Mem. S.A.It. Vol. 91, 128

Memorie della

Lithium and the chemical evolution of the Milky Way

F. Matteucci[1,2,3], V. Grisoni[1,2], and D. Romano[4]

[1] Dipartimento di Fisica, Sezione di Astronomia, Università di Trieste, via G.B. Tiepolo 11, I-34131, Trieste, Italy, e-mail: matteucci@oats.inaf.it
[2] INAF Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34131, Trieste, Italy
[3] INFN Sezione di Trieste, via Valerio 2, 34134 Trieste, Italy
[4] INAF Osservatorio di Astrofisica e Scienza dello Spazio, Via Gobetti 93/3, I-40129 Bologna, Italy

Abstract. The evolution of the abundance of ^{7}Li is one of the most challenging facts in the study of the chemical evolution of the Milky Way. Lithium seems to be produced by stars and cosmic rays but is also very easily destroyed inside stars. We are presenting an historical summary of the chemical evolution models which have attempted to reproduce the upper envelope of the plot 12 +log(Li/H) vs. [Fe/H]. The various possible stellar Li producers are discussed: they include asymptotic giant branch stars, red giant stars, core-collapse supernovae and nova systems. We conclude that novae can be important Li producers and that they are the most likely Li source able to reproduce the steep increase of Li abundance for [Fe/H]> -1.0 dex. Recent Li(Be) detections in novae are mentioned. The "Li cosmological problem" is also discussed, namely the fact that the primordial measure of ^{7}Li, as suggested by WMAP and Planck, is a factor of three higher that the plateau value shown by halo stars (the so-called Spite plateau), which had always been interpreted as the primordial Li value.

Key words. nuclear reactions, nucleosynthesis, abundances - novae, cataclysmic variables - Galaxy: abundances - Galaxy: evolution - galaxies: ISM.

1. Introduction

In this section I will briefly review the history of modeling the evolution of ^{7}Li abundance in the Milky Way. The story began with the paper of Rebolo et al. (1988) who presented, for the first time, a plot of the abundance of Li versus metallicity ([Fe/H]) for stars in the solar neighbourhood. Such a plot was showing a plateau of the Li abundance for halo stars ([Fe/H]< -1.0 dex) the so-called *the Spite plateau* (Spite & Spite 1982), followed by a steep increase of Li abundance up to the meteoritic value at solar metallicity. The plot was also showing a large spread especially for stars with [Fe/H]> -1.0 dex, with the Sun showing a very low Li abundance. The interpretations of all these facts was that in the halo stars the Li abundance is the primordial one, whereas the Li abundance of the upper envelope of the data represents the Li abundance of the interstellar medium (ISM), which has increased up to the meteoritic and young star values during the lifetime of the Galaxy, due to Li stellar production. The spread at higher metallicity is due to the fact that in evolved stars the Li is destroyed by nuclear processes and therefore we should compare the results of chemical evolution models, predicting the evolution of the abundances in the ISM, only with the upper envelope values of the plot. The fact that halo stars show very little spread in the Li abundance was interpreted as due to the less efficient convection in metal poor stars, leading to no Li depletion in their atmospheres, so that their measured Li abundance represents the primordial one. An alternative interpretation, as discussed by Mathews et al. (1990), was that the primordial Li value is the meteoritic value and the Li in halo stars has been depleted by stellar evolution. However, this second interpretation would require a non-standard Big Bang. The most reasonable interpretation of the plot is the first one, and all the models appeared afterwards were aimed at explain it in that way. D'Antona & Matteucci (1991) analysed the possible Li stellar producers and in particular, asymptotic giant branch (AGB) stars, red giants and novae. There is practically only one channel to produce Li in stars. In particular, there should be a site where the reaction $^3He(\alpha,\gamma)^7Be$ can occur, but ^7Be should be rapidly transported by convection in regions of lower temperatures where it decays into ^{7}Li, and this is known as the *Cameron & Fowler (1971) mechanism*. D'Antona & Matteucci (1991) concluded that only novae, exploding with long time delays (being binary systems of low mass stars), could reproduce the steep rise of the Li abundance at [Fe/H] > -1.0 dex (see Figure 1) whereas AGB stars could not and red giants give a negligible contribution.

