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Study of FK Comae Berenices

VI. Spot motions, phase jumps and a flip-flop from time-series modelling

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ABSTRACT

Aims. Time-series spot modelling was used to follow the longitude changes of active regions responsible for the light variability of FK Com between 1987−2004.

Methods. The photometric data are analysed in the time-series mode of a spot modelling code. A scenario of one polar and two low-latitude active regions (hereafter spots, for simplicity) depicts the light variations very well. The role of the polar spot remains unclear because photometry in general does not provide direct latitudinal surface resolution, however, Doppler imaging results of FK Com also show very high latitude or even polar spots besides the low-latitude ones. We also used a light-curve inversion method to confirm some of the results.

Results. The two low-latitude spots slowly migrate around 90° and 270° longitudes with quasiperiods of 5.8 and 5.2 years. The spots prefer to stay alternately on one or the other, but on the same hemisphere of the star, with a separation of typically 90−140°. We monitored a flip-flop in the light curve of FK Comae in 1999. The two low-latitude spots, being ≈140−180° from each other during the season, gradually decreased until they both practically vanished. Shortly thereafter, two new spots appeared and started to grow. One of the new spots was near the location of the old one, whereas the other turned up 90° shifted in longitude; consequently, the activity as a whole was shifted to the other hemisphere of the star. We followed a phase jump in 1997, when the two low-latitude spots got closer in longitude and finally merged, or else one of them vanished. A new spot appeared soon, shifted by 100° in longitude, but the activity remained on the same hemisphere.

Conclusions. The difference between flip-flops and phase jumps is demonstrated. The derived longitude changes of activity centres may allow us to better constrain the theoretical modelling on the time-behaviour of stellar magnetic activity.

Key words. stars: starspots – stars: activity – stars: atmospheres – stars: late-type – stars: imaging – stars: individual: FK Com

1. Introduction

The phenomenon of photometric phase *flip-flops* was first described on FK Com by Jetsu et al. (1993) and extensively studied by Korhonen et al. (2002, 2004). Several single and binary stars are now known to exhibit quasi-periodic activity changes between active longitudes situated on opposite stellar hemispheres (see e.g. Berdyugina & Tuominen 1998). These results, originating directly from measurements, have become very fruitful for studying solar and stellar dynamos.

Recently, a number of theoretical dynamo papers have been published in order to explain the *flip-flop* phenomenon (Moss 2004, 2005; Fluri & Berdyugina 2004; Elstner & Korhonen 2005). The structure of magnetic fields of active stars which are composed of a strong poloidal and an additional smaller scale solar-like magnetic field has already been suggested by Walter & Byrne (1998) as a non-solar paradigm for active stars. It turns out that this magnetic configuration served as a starting point for describing *flip-flops* by dynamo models. Since FK Com is the star on which *flip-flops* were discovered and observed for the longest time, results of the dynamo calculations are usually compared to the observed features of this star.

The major drawback of most of the photometric modelling results of active stars is that the time resolution and sampling is rather limited, i.e., when only phased light curves over several rotations are used, the changes in spot positions and sizes are not followed well in time and could lead to spurious results. In this paper, we make use of the continuous data stream from automatic photoelectric telescopes (APTs; e.g. Strassmeier et al. 1997) and apply our spot-modelling code SpotModel (Ribárik et al. 2002). This allowed us to follow the spot parameters with a good time resolution. Two interesting time periods, during 1997 and 1999, are also investigated using light-curve inversions. Our results are then compared with previous photometric modellings, with the available Doppler images, and with the most recent findings of the corresponding dynamo calculations.

2. Data and method

For modelling we used a continuous 18 year long photometric dataset obtained between 1987−2004. Data are described and used in the studies by Korhonen et al. (2001, 2002, 2005), and for the University of Vienna twin APT details we refer to Strassmeier et al. (1997) and Granzer et al. (2001). For the present investigation only the V and y observations are used.

2.1. SpotModeL

The data are analysed in the time-series mode of SpotModeL (see Ribárik et al. 2002, for a description). We fit the entire seasonal light variations of FK Com in one computer run by minimising the fit residuals with a Marquardt-Levenberg non-linear least square approach. The program runs through the whole dataset using preset subintervals and steps. This way a good phase-coverage of the actual fitted light curve is ensured. We used 14.4 days subintervals (observations from 6 consecutive rotations), and steps were always 4.8 days long (2 rotations).

The model assumes three active regions that are approximated by circular spots. It is not known whether these spots are huge cool regions or aggregates of smaller spots and faculae (active nests on the Sun). A long-term colour-index variability that reflects spot-temperature changes points towards the second possibility (see e.g. the case of IM Peg, Ribárik et al. 2002). When compared to the active regions of the Sun, the circular approach seems to be acceptable. Thus, in this paper, active regions are called spots, for simplicity.

