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Differential Rotation in Young Low-mass Stars

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Abstract. Multi-line Doppler imaging methods allow us to image young, rapidly rotating stars brighter than about $V = 11.5$, with $\sim 3°$ surface resolution. We have recently measured the latitude dependence of the surface rotation rate in three young G and K stars by cross-correlating Doppler images reconstructed from data sets secured several days apart. As a result, new theoretical models of solar and stellar internal rotation can be tested directly against the form, amplitude and spectral-type dependence of differential rotation in both Sun and stars. We present new maps of AB Dor, PZ Tel and RX J1508.6–4423, which all show a solar-like differential rotation pattern and rate of surface shear.

1. Introduction

The surface differential rotation rate of a star provides an important upper boundary condition on models of rotational shear in stellar convective zones. Rotational shear is the principal means of converting poloidal to toroidal flux in $\alpha - \omega$ models of stellar dynamos. Moreover, in simple kinematic plane-wave dynamo models, the drift of the active belts toward or away from the stellar equator depends on whether the rotation rate decreases or increases with depth in the dynamo layer. On the Sun , the equator rotates faster than the poles. Magnetic features migrate equatorward at low latitudes and poleward at high latitudes as the solar cycle progresses. More recently, helioseismology has revealed that the solar rotation rate remains more or less constant with depth in the convection zone at any given latitude (Gough 2000). The radiative interior, on the other hand, appears to rotate more rigidly.

Understanding the flow patterns within the convective zone is a formidable challenge. Recent theoretical studies employing mean-field turbulence models have, however, had considerable success in reproducing the latitude and depth dependence of the rotation rate in the solar convective zone (Kitchatinov & Rüdiger 1999).

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In order to extend this understanding to stars with rotation rates and convective zone depths different from the Sun, we need to identify reliable tracers of stellar surface rotation. For normal main sequence stars with rotation rates comparable to the Sun, the most successful tracer has been rotational modulation of Ca II *H* & *K* emission arising in localised magnetic active regions. In over 30 years of monitoring, the Mt. Wilson group have measured both axial rotation periods and magnetic activity cycle periods for a large number of stars in the solar neighbourhood (Baliunas et al. 1998).

Among this well-studied sample of stars, many have been found to exhibit variable or multiple rotation periods. Donahue & Baliunas (1994) interpreted these secular changes in rotation rate as evidence that the surface rotation rates of these stars are latitude dependent. Active regions at different latitudes thus yield diferent rotation periods. Donahue, Saar & Baliunas (1996) found the range of rotation periods ΔP measured for a single star over time, to be correlated with the mean stellar rotation period $< P >$ with a power-law dependence:

$$\Delta P \propto < P >^{1.3 \pm 0.1} . \tag{1}$$

In these stars, however, there is no way of determining the dependence of differential rotation with latitude. This requires a more sophisticated approach to determining the locations of features that can be used as rotation tracers on the stellar surface. Once this is done, the latitude dependence of the differential rotation can be determined by tracking the rotation of surface features at different latitudes. In the solar case, sunspots are an easily observable tracer that can be used in this way. In the stellar case, it is also possible to cross-correlate maps of the surface-brightness or magnetic-field distribution taken several days apart, to measure the relative rotation rates of features at different latitudes. The Doppler imaging technique allows us to do this for rapidly rotating late-type stars.

2. Doppler imaging with least-squares deconvolution

Doppler imaging (Vogt & Penrod 1983) uses bright travelling "bumps" in rotationally-broadened line profiles to reconstruct an image of the surface brightness distribution on a rapidly rotating star. The main requirement for successful Doppler imaging is that the rotational Doppler effect should be the dominant line broadening mechanism for the majority of photospheric absorption lines. Each surface element on the star contributes a limb-darkened and Doppler-shifted copy of the local specific intensity profile. Integration over the visible disk at any instant then gives the rotationally-broadened spectrum. A dark spot on the stellar surface can then be regarded as a region where there is a deficit in the local spectrum. This has the effect of depressing the continuum slightly at all wavelengths, and leaving bright but narrow "bumps" in the photospheric absorption-line profiles. For the case of solid-body rotation, the displacement of the bump from line centre is directly proportional to the projected distance of the spot from the stellar rotation axis. A sequence of spectra (Fig. 1) then shows these bumps drifting across the profile at rates dictated by the latitudes of the spots in which they originate.