The Li production from novae was uncertain at that time, although it had been suggested by Starrfield et al. (1978). Later on, evidence against Li production in novae grew (see Boffin et al. 1994), and Matteucci et al. (1995) introduced core-collapse supernovae (SNe) as possible Li producers by means of the neutrino-process (Woosley et al. 1990), and considered also AGB stars and C-stars, but not novae. The neutrino -process occurs in the shell above the collapsing core in a pre-supernova. The high flux of neutrinos evaporates neutrons and protons from heavy nuclei with the result of producing Li. The fit to the Li plot was acceptable but not as good as the fit of D'Antona & Matteucci (1991), obtained by introducing novae as Li producers. In the following years, Romano et al. (1999) studied again the Li evolution by considering AGB, Type II SNe, novae

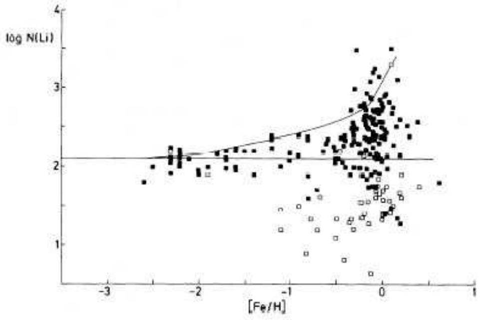

Fig. 1. Log ϵ(Li) versus [Fe/H] (Log ϵ(Li)= 12+log(Li/H)) for stars in the solar vicinity. The plateau value of Logϵ(Li)$\sim$ 2.2 for [Fe/H] < -1.0 dex is interpreted as the primordial value, whereas the highest Li abundance relative to young stars and meteorites is Log ϵ(Li)=3.3. Figure from D'Antona & Matteucci (1991).

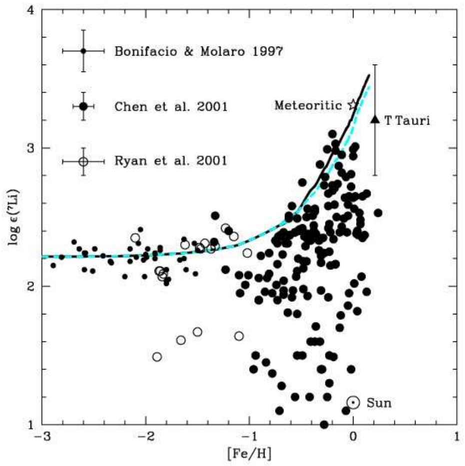

Fig. 2. Log ϵ(Li) vs. [Fe/H]. Models and figure from Romano et al. (2001) (see text). Reference to the data in Romano et al. (2001). The Li in T Tauri stars is reported. The blue dashed line represents the model with all the Li sources except the cosmic rays, whereas the black continuous line contains all the sources.

and cosmic rays as Li producers and concluded that novae and cosmic rays are the most important Li producers. The paper of Romano et al. (2001) decided the fall of AGB stars as important Li producers, since they adopted detailed Li yields from Ventura et al. (1998) which are much smaller than believed before that time. The results of Romano et al. (2001) are shown in Figure 2. On the other hand, Travaglio et al. (2001) had assumed AGB stars as the major Li producers, by assuming a very high mass loss before the evolution off the AGB phase, but again, without novae, their fit to the increasing Li abundance in disk stars was too flat. Later on, Matteucci (2010) studied the problem of the discrepancy between the measured primordial Li by WMAP and Planck and the value of Li measured in the Spite plateau. The Spite plateau value in fact is logϵ(Li) ~ 2.2 dex, whereas the value derived from the CMB is logϵ(Li)=2.66-2.73 (see Planck results, Coc et al. 2014). The most simple explanation for this discrepancy is that Li has been depleted in halo stars by the same amount in all stars. Diffusion and turbulent mixing have been suggested to deplete Li (Korn et al. 2006). However, that was not the end of the story since data taken at [Fe/H]< -3.0 dex seems to show a decrease of Li abundance. In Figure 3 are shown the models of Matteucci (2010) starting from a primordial Li abundance of 2.6.

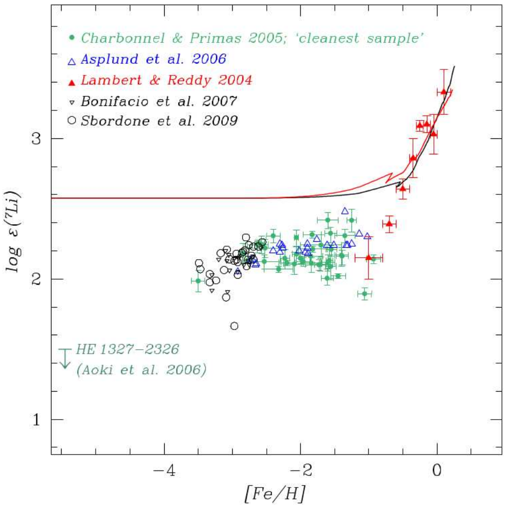

Fig. 3. Log ϵ(Li) versus [Fe/H] for stars in the solar vicinity. The model predictions are the same as in Romano et al.'s (2001) best model. The primordial Li abundance here is assumed to be 2.6, in agreement with the results of WMAP and Planck. Figure from Matteucci (2010).

