Mem. S.A.It. Suppl. Vol. 22, 97

Memorie della
Supplementi

Lithium in M67

From the Main Sequence to the Red Giant Branch

G. Pace[1], M. Castro[2], J. Meléndez[3], S. Théado[4], and J.D. do Nascimento Jr[2]

[1] Centro de Astrofísica da Universidade do Porto, Porto, Portugal
[2] Departamento de Física Teórica e Experimental, UFRN, Natal, Brazil
[3] Departamento de Astronomia, IAG/USP, São Paulo, Brazil
[4] Institut de Recherches en Astrophysique et Planétologie, Université de Toulouse, Toulouse, France

Abstract. Lithium abundances in open clusters have been widely used as probe of mixing processes in the sun. The open cluster M67 is especially interesting in that its age and metallicity make it a perfect tool to help understand the large depletion of lithium in the sun. Although M67 has been studied several times, a homogeneous global analysis of lithium in stars from subsolar up to the most massive members, was never accomplished for a large sample based on high-quality spectra. We collected literature data to follow, for the first time in a homogeneous way, NLTE lithium abundances of all observed single stars in M67 more massive than about 0.9 solar masses, and we then used these data to test our non-standard models. Our grid of evolutionary models were computed with rotational mixing at metallicity [Fe/H]=0.01 dex, using the Toulouse-Geneva evolution code.

Key words. open clusters, stars

1. Introduction

Being single stellar populations, open clusters are ideal laboratories to test the models of mixing in stars, as they allow us to check how lithium depletion depends on mass, for fixed age and initial chemical composition. As a matter of fact, observations in open clusters provided the information necessary to achieve several important conclusions on lithium depletion, for instance that, at odds with predictions of standard models, little depletion occurs during the Pre Main Sequence, while most of the lithium is destroyed during the Main-Sequence life time of stars. This led theoreticians to include in their models mixing processes other than convection, usually referred to as non-standard mixing models.

Observations in open clusters are especially useful to assess whether stars with the same age, mass and chemical composition, deplete the same amount of lithium, or there is some other parameter at work. One of the candidate extra-parameter is the evolution of angular momentum, which is in turn determined by the life time of the circumstellar disk during the early phases of the star. Long-lived circumstellar disks brake the rotation of the stellar envelope, provoking a core-envelope decoupling, which is thought to favor lithium depletion. Stars that had short-lived circumstellar disks, on the contrary, do not undergo the core-envelope decoupling

After initial claims of scatter of lithium abundances in several open clusters have been revised, M67 remained one of the few open clusters, and the best studied, for which considerable dispersion of lithium abundances is found for stars at the same mass. M67 also has special interest for its age and metallicity, that makes it very similar to the Sun. However, a homogeneous lithium abundance analysis of its stars, from the low Main Sequence to the Red Giant Branch was never accomplished before.

This is the rationale for our work, in which we homogenize all previous studies on M67 stars by obtaining a consistent set of temperatures, and by applying corrections to the lithium abundances when needed (due to revised effective temperatures) and taking into account non-LTE effects on the lithium abundances. We analyze stars from the main sequence to the red giant branch, comparing our models to the observed behavior of lithium abundance as a function of mass.

2. Sample and data

Our database is a compilation of literature sources of lithium abundance measurements in M67, based on high resolution spectra (Canto Martins et al. 2011; Castro et al. 2011; Pasquini et al. 2008; Randich et al. 2007; Jones et al. 1999; Balachandran 1995). The final sample contains 103 stars. Information on photometry and membership was taken, whenever possible, i.e. for 95 out of 103 stars, from Yadav et al. (2008), otherwise from the same source as lithium abundance. Radial velocities were available for 93 stars of the final sample. We discarded stars with radial velocities significantly different from the cluster mean value and all known binaries.

Temperatures were recomputed using both isochrone fitting and photometric calibration. As for the former method, we used models and parameter estimation in Castro et al. (2011), we built an isochrone with M67 age and metallicity, we shifted it according to M67 distance modulus and color excess, and we took on the isochrone the point closest to the position of a given star in the CMD. Then, for such star, we adopted the temperature corresponding to this isochrone point. As for the latter temperature evaluation, we used the calibration of Casagrande et al. (2010) for dwarfs and that of Kučinskas et al. (2005) for giants. We then corrected lithium abundance measurements according to each temperature evaluation following the grid of NLTE corrections computed by Lind et al. (2009).

