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Evidence for strong differential rotation in Li-depleted fast rotating F-stars[⋆]

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Abstract. We report the detection of strong differential rotation on ten fast rotating ($v \sin i > 10\,\mathrm{km\,s^{-1}}$) stars of spectral types F0–G0 using the Fourier Transform Method, in three cases we find $\alpha > 20\%$. Among the six differential rotators with $v \sin i > 15$ km s^{-1}, five have Li abundances of $\log \epsilon(\mathrm{Li}) < 1.5$, for one object no Li abundance is available to our knowledge. No differentially rotating star with high Li abundance was found, although the average Li abundance of fast rotators in the literature is $\log \epsilon(\mathrm{Li}) > 2.0$. Our results suggest that Li-depleted fast rotators tend to show differential rotation. Interpreting high rotational velocity as indicator of youth, this finding supports the idea of the connection between mixing processes and differential rotation during magnetic breaking in F-stars.

Key words. stars: abundances – stars: evolution – stars: rotation

1. Introduction

The detection of differential rotation on other stars or the Sun is a difficult observational task. Extensive measurements of photometric variability, migration of photosperic spots and deviations in the rotational profile have been carried out in order to detect its effects. Recently results of differential rotation measurements were reported using the Doppler Imaging technique (e.g., Donati & Collier Cameron 1997).

The main driver of this quest is the poor understanding of stellar dynamo theory, that is believed to be the primary source of all solar and stellar activity phenomena. An empirical dependence of differential rotation on fundamental stellar parameters can provide a key ingredient of stellar dynamo theory.

The results from Doppler Imaging lend support to theoretical studies of the dependence of latitudinal differential rotation on rotational frequency. Using a mean-field approach Kitchatinov & Rüdiger (1999) found that the rotational shear $\Delta\Omega$ is approximately constant in solar like stars for all rotational frequencies. Thus the relative amount of differential rotation,

$$\alpha = \frac{\Delta\Omega}{\Omega_0}, \qquad \Delta\Omega = \Omega_1 - \Omega_0, \tag{1}$$

with Ω_0 the angular velocity at the equator and Ω_1 at the poles, becomes less with faster rotation.

However, the rotational velocity plays an important role for the understanding of a second physical process taking place on stars, namely lithium depletion. Early measurements of Li abundances were believed to be due solely to the depth of the convection zone, but extensive observations during the last decades revealed that the Li depletion processes are much more complicated.

During the evolution on the main-sequence, F-stars undergo magnetic braking. Angular momentum transport induces radial differential rotation, thereby Li is transported in the deeper layers of the star that becomes Li-depleted (cf. Pinsonneault et al. 1989). After the phase of rotational breaking, at the end of the main sequence, a large spread in Li abundances is believed to represent the spread of initial angular momentum among those stars, although a similar initial Li abundance is assumed. Observations of, e.g., Balachandran (1990) show that slowly rotating F-stars do have a large spread in Li abundances.

On the other hand, again assuming similar initial Li abundances, it is surprising that stars with high rotational velocities also show a spread in Li abundance, too. Those stars should be younger and mixing processes should not have depleted Li as expected for the old and slowly rotating stars. Balachandran (1990) showed that fast rotators are indeed mainly Li-rich but a few cases of fast rotating Li-depleted F-dwarfs were also found. Boesgaard & Tripicco (1986) pointed out, that despite the observed general trend of fast rotating Li-rich and slowly rotating Li depleted stars, they found some "misfits" with high $v \sin i$ but low $\log \epsilon(\mathrm{Li})$.

Our work connects the observational data of Li abundances with our measurements of latitudinal differential rotation. We focus on the "misfitting" group of fast rotating Li-depleted stars. A deeper examination of our measurements and

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[⋆] Based on observations collected at the European Southern Observatory, La Silla.

Table 1. Observations.

Date	# Objects	Region	Resolution
13.10.2000	11	5770–5810 Å	235 000
01.–04.10.2001	62	5770–5810 Å	235 000
01.–03.04.2002	77	6225–6270 Å	235 000

correlations to other stellar parameters will be presented in a forthcoming paper.

