Doppler Imaging of the Young, Single, Solar-Type Stars
LQ Hya and EK Dra

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Abstract:
This poster paper presents the first Doppler image of a truly solar-like star (EK Dra) and a further image of the ZAMS K-dwarf LQ Hya from 1995. EK Dra shows a very high latitude spot feature close to the rotation pole while the more rapidly-rotating star LQ Hya has more like a low-latitude band of spots.

1. Introduction

One of the major puzzles in the study of stellar surfaces has been the discovery of cool starspots at high latitudes even straddling the rotation poles of rapidly-rotating late-type stars. The puzzle comes because the Sun shows spots only in two narrow equatorial bands. However, since most of the stars with polar features are either evolved and/or in a close binary system or even pre-main sequence a direct comparison may not be valid and the puzzle would vanish. The role of the Sun in understanding stellar magnetic activity is nevertheless important and intercomparisons should be made whenever possible. Therefore, we chose a single solar-type star as a target for Doppler imaging, but emphasize that the Doppler-imaging technique per se requires a much more rapidly rotating star than the Sun and our example thus still remains a poor comparison.

Our targets are the single K2 dwarf LQ Hydrae (HD 82558, $P_{\text{rot}}=1.6$ days) believed to have just arrived on the zero-age main sequence and the single, G2-dwarf EK Draconis (HD 129333, $P_{\text{rot}}=2.6$ days).

All spectroscopic observations in this paper were obtained with the new f/4 Gecko coudé spectrograph$^4$ at the 3.6m Canada-France-Hawaii telescope (CFHT)$^5$ in March 12–17, 1995 giving a resolving power of 120,000 and a typical signal-to-noise ratio of 250:1. Photometric observations were provided by the two 0.75m Vienna-Observatory APTs$^6$ (Strassmeier et al. 1997) and are shown in Figs. 1 and 4.

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Figure 1. The long-term V-light curve observations of LQ Hydrae possibly reveal a 7-year sinusoidal variation.

2. LQ Hydrae = HD 82558

The map in Fig. 2 strongly suggests that the spots are mainly concentrated within a relatively narrow latitudinal belt between $-10^\circ \pm 5^\circ$ and $+40^\circ \pm 5^\circ$. The average temperature difference of the spots with respect to the unspotted photosphere is thereby approximately 400 K, with the strongest features being 700 K cooler. A single hot/bright feature with a temperature of 400–500 K above photospheric consistently exists in all maps at around a longitude of 320$^\circ$ and a latitude of 60$^\circ$. In addition to the low-latitude spots, there seem to be two, slightly less cooler spots located very near the visible rotation pole but apparently not a big cap-like feature as seen on several evolved stars (e.g., HR1099, UX Ari, HU Vir$^7$, HD 199178$^8$, EI Eri$^9$, UZ Lib$^{10}$ and others) and on the ultra-rapidly rotating, single ZAMS-star AB Dor$^{11}$.

To judge the consistency of particular surface features reconstructed from the individual spectral lines we plot in Fig. 2 the standard deviations $\sigma$ from the average temperature map. Two representative sets of line profiles and their

7http://www.ast.univie.ac.at/kgs/pics/DI/HUVir.jpg
8http://www.ast.univie.ac.at/kgs/pics/DI/PS/HD199178.ps
9http://www.ast.univie.ac.at/kgs/pics/DI/PS/EIEri.ps.gz
10http://www.ast.univie.ac.at/kgs/pics/DI/PS/UZLib.ps.gz
Figure 2. Average Doppler image of LQ Hya in pseudo-Mercator projection. The map at the top is the unweighted average map from eight spectral lines and three photometric bandpasses while the lower map shows the distribution of the standard deviations in temperature per surface pixel from the altogether 16 maps. Their distribution in most parts of the surface is remarkably homogeneous but the polar regions do show the largest deviations indicating that the different mapping lines recover slightly different sizes for the polar feature.
Figure 3. Observed and computed line profiles for two representative spectral lines of LQ Hydrae. Top, the FeI 6173 Å line and bottom, the FeI 6430 Å line with about twice the equivalent width. The crosses are the observations and the lines are the fits. Rotational phase is indicated on the right side of each panel in units of degrees on the stellar surface.
fits are shown in Fig. 3. The surface distribution, based on the altogether 16 maps, suggests a spatially very homogeneous reconstruction from line to line and could be viewed as a “sensitivity” or “consistency map” in absence of a real (external) error map. Obviously, the most systematic discrepancies occur at the visible pole above a latitude of, say, 75° with up to $\sigma = \pm 40$ K (relative to the local average temperature). This would be easily explained if the spot area were proportional to the optical depth of the formation of the line core, in the sense that the stronger lines show larger spot area. As such it just verifies our finding from our previous CFHT-map in 1991 (Strassmeier et al. 1993) where the stronger lines recovered a polar-cap like feature while the weaker lines — weaker by a factor 3–4 in equivalent width — did not.

