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Study of FK Comae Berenices

VII. Correlating photospheric and chromospheric activity[*],[**],[***]

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ABSTRACT

Aims. We study the connection between the chromospheric and photospheric behaviour of the active late-type star FK Comae.
Methods. We use spot temperature modelling, light curve inversion based on narrow- and wide-band photometric measurements, Hα observations from 1997−2010, and Doppler maps from 2004−2010 to compare the behaviour of chromospheric and photospheric features.
Results. Investigating low-resolution Hα spectra, we find that the changes in the chromosphere seem to happen mainly on a time scale longer than a few hours, but shorter variations are also observed. According to the Hα measurements, prominences are often found in the chromosphere that reach to more than a stellar radius and are stable for weeks, and they seem to be often, but not always connected to dark photospheric spots. The rotational modulation of the Hα emission typically seems to be anticorrelated with the light curve, but we did not find convincing evidence of a clear connection in the long-term trends of the Hα emission and the brightness of the star. In addition, FK Com seems to be in an unusually quiet state in 2009−2010 with very little chromospheric activity and low spot contrast, which might indicate the long-term decrease in activity.

Key words. stars: magnetic field – stars: atmospheres – stars: chromospheres – stars: individual: FK Comae Berenices – stars: late-type – stars: activity

1. Introduction

FK Comae is the eponymous member of a group of active stars (Bopp & Rucinski 1981), where the members are fast-rotating G–K giants that show chromospheric and coronal activity signs similar to the RS CVn-type binaries. Their typical $v \sin i$ is of the order of 100 km s^{-1}, but no periodic radial velocity variations have been detected, indicating that these stars are single or that they have a companion of very low mass. Studying the Na D line, McCarthy & Ramsey (1984) gave 5 km s^{-1} as an upper limit of the radial velocity variations caused by a possible companion, corresponding to a mass of 0.054 $M_{\rm Sun}$. Huenemoerder et al. (1993) gave an upper limit of the semi-amplitude of 3 km s^{-1}, which makes the presence of the companion even more unlikely. Photometric observations showed periodic, quasi-sinusoidal changes of $\Delta V = 0\overset{\rm m}{.}1-0\overset{\rm m}{.}3$, which was

interpreted as starspots by Bopp & Rucinski (1981). They also suggested that these stars are coalesced W UMa-type systems, based on the rapid rotation and the lack of radial velocity variations, following the scenario proposed by Webbink (1976).

FK Com is the most active and most thoroughly studied star of this group. The star shows signs of activity from photosphere to corona (Merrill 1948; Chugainov 1966; Ramsey et al. 1981; Dorren et al. 1984; Oliveira & Foing 1999; Ayres et al. 2006; Drake et al. 2008). FK Com was also the first object where the so-called flip-flop phenomenon was observed (Jetsu et al. 1993, 1994): it shows active longitudes separated by ∼180°, and the dominance between these regions is exchanged every few years. Oláh et al. (2006) find that both flip-flops and phase jumps can be found on FK Com. They conclude that these are two different, although possibly connected phenomena. Hackman et al. (2013) also show that flip-flops are not a single phenomenon. They can occur gradually (through differential rotation) or suddenly, and the phase shift varies as does the stability of the new primary spot region.

Ramsey et al. (1981) have described the broad, double-peaked Hα profiles of FK Com with an "excretion" disk around the star, which itself makes a small contribution to the Hα emission. Huenemoerder et al. (1993) presented photometric and spectroscopic data and concluded that FK Com is a single star

with extended matter around it. From long-term Hα observations Welty et al. (1993) found evidence of co-rotating emitting material around FK Com within two stellar radii with lifetimes longer than a few weeks. Oliveira & Foing (1999) modelled highly variable Balmer line profiles and confirmed the complex circumstellar structures. Kjurkchieva & Marchev (2005) present high-resolution Hα observations spanning over two years. The authors propose a model where FK Com is a binary system with a low-mass secondary star illuminating a circumstellar accretion disk. The model contains additional sources of absorption and emission at phases 0.0 and 0.5, respectively.

In this paper, the seventh in a series on FK Comae, we analyse Hα data spanning more than a decade from 1997 to 2007. The chromospheric activity patterns from the Hα data are compared, in most epochs, to the contemporaneous photospheric spot maps obtained using the Doppler imaging technique.

2. Observations

Most of the spectroscopic observations presented here were obtained at the 2.56 m Nordic Optical Telescope (NOT) during 13 observing runs using the SOFIN high-resolution spectrograph and one run of low-resolution spectroscopy using ALFOSC. In addition, three datasets of high-resolution spectra were obtained at the Kitt Peak National Observatory (KPNO) in Arizona. All the runs from KPNO and ten runs with the SOFIN at NOT (1998−2003 and 2004 February) were already used in Oláh et al. (2006), Ayres et al. (2006), and Korhonen et al. (2007) for investigating the photospheric activity. Thus, only the unpublished observations from SOFIN and ALFOSC are described in detail here. In addition to these spectroscopic observations, previously published photometric observations from Korhonen et al. (2001) and Hackman et al. (2013) are also used.

The phases for all the observations presented here were calculated using the ephemeris obtained from 25 yr of photometric observations, HJD = 2 439 252.895 + (2$^{\rm d}$4002466 ± 0$^{\rm d}$0000056)E, referring to a photometric minimum calculated by Jetsu et al. (1993, 1994).

2.1. High-resolution spectroscopy

High-resolution NOT observations for five epochs (2004 July, 2005 July, 2007 July, 2009 August, and 2010 January) were carried out using SOFIN échelle spectrograph with the low-resolution camera, giving resolving power ($\lambda/\Delta\lambda$) of 27 000. The échelle spectra consisted of typically 45 orders and were centred at 5200 Å. The signal-to-noise ratio in the Hα order varied between 90 and 310, with a typical value being around 200. The data were reduced using the 4A reduction package (Ilyin 2000). Table 1 gives the summary of the high-resolution spectra used in this paper, including the previously published datasets.

2.2. Low-resolution spectroscopy

For investigating the possible rapid variations in the Hα profiles, low-resolution spectra with high cadence were obtained using ALFOSC at the NOT during 1999 February 26−27. We used the 0.4 arcsec slit and the échelle grism #9, together with the Hα filter #22. With this configuration we selected only the order containing Hα, without using a cross disperser. The resolving power obtained with this configurations was approximately 4000.

The observations were done in sets of two observations with 60 s exposure times and taking halogen flat and helium-neon

Table 1. List of Hα observations.

High-resolution spectra			
Date	Telescope	# of spectra	
1997/04/07−04/16	KPNO	10	
1998/03/10−03/17	NOT	7	
1998/04/01−04/22	KPNO	19	
1998/07/02−07/15	NOT	38	
1999/03/03−03/05	NOT	6	
1999/05/24−06/04	NOT	19	
1999/07/23−08/03	NOT	12	
2000/03/29−04/08	KPNO	10	
2000/04/26−05/05	KPNO	10	
2000/08/07−08/18	NOT	12	
2001/05/06−05/09	NOT	6	
2001/06/03−06/12	NOT	17	
2002/08/20−08/29	NOT	7	
2003/06/03−06/22	NOT	13	
2004/01/30−02/11	NOT	10	
2004/07/25−08/08	NOT	10	
2005/07/15−07/23	NOT	7	
2007/07/18−07/29	NOT	12	
2009/08/26−09/06	NOT	11	
2009/12/27−01/04	NOT	18	
Low-resolution spectra			
Date	Telescope	# of spectra	Phase
1999/02/06	NOT	11	0.35−0.40
1999/02/07	NOT	43	0.75−0.78

arc observations before and after each pair. Because we selected only a narrow spectral region, only a couple of arc lines were seen. Thus, no accurate wavelength calibration could be carried out. An approximate wavelength solution was obtained from the theoretical calculations for the grism #9, and the solution was fine-tuned for each observation by cross-correlating the arc spectra and introducing the shifts obtained to each corresponding observation. Since we were only interested in the rapid variability of the profiles, this procedure gave a wavelength solution that was sufficient for our purpose. All the observations were reduced using the Image Reduction and Analysis Facility (IRAF) which is distributed by KPNO/NOAO.

2.3. Photometry

Besides the ΔV observation presented in Oláh et al. (2009) and Hackman et al. (2013), we have used all the data taken in different other colours ($U, B, I_{\rm C}, b, y$), parallel with the V measurements of Korhonen et al. (2001, 2007), to estimate the temperatures of active regions in FK Com.

3. Results

3.1. Long-term chromospheric activity

A sample of the Hα spectra is plotted in Fig. 1. For each observing run, five to ten spectra that show the behaviour of the region well were chosen and plotted. As can be seen, the profiles are highly variable, but at each epoch they display a broad double-peaked emission that is indicative of a circumstellar disc.