2. Observations and data analysis

Our primary data sample consists of 142 F-, G- and K-dwarfs mostly brighter than $M_V = 6$ mag and visible at ESO La Silla, Chile. We concentrated on stars with known rotational velocity and $10\,\mathrm{km\,s^{-1}} < v\,\sin i < 40\,\mathrm{km\,s^{-1}}$, however, we also observed 30 stars without known rotational velocities.

With the Fourier Transform Method (FTM), differential rotation can be measured in stars with $v\,\sin i \gtrsim 10\,\mathrm{km\,s^{-1}}$ (cp., Reiners & Schmitt 2002a). The zero positions q_1 and q_2 of the Fourier transformed broadening profile are used to measure the differential rotation rate. For stars with lower rotational velocity, other line broadening effects become dominant and the measurement of q_2 is not reliable. To detect differential rotation on stars with $v\,\sin i < 20\,\mathrm{km\,s^{-1}}$, high resolution spectra of $R \geq 100\,000$ are needed. The data was taken with Ces at the ESO 3.6 m telescope at La Silla, Chile. In its highest resolution mode ($R = 235\,000$) the spectral region covers ~40 Å. We used two different wavelength regions (5770–5810 Å and 6225–6270 Å) in the three observing runs listed in Table 1. For a detection of the subtle effects of differential rotation high S/N-ratios are essential. The S/N-ratio of our data is between 400 and 900 for all observations.

To measure differential rotation we extracted an overall broadening profile by a "Physical Least Squares Deconvolution" process. We constructed an unbroadened δ-template using a slowly rotating star of similar spectral type. Central wavelengths were optimized to correct for convective wavelength shifts. With that template as a starting point the equivalent widths of the individual lines and the broadening profile of the star were iterated. For line profiles of stars rotating as slowly as our sample stars, thermal broadening becomes important. Thus after the iteration we broadened the template lines according to the effective temperature of the star and the atomic weight of the absorbing atom. With that final template we deconvolved the final broadening profile.

The broadening profile was Fourier transformed and differential rotation was measured as described in Reiners & Schmitt (2002a). To show the quality of the deconvolution process, we convoluted the final template with the final broadening profile. The result is plotted over the error bars of the data points in Fig. 1.

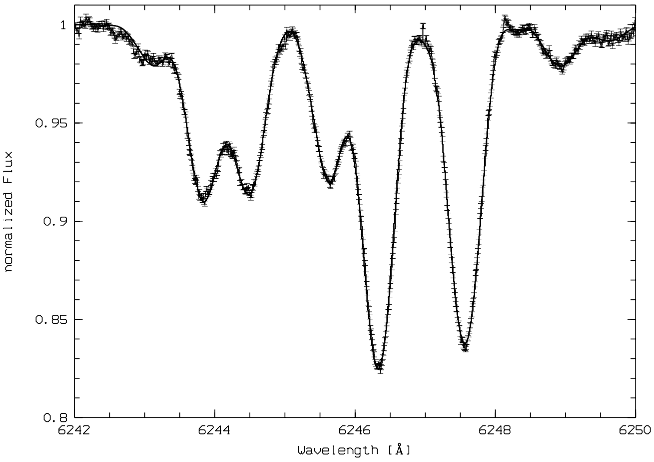

Fig. 1. Example of the quality of the deconvolution process. The convolution of the thermal broadened template with the derived broadening profile is plotted over the error bars of the data.

3. Results

Of the 142 observed stars we found 80 objects rotating below $10\,\mathrm{km\,s^{-1}}$. As mentioned above it is not possible to derive informations about differential rotation for these stars with our method. Data quality limited us to stars with $v\,\sin i > 12\,\mathrm{km\,s^{-1}}$, and five stars of our sample were multiple stars or showed peculiar line profiles and no reliable broadening profile could be derived for these cases. The remaining 53 stars can be sorted in two groups; 32 symmetric and 21 asymmetric profiles with respect to the error bars. The asymmetric ones are suspected to be mainly due to spots and flux variations within the photosphere. Thus the shape of the profile can be dominated by temperature variations and not by the rotational law. For this study we did not use those profiles and analyzed only the symmetric ones.

