Lithium and binarity

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Abstract. We present an analysis of the lithium abundances in late spectral type binaries of different ages. They belong to several open clusters (Pleiades, Hyades and M67), as well as to Chromospherically Active Binary Systems (CABS).

All these binaries have reliable ages, since they are members of well-known open clusters or, in the case of the CABS, some stellar parameters such masses and radii are accurate enough to derive ages using theoretical isochrones. Their age span covers from barely one hundred million years to several gigayears.

We have compared different stellar properties, such as lithium abundances, stellar masses, effective temperatures and orbital periods. It is shown that, in general, close binaries have lithium abundances larger than those characteristic of single stars or binaries with larger orbital periods. The largest difference between the abundances of binaries and single stars appears at Hyades’ age. The origin of those overabundances are discussed in the context of the proposed mechanisms for the lithium depletion phenomenon and the stellar evolution.

1. The problem

Lithium depletion depends on different parameters (mass, age, metallicity and rotation). The internal structure is very important in this phenomenon, but all theoretical models predict temperatures at the bottom of the convective envelope too low to destroy lithium. Therefore, some extra–mixing mechanism, beside pure convection, is needed (see Figure 1). Nowadays there are a large amount of observational data (see the review by Balachandran 1994). There are at least 2 different mechanisms, related to rotation, which could be responsible of the lithium depletion in late spectral–type stars. One is related with the way angular momentum evolves and the mixing associated to it (rotational breaking), and in other the key factor is the magnetic field and its influence over the gravitational waves.

Studies of lithium abundance in binaries can provide interesting information about this phenomenon. First, binaries have different rotational story than single stars (either during the first moments of the evolution in the Premain

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Figure 1. Temperature against the fraction of the radii for a 1.05 solar mass star at different ages, corresponding to Pleiades, Hyades and M67. The vertical lines locate the position of the bottom of the convective zone, whereas the bold horizontal line points out where the lithium is started to be destroyed. We also indicate the distance between the bottom of the convective envelope and the location where the lithium destruction starts.
Figure 2. Lithium abundances against effective temperatures. 

a.- Hyades (solid symbols) and Pleiades (open symbols) data. TLBS are superposed as triangles. 

b.- Comparison between Hyades main–sequence binaries (circles) and M67 binaries (triangles). Solid symbols represent synchronized binaries, whereas open ones show other binaries. The solid, dashed and dotted lines represent the behavior of main–sequence M67, evolved M67 and main–sequence Hyades single stars, respectively.

Sequence –PMS– or afterwards, if they are Tidally Locked Binary Systems – TLBS). Second, masses and radii (for eclipsing binaries) are well known, allowing a direct contrast between theory and observations. In the case of eclipsing binaries, isochrones can be fitted and ages estimated. Third, in the case of members of open clusters, we know the age of all members, and it is possible to perform direct comparisons between single and binary stars of the same mass (looking for systematic differences) and comparisons with different theories can be also carried out. In this particular context, binaries can help us to understand the role of rotation in the lithium depletion. In the rotational braking scenario, Tidally Locked Binary Systems would inhibit the lithium depletion due to the transfer of angular momentum between the orbit and the rotation, mechanism which would be able to prevent the mixing of material between the convective envelope and the radiative core, where lithium is destroyed (Pinsonneault et al. 1989, 1990; Zahn 1994). In the case of a mixing mechanism dominated by the presence of magnetic fields and gravitational waves, lithium could be conserved because of the inhibition of the transport of material due to gravitational waves (García–López & Spruit 1991), inhibition which would appear because of the presence of strong magnetic fields (Schatzman 1993; Montalbán 1994; Montalbán & Schatzman 1996), due themselves to the rapid rotation characteristic of TLBS.
We present here a comprehensive study of the lithium abundances of main sequence binaries belonging to several open clusters (Pleiades, Hyades and M67), having ages ranged from 120 million years to 5 gigayears, as well dwarf components of Chromospherically Active Binary Systems.

2. Lithium, Temperature and Stellar Mass

The lithium abundances, effective temperatures and other stellar parameters analyzed here have been collected from several previous studies. In particular, the core of the samples were selected from Soderblom et al. (1990) –Pleiades–, Barrado y Navascués & Stauffer (1996) –Hyades–, Barrado y Navascués et al. (1997a) –CABS– and Barrado y Navascués et al. (1997b) –M67. We have searched through the published literature to complete these samples (Hobbs & Pilachowski 1996; Spite et al. 1987; Butler et al. 1987; Pilachowski & Hobbs 1987; García–López et al. 1988; Boesgaard et al. 1988; Soderblom et al. 1993; García–López et al. 1994; Balachandran 1995).

