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Galactic evolution of ^7Li

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Abstract. Lithium represents a key element in cosmology, as it is one of the few nuclei synthesized during the Big Bang. The primordial abundance of ^7Li allows us to impose constraints on the primordial nucleosynthesis and on the baryon density of the universe. However,^7Li is not only produced during the Big Bang but also during galactic evolution: measures of stellar Li in our Galaxy suggest an almost constant Li abundance (the so-called Spite plateau) at low metallicities and a subsequent increase in the disk stars, leading to a Li abundance in Population I stars higher by a factor of ten than in Population II stars. This means that there must exist several possible stellar sources of ^7Li: asymptotic giant branch stars, supernovae, novae, red giant stars. ^7Li is also partly produced in spallation processes while ^6Li is entirely produced by such processes. All of these sources have been included in galactic chemical evolution models and constraints have been derived on the primordial ^7Li and its evolution, as well on stellar models. I will review these models and their results and what we have learned about ^7Li evolution. Some still open problems, such as the disagreement between the primordial ^7Li abundance as derived by WMAP and as measured in Population II stars, and the uncertainties about the main sources of stellar ^7Li will be discussed.

Keywords. Stars: abundances – Galaxy: evolution

1. Introduction

Standard Big Bang nucleosynthesis predicts the abundances of ^2D, ^3He, ^4He and ^7Li and if these abundances are in agreement with the observationally derived primordial abundances, then we can derive the baryon to photon ratio and the baryonic density parameter Ω_b. This was the case until WMAP results became available (Spergel *et al.* 2003), suggesting directly a value for the baryon to photon ratio $\eta_{10} = 6.1^{+0.3}_{-0.2}$. More recently, the last release of WMAP (Hinshaw *et al.* 2009) suggests a revised value of $\eta_{10} = 6.23 \pm 0.17$. This value of η_{10} gives primordial abundances of ^2D, ^3He and ^4He in good agreement with observations except for ^7Li, for which the primordial abundance estimated from WMAP is higher by a factor of 3-4 than the abundance of ^7Li measured in low-metallicity halo stars, always interpreted as the primordial one. If the WMAP value is correct, we therefore should revise our interpretation of the ^7Li abundance in halo stars (Population II stars) and assume that some Li astration has taken place in these stars. In recent years some suggestions were put forward to explain the low Li abundance in metal-poor stars, such as diffusion and turbulence in the presence of weak turbulence (e.g. Richard *et al.* 2005; Melendez *et al.* 2009) and rotational mixing (Pinsonneault, this conference). Alternatively, this discrepancy could be solved by Li destruction during the Big Bang (Jedamzik, this conference). In this review we will focus on the interpretation of the plot $\mathrm{Log}\epsilon(Li)$ versus [Fe/H] in terms of Galactic production of ^7Li. We will review the main sources of ^7Li: stars, cosmic rays, and Big Bang. Then we will describe how to model the Galactic evolution of ^7Li by taking into account in detail all the various

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^7Li sources. The most important results from 1990 up to now will be described, and the constraints derived from the comparison theory-observations as well as the still existing uncertainties will be summarized. Finally, we will discuss the ^7Li discrepancy originated by the difference between the primordial Li abundance derived from WMAP and the measured one.

