EVOLUTION OF STELLAR ACTIVE REGIONS: DIFFERENTIAL ROTATION OF FIVE K GIANTS

M. Weber\textsuperscript{1} and K. G. Strassmeier\textsuperscript{1}

Astrophysical Institute Potsdam (AIP), Germany

Abstract

We present results from time series Doppler imaging of K-type giant stars observed over a period of 70 d. The evolution of the reconstructed starspots was monitored over the available time span, which represented at least two rotation periods for all of the stars. We fitted a solar type differential rotation law to the average cross-correlation images computed for each of the program stars. Wherever possible, a sheared image analysis was done on supplementary data that was not suitable for the cross-correlation technique. The differential rotation parameters $\alpha$ of these stars together with comparable values found in the literature are then plotted in the $\alpha$ vs. period plane to detect possible correlations.

Key words: Stars: activity – Stars: imaging – starspots

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 resolution of approximately 40 000, and the KPNO/coudé–feed’s spectrograph with a resolution of $\approx 30 000$. 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.

IL Hydrae was observed during all three observing runs, HK Lac during the first two, all other stars presented here were only observed during the NSO run in 1996. We divided the data sets of the individual stars into independent subsets. For each of those subsets, one Doppler image was computed if possible (for HK Lac and IM Peg the phase coverage of the incomplete third data set was not sufficient for an independent image). These images are usually averaged over two to three (four for the KPNO 2000 data) Doppler maps computed from different spectral lines. The lines used (along with typically five line blends) were Fe I 6411 (where available), Fe I 6430 and Ca I 6439. For the KPNO 2000 data we additionally used Fe I 6393.

2. IL Hydrae

IL Hydrea = HD 81410 is an K0III-IV RS CVn-type double-lined spectroscopic binary. Its orbital period, $P_{\text{orb}} = 12.904982$ d, while its photometric period is about 12.73 d. Data suitable for Doppler imaging is available from KPNO 1994, 1995, 1997/98, and 2000, and from the NSO 1996 run. We used the 1996 data for the cross correlation analysis (Fig. 1 left) and the KPNO 1997/98 data for sheared image analysis (Fig. 1 right). For comparison, we also did a sheared image analysis of the data sets from 1994 and 2000 (Fig. 2), but the results are not as convincing for those epochs as for the 1997/98 data. The derived values for the differential rotation parameter are $\alpha = -0.025$ for the cross-correlation analysis and $\alpha = 0.03$ for the sheared image analysis.

Here the premises for the sheared image technique can be clearly seen: The 1997/98 data spans 1.5 stellar rotations, S/N is above 200, spectral resolution is 38 000. For the 2000 data the data spans 2 rotations but with a gap of one rotation and with sparse coverage of one of the two rotation, S/N is also above 200, but the spectral resolution is only 25 000. For the 1994 data the spectral resolution and the signal is comparable to 1997/98, but the data covers only one stellar rotation. Additionally, the lightcurve amplitude and therefore the spot contrast, is highest for the 1997/98 epoch. Thus, a resolution of about 50 000, high signal-to-noise ratio (> 200), and a dense phase coverage spanning more than one stellar rotation are needed, making the STELLA telescopes ideal for this work.

3. HK Lacertae

HK Lac (K0III, $V_{\text{max}} = 6.8$) is a RS CVn-type binary system with an orbital (and rotational) period of 24.42 d. As for most of the stars in our sample we computed an average cross-correlation image starting from a number of consecutive subsets of the NSO 1996 data (Fig. 3 left). A least square fit of a solar-like differential-rotation law results in an insignificant $\alpha = -0.001$. Applying the sheared image method on the data from KPNO 1997/98, one gets $\alpha = -0.05$, but with an uncertainty of about the same order of magnitude (Fig. 3 right). 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.

4. HD 208472

HD 208472 (K0 III, \(V_{\text{max}} = 7.48\)) is a RS CVn-type binary system with an orbital period of 22.6 d. We computed an average cross-correlation map using 23 consecutive sub-sections of the available data set. The result (Fig. 4 left) exhibits a differential rotation parameter \(\alpha = -0.03\). Application of the sheared image technique to the same data set (Fig. 4 right) lead to the similar result of \(\alpha = -0.04\).