Essentially, lithium abundances were estimated by measuring equivalent widths, removing the blends with other lines, correcting the effect of the companion and using curves of growth to compute the final value. (See Barrado y Navascués & Stauffer 1996 or Barrado y Navascués et al. 1997a for details.

Figure 2a shows Li against $T_{\text{eff}}$ for members of Pleiades (empty symbols) and Hyades (solid symbols). Triangles represent TLBS. Note that all Hyades stars are binaries in the figure (the behavior of single stars is shown by a solid–dashed line), whereas open circles are single and wide binaries from Pleiades simultaneously. It is clear that Hyades TLBS have lithium excesses above the average
value of other Hyades single and binary stars. This does not happen in Pleiades (note that there a few data available in this case). Therefore, it seems that the inhibition of the lithium depletion takes places after an age of $\sim 100$ Myr.

Figure 2b represents M67 data together the Hyades. Solid and empty symbols are TLBS and other binaries, respectively. Hyades are shown as circles. Main sequence and evolved M67 binaries appear as squares and triangles, respectively. The long dashed line is the average lithium abundance of single Hyades stars. The solid and short dashed lines correspond to the average abundance of single MS and giant M67 members, respectively. Although some M67 TLBS have lithium excesses, it is easy to notice that several main sequence M67 TLBS have undergone an important depletion, contrary to what happens in the Hyades.

The comparison between Hyades and M67 main sequence G binaries shows that their rates of lithium depletion are different, in the sense that the average abundance of Hyades TLBS is 0.6 dex higher than the average abundance of other binaries or respect single stars belonging to the same cluster, whereas main sequence G binaries of M67 have an average abundance only 0.22 dex higher than that corresponding to the single main sequence G stars. The difference between the abundances of binaries of Hyades and M67 is, on average, 0.65 dex, whereas the value is 0.37 in the case of the single stars. These facts seem to indicate that essentially the process which produced the overabundances, at least in the case of main–sequence stars in the range $6500 > T_{\text{eff}} > 5500$ K, took place before having the Hyades’ age. (It could last a little bit longer.) Moreover, since the difference between the average abundances of binaries and single stars are larger in Hyades than in M67, it might be that not only the inhibition in the lithium depletion was stopped at an intermediate age, but that effect of binarity has been reversed. That is, the depletion could be faster in binaries than in single stars during the lapse of time passed since M67 had Hyades’ age to the present. Note that in this whole discussion, we have assumed that the properties of M67 members where analogous to the Hyades stars. In particular, that the lithium abundance distribution was similar when M67 was 600–800 Myr old.

Additional information about how lithium is depleted in old MS binaries can be obtained by studying Chromospherically Active Binary Systems. In order to facilitate the interpretation of the data, we substituted $T_{\text{eff}}$ by the stellar mass in Figure 3a. Hyades TLBS are shown as open squares, CABS with similar age (see Barrado et al. 1994 for the estimation of ages) to Hyades’ appear as solid squares, whereas other CABS are shown as solid circles (all of them, when the age is known, are older). CABS have a large spread in the abundance for a mass close to 0.8 $M_{\odot}$. Several CABS have also larger abundances than similar Hyades stars, although the former group is older. Figure 3b is as Figure 3a, but in this case M67 binaries are shown instead Hyades members (see key in the figure). Despite the fact that CABS have large uncertainties in their abundances and in the other stellar parameters (except, in the case of eclipsing binaries, for masses and radii), this plot adds new evidences to the connection between lithium depletion and binarity. Similar results have been found in evolved CABS by Pallavicini et al. (1992, 1993) and Randich et al. (1994).
Figure 4. Lithium excesses against orbital periods. Main-sequence Hyades binaries are shown as solid circles. Main Sequence and evolved M67 binaries appear as open squares and triangles. The vertical lines differentiate the systems which have synchronization between the orbital and the rotational periods for both clusters.
Figure 5. Li abundances against orbital periods for CABS.
3. Orbital Period and Lithium abundance

Barrado y Navascués & Stauffer (1995) obtained that all TLBS in the Hyades have clear lithium excesses and that these are related with the orbital period, as shown in Figure 4. An analogous result has been obtained by Barrado y Navascués et al. (1997b) for M67. Figure 4 shows the differences of lithium abundance between the estimated value for binaries and the computed average of stars at the same color against the orbital period. Hyades binaries are represented with solid circles, M67 dwarfs appear as empty squares and evolved M67 binaries are plotted as empty triangles. Note that the cut-off of the orbital periods for Hyades in order to have synchronization between the orbit and the rotation is smaller than in the case of M67, due to the age difference. In the case of M67, not all TLBS have overabundances. The situation is similar for CABS (Figure 5). In this case, we have shown the lithium abundances against the orbital periods for the subsample of dwarf components of CABS having masses in the interval 0.75–0.95 M\(_\odot\) (these stars have similar age). There is a clear trend, although, as happens in the case of M67, short orbital period TLBS can have low abundances.

