

The solar, exoplanet and cosmological lithium problems

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Abstract We review three Li problems. First, the Li problem in the Sun, for which some previous studies have argued that it may be Li-poor compared to other Suns. Second, we discuss the Li problem in planet hosting stars, which are claimed to be Li-poor when compared to field stars. Third, we discuss the cosmological Li problem, i.e. the discrepancy between the Li abundance in metal-poor stars (Spite plateau stars) and the predictions from standard Big Bang Nucleosynthesis. In all three cases we find that the “problems” are naturally explained by non-standard mixing in stars.

Keywords Sun; solar twins; exoplanets; metal-poor stars; big bang nucleosynthesis

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1 The solar Li problem

As illustrated in Fig. 1, the present day solar Li abundance ($A_{\text{Li}}^1 = 1.05$; Asplund et al. 2009) is much lower than the meteoritic Li abundance ($A_{\text{Li}} = 3.26$; Asplund et al. 2009). This large depletion in the observed solar Li abundance by a factor of 160 relative to the primordial solar system composition remains one of the most serious challenges of standard solar models, which, as illustrated in Fig. 1, destroy only a minor amount (0.06 dex) of Li (e.g. D’Antona & Mazzitelli 1984). It is important to note that modern models using updated OPAL opacities predict too much lithium destruction during the pre-main sequence (e.g. Piau & Turck-Chièze 2002; D’Antona & Montalbán 2003), at variance with the observations of Li in solar-mass stars in young open clusters (see e.g. Fig. 6). When the new low solar abundances (Asplund et al. 2009) are used the problem is reduced (Sestito et al. 2006), but in general classical models have problems dealing with pre-main sequence convection, so other parameters are invoked to reduce the efficient lithium destruction during the pre-main sequence (e.g. Ventura et al. 1998).

1.1 Comparison to solar analogs

A comparison between the Sun and solar analogs of one solar mass and solar metallicity (Lambert & Reddy 2004) shows the Sun to be “lithium-poor” by a factor of 10. This apparent peculiarity in the solar Li abundance, led Lambert & Reddy (2004) to suggest that the Sun may be of dubious value for calibrating non-standard models of Li depletion. However, Pasquini et al. (1994) have shown that there are solar-type stars that have

¹ $A_X = \log(N_X/N_H) + 12$

a Li abundance as low as in the Sun. Nevertheless, Pasquini et al. (1994) comparison sample of solar-type stars span a wide range in stellar parameters ($5400 \text{ K} < T_{\text{eff}} < 6100 \text{ K}$, $3.6 < \log g < 4.6$, $-1.6 < [\text{Fe}/\text{H}] < +0.2$) and therefore they are not representative of one-solar-mass solar analogs. In Fig. 2, we restrict the comparison sample of Pasquini et al. (1994) to only solar analogs within $\pm 200 \text{ K}$ in solar effective temperature, ± 0.3 dex of the solar surface gravity and ± 0.3 dex of the solar metallicity. As we can see, these solar analogs seem to cluster in two groups, one with very high lithium abundances of $A_{\text{Li}} \sim 2.4$, i.e., 20 times higher than solar, and the other group with Li abundances as low as solar. Why are there no solar analogs with intermediate Li abundances? Why the number of solar analogs with low Li abundances is much lower than the number of analogs with high Li abundances? Could this be the reason why Lambert & Reddy (2004) only found stars with high Li abundances around one solar mass? The lack of stars with intermediate Li abundances in the Pasquini et al. (1994) solar analog sample, and the lack of stars with both intermediate and low Li abundance around one solar mass in the Lambert & Reddy (2004) sample are probably telling us that both samples have biases, perhaps due to a selection of stars mostly in one or two evolutionary stages, e.g., mainly young stars, which are known to have high Li abundances.

The recent work by Pasquini et al. (2008) for solar analogs and solar twins in the solar-age open cluster M67, shows that solar twins (M67 stars around solar effective temperature) have Li abundance as low as solar, but stars 100 or 200 K hotter span a broad range in Li abundances. So, it is important that the temperature scale of the comparison sample is accurate; otherwise offsets of about 100 K may introduce a bias in the comparison between the Sun and stars.

