Astron. Astrophys. 336, 972–979 (1998)

ASTRONOMY AND ASTROPHYSICS

Doppler imaging of stellar surface structure

VII. The very young, single K2-dwarf LQ Hydrae

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Received 26 January 1998 / Accepted 25 May 1998

Abstract. A Doppler image of the young K2V star LQ Hya is presented for March 1995 and is compared with earlier images taken in 1991 and 1993. Comparison is also made with a recently completed image of EK Dra, another young star that is more nearly one solar mass than LQ Hya. The image for 1995 seems to show a consistent pattern of spot concentration to the equatorial region in either a continuous wide band of features averaging only about 600 K cooler than photospheric or perhaps a double band symmetrically located either side of the equator like the solar pattern. A weak polar feature is evident but it is apparently a somewhat less pronounced depression in temperature than seen in 1991 and of reduced area. The polar feature is less pronounced than that of EK Dra and the spot pattern at the equator of LQ Hya does not extend to latitudes as far toward the poles as does the pattern of spots at the equatorial and mid-latitudes of EK Dra. When these results are compared with theoretical predictions for the location of spots on such young stars of solar mass, it appears surprising that the observations for LQ Hya and EK Dra are not reversed given that LQ Hya is apparently significantly less massive than EK Dra.

Key words: stars: activity – stars: atmospheres – stars: imaging – satars: individual: LQ Hya

1. Introduction

One of the major puzzles in the study of stellar surfaces has been the discovery of cool starspots at high latitudes or even, as frequently appears, a cool cap at the rotation poles of rapidly-rotating late-type stars. The puzzle comes because the Sun shows spots only in two narrow equatorial bands. Since most of the stars observed to have polar features are either evolved, in a close binary system, or are pre-main-sequence stars, a direct comparison with the Sun may not be valid and there may be no dilemma. The task of understanding solar magnetic activity is nevertheless the ultimate problem and intercomparisons of the Sun with active stars of similar mass and at various evolutionary stages should be made whenever possible. Therefore, we chose a single main-sequence star that is somewhat cooler than the Sun as a target for repeated Doppler imaging, but we emphasize that the Doppler-imaging technique per se requires a much more rapidly rotating star than the Sun and our target, with its relatively short period, thus still remains a poor comparison with the Sun.

Our chosen star is the single K2-dwarf LQ Hya (HD 82558) which is believed to have just arrived on the zero-age main-sequence (Fekel et al. 1986) and which has so far maintained most of its rotational momentum. The star has been studied extensively in the past. Fekel et al. (1986) and Eggen (1984) were the first to draw attention to it and Fekel et al. determined a projected rotational velocity of 25 km s^{-1} and a rotation period of 1.6 days. More detailed studies involving temperature and magnetic Doppler imaging were presented by Strassmeier et al. (1993) and Saar et al. (1992,1994), respectively. The star displays extreme chromospheric activity as well as a variable photospheric spot distribution mainly at low to intermediate latitudes but not a large polar spot as seen in some RS CVn's.

According to Schüssler et al. (1996), for stars of about one solar mass only the youngest pre-main-sequence stars and the evolved giants should have spots near their rotational poles since only they have convection zones that are sufficiently deep. LQ Hya seems to be some intermediate case – on the main-sequence and still rapidly rotating – and thus a very interesting target for repeated observations. In this paper we present a new multiline Doppler image of LQ Hya from high-resolution observations in 1995 and compare it to previously published maps.

2. Observations

All spectroscopic observations in this paper were obtained with the new f/4 Gecko coudé spectrograph at the 3.6m Canada-France-Hawaii telescope (CFHT) in March 12–17, 1995 (HJD 2,449,788.8 - 792.9). Together with the 2k-Lick CCD the disperion of 1.6 Å/mm provided a resolving power of 120,000 in a useful wavelength range of around 50 Å. Almost all integrations were set at an exposure time of 4×10 min and have typical signal-to-noise ratios of 250:1 and were centered alternately at 6420 Å and at 6160 Å. These conditions produced a smearing

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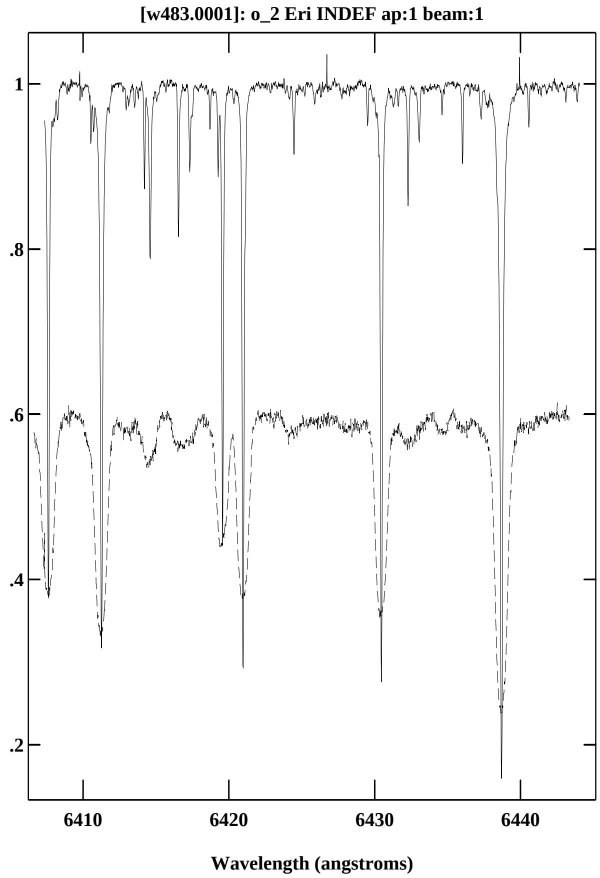