3. The models

Stellar evolutionary models were computed using the TGEC code (Hui-Bon-Hoa 2008). They include atomic diffusion and rotation-induced mixing as described in Théado & Vauclair (2003a). This prescription is an extension of the approach of Zahn (1992) and Maeder & Zahn (1998). The abundance variations in the following chemical species were computed individually: H, He, Li, Be, C, N, O, Ne and Mg. We calibrated a model of one solar mass to match the observed solar effective temperature and luminosity at the solar age.

4. Results

M67 stars close to the turn-off, with masses $M = 1.1 - 1.28\ \mathrm{M}_{\odot}$, have a peak or a plateau in lithium abundances. Less massive stars ($M < 1.1\ \mathrm{M}_{\odot}$) show strong lithium depletion, which increases for lower masses due to a deepening of their convection zones. Evolved subgiant and giant stars with $M > 1.28\ \mathrm{M}_{\odot}$ also show lower Li abundances. The above pattern is qualitatively well-reproduced by our models, as well as by the independent models of Xiong & Deng (2009).

The lithium abundance appears to be a tight function of the mass, for stars more massive than the sun, with a few notable exceptions that deserve a closer look. In particular, based on 3 over-depleted stars, we suggest that, at about $1.15\ \mathrm{M}_{\odot}$, the presence of a small companion may trigger a strong extra mixing, or perhaps the initial rotation velocity was higher in these stars. More observations are needed

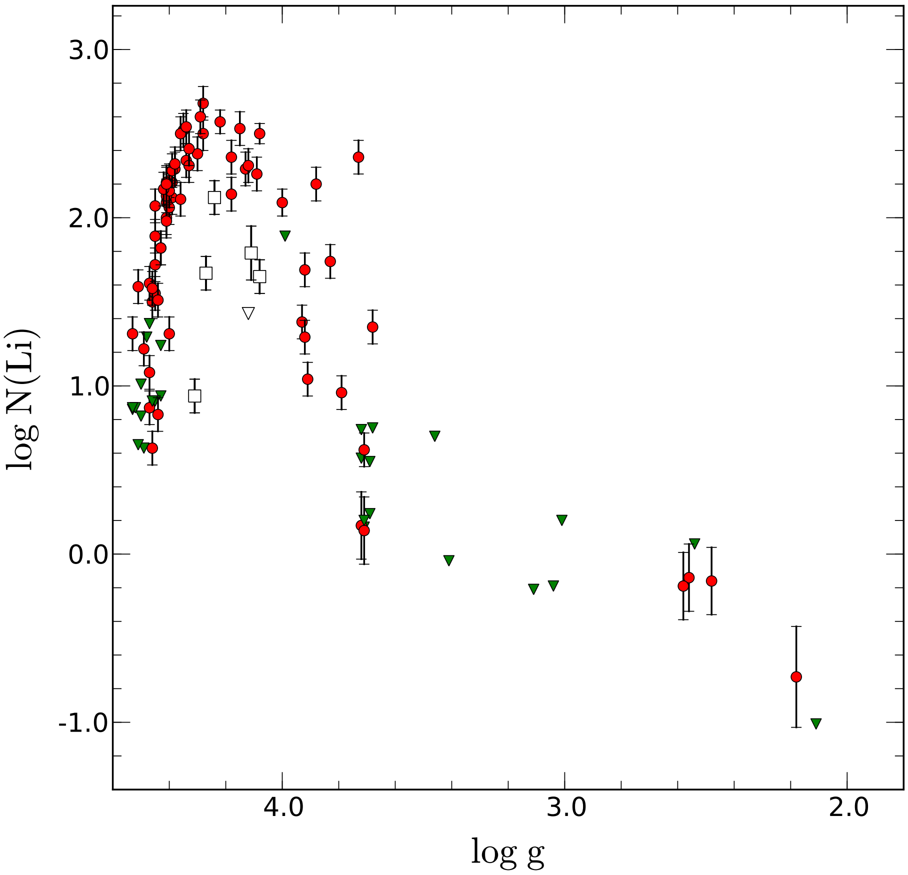

Fig. 1. Lithium abundances as a function of gravity. Downward triangles represent upper limits. Open symbols represent stars whose lithium abundances do not follow the overall trend as a function of mass. Stars with A(Li) 4.1 dex are the ones with the highest lithium abundances.

before drawing firm conclusions on these outliers.

For stars not more massive than the sun, on the contrary, we note a considerable scatter in lithium abundances at any given mass.

4.1. The lithium rich field stars

Recently, Baumann et al. (2010) found some relatively old stars (about 4 Gyr and older) with lithium abundances unusually high for their ages (A(Li) $\sim$ 2.5). It is not yet clear whether the enhanced lithium content in these stars is due to the absence of depletion or to some lithium production. Such production, however, is not predicted by any of the non-standard models available in the literature.

