Astron. Astrophys. 346, 101–110 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Study of FK Comae Berenices

I. Surface images for 1994 and 1995*

H. Korhonen[1,3], **S.V. Berdyugina**[1], **T. Hackman**[2], **R. Duemmler**[1], **I.V. Ilyin**[1], **and I. Tuominen**[1]

[1] Astronomy Division, University of Oulu, P.O. Box 3000, FIN-90401 Oulu, Finland
[2] Observatory, P.O. Box 14, University of Helsinki, FIN-00014 Helsinki, Finland
[3] Nordic Optical Telescope, Apartado 474, E-38700 S/C de La Palma, Canarias, Spain

Received 2 September 1998 / Accepted 10 March 1999

Abstract. We present new surface images of FK Com for August 1994 and July 1995. For the 1995 images two different inversion methods, Tikhonov regularization and the Occamian approach, are used to check the dependence on the formal assumptions. The images are found to be very similar when the same local line profiles, models, stellar parameters and observations are used as inputs for both methods. The validity of the maps and their temperature scales are independently checked with photometric observations.

The maps for both years show active regions of very similar substructures and latitudes. It seems that the same spot group has survived on the surface of FK Com for the 11 months between the observations; however, during that time it has moved about 0.2 in phase. The movement and evolution of the spot groups seem to cause the photometrically observed “flip-flop” phenomenon, which is noticed to be repeated with an average period of 6.5 years, similar to some RS CVn-stars.

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

1. Introduction

FK Com (HD 117555) is the prototype of the small class of extremely rapidly rotating G-K giants with strong emission from the chromosphere and transition region. They do not show radial velocity variations, indicating that they are probably not binaries. In the case of FK Com, the upper limit for radial velocity variations has been set to $\pm 5\,\mathrm{km\,s^{-1}}$ by McCarthy & Ramsey (1984) and to $\pm 3\,\mathrm{km\,s^{-1}}$ by Huenemoerder et al. (1993). These values give rather extreme limits for the mass of a possible companion. Nevertheless, the UV-flux and the rotation rate of the FK Com-type stars clearly exceed those of the RS CVn-binaries. Originally, this class only consisted of three stars: FK Com, UZ Lib and HD 199178 (Bopp & Rucinski 1981; Bopp & Stencel 1981; Bopp 1982). Later UZ Lib has turned out to be a binary (Bopp et al. 1983) and was excluded from the class. Some new candidates for the class have been suggested over the years: HD 32918 (Cameron 1982), Star I-1 in NGC 188 (Harris & McClure 1985) and 1E 1751+7046 (Fleming et al. 1987). All the FK Com-type stars are photometrically variable by $0\overset{\mathrm{m}}{.}1 - 0\overset{\mathrm{m}}{.}2$ and have photometric rotation periods of a few days (Bopp & Stencel 1981; Bopp 1982).

The spectrum of FK Com was first described by Merrill (1948). He noted a large projected rotational velocity, Hα and Ca II H&K emission and the variability of the Hα profile. The spectral type of the star is still not well determined, and its estimates range from G0 III to G8 III (Rucinski 1981; Bopp 1982; Walter & Basri 1982). Small visual brightness variations in FK Com of $0\overset{\mathrm{m}}{.}1$ with the period of $2\overset{\mathrm{d}}{.}412$ were first reported by Chugainov (1966). During the variations in the light curve, little or no colour variations are seen. This photometric variability was considered by Bopp & Rucinski (1981) to be most probably caused by asymmetrically distributed spots. The value of the photometric rotation period has been improved many times since Chugainov’s first estimate. At present, the most accurate value of $\mathrm{P_{phot}}$ is $2\overset{\mathrm{d}}{.}4002466 \pm 0\overset{\mathrm{d}}{.}0000056$ (Jetsu et al. 1993).

Dorren et al. (1984) explained the variations in the light curve of FK Com by spots which are ∼600–800 K cooler than the unspotted surface. They also observed a rapid evolution of the light curve which, according to them, appears to be the result of changing spot area and longitudinal motion of the spotted regions relative to each other. The level of the spot activity in FK Com varies significantly even within short periods of time. Nevertheless, the quarter of a century photometry investigated by Jetsu et al. (1993) and Jetsu et al. (1994a) still shows no clear periodicity, though two overall maxima in the spot activity were detected near 1976 and 1986.