Fig. 1. A comparison of a typical 6430Å spectrum of o^2 Eri above, an inactive K2V star, and LQ Hya below. Both spectra were taken with the Gecko spectrograph of the CFHT during the March 1995 run. The lines from the 6400 A region that were used for imaging are at 6411Å, 6430Å and 6439Å. The LQ Hya spectrum has been shifted vertically by 0.3 for better visibility

per observation of less than 0.02 in phase and a total of 16 spectra in the 6160-Å region and 17 spectra in the 6420-Å region. The reduction procedure was identical to that in our first paper on LQ Hya (Strassmeier et al. 1993) and for further details we refer the reader to this paper.

Contemporaneous photometric observations were provided by the 0.75m Vienna-Observatory Automatic Photoelectric Telescope (APT), then still located on Mount Hopkins, Arizona (see Strassmeier et al. 1997a). The new observations were transformed to the Johnson-Cousins $V(RI)_C$ system and used HD 82447 and HD 82508 as the comparison and check stars, respectively. Unfortunately, due to a problem with the telescope focus during early 1995 the standard error of a nightly mean from the overall long-term mean increased to 0.008 mag in V and 0.013 mag in R and I.

Strassmeier et al. (1997b) performed a period analysis on all available data since the discovery of the light variability of LQ Hya and found a long-term average photometric period of 1.60088±0.00003 days from the combination of 12 years of V-band data. Slightly longer individual seasonal periods indicated that seasonal changes of the spot distribution are likely to occur.

Table 1. Identification of the main spectral lines for Doppler imaging

Element	Wavelength (Å)	$\log gf$ (–)	χ (eV)	W_λ (mÅ)
Fe I	6151.624	–3.30	2.176	72
Fe I	6157.732	–1.26	4.076	87
Fe I	6165.361	–1.55	4.143	60
Ca I	6166.440	–0.90	2.521	116
Fe I	6173.341	–2.88	2.223	105
Ni I	6175.370	–0.68	4.089	56
Fe I	6411.659	–0.82	3.654	235
Fe I	6430.844	–1.85	2.176	187
Ca I	6439.075	+0.47	2.526	325

The best photometric period during the spectroscopic observations in 1994/95 was 1.6033±0.0014 days while in 1995/96 it was 1.60689±0.00072 days. However, for this paper we adopted the long-term photometric period derived earlier by Jetsu (1993) to phase the spectra. This is still the period with the highest (claimed) precision so all data in this paper were phased using as the ephemeris for the time of photometric minimum the expression

$$HJD_{min} = 2,448,270.0 + (1.601136 \pm 0.000013)E. \quad (1)$$

We note that the various periods used in mapping LQ Hya are all so close in value that over the short span of observations used for the mapping there is no significant effect upon the image that is a consequence of the choice of period. Long term comparisons of images will require a much more careful look at the period question but it is doubtful that individual features survive long enough on the surface of LQ Hya to require a thorough definition of the period immediately for imaging purposes.

3. Multiline Doppler imaging

3.1. The inversion code

Our Doppler-imaging code[1] is a variation of code described in Rice (1991) for mapping Ap stars and the modifications for temperature mapping have been described in Strassmeier et al. (1991) and reviewed by Piskunov & Rice (1993) as well as in the previous papers of this series. For this work on LQ Hya, however, we apply a significantly modified version that includes a full spectrum synthesis to each of the used wavelength regions, simultaneous inversions of up to twenty lines using either a maximum-entropy or a Tikhonov regularisation. There is additional input from absolute instead of relative photometry to further constrain the solution.

The calculation of the photometric magnitudes for each colour at each rotational phase is done by means of a semi-empirical approximation. First, during the initial table set up in TEMPMAP, an additional calculation of the continuum flux level for the center wavelength for each of the photometric bands that have been observed is done. This calculation is performed