In Fig. 1, we show lithium abundances as a function of $\log g$ for our M67 sample, triangles are upper limits to lithium abundance. Gravities were computed with the help of the isochrone and the CMD of M67, in the very same way we did for the temperatures. Again, the isochrone and the parameters for M67 are

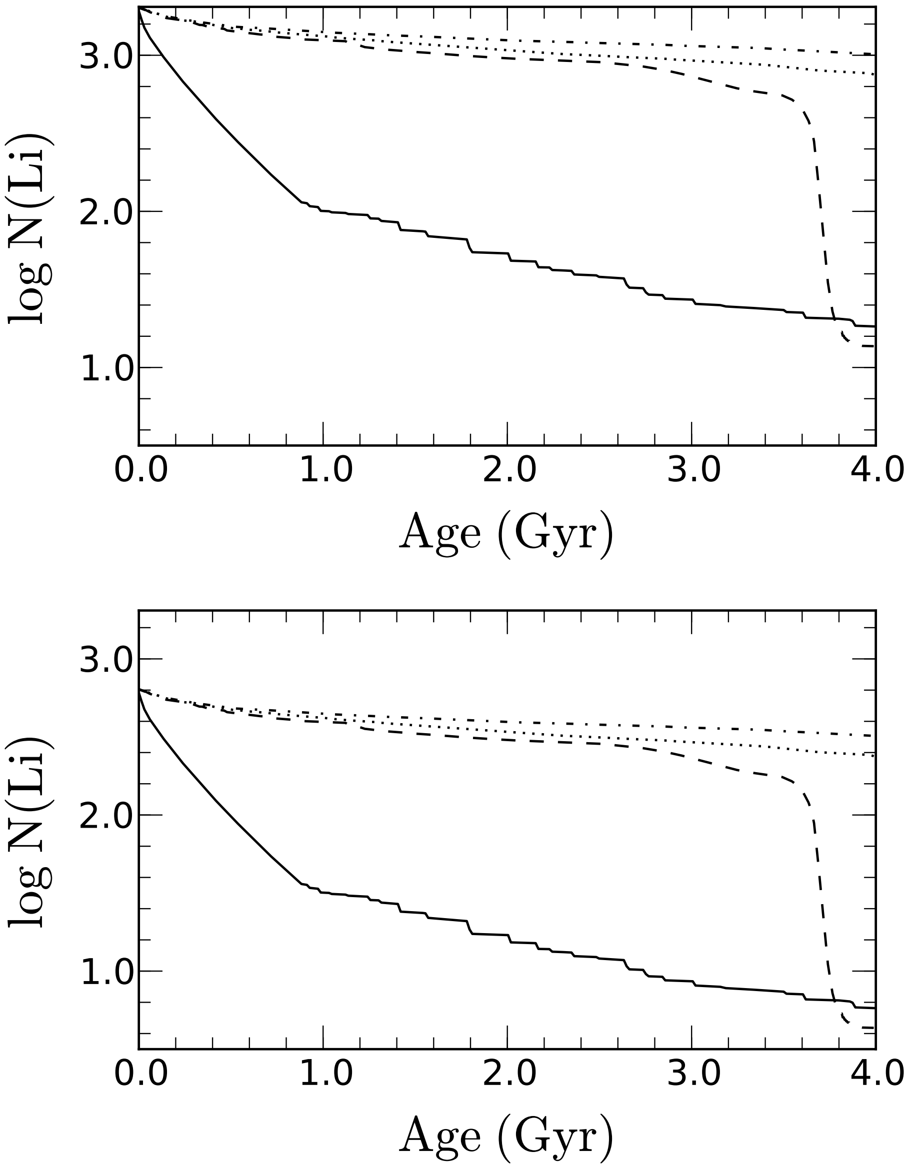

Fig. 2. Lithium abundance predicted by our models as a function of time for different masses. *Upper panel*: for a main sequence star with M = 1 $M_{\odot}$(solid line), stars of M = 1.15 $M_{\odot}$(dot-dashed) and 1.28 $M_{\odot}$(dotted) currently around the turn-off, and a more massive star of 1.33 $M_{\odot}$(dashed line) that is already a giant. *Lower panel*: same plot, but after a -0.45 dex shift was applied (as in Fig.3).