According to the photometric observations, active regions of FK Com show a “flip-flop” effect (Jetsu et al. 1991, Jetsu et al. 1993), which means that the dominant part of the spot-activity shifts in longitude to the other side of stellar surface (i.e. a longitude shift by about $180°$) and remains there for a period of time. The time interval between two shifts seems to vary from a few years to a decade (Jetsu et al. 1991, Jetsu et al.

Send offprint requests to: H. Korhonen (heidi.korhonen@oulu.fi)

[*] Based on the observations obtained at the Nordic Optical Telescope, Observatorio Roque de los Muchachos, La Palma, Canary Islands, Spain.

1993). Recent UBVR photometry (since 1991) showed evidence for a new "flip-flop" which is the fourth detected during 26.3 years (Jetsu et al. 1994b).

Because of the rapid rotation and photometrically detected spots, FK Com-type stars, and FK Com itself, are very interesting objects for surface imaging. With temperature maps more information on the spot distribution can be obtained than with the photometric observations, and the "flip-flop" effect can be investigated in more detail. Three FK Com-type stars have been studied with different surface imaging techniques: FK Com (Piskunov et al. 1994), HD 32918 (Piskunov et al. 1990, Kürster & Dennerl 1993), and HD 199178 (Vogt 1988, Strassmeier 1996, Hackman et al. 1999). These images generally show polar or high-latitude spots along with numerous low-latitude spots. The image of FK Com by Piskunov et al. (1994) showed a large equatorial spot of moderate contrast (ΔT=350 K) similar to the result for HD 32918 (Piskunov et al. 1990).

In the present paper we analyse new high-resolution and high signal-to-noise ratio observations of FK Com obtained in 1994 and 1995. New estimates of the stellar parameters $T_{\rm eff}$, $\log g$, and $v \sin i$ are obtained. Two different surface imaging techniques, Tikhonov regularization and the Occamian approach, are applied to the 1995 observations to check the dependence of the image on the formal assumptions. The reality of the images is tested using near-simultaneous photometry.

2. Observations

High-resolution spectral observations of FK Com have been obtained with the Nordic Optical Telescope (NOT, La Palma) and the SOFIN échelle spectrograph with the medium resolution camera. Typically, the échelle spectra consisted of 14 orders and were centered at 6427 Å.

In 1994, the slit width was 80 μm, providing a resolution ($\lambda/\Delta\lambda$) of 75 000. The observations consist of 12 spectra taken during different nights between the 13th and 24th of August. No simultaneous photometric observations of FK Com are available for this season. We have used B and V band observations obtained between the 8th of April and 4th of July 1994 and another set of V band observations obtained between 11th of March 1995 and 23rd of June 1995, both sets published by Strassmeier et al. (1997).

In 1995, the slit width was 103 μm, which gave a resolution of 60 000. The observations consist of 20 spectra, taken between the 11th and 22nd of July. For the inversions, spectra taken during the same night, immediately after each other, were averaged to a single spectrum, so in the temperature mapping 12 spectra with higher S/N ratios were used. Almost simultaneous (8th of June - 10th of July 1995) photometric APT (Automatic Photometric Telescope) observations of FK Com in the B and V bands have been kindly provided for us by L. Jetsu and will be published elsewhere.

All spectra were reduced with the 3A software system (Ilyin 1997). The reduction included bias, flat field, and scattered light corrections, extraction of spectral orders, and wavelength calibration. The latter was obtained using a Th-Ar comparison spectrum. The zero point of the wavelength scale was adjusted using atmospheric lines in order to correct for small shifts between the comparison and stellar images.

Table 1. The spectral observations of FK Com used in surface imaging. The heliocentric Julian date is given for the middle of the exposure. The S/N ratio is measured from the reduced spectra.

