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Study of FK Comae Berenices

III. Photometry for the years 1993–2001*,**

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Abstract. We present 8 years of previously unpublished photometric observations of FK Com together with the determination of the stability of the primary comparison star HD 117567. The observations have been carried out between 1993 and 2001 at four different observatories and they consist of 5157 data points in total: U(903), B(994), V(1643), R(166), I_c(573), b(461) and y(417). We also analyse this new data together with the previously published photometric observations. The V magnitude shows variations with dominant periods of about 3, 6, 12, 14 and 31 years. The short-term light curve variations appear to be caused by rearrangement of approximately constant amount of cool spots. From the values for different colours obtained during the brightest season observed, corresponding to the supposedly unspotted surface, the spectral type of FK Com is determined to be G7 III.

Key words. stars: individual: FK Com – stars: individual: HD 117567 – stars: starspots – stars: variables: general

1. Introduction

FK Com (HD 117555) is the prototype of the FK Comae stars, which are rapidly rotating, single, late-type giants with strong chromospheric activity (Bopp & Stencel 1981; Bopp & Rucinski 1981; Bopp 1982).

The first photometric observations of FK Com were carried out by Chugainov (1966). He detected rotationally modulated light curve variations with an amplitude $\Delta V \approx 0\overset{\text{m}}{.}1$ and a period of $\sim 2\overset{\text{d}}{.}4$. Since the classification of the FK Comae stars, intensive photometric observations of FK Com have been carried out. Jetsu et al. (1994a) collected all the available photometry of FK Com and combined it with new observations obtained before 1991. This photometry, spanning 25 years, was analysed by Jetsu et al. (1993). They discovered active longitudes on FK Com and the "flip-flop" phenomenon, where the stellar activity changes its longitude by 180° over a short period of time. A new "flip-flop" was reported and the data published for the years 1991 and 1992 by Jetsu et al. (1994b). Further photometric observations of FK Com for the years 1993–1997 were published and analysed by Strassmeier et al. (1997a, 1997b, 1999). A commonly accepted interpretation of the brightness variability of FK Com is that these rotationally modulated variations are caused by extended cool spots on the stellar surface.

A detailed analysis of the spot evolution and structure can be obtained from spectroscopic observations using surface (Doppler) imaging. For FK Com, surface temperature maps exist for the year 1989 (one map, Piskunov et al. 1994) and for the years 1994–1997 (six maps, Korhonen et al. 1999, 2000). This gives a baseline of only 10 years

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* Based on the observations obtained at Phoenix 10, Arizona, USA; Wolfgang and Amadeus, Arizona, USA; Mount Maidanak Observatory, Uzbekistan; La Palma KVA 0.6 m Cassegrain telescope, La Palma, Spain.

** Tables 2a-e are only available in electronic form at the CDS via anonymous ftp to
`cdsarc.u-strasbg.fr (130.79.128.5)` or via
`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/374/1049`

Table 1. Summary of the photometric observations of FK Com for the years 1993–2001.