2. ^7Li production in stars

There is only one way to produce ^7Li during normal stellar evolution and it is by means of the nuclear reaction $^3He(\alpha,\gamma)^7Be$. The fresh ^7Be should be then transported by convection into stellar regions of lower temperature, where it decays into ^7Li by k-capture. This mechanism was originally proposed by Cameron & Fowler (1971). However, ^7Li is also destroyed during stellar evolution, and in general it is assumed that all the original Li present in the star is destroyed in the course of the evolution. From the observational point of view, K giants and M supergiants are Li-rich (Smith & Lambert 1989, 1990) indicating that ^7Li is produced by asymptotic giant branch stars (AGBs) (see Gratton 1991, for an exhaustive review on the subject). Theoretical models of AGB stars (Sackmann & Boothroyd 1999) have suggested that stars in the mass range (4-6)$M_{\odot}$ can produce noticeable quantities of ^7Li (Log$\epsilon(Li) \sim 4-4.5$, with Log$\epsilon(Li)$ being the number density of Li in the unit system Log(X/H) +12, where 12 is the hydrogen). This result was later confirmed by Travaglio *et al.* (2001). On the other hand, Ventura *et al.* (1998) found a negligible ^7Li production from AGB stars, so the situation is still unclear. Classical novae could also in principle be ^7Li producers, although so far only one detection of ^7Li in novae has been reported (Della Valle *et al.* 2002). From the theoretical point of view, Starrfield *et al.* (1978) had suggested novae as possible ^7Li producers and that the amount of freshly produced Li would depend crucially on the amount of ^3He present in the matter accreted onto the white dwarf. Later on, José & Hernanz (1978) recomputed the ^7Li yields from novae and confirmed that these objects can be Li producers but their predicted Li was not as high as in Starffield *et al.* (1978). In particular, José & Hernanz (1998) suggested an average mass of Li produced in a nova outburst $< M_{Li} >= (1.8-7.5)\cdot 10^{-7}M_{\odot}$, and considering that each nova has $\sim 10^4$ outbursts during its life, this leads to an average total mass of Li produced by a nova $< M_{Li} >= (1.8-7.5)\cdot 10^{-3}M_{\odot}$. Another possible stellar ^7Li source are supernovae (SN) II: neutrino-induced nucleosynthesis can produce ^7Li (Woosley *et al.* 1990). In particular, SNe II can produce ^7Li in the He-shell by excitation of He by μ and τ neutrinos, produced during the formation of the neutron star in the pre-explosion phase, followed by de-excitation with emission of a proton or a neutron which in turn reacts with He and forms ^7Li. Woosley & Weaver (1995) computed detailed ^7Li yields from SNe II as functions of the initial stellar metallicity. Unfortunately, no detection of ^7Li in SNe has been reported so far. Finally, low-mass giants could in principle produce ^7Li since in some of them it has been measured a high Li abundance. The production of ^7Li in this case should occur during the upper part of the red giant branch (RGB), between the first episode of dredge-up and the tip of the RGB, coupled with mass loss (see de la Reza *et al.* 2000). Unfortunately, only a very small fraction of these stars ($< 5\%$) show overabundances of ^7Li in their atmospheres (Log $\epsilon(Li) \sim 4$).

3. ^7Li production in the Big Bang and cosmic rays

During the Big Bang a tiny fraction of ^7Li was produced, whereas ^6Li has been entirely produced by cosmic rays (Reeves 1994). The isotope ^6Li has been detected in halo stars

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(Asplund *et al.* 2006), thus suggesting that also some of the original ^7Li in the same stars originates from Galactic cosmic rays (GCRs). Calculations of the amount of ^7Li produced by GCRs can be found in Lemoine *et al.* (1988).

4. Galactic chemical evolution of ^7Li

The abundance of ^7Li measured in the stellar atmospheres of stars which have not yet depleted their original Li should provide, in principle, the history of the Galactic evolution of this element. In fact, the measured ^7Li abundance in very metal-poor halo stars is lower by a factor of ten than the ^7Li abundance measured in young stars, such as the Pleiades. This means that ^7Li has been produced by stars and cosmic rays during Galactic evolution. In Figure 1 we show the famous plot Log $\epsilon(Li)$ vs. [Fe/H], where the ^7Li evolution is given by the upper envelope of the data. The large spread in the disk stars is clearly due to the fact that Li is depleted in different ways in different stars. On the other hand, the halo stars ([Fe/H] <-1.0) show a quite remarkable plateau and a small spread. Such a plateau was discovered first by Spite & Spite (1982) and confirmed later on by other authors with some exceptions (Thornburn 1994; Ryan *et al.* 1999) and the primordial ^7Li value was fixed (Log $\epsilon(Li) = 2.1 - 2.3$, e.g. Bonifacio *et al.* 2002). More recently, the newest data (28 halo dwarfs observed with UVES at the VLT) seem to indicate that the plateau does not exist any more for $[\mathrm{Fe/H}] < -3.0$ (Sbordone *et al.* 2009, this conference). So the "Spite-plateau" does not exist any more and we should understand how Li has been depleted at an almost constant level in all stars with $-3.0 < [Fe/H] < -1.0$, and then how the depletion increases for $[\mathrm{Fe/H}] > -3.0$. Anyway, the diagram of Figure 1 is the one that was adopted by all the chemical evolution modelists up to now and we will start this review by describing the history of the interpretation of this important diagram. In particular, chemical evolution models should aim at fitting the upper envelope of the diagram of Figure 1. Detailed chemical evolution models follow the evolution in time of the gas abundances in the Galaxy by taking into account the star formation history, the stellar yields and possible gas flows (infall/outflows) (see Matteucci 2001).

