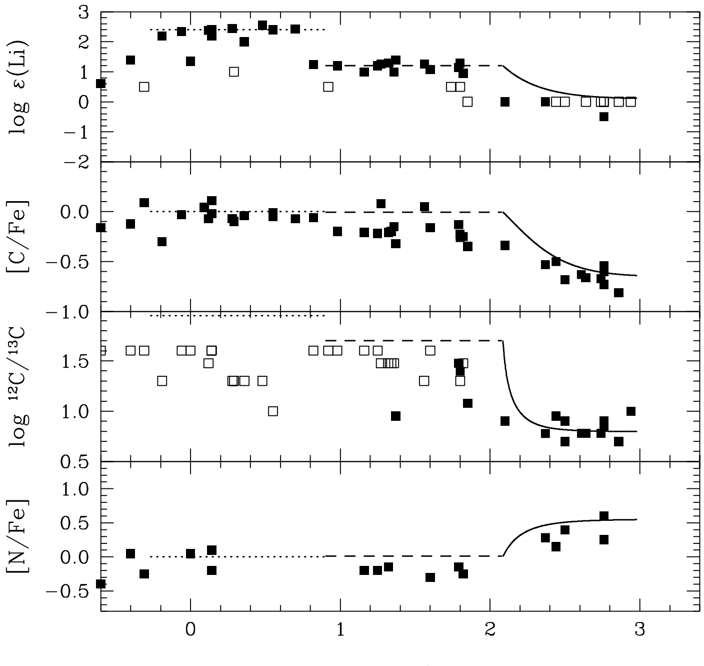

Fig. 1. Li, C, N abundances and $^{12}C/^{13}C$ ratios in field stars with accurate luminosity estimates in the metallicity range $-2 \leq [Fe/H] \leq -1$ (Gratton et al. 1999); open squares are upper (for Li) or lower (for $^{12}C/^{13}C$) limits). Dotted and dashed horizontal segments mark the main sequence and 1st dredge-up luminosity ranges, respectively. Solid lines were calculated with extra-mixing modeled by diffusion with depth $\delta m_{\rm mix} = 0.12$ and rate $D_{\rm mix} = 5 \cdot 10^8$ cm^2·s^{-1}.

relative mass coordinate such that $\delta m = 0$ at the bottom of the HBS and $\delta m = 1$ at the BCE) and a rate $D_{\rm mix} = 5 \cdot 10^8$ cm^2·s^{-1} (for details about method and results, see also Denissenkov & Weiss 1996).

From the upper panel of Fig. 1 one can infer that *(i)* most of the Pop. II main sequence stars preserve the initial Li abundance in their atmospheres ($\log \varepsilon(^7\mathrm{Li}) \approx 2.3$ for Pop. II stars), *(ii)* during the 1st dredge-up Li is diluted exactly down to the level predicted by the standard theory (Sackmann & Boothroyd 1999), and *(iii)* extra-mixing on the upper-RGB further decreases the surface Li abundance; extra-mixing is therefore a necessary ingredient to explain this behaviour.

Contrary to the field Pop. II giants which show neither O depletion nor Na enhancement, in globular clusters there are star-to-star variations of both O and Na on the RGB. Even more important is the fact that in globular cluster red giants Na anticorrelates with O (Fig. 2, symbols). A summary of the observational status can be found in Sneden (1999). The global anticorrelation of [Na/Fe] vs. [O/Fe] can be explained by extra-mixing as well (Denissenkov & Weiss 1996), but in this case deeper mixing is required. In Fig. 2 we compare observational data with a sample calculation (solid line, calculated with $\delta m_{\rm mix} = 0.06$, $D_{\rm mix} = 5 \cdot 10^8$ cm^2·s^{-1}). The corresponding evolution of the surface Li abundance for this case is plotted in Fig. 3 (line 3a). We note that in all our cases (Fig. 1, solid lines; Figs. 2 and 3) the calculations with extra-mixing start from the same red giant model with $M = 0.8\,M_\odot$, $\log L/L_\odot = 2.1$ and a heavy elements content of $Z = 5 \cdot 10^{-4}$ ([Fe/H] $\approx \log Z/Z_\odot = -1.58$). Because of the shallower mixing in the models of the field Pop. II stars no Na was produced in that case, as observed (Gratton et al. 1999).

