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Indications for anti-solar differential rotation of giant stars

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Abstract. Observational evidence of anti-solar differential rotation of K-type giant stars is presented. Time-series Doppler imaging based on 70 nights of spectroscopic data was used to derive the spot evolution of the stellar surfaces. The relative differential rotation parameters (α) of the binary stars IM Peg, HD 208472, and HK Lac were obtained using two techniques, cross-correlation analysis and the sheared-image method. Additionally, two previously published single giant stars are revisited and qualitatively compared to recent theoretical models.

Key words: stars: spots – stars: activity – stars: imaging – stars: individual (IM Peg, HD 208472, HK Lac, KU Peg, HD 31993)

1. Introduction

In order to study the short-term variability of spots on late-type active stars, we carried out a 65 night observing run at the National Solar Observatory (NSO) in 1996, a 21 night run in 1997/98 at the Kitt Peak National Observatory (KPNO), and in 2000 a double 14 night (with 15 nights separation) observing run, again at KPNO. We used the stellar spectrograph at the NSO/McMath–Pierce telescope with a spectral coverage of approximately 45Å and a spectral resolution of approximately 40,000, and the KPNO/coudé–feed's spectrograph with a spectral coverage of 300Å and a resolution of ≈30,000. Supplemental photoelectric observations were made using our Amadeus 0.75-m automatic photoelectric telescope (APT), part of the University of Vienna twin APT at Washington Camp in southern Arizona.

Time series Doppler imaging was performed on all stars in the sample, and measurements of the evolution of the stellar surface features were attempted for all stars.

The differential-rotation signals detected for some of the stars in the observed sample exhibit anti-solar behavior, meaning that the rotation rate at the pole is higher than that at the equator. These stars are the binaries IM Peg, HD 208472, HK Lac, and the single star HD 31993. Another effectively single star, KU Peg, exhibits a similar behavior as HD 31993, namely acceleration of the rotation rate at low latitudes and deceleration at higher latitudes. Even though its pole rotates slower than the equator, it is nevertheless included here. Until recently, anti-solar differential rotation has been in contradiction with theory, e.g. Kitchatinov & Rüdiger (1999), but recently it has been theoretically confirmed for single giant stars by Kitchatinov & Rüdiger (2004).

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2. Binary stars

2.1. HK Lacertae

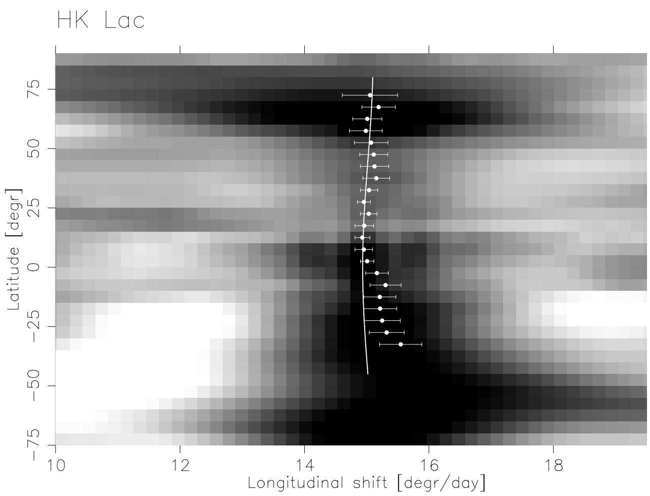

Fig. 1. Average cross-correlation image of HK Lac (dark color meaning good correlation), based on all NSO 1996 data. The solid line represents a differential-rotation law with α=−0.05, the dots are the measured maxima of the cross-correlation function.