1.2 Comparison to solar twins

Solar twins, stars with stellar parameters very similar to the Sun, are ideal targets to see if the Sun is normal (or not) in its Li abundance. Being so similar to the Sun, it is possible to obtain reliable stellar parameters, and provided the Sun and the twins are analyzed (and observed) in a consistent way, the temperature scale is accurate. Furthermore, being selected due to their similarity in colors and luminosity to the Sun, they should span a range of ages very close to solar, avoiding thus potential biases in the selection of comparison stars in only one evolutionary stage very different to the present Sun.

Solar twins have been searched for a long time, and although interesting solar twin candidates like 16 Cyg B

(HD 186427) were identified in the past, detailed analysis showed that they were significantly different to the Sun (see review by Cayrel de Strobel 1996).

When the first close solar twin (18 Sco) was found (Porto de Mello & da Silva 1997), it seemed to have a Li abundance near solar, but much better data (e.g. Meléndez et al. 2006) showed that its Li abundance is actually three times higher than solar. One solar twin is certainly not an acceptable number for a comparison between the Sun and stars, so a large survey of solar twins was urgently needed. The two largest recent efforts for finding field solar twin stars are being undertaken by the group of Y. Takeda (e.g. Takeda et al. 2007) and by our group (Meléndez et al. 2006; Meléndez & Ramírez 2007; Meléndez et al. 2009a; Ramírez et al. 2009). Importantly, whenever possible, we are obtaining very high S/N for our sample stars, because otherwise only upper limits can be obtained for their Li abundances. Indeed, as shown by Takeda et al. (2007) in their Fig. 12, their data with S/N ~ 150 can only estimate upper limits for stars with $A_{\text{Li}} < 1.5$, i.e., they can only reliably determine Li abundances when they are three times higher than solar.

Our solar twin survey has been performed mainly with the 2.7m telescope at McDonald observatory in the North and with the 6.5m Magellan Clay telescope at Las Campanas observatory in the South. We have also obtained some Keck+HIRES data in the North and VLT+UVES and HARPS data in the South. Our data has been taken at $R = 60,000\text{-}110,000$ and achieving S/N = 200-1000. The first pilot data set taken at Keck resulted in the discovery of the second best solar twin, HD 98618 (Meléndez et al. 2006), about a decade after the discovery of the first solar twin 18 Sco. HD 98618 seems to be a solar twin as good as 18 Sco, and, as this twin, it has also a Li abundance three times higher than solar. Learning from the experience of our pilot Keck observations, we improved our criteria to select the best solar twins, empirically adjusting our T_{eff} scale (Ramírez & Meléndez 2005) for an apparent zero-point problem (Casagrande et al. 2009). This is probably the reason why our first solar twin run at McDonald was very successful. Besides confirming the solar twin nature of 18 Sco and HD 98618, we identified two additional solar twins, HIP 56948 and HIP 73815 (Meléndez & Ramírez 2007), both with a low Li abundance similar to solar. HIP56948 remains to this date the star that most closely resembles the Sun, with a T_{eff} similar to solar within 10 K, as recently confirmed by Takeda & Tajitsu (2009) using Subaru+HDS observations. The year 2007 was very prolific for solar twin studies, besides the twins found by our group, Takeda et al. (2007) reported the discovery of the fifth

solar twin, HIP 110963. Interestingly, this solar twin has a high Li abundance of $A_{\text{Li}} = 1.7$. These five solar twins were starting to fill the Li desert seen in Fig. 2.

The year 2009 has been even better, with many more solar twins found using our McDonald data (Ramirez et al. 2009) and Magellan+MIKE observations (Meléndez et al. 2009a), which together have found more than 30 stars very similar to the Sun. Thus, we are starting to have a large sample of solar twins for meaningful statistics, in particular for addressing the long-standing question on chemical peculiarities in the Sun (Meléndez et al. 2009a; Ramirez et al. 2009; Gustafsson et al. 2009).

In Fig. 3 we show the Li abundance for solar twins and solar analogs that have been analyzed for Li in our survey. Most stars from the Magellan run have already been analyzed, but the McDonald Li analysis is just starting. Open circles show detections and filled circles upper limits. The Sun is also shown for comparison. The first important point to note in this plot is that, unlike the lack of stars with both intermediate and low Li in the Lambert & Reddy (2004) sample, and the lack of stars with intermediate Li abundances in the Pasquini et al. (1994) sample, our sample nicely covers a broad range of Li abundances $0.6 < A_{\text{Li}} < 2.4$, meaning probably that our sample is not affected by any significant selection bias.

