Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Doppler Imaging of Stellar Surface Structure: The Differential Rotation of the K-giant IL Hydrae

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Abstract. We re-determined the differential rotation law at the surface of the K giant IL Hydrae (P_{rot}≈12.9 days). Using new NSO and KPNO spectra covering five consecutive rotations in 1996 and two rotations 15 days apart in 2000, we cross-correlate three independent Doppler images from 1996 and two from 2000. Assuming a solar-like differential rotation law, we derive $\alpha = \Omega_1/\Omega_0 \approx -0.047$ and $1/\Delta\Omega \approx$277 days. This is more than double the solar value of 120 days and in the *opposite* direction, i. e. the polar regions rotate faster than the equatorial regions. This result is in contrast to earlier measurements showing a weak differential rotation in the same direction as the Sun, but based on only two Doppler images taken one year apart. This indicates, that average spot lifetimes on IL Hya are on the order of a few stellar rotations.

1. Introduction

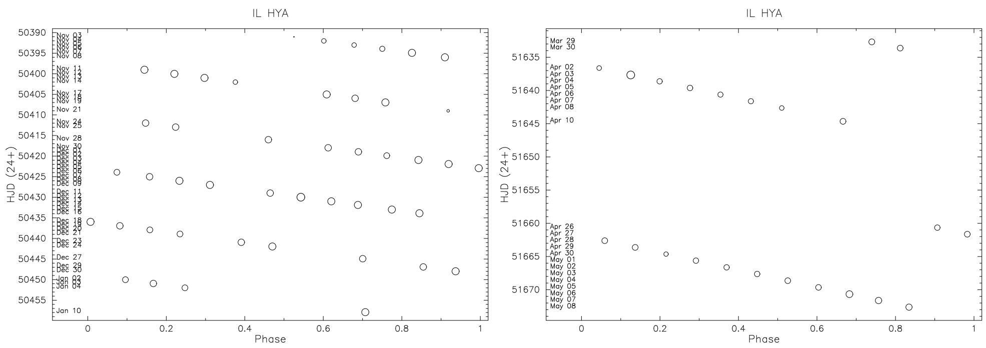

Figure 1. Distribution of the rotational phases of IL Hya versus date for the 1996/97 NSO run (**left**) and for the 2000 KPNO run (**right**). The sizes of the circles are proportional to the S/N ratio of the spectra.

IL Hydrae = HD 81410 is an K0 III-IV RS CVn–type double-lined spectroscopic binary. A summary of the stellar parameters used for our computations (along with the first Doppler maps for this star) can be found in Weber & Strassmeier(1998) (paper V), but for phase calculation we used the updated values $P_{\rm orb}$=12.904982 days and T_0=2447093.4936 from Fekel et al.(1999). In