HJD 2440000+	Phase	S/N	HJD 2440000+	Phase	S/N
August 1994			*July 1995*		
9578.382	0.84	189	9910.467	0.18	377
9579.392	0.27	205	9911.386	0.58	272
9580.386	0.68	215	9912.379	0.99	305
9581.380	0.09	186	9913.383	0.41	354
9582.369	0.51	202	9914.394	0.84	389
9583.366	0.92	229	9915.405	0.26	363
9584.365	0.34	228	9916.415	0.68	359
9585.363	0.75	146	9917.381	0.08	408
9586.364	0.17	215	9918.389	0.50	311
9587.392	0.60	159	9919.393	0.92	350
9588.366	0.00	148	9920.390	0.33	287
9589.356	0.42	141	9921.388	0.75	335

More information on the spectroscopic observations are presented in Table 1. As can be seen, the phase coverage is very good for both seasons, and the S/N ratios achieved are quite high, especially for 1995. The ephemeris used for the phase calculation was given from the quarter of a century photometry by Jetsu et al. (1993) and Jetsu et al. (1994a):

$$\mathrm{HJD} = \left\{ \begin{array}{l} (2439252.895 \pm 0.010)+ \\ (2\overset{\mathrm{d}}{.}4002466 \pm 0\overset{\mathrm{d}}{.}0000056)E, \end{array} \right. \tag{1}$$

where the period is the long-term average photometric period, and the epoch is a time of the light curve minimum. This ephemeris is chosen for this work in order to see if the spot distribution is consistent with the previously detected "flip-flop" phenomenon.

3. Temperature mapping

3.1. Stellar parameters

The inversion procedure is known to be very sensitive to changes in some stellar parameters, especially in $v \sin i$ and microturbulence, which will determine the average temperature of the result. We estimated some stellar parameters using all available information and our spectral observations for 1995, which have better S/N ratios. For this, all spectra were averaged to a single spectrum with a S/N ratio of 550.

FK Com is the most rapidly rotating star among the FK Com-type stars. First estimates for its $v \sin i$ ranged from 70 km s^{-1} (Chugainov 1976) to 200 km s^{-1} (Walter et al. 1984). Currently, values for $v \sin i$ are 159±4 km s^{-1} (Rucinski 1990) and 162.5±3.5 km s^{-1} (Huenemoerder et al. 1993). We determined $v \sin i$ of FK Com independently of the inversions with the Fourier transform method described by Gray (1992, p. 370).

Four spectral features from three different orders were investigated: the blend of Fe I lines at 6419.9500 Å & 6421.3510 Å, the Ca I line at 6439.0750 Å, the blend of Fe I lines at 7491.6490 Å & 7495.0600 Å, and the Ca II line at 8662.1410 Å. The final value of 155±3 $\mathrm{km\,s^{-1}}$ was averaged from the values obtained from these features and was adopted for the inversion. Note that with such a large value of $v \sin i$, changes in the map are not significant within the error interval ±3 $\mathrm{km\,s^{-1}}$, while possible larger errors can easily be seen from the inversion by comparing the wings of the observed and calculated line profiles.

As was already mentioned the spectral type of FK Com is determined to be between G0 III and G8 III. According to Gray (1992, Appendix B) this interval corresponds to effective temperatures $\mathrm{T_{eff}}$ from 5743 K to 4952 K and surface gravities $\log g$ from 3.4 to 3.3. Using the stellar atmosphere models by Kurucz (1993) with $\log g$=3.5 we tried to fit the averaged spectrum of FK Com with many different combinations of effective temperature and microturbulence. We found that the best fit can be obtained with v_{micro}=1.4 $\mathrm{km\,s^{-1}}$ and $\mathrm{T_{eff}}$=5080 K. This effective temperature corresponds to the spectral type G5 III.

The measurements of the Hipparcos satellite give a parallax of 4.27 mas for FK Com. This value corresponds to a distance of 234 pc, which is in agreement with the results by Eggen & Iben (1989) who associated FK Com with a moving group and calculated from the group modulus the distance of FK Com to be 238 pc. According to Strassmeier et al. (1997), the brightest V-magnitude of FK Com (the best approximation to the magnitude of the unspotted star) was $8\overset{\mathrm{m}}{.}04$; with a distance of 234 pc and an upper limit to the extinction in the direction of FK Com of E(B-V)=0.015 (Schlegel et al. 1998) an absolute magnitude of $\mathrm{M_V} \approx 1\overset{\mathrm{m}}{.}2$ is obtained. Compared to the range of absolute magnitudes of G0–G8 III: $1\overset{\mathrm{m}}{.}2 - 0\overset{\mathrm{m}}{.}7$ (Gray 1992, Appendix B), this is normal for the earlier part of the interval of possible spectral types.