[1] hereafter referred to as TEMPMAP

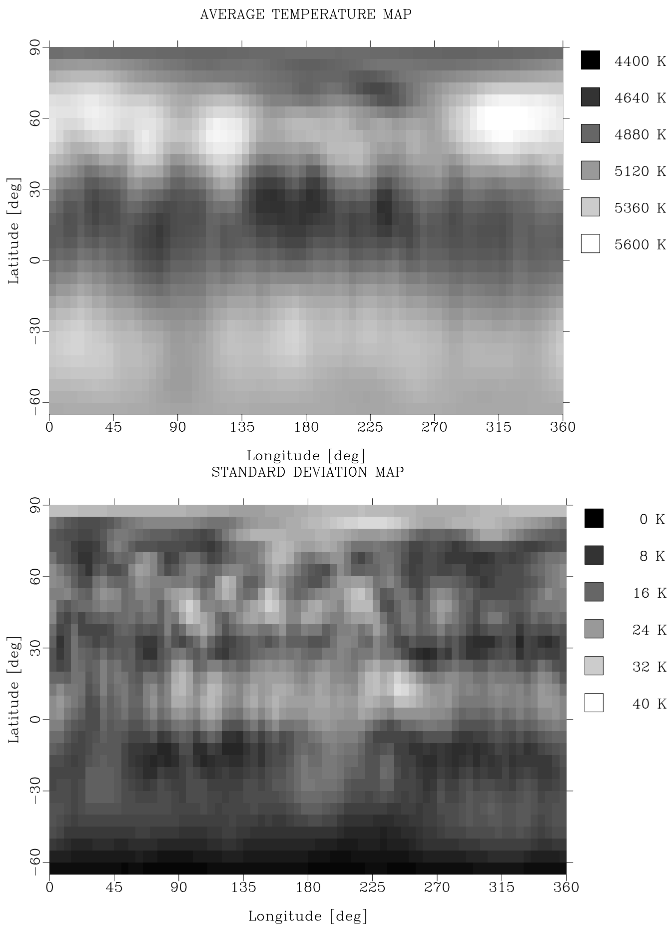

Fig. 2. Average Doppler image of LQ Hya for March 1995 displayed in pseudo-Mercator projection. The map in the top panel (a) is the unweighted average map from eight spectral lines and two colour indices while the map in the lower panel (b) shows the distribution of the standard deviations in temperature per surface pixel from all 16 maps. Note that the standard deviation is smaller (the map to map agreement is better) where the lower map is darkest. The deviation in most parts of the surface is fairly homogeneous but the polar regions do show the largest deviations indicating that the different mapping lines recover slightly different sizes for the polar feature. The temperature map in the top panel is represented in Fig. 3 as a more realistic spherical projection.

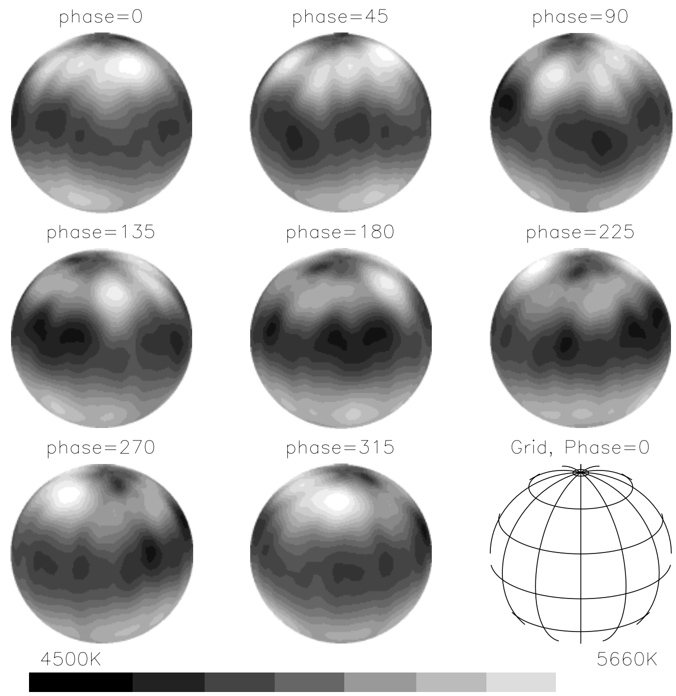

Fig. 3. The same image of LQ Hya as in the top panel of Fig. 2. This representation is a set of spherical projections at eight rotational phases. The spherical projection restores the correct area perspective to the polar features in the maps.

for model stars with a uniform $T_{\rm eff}$ to match each of the ten model atmospheres supplied to the program. A spline curve is then fitted through the standard magnitude versus central wavelength flux data for each band. In the subsequent iterations we obtain the surface map of the observed star, the flux at the central wavelength of each band at each rotational phase observed and use the spline fit to transform the central flux to a corresponding magnitude.

A grid of ten model atmospheres with temperatures between $T_{\rm eff}$ = 3500 and 6250 K and fixed $\log g = 4.0$ were taken from the ATLAS-9 CD (Kurucz 1993). For each model atmosphere local line profiles are computed for the lines listed in Table 1 under the assumption of a slight overabundance of iron (0.1 dex), calcium (0.1 dex) and nickel (0.3 dex) but otherwise the solar abundances as adopted in the ATLAS-9 models are presumed. The adjustments in the abundances of iron, calcium and nickel were required by the Doppler imaging code so that the program could simultaneously fit the observed line strengths of these elements and still maintain a mean effective temperature over the surface of the model of the star that matches the observed photometric colour of LQ Hya. Deviations of greater than 0.05 dex in the abundances of iron, calcium or nickel assumed above caused, when imaging with the lines of these elements, a mismatch between the observed and model colours that was just noticeable so no greater precision can be attributed to the abundance estimates than about ± 0.05 dex.