In this paper, I will first describe how to build chemical evolution models of the Milky Way and then discuss the most recent results on Li evolution both from a theoretical and observational point of view. Then, some conclusions will be drawn.

2. Chemical evolution models

Chemical evolution models for the Milky Way can be: one-infall or multi-infall In the one-infall model the formation of halo, thick and thin disk is seen as a continuous sequence where the different structures form sequentially as a consequence of a unique episode of gas infall (Matteucci & François, 1989). In the two-infall model (Chiappini et al. 1997) there are two main episodes of gas accretion. During the first one, the halo and the bulge form and also the thick disk, while during the other episode the thin disk forms. The infall timescales are quite different (1-2 Gyr for halo-thick and 7-8 Gyr for thin disk) The two-infall model can be applied also to the thick and thin disk, but they can evolve also as two independent one-infall models (Grisoni et al. 2017). The main ingredients of the models are:

i) initial conditions (closed or open model, primordial or enriched composition of the gas);
ii) the stellar birthrate (the product of the star formation rate (SFR) and the initial mass function (IMF));
iii) the stellar yields;
iv) possible gas flows (inflow, outflow).

We aim at computing the evolution of the gas and its chemical composition in time. In particular, here we focus on the evolution of the abundance of ^{7}Li and compare it with the upper envelope of the cloud of data in the plane logϵ(Li) vs. [Fe/H]. The most common parametrization for the SFR is the Schmidt-Kennicut law assuming that the SFR is proportional to the surface gas density (a power law with index k=1.4-1.5). For the IMF we assume the one derived for the solar neighbourhood by Kroupa et al. (1993). The possible Li stellar producers are: AGB stars, red giants, novae, supernovae II and cosmic rays. Concerning Fe, this element is formed mainly in Type Ia SNe (white dwarfs in binary systems) and partly by core-collapse SNe.

The question is whether there are observational evidences for stellar ^{7}Li production. Some AGBs and red giants are Li-rich but concerning novae the first and only detection is by Izzo et al. (2015). They claimed the detection of an absorption feature in nova V1369Cen at 6695.6 A, identified as a blue shifted Li λ6708 A. They derived a mass of Li produced by a single nova outburst of $M_{li} = 0.3 - 4.8 \cdot 10^{-10} M_{\odot}$. This is a large amount of Li, since a nova suffers roughly 10^4 outbursts during its lifetime, if compared with theoretical nova yields from Jose & Hernanz (1998, this conference). However, detection of ^{7}Be seems more common and ^{7}Be decades into Li (Tajitsu et al. 2015;2016, Molaro et al. 2016, Izzo et al. 2018).

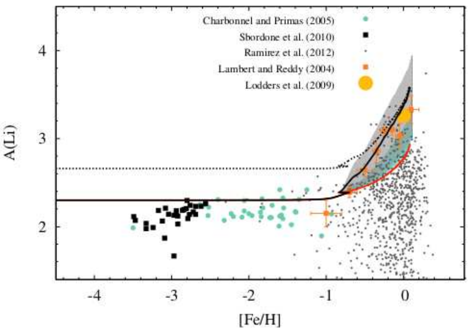

Fig. 4. A(Li) vs. [Fe/H] (A(Li)=12+ log (Li/H)) for the solar neighbourhood stars and meteorites, compared to the predictions of chemical evolution models (lines and coloured areas. Figure from Izzo et al. (2015).

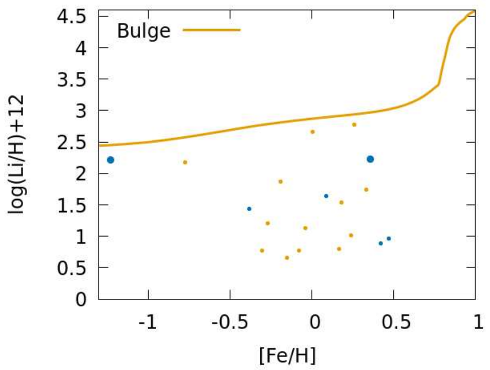

Fig. 5. Evolution of the abundance of Li in the bulge. The bulge model (see text) is that of Matteucci et al. (2019). The data are from Gonzalez et al. (2009) ans Bensby et al. (2011).