Some tests were also made to find a suitable value for the macroturbulence, although this parameter does not significantly affect the profiles because of the large rotational velocity. We used the value 2 $\mathrm{km\,s^{-1}}$. Throughout this paper, an inclination of $i = 60°$ is adopted.

The stellar parameters used in the temperature mapping of FK Com are summarized in Table 2.

Table 2. Adopted values of the stellar parameters of FK Com.

Parameter	Adopted value
$\mathrm{T_{eff}}$ (unspotted)	5080 K
$\log g$	3.5
$v \sin i$	155 $\mathrm{km\,s^{-1}}$
Microturbulence	1.4 $\mathrm{km\,s^{-1}}$
Macroturbulence	2.0 $\mathrm{km\,s^{-1}}$
Inclination	60°

3.2. Local line profiles

Errors in the calculations of the local line profiles have a strong effect on the inversion. They easily cause artificial features in the maps, like polar caps and belts of cool and hot spots. Local line profiles were calculated with a code by Berdyugina (1991), which includes calculations of opacities and intensities in the continuum and in atomic and molecular lines. Also, number densities of atoms and molecules are calculated under the assumption of dissociative equilibrium. Atomic line parameters were obtained from VALD (Piskunov et al. 1995), while molecular line parameters were calculated in the same way as was described by Berdyugina et al. (1998a). LTE stellar model atmospheres from Kurucz (1993) are used.

The atomic line parameters were requested from VALD using solar abundances. It seems that either these abundances are not always correct for FK Com or the line parameters contain errors. Uncertainties in the stellar parameters, e.g. elemental abundances and microturbulence, will also cause problems. However, for surface imaging it is sufficient to get the right equivalent widths for the local line profiles. Therefore, the $\log(gf)$ values of some lines were changed to be able to fit the observations better. For finding the proper $\log(gf)$ values we used observations of slowly rotating stars with spectral types close to that of FK Com: β Gem (K0 III) and μ Peg (G8 III). Changes in the $\log(gf)$ values were usually within ±0.1–0.2, but could reach ±1.0 for very weak lines.

The local line profiles were calculated for 20 values of $\mu = \cos\theta$ from the disk centre to the limb. Spectra were calculated for temperatures ranging from 3500 K to 6000 K in steps of 250 K and with gravity $\log g = 3.5$.

3.3. Inversion techniques

The main idea of surface imaging is to trace distortions appearing in the observed line profile due to the presence of spots on the stellar disk and moving due to stellar rotation. An assumption on the nature of those spots is the main part of the model calculations. FK Com is suggested to have temperature inhomogeneities on its surface, which is also supported by the photometric observations. Therefore, considering the intensity of radiation $I(X(M), \lambda, \mu)$ emitted by the stellar surface from the point M in the direction μ at the wavelength λ, let us define $X(M)$ as a local characteristic of M which determines the intensity I. This characteristic can be the chemical abundance, effective temperature, magnetic field, etc. Here, $X(M)$ represents the effective temperature of the model used for the calculation of the local line profile at the point M. Integration over the stellar disk, given rotational phase ϕ and a set of wavelengths, results in the residual flux $r_\lambda(\phi)$ which contains information on the temperature distribution on the stellar surface $X(M)$ and, therefore, is to be compared with the observed residual flux $r_\lambda^{\mathrm{obs}}(\phi)$. Thus, the integration determines the model for the subsequent inversion. A comparison of the residual fluxes determines the discrepancy function $D(r_\lambda^{\mathrm{obs}}, r_\lambda)$, which, in fact, is the negative of the logarithm of the likelihood function. By minimizing D, one can obtain a unique solution with minimum variance, but, nevertheless, it is not feasible due to noise in the data. On the other hand, any “reasonable” fitting of the data (i.e.

somehow smoothing the noise) results in many different stable solutions. Then, searching for the unique and stable solution is a so-called ill-posed inverse problem, and there are different approaches and methods developed for solving it.

In the present study two different inversion methods have been applied to the same observations for obtaining surface temperature maps of FK Com: the Tikhonov regularization (Piskunov 1991) and the Occamian approach (Berdyugina 1998).