The geometric and atmospheric parameters assumed for LQ Hya in calculating the Doppler images from various lines are given in Table 2. The values given in Table 2 for LQ Hya give the best fit to the spectral lines used in the inversion and the values for $v \sin i$, i and P (when combined using the simple expression R = P$V_{\rm e}$/50.6) imply a radius for LQ Hya of 0.98 solar radii compared to the standard value of about 0.80 for a K2V star.

3.2. Results

Fig. 2a shows the average map from the independent inversions of eight wavelength regions around the major lines listed in Table 1 and combined with the continuum variations in two colour indices ($V - R$ and $V - I$). The averaging suppresses the spurious detail from noise or peculiar distortions in the individual mapping lines. Fig. 3 shows the same average map in the more realistic spherical projection so that the relative scale of

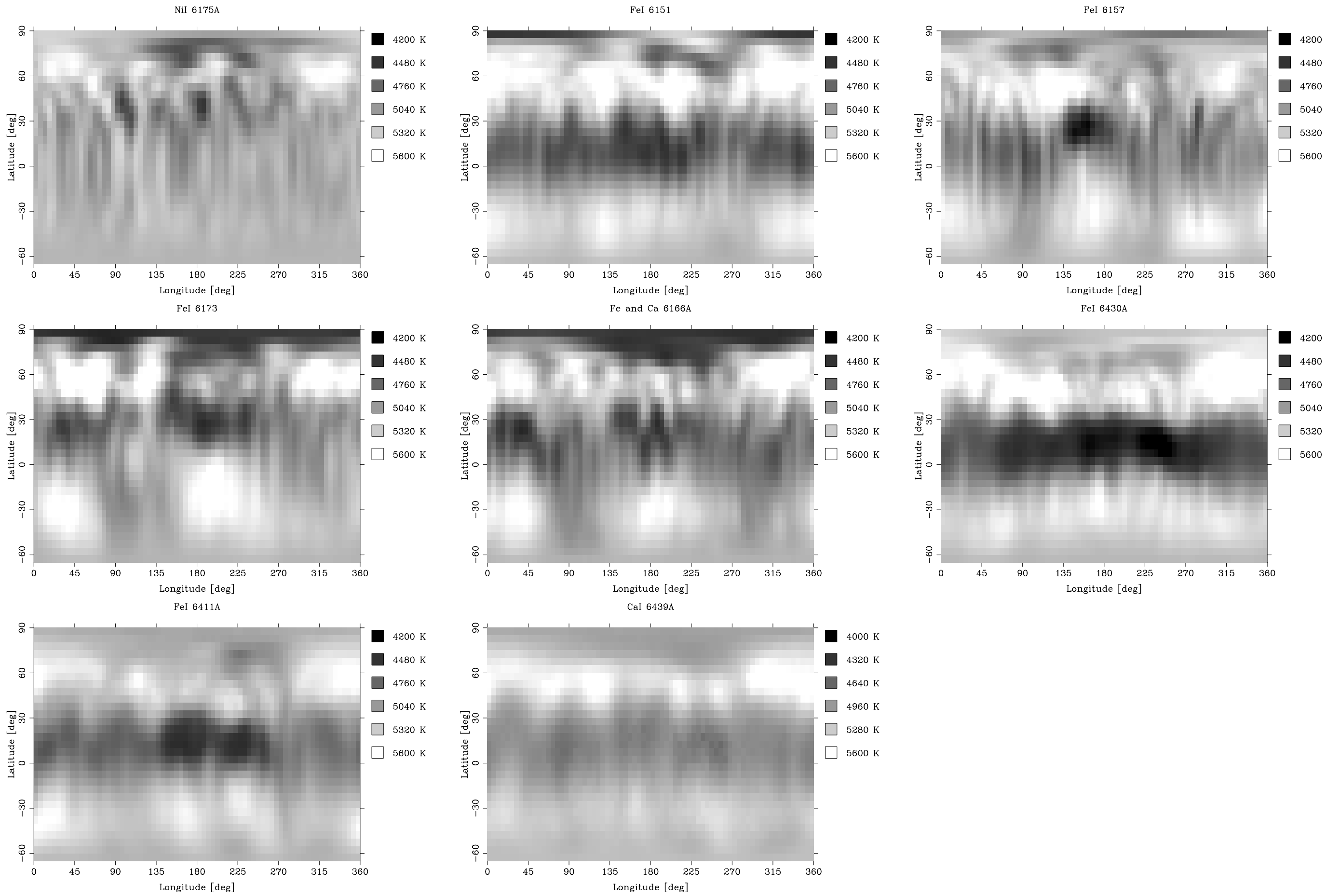

Fig. 4. Plots of the reconstructed surface maps for LQ Hya from the individual spectral regions and using the V and R photometry only. Each map is a pseudo-Mercator projection and plots temperature in Kelvin. The main spectral line is identified at the top of each map and refers to the spectral regions listed in Table 1. Note also from Table 1 that the maps are arranged so that they are in order of increasing line strength from the upper left to the lower right. The well known tendency for features near the equator to smear in latitude is evident in some of the maps. This smearing arises because of the very small difference in the variation of radial velocity with time for locations that are within a few degrees of the equator. This effect is more pronounced with stars of small $v \sin i$ such as LQ Hya.