JD 2400000+	Date	No. of obs. at different bands	Telescope
49140.3–49231.2	01.06.1993–31.08.1993	38(U), 55(B), 55(V), 55(R)	Mt. Maidanak
49514.2–49596.1	10.06.1994–30.08.1994	50(U), 51(B), 51(V), 51(R)	Mt. Maidanak
49876.8–49908.7	08.06.1995–10.07.1995	20(U), 24(B), 23(V)	Phoenix 10
50085.1–50168.8	02.01.1996–26.03.1996	45(U), 49(B), 51(V)	Phoenix 10
50174.9–50265.7	01.04.1996–01.07.1996	59(U), 65(B), 61(V)	Phoenix 10
50412.0–515449.0	24.11.1996–31.12.1996	17(U), 22(B), 24(V)	Phoenix 10
50450.9–50534.8	02.01.1997–27.03.1997	72(U), 82(B), 84(V)	Phoenix 10
50535.7–50636.7	28.03.1997–07.07.1997	100(U), 103(B), 102(V)	Phoenix 10
50778.0–50813.9	25.11.1997–31.12.1997	19(U), 22(B), 22(V)	Phoenix 10
50787.1–50885.8	04.12.1997–13.03.1998	86(b), 77(y)	Wolfgang
50814.9–50904.8	01.01.1998–01.04.1998	88(U), 91(B), 90(V)	Phoenix 10
50850.9–50898.8	06.02.1998–26.03.1998	72(V), 74(I_c)	Amadeus
50900.7–50997.7	28.03.1998–03.07.1998	139(V), 128(I_c)	Amadeus
50904.7–50997.7	01.04.1998–03.07.1998	163(b), 140(y)	Wolfgang
50906.7–50997.7	03.04.1998–03.07.1998	90(U), 95(B), 93(V)	Phoenix 10
51144.0–51179.0	26.11.1998–31.12.1998	17(U), 17(B), 19(V)	Phoenix 10
51152.0–51268.8	04.12.1998–31.03.1999	193(V), 192(I_c)	Amadeus
51181.9–51268.8	03.01.1999–31.03.1999	87(U), 95(B), 95(V)	Phoenix 10
51184.1–51252.9	05.01.1999–15.03.1999	35(b), 31(y)	Wolfgang
51269.8–51362.7	01.04.1999–03.07.1999	62(U), 64(B), 65(V)	Phoenix 10
51274.7–51360.7	06.04.1999–01.07.1999	158(V), 138(I_c)	Amadeus
51316.5–51323.5	18.05.1999–25.05.1999	23(R_B)	La Palma 0.6 m
51316.5–51323.6	18.05.1999–25.05.1999	18(R_B)	La Palma 0.2 m
51362.4–51379.4	03.07.1999–20.07.1999	19(R_B)	La Palma 0.6 m
51362.4–51380.4	03.07.1999–21.07.1999	29(V)	La Palma 0.2 m
51508.0–51541.9	25.11.1999–29.12.1999	15(U), 17(B), 20(V)	Phoenix 10
51527.1–51684.8	14.12.1999–20.05.2000	47(V), 32(I_c)	Amadeus
51546.9–51634.8	03.01.2000–31.03.2000	72(U), 79(B), 77(V)	Phoenix 10
51635.8–51731.7	01.04.2000–06.07.2000	52(U), 63(B), 62(V)	Phoenix 10
51537.7–51729.7	03.04.2000–04.07.2000	130(b), 123(y)	Wolfgang
51873.0–51908.0	24.11.2000–29.12.2000	15(U), 26(B), 28(V)	Phoenix 10
51883.9–51952.9	04.12.2000–12.02.2001	11(V), 9(I_c)	Amadeus
51891.0–51953.0	12.12.2000–12.02.2001	47(b), 46(y)	Wolfgang

for the study of spot evolution and possible magnetic cycles. The photometric observations of FK Com started in 1966 (Chugainov 1966) give a baseline of more than three decades. For this reason, the photometric observations are very important when studying possible magnetic cycles in other stars than the Sun.

In this paper, new photometric observations of FK Com from the years 1993–2001 are reported. The stability of the primary comparison star, HD 117567, and the spot properties of FK Com are analysed and presented together with the estimate of the temperature of the unspotted surface. Further analysis of the photometric data of FK Com will be presented in a forthcoming paper (Korhonen et al. in prep.).

2. Observations

The photometric observations of FK Com have been obtained at three different sites, using five different telescopes. The summary of the observations is presented in Table 1. The actual data is given in Tables 2a–2e.

The observations are all differential photometry with respect to the nearby comparison star HD 117567. In the automatic photometric telescope (APT) observations, HD 117876 was used as a secondary comparison star. The magnitude of HD 117567 in the broad bands was taken from Jetsu et al. (1994a) and in $b-y$ as an average from Knude (1981), Hill & Barnes (1982) and Olsen (1983): $U = 8\overset{m}{.}006$, $B = 8\overset{m}{.}046$, $V = 7\overset{m}{.}616$, $R = 7\overset{m}{.}221$ and $b-y = 0\overset{m}{.}292$.