3. Results

In the paper by Izzo et al. (2015) we assumed a value of ^{7}Li produced per nova outburst of $2.55 \cdot 10^{-10} M_{\odot}$, well inside the range suggested by the Li detection. A present time nova rate in the Galaxy of $\sim$ 17 events yr^{-1} and a primordial Li abundance either of 2.3 or 2.6 dex were adopted. We considered also AGBs and super-AGBs (Karakas, 2010, Doherty et al. 2014) as well as cosmic rays (Lemoine et al.1998). We did not consider red giants nor Type II SNe as Li producers. The predicted Li evolution is shown in Figure 4.

In Grisoni et al. (2019) the Li evolution was revised by studying the different Galactic components: bulge, thick and thin disks. In Figure 5 it is shown the prediction for the Li abundance in the Galactic bulge. The model adopted for the bulge is the same as in Matteucci et al. (2019), which assumes a high star formation rate and short timescale of gas accretion, so that the majority of bulge stars are formed before 1 Gyr. The stellar Li prescriptions include novae, supernovae (neutrino-process), AGBs and cosmic rays. The yield of Li per nova is the same as in Izzo et al. (2015). As one can see from Fig.5, the steep rise of Li due to nova contribution here occurs at very high metallicity, in agreement with the time-delay model (Matteucci 2012) which predicts a shift of the [X/Fe] ratios at higher metallicities if the SFR is higher than in the solar vicinity. Finally in Figure 6, we show the predictions of Grisoni et al's (2019) models for the thin disk. They assumed that the two disks evolve in parallel with

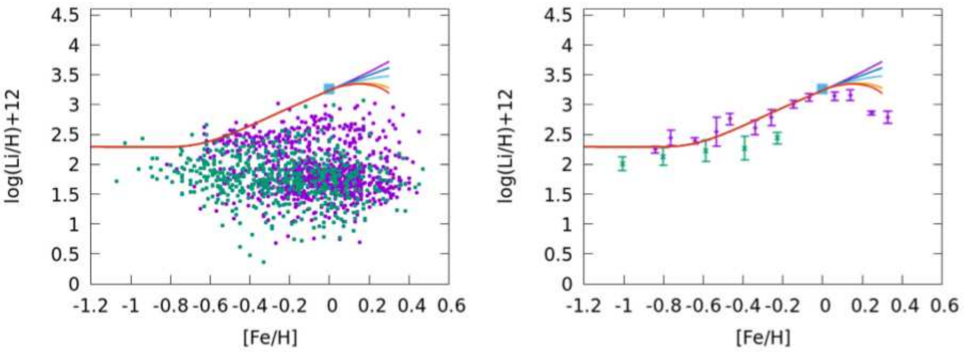

Fig. 6. Li evolution in the thick and thin disk.The models are from Grisoni et al. (2019) and refer only to the thin disk. The data are Gaia-ESO (the thin disk in purple and the thick disk in green) in the left panel, whereas in the right panel we show AMBRE data for thin (purple) and thick (green) disks. The bending of Li in the thin disk at high metallicity is reproduced by the models assuming a decreasing fraction of nova systems at high metallicity (all the colors except purple which indicates the model with constant fraction of nova systems). Figure from Grisoni et al. (2019) where the references to the data can be found.

the thick disk evolving faster (see Grisoni's contribution). Moreover, they tried to explain the apparent decrease of the Li abundance at high metallicities in the thin disk. If real, this decrease could be due to a fraction of nova systems decreasing with metallicity. Other explanation for such a decrease are stellar migration from the inner disk regions (Guiglion et al. 2019) or Li yields depending on metallicity (Prantzos et al. 2017). Finally, Cescutti & Molaro (2019) also computed Li evolution in the thick and thin disk, assuming novae, AGBs and cosmic rays as Li producers.