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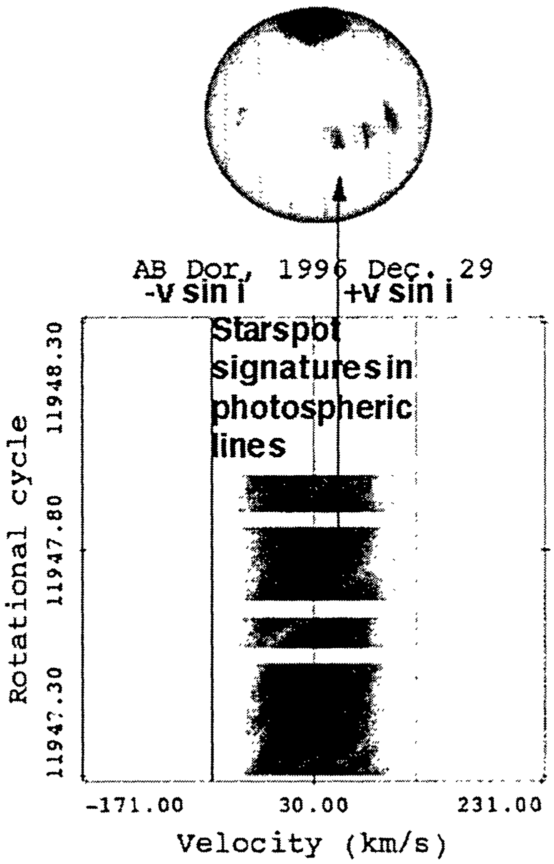

Figure 1. Schematic illustration of the basic principles of Doppler imaging for spotted stars. The spectral signature of the light “missing” from the spotted regions contains a Doppler-shifted absorption line, leaving bright bumps in the observed spectrum which migrate across the stellar disk at a rate that depends on the spot’s stellar latitude.

The resolution that can be attained on the stellar surface depends principally on the ratio of the intrinsic widths of the stellar photospheric lines, to the width of the rotational Doppler profile. In principal, resolutions of order a few degrees are attainable profile in stars with equatorial rotation speeds of order 100 km s^{-1} or more. The practical difficulties in achieving this goal arise from the need to measure the highly smeared rotation profile of the star at a very high signal-to-noise ratio (S/N), in a short exposure time (Collier Cameron 1992). The higher the rotation rate, the shallower the profiles become and the higher the S/N needed to detect a surface feature of given size. At high rotation rates, however, the radial acceleration of features is high enough that the spectral signatures of small surface features can become smeared during the course of an exposure long enough to attain the required S/N. The combination of high spectral resolution and short exposure times with the need to monitor targets over two or more complete nights of observation, has restricted surface imaging studies to telescopes of modest (2- to 4-metre) aperture, and to relatively bright objects (Strassmeier 2000).

The least-squares deconvolution (LSD) method, first applied by Donati & Cameron (1997) to a Doppler imaging study of the southern K-type rapid rotator AB Doradus, circumvents these problems by combining information from the thousands of images of intermediate-strength photospheric lines recorded in an echelle spectrum. The method, described in detail by Donati et al. (1997), approximates the observed spectrum as the convolution of a mean stellar plus instrumental profile, with a forest of delta functions at the wavelengths of thousands of known photospheric lines. The weights attached to the individual lines are in proportion to their equivalent widths in a star of the appropriate photospheric temperature, dnd are derived from a model atmosphere and spectrum synthesis. The multiplex gain in the S/N of the composite profile over the individual line profiles in the original spectrum, scales in proportion to $\sqrt{N}$ where N is the number of lines used. In this way it is possible to boost the S/N by a factor 30 or more.