2.1. Mt. Maidanak

The first sets of observations published here were obtained at the Mt. Maidanak observatory in Tashkent, Uzbekistan, using the 60 cm telescope. Each magnitude is an average of 3–5 integrations. Standard stars were observed each night to be able to make the transformations from the instrumental to the Johnson system. Shevchenko (1980) gives a more detailed description of the observation and reduction procedures used at Mt. Maidanak.

2.2. Phoenix 10

The 0.25 m APT Phoenix 10 in Arizona, USA, has been in regular operation since 1983 and is managed by M. Seeds as a multi-user telescope (Seeds 1995). The telescope is equipped with the standard Johnson UBV filters. For FK Com the integration time was always 10 s. The data quality of this telescope has been investigated carefully (see e.g., Strassmeier & Hall 1988; Henry 1995). Strassmeier & Hall (1988) give external uncertainties of $\pm 0^{\mathrm{m}}.028$, $\pm 0^{\mathrm{m}}.020$ and $\pm 0^{\mathrm{m}}.010$ for U, B and V, respectively. All the measurements with mean errors larger than $\pm 0^{\mathrm{m}}.02$ are automatically discarded. The observations also include differential magnitudes between the primary and secondary comparison star.

2.3. Wolfgang and Amadeus

Wolfgang (T6) and Amadeus (T7) are twin 0.75 m automatic photometric telescopes on Mt. Hopkins, which have been operational since 1993 (Strassmeier et al. 1997b). Wolfgang has been optimized for blue wavelengths and Amadeus for red. The FK Com observations with Wolfgang have been obtained in Strömgren b and y, and with Amadeus in V and I_c. The integration time was usually 10 s for the broad band photometry and 30 s for the narrow bands. According to Strassmeier et al. (1999) the external standard deviation for Amadeus is $\pm 0^{\mathrm{m}}.006$ in V and below $\pm 0^{\mathrm{m}}.010$ in R and I and for Wolfgang it is $\pm 0^{\mathrm{m}}.004$ for both b and y. All the observations with errors larger than $\pm 0^{\mathrm{m}}.02$ were removed from the data set.

2.4. La Palma

Some observations were also obtained at the La Palma KVA 0.6 m Cassegrain telescope and the 0.2 m wide field camera attached to it (Canary Islands, Spain). At the 0.6 m telescope the CCD used was SBig ST-6 and in the wide field camera a 1k×1k KAF-1600 chip. The observations were done using two different filters, Johnson V and Bessel R_{B}, the integration time was from 5 to 10 s and one measurement is an average of 2 to 15 separate exposures. The observations were reduced using the Image Reduction and Analysis Facility (IRAF). The magnitude of FK Com was obtained as differential magnitude with respect to the comparison star HD 117567.

3. Discussion

3.1. Photometry of the comparison star HD 117567

The observations of FK Com from APTs are differential photometry relative to the star HD 117567, which is at an angular separation of $1'16''$ from FK Com. It is therefore important to verify that this comparison star is constant in magnitude. In the Phoenix 10 observations a secondary comparison star (HD 117876) was used to verify the stability of the primary comparison star. In total, 819 differential magnitudes in the V band between the primary and secondary comparison star, distributed over the years 1995 to 2000, were analysed. Least squares Fourier decomposition (see Sect. 3.2) did not reveal any evidence for periodic variations in the light curve for periods from 1 to 1000 days. When averaging the differential magnitudes on a yearly basis, evidence for a long-term trend was found. For the years 1997 to 2000 the average differential magnitude in the V band was stable to within $0^{\mathrm{m}}.001$, while it was brighter by $0^{\mathrm{m}}.004 \pm 0^{\mathrm{m}}.001$ in 1996 and by $0^{\mathrm{m}}.012 \pm 0^{\mathrm{m}}.002$ in 1995. While this very weak change in the differential magnitude between the primary and secondary comparison star appears to be statistically significant, the level of variation is too low to have any impact on the analysis of the FK Com observations, and the change might be also due to the secondary comparison star and not the primary comparison itself.