Since photometric data have very limited latitude information, one spot is put on the stellar pole to account for the general dimming of the star from the unspotted level, and two other spots are fixed at 50° latitude. The existence of high latitude spots up to 75°, as well as low-latitude spots down to about 35°, was proven by Doppler images of FK Com (cf. Korhonen et al. 2004, and references therein). Generally, the Doppler imaging reveals many spots close to the polar region of FK Com, therefore supposing a polar active region seems to be reasonable, and as mentioned earlier this feature is mainly used for modelling the general brightness of the star.

The five unknown parameters in the procedure are the radii of the three spots and the longitudes of the two low-latitude spots. A spot temperature of 1000 K below the photospheric temperature of 5000 K is fixed and assumed to be uniform in the three spots. The average spot temperature of 4000 K is the mean spot temperature found from Doppler images (Korhonen et al. 2005), so its use is justified. A summary of the parameters is given in Table 1.

2.2. Light-curve inversions

Phased light curves were used for obtaining spot filling factor maps of the stellar surface with an inversion technique using the maximum entropy method (e.g. Vogt et al. 1987). The exact formulation follows the one by Lanza et al. (1998) closely. For the inversions, the stellar surface was divided into areas of 10°×10°, and the stellar parameters used in the inversion were the same as for SpotModeL. Due to the limited latitude information in the photometric data, this method tends to put the spots in the centre of the visible stellar disk (30° for FK Com) where they have the maximum impact on the light curve.

As this method uses phased light curves, instead of the time of the observations, studying long time series of data is not as easy as with SpotModeL. For this reason light-curve inversions were only used for studying some specific, interesting time periods.

Table 1. Stellar and modelling parameters for FK Com*.

Parameter	
Rotational period [days]	2.4002466 ± 0.0000056**
Epoch [day]	2 439 252.895 **
Inclination, i [°]	60
$T_{\rm eff}$, $T_{\rm spot}$ [K]	5000, 4000
log g	3.5
Limb darkening	0.719 (van Hamme 1993)
Unspotted ΔV, Δy [mag]	0.388***
Spot latitudes [°]	50, 50, 90, fixed
Spot longitudes	free (except for the polar spot)
Spot radii	free

* Stellar parameters from Korhonen et al. (2004). ** From Jetsu et al. (1993). *** From Korhonen et al. (2004), using V = 7.612 from Holtzman & Nations (1994).

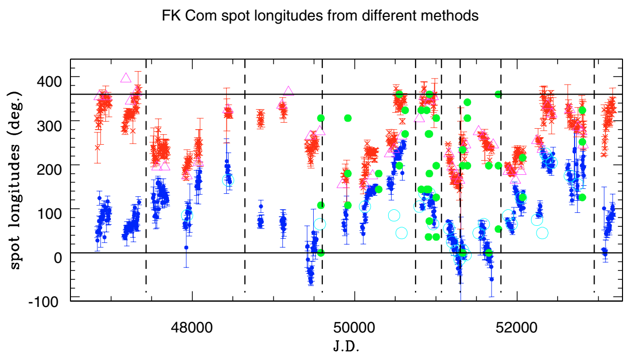

Fig. 1. Comparing spot longitudes from our time series modelling (small crosses and dots with error bars) with results from Korhonen et al. (2002, 2004; big empty triangles and circles), and with spot longitudes measured in all Doppler images of FK Com available to us to date (Korhonen et al. 2005, bigger dots). The bi-modal distribution of spot longitudes is evident using all of the three different techniques. The longitudes are plotted betwen 0°−360° (marked with horizontal lines), with a very few exceptions, in most cases when the time series results moved continuously around 0°.

3. Results

Our analysis using SpotModeL describes the time-series behaviour of the spot longitudes and spot areas for 18 years between 1987−2004. The spot placed to the stellar pole accounts for the uniform spottedness whose changes are reflected in the long-term light variation, whereas the lower latitude spots cause the rotational modulation of FK Com.

The stability of determining spot longitude values is presented in Fig. 1. The figure shows our resulting time-series spot longitudes, plotted together with those of phased light curves from Korhonen et al. (2002, 2004) and with all the spot longitudes measured in Doppler maps available to date (Korhonen et al. 2005). In the cited papers the authors used the same photometric dataset as we do here. Korhonen et al. (2002) analysed phased light curves (several in each season) using light-curve inversions with Occamian approach inversion technique (see their paper for more details). The agreement between longitude values derived by different techniques is very good, which shows the stability of our results. The advantage of the time-series analysis makes it possible to investigate the spot-longitude variability in detail.