3.3.1. Tikhonov regularization

The Tikhonov regularization method was applied to the surface imaging problem as a first inversion technique with minimization by Goncharsky et al. (1977). Here, it is presented in the formulation given by Piskunov (1991), where more details can be found.

When the model for the inversion is defined as above, the discrepancy function D has to be defined as well. Here, it is adopted as the negative of the logarithm of the likelihood function for a Gaussian probability function:

$$D(X) = \sum_{\phi,\lambda} \omega_{\phi\lambda} \frac{(r_\lambda(\phi) - r_\lambda^{\mathrm{obs}}(\phi))^2}{N_\phi N_\lambda}, \tag{2}$$

where $\omega_{\phi\lambda}$ are the weights taking into account differences in the errors of the observations of the individual phases and wavelengths, N_ϕ is the number of phases and N_λ is the number of wavelengths. In the discrepancy function the summing is done over all available rotational phases and wavelengths. As was mentioned, minimizing D by varying $X(M)$ is an ill-posed problem due to the presence of noise, so additional constraints must be applied to get a unique and smooth solution. In the case of the Tikhonov regularization this additional constraint is a regularization functional.

In the regularization the original problem is replaced by another, which has a unique solution. This new function also approximates, in a certain known way, the real $X(M)$. The regularization problem can be expressed in the form:

$$\Phi(X) = D(X) + \Lambda \cdot R(X), \tag{3}$$

where Λ is a Lagrange multiplier and $R(X)$ is the regularization functional, which makes the solution unique. The value of Λ should be selected so that if $X(M)$ minimizes Φ then the rms deviation of the fit of the profiles is of the order of the noise in the observations. In practice, however, we will have to deal with systematic errors in the calculated line profiles and observations (although all effort is done to minimize these). The value of Λ will influence the temperature differences in the resulting map and especially the artifacts produced by errors. In this study we try to choose the value of Λ in such a way that the resulting map is consistent with the photometric observations.

The Tikhonov regularization functional is

$$R^T(X) = \int\int \parallel \bigtriangledown X(M) \parallel^2 d\sigma, \tag{4}$$

where $\parallel \bigtriangledown \parallel$ is the length of the gradient vector. $R^T(X)$ measures the smoothness of $X(M)$. The resulting map provides the smoothest possible solution which is able to reproduce the observations within the observational errors.

3.3.2. Occamian approach

The Occamian approach was recently developed by Terebizh (1995a, 1995b) as a new approach to inverse problems, which does not use any artificial constraints for obtaining a unique and stable solution. It was applied to the surface imaging problem by Berdyugina (1998).

In the present realization of the Occamian approach, the discrepancy function is the negative of the logarithm of the likelihood function for the Poisson probability function. In the case of high signal-to-noise observations the latter approaches the Gaussian function, and it is never negative for lower signals. The mean information principle has been used for testing the fit to the data as was proposed by Terebizh & Biryukov (1994).

In the Occamian approach the choice of the solution is based on the analysis of all available information, namely the observations and the model. Possessing such information, one can build the Fisher information matrix F, whose eigenvectors and eigenvalues determine the error ellipsoid. The directions of the axes of the ellipsoid, the eigenvectors V, define a new reference frame with the coordinates Y which are linear combinations of the unknown parameters X:

$$Y = V^T X, \; X = VY. \tag{5}$$

The new coordinates Y comprise the so-called *principal components* of the solution. Small eigenvalues of F indicate principal components with relatively large errors of the inverse solution, and the error ellipsoid is extremely elongated in these directions. Moreover, in case of a lack of data some of the eigenvalues become zero, and the corresponding parameters are linearly dependent. Therefore, only a part of the principal components $Y^{(p)}$ completely exhausts the available information on X. $Y^{(p)}$ are estimated instead of X, while those principal components lacking enough information are assumed to be zero. Then, the transform

$$\tilde{X} = V\tilde{Y}^{(p)} \tag{6}$$

leads to the desired unique and stable solution $\tilde{X}$. Thus, the solution in the Occamian approach is that which statistically satisfactorily fits the observed data with a minimum set of $\tilde{Y}^{(p)}$. Then, the solution is unique because of the choice of p and stable because of removing those principal components which contain no significant information but noise. Therefore, the solution in the Occamian approach is searched under the condition of maximum simplicity and consistency with the observational data. The inverse Fisher information matrix gives estimates of the variances of the solution.