3. Differential rotation rates from Doppler imaging

Donati & Collier Cameron (1997) and Donati et al (1999) applied least-squares deconvolution to echelle spectra of the rapidly rotating southern K0 dwarf star AB Doradus in 1995 December and 1996 December. The observations were secured with the UCL Echelle Spectrograph (UCLES) on the 3.9-m Anglo-Australian Telescope, fed by a dual-fibre circular spectropolarimeter mounted at the cassegrain focus of the telescope. The instrumental configuration is described in detail by Donati et al. (1997).

Donati & Collier Cameron (1997) cross-correlated images of AB Doradus secured 5 nights apart in 1995 December , to determine the latitude dependence of the differential rotation on this star. They fitted a rotation law of the form:

$$\Omega l = \Omega_0 - \Delta\Omega \sin^2 l \text{ radian d}^{-1}, \tag{2}$$

similar to that used for the Sun but omitting higher-order terms. The coefficient $\Delta\Omega$ of the term in $\sin^2 l$ in Eq. 2 is the beat frequency between the polar and equatorial rotation periods. The best-fitting value of this coefficient for AB Dor, $\Delta\Omega = 0.0564$ radians per day, implies that the stellar equator pulls a complete rotation ahead of the polar regions every $2\pi/\Delta\Omega \simeq 110$ days. The result was confirmed with a more extensive data set secured in 1996 December by Donati et al. (1999).

Figure 2 shows the three images from the latter data set, together with the latitude-by-latitude cross-correlation functions derived from the surface-brightness and magnetic-field maps. The width of the cross-correlation peak indicates that majority of features contributing at low to intermediate latitudes have an extent of only 2 or 3 degrees in longitude. This confirms that we are indeed detecting surface structure repeatably on these scales, and the effects of differential rotation are clearly seen.

Donati et al. (2000) secured a pair of images of the pre-main sequence G star RX J1508.6–4423 on 1998 May 06 and 10. Although most of the activity in this object appears to be concentrated at high latitudes, a latitude-by-latitude cross-correlation of the two images yielded strong evidence of differential rotation.