HK Lac (K0III, $V_{\max}$ =6.8) is a RS CVn-type binary system with an orbital (and rotational) period of 24.42 days. As for most of the stars in our sample, we computed an average cross-correlation image from a number of consecutive subsets of the NSO 1996 data (Fig. 1). A least-square fit of a solar-like differential-rotation law results in an insignificant α=−0.001. Applying the *sheared-image* method on the data from KPNO 1997/98, one gets an equatorial rotation period of 24.2±0.1 days and α=−0.05±0.05. This is more significant than the cross-correlation result, but still quite uncertain (Fig. 2). It seems that HK Lac exhibits anti-solar differential rotation, but possibly the differential rotation pattern is masked by either rapid spot evolution or another motion pattern.

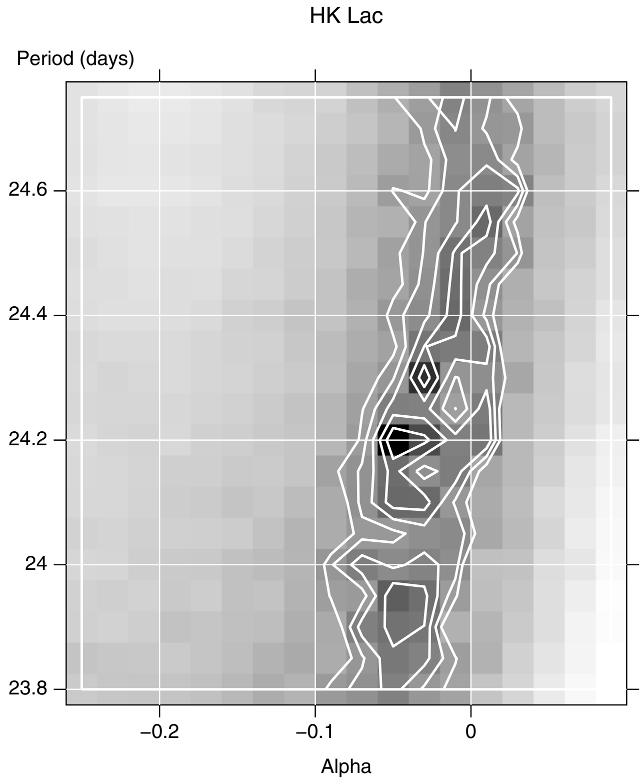

Fig. 2. χ^2 landscape calculated from the 1997/98 data. The solid lines are contours of constant χ^2. Assuming a rotation period of approximately 24.2 days, the most probable α-value is −0.05.

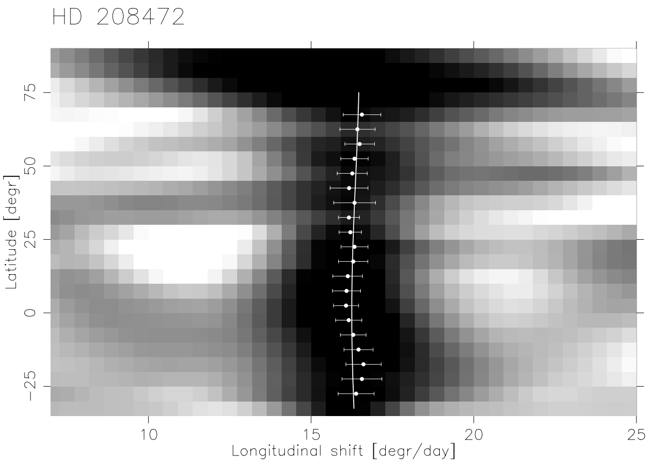

Fig. 3. Average cross-correlation image of HD 208472 (dark color meaning good correlation), based on all NSO 1996 data. The solid line represents a differential-rotation law with α=−0.03, the dots are the measured maxima of the cross-correlation function.

