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Rotation and lithium in single giant stars*,**

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Abstract. In the present work, we study the link between rotation and lithium abundance in giant stars of luminosity class III, on the basis of a large sample of 309 single stars of spectral type F, G and K. We have found a trend for a link between the discontinuity in rotation at the spectral type G0III and the behavior of lithium abundances around the same spectral type. The present work also shows that giant stars presenting the highest lithium contents, typically stars earlier than G0III, are those with the highest rotation rates, pointing for a dependence of lithium content on rotation, as observed for other luminosity classes. Giant stars later than G0III present, as a rule, the lowest rotation rates and lithium contents. A large spread of about five magnitudes in lithium abundance is observed for the slow rotators. Finally, single giant stars with masses $1.5 < M/M_{\odot} \leq 2.5$ show a clearest trend for a correlation between rotational velocity and lithium abundance.

Key words: stars: abundances – stars: evolution – stars: late-type – stars: rotation

1. Introduction

One of the best known properties of the late-type evolved stars is that their rotational velocity and lithium content decrease with age. Nevertheless, the root cause of this property, as well as the relationship between rotation and lithium abundance, are not yet completely established. Which physical processes control the behavior of rotation and lithium once stars evolve along the giant branch? In particular, how does rotation affect lithium dilution? How does magnetic braking affect rotation and lithium content in evolved stars? Solid answers to these questions have been hampered by the difficulties in the measurement of rotation rates for cool stars as well as by the paucity of lithium abundance measurements for large and complete sample of evolved stars. However, over the last 10 years it has become possible to measure rotational velocities of evolved stars with a precision better than $1.0\,\mathrm{km\,s^{-1}}$ (e.g.: Gray 1989; De Medeiros & Mayor 1989, 1999). In addition, large observational surveys of the lithium line 6 707.81 Å, with high precision, were carried out (e.g.: Brown et al. 1989; Wallerstein et al. 1994; Balachandran 1990; Randich et al. 1999; Lèbre et al. 1999). As a result, some very interesting new features on the behavior of rotation and lithium content in evolved stars are emerging.

A dramatic drop in the rotation of subgiant and giant stars occurs, respectively, near the spectral types F8IV and G0III (Gray & Nagar 1985; Gray 1989; De Medeiros & Mayor 1989, 1991). For the more luminous classes, namely bright giant and Ib supergiant stars, De Medeiros & Mayor (1989, 1991) observed a sudden decrease in their rotation near the spectral types F9II and F9Ib, respectively. On the other hand, the giant stars, to the left of the rotational discontinuity, namely in the F spectral region, present a wide range of rotational velocity values, from a few $\mathrm{km\,s^{-1}}$ to about one hundred times the solar rotation rate. To the right of this discontinuity, namely along the G and K spectral regions, the large majority of stars show low rotation. Along this spectral region only binary systems presenting orbital periods shorter than about 250 days and circular or nearly circular orbits and a dozen of apparently single giant stars present enhanced rotation. Should one expect some kind of link between the rotational discontinuity and the distribution of lithium abundances? A gradual decrease of surface lithium abundance is expected once stars evolve along the giant branch. At the end of the main-sequence, theory predicts that lithium is confined to the outermost regions of the star in a thin convective layer. Once the star evolves up the giant branch, the convective envelope expands towards the stellar interior and the convective mixture of the outer material rich in lithium with deeper and Li-free material leads to the depletion of this fragile element (e.g.: Iben 1967a,b). Lithium is destroyed when the convective envelope with Li-rich material reaches stellar inner regions with temperatures higher than about 2.5×10^{6} K. Following the initial study by Bonsack (1959), different studies have attempted to analyse the observational behavior of the lithium abundance along the giant branch. The abundance of lithium in F and early-G giants has been investigated by Wallerstein (1966), Alschuler (1975) and Wallerstein et al. (1994). These works have shown a steady decline in lithium abundances from F5III to F8III, a