The complex Hα profile shape of FK Com indicates many different components: circumstellar disc, plages, and prominences. The disc contribution is removed to study just the contribution from the stellar component (plages and prominences). To facilitate this, we subtracted the spectrum that showed the least
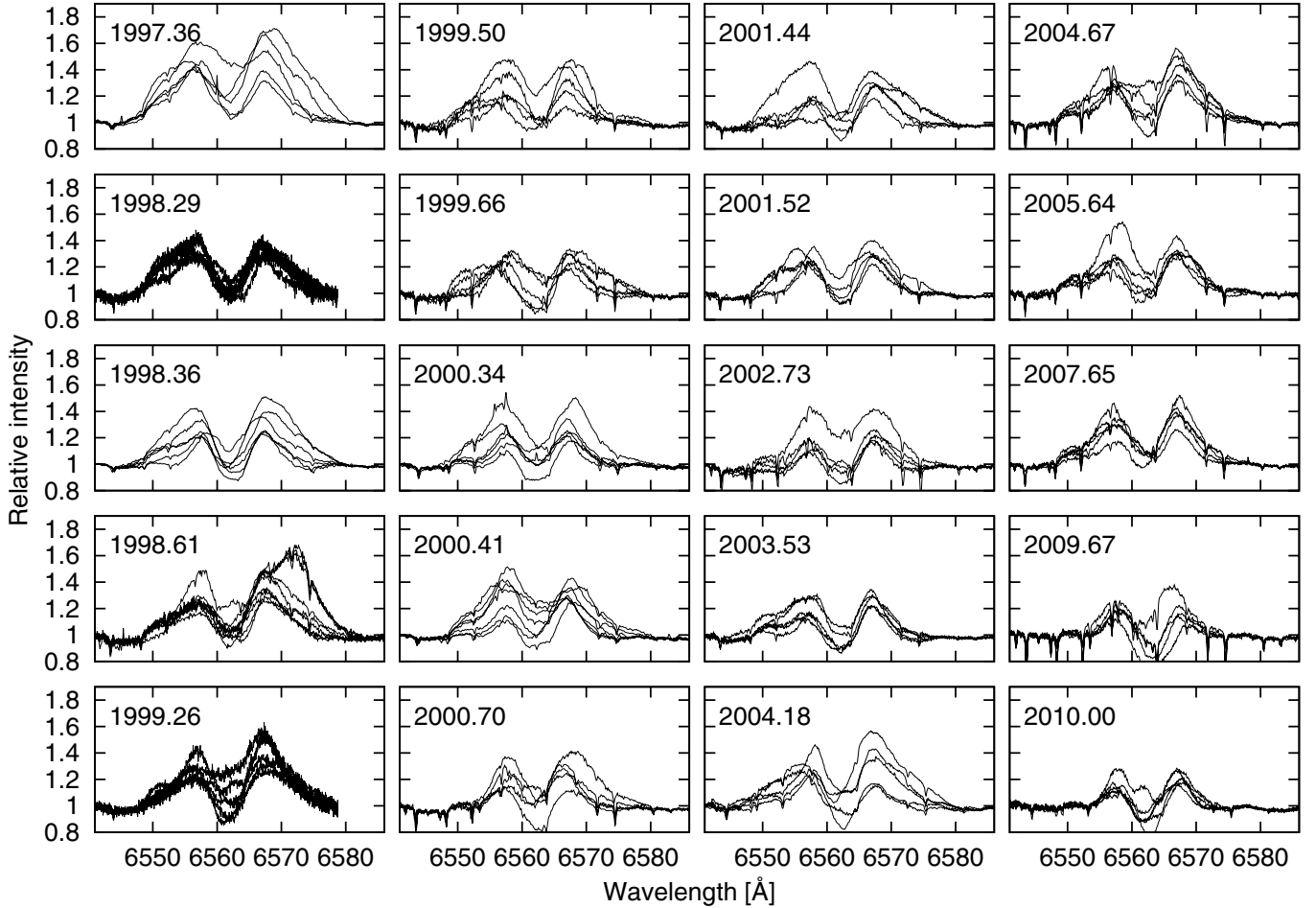
Fig. 1. Samples of high-resolution Hα profiles from different observing runs.

amount of stellar Hα emission and seemed to only show the circumstellar disc component (a NOT spectrum from 2000/08/10) having a symmetric Hα profile with no other emission feature than the two circumstellar disc-peaks. However, it is possible that this lowest intensity spectrum is just a local activity minimum in the decade-long observations, and even this one contains some low-level plage- or prominence-like chromospheric activity. Using these residual spectra, we have plotted the dynamic spectra in Fig. 2 for each observing run. The plots show the excess emission at different velocities (*x*-axis) and rotational phased (*y*-axis, times of observations). The dashed white line denotes the location of the stellar disc centre and the dotted lines the edges of the stellar disc. Colour coding (black-red-green-blue) shows the intensity of the Hα region. Crosses mark the phases of the observations, for phases where there is no data, the plot is interpolated to the closest measurements. More information on how these dynamical spectra were calculated can be found from Korhonen et al. (2009). On the whole, most of the excess emission is seen outside the stellar disc, implying material located higher in the stellar atmosphere. Sometimes, excess emission is also seen on the stellar disc, implying plage-like region in the chromosphere of FK Com. The wave-like features seen in these plots are probably the result of prominences rotating well outside the stellar radius. This feature can be seen best at 1998.27, 1998.30, 1999.41, 2000.33, 2001.35, 2004.10, 2004.58, and 2007.56. The shape of the waves changes continuously, indicating that these prominences are constantly evolving. It is possible that some of the prominence-like features is related to the circumstellar disc: it could get heated unevenly,

for example by stellar flares. This could cause some transient features in the disc emission. We cannot completely rule out that some of the emission seen would come from the disc, but the activity of the star itself is more likely the origin. (The star is very active, as shown by all indicators.)

To check the long-term behaviour of the Hα line and give a more quantitative description, we fitted Gaussians to the residual spectra for measuring the changes in the whole Hα region and a simple model consisting of two Gaussians to the original spectra to describe the violet and red peaks of the Hα region individually. In Fig. 3 we plotted the ΔV light curve from Oláh et al. (2009) and Hackman et al. (2013), together with the strength of the Hα emission measured as the area of the fitted Gaussians (both from the residuals and the individually fitted violet and red peaks). The strength of the line decreases until about 2002−2003, then increases in all cases, indicating a change of chromospheric activity on a time scale of a few years.

3.2. Fast variability in chromospheric activity

Along with the long-term variations, we have also searched for minute-scale variations using lower resolution spectra obtained in 1999 February (see Table 1). The spectra from the two nights are plotted in Fig. 4. The Hα profile of FK Com does not show relevant changes during the time span of about two to three hours of each night. The observations from the first night show more small-scale variations. To check that these changes are real or caused by the lower signal-to-noise ratio of these observations
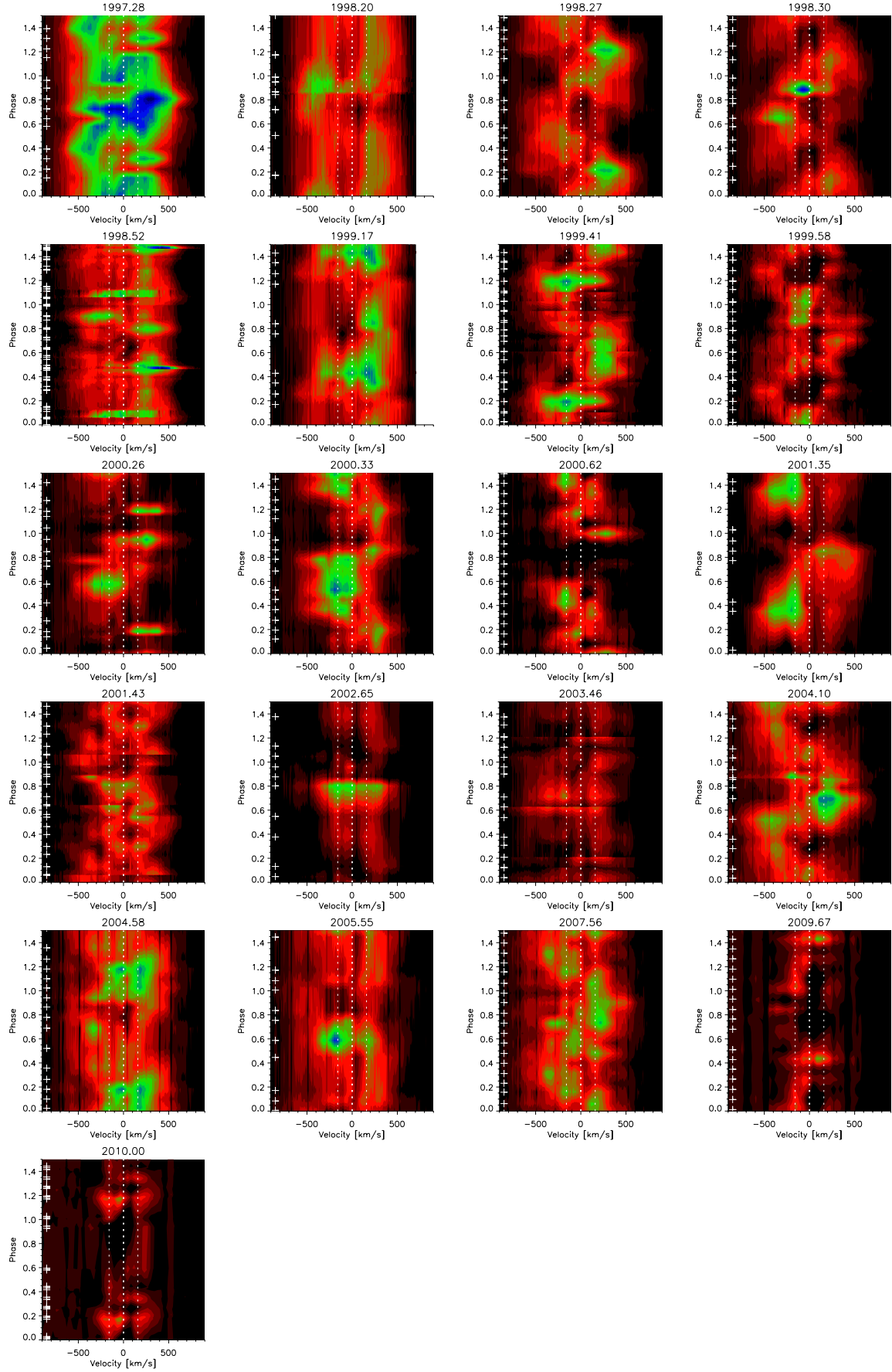
Fig. 2. Dynamic Hα residual spectra of FK Comae. Crosses on the left show the phases of individual spectra. Thick dashed lines mark the 0 km s^{-1} velocity shift (i.e., the centre of the stellar disk), and the thin lines correspond to the edges of the disk.
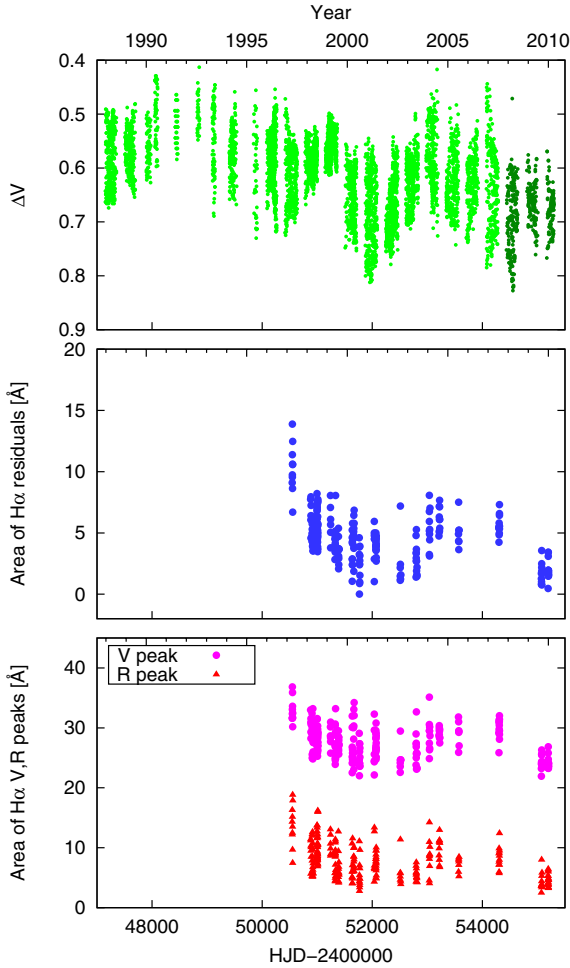
Fig. 3. *From top to bottom*: ΔV photometry of FK Comae from Oláh et al. (2009) and Hackman et al. (2013; the latter after 2008, with darker colour), Hα line areas from Gaussian fits of the residual spectra, and the area change of the Hα violet (V) and red (R) peaks (V peak shifted arbitrarily by 20 Å for clarity).