In Fig. 4 we show the Li abundances vs. T_{eff} of our solar twin and solar analog sample restricted to stars with mass within $\pm 3\%$ solar and $[\text{Fe}/\text{H}]$ within ± 0.1 dex solar. The Sun does not look peculiar on this plot. One star with relatively high Li abundance stands out. As shown in Fig. 5, where Li is plotted as a function of age, the high Li abundance of this star is due to its young age. This plot has a smaller number of stars than Figs. 3-4 because here, besides the constraint to $\pm 3\%$ in mass and ± 0.1 dex in $[\text{Fe}/\text{H}]$, we show only stars for which we could determine reliable ages (≥ 2.5 sigma). This figure definitely shows that the solar Li abundance is not abnormal, at least not for a solar-metallicity solar-age one-solar-mass star, which at about 4.6 Gyr has already depleted a significant fraction of its original Li abundance.

A comparison of our solar twin results to one-solar-mass stars in solar metallicity (± 0.15 dex) open clusters (selected from the sample of Sestito & Randich 2005, and including the results from Pasquini et al. 2008) is shown in Fig. 6. Again, the agreement is excellent, and reinforces a strong correlation between Li depletion and age for one-solar-mass stars.

Non-standard models (e.g. Montalbán & Schatzman 2000; Charbonnel & Talon 2005; Xiong & Deng 2009; Do Nascimento et al. 2009) can reproduce the observed

data, as shown in Figs. 7 and 8. We are in the process of obtaining better Li abundances and ages for our sample stars, which can potentially constrain the range of initial rotational velocities of our solar twins.

Based on the results shown above, we conclude that the solar Li abundance is not peculiar but a product of depletion due to non-standard mixing which affect both the Sun and the solar twins.

2 Is Li depleted in stars with planets?

Many works have compared stars with planets to field stars instead of stars without detected planets. This has been usually done to have a large comparison sample.

Gonzalez & Laws (2000) compared the Li abundance of stars with planets to the Li abundance of field stars with detectable Li, finding that (as previously believed for the Sun), stars with planets tend to have smaller Li abundances. This apparent peculiarity in the comparison between stars with planets and field stars could be due to a selection bias, as we have shown in the previous section for the case of the Sun. Indeed, the same year, Ryan (2000) showed that stars with planets have Li abundances indistinguishable from field stars, when stars of the same temperature, age and composition were compared.

Israelian et al. (2004) compared also planet hosting and field stars, showing that indeed they have the same Li abundance, except perhaps for stars around solar T_{eff} . It is important to note that this analysis is not fully consistent, as the comparison sample used by Israelian et al. was taken from the literature (Chen et al. 2001), potentially having problems with different temperature scales. Also, as we have shown in the previous section, there are indeed many field stars around solar temperature showing a low Li abundance, thus, stars with planets probably do not have anomalous Li abundances even around the solar T_{eff} .

Takeda & Kawanamoto (2005) also compared stars with planets and field stars, showing that their Li abundances are identical at any temperature except for a small narrow range around $5850 \text{ K} \pm 50 \text{ K}$. This T_{eff} range is so narrow that the difference between stars with planets and field stars could probably vanish when more comparison stars were included. Interestingly, Chen & Zhao (2006) found that the discrepancy could occur at lower temperatures, around $5750 \pm 50 \text{ K}$. Again, the lack of Li-poor solar analogs, could be misleading many authors to believe that stars with planets may be different to field stars around solar T_{eff} , but our sample of solar twins with low Li abundances weakens those claims.

In the largest homogeneous Li study of stars with planets and field stars, Luck & Heiter (2006) concluded that there is no discernible difference between planet hosts and comparison stars.

In Fig. 2 of Gonzalez (2008), planet hosting stars also seem identical to field stars, except in the narrow T_{eff} range of 5850 ± 50 K. No conclusions can be made for stars with $T_{\text{eff}} < 5800$ K because only three planet hosts are available. Note that the Gonzalez (2008) study is not homogeneous, as the Li abundances were obtained from different literature works with probably different T_{eff} scales and different selection criteria. Thus, there could be potential selection biases, as we have shown for the case of the apparent low solar Li abundance. Indeed, we have just finished the analysis of 4 planet hosting stars and 6 stars without detected planets (Meléndez et al. 2009a), both around the above temperature range where Gonzalez (2008) found anomalously low Li abundances in planet hosts. As shown in Fig. 9, our planet hosting stars do not show anomalously low Li abundances with respect to our stars without detected planets.