To conclude, extra-mixing (with specific values for mixing depth and speed) is necessary to explain abundance trends in the *majority* of field giants and abundance anomalies in a *large* number of globular cluster giants. We now turn to the even more peculiar effect of Li-richness.

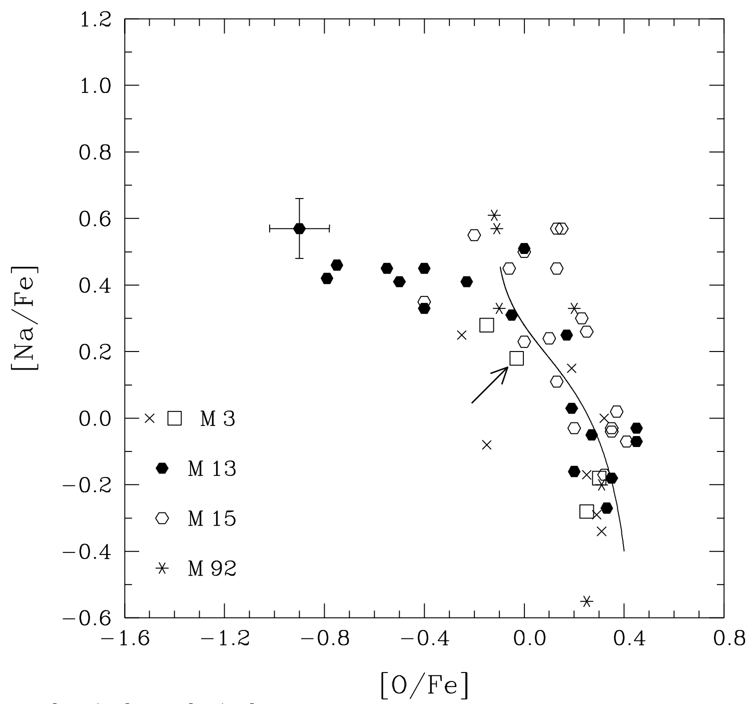

Fig. 2. The global [Na/Fe] vs. [O/Fe] anticorrelation in globular cluster red giants and its theoretical reproduction by diffusive extra-mixing with depth $\delta m_{\rm mix} = 0.06$ and rate $D_{\rm mix} = 5 \cdot 10^8$ cm^2·s^{-1} (solid line). Open squares are M 3 giants from the recent Li-study of Kraft et al. (1999). The Li-rich giant IV-101 is shown by the arrow. Data from Kraft et al. (1992; M3), Kraft et al. (1997; M13), Sneden et al. (1997; M15), Shetrone (1996; M92)

3. A solution to the problem of Li-rich giants

Following their first discovery that the "^{7}Be-mechanism" can naturally work in luminous intermediate-mass asymptotic giant branch (AGB) stars (Sackmann & Boothroyd 1992), Sackmann & Boothroyd (1999) have demonstrated that under certain conditions the same process can produce Li on the first giant branch, too. In AGB stars, ^{7}Be freshly minted in the reaction ^{3}He$(\alpha,\gamma)^7$Be is quickly mixed away to a cooler region (where Li produced in the reaction ^{7}Be$(e^-,\nu)^7$Li can survive) by ordinary convection whereas in RGB stars some extra-mixing is required for this.

The majority of field LIRGs have circumstellar dust shells (De la Reza et al. 1996) and a large number of additional LIRGs have been discovered among stars with IR excess. This feature seems to be the only one to distinguish the LIRGs from ordinary K giants and led De la Reza et al. (1996) to propose a scenario linking the high Li abundances in these stars to the evolution of circumstellar shells. In this scenario *every* low-mass red giant passes through a short phase during which some internal mechanism initiates atmospherical Li enrichment accompanied by a prompt mass-loss event. De la Reza et al. (1996) have calculated evolutionary paths (in the IRAS color-color diagram) of the detached shells and inferred that the whole cycle completes in about 10^5 years, the very fast initial increase of the surface Li abundance (during the first several thousand years) being followed by the much longer period (up to 10^5 years) of Li depletion.