4.1. *The interpretation of the Log* $\epsilon(Li)$ *vs. [Fe/H]*

In principle, two possible interpretations can be suggested for the diagram of Figure 1: i) the ^7Li abundance of the plateau is the primordial Li value, whereas the Li abundance of young stars is the effect of Li production by stars and GCRs during Galactic evolution, ii) the primordial ^7Li abundance is the one measured in young stars, whereas that of the plateau is the consequence of Li depletion in stars. This second hypothesis, however, would require a non-standard Big Bang nucleosynthesis. Mathews *et al.* (1990) explored these two possibilities by means of a detailed chemical evolution model for the Milky Way and concluded that, on the basis of only chemical evolution models, it is difficult to distinguish which hypothesis works better. In Figure 2 we show the model predictions for the two cases: in case i) they started from the primordial abundance of the Spite plateau and assumed carbon stars (low-mass giants) and SNe II as possible ^7Li producers and explored different star formation rates. They found that the observed data could be reproduced by assuming ad hoc yields for both stellar sources, since at that time detailed Li yields were missing. In case ii) Mathews *et al.* (1990) started with a high ^7Li primordial abundance and then assumed a gradual exponential main-sequence destruction of this element. Also in this case the agreement with data is good. In the following years, case ii) was abandoned since it requires a non-standard Big Bang nucleosynthesis not supported by the primordial abundances of the other light elements, and since now on we will refer

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only to case i). D'Antona & Matteucci (1991) produced a chemical evolution model for the Milky Way, well reproducing the majority of observational constraints, and computing the Galactic evolution of the ^7Li abundance by considering Li production from novae and AGBs. The results are shown in Figure 3 where one can notice how the inclusion of novae as Li producers, reproduces very well the steep rise off the spite-plateau for [Fe/H] > -1.0. This is due to the fact that novae are long-living systems (white dwarfs in binary systems) and contribute to Galactic chemical enrichment with time delays as long as 1-5 Gyr. These authors computed the nova formation rate by assuming that it is a fraction of the rate of formation of the white dwarfs. Then they assumed that each nova has 10^4 bursts during its life and adopted the yields for Li as suggested by Starrfield *et al.* (1978). Under these assumptions the evolution of the ^7Li abundance could be well reproduced just by assuming novae and AGBs as Li producers. In particular, each nova was assumed to produce from 10^{-8} to $10^{-5} M_{\odot}$ per outburst, thus contributing to more than 50% of the total Li production.

In Figure 4 we show the results of a more recent model from Romano *et al.* (2001), who took into account novae, SNeII, low-mass giants, AGBs, and cosmic rays as ^7Li producers. Here, low-mass giants ($M = 1 - 2.5 M_{\odot}$) are assumed to produce a fair fraction of the total ^7Li: in fact, it is assumed that each star produces $Log\epsilon(Li) = 4.0$, whereas the AGB stars are producing a negligible amount of Li, as suggested by Ventura *et al.* (1998). Novae produce a non negligible amount of Li, as suggested by José & Hernanz (1998). The Li yields from SNe II are from Woosley & Weaver (1995) and the ^7Li from GCRs is taken from Lemoine *et al.* (1998). It should be noted that the yields of Woosley & Weaver (1995) have been halved in order not to overproduce boron, in agreement with results from Duncan *et al.* (1997.) In Figure 4 the contributions from the different sources are separated. Again, we should note that assuming ^7Li sources with only short lifetimes (SNeII and AGBs) does not reproduce the steep rise off the Spite plateau which is instead obtained by long-living Li producers, such as novae and low-mass stars. In Figure 4 we