We conclude that stars with and without planets probably share similar Li abundances, at least to the level of precision of current analyses, although a definitive conclusion is not possible because Li depends on both mass and age (like we have shown for the Sun). It is important that in future studies the comparison between planet hosts and stars without detected planets is performed for stars with similar parameters (mass, metallicity, age), and both samples must be analyzed in a consistent way. Any claim for differences in Li between stars with and without planets must be taken with skepticism unless reliable ages and masses are determined for planet hosts and the comparison sample.

3 The cosmological Li discrepancy

One of the most important discoveries in the study of the chemical composition of stars was made in 1982 by Monique and François Spite, who found an essentially constant Li abundance in warm metal-poor stars (Spite & Spite 1982), a result interpreted as a relic of primordial nucleosynthesis. Due to its cosmological significance, there have been many studies devoted to Li in metal-poor field stars (e.g. Ryan et al. 1999; Meléndez & Ramírez 2004; Boesgaard et al. 2005; Charbonnel & Pritzl 2005; Asplund et al. 2006; Shi et al. 2007; Bonifacio et al. 2007; Hosford et al. 2009; Aoki et al. 2009), with observed Li abundances at the lowest $[\text{Fe}/\text{H}]$ from as low $A_{\text{Li}} = 1.94$ (Bonifacio et al. 2007) to as high as $A_{\text{Li}} = 2.37$ (Meléndez & Ramírez 2004).

Using the theory of big bang nucleosynthesis (BBN) and the baryon density obtained from WMAP data (Dunkley et al. 2009), a primordial Li abundance of $A_{\text{Li}} = 2.72^{+0.05}_{-0.06}$ is predicted (Cyburt et al. 2008, see also e.g. Steigman (2007)), which is a factor of 2-6 times higher than the Li abundance inferred from halo stars. There have been many theoretical studies on non-standard BBN trying to explain the cosmological Li discrepancy by exploring the frontiers of new physics (e.g. Coc et al. 2009; Jedamzik & Pospelov 2009; Kohri & Santoso 2009). Alternatively, the Li problem could be explained by a reduction of the original Li stellar abundance due to internal processes (i.e., by stellar depletion). In particular, stellar models including atomic diffusion and mixing can deplete a significant fraction of the initial Li content (Richard et al. 2005; Piau 2008), although such models depend on largely unconstrained free parameters. Due to the uncertainties in the Li abundances and to the limited samples available, only limited comparisons of models of Li depletion with stars in a broad range of mass and metallicities have been performed.

In order to provide meaningful comparisons with stellar depletion models, precise Li abundances for a large sample of stars are needed. We have recently finished such a study (Meléndez et al. 2009b), achieving errors in Li abundance lower than 0.035 dex, for a large sample of metal-poor stars ($-3.5 < [\text{Fe}/\text{H}] < -1.0$), for the first time with precisely determined masses in a relatively broad mass range ($0.6-0.9 M_{\odot}$).

Our recent work shows that Li is depleted in Spite plateau stars. As can be seen in Fig. 10, the spread of the Spite plateau at any metallicity is much larger than the error bar. Also, there seems to be a correlation with T_{eff} at any probed metallicity. Actually the correlation is better when Li is plotted versus stellar mass (Fig. 11), showing thus that Li has been depleted in Spite plateau stars at any metallicity. In this figure we confront the stellar evolution predictions of Richard et al. (2005) with our inferred stellar masses and Li abundances. The models include the effects of atomic diffusion, radiative acceleration and gravitational settling but moderated by a parametrized turbulent mixing; so far only the predictions for $[\text{Fe}/\text{H}] = -2.3$ are available for different turbulent mixing models. The agreement is very good when adopting a turbulent model of T6.25 (see Richard et al. for the meaning of this notation) and $A_{\text{Li}} = 2.64$. The stellar Li abundances used above were obtained with the latest MARCS models (Gustafsson et al. 2008), but if we use instead the Kurucz convective overshooting models, then the required initial abundance to explain our observational data would correspond to $A_{\text{Li}} = 2.72$.