During May and July 1999, FK Com was observed with the La Palma KVA 0.6 m Cassegrain telescope and the 0.2 m wide field camera, using CCDs. With many observations per night, this dataset made it possible to search for short-term variations. For this, the differential magnitude between FK Com itself and the comparison star was used, after removing the 2.4 day periodic variation of FK Com. From a set of 157 unaveraged R_{B} observations from May and 154 unaveraged V observations from July, there was no evidence for periodic variations with amplitudes above $\sim 0^{\mathrm{m}}.01$ with periods in the range 15 min to 1 day. The primary comparison star is an apparent visual binary with a separation of $19''$ and a difference in brightness of $3^{\mathrm{m}}.81$ in R_{B}, corresponding to a flux contribution of about 3%. Thus, depending on the seeing and centering of the aperture, the companion will contribute to the flux when measuring the magnitude of the comparison star.

3.2. Photometry of FK Com

We present 5157 previously unpublished observations of FK Com in U, B, V, R, I_c, b and y. The new V band measurements are plotted in Fig. 1 together with all the previously published V observations. The V magnitude shows variations which can be studied in more detail from the individual observing seasons.

In Fig. 2 the long-term variations of mean, maximum and minimum V magnitudes and the full V amplitude at different observing seasons are plotted versus the Julian date. For each observing season we have 10 to 232

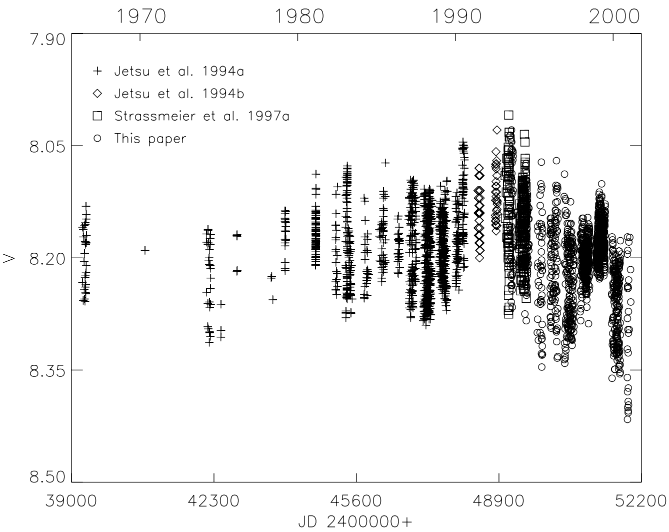

Fig. 1. All the available photometric observations of FK Com in the V band starting from 1966. The crosses are from Jetsu et al. (1994a) and references therein, diamonds are from Jetsu et al. (1994b) and squares from Strassmeier et al. (1997a). The observations presented in this paper are shown with open circles.

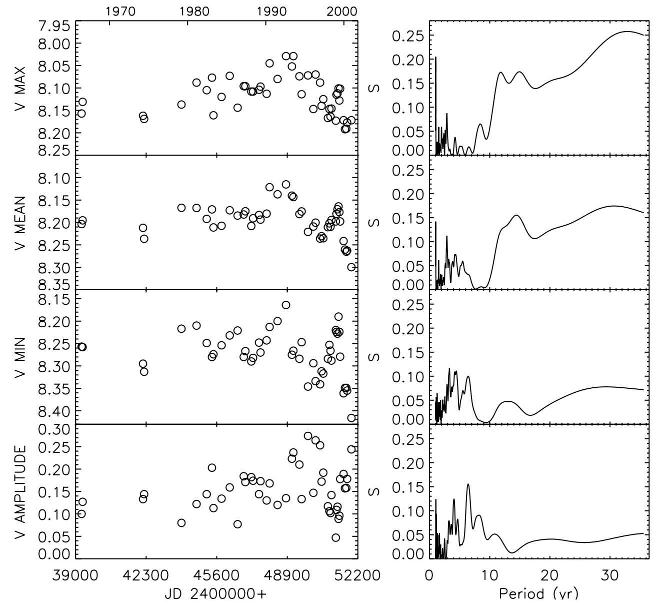

Fig. 2. The maximum, mean and minimum V magnitude and the full amplitude in V for FK Com at different observing periods (left column) together with the corresponding S-spectrum (right column).

individual V observations, the median being 59, spread over all the rotational phases. This implies that we can, within the observational errors, recover the minimum and the maximum of each individual light curve.