Recently, Siess & Livio (1999) have considered an original external scenario: a red giant engulfs an orbiting body of sub-stellar mass (brown dwarf or giant planet) which has the initial abundance of Li left unprocessed. This body deposits its Li into the giant's envelope and also causes a shell ejection as a consequence of associated processes (mass accretion near the BCE where the body is expected to dissolve and subsequent thermal expansion of the overlying layers; for details see the cited paper). This scenario has an obvious disadvantage: it cannot account for Li abundances exceeding the initial one.

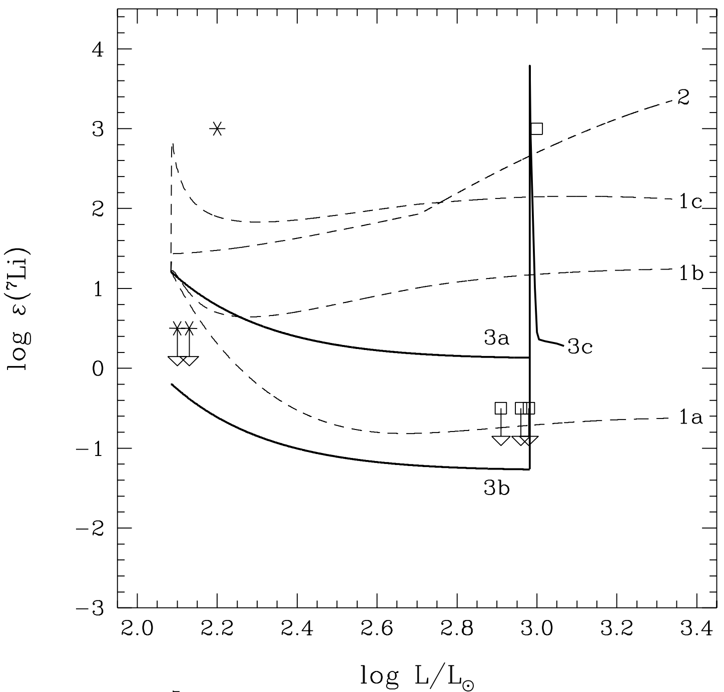

Fig. 3. Evolution of the surface ^{7}Li abundance on the upper-RGB caused by extra-mixing. The mixing parameters used in our calculations (for which we used code and method described in Denissenkov & Weiss 1996) are **1**: $\Delta \log T = \log T(\delta m = 0) - \log T(\delta m_{\rm mix}) = 0.26$ ($\delta m_{\rm mix} \geq 0.14$), **a** – $D_{\rm mix} = 10^9$ cm^2·s^{-1}, **b** – $D_{\rm mix} = 5 \cdot 10^9$ cm^2·s^{-1}, **c** – $D_{\rm mix} = 10^{11}$ cm^2·s^{-1}; **2**: $\Delta \log T = 0.36$ ($\delta m_{\rm mix} \geq 0.17$), $D_{\rm mix} = 10^{11}$ cm^2·s^{-1}; **3a,b**: $\delta m_{\rm mix} = 0.06$, $D_{\rm mix} = 5 \cdot 10^8$ cm^2·s^{-1}; **3c**: $\delta m_{\rm mix}$ decreases with time by 0.01 every $8 \cdot 10^3$ years from 0.16 to 0.06 and after that retains the constant value 0.06, $D_{\rm mix} = 10^{12}$ cm^2·s^{-1} during all this time. Open squares and asterisks are M3 and Berkeley 21 giants from the recent Li-studies of Kraft et al. (1999) and Hill & Pasquini (1999), respectively.

In this *Letter* we propose a combined scenario in which engulfing of a giant planet by a red giant initiates the internal "^{7}Be-mechanism": It takes into account results of quite recent publications where for the first time extremely high Li abundances have been measured in *cluster* giants. These are the stars IV-101 ([Fe/H] = −1.50) in the globular cluster M 3 (Kraft et al. 1999) and T33 ([Fe/H] = −0.58) in the metal-poor open cluster Berkeley 21 (Hill & Pasquini 1999). In both cases a Li abundance of $\log \varepsilon(^7\mathrm{Li}) \approx 3.0$ has been reported. The LIRGs IV-101 and T33 are plotted in Fig. 3 in comparison with 5 Li-normal giants from the same studies. One realizes that an episodical Li-enrichment can happen at any time on the upper-RGB, independent of the red giant's evolutionary state, thus indicating an external source. Fig. 2 supports this conclusion: Both the Li-rich giant IV-101 (open square and arrow) and another Li-normal one (open square) close to it have Na increased and O decreased and fit well to the global [Na/Fe] vs. [O/Fe] anticorrelation. At the same time extra-mixing with the parameters adjusted to reproduce this anticorrelation (Fig. 2, solid line) fails to make LIRGs (Fig. 3, lines 3a and 3b for two different values of initial Li). It appears that after having been exposed for a rather long time ($\sim 3 \cdot 10^7$ years) to the "ordinary" extra-mixing which is responsible to the Na-O-anomalies, the star IV-101 – but not the other one – experienced something which suddenly changed its extra-mixing parameters to values appropriate for Li-production.