Our results imply that the Li abundances observed in Li plateau stars have been depleted from their original values and therefore do not represent the primordial Li abundance. It appears that the observed Li abundances in metal-poor stars can be reasonably well reconciled with the predictions from standard Big Bang nucleosynthesis (e.g. Cyburt et al. 2008) by means of more realistic stellar evolution models that include Li depletion through diffusion and turbulent mixing (Richard et al. 2005). We caution however, that, although encouraging, our results should not be viewed as proof of the correctness of the diffusion+turbulence models of Richard et al. models until the free parameters required for the stellar modeling are better understood from basic physical principles. In this context, new physics should not be discarded yet as a solution of the cosmological Li discrepancy, as perhaps the low Li-7 abundances in metal-poor stars might be a signature of supersymmetric particles in the early universe, which could also explain the Li-6 detections claimed for some metal-poor stars (Asplund et al. 2006; Asplund & Meléndez 2008).

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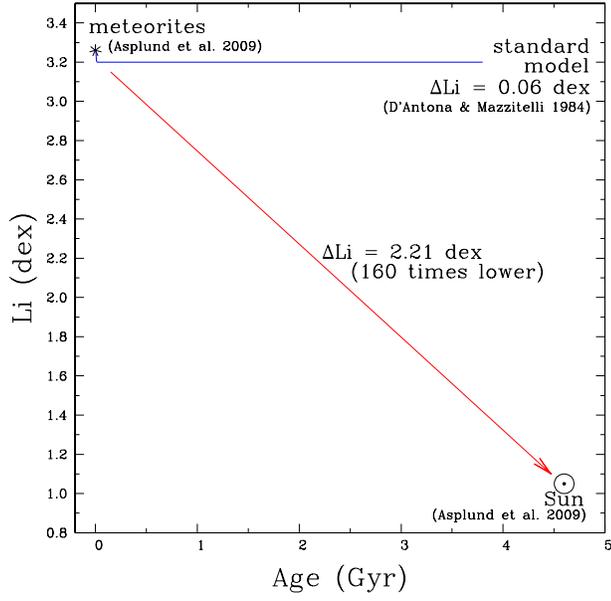


Fig. 1 The standard solar model (e.g. D’Antona & Mazzitelli 1984) can not reproduce the large decrease in Li abundance at the present solar age. The Sun is represented by the \odot symbol

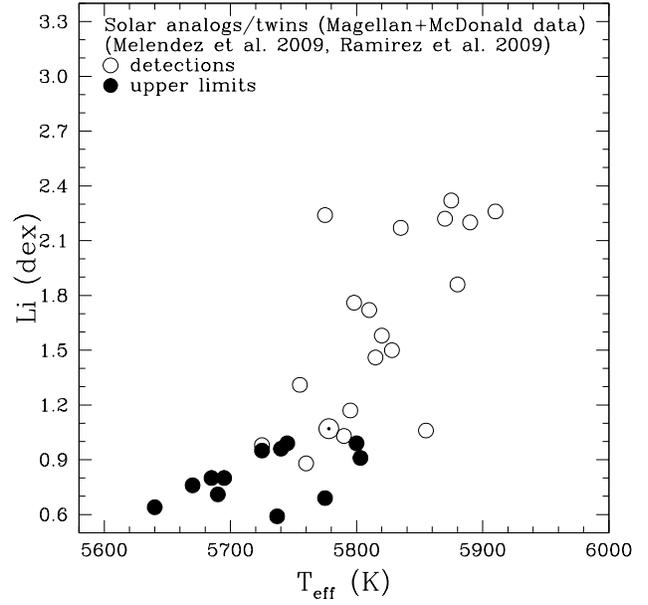


Fig. 3 Magellan and McDonald solar analogs and twins covering a relatively broad range in stellar parameters ($5640 \text{ K} < T_{\text{eff}} < 5920 \text{ K}$), $4.31 < \log g < 4.56$, and $-0.45 < [\text{Fe}/\text{H}] < +0.45$). Open circles are detections and filled circles are upper limits