Together with the interpretation provided in the previous section, it would be also possible to speculate that synchronization is not enough for old low mass stars. On the other hand, if the story of the rotation is the most important factor (that is, the way the angular momentum has been transported from the orbit to the rotation), it would be possible to find systems with synchronization and low abundances. It would be due to the fact that initial rotational periods would be very important in that case. Stellar rotation can change dramatically during the first stages of the synchronization, with sudden increases and decreases, depending on the particular combination of orbital and rotational periods, and stellar masses. Therefore, a very enhanced mixed of material can take place during some of these first moments, leading to rapid lithium depletion. After synchronization, the lithium depletion would be inhibited. Although the rotational braking mechanism seems to fit better the observations, the presence gravitational waves as a way to mix material cannot be ruled out yet. A detailed calculation could provide some quantitative arguments in order to select the proper mechanism.

4. Conclusions

There is a clear connection between the way lithium is depleted and binarity. We have shown that some binaries have larger abundances than similar single stars. Therefore, rotation is an essential parameter in the lithium depletion phenomenon. The mechanism scenario and the role of binarity are not clear.

The comparison of the lithium abundances of binaries in several open clusters shows that the lithium excesses are maximum at Hyades’ age. Binaries at the Pleiades’s age have lithium abundances compatible with single stars.

In the case of main sequence F–K binaries at Hyades’ age, lithium depletion is inhibited always if P\(_{\text{orb}}\) ≤ 8 days (if the system arrives synchronized at the MS).
Older TLBS exhibits, but not always, lithium excesses. Their nature of these excesses is not clear, and they could be a remain of those excesses developed during the first hundred years in the MS.

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References

Balachandran, S. 1995, ApJ, 446, 203
Barrado, D., Fernández-Figueroa, M. J., Montesinos, B., De Castro, E., Cornide, M. 1994, A&A, 290, 137
Barrado y Navascués, D., Stauffer, J.R. 1996, A&A, 310, 879
Barrado y Navascués, D., Fernández–Figueroa, M.J., García–López, R.J., de Castro, E., Cornide, M. 1997a, A&A, in press
Barrado y Navascués, D., Stauffer, J.R., Hartmann, L., Balachandran, S. 1997b, Mem.S.A.It, in preparation
Boesgaard, A.M., and Budge, K.G., Ramsay M.E. 1988, ApJ, 327, 389
Butler, R.P., Marcy, G.W., Cohen, R.D., Duncan, D.K. 1987, ApJ, 319, L19
García–López, R.J, Rebolo, R., Beckman, J.E. 1988, PASP, 100, 1489
García–López, R.J., Spruit, H.C. 1991, A&A, 377, 268
García López, R. J., Rebolo, R., Martín, E. L. 1994, A&A, 282, 518
Hobbs, L.M., Pilachowski, C. 1986, ApJ, 311, L37
Montalban, J. 1994, private comm.
Montalban, J., Schatzman, E. 1996, A&A, 205, 513
Pallavicini, R., Randich, S., and Giampapa, M. S. 1992, A&A, 253, 185
Pallavicini, R., Cutispoto, G., Randich, S., Gratton, R. 1993, A&A, 267, 145
Pilachowski, C., and Hobbs, L.M. 1987, PASP, 99, 1208
Pinsonneault, M. H., Kawaler, S. D., Sofia, S., Demarque, P. 1989, ApJ, 338, 424
Pinsonneault, M. H., Kawaler, S. D., Demarque, P. 1990, ApJS, 74, 501
Randich. S., Gratton, R., Pallavicini, R. 1993, A&A, 273, 194
Schatzman, E. 1993, A&A, 271, L29
Soderblom, D.R., Oey, M.S., Johnson, D.R.H., Stone, R.P.S. 1990, AJ, 99, 595
Soderblom, D.R., Jones, B.F., Balachandran, S., Stauffer, J.R., Duncan, D.K., Fedele, S.B., Hudon, J.D. 1993, AJ, 106, 1059
Spite, F., Spite, M., Peterson, R.C., Chafee, F.H.Jr. 1987, A&A, 171, L8
Zahn, J.-P. 1994, A&A, 288, 829