Fig. 4. Low-resolution Hα from 1999 February. Red continuous line shows the first, and the blue dashed line shows the second night. The first night covers ~3, the second night ~2 h. The same spectra, averaged in 30 min windows, are plotted above the original, with colours brightening with time.

(average signal-to-noise ratio was 88 on the first night and 118 on the second), we averaged the spectra in 30-min windows and plotted the result in Fig. 4. These averages indicate small variations in the Hα region on the time scale of hours, especially during the first night, which exhibited higher activity levels. Either way, there is more prominent difference between the two nights. Thus we can conclude that, at least during the two nights of our observing run, the chromospheric structure of the star shows significant night-to-night variability and much weaker variations on smaller time scales. Also, the low resolution of the observations can mask some smaller scale variability.

3.3. Photospheric spots from Doppler imaging

For the five previously unpublished high-resolution spectral datasets we also obtained surface temperature maps using Doppler imaging techniques. For this the Tikhonov regularisation inversion code INVERS7PD, which was written by Piskunov (Piskunov et al. 1990) and modified by Hackman (Hackman et al. 2001), was used. The adopted stellar parameters and additional details on the inversion technique and line-profile calculations can be found, for example, in Korhonen et al. (2000, 2007). The obtained temperature maps are shown in Fig. 5 and discussed in the following.
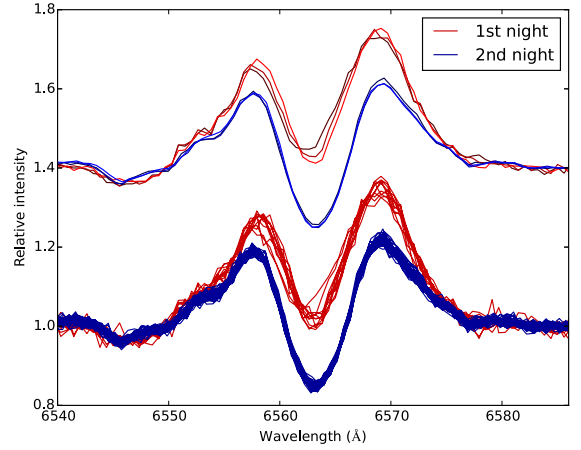
In 2004 July observations from ten rotational phases of FK Com were obtained. The phase coverage of these observations is good, and the largest phase gap is 0.17, spanning the phases 0.36−0.52. The map obtained from the data shows two high latitude, 47−79°, spot concentrations around the phases 0.25 and 0.85. A lower latitude active region is seen around phase 0.15, which spans the latitudes 20−29°. The average spot latitude obtained from this map is 54.9 ± 3.4° according to the output of the inversion code. The average spot latitudes were determined from the Doppler images using areas that were cooler than the limiting temperature of $T_{\rm lim}$ = 4550 K ($T_{\rm eff}$ = 5000 K unspotted surface temperature assumed), and its error was estimated by the standard error of the weighted mean. The area at individual latitude strips were measured and, when averaging the spot areas at each latitude, were used as weights. The two spots located at the phases 0.1−0.3 are approximately 1200 K cooler than the unspotted surface, and the one at the phase 0.8 is 800 K cooler. The coolest temperatures in the spot group around the phases 0.1−0.3 are up to 1500 K cooler than that of the unspotted surface.

The SOFIN observations obtained in 2005 July consist of eight different phases, with the largest gap spanning the phases 0.17−0.45. Not many cool regions are seen in this epoch. Only one spot, which is approximately 500 K cooler than the unspotted surface, is present at phases 0.7−0.8, spanning the latitude range 56−70°. The average latitude of this region is 61.1 ± 0.7°. The coolest temperature in this spot region is about 600 K cooler than the unspotted surface.

The phase coverage of the 12 spectra obtained in 2007 July is very good, and there are no phase gaps longer than 0.1. Also this map shows two spot concentrations on the surface, similar to the 2004 July map. The main spot group is approximately 600 K cooler than the unspotted surface, with the coolest temperatures going down to 800 K cooler than the unspotted surface. This spot is located at the phases 0.7−0.8 and spans the latitudes 56−74°. The second spot group has similar temperatures, is located at phases 0.1−0.2, and spans latitudes 61−70°. The average spot latitude is 65.3 ± 0.8°.

The observations carried out in 2009 August consist of 11 spectra, which are relatively evenly distributed over the stellar rotation. The largest phase gap of 0.17 in phase is located at
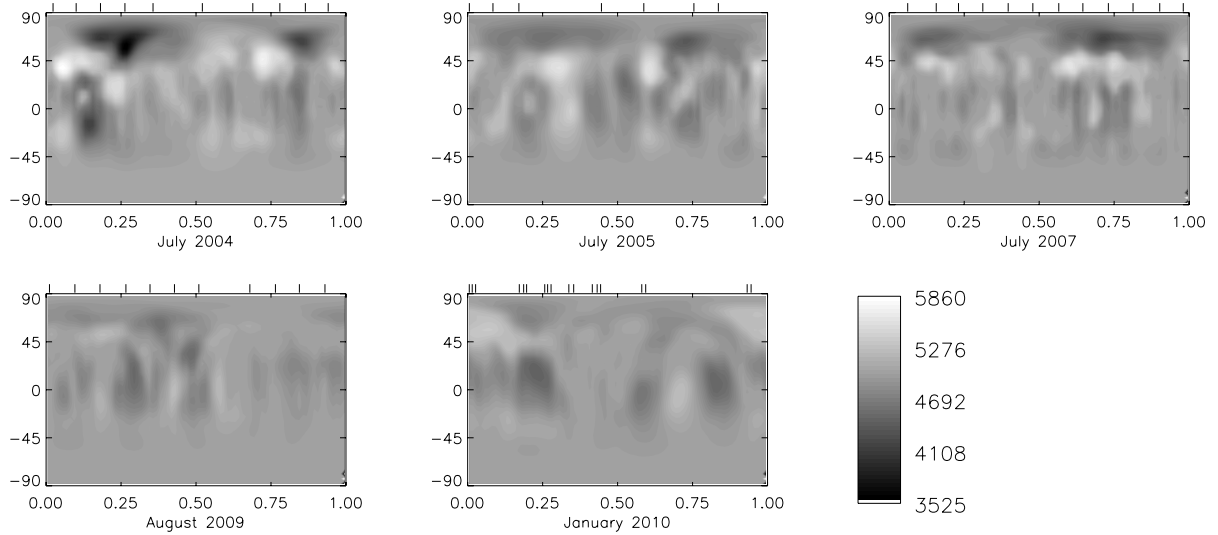
Fig. 5. Surface temperature maps for the 2004 July, 2005 July, 2007 July, 2009 August, and 2010 January datasets. The lines above the maps indicate the phases of the observations.

the phases 0.51−0.68. As for the 2005 July map, there are no prominent cool spots at this epoch. The coolest regions, which occur around phases 0.25−0.5, are only approximately 500 K less than the temperature of the unspotted surface. The latitude of the spots is also relatively lower than what is typically seen in FK Com, 7−34° with an average latitude of 18.5 ± 1.5°.

