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Pre-MS depletion, accretion and primordial ^{7}Li

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Abstract. We reconsider the role of pre-main sequence (pre-MS) Li depletion on the basis of new observational and theoretical evidence: i) new observations of Hα emissions in young clusters show that mass accretion could be continuing till the first stages of the MS, ii) theoretical implications from helioseismology suggest large overshooting values below the bottom of the convective envelopes. We argue here that a significant pre-MS ^{7}Li destruction, caused by efficient overshoot mixing, could be followed by a matter accretion after ^{7}Li depletion has ceased on MS thus restoring Li almost to the pristine value. As a test case we show that a halo dwarf of 0.85 $M_\odot$ with an extended overshooting envelope starting with an initial abundance of A(Li) = 2.74 would burn Li completely, but an accretion rate of the type $1 \times 10^{-8} e^{-t/3\times10^6}$ $M_\odot$ yr^{-1} would restore Li to end with an A(Li) = 2.31. A self-regulating process is required to produce similar final values in a range of different stellar masses to explain the PopII Spite plateau. However, this framework could explain why open cluster stars have lower Li abundances than the pre-solar nebula , the absence of Li in the most metal poor dwarfs and a number of other features which lack of a satisfactory explanation.

Key words. Lithium, Pre-MS Stellar evolution, Primordial nucleosynthesis

1. Introduction

1.1. The PopII-WMAP puzzle

The WMAP value for $\Omega_b h^2$ yields $\eta_{10} = 10^{10}(n_b/n_\gamma)_0 = 6.16$ (Komatsu et al 2011), light elements in the framework of SBBN. The predicted primordial ^{7}Li abundance is A(Li)=2.72 , in the scale where A(Li)=log[$N(Li)/N(H)$] + 12, (Coc et al 2012).

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On the other hand, almost 3 decades of Li observations in PopII stars provided an abundance of A(Li)≈ 2.26 (cfr Molaro 2008), missing the WMAP prediction by about a factor 3 as emphasized in Fig 1. The data in the figure are drawn from the 1D non-LTE abundances with IRFM temperatures from Bonifacio and Molaro (1997) and Sbordone et al (2010).

The solution of the Li problem was widely debated at this conference. Very different approaches have been considered from the nuclear reaction rates in the SBBN (Coc et al

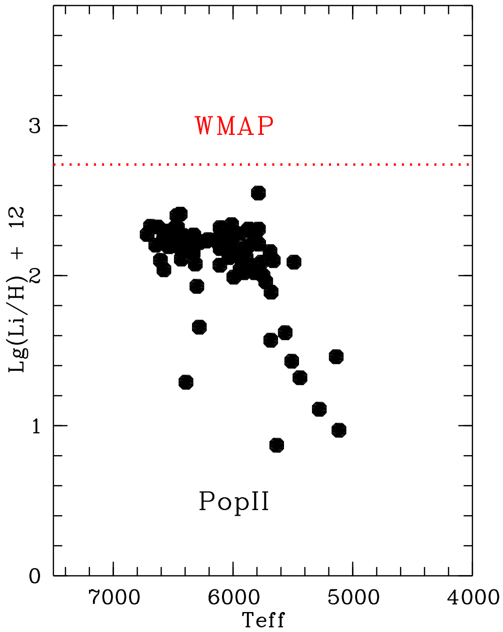

Fig. 1. Li observations in PopII stars. The red line marks the WMAP Li prediction

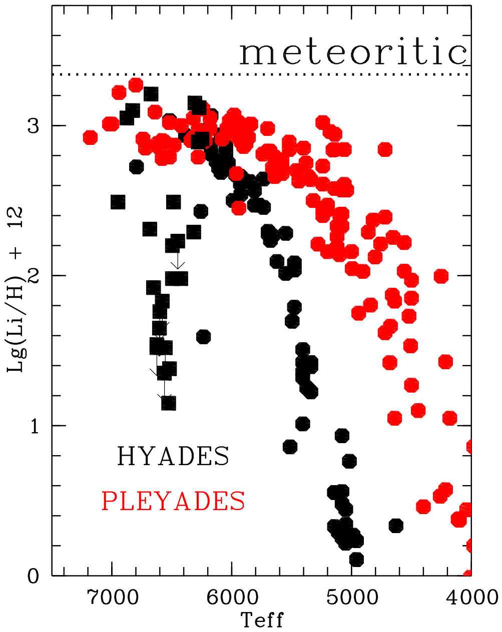

Fig. 2. Li observations in Hyades, black dots and squares, and Pleiades, red dots. The dotted line shows the level of meteoritic ^{7}Li abundance

2012) to new physics beyond the standard model (Olive 2012, Kajino's talk at this conference) or depletion in stars by diffusion (Richard 2012, Korn 2012).