The remaining 32 stars are of spectral type F0 – G0. For their symmetric profiles with $v\sin i > 10\,\mathrm{km\,s^{-1}}$ the ratio of the first two zeros of the Fourier transform was calculated. Following Reiners & Schmitt (2002a), a ratio $q_2/q_1 < 1.72$ is a direct indication for solar-like differential rotation (equator faster than pole). $1.72 < q_2/q_1 < 1.83$ is typical for solid rotation with arbitrary limb darkening, and a value of $q_2/q_1 > 1.83$ indicates anti solar-like differential rotation (pole faster than rotator) or a polar spot (Reiners & Schmitt 2002b).

In Fig. 2 the distribution of the measurements of q_2/q_1 among the 32 profiles is shown. The region occupied by unspotted solid rotators is indicated by dashed lines. The majority of our objects (20 of 32) lie within that region. Ten of the 32 objects show significant differential rotation with $q_2/q_1 < 1.72$. Only two objects have $q_2/q_1 > 1.83$.

In the literature we found lithium abundances for 18 of the 32 analyzed stars. No lithium line lies within our spectral region and it was not possible to derive Li abundances for the remaining 14 objects. In Table 2 the parameters of the ten differential rotators and of the two stars with $q_2/q_1 > 1.83$ are shown.

In Fig. 3 we plot the Li abundances vs. q_2/q_1. Since the mentioned studies on connections between Li abundance and $v\,\sin i$ suggest that a large spread of Li abundances is common for stars with $v\sin i \lesssim 15\,\mathrm{km\,s^{-1}}$, and that fast rotators ($v\sin i \gtrsim 15\,\mathrm{km\,s^{-1}}$) are in general Li-rich, we divide our sample in two

Table 2. Stars with $q_2/q_1 < 1.72$ or $q_2/q_1 > 1.83$; i.e., not consistent with solid ration of an unspotted photosphere.

HD	HR	Type	$v \sin i$ [km s^{-1}]	q_2/q_1	$\log \epsilon$(Li)
89449	4054	F6IV	17.3 ± 1.7	1.44 ± 0.04	$<1.10^{a}$
89569	4061	F6V	12.2 ± 0.7	1.57 ± 0.02	n.a.
100563	4455	F5V	13.5 ± 0.4	1.67 ± 0.04	2.66^{c}
105452	4623	F0IV/V	23.5 ± 1.2	1.59 ± 0.02	n.a.
120136	5185	F7V	15.6 ± 1.0	1.57 ± 0.04	$<0.60^{d}$
121370	5235	G0IV	13.5 ± 1.3	1.46 ± 0.03	$<1.81^{b}$
160915	6595	F6V	12.4 ± 0.5	1.60 ± 0.03	2.26^{c}
173667	7061	F6V	18.0 ± 2.0	1.40 ± 0.02	$<1.37^{b}$
175317	7126	F5IV/V	17.1 ± 0.7	1.58 ± 0.04	$<0.46^{b}$
197692	7936	F5V	41.7 ± 1.7	1.62 ± 0.02	$<1.18^{c}$
23754	1173	F5V	13.8 ± 0.3	1.87 ± 0.05	n.a.
124850	5338	F7IV	15.0 ± 0.6	1.91 ± 0.04	$< 1.21^{a}$

[a] Cutispoto et al. (2002).
[b] Balachandran (1990).
[c] Boesgaard & Tripicco (1986).
[d] Boesgaard & Lavery (1986).