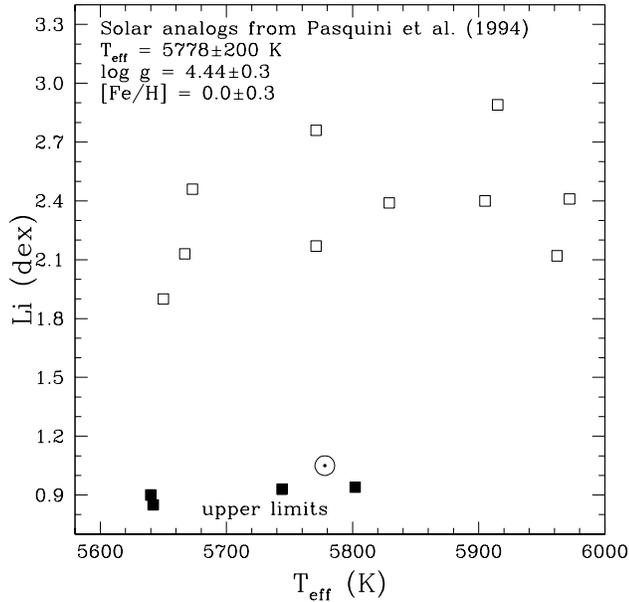


Fig. 2 Li in the solar analog sample of Pasquini et al. (1994) restricted to stars with T_{eff} within 200 K solar, and both $\log g$ and $[\text{Fe}/\text{H}]$ within 0.3 dex solar. Open symbols are detections, filled symbols are upper limits

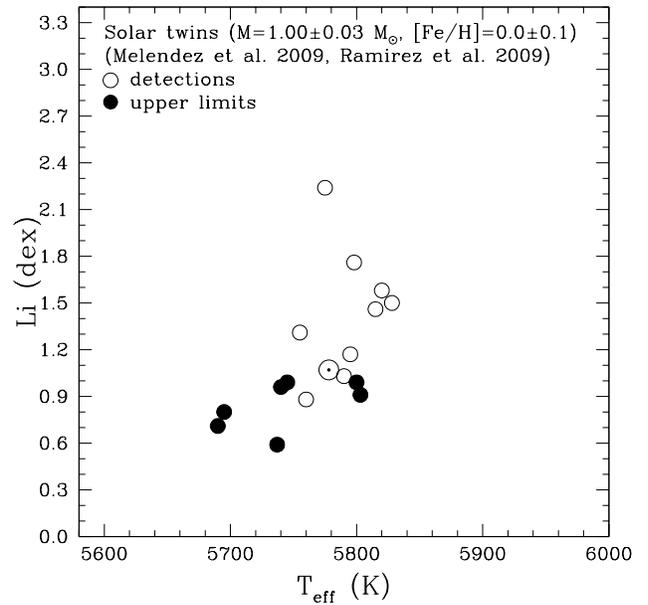


Fig. 4 Magellan and McDonald solar twins with one solar mass ($\pm 3\%$) and solar $[\text{Fe}/\text{H}]$ (± 0.1 dex). Symbols as in Fig. 3

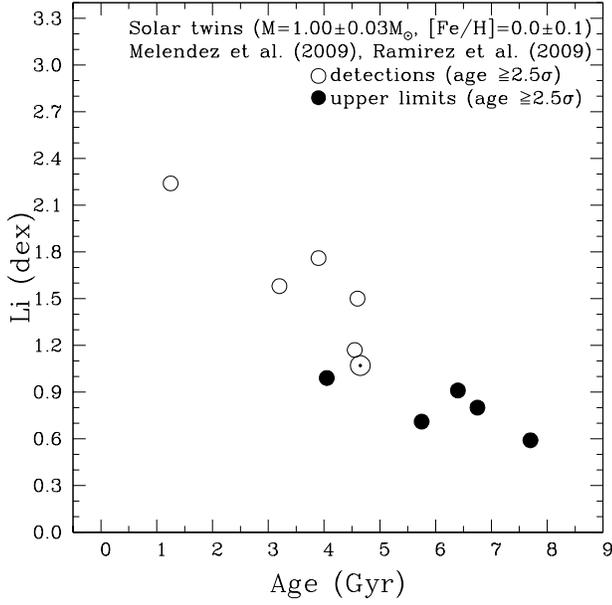


Fig. 5 Li as a function of age for our Magellan and McDonald solar twins with one solar mass ($\pm 3\%$) and solar $[\text{Fe}/\text{H}]$ (± 0.1 dex). Symbols as in Fig. 3. Only stars with reliable ages ($\geq 2.5\sigma$) are shown