1.2. The PopI-meteoritic puzzle

The PopII-WMAP problem is mirrored at high metallicity by the difference between the meteoritic ^{7}Li abundance and that observed in the open clusters. The present ^{7}Li abundance at the time of the formation of the solar system as obtained from meteorites is A(Li)= 3.34 ± 0.02 (Anders and Grevesse 1989). For recently born stars, the initial ^{7}Li abundance has been estimated in young T-Tauri stars where no Li depletion could yet have taken place A(Li) = 3.2 ± 0.1 (Cunha et al 1995). The hotter F stars of slightly older clusters such as Pleiades (≈ 100 Myrs) and Hyades (670 Myrs) show a top value of A(Li)≈ 3.0, Thorburn 1994, Soderblom 1993) and never reach the meteoritic value as shown in Fig 2. The behavior of several other young clusters is quite similar to the Pleyades but the data are omitted in the figure for clarity (Sestito and Randich 2005). Considering that the present Li abundance could be higher than the meteoritic value due to Li Galactic enrichment, the disagreement between PopII and WMAP and cluster plateau's and meteoritic values could be considered of comparable scale. We examine here the possibility that they may share a common origin dealing with the pre-MS ^{7}Li evolution.

2. Pre-MS Li evolution

Pre-MS stars with masses $M < 0.5\,M_\odot$ are almost fully convective all the way to the ZAMS and as the star contracts along its Hayashi track, its core heats up. When the core temperature T_c reaches $\simeq 3 \times 10^6$ K, Li begins to burn in p, α reactions. These reactions are very temperature-sensitive ($\propto T_c^{16-19}$) and convective mixing so fast that all ^{7}Li is burned in a few Myr.

In 1 $M_\odot$ stars photospheric Li depletion begins at about 2 Myr and terminate at about

15 Myr. This range shifts towards older ages in lower mass stars and Li-burning temperatures are never reached for $M < 0.06\,M_\odot$.

Li depletion is therefore a sensitive function of age between about 10 and 200 Myr. In PMS stars luminosity, $L \propto M^2$ and in Fig 3 the locus of the HR diagram corresponding to the Li burning is shown. The red segments show the luminosities for the maximum burning of different masses.

The overall amount of Li-depletion is also extremely sensitive to mass and there should be relatively little depletion in solar mass stars if compared with lower-mass stars. For $M < 0.6\,M_\odot$ all the Li is burned. For higher mass stars the radiative core develops before Li burning is complete and the temperature at the base of the convective envelope, T_{bcz}, decreases. In the absence of convective mixing, Li-depleted material cannot get to the photosphere, so once T_{bcz} drops below the Li-burning threshold, photospheric Li-depletion ceases.

Photospheric Li-depletion arises from rapid Li burning in a very thin region above the convection zone base, and current models are too coarse to predict Li depletion accurately. The exact amount of expected Li depletion is dependent on a number of model details such as the time at which the radiative core develops, the position of the convection zone base and hence T_{bcz}. As a result, large changes in Li depletion predictions can result from relatively minor perturbations in model parameters. As discussed in Ventura et al (1998) and also Tognelli et al at this conference, there is a unsatisfactory agreement between models and the observational data. However, the models are generally made to fit the Li abundances of the hotter stars in the open clusters. Convective efficiency and overshooting are crucial model parameters which determine the extension of the convection zone. If overshooting is present, then the temperature at the base of the convective zone is higher resulting in much more photospheric ^{7}Li depletion.