Figure 4. Photometric monitoring of EK Draconis throughout 1996/97 shows the star with a variable monthly light curve (panels d from December 1996 through April 1997). From early March on the overall $V$ brightness decreased by approximately 0.05 mag (panel a) while the $V - I_C$ color remained constant (panel b). Panel c plots the $V$ magnitudes of the comparison star from our all-sky solution.

3. **EK Draconis = HD 129333**

Due to the very small rotational broadening of the spectral lines of EK Dra ($v \sin i \approx 17.5$ km s$^{-1}$) – and thus the even more important accuracy of the local line profile – we first compared the standard Kurucz (1993) ATLAS-9 atmospheres with a set of model atmospheres that were computed with the Canuto & Mazzitelli (1992) (CM) convection model (kindly provided by F. Kupka) instead of the parametrized mixing-length theory as implemented in ATLAS-9. The main difference between these two sets of atmospheres comes from the fact that in the CM model the onset of efficient convection already appears at tem-
Figure 5. A comparison of the ATLAS-9 model atmospheres computed with mixing-length theory (MLT) and the Canuto & Mazzitelli (CM) convection model. At the expected temperatures of EK Dra the differences between the two models are only obvious at the very deep layers of the photosphere.

Temperatures approximately 1000 K cooler than in the mixing-length theory and results in a divergence of the atmospheres’ temperature gradient at high optical depths. Although not as obvious at solar-type effective temperatures as for A–F and again M-type dwarf stars the computed equivalent width of lines formed in the deep photosphere can change by a few percent. Fig. 5 compares the two sets of model atmospheres.

At the resolving power of $\lambda/\Delta\lambda=120,000$ and a full width of the lines of EK Dra at the continuum level of 0.77 Å we have still 15 resolution elements across the stellar disk. According to Piskunov & Wehlau (1990) this is quite sufficient because their numerical simulations with artificial data showed a reasonably correct recovery even when only five resolution elements were available.

Test reconstructions with $v \sin i = 17.5$ km s$^{-1}$ immediately show the major shortcomings of any Doppler imagery of EK Dra. First, and most notably, are the blurred surface features due to the low spatial resolution of 13° on the stellar surface (determined by the amount of phase smearing and the spectral resolution of 2.5 km s$^{-1}$). Second, the global redistribution of temperature to conserve the total flux (actually to reproduce the line equivalent width) leads to smaller
Figure 6. Observed and computed Fe I 6430 Å line profiles for EK Draconis in March 1995. The dots are the observations and the lines are the fits. Rotational phase is indicated on the right side of each profile.

contrast in the recovered map, i.e. smaller temperature differences between spotted and unspotted photosphere and, third, a general shift of equatorial features to the sub-earth latitude at \( \approx 30^\circ \). Nevertheless, in spite of the expected shortcomings at such a low \( v \sin i \), the test reconstructions clearly preserved the general surface features.

Figs. 6 and 7 show the Fe I 6430 Å line profiles and the resulting (preliminary) Doppler image, respectively. The map reveals one large high-latitude (70–80°) spot at a longitude of +45° and several smaller spots at intermediate latitudes.

We used an updated version of the MHD code of Schüssler et al. (1996) to generate trajectories of the rising toroidal flux tubes for a stellar model matching EK Draconis (for details see Granzer et al., these proceedings). The stellar cross section in the top panel in Fig. 7 and the tube’s predicted emerging latitudes can be directly compared with our Doppler image. But while the model predicts spots only between latitudes of 25–65°, with a preferred emergence at 30–35°, our Doppler image shows spots at significantly higher and lower latitudes. Part of the discrepancy may very well be, e.g., with the poleward slip of loops already formed at very high latitudes (see the discussion session on evolved stars in these proceedings) but not taken into account in the models. Or, the dynamo might be of qualitatively different design than the solar boundary-layer dynamo as could be suspected by the rapid rotation of EK Dra when compared to the Sun.
Figure 7. Preliminary Fe I 6430 Å Doppler image of EK Dra in pseudo-Mercator projection (bottom panel) and a stellar model showing the meridional projection of trajectories of rising flux tubes and the predicted latitude distribution of emerging magnetic flux (upper panel, for $\omega = 10\omega_\odot$).
Whether the large feature is just an appendage of a polar cap-like spot or not is currently under investigation using additional lines and no firm conclusions can be made at this stage. The very high-latitude spot, however, seems to be well established and its existence strongly supports that the dynamo action on a rapidly rotating young star is qualitatively different from the Sun’s.

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