The variations of mean, maximum and minimum V magnitudes show a clear maximum around the years 1991–1992 and a minimum in the 1970s and at the present time. The peak-to-peak variation in the minimum magnitude is $\sim 0\overset{\mathrm{m}}{.}25$, in the mean $\sim 0\overset{\mathrm{m}}{.}18$ and in the maximum $\sim 0\overset{\mathrm{m}}{.}17$. The change in the full V amplitude itself is from $0\overset{\mathrm{m}}{.}04$ to $0\overset{\mathrm{m}}{.}27$. The exact time for the minimum in the 1970s is difficult to confirm due to lack of data before 1979. The most recent observations, from December 2000–February 2001, show FK Com at its faintest in 35 years. The V magnitude goes to as faint as $8\overset{\mathrm{m}}{.}42$ at the minimum – compare this to the brightest magnitude $V = 8\overset{\mathrm{m}}{.}03$ observed in 1993. All these variations indicate a highly variable spot distribution on the stellar surface, of which we are going to do a detailed analysis in our forthcoming paper.

The temporal behaviour of the V magnitude gives evidence for quasi-periodic processes in the spot evolution. Therefore, using least squares Fourier decomposition described e.g., by Vaniĉek (1971) and Andreasen (1987), we made a period analysis for maximum, mean and minimum V magnitudes and the full amplitude. The resulting S-spectra are shown in the Fig. 2. The S values have been calculated from

$$S = 1 - \frac{\sigma_\nu}{\sigma_{\mathrm{obs}}}, \tag{1}$$

where σ_ν is the standard deviation with the fit of frequency ν and σ_{obs} is the standard deviation without any fit.

Table 3. The periods found from the period analysis of the mean, maximum and minimum V magnitudes and the full V amplitude at different observing seasons. The most significant period of each set is marked with an asterix. The periods in parenthesis are of small significance.

Max	Mean	Min	Amplitude
33.0 yr*	30.8 yr*	(29.5 yr)	-
15.0 yr	14.4 yr	(13.1 yr)	-
11.9 yr	11.9 yr	-	-
-	-	6.4 yr	6.4 yr*
-	-	4.5 yr	4.1 yr
-	-	3.3 yr*	-
-	2.9 yr	(2.9 yr)	-

In the period analysis, two dominant types of periods were found. The long-term variations of about 12, 14 and 31 years were seen in the maximum, mean and minimum magnitudes. In the maximum and mean magnitudes these periods were very significant, but in the minimum magnitude were only of small significance. The longest period found ($\sim$31 yr) corresponds to the total minimum-maximum variation from the 1970s to the 1990s and seems to indicate the total spottedness change on the stellar surface.

The short-term variation with periods of 3, 4 and 6 years were mainly seen in the minimum magnitude and in the full amplitude, except that the mean magnitude also showed the 3 year period. The 4 year period can possibly be spurious, as it can be obtained as a combination of 12 and 6 year periods. The periods around 3 years correspond to the period of the "flip-flops" determined by Korhonen et al. (in prep.) from the individual light