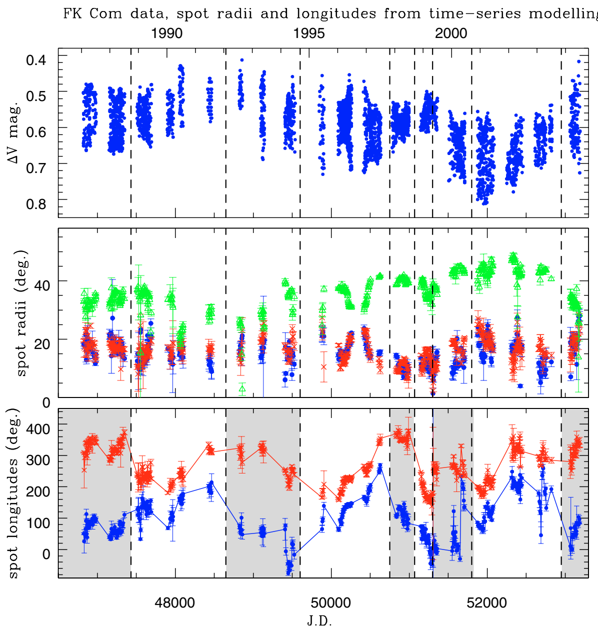

Fig. 2. *From top to bottom*: FK Com data; spot radii (crosses: *spot 1*, dots: *spot 2*, triangles: polar spot); spot longitudes (crosses: *spot 1*, dots: *spot 2*) for the years 1987–2004. Broken vertical lines represent the times when the two low-latitude spots are 180° apart from each other and continue moving closer on one or on the other side of the star, i.e. the *flip-flop* times. The shaded and clear time intervals in the bottom panel mark when the spots are closer to each other around 0° and 180° longitudes, respectively, i.e., in the two hemispheres of the star.

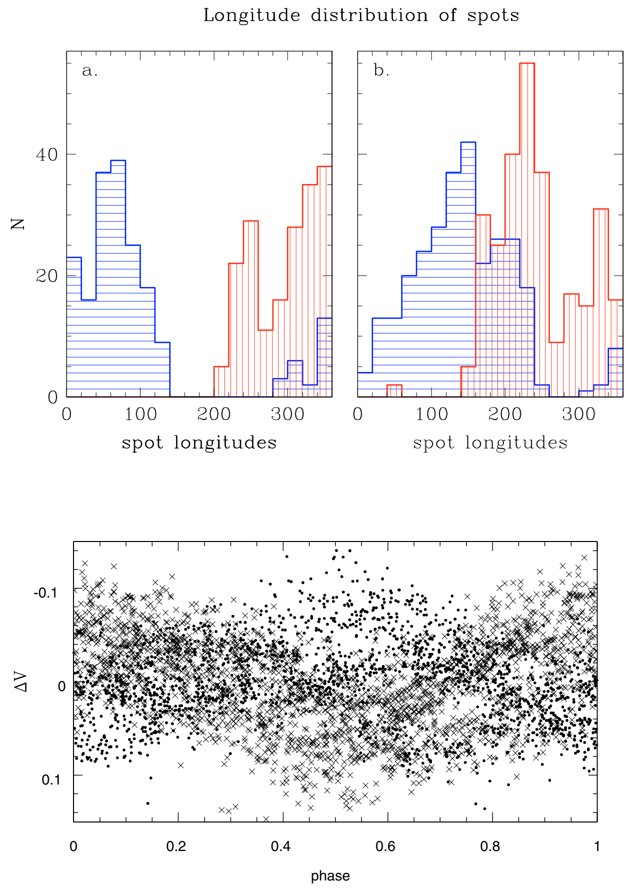

Fig. 3. *Top*: the distribution of longitudes of the two low-latitude spots of FK Com when they are closer to each other **a)** around 0° and **b)** around 180° longitudes. *Bottom*: phased original observational data (with long-term, overall variability removed) from the time-intervals when spots are around 0° (dots) and 180° (crosses). See the bottom panel of Fig. 2 for further orientation.