From our model calculations we found that the "^{7}Be-mechanism" can efficiently synthesize Li and after that maintain its high abundance for a long time only if $0.12 \leq \delta m_{\rm mix} \leq 0.18$ and, even more important, only if $D_{\rm mix} \geq 10^{11}$ cm^2·s^{-1} (Fig. 3, lines 1c and 2). Denissenkov & Tout (2000) have proposed Zahn's rotation-driven meridional circulation and turbulent diffusion (Zahn 1992; Maeder & Zahn 1998) as a physical mechanism for extra-mixing in low-mass red giants. It turns out, however, that with Zahn's mechanism, values of $D_{\rm mix} \geq 10^{11}$ cm^2·s^{-1} can be obtained only as upper limits for rotation close to the Keplerian one. In a scenario with engulfing a planet such fast rotation is explained naturally as a result of transferring the planet's orbital angular momentum to the giant's envelope (Siess & Livio 1999). The next question then is how to get the correct mixing depth in this scenario.

The dashed lines in Fig. 3 are similar to those shown in Fig. 10 of Sackmann & Boothroyd (1999). They are the result of calculations under the assumption that mixing depth and rate favourable for the Li-production are constant on the upper-RGB. One of them (like our line 2) has even been used to interpret a LIRG near the RGB tip in the globular cluster NGC 362 by Smith et al. (1999). However, such a straightforward interpretation is not so simple because: *(i)* mixing under these conditions does not produce Na nor deplete O as is observed in IV-101; *(ii)* it explains neither the Li-depletion immediately following the Li-production nor the rather short time-scale for the whole cycle; *(iii)* it requires a very unusual, precise and long-term tuning of the mixing parameters; the tuning appears to be unusual because it assumes shallow but extremely fast mixing compared to that reproducing the [Na/Fe] vs. [O/Fe] anticorrelation; it would be more natural to expect that faster mixing should be deeper as well.

Thus we propose the following explanation of how the correct mixing depth could appear in the engulfing scenario. According to Siess & Livio (1999) the giant planet (or brown dwarf) dissolves near the BCE in a red giant. After that the rotation profile in the radiative zone takes a step-like shape with a steep increase of the angular velocity up to about a local Keplerian value at the point of deepest penetration by the planet. In the course of the subsequent evolution the HBS moves outwards in mass and after $\sim 8 \cdot 10^5$ years will reach the step in the rotation profile. During a time interval of $\sim 8 \cdot 10^4$ years this step will be crossing a zone $0.06 \leq \delta m \leq 0.16$ where and when the Li-production becomes efficient. Thus we do not need to fix the mixing depth to a preferred value. Instead, the natural growth of the helium core assures that suitable depths will be encountered and very fast mixing (due to the planet's engulfing) produces Li during this passage (Fig. 3, line 3c).

4. Conclusion

A great advantage of the proposed solution is that it can account not only for the Li-production but also for the subsequent Li-depletion. Indeed, we find that after the mixing depth has reduced to less than ~ 0.08, Li begins to be destroyed on a time-scale consistent with the results of De la Reza et al. (1996). It should be emphasized that it is even more difficult to deplete Li quickly after its production than to produce it, and our scenario deals with this naturally.