In the 2010 January 18 spectra were obtained on three nights during a four-night time period. Therefore, even though there are many phases, they are grouped together and there are large phase gaps in the dataset. The largest gap occurs between the phases 0.59 and 0.93. As in the 2009 August and 2005 July maps, the cool spots have very low contrast, and the difference between them and the unspotted surface is only approximately 550 K. Two main spot groups can be seen on the surface, one spanning phases 0.15−0.25 and another one around phase 0.8. As is the case for 2009 August, the spots in 2010 January are located at low latitudes, 2−25° with an average latitude of 12.4 ± 1.2°.

4. Discussion

4.1. Photospheric activity

The evolution of the photospheric activity of FK Com in 2004−2010 can be studied based on the five new Doppler images presented in this paper. The first map, 2004 July, has the highest spot contrast of all the new maps presented here. The second highest spot contrast is seen in the 2007 July map, where a spot contrast typical of FK Com of approximately 800 K is seen. 2005 July, 2009 August, and 2010 January maps, on the other hand, have similarly low spot contrasts with the coolest spots being only 500−600 K cooler than the unspotted surface. Often these kinds of low-contrast maps are produced if the data quality is bad, but here especially the 2007 July and 2009 August maps are of good quality and particularly have very good phase coverage. Therefore, it is clear that the temperature of the spots has drastically changed between 2004 July and 2005 July and that in the later years FK Com was also still in the low activity state. Hot features in the maps at the same longitude as the prominent cool spots are most likely artefacts caused by changing continuum

levels with changing temperature. If the hot features are separated well from the cool spots they could be real (see Sect. 4.4).

All the maps show the spots at similar phases around 0.2 and 0.8. All the spots have very low contrast in the 2005 July, 2009 August, and 2010 January maps, and it is debatable if they can even be considered active regions. The spot group around phase 0.8−0.9 is seen in all the maps, except 2009 August, but in the 2004 July map, it is the secondary spot group and the main group in the 2005 July and the 2007 July maps. This could indicate a possible flip-flop event between 2004 July and 2005 July, an event that is supported by the 2007 July map. On the other hand, the two later maps, 2009 August and 2010 January, again show 0.2 as the more active phase. This would imply yet another flip-flop, which would have taken place between 2007 and 2009. Korhonen et al. (2002) report that flip-flop events occur on average every 3.2 yr, which would mean that two flip-flops could in principle have happened in the 5.5 yr that the observations cover (although the flip-flops are not regular phenomena, see e.g. Oláh et al. 2006; Hackman et al. 2013). Still, as also concluded by Korhonen et al. (2007), flip-flops are difficult to detect from sparse Doppler imaging alone, and are better seen based on photometric observations with denser coverage. For this reason, we also carried out light curve inversion, where inversion techniques are applied to broad-band photometry, and maps of the fraction of each pixel on stellar surface covered by spots, the so-called spot-filling factor are calculated. More on the technique can be found, for example, in Lanza et al. (1998).

The light curve inversion results are shown in Fig. 6. The data were divided into 21 subsets based on the stability of the light curve. Continuous phase shifts of the spotted longitudes can be followed in six subsequent maps between the JD 2 453 843.94−2 454 254.98 maps with one seasonal gap of 150 days in the data. Another continuous shifting of the spots is observed on four consecutive maps between 2 454 520.78 and 2 454 623.75, corresponding to data without long interruptions. A drastic difference is seen between the maps of 2 454 254.98 and 2 454 464.92 and of 2 454 623.75 and 2 454 835.65, with seasonal gaps in the data of about 150 days. In these cases, which lack more continuous sequences, the changes can also be explained by continuous phase shifts, but could not be followed. Although shown by low amplitude light curves, a substantial
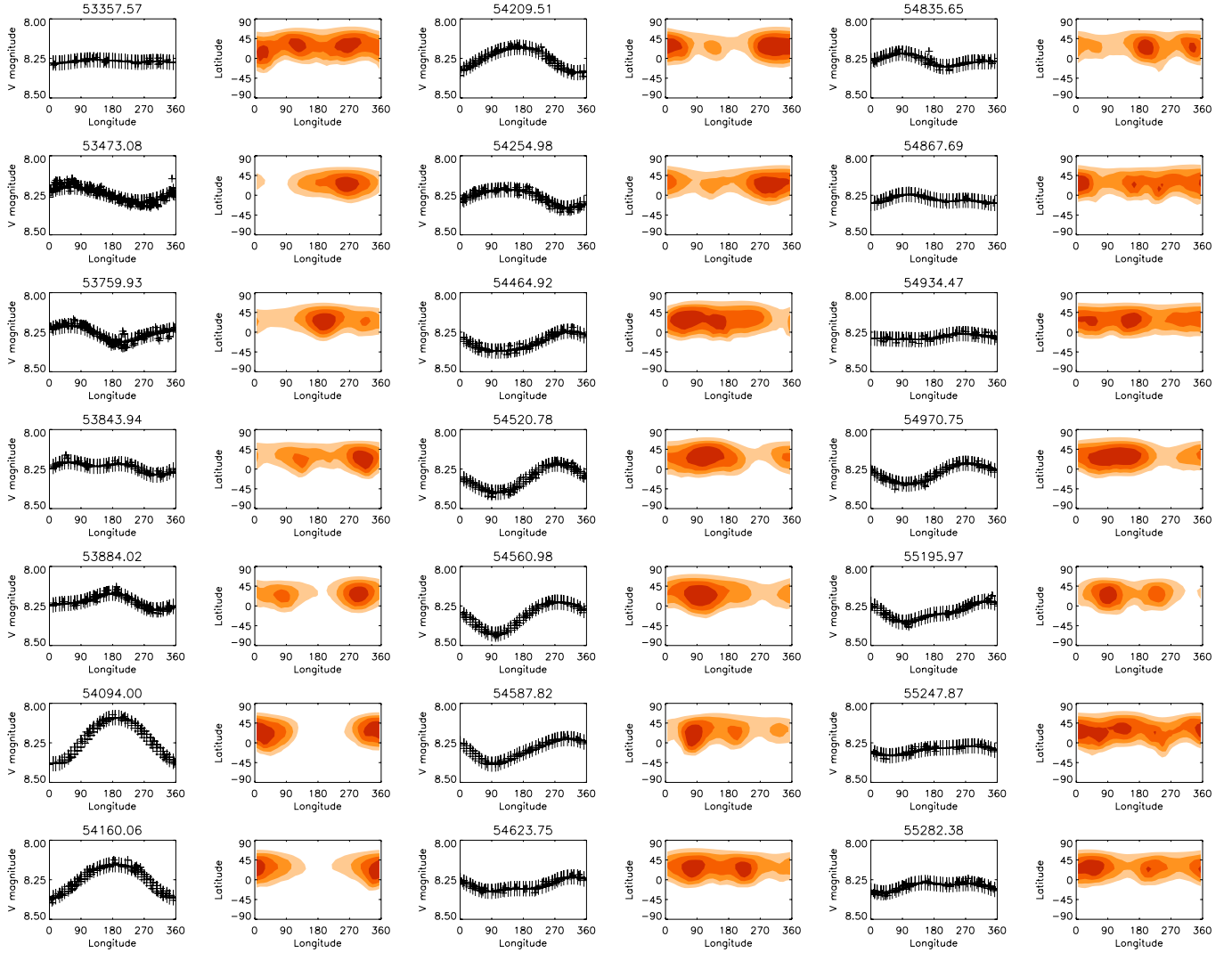
Fig. 6. Spot filling factor maps for 2005 January–2010 April. In light curve plots, the crosses denote the observations and the solid line the inversion result. In the spot-filling factor maps, the darker colour means a larger spot filling-factor. In both plots, the *x*-axis is longitude in degrees, the *y*-axis in the light curve plots is *V* magnitude, and in the spot-filling factor maps latitude in degrees. The mean Julian Date (HJD−2 400 000) of the observations for each set is given above the light curve plots.

change in the activity pattern occurred between the 2 454 867.69 and 2 454 934.47 maps with a small gap of 28 days in the data sometime in 2009 March, which can be considered as a flip-flop-like event (see Discussion later).