3.1. Spot longitudes during 18 years

Figure 2 shows the time-series spot modelling results for the entire 18-year dataset, together with the data themselves. The radius changes of the polar spot follow the seasonal light variation of the star, whereas the radii of *spot 1* and *spot 2* show fluctuations around an average of 15° each (i.e. a spot area of about 2%). The total spottedness is changing between 7–20%, which is comparable to the spot coverage of 1–20% on the northern hemisphere, reported by Korhonen et al. (2005) based on Doppler images. A Fourier analysis of the total spottedness, i.e. the sum of the areas of all three spots at a given time, was carried out with the program package MUFRAN (Kolláth 1990). After removing the long-term trend from the *spot area changes*, a clear periodicity of 6.34 ± 0.48 years is found. Including all available *photometric* data of FK Com back to 1966, and using the same procedure, the result is 6.35 ± 0.41 years.

Longitudes of *spot 1* and *spot 2* on the bottom panel of Fig. 2 also show continuous quasiperiodic changes. Fourier analysis of the longitudinal motions reveals approximate periods of 5.8 ± 0.4 years for *spot 1* and 5.2 ± 0.4 years for *spot 2*.

The two low-latitude spots thus migrate with slightly different (the same within 2σ) periods around 90° and 270° evident from Fig. 2, bottom panel. The shaded and clear time intervals in this figure show when the spots are located on the same hemisphere of the star, surrounding 0° and 180°, respectively. The vertical dashed lines in Fig. 2 thus mark the times of *flip-flops*, of which three agree with those from Korhonen et al. (2004).

The migration of spots does not mean necessarily that the spots keep their identity through the studied time interval; rather, they are on migrating active longitudes, for which it is irrelevant if a spot is old or is newly emerged. A scenario of spots, both migrating between 0° and 360° (cf. Fig. 2, lower panel) and crossing each other's paths from time to time is not excluded. Except for the quasiperiodic changes of the longitudes, we study the positions of the spots relative to each other; thus, in the case of this latter scenario, all the following results and discussion remain valid.

The longitude distributions of the two low-latitude spots are plotted in Fig. 3 in two panels, from the shaded (**a.**, spot longitudes closer to 0°) and clear (**b.**, spot longitudes closer to 180°) time intervals from Fig. 2. This figure shows the evident *flip-flop* feature: activity is located alternating on the opposite sides of the star. After removing the long-term variations from the original dataset, we phased the data separately for the two time-interval sets of spots as displayed in the bottom panel of Fig. 3. Indeed, the light minima of the two subsets of the original data occur near phases 0.0 and 0.5, as suspected from the modelling results.

Figure 4 presents the distribution of spot separations from SPOTMODEL, and results both from the light-curve inversions by Korhonen et al. (2002, 2004) and from available Doppler images. Spot distance is defined as the shorter longitude difference, thus always 180° or less. It can be seen that most of the time spots are about 90–140° apart from each other, i.e., significantly closer than 180°, staying together on the same hemisphere of the star. The small differences between the peaks of the three histograms in Fig. 4 are probably due to the specialities of the different modelling techniques used. Supposing a polar cap to account for the long-term brightness change, the two lower

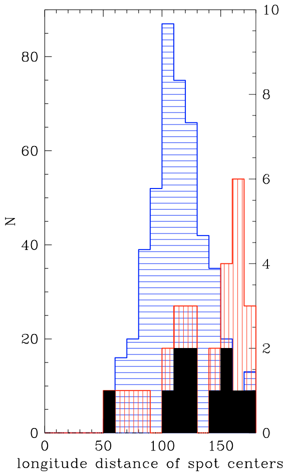

Fig. 4. The distribution of longitude distances of the two low-latitude spots from the present results (horizontally shaded), from Korhonen et al. (2002, 2004; vertically shaded), and from Doppler maps (filled). Results of the present paper are plotted with respect to the left y-axis, the other results (lower in number) with respect to the right y-axis.

latitude spots, on average, are closest (≈115°) to each other in the results from SpotModel. Modelling the overall brightness with light-curve inversion results in a spotted belt around the star at the same latitude as spots causing the rotational modulation; the results give the biggest spot distances (≈140°). Spot distances from Doppler images (≈130°), which are not disturbed by preset spot locations, are between the results from the two different photometric approaches.

We stress that using two circular spots for modelling the rotational modulation is just an approximation. It is well possible that the two supposed spots make up just one elongated feature that we are not able to resolve. However, this does not affect the result of the alternating preferred spotted hemispheres, as Fig. 3 reveals.

3.2. Flip-flops and phase-jumps

Modelling results of Elstner & Korhonen (2005) for stars with thick convection zones show that, after a spot decays, the new one appears shifted by about 90°. Such sudden spot longitude shifts of ≈90° were found from our time-series results on three occasions, in 1997, 1999, and possibly in 2002, but the poor data quality at the beginning of the 2002 season did not allow us to draw a firm conclusion. The phase shift of a newly emerged activity caused a *flip-flop* in 1999.