4. Conclusions

In this paper we have reviewed the Li evolution results from chemical models of the Milky Way. Here is our summary:

- The primordial value of ^{7}Li deduced from WMAP and Planck studies of the CMB is higher by a factor of $\sim$3 than the roughly constant value observed in metal poor stars ($-3.0 \leq [Fe/H] \leq -1.0$) in the so-called Spite plateau. The most reasonable explanation is that Li has been depleted in metal poor stars. Diffusion and turbulent mixing have been suggested to explain this depletion (Korn et a. 2006).
- The stars with [Fe/H]> -1.0 dex show an increase of the Li abundance from 2.2 to 3.3 (meteoritic value), and a very large spread in the Li abundance, due to the Li destruction in nuclear reactions. Therefore, models of chemical evolution aim at reproducing the upper envelope of the diagram 12+log(Li/H) vs. [Fe/H], under the assumption that the highest Li values measured in stars are representative of the ISM out of which the stars formed.
- The increase of Li abundance is interpreted as caused by stellar production. However, the stellar origin of ^{7}Li is still uncertain and several sources are candidates: i) AGBs, red giants, SNe II and novae. Also cosmic rays should produce ^{7}Li.
- Novae seems to be the most important Li producers, especially to reproduce the steep rise of Li evolution for [Fe/H]> -1.0 dex. Theoretical predictions of Li yields are uncertain but several detections of ^{7}Be in nova ejecta seem to support this hypothesis (only one ^{7}Li detection in nova ejecta exists).
- Several solution have been proposed for the decrease of Li abundance at high metallicity in thin disk stars among which stellar migration, Li stellar yields depending on metallicity and a decreasing fraction of

nova systems with metallicity, but this issue is still unsettled.

Acknowledgements. V.G. and F.M. acknowledge financial support from the University of Trieste (project FRA2016).

References

Bensby, T., Adén, D., Melendez, J., et al. 2011, A&A, 533, 134
Cameron, A.G.W., Fowler, W.A. 1971, ApJ, 164, 111
Cescutti, G. & Molaro, P. 2019, MNRAS, 482,4372
Chiappini, C., Matteucci, F., Gratton, R. 1997, ApJ, 477, 765
Coc, A., Uzan, J.-P., & Vangioni, E. 2014, J. Cosmol. Astropart. Phys., 2014, 050
D'Antona, F. & Matteucci, F. 1991, A&A, 248, 62
Doherty, C.L., Gil-Pons, P., Herbert, H.B., et al. 2014, MNRAS, 441, 582
Gonzalez, O.A., Zoccali, M., Monaco, L., et al. 2009, A&A, 508, 289
Grisoni, V., Spitoni, E., Matteucci, F., et al. 2017, MNRAS, 472, 3637
Grisoni, V., Matteucci, F., Romano, D., Fu, X. 2019, MNRAS, 489, 3539
Guiglion, G., Chiappini, C., Romano, D., Matteucci, F., et al. 2019, A&A, 623, 99
Izzo, L., Della Valle, M., Mason, E., Matteucci, F., et al. 2015, ApJ, 808, L14
Izzo, L., Molaro, P., Bonifacio, P., et al. 2018, MNRAS, 478, 1601
José, J. & Hernanz, M. 1998, ApJ, 494, 680
Karakas, A., 2010, MNRAS, 403, 1413
Korn, A.J., Grundhal, F., Richard, O., et al. 2006, Nature, 442, 657
Kroupa, P., Tout, C.A., Gilmore, G. 1993, MNRAS, 262, 545
Lemoine, M., Vangioni-Flam, E., Cassé, M. 1998, ApJ, 499, 735
Matteucci, F. 2010, in Light Elements in the Universe, C. Charbonnes et al. eds. (Cambridge University Press, Cambridge), IAU Symposium, 268, 453
Matteucci, F. 2012, Chemical Evolution of Galaxies, Astronomy and Astrophysics Library (Springer, Heidelberg)
Matteucci, F., D'Antona, Timmes, F.X. 1995, A&A, 303, 460
Matteucci, F. & François, P. 1989, MNRAS, 239, 855
Matteucci, F., Grisoni, V., Spitoni, E., et al. 2019, MNRAS, 487, 5363
Molaro, P., et al. 2016, MNRAS, 463, L117
Prantzos, N., et al. 2017, A&A, 606, 132
Rebolo, R., Beckman, J.E., Molaro, P. 1988, A&A, 192, 192
Romano, D., et al. 1999, A&A, 352, 117
Romano, D., Matteucci, F., Ventura, P., D'Antona, F., 2001, A&A, 646, 655
Spite, F., Spite, M. 1982, A&A, 115, 357
Starrfield, S., et al. 1978, ApJ, 222, 600
Tajitsu, A., et al. 2015, Nature, 518, 381
Tajitsu, A., et al. 2016, ApJ, 818, 191
Travaglio, C., Randich, S., Galli, D., et al. 2001, ApJ, 559, 909
Ventura, P., et al. 1998, A&A, 363, 605
Woosley, S.E., et al. 1990, ApJ, 356, 272