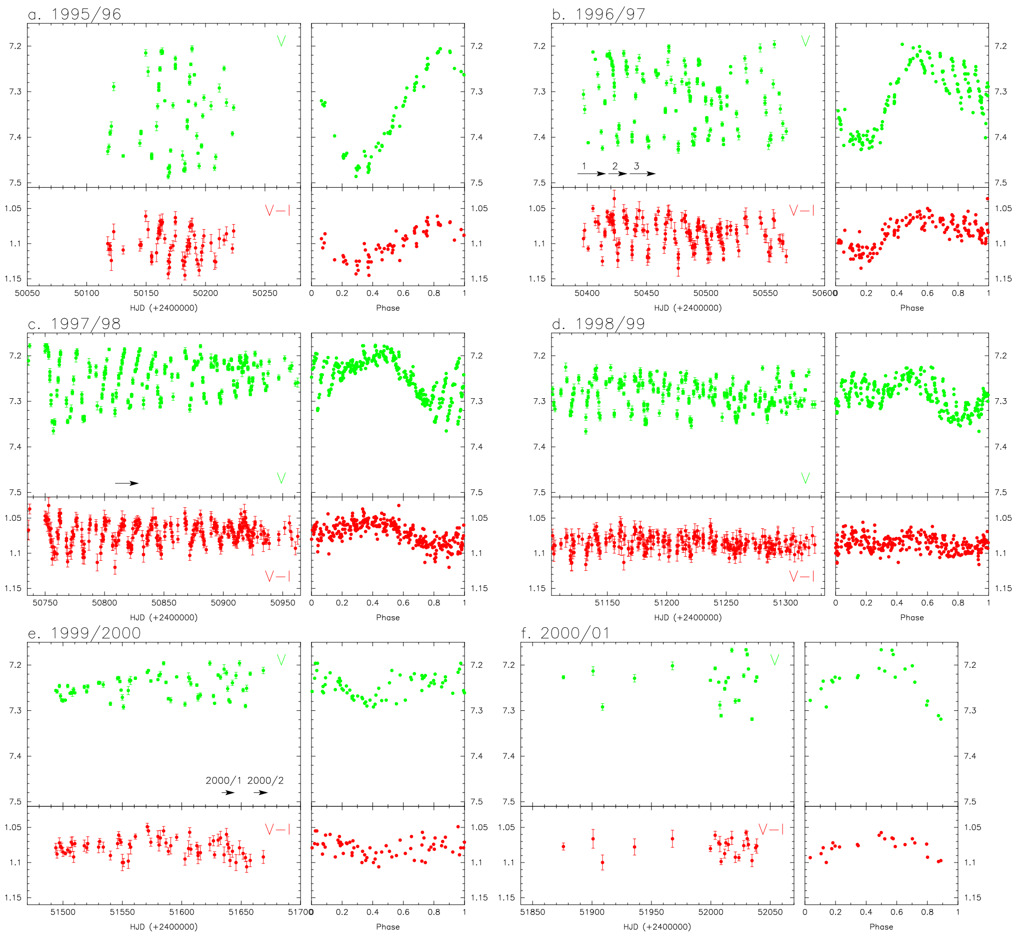

Figure 2. Six years of photometry of IL Hya. **a.** (left) The 1995/96 APT data versus Julian date and (right) versus phase calculated with the orbital period and ephemeris (given in the text), **b**, **c.**, **d.**, **e.** and **f.** the same for the 1996/97, 1997/98, 1998/99, 1999/2000 and 2000/01 seasons.

paper V we computed the differential rotation using two Doppler images; one an average of 5 maps derived independently from different spectral lines, the other based on only one spectral line. The time separation of these images was more than one year corresponding to 27 stellar rotations.

New observations at the National Solar Observatory (NSO, 70 nights) in 1996 and at the Kitt Peak National Observatory (KPNO, 14+14 nights) in 2000 were carried out to study the variations on timescales of the stellar rotation period in more detail. Fig. 1 shows the phase coverage obtained during those two observing runs. Even though it spans 5 rotations, the data from the NSO-run were divided into only three parts to improve the phase coverage of the individual maps. The data from the KPNO-run were split into two parts for obvious reasons. The spectral resolution of those observations are 30,000 (KPNO 2000) to 40,000 (NSO & KPNO 1997), the spectral coverages of the (coudé)

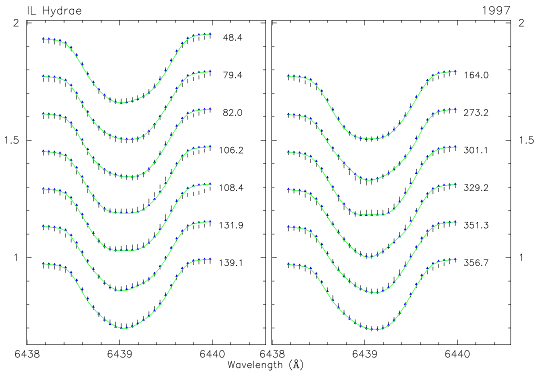

Figure 3. Example line profiles of the Ca I 6439 line from KPNO 1997 data. The black vertical lines are the observed spectral data $\pm 1\sigma$, the solid green line is the Doppler-imaging fit to that data, and the blue triangles represent the profiles computed from the average map as show in Fig. 4d.

spectra are approximately 45Å (NSO), 80Å and 300Å (KPNO 2000), and the typical S/N-ratio is (150–200):1.