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** Table 2 is only available electronically with the On-Line publication at http://link.springer.de/link/service/00230/

wide spread around the spectral type G0III and low values up to G5III. Wallerstein et al. (1994) have analysed the behavior of lithium abundances of F2 – G5 giants looking for the main features of lithium in the Hertzsprung gap. These authors have found that rapidly rotating giants, namely stars with $v \sin i > 50$ km s^{-1}, located in the color interval from $(B-V)$ = 0.40 to $(B-V) = 0.70$ present lithium abundances close to the presumed primordial value $\log n(Li) = 3.0$. For slow rotators, $v \sin i < 50$ km s^{-1}, a drop in lithium abundance appears in the color interval $(B-V) = 0.45$ to $(B-V) = 0.60$, i.e. stars with $(B-V) > 0.45$ show reduced lithium abundances in spite of their early spectral types. Luck (1977), Lambert et al. (1988) and Luck and Lambert (1982) have determined lithium abundances for normal G, K and M-type field giants. From these works, strong evidences have emerged that the content of lithium in this spectral region is primarily controlled by the stellar mass. On the basis of a very large survey of about 644 G and K-type giants Brown et al. (1989) have found that a small percentage of late-type giant stars have lithium content far in excess of the standard predictions, a few of them approaching the primordial value. The lithium content distribution of the remaining stars in such survey shows that giants only very rarely are in agreement with standard first dredge-up predictions, in the sense that their lithium content falls below the theoretical predictions. De Medeiros et al. (1996a) have shown that, except for a few chromospherically active giants, Li-rich evolved stars show normal rotational velocity with respect to the typical lithium-normal evolved stars of the same spectral type. Recently, a study of lithium abundance for population I subgiants carried out by Lèbre at al. (1999) have shown a sudden decrease in the lithium abundance around Teff = 5 600 K, corresponding to a spectral type near G2IV. Such a feature occurs slightly later than the rotational discontinuity at F8IV. Furthermore, some dependence of lithium abundance on rotation, in the sense that fastest rotators show enhanced lithium content, was observed in different classes of luminosity. This dependence, for example, was found for population I subgiant (Randich et al. 1999, De Medeiros et al. 1997, do Nascimento et al. 2000) and for unevolved late-type stars in young clusters (Garcia Lopez et al. 1994, Randich et al. 1998).

In spite of the important results obtained from the works discussed above, up to date there have been no studies on the link between rotation and lithium content along the giant branch. In the present work we investigate specifically the relationship between rotational velocity and lithium abundance for giant stars on the basis of a large and homogeneous data sample for which we have now precise rotational velocities obtained with the CORAVEL spectrometer.

2. Observational data

The data sample selected for the present investigation has as its main characteristics the high precision of the rotational velocity and lithium abundance, as well as the large size of the sample. The rotational velocity measurements were taken from the Catalog of Rotational and Radial Velocities for Evolved Stars by the De Medeiros & Mayor (1999). By using the CORAVEL spectrometer (Baranne et al. 1979) these authors have measured rotational velocities for a large sample of about 2 000 evolved stars. For giant stars of luminosity class III, in particular, these authors have shown that CORAVEL $v \sin i$ values present an uncertainty of about 1.0 km s^{-1} for stars with $v \sin i$ lower than about 30.0 km s^{-1}. For higher rotators, the estimations indicate an uncertainty of about 10%. For a complete discussion on the observational procedure, calibration and error analysis the reader is referred to De Medeiros & Mayor (1999). Lithium abundances were taken from three different sources: 16 F and early-G stars from Wallerstein et al. (1994), 7 F stars from Balachandran (1990) and 286 late-G and K type giants from Brown et al. (1989), all of them with a $v \sin i$ given by De Medeiros & Mayor (1999). Because lithium abundances come from different authors, a comparison for those stars in common in the given sources would be important. For four stars observed by Wallerstein et al. (1994) and Balachandran (1990) a least-square solution yields a linear correlation coefficient of about 0.91 and standard deviation about 0.27, indicating for an excellent agreement between the lithium abundance values obtained by these authors. Brown et al. (1989) and Wallerstein et al. (1994) present only two stars in common. Let us underline here the uncertainties in lithium abundances estimated by the different authors mentioned above. Wallerstein et al. (1994) estimate an uncertainty of ± 0.1 dex in $[Li/Fe]$ for stars presenting low rotation and weak Li lines and ± 0.3 dex for rotating stars with strong Li lines, but for rotating stars with $(B-V) < 0.5$ such uncertainty may rise by 0.1 or 0.2 dex. Balachandran (1990) estimates uncertainties for $\log n(Li)$ to be ± 0.02 dex at large equivalent widths and ± 0.07 dex at small equivalent widths, while for rapidly rotating stars the error in lithium abundances is probably ± 0.1 dex. Finally, Brown et al. (1989) have estimated an uncertainty of