those in Castro et al. (2011). As can be seen, M67 stars with $\log g \sim 4.1$ have high Li. This is the same surface gravity of the Li-rich field stars of the sample of Baumann et al., some of which, therefore, may just happen to be somewhat more massive than 1.1 $M_\odot$ and close to the turn-off. In other words, at least some of the Li-rich field stars may be the field counterpart of the stars in the lithium plateau in M67, with masses in the range 1.1-1.28 $M_\odot$, which are more lithium rich than the rest of the sample for not having depleted lithium. They are not believed of having produced any lithium at all. This can also be seen also in Fig. 2, where lithium vs. age is plotted for different masses. In the *Upper panel*, this is done for a main sequence star with $M = 1.00\ M_\odot$ (solid line), stars of $M = 1.15\ M_\odot$ (dot-dashed) and 1.28 $M_\odot$ (dotted) currently around the turn-off, and a more massive star of 1.33 $M_\odot$ (dashed line) that is already a giant. In the *Lower panel* we show the same plot, but after applying a -0.45 dex shift to reproduce the peak of Li abundances. The difference in lithium abundance between the solar-mass star on one side, and the other 2 unevolved stars on the other side, is explained by the different amount of depletion after ~ 4 Gyr of main-sequence life-time, without invoking any production.

Stars more massive than 1.28 $M_\odot$ have already passed the turnoff, so they deplete lithium by dilution. For example, a star with $M = 1.33\ M_\odot$ (dashed line) is predicted to have as little lithium as $A(\mathrm{Li}) \sim 1.0$ at 4 Gyr.

4.2. Chromospheric activity and rotation

Rotation is the main parameter driving chromospheric activity, and, as we saw above, is also thought to be at the base of lithium depletion. It is therefore natural to investigate the relation between rotation, chromospheric activity and lithium abundance.

In order to do this, we gathered from the literature measurements of the strength of the chromospheric emission in the core of the Ca II H and K line (Giampapa et al. 2006), which are widely used as proxy of chromospheric activity, and projected rotational velocity measurements (Reiners & Giampapa 2009).

Two stars in our compilation have chromospheric activity levels higher than the bulk of M67 stars. They are both highly lithium depleted but, apart of this circumstance, no strong relationship between chromospheric activity and lithium abundance seems to be present. Only for one of the two chromospherically active stars, projected rotation velocity was measured, and it is of 4 km/sec, the only value that exceeds 2 km/sec among 9 measurements in our sample. This suggests that rotation is at the base of both lithium depletion and higher chromospheric activity in this star, but other extra mixing processes must be at least as efficient in some slow rotators.

5. Conclusions

We analyzed literature data to compute, for the first time in a homogeneous way, NLTE lithium abundances for all M67 members, from 0.9 $M_\odot$ on the main sequence, up to the Main Sequence to the Red Giant Branch. We then compared these observations with the predictions of our non-standard models.

Lithium in M67 is a tight function of mass for stars more massive than the Sun, apart of a few outliers. We clearly identify a plateau in lithium abundances for turn-off stars. Both less massive ($M \leq 1.10\ M_\odot$) and more massive ($M \geq 1.28\ M_\odot$) stars are more depleted than those in the plateau. Our models successfully reproduce these features, although only in a qualitative way. There is a significant scatter in lithium abundances for any given mass lower than $M \leq 1.1\ M_\odot$.

A fraction of the Li-rich field stars reported in the literature, are probably similar to the turn-off stars in M67, i.e., they underwent little lithium depletion but they did not produce any lithium.

Despite hints that chromospheric activity and rotations play a role in lithium depletion, no firm conclusion can be drawn with the presently available data.

References

Balachandran, S. 1995, ApJ, 446, 203
Baumann, P. et al. 2010, A&A, 519, 87

Canto Martins, B. L. et al. 2011, A&A, 527, A94
Casagrande, L. et al. 2010, A&A, 512, 54
Castro, M. et al. 2011, A&A, 526, A17
Giampapa, M. S. et al. 2006, ApJ, 651, 444
Hui-Bon-Hoa, A. 2008, Ap&SS, 316, 55
Jones, B. F. et al. 1999, AJ, 117, 330
Kučinskas, A. et al. 2005, A&A, 442, 281
Lind, K. et al. 2009, A&A, 503, 541
Maeder, A. & Zahn, J.-P. 1998, A&A, 334, 1000
Pasquini, L. et al. 2008, A&A, 489, 677
Randich, S. et al. 2007, A&A, 469, 163
Reiners, A. & Giampapa, M. S. 2009, ApJ, 707, 852
Théado, S. & Vauclair, S. 2003, ApJ, 587, 784
Xiong, D. R. & Deng, L. 2009, MNRAS, 395, 2013
Yadav, R. K. S. et al. 2008, A&A, 484, 609
Zahn, J.-P. 1992, A&A, 265, 115