5. IM Pegasi

IM Peg (K2 III, \(V_{\text{max}} = 5.8\)) is a RS CVn-type binary system with an orbital period of 24.6 d. As for HK Lac and HD 31993, only two independent Doppler maps were obtained from our data set. The results presented here are preliminary and based on Doppler maps from only one spectral line (Ca i 6439). By averaging 50 cross-correlation maps obtained by Monte-Carlo variation of the number of phases in the corresponding Doppler images (Fig. 5 left), we get a differential-rotation parameter \(\alpha = -0.04\). Using the sheared image method (Fig. 5 right), one gets \(\alpha \approx -0.05\), but with an uncertainty of the same order of magnitude.

6. II Pegasi

II Peg (K2 IV, \(V_{\text{max}} = 6.9\)) is a RS CVn-type binary with an orbital period of 6.7 d and is thus the star with the
shortest period of our sample. This allowed us to compute five independent Doppler maps, which are separated by 1.5 to 2 d.

We cross-correlated the first Doppler images with all other images, and tried to fit a solar-type differential-rotation law to the resulting correlation functions. Since these results were not too convincing we again subdivided the data into many successive sets (here 26) and averaged the resulting cross correlations. The resulting average cross-correlation image is shown in Fig. 6, the differential rotation law fitted to this data represents a value of $\alpha=0.04$. The sheared image analysis on this data did not show a minimum. This together with the low significance of the cross-correlation measurement makes this differential rotation measurement quite uncertain.

7. Summary
To attempt a detailed analysis of the results, the values derived here were combined with differential rotation measurements obtained using Doppler imaging. Data of the following stars was used: LQ Lup (Donati et al. 2000), HD 197890 (Wolter 2004), AB Dor (Donati & Col-
Figure 5. Left: Cross-correlation image of IM Peg (dark green color meaning good correlation) with a least square fit of a solar-type differential rotation law. Right: $\chi^2$ landscape constructed using the same data, contour lines of equal $\chi^2$ are shown.

Figure 6. Left: Cross-correlation image of II Peg (dark green color meaning good correlation) with a least square fit of a solar-type differential rotation law. Right: $\chi^2$ landscape constructed using the same data.

... values used are summarized in Fig. 7.

All stars of our sample show differential rotation to some degree. Some of our sample stars seem to have a pattern more complex than the Sun (e.g. HD 218153, see Weber & Strassmeier 2001, or IL Hya). However, all of them show systematic trends. Note that since the latitudinal position is not as well reconstructed as the longitudinal one, a complex pattern in our cross-correlation images does not necessarily mean a complex differential-rotation pattern on the stellar surface. In Fig. 8 we plot the $|\alpha| = |\Omega_1/\Omega_0|$ values of our sample stars against their rotation periods. The left panel shows the stars with positive $\alpha$ (where the equator rotates faster than the pole), the right panel the stars with differential rotation in the opposite sense.

It has been claimed that binarity can suppress differential rotation. We therefore tried to distinguish binaries from effectively single stars. Fig. 9 shows the result which suggests a smaller exponent (effectively zero) for binaries than for single stars.
Evolution of stellar active regions: differential rotation of five K giants

Figure 8. Left: The correlation of the differential rotation parameter $\alpha = \delta \Omega / \Omega$ with rotational period (at the equator) for the stars which show solar-like differential rotation. The solid line is a exponential fit with an exponent of $0.87 \pm 0.46$. Right: The same for anti-solar rotation. The exponent is $5.1 \pm 4.0$.

Figure 7. The correlation of absolute value of the differential rotation parameter $\alpha = \delta \Omega / \Omega$ with rotational period (at the equator) for all stars used here. The exponent of the fit is $1.14 \pm 0.67$.

Figure 9. The correlation of the absolute value of the differential rotation parameter $\alpha$ with rotational period for binaries and for single stars. The exponent is $0.25 \pm 0.24$ and $0.75 \pm 0.51$, respectively.

Acknowledgements
We acknowledge support from the German BMBF Verbundforschung and from the Deutsche Forschungsgemeinschaft (DFG) grant STR 645/1.

References