Differential Rotation in F Stars

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Differential rotation can be detected in single line profiles of stars rotating more rapidly than about $v \sin i = 10 \text{ km s}^{-1}$ with the Fourier transform technique. This allows to search for differential rotation in large samples to look for correlations between differential rotation and other stellar parameters. I analyze the fraction of differentially rotating stars as a function of color, rotation, and activity in a large sample of F-type stars. Color and rotation exhibit a correlation with differential rotation in the sense that more stars are rotating differentially in the cooler, less rapidly rotating stars. Effects of rotation and color, however, cannot be disentangled in the underlying sample. No trend with activity is found.

1 Introduction

Stars are born from molecular clouds carrying net angular momentum that makes every star rotate more or less rapidly. During their evolution stars are being braked more or less efficiently, but even after several Gyrs of efficient braking stars as strongly braked as the Sun still show substantial angular velocity. This rotation in general must be expected to be differential, i.e. angular velocity changes with depth and latitude. In a rotating star, it is already the temperature difference due to rotationally induced surface gravity gradients which leads to meridional flow and differential rotation. More severe effects like magnetic forces and inhomogeneities in the convective structure may lead to even more severe effects of differential rotation.

The star with the best studied rotation law is the Sun, its equatorial angular velocity is roughly 20% higher than the polar one, which has been observed centuries ago by following the rotation of spot groups on the solar surface. Today it is believed that these spots are due to magnetic activity of which at least the cyclic part is generated by a dynamo mechanism requiring the shear that is caused by differential rotation.

Detecting differential rotation on stars other than the Sun unfortunately is not as straightforward as on our host star. Other stars cannot (yet) be spatially resolved so that we cannot just follow the latitude-dependent motion of spot groups – on some stars such spots might even be absent. Instead, one has to apply indirect techniques. One way to detect differential rotation is the reconstruction of the stellar surface using Doppler Imaging (DI) and comparing the spot’s migration at different epochs. This method was applied successfully to many objects, and a summary of the state of the art is presented by Collier Cameron in this volume. DI correlates spot configurations between different epochs that can in principle be temporally separated as long as the lifetime of the spots, i.e. on the order of month in the Sun. Hence DI allows the detection of very small angular velocity differences. This method, however, requires that for each epoch the star is observed for a full rotation period in order to reconstruct a good picture of its surface. Depending on the rotation period and the brightness of the target that requires large amounts of telescope time, which in case of faint targets have to be quite big to ensure the small exposure times necessary for a good resolution of the surface.

A different approach to detect differential rotation is to scrutinize the shape of the rotationally broadened line profiles, which yields characteristic differences between rigid and differential rotation. This method was pioneered in the seventies (Gray, 1977). The problem of the degeneracy of differential rotation, limb darkening and inclination was investigated by several authors, (see Reiners & Schmitt 2002a and references therein). These authors also provide a recipe how to detect differential rotation in stellar line profiles.

Since then, differential rotation was searched for in more than a thousand spectra of stars from spectral types A–G. This resulted in many detections of differential rotation. The results of this project are published in Reiners & Schmitt (2003a, 2003b), Reiners & Royer (2004), and Reiners (2006). In this paper, I summarize the results concentrating on the dependency of differential rotation on temperature, rotation, and activity. I focus on the F-stars, i.e. I will take into account data from different samples for stars of colors $0.2 < B - V < 0.6$.

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Data are taken from Reiners & Schmitt (2003a, 2003b),
Reiners & Royer (2004), and Reiners (2006). The spectra
were obtained with FOCES (CAHA\textsuperscript{1}), FEROS, FLAMES,
CES and ECHELEC (ESO). In order to measure the rota-
tion law from a line profile of a star, it is required that the
profile is not distorted by features due to spots. Hence stars
that show asymmetries in their line profiles are neglected,
in their spectra it is not clear whether line profile distortions
are due to the rotation law or surface features. It should be
mentioned that also the symmetric line profiles could be
affected by spots, but the probability of a yielding a symmetric
line profile in the presence of spots is rather low (see Rein-
ers & Schmitt, 2002b). An exception to this are polar spots
that always lead to symmetric profiles, these are discussed
in Section 4.