The spot-filling factor (SFF) maps can be compared with the Doppler images. The map closest to the 2005 July is the one from Julian Date 2 453 473.08 (second map in the plot). The location of the main spot measured from the SFF map is 0.73 in phase, similar to what is seen in the Doppler image. The 2007 July Doppler image is close to the map from Julian Date 2 454 254.98. Again the location of the main spot in both maps is very similar. For 2009 August, there is no contemporaneous SFF map, but the map of 2 454 970.75 was obtained a few months before it. The Doppler image of 2009 August shows very few spots, but they are located at the same phases as the main activity seen in the SFF map. Naturally, the activity could have gotten weaker within the approximately two months separating the map and the Doppler image. The SFF map of Julian Date 2 455 247.87 is contemporaneous to the 2010 January Doppler image. This map, like the Doppler image, shows its main activity around the phase 0.25, and the surface could be covered by relatively low-contrast spots.

On the whole, the SFF maps obtained from the photometry correspond very well to the Doppler images that are based on high-resolution spectra. The possible flip-flop events seen in the Doppler images are also seen in the SFF maps, but suspiciously most of them occur during the long gap when the star is not observable.

4.2. Correlating chromospheric and photospheric activity regions

The low-resolution Hα spectra from 1999 were observed between phases 0.35−0.40 on the first night and 0.75−0.78 on the second night. Although no changes could be observed during the nights, there is considerable difference between the spectra of the two nights. On the first night, the Hα emission is stronger than on the second one. Korhonen et al. (2002) published light curves and light curve inversions of FK Com from 1979 to 2001. The light curve from 1999.21 is obtained just a few days after the low-resolution Hα spectra. Two spots can be seen in the light curve: one at phases between 0.3 and 0.6 and one between 0.9 and 0.1. The Doppler map from 1999

April in Korhonen et al. (2007) also shows that the most spotted state is around Phase 0.3, where the star showed high-latitude spots. Thus the spectra of the first night show a spotted phase, while those from the second night show a less-spotted phase of FK Com. This can indicate a connection between the photospheric and chromospheric activity, as observed on the Sun and also on other stars: e.g., on the BY Dra-type EY Dra (e.g., Korhonen et al. 2010) on the T Tauri-type TWA 6 (Skelly et al. 2008); on the K-dwarf LQ Hya (Frasca et al. 2008); and on RS CVn-type binaries, e.g. RT Lacertae (Frasca et al. 2002); and on the W UMa-type VW Cep (Frasca et al. 1996). The Hα emission is, however, not necessarily connected to the photospheric spots: no modulation of Hα was observed on SAO 51891, although changes caused by chromospheric inhomogeneities were clearly detected in the *V* light curve and in the Ca II HK, IRT, and Hε lines. In this case the Hα modulation might possibly be hidden by other activity signatures, such as microflares (see Biazzo et al. 2009).

It is interesting to note that the spectra taken in the spotted phase of the star have asymmetric shapes with a stronger peak on the red side of the Hα line. Kjurkchieva & Marchev (2005) found that the violet peak of the Hα spectra shows a quasi-sinusoidal change with a maximum at phase 0.75 and a minimum at 0.25. The red peak was at its maximum in Phase 0.25 and at minimum at 0.75, but the changes were not as significant as for the violet one. During this time, the main spotted area could be seen between Phases 0.5 and 1.0 (see Korhonen et al. 2004): i.e., at the light curve minimum, the violet peak was in maximum.

4.3. Prominences

In some cases in Fig. 2, noticeable wave-like features can be seen in the residual spectra. These are probably caused by prominences in the outer stellar atmosphere. According to the maximum amplitude of these waves, the emission mostly originates about one stellar radius above the surface. In some cases in Fig. 2 (1999.58, and possibly in 1999.41, 2001.43), multiple waves can be seen, possibly caused by prominence arcs of different sizes and locations. We compared these spectra to the photospheric features seen in the nearby light curve inversions (Korhonen et al. 2002, and this paper) and Doppler-images (Korhonen et al. 2007, and this paper in Fig. 5). In Fig. 7 the phases of the spots, flares, and prominences can be seen. We have labelled the photospheric spot locations both from light curve inversions and from Doppler images. We determined the approximate phases of the prominences by visual inspection of the dynamic Hα spectra shown in Fig. 2, selecting the phase when the Doppler shift of the prominence is zero. Sudden increases (probably caused by flares) of Hα emission are also shown.

In most cases, when the wave-like behaviour of the Hα region was observed, the prominence appeared at a spotted phase, except in 2004 October. In many cases, the phases of the prominences coincide with the increased level of Hα activity: in 1998.30, 2000.33, 2004.10, 2004.58. At 1998.30, 1999.58, 2001.35, 2004.58, and 2007.56 the prominence is very close in phase to a dark spotted feature seen in the Doppler map. These can be an indication that there is a connection between the prominence and the photometric spots as found by Huenemoerder et al. (1993), who also observed in 1989 that the dark photometric spots and Hα excess coincide in phase.

A detailed description of the possible connection between the different activity features is given in Appendix A.
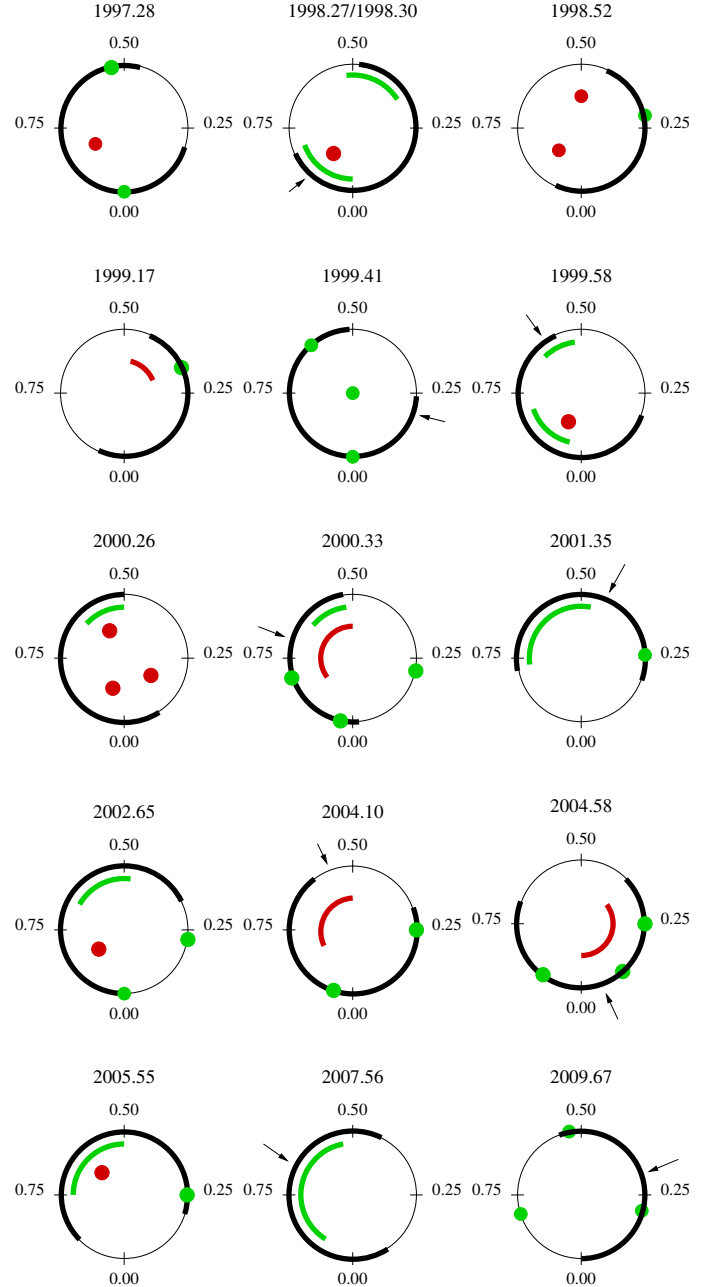
Fig. 7. Possible connection between the dark photospheric spots and the chromospheric features. The approximate locations of starspots from light curve inversion (Korhonen et al. 2002) and from this paper (see Fig. 6) are indicated with black arcs. Stronger spots from Doppler images in Korhonen et al. (2007) and from this paper (see Fig. 5) are shown with green dots or arcs, and green dots in the middle of the circles indicate polar caps. Phases of prominences (see Fig. 2), i.e., when the prominences cross the stellar disk, are shown with black arrows outside the circles. Phases of increased Hα emission seen in Fig. 2 are labelled with red dots/arcs inside the circles.