A recent analysis of helioseismology data (Christensen-Dalsgaard et al 2011) indicates that external convection in our Sun could penetrate into the underlying stable regions by a significant amount, corresponding to an overshoot scale $\Lambda_{\rm OV} \sim 0.4 \sim 0.6 H_P$. These values indicate that overshoot mixing could be much more efficient than previously believed.

In the following we will assume that the efficiency of the overshoot process during the PMS phase is large enough to allow an almost complete depletion of ^{7}Li. For the test case presented here (Fig 4) we consider a star with 0.85 $M_\odot$, [Fe/H]=-2.2, initial A(Li)=2.74 and an overshooting parameter $\Lambda_{\rm OV} = 1.5 H_P$. The latter is not unreasonable since, during the PMS phase, a significant fraction of the star is convective.

3. Pre-MS LI evolution with mass accretion

Recent observations of Hα emissions in several fields suggest that accretion could last longer than formerly believed (De Marchi et al 2010, 2011, Spezzi et al 2012). It is noteworthy that the majority of PMS objects showing evidence of matter accretion are very close to the MS. The median mass accretion rate they derive on the MS is of $\dot{M}_{\rm acc} = 2.6 \times 10^{-8} M_\odot\ {\rm yr}^{-1}$.

We note that this is gas and not planetesimal accretion. The latter is H/He depleted and in order to explain the Li abundance scatter this would also lead to Fe abundance anomalies of the order of 0.2-0.3 dex – much higher than allowed by current observational constraints.

If accretion occurs only during the initial phases of pre-MS evolution, the new Li brought in by accretion is depleted as the initial one.

However, the Li evolution would be completely different if the accretion takes place also *after* the Li depletion phase. In fact, accretion occurring after Li-burning has ceased would enrich again the convective zone with Li.

The convective zone masses for these stars are few percent of their mass. They are $M_{CZ} = 0.01 - 0.06\,M_\odot$, for 1 to 0.7 $M_\odot$, respectively. The accreted material with pristine ^{7}Li is rapidly diluted in the convection zone (CZ) where ^{7}Li has been previously burnt and even a relatively small mass accretion has a non-

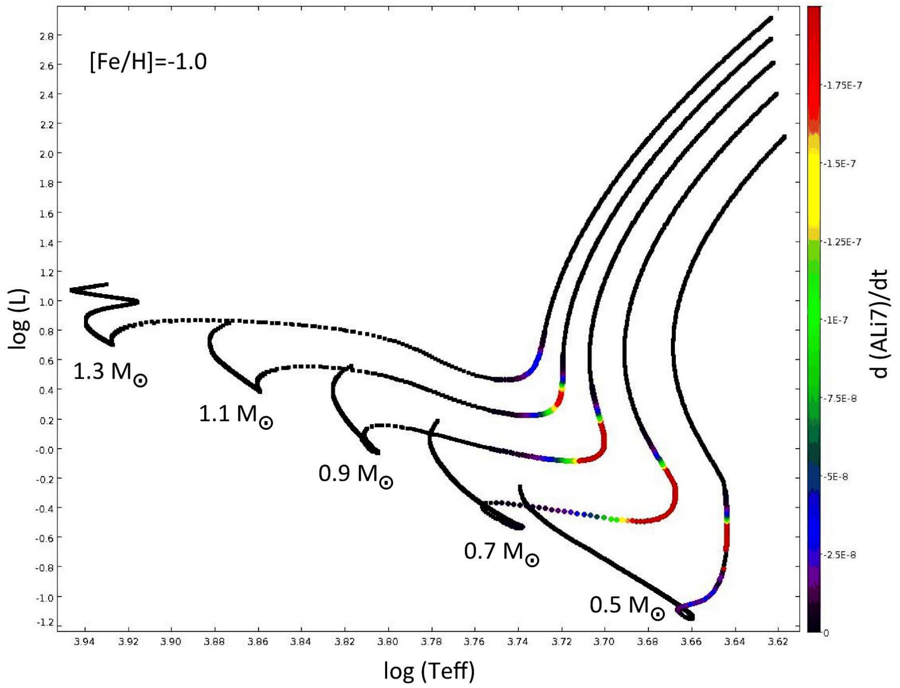

Fig. 3. Locus in the HR diagram corresponding to the Li burning. The red segment shows the maximum burning.

negligible impact on the resulting Li abundance.