At the same time, however, it cannot be applied to the Li-rich ($\log \varepsilon(^7{\rm Li}) \approx 1.8$) star V42 in M5 (Carney et al. 1998), which appears to be a (low-mass) post-AGB star. Due to the timescales, the Li-enrichment cannot have happened already during the first red giant phase. On the other side, since V42 is only as bright as the RGB-tip ($M_{\rm Bol} = -3.38$), but hotter and thus smaller, capturing a companion would have happened already on the RGB. Thus, our scenario fails for this star, which otherwise appears to be typical M5 member, showing standard α-enhancement and even the O-Na-anticorrelation (Carney et al. 1998). We can only speculate that its Li-overabundance happened (via the Cameron-Fowler mechanism) during the AGB, where additional deep mixing initiated hot bottom burning as is standard in intermediate-mass stars (Sackmann & Boothroyd 1992). Due to the thin envelope of this star very modest extra mixing might already be sufficient. We will investigate this possibility in forthcoming work.

Our scenario does neither provide a direct link to the dust shell formation. Siess & Livio (1999) have ascribed the shell detachment to an increased mass loss during the planet's engulfing but in our scenario this event is separated from the Li-enrichment episode by a time interval of $\sim 7 \cdot 10^5$ years. The following two speculations towards a solution of this problem can be envisaged: (1) The mass of the radiative zone is negligible, and the angular velocity inside it scales as $\propto r^{-2}$ (Denissenkov & Tout 2000); hence, the ratio of the centrifugal acceleration to the gravity scales as $\propto r^{-1}$; as after engulfing the planet this ratio is expected to become close to unity near the BCE, then during the subsequent inward excursion of the step in the rotation profile it will surely exceed unity somewhere in the radiative zone, which may initiate dynamical processes of the angular momentum transfer outwards; the latter may be responsible for the increased mass loss. (2) The process of planet engulfing itself may be associated with various dynamical and thermodynamical processes, for instance, a deepening of the convective envelope (Siess & Livio 1999), which may redistribute the material with the high angular momentum throughout the radiative zone; in this case the fast mixing will be able to penetrate the zone of correct mixing depths from the very beginning. Whether such phenomena happen in a real red giant can be verified only by 3D hydrodynamical simulations.

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References

Berdyugina S.K., Savanov I.S., 1994, SvA Lett. 20, 639
Boothroyd A.I., Sackmann I.-J., 1999, ApJ 510, 232
Brown J.A., Sneden C., Lambert D.L., Dutchover E., 1989, ApJS 71, 293
Cameron A.G.W., Fowler W.A., 1971, ApJ 164, 111
Carney B.W., Fry A.M., Gonzalez G., 1998, AJ 116, 2984
Castilho B.V., Spite F., Barbuy B., Spite M., De Medeiros J.R., Gregorio-Hetem J., 1999, A&A 345, 249
Charbonnel C., 1994, A&A 282, 811
Da Silva L., De la Reza R., Barbuy B., 1995, ApJ 448, L41
De la Reza R., Drake N.A., Da Silva L., 1996, ApJ 456, L115
De la Reza R., Drake N.A., Da Silva L., Torres C.A.O., Martin E.L., 1997, ApJ 482, L77
Denissenkov P.A., Weiss A., 1996, A&A 308, 773
Denissenkov P.A., Tout C.A., 2000, MNRAS, accepted
Gratton R.G., Sneden C., Carretta E., Bragaglia A., 1999, A&A 354, 169
Hanni L., 1984, SvA Lett. 10, 51
Hill V., Pasquini L., 1999, A&A 348, L21
Jasniewicz G., Parthasarathy M., de Laverny P., Theévenin F., 1999, A&A 342, 831
Kraft R.P., Sneden C., Langer G.E., Prosser C.F., 1992, AJ 104, 645
Kraft R.P., Sneden C., Smith G.H. et al., 1997, AJ 113, 279
Kraft R.P., Peterson R.C., Guhathakurta P., Sneden C., Fulbright J.P., Langer G.E., 1999, ApJ 518, L53
Maeder A., Zahn J.-P., 1998, A&A 334, 1000
Sackmann I.-J., Boothroyd A.I., 1992, ApJ 392, L71
Sackmann I.-J., Boothroyd A.I., 1999, ApJ 510, 217
Shetrone M.D., 1996, AJ 112, 1517
Siess L., Livio M., 1999, MNRAS 308, 1133
Smith V.V., Shetrone M.D., Keane M.J., 1999, ApJ 516, L73
Sneden C., 1999, Ap&SS 265, 145
Sneden C., Kraft R.P., Shetrone M.D. et al., 1997, AJ 114, 1964
Wallerstein G., Sneden C., 1982, ApJ 255, 572
Zahn J.-P., 1992, A&A 265, 115