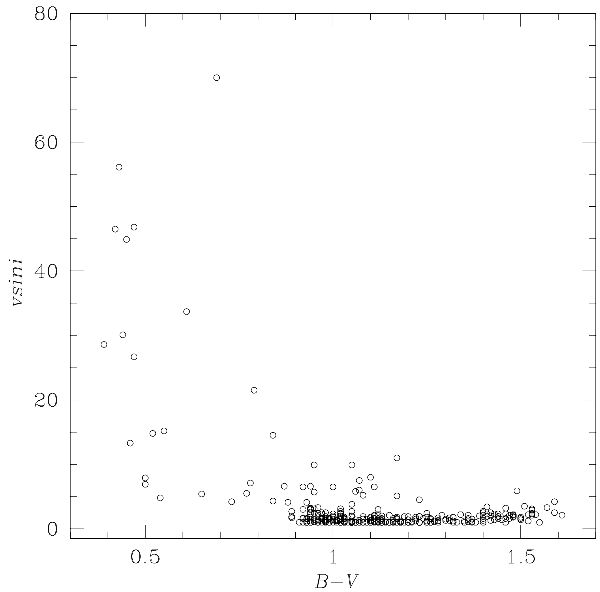

Fig. 1. The rotational velocity $v \sin i$ of single giant stars as a function of color index $(B-V)$.

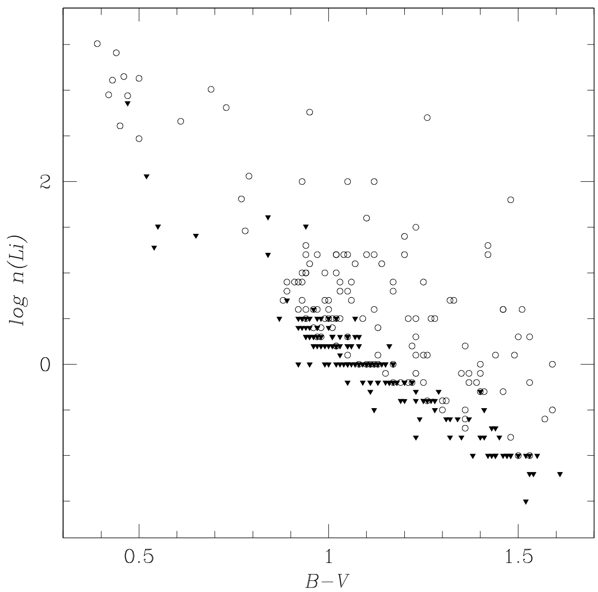

Fig. 2. Lithium abundance as a function of color index $(B-V)$ for single giant stars. Upper limits for $\log n(Li)$ are indicated by triangles.

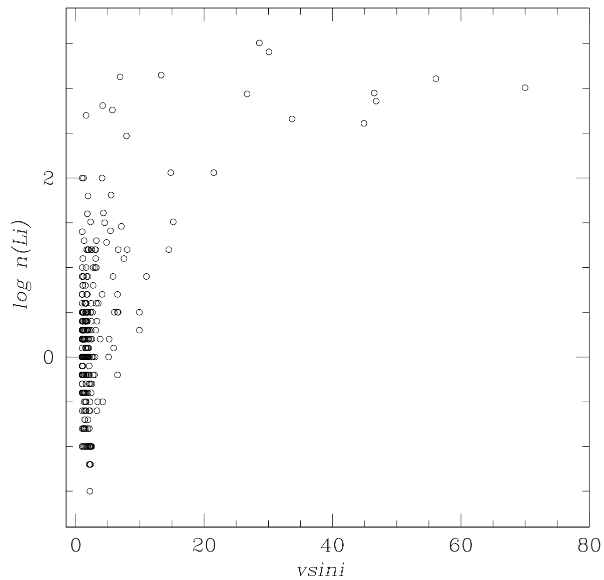

Fig. 3. Lithium abundance as a function of rotational velocity $v \sin i$ for single giant stars.

about ± 0.2 dex. Moreover, Wallerstein et al. (1994) obtained spectra with a signal-to-noise ratio of about 200, Balachandran (1990) pointed out a signal-to-noise ratio of about 100 for the spectra, whereas all spectra obtained by Brown et al. (1989) showed a signal-to-noise ratio of at least 150. In fact, the detailed error analysis made by these authors indicate that their lithium abundance measurements have the same high quality. The entire sample with rotational velocities and lithium abundances is listed in Table 2.