We modified our stellar evolution code (Bressan et al 2012) in order to account for low accretion rates. In our test case we consider that the accretion rates declines as $\dot{M}_{\rm acc} = 1 \times 10^{-8} e^{-t/t_0}\ M_\odot\ {\rm yr}^{-1}$ where t is in yr and $t_0 = 3 \times 10^6$yr.

The accreted material is mixed through the convective zone and eventually burned by nuclear reactions in the star center or at the bottom of the convective zone if the temperature is high enough.

Our results do not depend on the previous evolution along the stellar birth-line (Stahler, 1983) because, when large accretion ends, deuterium burning cannot more be sustained and the star exits from the stellar birth line (blue dashed line in the HR diagram of Fig. 4) and evolves along the almost constant mass path (red line). Soon after, deuterium is almost completely exhausted. This phase is marked with a triangle in the same figure.

The time behavior of surface element abundances, central temperature, temperature at the bottom of the convective envelope and mass accretion rate are all shown in the right panel of Fig. 4. Deuterium is almost immediately destroyed and at the base of the Hayashi track also ^{7}Li starts to be depleted. Due to the large overshoot it is almost completely depleted after about 4 Myr since Deuterium depletion. At this stage the central region becomes radiative and convection starts receding towards the external layers. The temperature at the base of the convective envelope falls below the ^{7}Li burning limit and eventually also below the deuterium burning limit. Here accretion is $\sim 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ but, since the convective region gets smaller and smaller, this rate is high enough to restore high values of the surface ^{7}Li abundance.

Incidentally surface Deuterium rises to almost the pristine value but then it is burned again and destroyed. With the parameters adopted in this test case the surface ^{7}Li stabilizes at A(Li)=2.31, i.e. close to what observed in the PopII stars.

4. Conclusions

Pre-MS Li depletion is presently considered to explain the scatter and the depletion of the low temperature side of Li diagrams in young clusters but thought to be minimal for the hotter members of cluster members (Tognelli et al 2012). It is generally considered absent in PopII dwarfs. D'Antona & Mazzitelli (1984) allow a rather small amount of Li depletion in pre-MS of the order of 0.15 dex. Instead, we argue for an effective Li burning along the pre-MS phase. The apparent contrast with the observations which do not show clear evidence for pre-MS depletion could be removed if the destruction is substantially balanced by Li accretion occurring in the late stages of the pre-MS evolution after Li has been burned in the stellar convective zones. We have shown a test case of a 0.85 $M_{\odot}$ PopII dwarf with [Fe/H]=-2-2 with an original Li at the WMAP value. A self-regulating process, not yet identified, should be at work in order to produce almost the same dilution factor for the variety of stellar masses which are on the Spite plateau or in the hotter stars of the open clusters. The onset of the stellar wind could counteract the lithium restoration both by removing the outer layers and also by dissipating the accreting disk. This is a working hypothesis but we note that it has several specific assets, namely:

- Providing a possible explanation of the disagreement between PopII Li abundances and WMAP predictions.
- Providing a possible explanation of why models with no pre MS Li depletion fail in explaining open clusters Li diagrams and in particular of why F stars Li abundances are always below the solar-meteoritic value.
- Failure or increase of the accretion process could provide an explanation for the few Pop II ^{7}Li depleted stars ($\approx$ 3%) or of the few Pop II star showing a ^{7}Li abundances at the WMAP level, respectively. Among the latter there is BD +23 3912 with $A(Li)$=2.60 which stands out the others in Fig 1(Bonifacio and Molaro 1997).
- The extreme metal poor dwarfs of Caffau et al (2011) and Frebel et al (2005) without detectable Li could have been formed in a fragmentation process and never accreted material after a complete ^{7}Li depletion in the pre-MS phase. Caffau et al (2012) by using a set of different isochrones to match the observed colors estimate a mass in the range 0.62-0.70 $M_{\odot}$. Since for $M < 0.6\,M_{\odot}$ all the Li is burned in pre-MS, the absence of Li could be explained by an extended pre-MS depletion in a star with an initial mass below this threshold. In fact the absence of Li in these stars can be considered as evidence of pre-MS Li depletion in extreme metal poor stars. The melting of Li abundances for [Fe/H] $\leq$ -3.0 observed by Sbordone et al (2010) could be another feature of the mass decrease at lower metallicity for a given effective temperature. Towards the low metallicity tail stars have progressively smaller masses and the mass accretion could be not enough to restore Li at the level of the more massive stars.
- It could provide an explanation of the Li paradox in the metal poor spectroscopic binaries. The PopII spectroscopic binaries CS 22876-032 (González Hernández et al 2008) and G 166-45 (Aoki et al 2012) are composed by dwarfs with a temperature characteristic of the plateau but show slightly different Li abundances. The hotter is on the Spite Plateau but the cooler show a lower Li abundance of $\approx$ 0.4 dex and $\approx$ 0.2 dex respectively. The masses of the CS 22876-032 system are $m_1 = 0.70 \pm 0.02$ and $m_2 = 0.64 \pm 0.02$ and those of the G166-45 system are $m_1 = 0.76 \pm 0.02$ and $m_2 = 0.67 \pm 0.02$. The cooler has also a smaller mass and very close to the full convective limit. Thus it is quite possible that with the same accreted mass the restoring of Li has been lower in the smaller mass

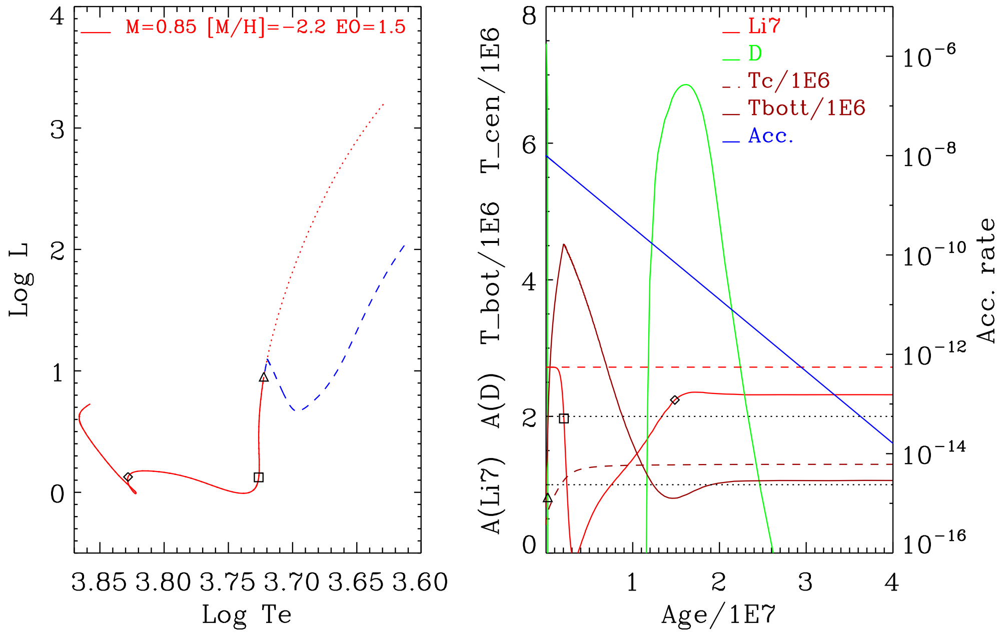

Fig. 4. Left panel: pre MS evolution of a star with 0.85 $M_{\odot}$, with [Fe/H]=-2.2 and an overshooting envelope of 1.5. The dotted blu line is the evolution of a star with initial mass of 0.2 $M_{\odot}$ accreting mass at a rate of $\sim 10^{-5}$ $M_{\odot}$ yr^{-1} till it becomes a star of 0.85 $M_{\odot}$. Since then the accretion is reduced to $\sim 10^{-8}$ $M_{\odot}$ yr^{-1}. The empty square marks the onset of Li burning and the diamond the end of the Li accretion. The triangle marks the end of the D burning and of the birthline track. Right panel: Li evolution from an initial A(Li)=2.7 (red line) , an accretion rate with the law given in the text (blue line).

star due to the relatively larger convection zone.

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