Supplemental photoelectric observations using our Amadeus 0.75-m automatic photoelectric telescope (APT), part of the University of Vienna twin APT at Washington Camp in southern Arizona (Strassmeier et al. 1997), are shown in Fig. 2. The parts marked in the corresponding figures were used together with spectroscopic data to obtain the Doppler maps. A significant change in average brightness and lightcurve amplitude is seen through the six observing seasons. A detailed study of the long-term lightcurve variations revealing a 13–year cycle, and a long-term brightening trend can be found in Oláh et al. (2000).

2. Doppler Maps

Using our Maximum-Entropy Doppler imaging code TempMap (see e.g. Rice & Strassmeier (2000) for a recent description of the code and tests with artificial data) we computed new Doppler images: 3 maps from the 1996 NSO data, one map from 1997/98 KPNO data and two maps from the two consecutive KPNO runs in March/April and April/May 2000. Due to the small wavelength coverage of the NSO-data, only the three spectral lines Fe I 6421, Fe I 6430 and Ca I 6439 were used. For the remaining data sets we also used Fe I 6393, Fe I 6400 and Fe I 6411 lines. The resulting average images shown in Fig. 4 are thus made from three and six individual maps for the NSO and the KPNO data sets, respectively.

In Fig. 3 the measurements of the spectral line profiles along with $\pm 1\sigma$ error bars, the fit computed by TempMap (solid line), and the artificial line profiles computed with the average map of all six individual surface maps of that data set (blue triangles) are shown. The difference between the latter two could be caused by a difference of the stellar surface pattern because of different line-forming depths or, more probably, by uncertainties of the line-blend parameters used for the LTE calculations.

3. Differential Rotation

To identify the differential rotation of IL Hya, we cross-correlated the three Doppler images from the 1996 NSO data set with each other, and the two Doppler maps from the KPNO observing runs in 2000. This resulted in all

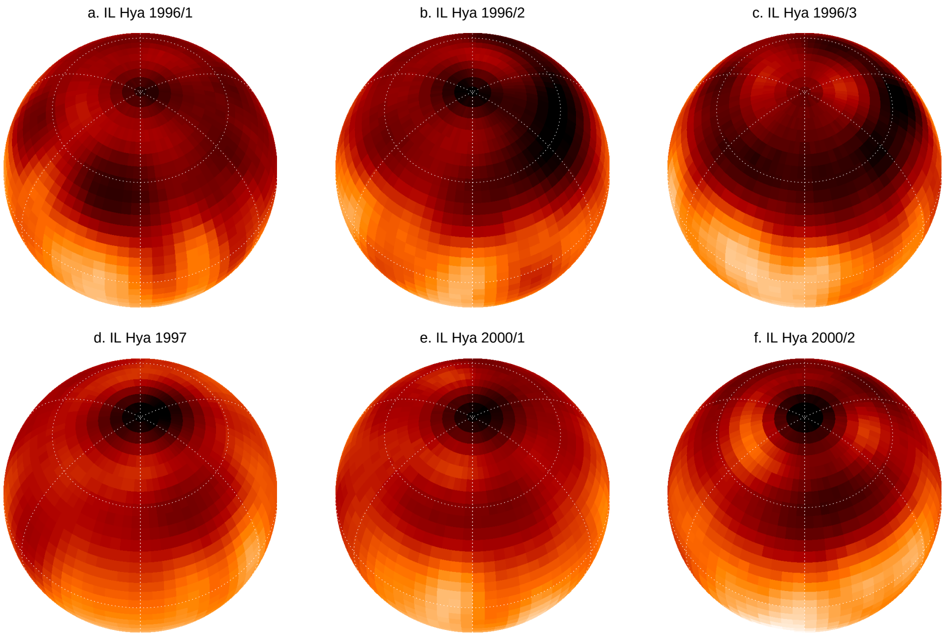

Figure 4. Average Doppler images of IL Hya in orthographic projection, plotted with the most probable inclination of 55°. The left column shows the three 1996 NSO maps in consecutive order (**a** to **c**), the top right image is the single map from the 1997/98 KPNO data (**d**), the two bottom ones (**e** and **f**) are from KPNO 2000.