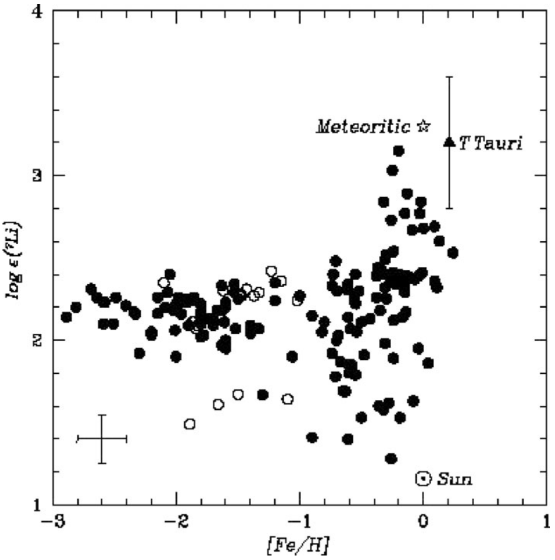

Figure 1. $Log\epsilon(Li)$ versus [Fe/H] for stars in the solar vicinity. The plateau value of $Log\epsilon(Li) \sim 2.2$ for [Fe/H] < -1.0 is interpreted as the primordial value, whereas the highest Li abundance relative to young stars and meteorites is $Log\epsilon(Li) = 3.3$. The value of the Li abundance in the Sun is indicated.

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show also the predictions considering all sources together but the GCRs. The conclusions of Romano *et al.* (2001) were that most of Li in the solar system was produced by low-mass stars ($\sim 41\%$), that novae contribute by $\sim 18\%$, SNeII by $\sim 9\%$, AGB stars by only $\sim 0.5\%$ and finally that GCRs contribute for roughly 25%. The same conclusions were not shared by Travaglio *et al.* (2001,) who concluded that the major contributors to ^7Li in the Galaxy are AGB stars with minor contributions from low-mass stars, novae and SNe II. The different approach of Romano *et al.* (2001) and Travaglio *et al.* (2001) about ^7Li production from AGB stars was due to different assumptions about the mass loss in these stars made by these authors. However, not considering long-living Li producers as important, the Travaglio *et al.* model cannot reproduce the steep rise of the Spite plateau. In the following years, the advent of WMAP changed the situation depicted up to now. In particular, the primordial value suggested was Log $\epsilon(Li) = 2.6$ (Spergel *et al.* 2003), higher by a factor of ~ 2 than the value of the Spite plateau, thus implying that

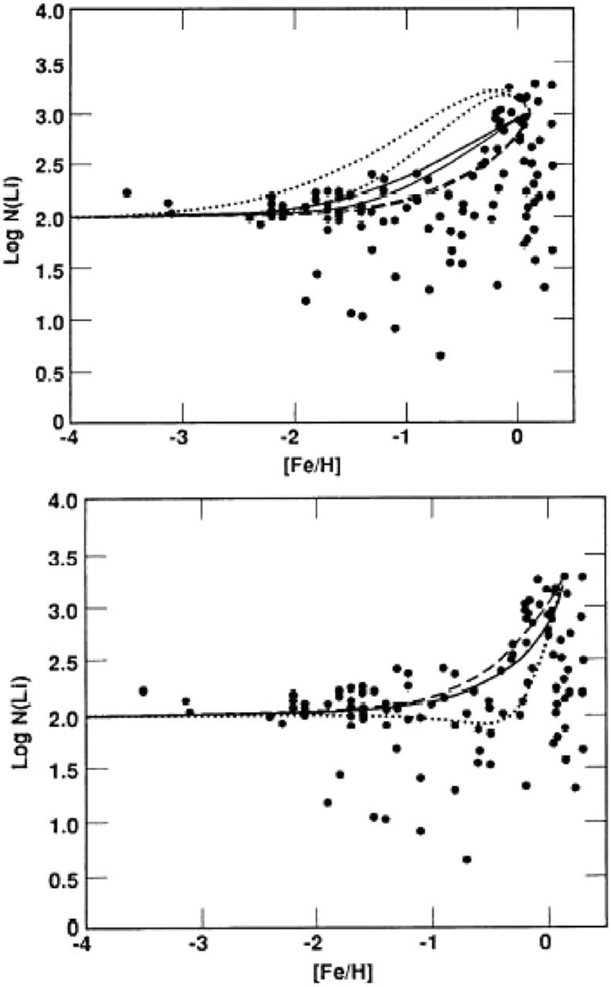

Figure 2. Log N(Li)(the equivalent of Log $\epsilon(Li)$) versus [Fe/H] for stars in the solar vicinity compared with chemical evolution models. Data are from Rebolo *et al.* (1988). In the upper panel are shown model results for case i) and different star formation histories, in the lower panel are shown model results for case ii) and the same star formation rates as for case i). Figure from Mathews *et al.* (1990).