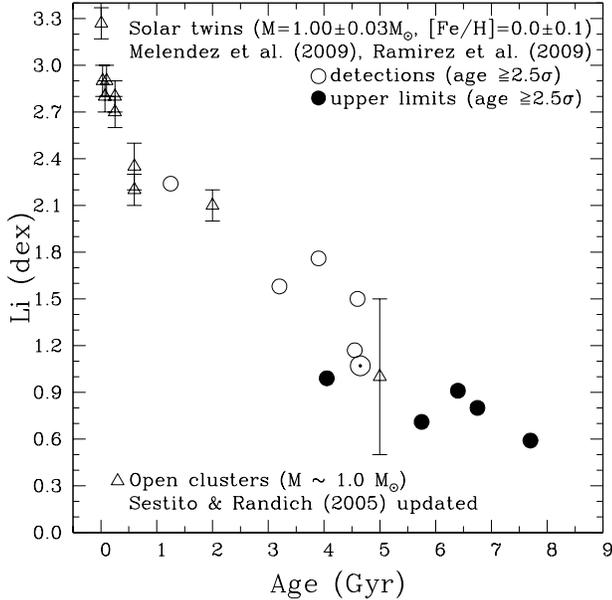


Fig. 6 Li for our solar twins with one solar mass ($\pm 3\%$) and solar $[\text{Fe}/\text{H}]$ (± 0.1 dex), and for one-solar-mass stars in solar metallicity (± 0.15 dex) open clusters selected from Sestito & Randich (2005), although for M67 we used the sample of Pasquini et al. (2008). Field stars are shown as circles while open clusters (NGC 2264, IC2602/IC2391, Pleiades, Blanco 1, NGC6475, M34, Coma Berenices, Hyades, NGC762, M67) with triangles

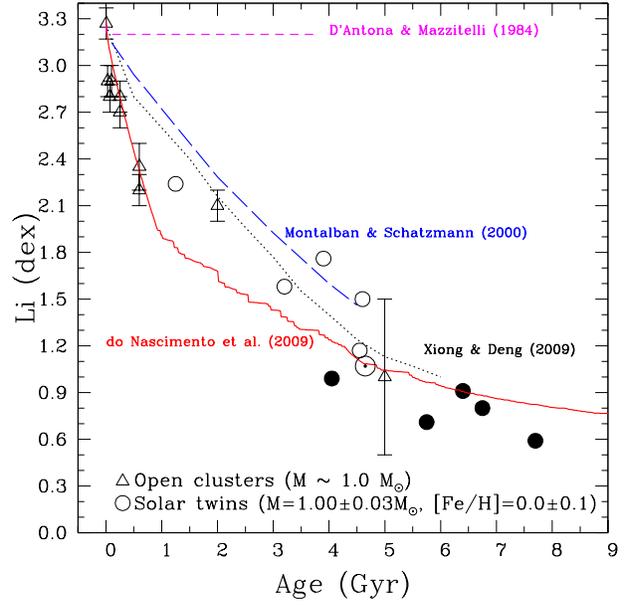


Fig. 7 Comparison of non-standard solar models to field and open cluster stars

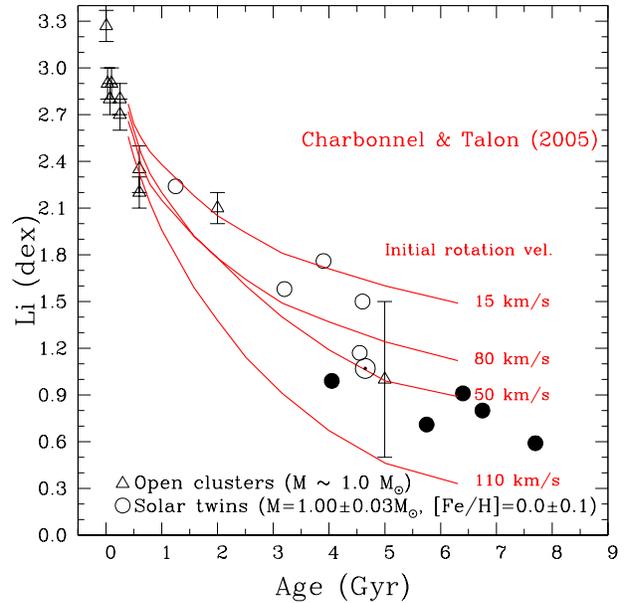


Fig. 8 Non-standard models of Li depletion by Charbonnel & Talon (2005) for different initial rotation velocities