together three cross-correlation images for 1996, and one for 2000 (see Fig. 5). We used the IRAF image reduction facility to cross-correlate the corresponding images latitude by latitude, and fit a Gaussian to each of those one-dimensional correlation functions.

To get a quantitative measure of the changes on the stellar surface, we fitted a solar-like differential-rotation law ($\Omega(b) = \Omega_0 - \Omega_1 \sin^2 b$) to the cross-correlation functions from $b = -45°$ to $60°$. Higher latitudes were excluded because of the increasing uncertainties caused by the decrease in surface resolution due to the smaller projected rotational velocity, but using all latitudes does not change the results significantly. The absence of good correlation around 30° latitude is due to a lack of surface features in the corresponding Doppler images at that latitude. Also, leaving out observations at phases where the secondary component could comtaminate the spectral line does not change the results for the KPNO 2000 data set. Due to the only marginal detection in case of the NSO 1996 data (the rms for 1996 is two to three times larger than for the 2000 data), omitting additional data results in insignificant cross-correlations; we therefore used all spectra for the NSO 1996 results listed in Table 1.

The results for each of the four maps along with the average are listed in Tab. 1. Using a solar-type law may seem too simple for the complex-looking patterns in Fig. 5, but since there are only a few extended spots on the stellar surface, and because of the significant time-span between the images (19–27

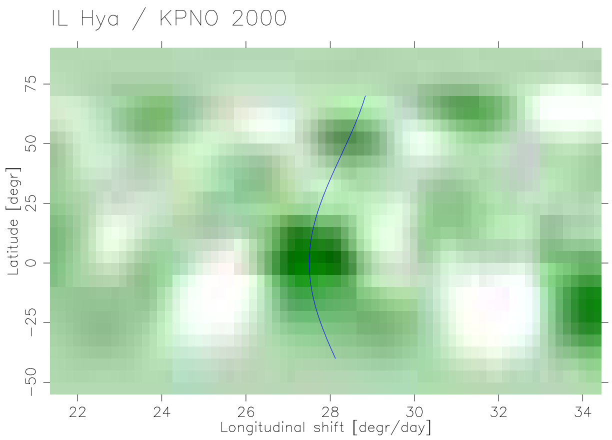

Figure 5. Cross-correlation images (dark green color meaning good correlation) with a least square fit of a solar-type differential rotation law for the two maps in 2000.

Table 1. Differential rotation derived from the four cross-correlations.

Season	Ω_0 (°/day)	Ω_1 (°/day)
1996/1–2	27.734	1.463
1996/1–3	27.715	1.037
1996/2–3	27.847	1.151
2000	27.64	1.51
average	27.73±0.09	1.3±0.3

days), where small changes in the spot pattern can occur, a more complex function would result in an over-interpretation of the data. Assuming the same differential-rotation law for both 1996 and 2000, we get an average measure for the surface motion of $\Omega(b) = 27.73 + 1.3\Omega_1 \sin^2 b$. The positive sign in this equation means, that the pole rotates faster than the equator (which is just the opposite of the solar case), and thus $\alpha = \Omega_1/\Omega_0 = -0.047$ and $1/\Omega_1$=(−)277 days. This is more than twice the solar value of 120 days.

Acknowledgments. Supported by the German Forschungsgemeinschaft (DFG) under grant HU 532/8 and STRG 45/1.

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