3. Results and discussion

The rotational velocity $v \sin i$ as a function of the color index $(B-V)$ is plotted in Fig. 1, where one sees clearly the sudden decline in rotation near $(B-V)$ = 0.70, corresponding to the spectral type G0III (De Medeiros & Mayor 1989, 1991, Gray 1989). This cutoff in the distribution of the rotational velocity results from a mixing in age and masses associated with the rapid evolution of giant stars into the Hertzsprung gap (De Medeiros & Mayor 1991). To the left of this cutoff one sees a wide range of rotational velocity values, which seems to reflect the distribution of rotation of the progenitors of giant stars. To the right of the cutoff, as pointed out by De Medeiros & Mayor (1991), single giants with high rotation are unusual. Only a dozen of single G and K single giants, in addition to synchronized binary systems, present enhanced rotation. As shown by De Medeiros et al. (1996b), to the right of the cutoff rotation decreases smoothly from about 6.0 km s^{-1} at G1III, to about 3.0 km s^{-1} at G5III and to about 2.0 km s^{-1} along the spectral region from G8III to K7III.

The well established gradual decline of lithium abundances as a function of the color index $(B-V)$ for single giant stars is illustrated in Fig. 2. Let us recall that the $(B-V)$ interval represented in that figure covers the spectral range from F2III to K5III. Such a decline is interpreted as an evidence of convective mixing. The convective zone begins to grow towards the stellar interior as the star evolves from the F to the G spectral region and finally deepens rapidly as the star ascends the first giant branch, so that the thin surface layer containing lithium is mixed with the larger inner Li-free stellar material. Lithium is then burned when the convective envelope drags the mixed material into regions with temperatures of about $2 \times 10^6 K$. However, such observed decline in lithium abundance is not yet fully explained by the standard stellar evolution theory. Along the giant branch the lithium abundance falls below the standard predictions. In fact, standard theory shows a factor of dilution of about 40 to 60 for 1.0 M$_\odot$ and 2.0 M$_\odot$, respectively. Nevertheless, from a comparison of the lithium abundances listed in Table 2 with the standard theoretical predictions, one can observe a factor of dilution as large as 400, in particular for stars in the spectral region G8III – K0III. Such a contrast between predicted and observed factor of dilution was also observed by other authors (e.g.: Brown et al. 1989). However, the present work which combines a large sample of data from the literature (Brown et al. 1989; Balachandran 1990; Wallerstein et al. 1994) shows that the dilution of lithium from the spectral type F2III to K5III is far more important than pointed out up to date. Another important feature that emerges from Fig. 2 is the well known large spread in lithium abundance for a given color index or spectral type, which could result from the mixing in masses. A comparison of Figs. 1 and 2 shows, at first glance, no clear link between the drop in rotation near G0III and the behavior of lithium abundance around such a spectral type. As it has been already outlined, rather than a drop, the lithium abundance shows a gradual decrease. Zahn (1992) and Pinsonneault et al. (1989, 1990) have proposed, following different approaches, that depletion of lithium in single late-type stars is directly related to the loss of angular momentum. In this context, a correlation between rotation and lithium con-

Table 1. Statistical results for rotation and lithium abundance by mass interval.

Mass range ($M_\odot$)	Correlation Coefficient	rms residual	Number of stars
all stars	0.588	0.711	309
$all(B-V) < 0.7$	0.505	0.588	16
$all(B-V) \geq 0.7$	0.319	0.658	293
$0.7 < M \leq 1.5$	0.663	0.861	73
$1.5 < M \leq 2.5$	0.806	0.538	91
$2.5 < M \leq 3.5$	0.558	0.431	110
$M > 3.5$	0.297	0.688	35

tent should be expected. In spite of no clear discontinuity in the lithium contents presented in Fig. 2, the distribution of lithium abundances represented by the histogram displayed in Fig. 4 shows a trend for a bimodal behavior. In fact, one observes a first mode around $\log n(Li) = 0.2$, corresponding to stars later than G0III, namely stars located to the right of the rotational discontinuity, and a second mode around $\log n(Li) = 3.0$ which is mainly due to the lithium content of F-type giants. In principle, such a result seems to point in the direction of a discontinuity in the distribution of lithium at the same spectral region where the rotational discontinuity is observed, namely around G0III. One could inquire here about the root cause of this apparent discontinuity in lithium abundances. Could it be associated to the same root cause controlling the rotational discontinuity?

In Fig. 3 we show the behavior of lithium abundances as a function of rotational velocity. Several important features emerge from this figure. First of all, one observes that giant stars presenting the highest lithium content, typically stars earlier than the spectral type G0III, are also those with the highest rotation rates. Stars located to the right of the drop in rotation, namely stars later than G0III, present as a rule, the lowest rotation rate and lithium content. In fact, these features indicate a trend leading to a correlation between lithium abundance and rotation along the giant branch, which confirms, for single giant stars, the dependence of lithium on rotation, observed in other luminosity classes. An additional important feature is the large spread in lithium abundance of the slow rotators. Stars with a $v \sin i$ lower than about 4.0 km s^{-1} show a wide range of lithium abundance values with $\log n(Li)$ ranging from about -1.5 to the cosmic value, clearly five orders of magnitude.