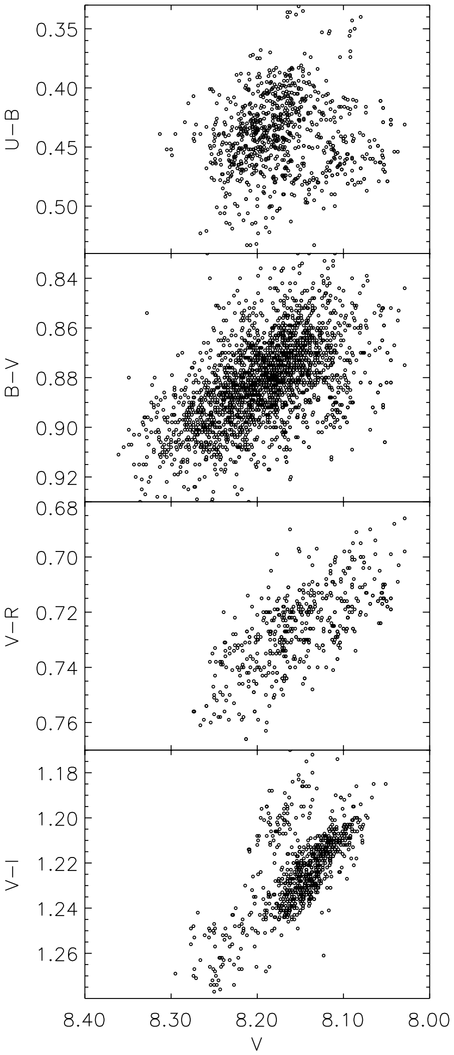

Fig. 3. All available colour observations plotted against the V magnitude.

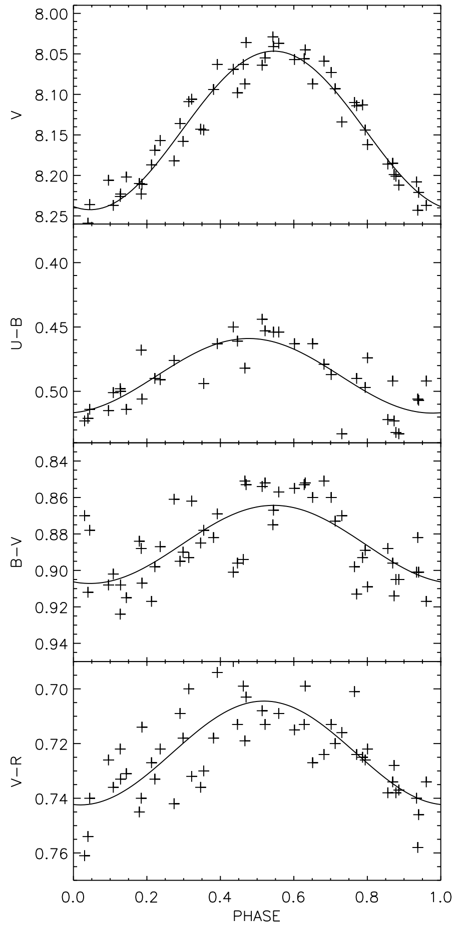

Fig. 4. The colour curves during June–August 1993 plotted against the phase. The crosses are the observations and the solid line the harmonic fit to the observations.

curves. Also, the period of 6.4 years is clearly related to the active longitudes and the "flip-flops" as we discussed in Korhonen et al. (1999). The summary of all the periods can be found in Table 3.

3.2.1. Colours

For determining the nature of the spots on FK Com, all the available colour measurements were plotted against the V magnitude (Fig. 3). The plots show that as the star becomes fainter it also becomes redder. This result can be explained with cool spots on the surface. The reason that the $U-B$ measurements do not clearly confirm this trend is most likely due to the fact that the U and B bands are more affected by flares and plages than by cool spots. Many flares have been detected on FK Com (see e.g., Jetsu et al. 1993) and these flares are usually seen in U. Also the observational errors are largest in the U band.

When looking at the individual light curves, the observations from June–August 1993 represent the period at which the star was least spotted, i.e. the maximum V magnitude was smallest ($V = 8\overset{\mathrm{m}}{.}03$). The V light curve and the available colour curves plotted versus the phase, together with harmonic fits to the observations, are presented in Fig. 4. To calculate the phases the ephemeris from Jetsu et al. (1993),

$$\mathrm{HJD} = 2439252.895 + 2\overset{\mathrm{d}}{.}4002466\ E, \qquad (2)$$

was used.