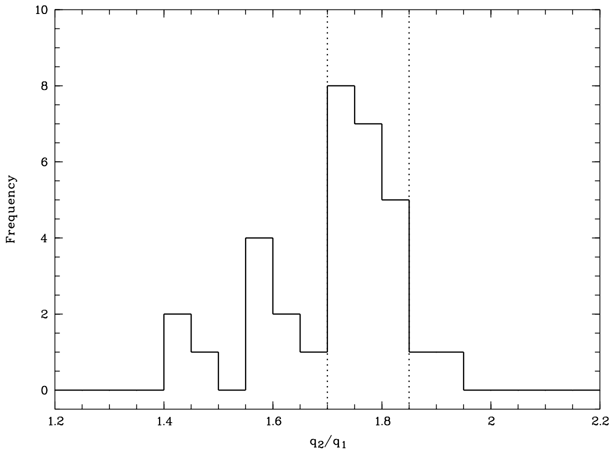

Fig. 2. Distribution of the ratio q_2/q_1 among the 32 analyzed profiles. The region between the dashed lines is occupied by solid rotators with arbitrary limb darkening coefficient according to a linear limb darkening law. $q_2/q_1 < 1.72$ indicates solar-like differential rotation, $q_2/q_1 > 1.83$ can be due to anti solar-like differential rotation or a polar spot.

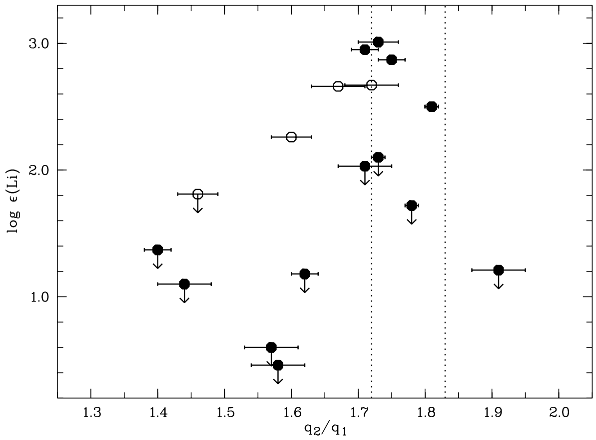

Fig. 3. Li abundance vs. q_2/q_1 for our sample stars, upper limits of Li abundances are marked with arrows, dashed lines as in Fig. 2. Open circles represent slow ($v \sin i < 15\,\mathrm{km\,s^{-1}}$), filled circles fast ($v \sin i > 15\,\mathrm{km\,s^{-1}}$) rotators. Two objects happen to have same values at $\log(\epsilon) = 2.5$, $q_2/q_1 = 1.81$. Note that the actual strength of differential rotation in terms of α or $\Delta\Omega$ is not simply a function of q_2/q_2, but that $q_2/q_1 < 1.72$ is always a direct indication for the presence of differential rotation.

subroups defined by $v \sin i = 15\,\mathrm{km\,s^{-1}}$. Stars with $v \sin i > 15\,\mathrm{km\,s^{-1}}$ are marked with full circles in Fig. 3, slower rotating stars with open circles. The region between the dashed lines is again consistent with solid rotation without spots.

Although, in agreement with stellar evolution theory, fast rotators tend in general to be Li-rich, a handful of Li-depleted fast rotators were found in observations by Boesgaard & Tripicco (1986) and Balachandran (1990).

In Fig. 3 it can be seen that we found five Li-depleted fast rotators with $q_2/q_1 < 1.72$ in our sample, while there is no differentially rotating Li-rich star with $v \sin i \geq 15\,\mathrm{km\,s^{-1}}$. For one fast differential rotator no Li-abundance is available to our knowledge. It should be mentioned that even for our whole sample of stars we find more Li-depleted than Li-rich differential rotators (six Li-poor vs. two or one Li-rich differential rotators, depending on whether we interpret $q_2/q_1 = 1.67 \pm 0.04$ on HD 100 563 as significant differential rotation).

Our sample of objects with measurable differential rotation and available Li abundances is rather small, but nevertheless we can determine the statistical significance of a correlation between differential rotation and Li depletion in our data.

In Table 3 the objects with $v \sin i > 15\,\mathrm{km\,s^{-1}}$ are sorted into subgroups defined by their Li abundance and measured value of q_2/q_1. Stars for which only upper limits of Li abundances are available have been qualified as Li-poor, neglecting the actual value of the upper limit. Stars with $q_2/q_1 < 1.72$ are qualified as differential rotators according to Reiners & Schmitt (2002a). We tested the null hypothesis on whether the obtained distributions of Li detections and upper limits for differentially and

Table 3. Subgroups of the fast rotators; $v \sin i > 15\,\mathrm{km\,s^{-1}}$.