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the Li abundance in metal-poor stars is not the primordial one. This can be explained if the primordial Li is depleted in these stars, and some papers suggested that this is possible by means of gravitational settling and also that the amount of depletion is the same in all metal-poor stars, thus explaining the plateau (Richard *et al.* 2005). This was confirmed by observations of globular clusters where this depletion was measured (Korn *et al.* 2006). Unfortunately, more recently new data have appeared (Sbordone *et al.* 2009, this conference) and the situation has became even more complicated since the data have shown that the Spite plateau exists only down to [Fe/H] = –3.0, for lower metallicities a decreasing trend is evident. This finding implies that the Li depletion in very metal-poor stars must be a function of metallicity. In Figure 5 we show a more recent model (Romano *et al.* in preparation) where cosmic rays, novae, SNe II, super- AGBs (7-11$M_{\odot}$) but not low-mass stars are considered as Li producers. The prescriptions for Li production in GCRs, SNeII and novae are like in Romano *et al.* (2001, 2003) but the Li produced by super-AGBs is a function of stellar metallicity, and increases with metallicity. The yields for Li from super-AGBs are taken from D'Antona (this conference). As one can see, the steep rise off the Spite plateau is well reproduced even without low-mass stars because of novae and AGBs becoming important Li producers only for [Fe/H]> -1.0.

5. Conclusions

We have traced the history of the computation of the evolution of the abundance of ^7Li in our Galaxy. We started from the diagram tracing the evolution of the Li abundance as a function of [F/H] measured in stars of the solar neighbourhood, and interpreted the lower Li abundance in Pop II stars as the primordial Li abundance and that of Pop I stars as the effect of Li production during the galactic lifetime. Several models in the past eleven years have attempted to fit the upper envelope of the Logϵ(Li) vs. [Fe/H], and although the uncertainties still existing in the ^7Li yields from stars are preventing us from drawing firm conclusions, we have understood the following:

- one or more delayed stellar Li sources are necessary to reproduce the steep rise off the Spite plateau,
- possible candidates are classical novae and low-mass stars although these latter are unlikely since only a small fraction shows an overabundance of ^7Li in the atmosphere.

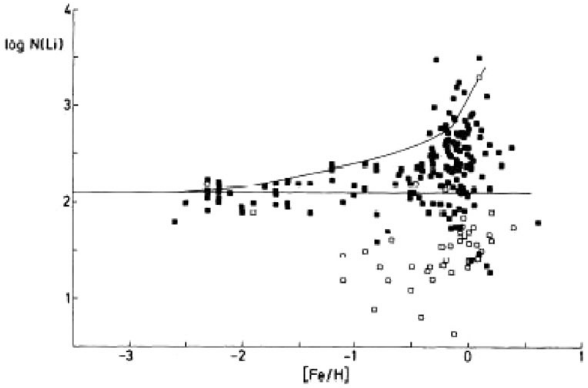

Figure 3. Log N(Li) versus [Fe/H] for stars in the solar vicinity compared with the chemical evolution model of D'Antona & Matteucci (1991) in the framework of case i). The assumed Li producers are novae and ABG stars.

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- On the other hand, super-AGB stars (7-11$M_\odot$,) producing more and more ^7Li with increasing stellar metallicity, can be very promising candidates.
- The primordial Li abundance derived from WMAP is higher than the Li abundance of the Spite plateau, thus suggesting that the primordial Li abundance has been depleted in Pop II stars. Several mechanisms to explain such a depletion have been suggested but there is still a potential problem related to the possible detection of ^6Li in Pop II stars (Asplund *et al.* 2006), which should have been more heavily depleted than ^7Li.