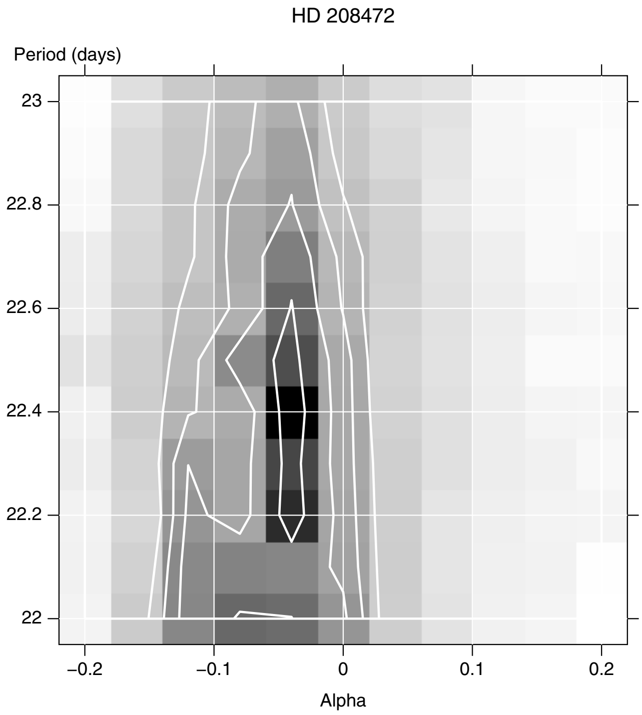

Fig. 4. χ^2 landscape calculated from the NSO 1996 data. The solid lines are contours of constant χ^2. The most probable α-value derived from this plot is −0.04.

2.2. HD 208472

HD 208472 (K0 III, $V_{\max}$ =7.48) is a RS CVn-type binary system with an orbital period of 22.6 days. We computed an average cross-correlation map using 23 consecutive subsections of the available data set. The result (Fig. 3) exhibits a differential rotation parameter α=−0.03±0.04 and an equatorial rotation period of 22.09 ± 0.10 days. The application of the *sheared-image* technique to the same data set (Fig. 4) lead to a encouragingly similar result of α=−0.04±0.02.

2.3. IM Pegasi

IM Peg (K2 III, $V_{\max}$ =5.8) is a RS CVn-type binary system with an orbital period of 24.6 days. As for HK Lac and HD 31993, only two independent Doppler maps were obtained from our data set. By averaging 50 cross-correlation maps obtained by Monte-Carlo variation of the number of phases in the corresponding Doppler images (Fig. 5), we get a differential-rotation parameter α=−0.04±0.03 and an equatorial rotation period of 25.0 ± 0.33 days. Using the *sheared-*

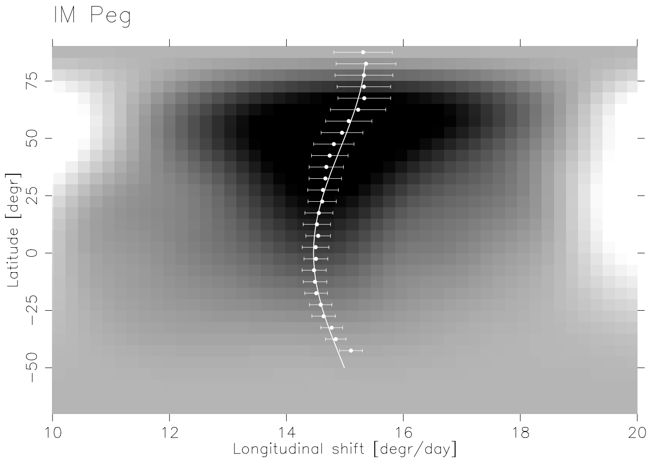

Fig. 5. Average cross-correlation image of IM Peg (dark color meaning good correlation), based on all NSO 1996 data. The solid line represents a differential-rotation law with α=−0.04, the dots are the measured maxima of the cross-correlation function.