4. Images

The spectral lines from the 6416–6444 Å region have been chosen for the inversions. Due to the rapid rotation of FK Com this

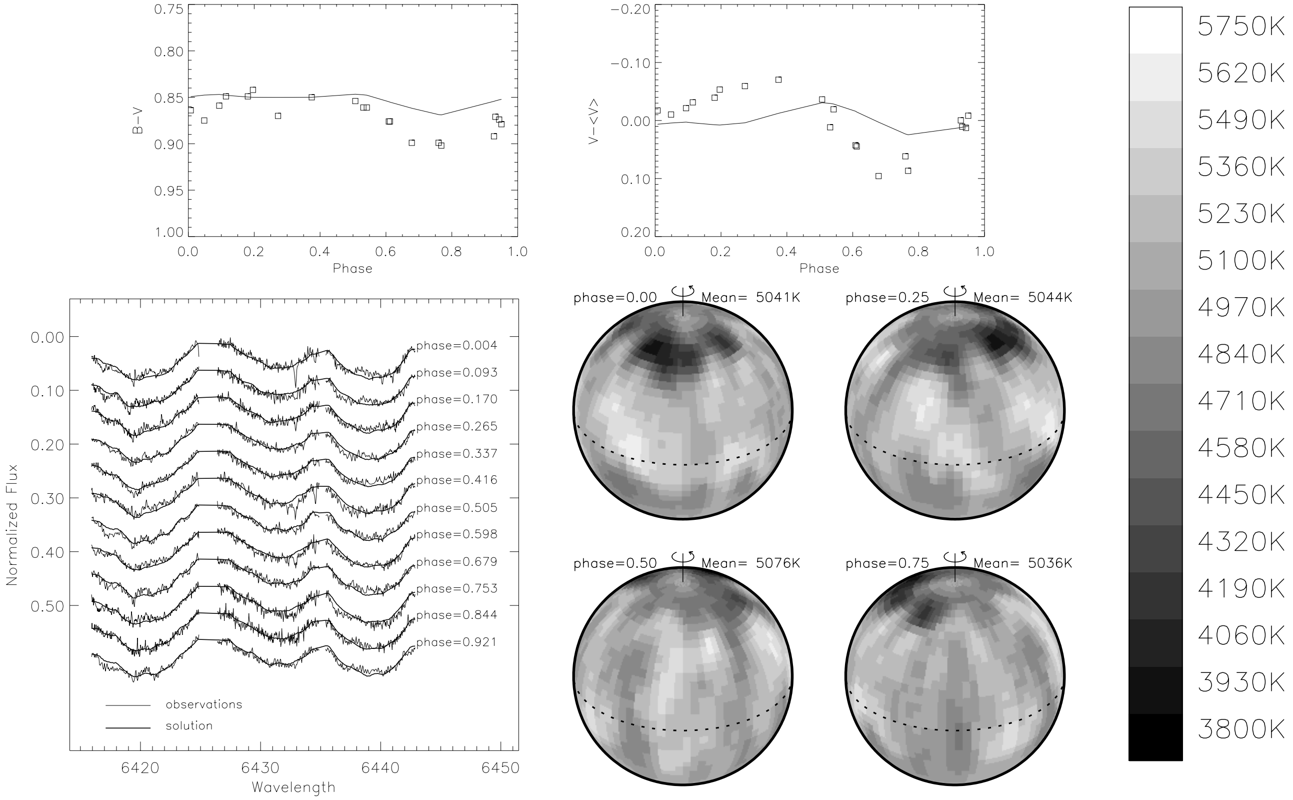

Fig. 1. The image of FK Com obtained with the Tikhonov regularization for the year 1994 (Map 1). A grid of 40 latitudes and 80 longitudes across the stellar surface is used in the map. Calculated and observed spectral lines are shown by thick and thin lines, respectively. Photometric observations are plotted with squares, and curves calculated from the map are presented by lines.

region contains three broad blends, where the main components are Fe I (6420 Å, 6421 Å and 6430 Å), Fe II (6432 Å) and Ca I (6439 Å). The iron blend near 6420 Å was situated near the edge of the CCD frame, which made the continuum correction difficult. There were also some problems in finding a good fit for the Ca I 6439 Å line.