Table 2. DI parameters assumed for this paper and *Hipparcos* data for LQ Hya

Parameter	Value
Spectral type	K2V
$v \sin i$	28 km s^{-1}
i	65°
P	1.601 days
R	0.98
$log(g)$	4.0
starting $T_{\rm eff}$	5200 K
Vmicro	0.5 km s^{-1}
Vmacro	1.5 km s^{-1}
distance	18.35 pc
V (1992 average)	7.82 mag
B-V (1992 average)	0.933 mag

the features are more properly represented. In Fig. 4 we see all of the individual maps that were reconstructed from individual line profile variations combined with contemporaneous $V - R$ photometry. The average map of Fig. 2a and Fig. 3 strongly suggests that the spots are mainly concentrated within a relatively narrow latitudinal belt between –10±5° and +35±5°. The average temperature difference of the spot regions with respect to the unspotted photosphere is approximately 400 K on average, with the strongest features being 700 K cooler. One hot/bright feature with a temperature difference of 400–500 K above photospheric consistently exists in all maps at around a longitude of 320° and a latitude of +60°. Somewhat less consistently we see an extension of this hot/bright feature at the same latitude of roughly +60° and through longitudes of 0° to about 140°. 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 is seen on several evolved stars such as HR 1099, UX Ari, HD 199178, EI Eri and UZ Lib

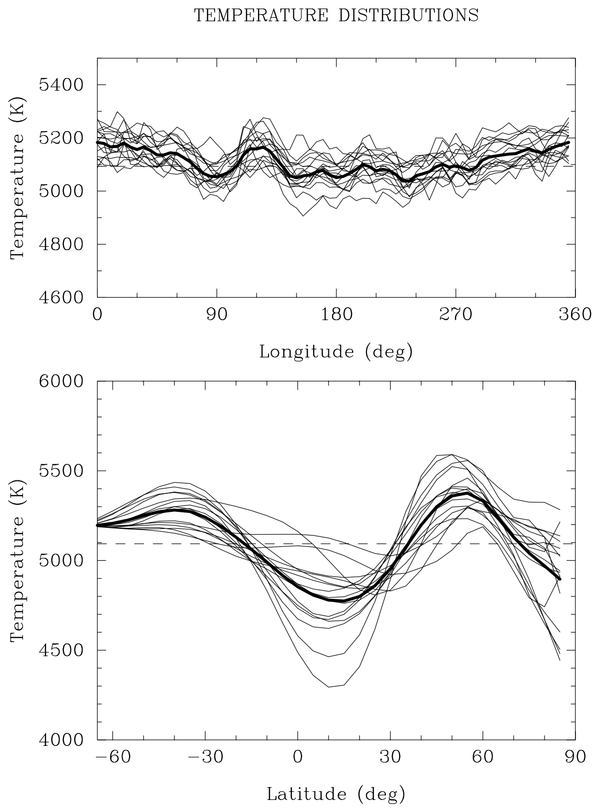

Fig. 5. Two plots showing the average temperature distributions along binned longitudes (top panel) and latitudes (bottom panel). Binning width is five degrees for both cases. The thin lines are from the individual maps and the thick line is from the average map. The surface integrated average photospheric temperature of LQ Hya was 5090 K in 1995 (dashed line).