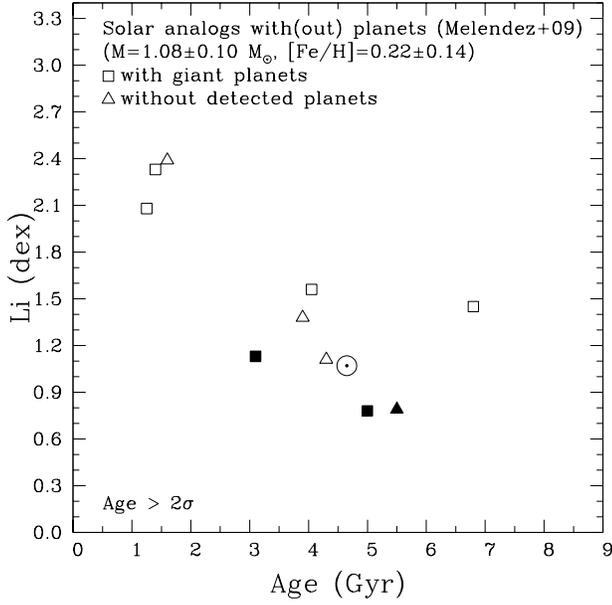


Fig. 9 Li in stars with (squares) and without (triangles) detected planets from the solar analog sample of Meléndez et al. (2009a). Open symbols are detections and filled symbols are upper limits

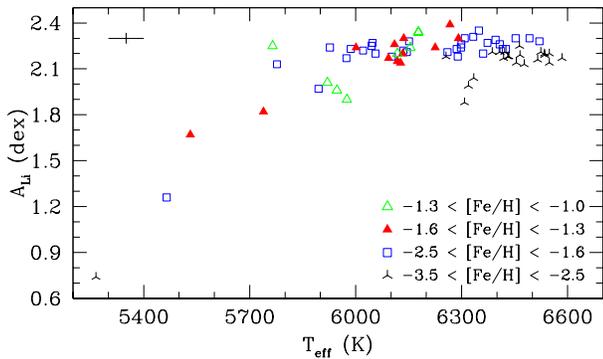


Fig. 10 Li abundances vs. T_{eff} for our sample of metal-poor stars in different metallicity ranges. The spread at any given metallicity is much larger than the error bar. Figure taken from Meléndez et al. (2009b)

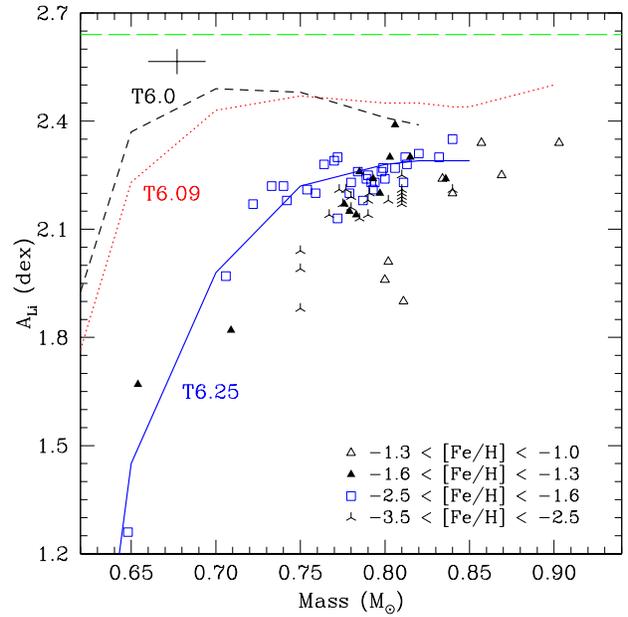


Fig. 11 Li abundances as a function of stellar mass in different metallicity ranges. Models at $[\text{Fe}/\text{H}] = -2.3$ including diffusion and T6.0 (short dashed line), T6.09 (dotted line) and T6.25 (solid line) turbulence (Richard et al. 2005) are shown. The models have been rescaled to an initial $A_{\text{Li}}=2.64$ (long dashed line). Figure taken from Meléndez et al. (2009b)