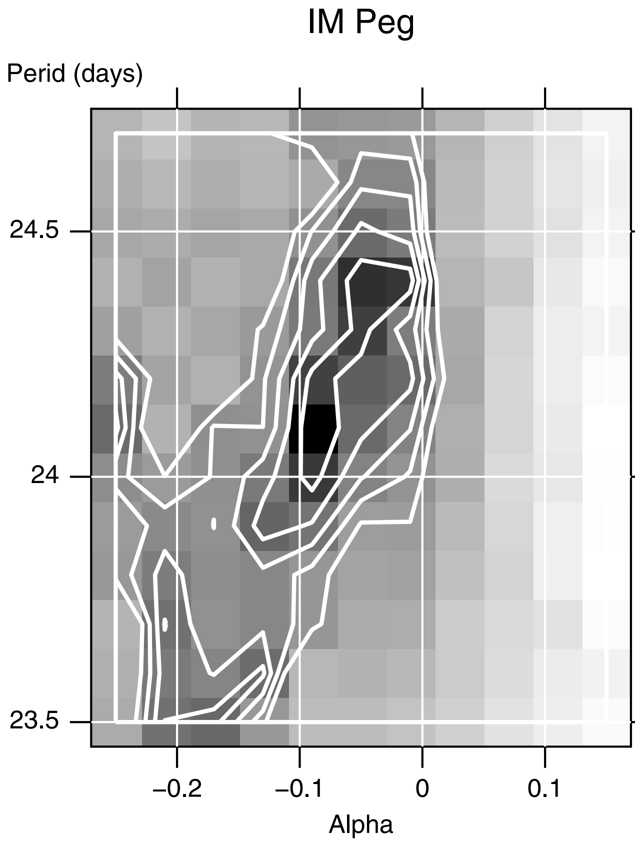

Fig. 6. χ^2 landscape calculated from the NSO 1996 data. The solid lines are contours of constant χ^2. The most probable α-value derived from this plot is −0.05.

image method (Fig. 6), one gets again a very similar measure of $\alpha \approx -0.05 \pm 0.05$.

2.4. Summary

The three giant stars presented here all show some sign of anti-solar differential rotation. unfortunately, the quality of the data and the available spectral resolution would need to be higher to draw more firm conclusions. All the detections of differential rotation are only marginal, better measurements are necessary to compare them with theory. Kitchatinov & Rüdiger (2004) presented an explanation for anti-solar differential rotation. They demonstrated this for single stars with large magnetic spots, but speculate that binarity could lead to a similar result. Thus, anti-solar differential rotation could be a common phenomenon on active giant stars, both single and binary.

3. Single stars

3.1. HD 31993

HD 31993 (K2 III V=7.48) is a single giant with a stellar rotation period of 25.95 days. It has only very small (δV=0.01mag) light-curve variations and only small deformations in the spectral line profiles. Therefor we averaged 50 cross-correlation maps obtained by Monte-Carlo variation of the number of phases in the corresponding Doppler images for the first and second stellar rotation covered by our observations. A least-squares fit to the corresponding cross correlation image resulted in a differential rotation function of $\Omega(b) = 13.87 + 1.73 \sin^2 b$ °/day (Fig. 7). We obtained $\alpha = \Omega_1/\Omega_0 = -0.125$ and a (polar) lap time of $1/\Omega_1$=208 days Strassmeier et al. (2003).

Using only the upper part (positive latitudes) of the Doppler images, one can measure the surface evolution in latitudinal direction. Using the same images as above, but with the lower half chopped off, one can obtain an average cross-correlation function for the latitudinal motion (Fig. 8). The latitudes around 180° and 315° stand out, showing a pole-ward flow of the order of 0.5°/day. This corresponds to a velocity at the stellar surface of approximately 1100 m/s. But one has to keep in mind, that this measure is highly uncertain, since the surface resolution on the stellar surface is limited by the relatively low spectral resolution of the NSO spectra. We therefore take this merely as evidence for a pole-ward surface flow, but conclude that observations of better quality need to be obtained for significant results.