For a more solid study on the link between rotational velocity and lithium abundance in single giant stars, we have carried out a least-square regression analysis of the stars listed in Table 1. A log-linear least-square fit of $\log n(Li)$ against $v \sin i$ was derived first for the entire sample of stars and then for stars located earlier and later the spectral type G0III. The least-square solution yields very poor linear correlation coefficients and standard deviations, as indicated in Table 1 and, at first glance, we could regard these results as an indication that rotation and lithium would be poorly correlated in single giant stars. As a second step, we have segregated the stars by mass intervals. The stellar masses were estimated from evolutionary tracks computed with the Toulouse-Geneva code for a range of stellar masses between 1 and 4 $M_\odot$ and for metallicities consistent with population I giants (see do Nascimento et al. 2000 for a description). However, solar composition being relevant to most objects in the sample, only tracks computed with $[Fe/H] = 0$ were considered here. Intrinsic absolute magnitudes M_V were derived from the parallaxes and m_V magnitudes given by Hipparcos. We have determined the bolometric corrections BC by using the Buser and Kurucz's relation (1992) between BC and V-I (again taken from the Hipparcos Catalogue). The stellar luminosity and the associated error were computed from the sigma error on the parallax. The correlation coefficients obtained from this regression analysis, by interval of mass, are listed in Table 1, from which one can observe a clear trend for a linear correlation between lithium and rotation for stars with masses between 1.5 and 2.5 solar masses. For the additional mass intervals the results of the present least-squares solutions indicates a poor correlation between lithium and rotation.

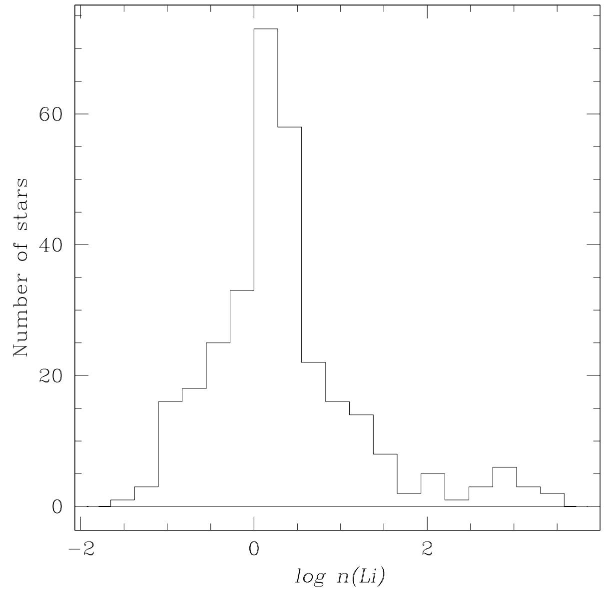

Fig. 4. A histogram plot of the distribution of the lithium abundances for single giant stars.

4. Conclusions

The distribution of lithium abundance for single giant stars shows a trend for a discontinuity near $(B-V)$ = 0.70, corresponding to the spectral type G0III. Such a discontinuity follows the one observed in rotational velocity. In addition, this work shows a clear dependence of lithium abundance on rotation, in the sense that the highest rotators are also the stars presenting the highest lithium content. One observes that giant stars, presenting the highest lithium content and highest rotation are typically stars earlier than the spectral type G0III. Stars located to the right of the drop in rotation, namely stars later than G0III, present as a rule, the lowest rotation rate and lithium content. In fact, these features show, for giant stars, the same dependence of lithium on rotation observed in other luminosity classes. Giant stars with masses $1.5 < M/M_\odot \leq 2.5$ show the more solid trend for a correlation between rotational velocity and lithium abundance. For other mass intervals the least-square solutions show a trend for poor correlation, indicating that the dependence of lithium content on rotation is mass dependent. An additional important feature is the large spread in lithium abundance of the slow rotators. Stars with a $v \sin i$ lower than about 4.0 km s^{-1} show a wide range of lithium abundance values with $\log n(Li)$ ranging from about -1.5 to the cosmic value, namely five orders of magnitude. Neverthless, because the sample of giants analyzed in the present work is somewhat limited, in particular for late F and early G type stars, additional measurements of lithium abundance are clearly required for stars located in this spectral region, for a more solid analysis of this apparent discontinuity in lithium.

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