A total number of 200 stars with colors $0.2 < B - V <$
0.6 yielded symmetric profiles from which the rotation law
could be determined. Many of the properties of differential
rotation were presented in Reiners (2006) and should not be
repeated here. In the following, I will focus on the stars that
do show differential rotation at all, and which parameters
affect or are affected by the presence of strong latitudinal
shear.

3 What parameters affect differential
rotation?

The measurement of differential rotation is carried out in the
deconvolved broadening function. From that profile, a
Fourier transform is calculated in which the ratio of the sec-
ond to the first zero is determined. This ratio is indicative

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of solar-like differential rotation (see Reiners & Schmitt,
2002a). However, depending on data quality and spectral
type, i.e., the number of useful lines, this ratio has also an
uncertainty. In the following, I will classify a star as differ-
entially rotating if the ratio $q_2/q_1$ indicates differential ro-
tation regardless of how significant this “detection” is (see
Reiners, 2006). The exact values of $q_2/q_1$ and their uncer-
tainty can be found in the references given above.

3.1 Effective Temperature

The upper left panel of Fig. 1 shows a histogram of the full
sample in color $B - V$, the subsample of differential rota-
tors is also plotted as a hatched histogram. In the lower left
panel, the fraction of stars with signs of differential rotation
is shown as a function of color. As mentioned in Reiners
(2006), there is a clear indication that cooler objects tend to
show differential rotation more frequently. The difference
to Fig. 3 in that paper is that about 50 more early F-stars
are added from the sample of Reiners & Royer (2004). This
leads to much better statistics in the early bins, but it does
not alter the results from Reiners (2006).

3.2 Rotation

The right panel of Fig. 1 shows a histogram of the sample
in $v \sin i$ in the upper panel and the fraction of differen-
tially rotating stars as a function of $v \sin i$ in the lower
panel. Again, the conclusions from Reiners (2006) are still
valid: detections of differential rotation are more frequent in
slowly rotating objects.

The observation that differentially rotating stars are
more frequently found among the late stars and among the
slow rotators is a significant result from line profile analy-
sis of several hundred F stars. However, both results are not
4 Negative differential rotation

Differential rotation might also be anti-solar like, i.e., the equator rotating at lower angular velocity than the polar regions. Obviously, this effect does influence stellar line broadening as well and could be detected in the presented data sample. In fact, there are a number of spectra that do show the observational signatures of anti-solar like differential rotation. However, the observational signature is identical to the signature of cool polar spots (see Reiners & Schmitt, 2002b), so that this relatively likely scenario (Schrijver & Title, 2001) may be the more realistic explanation. Nevertheless, negative differential rotation cannot be excluded in a couple of F stars.

5 Summary and outlook

I have presented the results from the analysis of several hundred high resolution spectra looking for differential rotation in F-stars. The fraction of stars with signatures of differential rotation in the overall sample of 200 stars is shown as a function of $B - V$ color, projected rotation velocity $v \sin i$, and normalized X-ray activity $\log L_X/L_{bol}$. The fraction of differential rotators shows a clear trend in color and rotation velocity, two parameters which unfortunately are not uncorrelated in the sample. So far the conclusion is that among the cooler, less rapidly rotating objects the fraction of differentially rotating stars is larger than among the hotter, more rapidly rotating stars. No trend is seen in the fraction of differential rotators as a function of activity.

From the current sample, it cannot be decided whether slow rotation, low temperature, or both conditions together drive the high fraction of differentially rotating stars. To decide this, observations in a well defined sample containing more slowly rotating early F-stars as well as more rapidly rotating late F-stars are required.

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