3.2. KU Pegasi

KU Peg (G9-K0 II-III, V = 7.61–7.72) is a single giant with a stellar rotation period of 23.77 days. We constructed two consecutive independent Doppler images from the available data. A least-squares fit to the resulting cross correlation image resulted in a differential rotation function of $\Omega(b) = 15.14 - 0.47 \sin^2 b$ °/day (Fig. 9). We obtained $\alpha = \Omega_1/\Omega_0$ =0.03 and an equatorial lap time of $1/\Omega_1$=766 days Weber & Strassmeier (2001).

As for HD 31993 above, one can cross correlate the upper halves of the Doppler images in latitudinal direction. The resulting cross-correlation function (Fig. 10) exhibits a pole-ward flow at latitudes of 40° and 330° with a peak velocity of 0.3 and 0.4 °/day, respectively. This corresponds to a surface velocity of approximately 750 and 1000 m/s. As outlined for

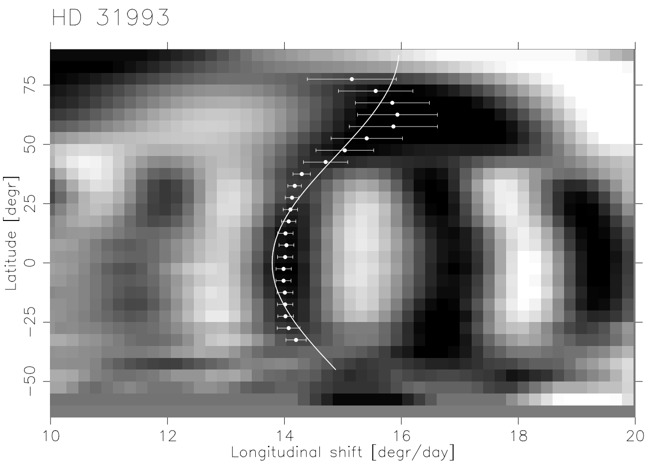

Fig. 7. Average cross-correlation image of HD 31993 (dark color meaning good correlation), based on all NSO 1996 data. The solid line represents a differential-rotation law with α=−0.125, the dots are the measured maxima of the cross-correlation function.

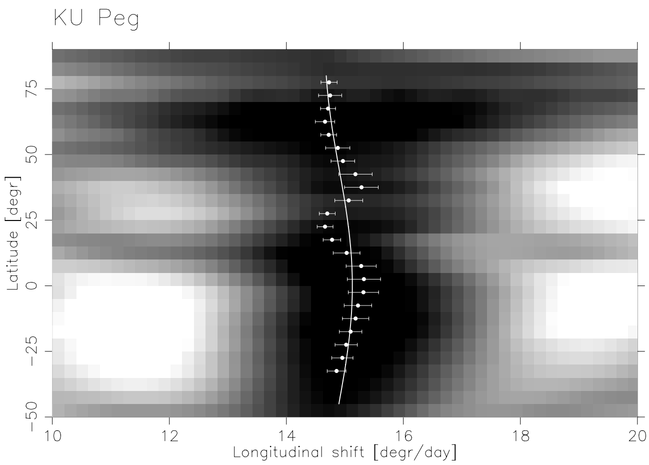

Fig. 9. Average cross-correlation image of KU Peg (dark color meaning good correlation), based on all NSO 1996 data. The solid line represents a differential-rotation law with α=0.03, the dots are the measured maxima of the cross-correlation function.