We next demonstrate the difference between *flip-flops* and *phase-jumps* through examples, studying both features in time-series modelled observations.

3.2.1. A flip-flop on FK Com in real time

The time-series fit of the dataset from 1999 is shown in Fig. 5. The fit follows the observed amplitude changes well down to the practical non-variability at JD 2 451 310, i.e., when the amplitude was less than 0.01 mag in V.

The resulting changes in the spot longitudes and sizes, together with the fitted dataset for 1999 is plotted in Fig. 6. Both low-latitude spots show slow longitudinal migration together with small, but systematic area changes of all three adopted spots. These variations account for the amplitude changes in the light variation from the beginning of the season until about

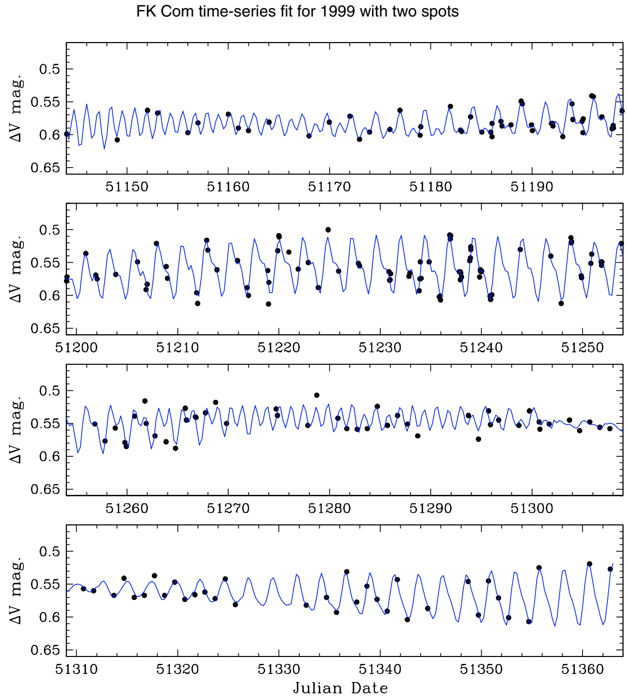

Fig. 5. Time-series fit for the 1999 dataset. Note the continuous change in the amplitude and the practically vanished amplitude at JD 2 451 310; and, that the rotation period of FK Com is 2.4 days.

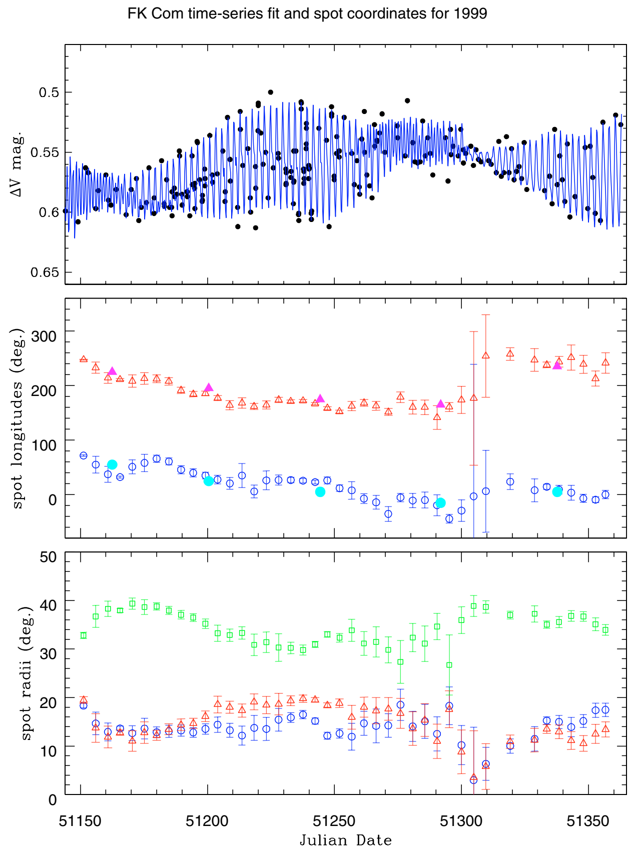

Fig. 6. Time-series fit for the 1999 dataset (*top panel*). The spot longitudes are shown in the middle panel (circles: *spot 1*, triangles: *spot 2*). Filled symbols are results taken from Korhonen et al. (2002). *The bottom panel* shows spot sizes (circles: *spot 1*, triangles: *spot 2*, squares: polar spot). Note the longitude discontinuity of *spot 2* by about 90°, and the disappearance of both *spot 1* and *spot 2* shortly after JD 2 451 300.