Three maps are obtained in total. Maps 1 and 2 were calculated using the FORTRAN77 code INVERS7-8PD, originally written by N.E. Piskunov, with some changes made by T. Hackman. Map 3 was calculated with an implementation of the Occamian approach written by S. Berdyugina.

4.1. Year 1994

Map 1 is obtained for the August 1994 data using the Tikhonov regularization. The surface image and the fits to the spectroscopic observations are shown in Fig. 1. The mean deviation of the spectroscopic observations from the model is 0.618%, which corresponds to a S/N ratio of about 162. The larger deviation of the calculations in comparison to the observations is mainly caused by some systematic errors in the model line profiles. The atmospheric line near 6433 Å may also cause some additional errors if it is not completely excluded from the inversions. The temperature range in the map is from 3926 K to 5615 K. The coolest feature in Map 1 consists of two spots which are situated close to phases 0.0 and 0.1 at latitudes of 60–70°. The temperature of this feature is ~ 1200 K cooler than that of the unspotted surface. There are other cool regions at phase 0.75 and 0.25. The regions at 0.75 are much larger than the one at 0.1 and situated at the equator and near the pole. They are cooler than the unspotted surface by about 500 K and 900 K, respectively. The spot at 0.25 is situated at high latitudes and has a moderate temperature contrast of ~ 900 K. There are also some hotter regions seen in the map. These features are probably caused by errors in the line profile calculation (e.g. wrong line parameters or missing lines) and noise in the data.

The photometric observations are not used as computational constraints in the inversions, but V and B-V can be calculated from the maps. We calculate B and V magnitudes in a similar way as the line profiles, using the same stellar model atmospheres and disk integration. Systematic errors in the fluxes of the B and V-passbands are corrected by comparison with tabulated values for the atmospheric models (Buser & Kurucz 1992) and the empirical formula for B-V for GK giants (McWilliam 1990).

Unfortunately, for August 1994 no simultaneous photometric observations could be found, only those of 2 months before or 8 months after the spectroscopic observations are available. The light curves calculated from the 1994 map are plotted in Fig. 1 with the photometric observations obtained 2 months before the spectroscopic observations. Both calculated curves, V and B-V, show the main minimum close to the one in the obser-