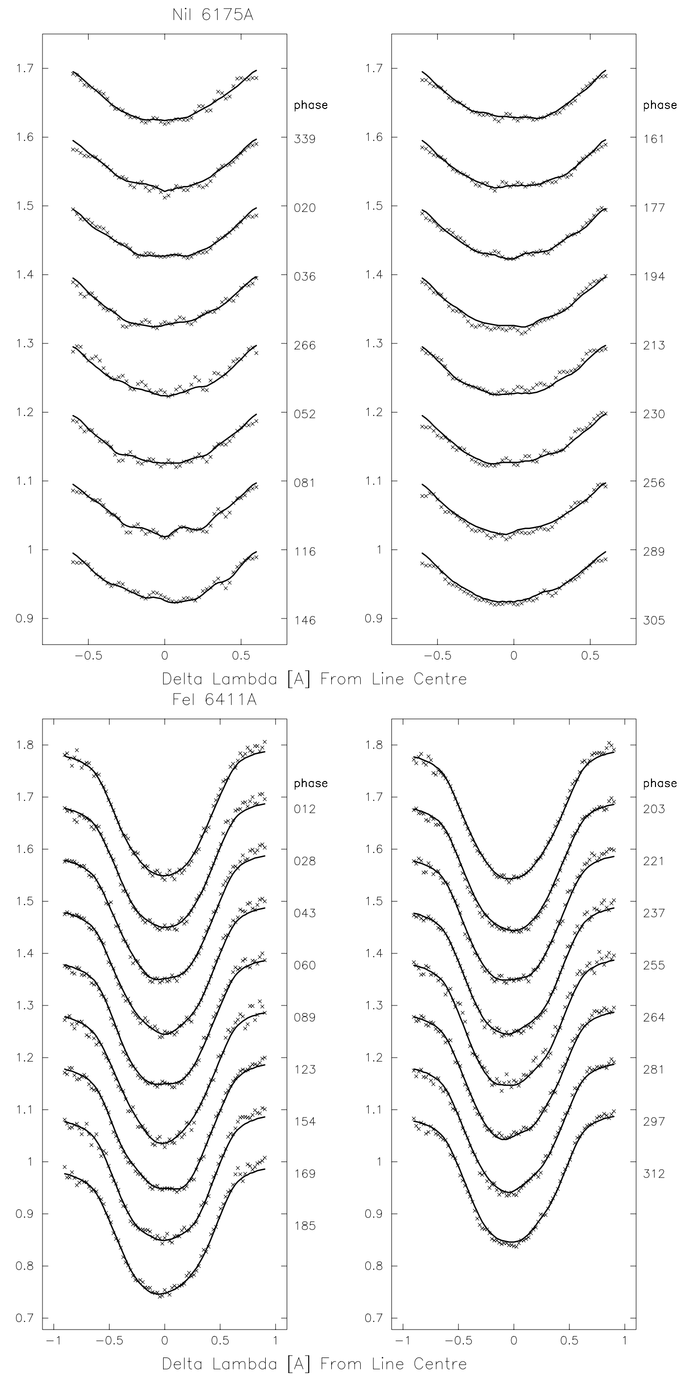

Fig. 6. Observed and computed line profiles for two representative spectral lines. Top, the Ni I 6175 line and bottom, the Fe I 6411 line with about four times the equivalent width. The crosses are the observations and the lines are the fits. Rotational phase is indicated on the right side of each panel in units of degrees on the stellar surface.

(see references in Strassmeier 1996) and on the single and even younger ZAMS-star AB Dor (e.g. Collier-Cameron 1995).

The coolest features that can be isolated from the inhomogeneous temperature distribution are always located close to a latitude of +30°. There do not seem to be spots directly centred along the equator nor is there a parallel band of spots at -30° as might be expected from the solar analogy. As may be seen from the following discussion of the average temperature structure with latitude (Fig. 5), this apparent lack of symmetry may be a byproduct of the Doppler imaging process. Since the recovered line of features is fairly close to the latitude of the subsolar line, the region of maximum sensitivity in Doppler imaging, we think that either a large band overlapping the equator or a double-band structure might not be resolved and may be recovered merely as a single, merged feature with emphasis on the subsolar region.

To judge the consistency of particular surface features reconstructed from the individual spectral lines we plot in Fig. 2b the standard deviations σ from the average temperature map. Their surface distribution, based on all 16 maps, suggests a very homogeneous reconstruction from line to line and could be viewed as a “sensitivity” or “consistency map” in the 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 is indicative of the conclusion that one can draw qualitatively, by examining Fig. 4, that the polar cool features are quite variable from map to map. In our previous CFHT-map in 1991 (Strassmeier et al. 1993) the stronger lines recovered a polar-cap like feature while the weaker lines – weaker by a factor 3–4 in

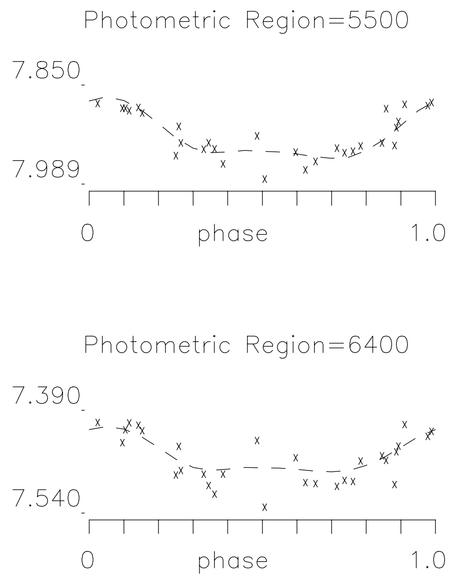

Fig. 7. Observed and computed broad-band light curves for the Fe I 6173 line. The crosses are the observations and the lines are the fits. Note, that in the current version of TEMPMAP the photometric zero point in each bandpass is yet another constraint to be fitted by the reconstructed Doppler image. Since the photometric observations are rather scattered, the program was not required to try to fit the photometry tightly.