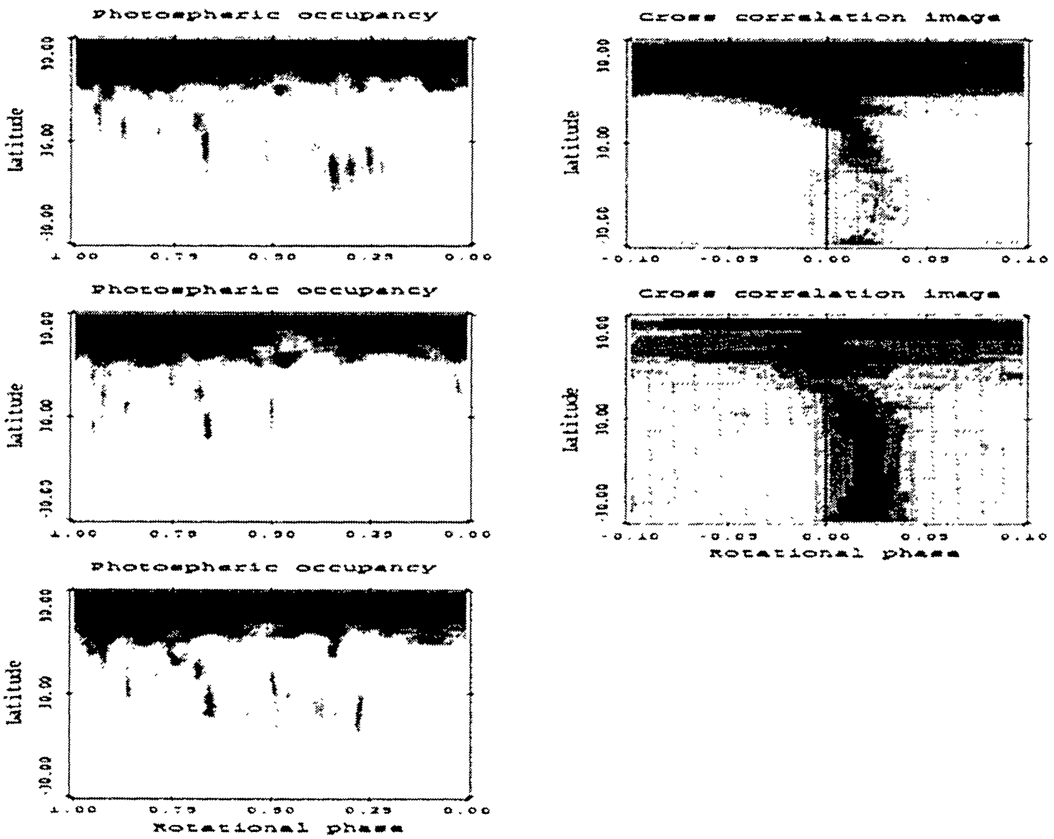

Figure 2. Three maps of the surface brightness distribution on AB Dor, on the nights of 1996 December 23+25 (top), 27 (middle) and 29 (bottom). Note relative phase drift of high- and low-latitude features in the best-observed phase range in the left-hand half of each map. The cross-correlation images at right are derived from brightness maps (upper) and the magnetic maps (lower). Adapted from Donati et al. (1999).

Barnes et al. (2000) applied the same technique to the more slowly rotating star PZ Tel, using echelle data secured simultaneously at using the 1.9-m telescope at the South African Astronomical Observatory and the 3.9-m Anglo-Australian Telescope, on 1998 July 09, 10 and 12. Although this star rotates almost a factor two more slowly than AB Dor, a similar pattern of rotational shear was found.

The stellar parameters and differential rotation rates are listed for all three stars, together with the Sun, in Table 1.

4. Comparison with slower rotators

The lap times in which the equator pulls a full turn ahead of the poles are thus remarkably similar to that of the Sun, in all three of the rapid rotators studied so far. If we measure the corresponding difference in rotation period, ΔP, and plot it against the mean rotation period at intermediate latitudes, we may plot

Table 1. Stellar parameters and differential rates from starspot tracking.

Star	Sp. type	$M/M_\odot$	Age (Myr)	$T_{\rm eff}$ (K)	$P_{\rm rot}$ (day)	Ω_0 (radian/day)	$\Delta\Omega$ (radian/day)
RX J1508–4423	G2	1.3:	15	5750	0.31	20.28	0.15[a]
AB Dor	K0/2 V	1.0:	30	5000	0.515	12.2434	0.0564[b,c]
PZ Tel	K0 IV/V	1.3:	20	5000	0.94	6.65	0.075[d]
Sun	G2V	1	4600	5780	27	0.235	0.0524

[a] Donati et al. (2000)

[b] Donati & Cameron (1997)

[c] Donati et al. (1999)

[d] Barnes et al. (2000)

these stars on an extended version of the ΔP versus P relation of Donahue, Saar & Baliunas (1996), as shown in Fig. 3.

The figure suggests that over a range of periods spanning two orders of magnitude, $\Delta\Omega$ depends very weakly if at all on rotation rate. There is possibly a slight tendency for stars with thinner convective zones to have higher differential rotation at a given rotation rate. If this were the case it might explain the apparently shallow slope of the fit to the Mt. Wilson data. The G and K stars in the Mt. Wilson sample do not have similar period distributions, but dominate the shorter and longer periods respectively.

5. Comparison with theory

Kitchatinov & Rüdiger (1999) recently developed a stellar differential rotation model capable of reproducing the solar interior and surface differential rotation, that makes testable predictions concerning the surface differential rotation of rapidly rotating stars such as those studied here. This model uses a mean-field approach to the hydrodynamics of rotating fluids (Rüdiger 1989). It defines the global axisymmetric flow and heat transport in a rotating spherical convective shell. For given stellar structural model, it provides the angular velocity distribution, meridional flow pattern, and entropy profile in the convection zone. It has a single free parameter, the ratio of the mixing length to the pressure scale height.