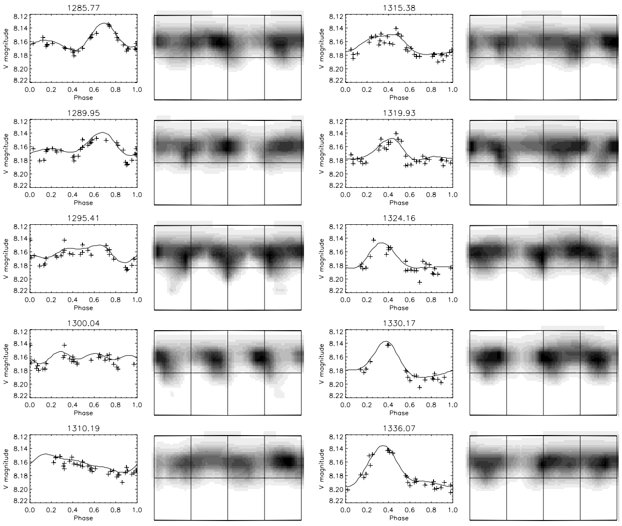

Fig. 7. Modelling the 1999 dataset in 10 segments with light-curve inversion. *Left panels* show the data with the fits, the corresponding *right panels* are the maps of the spot filling factor. Note the very small amplitude in the light curve for this time period.

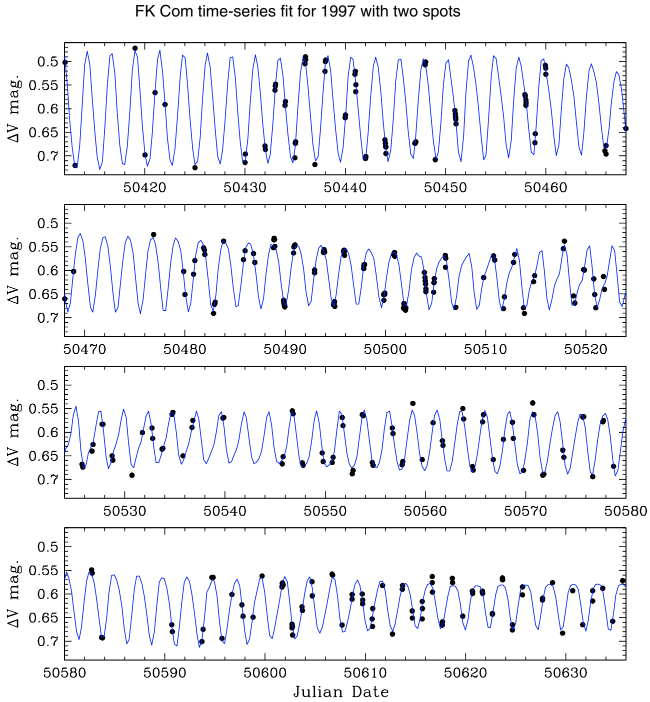

Fig. 8. Time-series fit for the 1997 dataset. The light variability changes smoothly and is never below 0.1 mag. A sudden change in the light curve shape is seen shortly after JD 2 450 500.

JD 2 451 310 when the amplitude becomes practically zero (cf. Fig. 5).

Figure 6 shows that near JD 2 451 300 the size of *spot 1* and *spot 2* gradually decreases, and finally both more-or-less vanish. Shortly thereafter, two new spots appear and start to grow. The new *spot 1* is near the location of the old one, around 0° longitude, whereas the new *spot 2* turns out to be shifted by 90° to a longitude of 260°. This shift of the spot position means that most of the activity is located now on the other hemisphere of the star than before, i.e. *we observe a flip-flop* on FK Com. Note that just before the *flip-flop* the light curve has a double humped shape and after it an asymmetric shape, which naturally arise from the spot positions being about 180° and 90° apart from each other, respectively.

Using the same dataset, but with a light-curve inversion method, we confirm the *flip-flop* event during the 1999 observing season. Figure 7 shows the modelled 1999 dataset divided into 10 segments between JD 2 451 280 and JD 2 451 340, i.e. around the time of the *flip-flop*. For better phase coverage, data from 10 days was used together for one map, and the dataset was moved 5 days in between the segments. This means that some data points in the consecutive segments are the same. The position of the spot concentration near 180° in the first two images of the left row has abruptly changed to near 270°, seen in the first three images of the right row, thus changing the more active hemisphere in the same time. This event can be clearly seen from the phases of the photometric maxima (least spotted phases). The features seen in the last two maps on the left (JD 2 451 300 and JD 2 451 310) are possibly artefacts. The amplitude of the light variation is too small and erratic during this time to allow reliable images to be obtained.