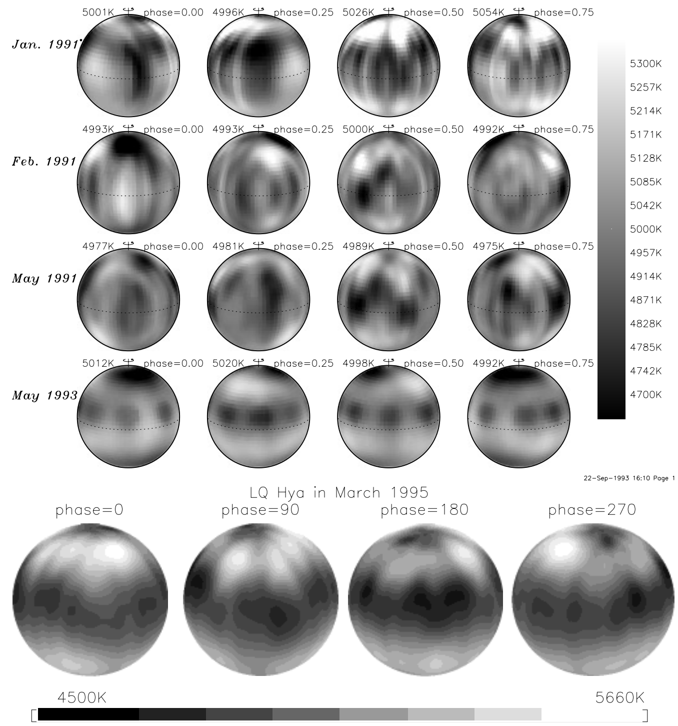

Fig. 8. The top four images represent the previously published (Saar et al. 1994) comparison of the images of LQ Hya, three obtained in early 1991 and one in 1993 . The image taken in Jan. 1991 is the image from our previous paper (Strassmeier et al. 1993). Below is the image from this paper taken in March 1995. In the top three images, all taken within five months, the pattern of dark features at phase 0.50 bear a strong resemblance to one another in each image.

equivalent width – did not show a pronounced feature of this sort at the polar region. In that paper we suspected that there was an optical depth dependence to the size of the cool polar-cap spot. Here, the qualitative correlation from Fig. 4 suggests that the polar feature is, if anything, cooler for lines of intermediate strength. The weakest lines recover a more structured spot with small areas of substantially reduced temperature and in general a smaller total overall area than either the spots in the maps recovered from lines of intermediate strength or those from the lines of the greatest strength. The greater uncertainty expressed by the lighter shade of grey in the "consistency map" of Fig. 2b is simply a reflection of these variations. On this occasion of mapping LQ Hya, we do not have such an obvious correlation between optical depth and the area of the polar cap feature although there does seem to be a tendency for the area, if not the temperature reduction of the polar feature, to be less for the weaker lines and greater for the stronger lines. This correlation though, is not totally convincing.

Averaging the individual maps in equal longitudinal and latitudinal bins shows the overall temperature distribution in these two directions (Fig. 5). The averaged latitudinal bins per longitude on the stellar surface indicate only weak minima near 90°, 150°, 180°, and possibly 240° in agreement with the low amplitude of the contemporaneous V-light curve while the averaged longitudinal bins per latitude show a clear minimum between -15° and +30°, a maximum between +40° and +70° with a roughly matching minimum south of the equator between -20° and -50°, and again a minimum towards the visible pole. The two bands of maxima do not appear in the maps to be perfectly symmetric north and south of the equator but this lack of perfect symmetry is most likely due to the loss in sensitivity that is shown by Doppler imaging for information that is only briefly in view south of the equator and the extreme southerly regions that are in view very briefly tend to remain at the starting temperature given in the input file for the blank initial map. With this understanding of the behaviour of Doppler imaging we can probably safely conjecture that the true temperature distribution is fairly symmetric about the equator. This temperature band structure with latitude appears in all maps except maybe the ones from Ca I 6439 (but the local line profile of this line is much broader than for the other lines) and we run numerous solutions with a widely different set of fixed input parameters, most notably $v \sin i$, inclination, abundance, and microturbulence (and with and without photometry) but the structure remained more or less the same. At this stage of the analysis we can not prove whether this is an artifact of the reconstruction process or not but currently favour the explanation that we detected spots arranged very similar to the Sun's latitudinal bands.

The area of the individual largest "coolest" spot regions represents perhaps 1% or 2% of the total stellar surface and is therefore considerably larger than the cooler photospheric parts of typical large active regions on the Sun.

A representative set of observed and computed line profiles from each of the two available wavelength regions is shown in Fig. 6. The Fe I 6411Å line is representative of a "strong" line having an equivalent width of over 200 mÅ while the Ni I 6175Å feature has an equivalent width of only approximately a quarter of that. Compared to spotted stars of the RS CVn type the spot signatures in the profiles of LQ Hya are only weak, reaching at most 2–3% of the continuum, e.g. at around phase $\approx 90°$ and at phase $\approx 150°$. Fig. 7 compares the photometric observations and the fits from the two lines already shown in Fig. 6.

4. A comparison with previous maps of LQ Hya

A summary of maps of LQ Hya, including that of our previous paper, was assembled by Saar et al. (1994) and are shown together in Fig. 8 along with a miniature version of the present image in four corresponding phases of rotation. All three images from 1991 show striking similarities in some specific features and all four earlier images show a stronger and larger polar feature than the image of this paper. The overall tendency for large moderately cool spot regions to be concentrated to the equatorial zone is consistent among all images as is the tendency for middle latitude regions to be unspotted or hotter. There does seem to be a tendency for the spotting in the equatorial zone to be a broader band of spots (i.e. extending to greater latitudes in both a positive and negative sense) in the images from 1991 compared to 1993 and the 1995 image produced for this paper. Since the retreat of the spots to a narrower equatorial band coincides with an apparent reduction in the intensity of the polar feature, this might be an indication of some longer term cycle in the spot distribution similar to what is seen during the 11 year solar cycle. At a minimum, the existence of a polar feature is consistent among the images in all years.