4.4. General level of activity

To measure the strength of the Hα line, we fitted Gaussians to the residual of the Hα region after subtracting the spectrum showing the lowest activity, thus removing the effects of a possible disk present around the star. Anti-correlated behaviour was observed between the *V* light curve and Hα by Huenemoerder et al. (1993), and this was the case in our low-resolution spectroscopic observations, too. If we compare phased light curves

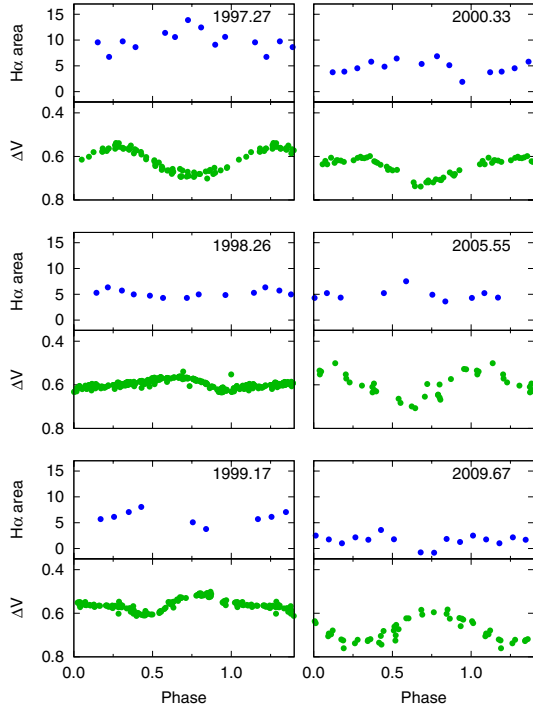**Fig. 8.** Comparison between the area of Hα residuals from Gaussian fits and light curves.
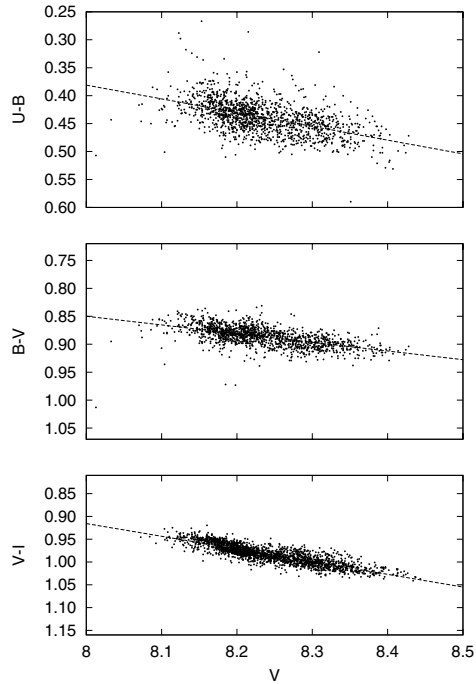

Fig. 9. Magnitude–colour index curves of FK Com using photometric data of Hackman et al. (2013) covering the years 1997−2010. Dashed lines show the best fit to the data.

Fig. 10. Light curve and magnitude–colour index curves of FK Com using photometric data of Hackman et al. (2013) covering the years 1997−2010. The magnitude–colour index plots show four section of the light curve having lower amplitudes plotted over all data, indicated by small dots. Dashed lines show the best fit to the given sections.

and the area of the residual Gaussians (see Fig. 8), we can find similar trends, although the relation here is much less clear, and was only found in some cases, while positive correlations and no Hα modulation have also been observed. One reason for this could be that the Hα emission originates in both plage regions and prominences, and these features can be observed better at different ph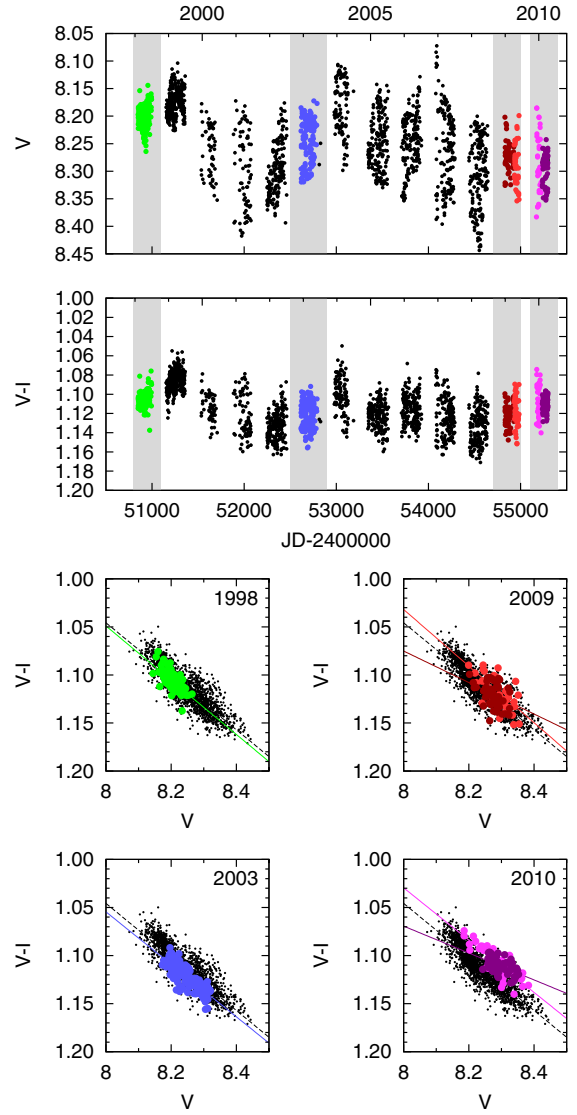ases. Namely, plage-like structures are better seen on the stellar disc, while prominences show themselves better when seen off-limb (see, e.g., Hall & Ramcey 1992). Strict anticorrelation between the *V* light curve and Hα is observed only when the spots and the Hα emitting regions are co-spatial.

Comparing the Hα intensities and the Δ*V* light curve (see Fig. 3), we find that they have a very similar trend between 2000 and 2006, although this connection cannot be seen in the earlier and later observations. The long-term positive correlation of the light curve and the Hα line (i.e., with a stronger chromospheric activity as the star gets brighter) could be explained by facula-dominated activity, i.e., that most of the optical brightness changes are caused by hot spots – facular regions, at least on a long-term basis. The magnitude–colour diagrams of Korhonen et al. (2001) show that activity of FK Com is dominated by spottedness and not photospheric facular regions: the star gets redder as it becomes fainter (see also Messina 2008). This finding can be confirmed by reconstructing these magnitude–colour diagrams using also the more recent photometric data of Hackman et al. (2013), see Figs. 9 and 10. These diagrams, though, show
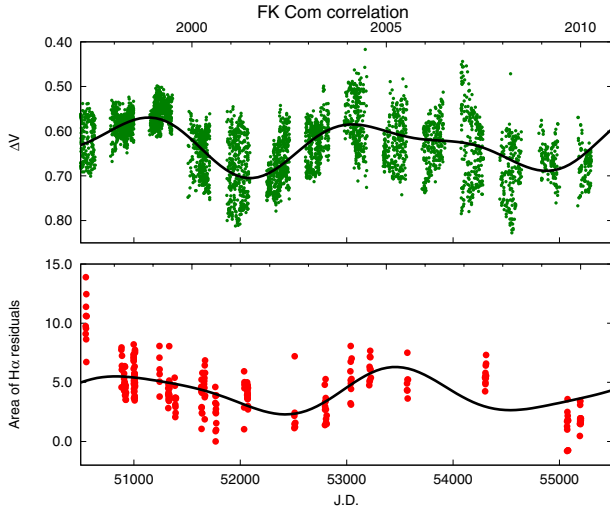
Fig. 11. *Top*: ΔV photometry of FK Comae, *bottom*: Hα line areas of the residual spectra. Continuous lines in the upper two plots show a two-period fit to the data (see text).

the cumulative effect of the rotational modulation and the long-term changes, which can hardly be separated.

In Fig. 11, a two-period fit to the V data is drawn in the upper panel, with lengths of 6.8 ± 0.5 and 4.1 ± 0.1 years. The errors of the periods were estimated by the frequencies of the Fourier-spectrum $0\overset{\text{m}}{.}0005$ below its maximum, which corresponds to 10% of the precision of the data used, cf. Press et al. (1992). A fit with the same periods is plotted on the Hα area dataset. and the fit describes it reasonably well, apart from the first data (1997) that has some phase shift. These two periods (or rather time scales) were found from a simple Fourier analysis (see Fig. 12) and only serve to show the long-term changes in Hα relative to V. However, these time scales are verified with a time-frequency analysis of the 32 yr long V light curve taken between 1979−2011, with the STFT (short-time Fourier transform). The results are shown in Fig. 13. For the details of this method and its application, see Kolláth & Oláh (2009) and Oláh et al. (2009). After JD 2 451 000 (i.e., around 1999), the long-term, mean brightness of the star shows an abrupt decrease. The cycle period increases from about 5.5 yr in 1982 (2 445 000) to the present 8.3 yr. In 1999 the cycle period was about 6.6 yr, and a constant other cycle showed up with an approximate length of 4.2 yr, lasting until the present. This other cycle showed up after the flip-flop event in 1997−1998. Whether any change in the cycle periods appear after the recent (2009) event remains to be seen in 15−20 yr.

The longer (∼7 yr) cycle dominates the Hα variations and seems to be shifted by about one to two years with respect to the brightness in V. With the growing spottedness between 1999 and 2002, the Hα excess decrease and spots dominate. From 2002 to 2004 the star brightens, which means fewer spots; by 2004 the Hα is stronger; and after that, more spots appear and the star gradually becomes fainter again. This could mean that we see the same quasi-periodic behaviour in the photometry and the Hα spectra – i.e., the photosphere and the chromosphere – but the chromospheric changes are delayed with respect to the photosphere.