The colour curves for June–August 1993 were used to determine the temperature of the unspotted surface. The colour values for the maximum were determined from the fits. The light curve maximum occurs at the phase 0.45–0.55. The colours for this phase are: 0.46 ($U-B$), 0.86 ($B-V$) and 0.70 ($V-R$). Using the empirical formulae for G and K giants (McWilliam 1990), the surface temperature was calculated to be 5130 ± 200 K from $B-V$ and 4910 ± 180 K from $V-R$. So, even though the temperature from $V-R$ is much lower than that calculated from $B-V$, it is still within the errors. Flower (1996) gives an effective temperature of 5140 K for $B-V = 0.86$. This is consistent with the results obtained from the formulae by McWilliam. It should be remembered that even if the star is at its brightest during this time, there is still a strong cool spot on its surface which may affect

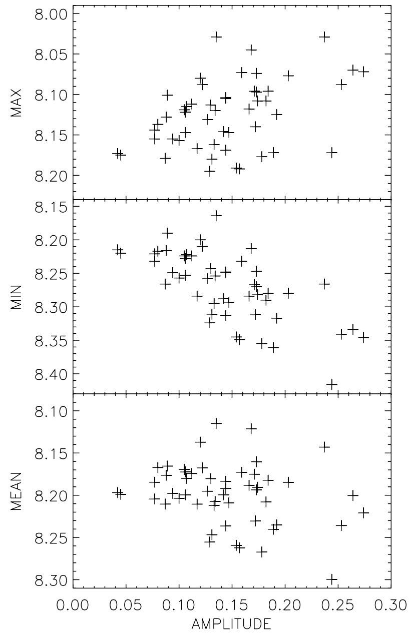

Fig. 5. The maximum, mean and minimum V magnitude of FK Com at different observing periods plotted against the amplitude.

the surface temperature and so also the colours, even at the phase of the light curve maximum. We conclude from these measurements that the temperature of the unspotted surface of FK Com is 5000 ± 270 K. This is the same temperature as has been determined for the unspotted surface from the spectroscopic observations (Korhonen et al. 2000). According to Gray (1992, Appendix B) this surface temperature corresponds to the spectral class G7 III.

3.2.2. Spot evolution

The photometric observations in the V band were also used to investigate the spot evolution in FK Com. In Fig. 5, the maximum, minimum and mean magnitudes in V at different observing periods are plotted against the V amplitude. As can be seen, there is no systematic trend in the mean magnitude with the amplitude, while the maximum and minimum magnitudes are systematically higher and lower, respectively, when the amplitude increases. This gives evidence that in FK Com the light curve variations are caused by rather symmetrical rearrangement of a more or less constant amount of dark spots, which on the other hand supports the hypothesis of two active longitudes on the surface of FK Com. Similar behaviour has been discovered in a number of stars, for example in σ Gem, II Peg and V711 Tau (Henry et al. 1995). To investigate the spot evolution, we have also made inversions from individual light curves to obtain the stellar images with more detail about the longitudinal spot distribution. These inversions will be published with further analysis in Korhonen et al. (in prep.).

4. Summary

We present new photometric observations of FK Com and analyse them together with previously published observations. The main results of this paper are:

– 5157 new observations of FK Com are published in U, B, V, R, I_c, b and y for the years 1993–2001. The data are available electronically.
– The primary comparison star of FK Com, HD 117567, shows some evidence of photometric variability, but at such a low level that it does not affect the FK Com observations.
– The period analyses of maximum, mean and minimum V magnitudes and the full V amplitude exhibits two dominant types of periods: long periods of around 12, 14 and 31 years and short periods of around 3 and 6 years. The short periods are most likely related to the "flip-flops".
– The light curve variations are caused by rather symmetrical rearrangement of an apparently constant amount of cool spots.
– Measured from the brightest phase observed, the colours give a temperature of 5000 ± 270 K for the unspotted surface. This corresponds to the spectral class G7 III.

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