At this point it is interesting to make a comparison of LQ Hya with the published models of Schüssler et al. (1996) of the distributions of starspots on cool stars. We should also compare LQ Hya with EK Dra (Strassmeier & Rice, 1998), a very young main-sequence star that is of type G1.5V and thus is presumably somewhat more massive than LQ Hya and closer to a solar mass. Both LQ Hya and EK Dra are rotating at roughly ten times the solar rate. The map of EK Dra shows spots at mid-latitudes as compared with the tendency on LQ Hya for the spots to be more concentrated to the equator. EK Dra also has a more pronounced polar feature than is evident in any of the maps of LQ Hya. In both cases the spot regions represent only an average reduction in temperature over that of the surrounding photosphere of well under 1000 K. (This observation should be interpreted in the light of the distinct possibility that we are actually seeing groups of many small spots, each perhaps very much cooler than 1000 K under photospheric.)

The physical differences between EK Dra (the star which is the subject of our paper VI in this series) and LQ Hya need to be noted here. EK Dra is substantially hotter and presumably the more massive of the two, as mentioned above, but from the data of Table 1 in Strassmeier & Rice, (1998), one can calculate that the radius of EK Dra is about 1.03 (close to the expected value for a main-sequence star of this spectral class) whereas the radius given in Table 2 of this paper for LQ Hya is only slightly less at 0.98. The two stars have been presumed to be about the same age. Fekel et al. (1986) suggests LQ Hya is as young as the youngest Pleiades stars and the *Hipparcos* space motions for EK Dra suggest it belongs to the Pleiades moving group so that it would be about 70 Myr old. We might note though that Vilhu et al. (1991) suggest that LQ Hya might even be slightly pre-main-sequence. From the foregoing, one would be inclined to believe that any differences in the depth of convection in the two stars would be such that LQ Hya would have the deeper convective envelope.

The work of Schüssler et al. deals with solar type stars of ages ranging from T Tauri through pre-main-sequence to main-sequence. They calculate the trajectories for rising flux tubes from the overshoot layer to the surface for stars of various rotation rates. In their Fig. 7 they show the model for pre-main-sequence and main-sequence stars of solar mass and rotation at ten times solar. The flux tubes appear to surface at mid-latitudes in both cases (pre-main-sequence and main-sequence) and, with the exception of the strong polar feature, these models may work for EK Dra. It can be seen in the figures in the paper by Schüssler et al. that generally stars with deeper convection have a tendency for the flux tubes to surface at higher latitudes. The more strongly equatorial spot distribution for LQ Hya in comparison with EK Dra should presumably be characteristic of a star with a shallower convective envelope than EK Dra rather than a deeper convective envelope as we have conjectured that LQ Hya may have. More rapid rotation tends to cause the flux tubes to surface at higher latitudes as well. Since LQ Hya is the more rapidly rotating of these two stars, this cannot be seen as the factor that causes the location of the spot pattern for LQ Hya to be a more equatorial one than that of EK Dra. This issue must be explored further with models for stars of somewhat less mass than the Sun.

It is evident that the lifetime of features on LQ Hya is far too short for there to be enough persistence in features from 1991 into 1995 to draw any conclusions about the effects of differential rotation with the present map. Some conclusions on this issue are presented in Saar et al. (1994).

5. Summary

Our main results can be summarized as follows:

1. The spot pattern on the current (1995) and earlier maps (1991 and 1993) of the young K2V star LQ Hya show spots concentrated to the equatorial region as either a wide continuous band of spots symmetric about the equator or as two bands that are parallel and close to the equator and that are arranged symmetrically to the north and south of the equator. There is a weak polar feature that seems less pronounced in the 1995 map than in the earlier maps.
2. As with previous images, the cool features on LQ Hya are no more than 700 K cooler than the surrounding photosphere. Since resolution is limited for LQ Hya by what is rather slow rotation for Doppler imaging, these may represent patches of many smaller much cooler spots.

3. The area of the largest "coolest" features is only of the order of perhaps 2% of the total surface area of LQ Hya.
4. Comparison with our recent publication of the map of the earlier main-sequence star EK Dra (G1.5V) shows that EK Dra has spots concentrated at mid-latitudes compared to the greater concentration of spots to the region near the equator for LQ Hya. EK Dra has a much stronger polar feature than has LQ Hya.

Acknowledgements. It is a great pleasure to thank John Glaspey and David Bohlender of CFHT for their help with Gecko and David Gray for the design of this superb instrument. JBR acknowledges support from the Natural Science and Engineering Research Council of Canada (NSERC) and KGS is very grateful to the Austrian Fond zur Förderung der wissenschaftlichen Forschung for support under grant S7302-AST and S7301-AST.

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