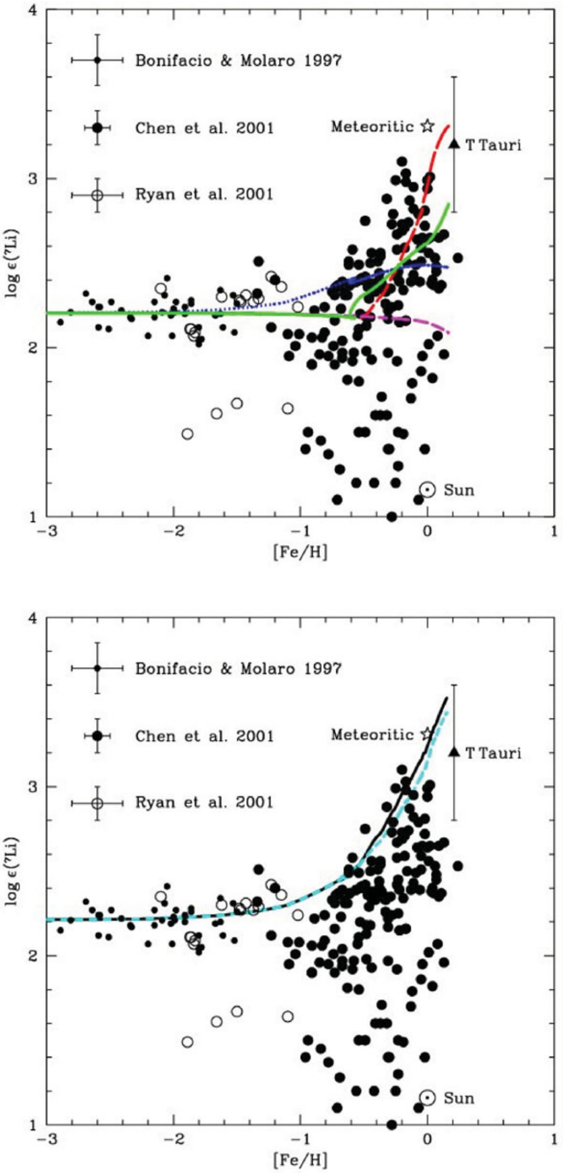

Figure 4. $Log\epsilon(Li)$ versus [Fe/H] for stars in the solar vicinity compared with the chemical evolution model of Romano *et al.* (2001) in the framework of case i). The assumed Li producers are novae, SNeII, low-mass stars, AGB stars and cosmic rays. The data sources are indicated in the figure.

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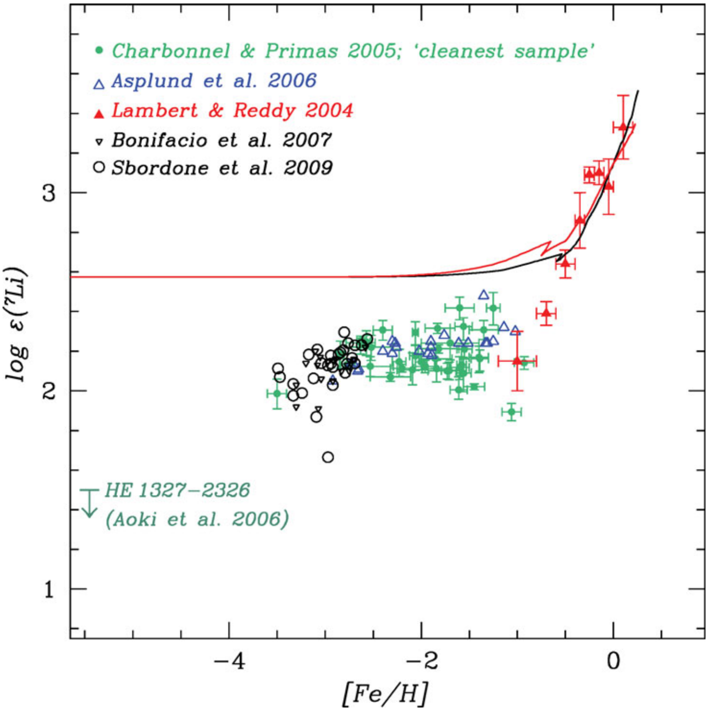

Figure 5. $Log\epsilon(Li)$ versus [Fe/H] for stars in the solar vicinity compared with the chemical evolution model of Romano *et al.* (in preparation) (upper line) and with the Romano *et al.* (2001) (lower line), in the framework of case i). The assumed Li producers are novae, SNeII, AGB stars, and cosmic rays, as described in the text. Note that the theoretical curve starts with the primordial Li value from WMAP which lies well above the Li abundances of halo stars. The data sources are indicated in the figure.

- The Li abundance characterizing the Spite plateau seems to be constant only for $-3.0 < [Fe/H] < -1.0$, then for very low metallicity the Li abundance seems to decrease. This suggests the existence of a depletion mechanism which is a function of metallicity.

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