On the of the strongest predictions to emerge from this model is that the differential rotation rate $\Delta\Omega$ should vary only weakly with rotation rate, yielding

$$\frac{\Delta\Omega}{\Omega} \propto \frac{1}{\Omega^{1.56}}$$

at the solar rotation rate, and

$$\frac{\Delta\Omega}{\Omega} \propto \frac{1}{\Omega}$$

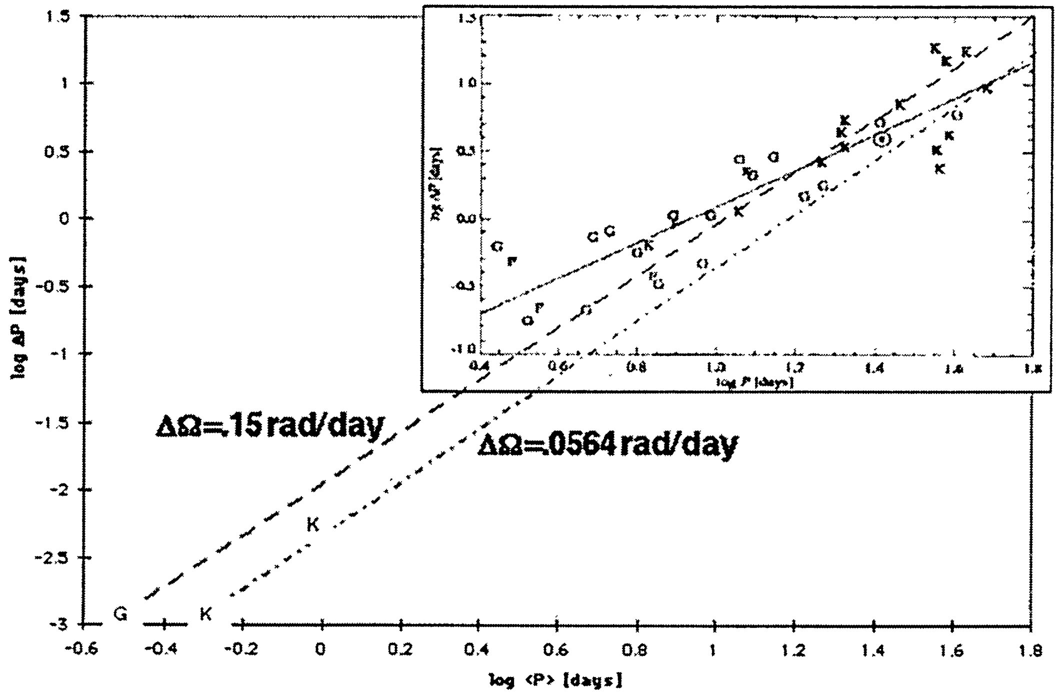

Figure 3. Spread in rotation periods versus mean rotation period for AB Dor and PZ Tel (K) and RX J1508–4423 (G), together with the sample of F, G and K stars studied by the Mt. Wilson group. The straight lines plotted on the extended version indicate a relation of the form $\Delta\Omega$ =constant. The upper-right panel is adapted from Donahue, Saar & Baliunas (1996).

at $P_{\rm rot} = 1$ day. The model also predicts that $\Delta\Omega$ should be higher in G stars than in K stars at fixed Ω. We have recently extended this work to simulate the internal rotation of AB Dor (Kitchatinov et al, work in progress). The model reproduces both the observed form and rate of surface differential rotation to within 20%.