3.2.2. A phase-jump on FK Com in real time

The fit to the 1997 dataset is displayed in Fig. 8. The light variability is smooth during the whole season, and the amplitude does not fall below 0.1 mag. Only a sudden change in the light-curve shape is seen shortly after JD 2 450 500. We observed a simple *phase-jump* on FK Com in 1997, as shown in Fig. 9, where the time-series spot coordinates and sizes are plotted. Around JD 2 450 500 *spot 1* decreased or merged with *spot 2* near 230° longitude, and then shortly after a new spot appeared at 330° longitude, i.e., shifted by 100°, as suggested by the theoretical modelling (Elstner & Korhonen, 2005). However, the activity as a whole remained on the same hemisphere of the star. What we observe is a decay of an old, and the emergence of a new, active region.

We analysed this whole dataset using light-curve inversion as well. The result, plotted in Fig. 10, confirms that we observed a *phase-jump*: spots in the first three images in the left row are getting closer to each other and stay near 200–250° for the rest of the season. A new spot emerges near 0° sometime around JD 2 450 500 as seen from the third image onwards. The main spot concentration remains in the same place, which can be followed well from the phases of the light-curve minima.

Concerning these results, we suggest that *flip-flops* and *phase-jumps* are two different features, although they can be connected. *Phase jumps* occur when an old active region disappears and a new one emerges, with a phase shift relative to the position of the decayed spot. This can happen at any time, and after the *phase-jump* still most of the activity can remain on the same hemisphere of the star. On the other hand, if the separation of the two supposed active regions is close to 180° which, according to Fig. 4 is not a typical case, the phase jump of the newly emerged spot may induce a *flip-flop* as well, causing the change in the location of the activity to the other hemisphere (cf. Figs. 6 and 7). However, the interchange of the active hemisphere seems to occur smoothly in most cases, just as the consequence of spot migration (cf. Fig. 2, lower panel) when spots move away from each other until they reach 180° distance. Then they just continue their migration getting closer in the opposite hemisphere of the star and also changing the phases of the light-curve minima to the opposite side.

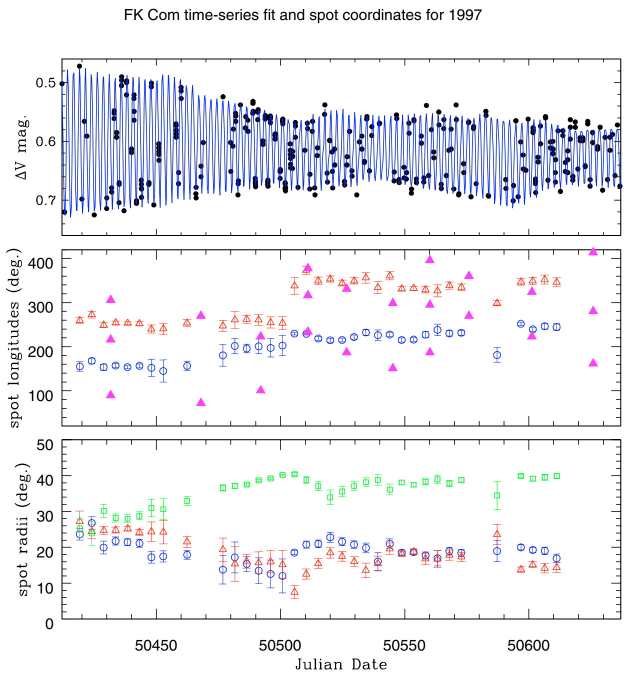

Fig. 9. Time-series fit for the 1997 dataset (*top panel*). The spot longitudes are shown in the middle panel (circles: *spot 1*, triangles: *spot 2*). Filled triangles are results of the light-curve inversion. *The bottom panel* shows spot sizes (circles: *spot 1*, triangles: *spot 2*, squares: polar spot). Note that *spot 2* either disappeared or merged with *spot 1* near JD 2 450 500, and a new *spot 2* appeared shifted by about 100°. The *phase-jump* is clearly seen from the light-curve inversion as well. The activity remained on the same hemisphere of the star.