Radick et al. (1998) investigated the long-term relations between the photospheric and chromospheric variations of 35 stars, including the Sun, using the Mount Wilson HK data (see, e.g., Wilson 1978) with contemporaneous photometry from Lowell

Observatory during the last decade before 1995. The results show that the younger stars of the sample, i.e., below 1−2 Gyr age are fainter, when their chromospheric emission increase, while the older stars, including the Sun, show parallel behaviour and brightening with higher chromospheric emission. These relations are not strict parallels or mirror images but show phase shifts and sometimes different patterns (see Radick et al. 1998, Fig. 3.).

It is also possible that cool spots are caused not just by magnetic activity but also by vortices, as proposed by Käpylä et al. (2011). In this case there would be no connection between the light curve and the Hα emission. Another possibility could be the structure of the spots – i.e. spot groups with mixed polarities vs. large unipolar spots – because these two kinds of structures could cause very different Hα emission. In principle, this could be verified by studying the magnetic field structure.

According to the Doppler images, bright regions are present on the surface. Such hot regions were found on FK Com in Doppler images of Korhonen et al. (2007), for example, in 1993 June or 2003 June or in some of the ones presented in this paper (see Fig. 5). These bright spots tend to get more pronounced when the data quality is poor, and especially large phase gaps in the data result in hot spots in Doppler images, suggesting they are artefacts of the inversion method. This possibility is also supported by the bright regions mostly occurring near the cool spots – this pairing of cool and bright features is a way for the inversion to mimic spectral features visible at certain phases but absent in others. This can also occur if there are significant changes in the spot configuration occurring during the observation run (see Hackman et al. 2013). Therefore, their reality cannot be conclusively verified.

In Fig. 14 we plotted spot temperatures from both Doppler images and spot modelling. Photometric spot temperatures were derived both from narrow- and wide-band data ($b − y$ and $B − V$, $V − I_C$ respectively) using SPOTMODEL (Ribárik et al. 2003). The spot temperatures derived from the different colour indices generally match each other well. On average, though, the spot temperatures from wide-band photometry are a little bit higher than from the narrow band data, which is probably due to more contribution of faculae to the wide bands. The temperatures of the coolest areas from Doppler imaging agree fairly well with spot temperatures from photometry. The hottest regions have about 500 K higher temperatures than the photosphere ($T_{\text{eff}} = 5000$ K assumed). By 2010 the temperature of the coolest regions from Doppler imaging became higher, which supports the measured increase (blueing) of the $V − I_C$ colour index.

The contrast of the Doppler images seems to decrease in time in the good-quality maps. Minimum and maximum map temperatures in a uniform sample of Doppler images are given in Fig. 14. All the maps used for this plot are from SOFIN data, and they have a maximum phase gap of <0.25, i.e., cases where strong artefacts are not expected (temperatures are collected from this paper, Korhonen et al. 1999, 2000, 2007). A linear fit to the coolest Doppler imaging temperatures in these maps shows that the spot temperature increases on average approximately 23 K per year during the time period 1994−2010. On the other hand, the hottest temperatures in the maps are typically around 5600 K (67% of the time 5500−5700 K). The fit to the hottest temperatures exhibits a slight decrease over the years, but only at a level of approximately 4 K per year, and it cannot be considered significant. One has to note, though, that the unspotted surface of FK Com has a temperature of approximately 5000 K, and therefore the hottest temperatures are significantly above this.
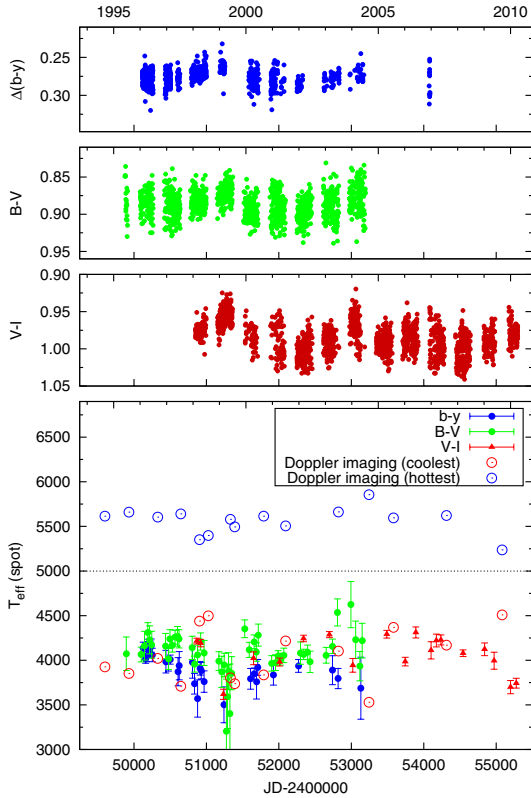
Fig. 14. *Upper three panels*: long-term behaviour of the $b − y$, $B − V$, and $V − I_C$ colour indices, which reflect the global temperature changes of the star. *Bottom panel*: starspot temperatures using photometry and Doppler Imaging. The data points for the Doppler-map temperatures are from this paper, Korhonen et al. (1999, 2000, 2007). The horizontal line at 5000 K shows the unspotted temperature.

The 2009/2010 observations are especially puzzling. The whole brightness level is low, and the light curve has a low-amplitude modulation. As photometric observations show, a sudden phase jump or flip-flop occurred in the rotational modulation amounting to about 130° in longitude, sometime in 2009 March. The phase of the main minimum jumped from phase 0.6 to 0.3 as seen from Fig. 6. The Hα spectral region, observed overlapping the photometric variations from late 2009/early 2010 shows very low level of chromospheric activity (see Fig. 8). In Fig. 2 we can see that the level of Hα emission is indeed steady, it is originating outside the stellar disk, and there is a wave-like structure indicating a prominence, which reaches the middle of the stellar disk at phase $0.2−0.4$, coinciding with the light curve minimum.

In the end of the 2009/2010 season by 2010 April, the amplitude of the rotational modulation became even lower and the main minimum shifted to Phase 0.1. The spot temperatures from $V − I_C$ was steadily decreasing from 2005 to 2010. In 2009 August the lower spot temperature from Doppler imaging (DI), observed later than the phase jump (or flip-flop?) happened in 2009 March, is significantly warmer than that from the $V − I_C$ colour index. Similarly, in the second half of 1997, a flip-flop was observed by Korhonen et al. (2001), and after that in early 1998, the lower spot temperature from DI was also warmer than those from photometry. (At that time we have temperatures from 3 colour indices.) These two observations suggest a correlation between flip-flop events and chromospheric activity on a long-term basis.

To investigate the relation of the bright and cool regions on FK Com further, we compared magnitude–colour diagrams from different epochs. Four of these diagrams are shown in Fig. 10. The V vs. $V − I_C$ plots have very similar trends, but in the last two epochs, this trend seems to be somewhat weaker (especially in the cases of lower amplitudes, plotted with a darker shade and with a separate fit). This can suggest that there is a change going on in the activity of FK Com. This change might be connected to the results of Korhonen et al. (2009) and Puzin et al. (2014), who studied longitudinal magnetic field on FK Com using low-resolution spectropolarimetry. According to Korhonen et al. (2009), the average longitudinal magnetic field strength of FK Com was in the order of 200 G in 2008 April, but Puzin et al. (2014) find that in 2012 May, there was no detectable magnetic field on the star. The measurements from 2011 April–May show significant detections of the longitudinal magnetic field, but with much reduced field strength compared to 2008 April (Korhonen et al., in prep.). The observations of Puzin et al. (2014) are of lower accuracy than the ones used by Korhonen et al. (2009), and therefore, the non-detection could be due to the field being too weak for them to detect, as the authors also hypothesise in their paper. All this supports the idea that the activity of FK Com has significantly decreased during recent years: decreasing spot contrast of the Doppler maps, weak Hα levels in the last epochs, and decreasing longitudinal magnetic field strength.

Describing the complex phenomena observed on FK Com is not an easy task. According to the most likely explanation, the object is a coalesced contact binary system, possibly with a surrounding disk (Webbink 1976) and often one or more prominence arcs. The stellar surface is covered by both bright plage regions and dark starspots, as seen in the Doppler images. The spots in some cases can form a belt-like structure, resulting in an unvarying light curve that is fainter than the brightest state of the star (e.g., in 1993.31, see Korhonen et al. 2002) There is a connection between the changes in the chromosphere and the photosphere, but it is far from obvious. According to the later light curve amplitudes, polarimetric measurements spot the contrast from Doppler images, the general activity level seems to decrease, but the average light curve level still indicates a spotted state.

5. Conclusions

Based on the high- and low-resolution spectra presented in this work, we draw the following conclusions:

– The Hα region shows double-peaked emission, possibly indicating a circumstellar disc, and often prominence-like structures that reach to more than a stellar radius and are stable for weeks.
– The low-resolution Hα spectra show small-scale fast variability during one observing night on a time scale of hours, and the shape of the line profile changes between the nights more significantly. The first observing night, which shows higher Hα emission level and a more asymmetric shape, coincided with the most spotted phase of the light curve and of the Doppler map.
– Comparing the phased ΔV light curves and the excess Hα emission, we often find an anti-correlated behaviour by the two. The Hα emission peaks at the faintest state of the star: at the most spotted phase on the light curve and on the Doppler maps.
– This trend is not obvious on the longer term. Between 2000 and 2006, the ΔV light curve and the Hα emission seem to

be correlated, but the observations before and after this time seem to behave differently.