	Li	
rotation	upper limit	detection
differential	5	0
rigid	3	5

rigidly rotating stars can be due to underlying identical population distributions. Using a χ^2-test (cf., Press et al. 1992) we found that the probability of obtaining our results from identical population distributions for differentially and solidly rotating stars is less than 2.4%, i.e., a correlation between Li depletion and differential rotation in our sample is significant on a $2.2\,\sigma$ level.

4. Conclusions

From our primary data sample of 142 F-, G-, and K-stars we excluded the profiles where it is impossible or unreliable to measure the subtle effects of the rotational law. Stellar velocity fields and data quality limited us to stars rotating faster than $12\ \mathrm{km\,s^{-1}}$. Dominant photospheric distortions make measurements of the ratio q_2/q_1 unreliable in stars with asymmetric profiles.

For symmetric profiles the possibility of significant influences of photospheric features on q_2/q_1 is discussed in Reiners & Schmitt (2002b) and can be neglected as a source of our differential rotation measurements. Reliable measurements were possible in 32 objects in the spectral range F0–G0.

From mean-field theory no significant differential rotation is expected for stars rotating faster than $v \sin i = 10\,\mathrm{km\,s^{-1}}$. The profiles of the majority of the sample stars (20 of 32; 63%) are consistent with solid rotation and an unspotted photosphere. Two cases are found with signatures of either anti solar-like differential rotation or a polar spot ($q_2/q_1 > 1.83$). However, in contrast to the predictions, significant effects of solar-like differential rotation ($q_2/q_1 < 1.72$) are detected in 10 of our 32 sample stars (31%), nine of them have $q_2/q_1 < 1.65$. We want to emphasize that for this study we concentrated on the question, if the stars show *any* signatures of differential rotation, regardless of its actual value of α or $\Delta\Omega$. However, from Fig. 6 of Reiners & Schmitt (2002a) we derive a value of $\alpha > 20\%$ for the three stars with $q_2/q_1 < 1.5$.

For 18 of the 32 analyzed objects Li abundances are available in the literature, making it feasible to search for connections between Li-depletion and evidence of differential rotation. Observations done by Boesgaard & Tripicco (1986) and Balachandran (1990) show a large spread in Li abundances for slow rotators, while stars with $v \sin i \gtrsim 15\,\mathrm{km\,s^{-1}}$ tend to be Li-rich. Nevertheless, a handful of Li-depleted fast rotating "misfits" were found in the mentioned works. It is this group of "misfits" we focused on. While Li-depletion seems to be a common phenomenon in slowly rotating stars and in good agreement with calculations (Pinsonneault et al. 1989), in fast rotators it is an exception.

In our sample Li measurements are available for five of the observed fast differential rotators ($v \sin i > 15\,\mathrm{km\,s^{-1}}$). As mentioned, no differential rotation is expected for these stars from theory. All of them have measured Li abundances of $\log\epsilon\,(\mathrm{Li}) < 1.5$, i.e., we can identify these stars with surprisingly strong evidence of differential rotation with a subgroup of the "misfits" in the works of Boesgaard & Tripicco (1986) and Balachandran (1990).

In statistical terms, the correlation of Li-depletion and presence of differential rotation in our sample of fast rotating F-stars is significant at a $2.2\,\sigma$ level. Under the assumption that the high rotational velocity of these objects is mainly due to their youth, this correlation lends support to the idea that during magnetic breaking differential rotation takes place on F-stars and that Li becomes depleted already before the star has spun down. We emphasize that in our limited sample other effects like, e.g., undetected binarity, could also be the reason for high rotational velocities. In such case differential rotation may reflect the higher evolutionary stage of older stars.

The derivation of the strength of differential rotation in terms of α and $\Delta\Omega$ and further correlations between stellar parameters like mass, metallicity and especially age may clarify the situation. This will be presented together with the other stars of our sample in a subsequent publication.

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