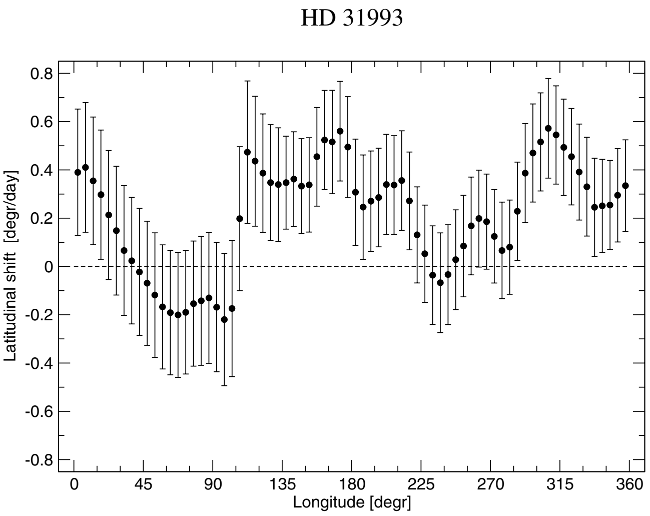

Fig. 8. Latitudinal cross correlation of HD 31993.

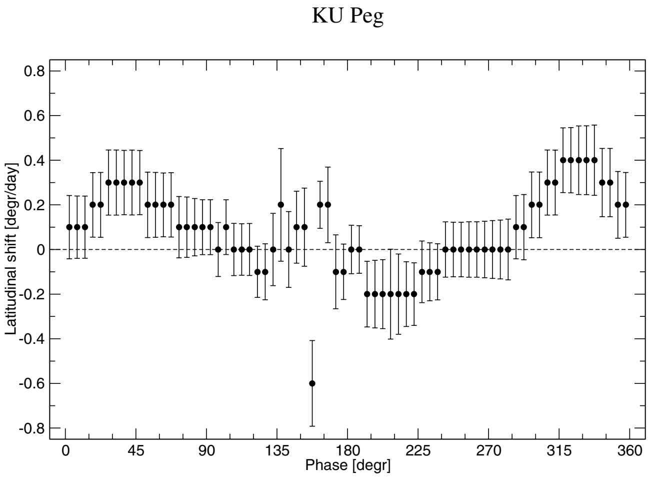

Fig. 10. Latitudinal cross correlation of KU Peg.

HD 31993 above, this should only be taken as evidence for pole-ward flows. Repetition of the measurements based on higher quality spectra are needed to draw further conclusion.

3.3. Discussion

Even though the two single stars presented here are of bigger radius and lower mass than the model used by Kitchatinov & Rüdiger (2004), it is nevertheless interesting to qualitatively compare the results.

HD 31993 has a differential rotation curve which is very similar to the one presented in Kitchatinov & Rüdiger (2004). Starting from the equator, first the rotational rate accelerates up to a turning point around 50–60°, then the rotation decelerates up to the pole. But the polar rotation rate is still higher than the equatorial one. Also, the qualitative result that the polar rotation rate is 10% faster than the equatorial one is reproduced. Comparing the meridional flow, the agreement is not as good, since the model predicts approximately 100 m/s, while the observations suggest a velocity that is 10 times higher ($\approx$ 1100 m/s).

In the case of KU Peg, the similarity between the model and the results from Doppler imaging a little worse. Although the differential rotation function also has a turning point at mid latitudes (here it is about 40°) and there seems to be a component moving in anti-solar direction, the pole rotates about 3% slower than the equator. This would still be compatible with the model from Kitchatinov & Rüdiger (2004) for weaker (less than $\approx$ 100 G) magnetic fields. The meridional flow derived in the model is again roughly 100 m/s, and the flow derived from cross-correlation of the Doppler images is 750 and 1000 m/s, which is again about 10 times the expected value.

However, specific models for these two stars should be constructed. One could then see if the model values of the meridional flow match the observations more closely, and if the magnitude of the magnetic field can be obtained by fitting the differential rotation function. Additionally, polarimetric observations can be used to obtain an independent measure of the magnetic field of these stars. Moreover, an extension of these models to binary stars would largely increase the sample of stars the model can be applied to.

With upcoming robotic observatories like STELLA Strassmeier et al. (2004a), long term observations for a study like the one presented here are becoming easier to carry out. This makes the extension to a larger sample of stars possible, and also eases the confirmation of the results presented here using data of higher quality and resolution.

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