6. Summary and future prospects

Recent advances in cheap computational power allow us to apply powerful new signal-enhancement methods to Doppler imaging data secured with 2m- to 4m-class telescopes. As a result we can now obtain high-cadence time-series observations of rotationally broadened line profiles at high spectral resolving power, without compromising the signal-to-noise ratio. The wealth of surface detail we find in surface images recovered with these methods is repeatable in independent datasets. Cross-correlation of pairs of such images secured several days apart allows us to determine both the effective surface resolution on the star (from the width of the CCF peak) and the surface differential rotation rate. To date we have measured the surface differential rotation rates of three stars in this way. When combined with the differential rotation rates inferred for more slowly-rotating stars by the Mt. Wilson group, it appears that the rate of surface shear depends weakly if at all on the rotation period of the star. This trend is in excellent agreement with the predictions of internal rotation models based on a mean-field approach. We are currently working to extend our differential rotation observations to a wider range of rotation rates and spectral types.

Discussion

A. F. Lanza: What about the lifetimes of the small surface features you use to track photospheric differential rotations?

A. Collier Cameron: As far as we can determine, the small-scale structures that produce the main correlation ridges only persist for a month or so. Barnes et al. (1998) compared Doppler images of a G dwarf in the α Per cluster, taken a month apart. No clear correlation was found between the two images, suggesting that the small features had lost their identity in the intervening month. I'd like to emphasize, however, that this result only applies to dwarfs. The situation could be different in giants or subgiants.

K. G. Strassmeier: I just want to remind you that spot lifetimes are likely related to the rotational period. Spots on giants can last for years and thus can be used as tracers for differential rotation!

A. Collier Cameron: Yes - I think the evidence I've seen in the posters at this meeting, particularly Svetlana Berdyugina's work on II Peg, has gone a long way towards establishing that spot lifetimes in subgiants and giants are considerably greater than we find in young stars near the main sequence. I suspect that luminosity class may be more important than rotation period, however, in determining spot lifetimes.

J. L. Linsky: Is differential rotation in eclipsing tidally-locked systems like RS CVn itself similar or different from what you are learning about rapidly-rotating single stars?

A. Collier Cameron: There's some evidence to suggest that in some such systems, high-latitude structures may be present that rotate faster than the orbital angular velocity. The posters by the Oulu group at this meeting suggest that this may be happening. From the theoretical viewpoint, I don't know if anybody has taken on the problem of computing circulation models for tidally-locked systems. Even single stars are providing a pretty tough challenge at present!

N. Piskunov: Could the differential rotation of AB Dor be influenced by tidal interaction with the companion star?

A. Collier Cameron: I don't expect this to be the case. The orbital period of the low-mass astrometric companion, AB Dor C, is between 6 and 27 years according to Guirado et al. (1997). Although the orbit appears to be eccentric, it's unlikely that AB Dor C approaches within less than 0.7 AU or so even at periastron.

D. O. Gough: Galileo and Scheiner, and some others after them, measured differential solar rotation from sunspot motions, which implies that their measurements were confined to the equatorial regions. Because the solar photospheric angular velocity is well approximated by

$$\Omega \simeq \Omega_0(1 - \alpha_2 \cos^2 \theta - \alpha_4 \cos^4 \theta),$$

where θ is colatitude, with $\alpha_4 \simeq \alpha_2 \simeq 0.14$, fitting functions of this form with α_4 set to zero must give a value of α_2 that depends on the latitude range in which the fitting is carried out. Indeed, the solar equator laps the poles in about 90 days, whereas the two-term fit you quote yields 120 days. I therefore ask whether there is a variation amongst the stars you have observed in the range of latitudes in which you have succeeded in tracking spots, for if there is your inferences concerning $\Delta\Omega$ may be susceptible to bias.

A. Collier Cameron: We can't trace the differential rotation reliably at latitudes greater than 60° or so, for two reasons. First, the line spread function degrades our longitude resolution at high latitudes. Second, the three stars we've done so far had extensive dark polar caps at the epochs of observation, so cross-correlation doesn't yield anything useful at high latitudes. The uncertainty in the value of $\alpha_2\Omega_0$ is about 10 to 20%, so we can't justify a higher-order fit. I agree that this could introduce a small bias in the absolute value inferred for the lap time. But since we use a range of latitudes that is similar to the range of spot latitudes found on the Sun, the differential rotation rates we obtain should not be too badly biased in relative terms at least.

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