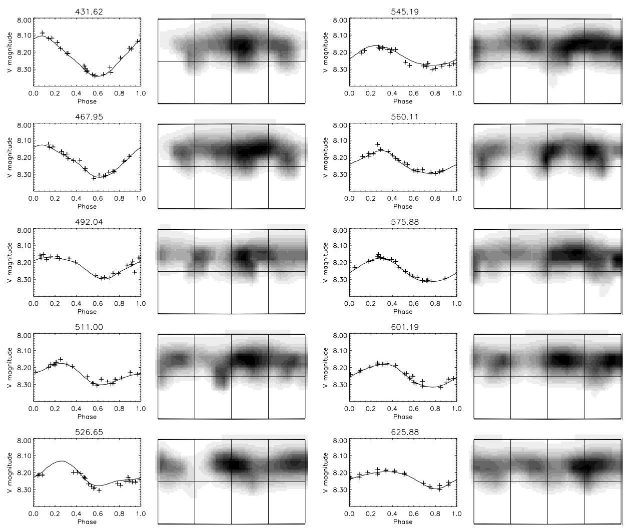

Fig. 10. Modelling the 1997 dataset in 10 segments with the light-curve inversion method. *Left panels* show the data with the fits, the corresponding *right panels* are the maps of the spot filling factor.

3.3. The possible effect of binarity

Our results would be highly supported if FK Com turns out to be the primary of a binary system, a possibility already proposed by Walter & Basri (1982). In this case, a similar scenario could be drawn on FK Com as on many other evolved close binaries, where the active longitudes point towards the companion and directly away from it. A good example (among many others) is UZ Lib, where by using 9 years worth of spectroscopic and photometric datasets, two stable active longitudes have been revealed as facing the unseen companion star and opposite to it, both from Doppler images and photometric modelling (see Oláh et al. 2002a,b, for details).

Recently, Kjurkchieva & Marchev (2005) arrived at the conclusion from three-years of Hα spectroscopy, that the Hα behaviour of FK Com can only be explained if the star is indeed in a binary system with a high mass ratio. Figure 18 in Kjurkchieva & Marchev (2005) shows the binary scenario of FK Com using the same ephemeris as we have used in the present paper. This allows us to check the spot positions of FK Com in the reference frame of the supposed binary. We find, as shown in Fig. 2, that the two low-latitude spots are migrating around 90° and 270° i.e., around the hypothetic substellar point and opposite to it.

3.4. Summary of the results

From time-series spot modelling we find

- that the total spottedness from models show a clear periodicity of 6.3 ± 0.5 years, equal to the value resulting from the data themselves;
- that two active longitudes around 90° and 270° exist and migrate with quasiperiods of 5.2 and 5.8 years;
- that the average distance between the two spots is about 90–140° and that they are situated alternately on the opposite side of the star causing light minima around phases 0.0 and 0.5, i.e., *flip-flops*;
- from one real-time *flip-flop* observation, that the spots that are 180° apart disappear just before the *flip-flop* and new spots appear, one of them in its previous position and the other shifted by 90° with respect to the old active longitude, thereby shifting the more active hemisphere to the other side of the star;
- from one real-time phase-jump observation, that the two spots either merge, or one of them disappears, a new spot emerges shifted by 100° with respect to its old longitude, and the main activity remains on the same hemisphere of the star.

4. Discussion and conclusions

We adopt the view that the longitudinal migration of individual spots are good indicators of the changing surface magnetic field topology. Due to the fact that, for any *spotted* light-curve modelling technique, spot longitudes (longitude positions of activity complexes causing light-curve minima) are the most reliable outputs and, because photometry exists for several systems on a decade-long time frame, systematic time-series studies of spot longitudes will give an excellent observational base for calculating dynamo models (cf. the recent review by Strassmeier 2005, and references therein).

Our modelling of FK Com relies on the assumption that there are one polar spot and two low-latitude spots as a proxy for the complex magnetic surface structure. The dynamo model by Elstner & Korhonen (2005) predicts a 90° change of the spot longitude during a flip-flop event for stars with thick convective envelopes. This kind of longitudinal shift was indeed observed by us during the *flip-flop* in 1999. However, 90° shifts of spots are observed other times as well, in 1997 and in 2002, but then the spots remained on the same hemisphere of the star. In these cases no *flip-flop* happened in the sense of changing the active hemisphere. The modelling results of *flip-flops* and *phase-jumps* were confirmed using a light-curve inversion technique.

Fluri & Berdyugina (2004) discuss two different sets of superposed axisymmetric and non-axisymmetric dynamo modes to generally explain the *flip-flop* phenomenon. Of their two possibilities, constant or oscillating modes, it seems that FK Com belongs to the case where alternating non-axisymmetric and constant axisymmetric modes are superposed. This suggests that the times between *flip-flops* are not strictly equidistant, as is also found for FK Com by Korhonen et al. (2004) and in the present paper. Furthermore, Moss (2005) raised the possibility of several other configurations that could explain *flip-flops* as well.

Further analyses of long-term datasets for deriving the longitude changes of activity centres may allow the theoretical modelling of the time-behaviour of the stellar magnetic activity to be better constrained.

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