– The long-term correlation between the light curve and the Hα emission could be explained by the plage regions, but the magnitude–colour index in Korhonen et al. (2001) does not confirm this scenario: the star seems to get redder as it gets fainter, indicating a spot-dominated activity.

– The connection between the Hα emission level and the light curve could be explained by the same quasi-periodic changes in the chromosphere and the photosphere, with the chromospheric changes being one to two years "late" compared to the photosphere.

– In the 2009/2010 observations, the average level of the ΔV light curve is very low compared to low level of the Hα emission and the low contrast of the Doppler maps.

– On the whole, the activity of FK Com is unusually weak in 2009−2010.

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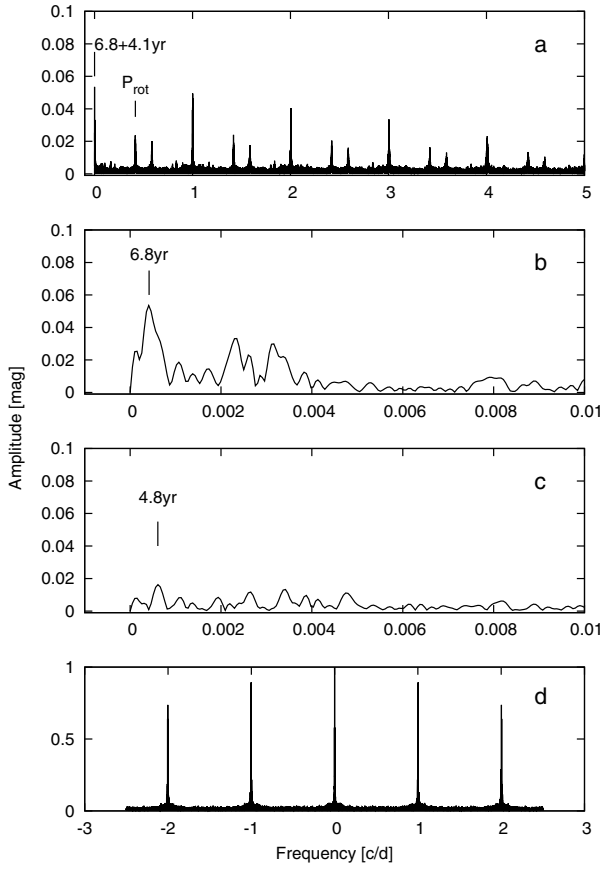Wilson, O. C. 1978, ApJ, 226, 379

Fig. 12. Fourier spectrum of the FK Com *V* light curve in those years where Hα observations exist. **a)** whole spectrum, **b)** is zoomed into the long-period region, and **c)** shows the zoomed-in spectrum after prewhitening with the 6.8 yr-long period. *Bottom plot* **d)** spectral window.
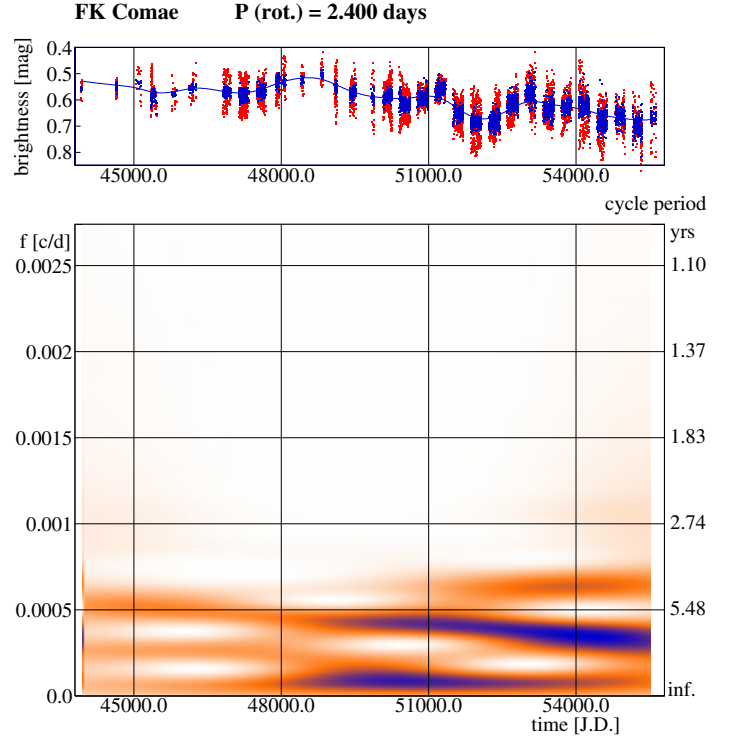

Fig. 13. Δ*V* light curve (*top*) and its time–frequency analysis using the STFT (short-time Fourier transform) method (*bottom*) showing multiple activity cycles of changing length on FK Comae.

Appendix A: Comparison between the different activity features

In the following, we give a detailed description of the Hα activity in those cases where indications of a prominence was seen and their possible connection with photospheric features:

1998.27/1998.30. The prominence crossed the stellar disk at ≈0.8−0.9 phase. The 1998.27 set shows steady Hα emission, but there is a flare in the 1998.30 set at phase 0.9. The light curve shows a minimum around 0.75 phase. The Doppler image in Korhonen et al. (2007) shows high-latitude spots at phases 0.34−0.52 and 0.78−1.00. The flare, the dark spots, and the prominence coincide in phase.

1999.41/1999.58. In the 1999.41 observations, we see a prominence at phase ≈0.2. The light curve shows a minimum at phase 0.9 and a maximum at 0.4. The Doppler image from 1999 May shows a polar spot, high-latitude spots at phases 0.6 and 1.0, and a southern spot at 0.97, but the one from 1999 July shows a much weaker spottedness around the same phases and no polar spot. In this case the prominence is close to the brightest phase of the star. In both May and July, there are brighter regions in the maps around the 0.25 phase: in May we see two bright areas on the northern hemisphere, while in July it was found on the southern part.
1999.58 is the only case where we see a strong indication of two coinciding prominence loops in the Hα dynamic spectra, one around the 0.5−0.6 phase and one at Phase 1.0.

2000.33. We see a prominence crossing the stellar disk at 0.7 in phase. The light curve at this epoch shows a minimum at Phase 0.7 and a maximum at 0.3. The Doppler map from 2000 March shows high-latitude spots around Phases 0.5−0.64, and the one from 2000 April has dark features around 0.23, 0.52−0.66, 0.59−0.70, 0.78−0.84, 0.97 phases in different latitudes. This latter map was marked in the paper as less reliable. The spotted regions between Phases 0.5 and 0.8 are present in both maps, and one of these might be connected with the prominence.

2001.35. The light curve in this epoch shows a very symmetric sinusoidal shape with a minimum at 0.46 and a maximum at 0.97 in phase. In this case the wave-like Hα structure at phase ≈0.5 in Fig. 2 is less obvious; probably the prominence is hidden by the stellar disk around Phase 1.0. This suggests a low-latitude feature. The Doppler map from 2001 May shows the strongest features – both dark and bright regions – around 0.25 phase, although this map was marked as less reliable. The following map from 2001 June shows two high-latitude spots at phases 0.20−0.38 and 0.54−0.74, an equatorial spot at 0.49, and a brighter feature around phase 0.5.

2004.10. The light curve in this epoch is a sinusoidal one with a minimum at 0.95 and a maximum at 0.43. The closest Doppler image is from 2004 July, shown in Fig. 5. (In July the shape of the light curve is similar to that in February, but the amplitude is higher and the maximum is around Phase 0.55.) In this map the most pronounced features are two dark spots: a mid-latitude one around Phase 0.1 and a high-latitude one between Phases 0.2 and 0.3. The dynamic spectrum shows that the prominence is crossing the stellar disk at ≈0.5 phase. The wave-like shape in the radial velocity is somewhat distorted, which could be a result of a mass ejection. We can see an increased level of Hα emission at Phase 0.7, which could be originating in the prominence. According to both the Doppler maps and the light curves, there is possibly no connection between the dark photospheric spots and the prominence in this case.

2004.58. The prominence crosses the stellar disk around phase 0.05, which is close in phase both to the light curve minimum and to the large dark spots seen in the Doppler maps.

2007.56. The light curve shows a minimum at Phase 0.8 and a maximum around Phase 0.27. The Doppler map in Fig. 5 is very interesting, because it is dominated by both bright and dark spots between Phases 0.55 and 1.00, with dark spots from the southern hemisphere reaching to higher latitudes and a bright elongated feature at ≈45° latitude. The dynamic spectrum shows a broad wave-like feature, indicating a prominence crossing the stellar disk around Phase 0.6, close to both the light curve minimum and the spots found in the Doppler maps.

2009.67. The Doppler maps from 2009.67 and 2010.00 are quite similar since both have a spot group around phase 0.25 at relatively low latitudes. The temperature contrast is low, about 500 K cooler than the unspotted surface in 2009 August and 600 K as in 2010 January. There is no sign of a polar spot. There is no photometric observation during this 2009.67 period, but the light curve before these observations is a sinusoidal one with a minimum at Phase 0.32 and a maximum at 0.78. The following ΔV data show similar behaviour to the previous one with an additional secondary minimum around phase 0.65. The dynamic spectrum is very interesting because it shows an obvious wave-like structure, but the general level of the Hα emission is very low, barely higher than the lowest observed one. The source of the emission crosses the stellar disk at Phase 0.3.