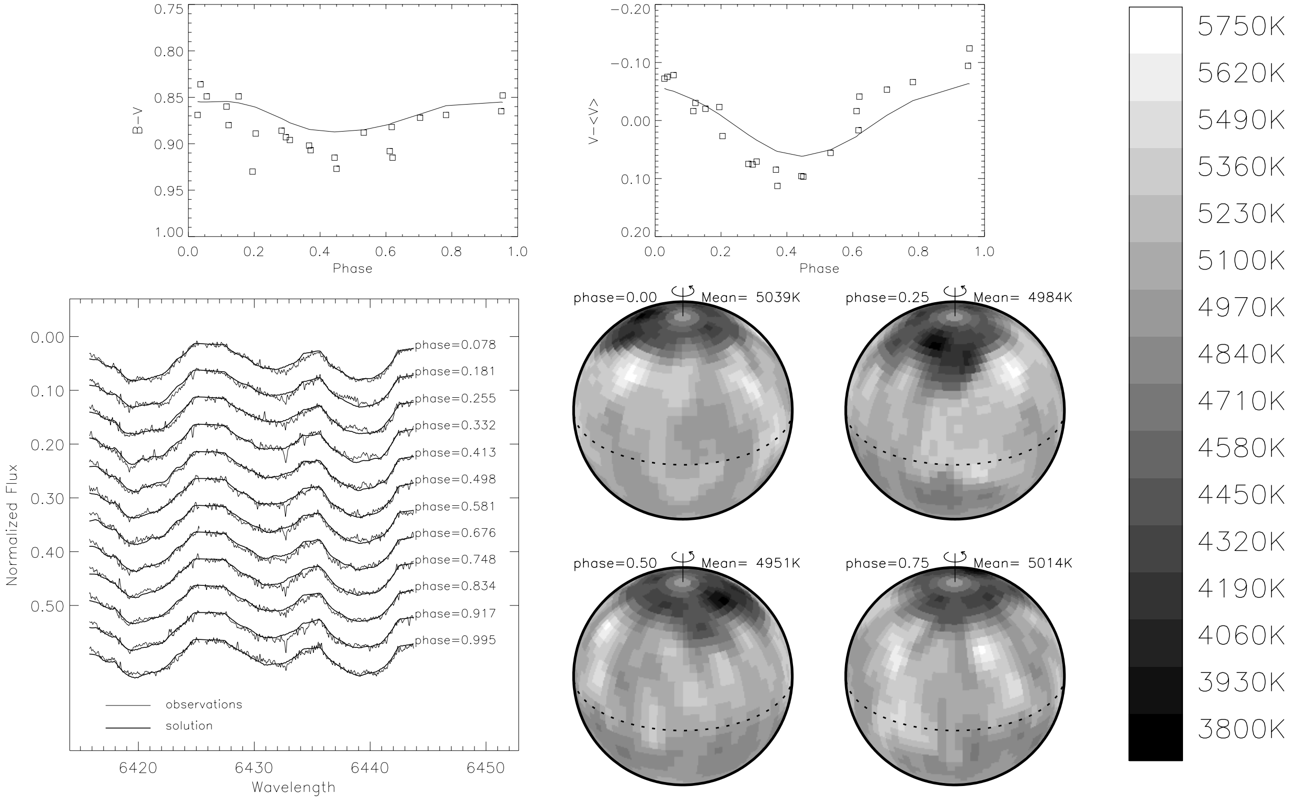

Fig. 2. The image of FK Com obtained with the Tikhonov regularization for the year 1995 (Map 2).

vations, i.e. near the phase 0.75. The calculated V-curve shows also another minimum at the phase 0.25. This minimum cannot be seen in the photometric observations; in fact, there is a maximum observed at that phase. More discussion about the light curve is in Sect. 5.2.

4.2. Year 1995

4.2.1. Tikhonov regularization

Map 2 and fits to the spectroscopic observations are shown in Fig. 2. The mean deviation of the spectral observations from the model is 0.460%, which corresponds to a S/N ratio of ~ 217. The temperatures in Map 2 are between 3853 K and 5660 K. Two cool regions are seen in the map at latitudes of 60-70°. The region at the phase 0.25 is ~ 1200 K cooler than the unspotted surface and consists of two spots. The region close to the phase 0.6 is ~ 900 K cooler than the unspotted surface and has no significant substructure. Both V and B-V calculated from the map correspond quite well to the observed curves. The spot configuration in Map 2 produces the light curve minimum at phase 0.4, as observed. The mean deviation of B-V is 0.019, which is close to the mean error of the observations (0.014). Since B-V is very sensitive to changes in the temperature, the good correlation between the observed and calculated curves indicates that the average temperature for the visible stellar disk at each phase is correct.

4.2.2. Occamian approach

Map 3 is obtained with the Occamian approach. Here, we used the same observations, local line profiles and stellar parameters as for Map 2, but the formal approach and the inversion code were different.

A grid on the stellar surface of 3° in longitudes and 6° in latitudes was chosen. With the adopted inclination $i = 60°$ it gives 3000 temperature parameters which have to be estimated. The total number of wavelength points in the profiles for all available phases was 7932. This can be considered sufficient for restoring most of the stellar surface according to the test calculations by Berdyugina (1998). Indeed, the number of principal components containing significant information on the solution is about 2800, that is close to the total number of the parameters. Note that the parameters corresponding to the latitudes less than $-30°$ cannot be determined with an acceptable accuracy due to negligible projected areas. In fact, they keep the values of the first approximation of the solution.

The mean deviation of the spectral observations from the model is 0.448%, which corresponds to a S/N ratio of ~ 223, virtually identical to the values obtained from Tikhonov regularization. The main feature seen in Map 3 (Fig. 3) is the group of two cool spots at the phases 0.2–0.3 (ΔT=1400 K) with some extension of less contrast spots (ΔT=800 K) to the phases 0.4–0.6. The temperature scale and spot structure determined from the spectroscopic observations reasonably fit the photometric observations, as well. The error distribution over the stellar surface

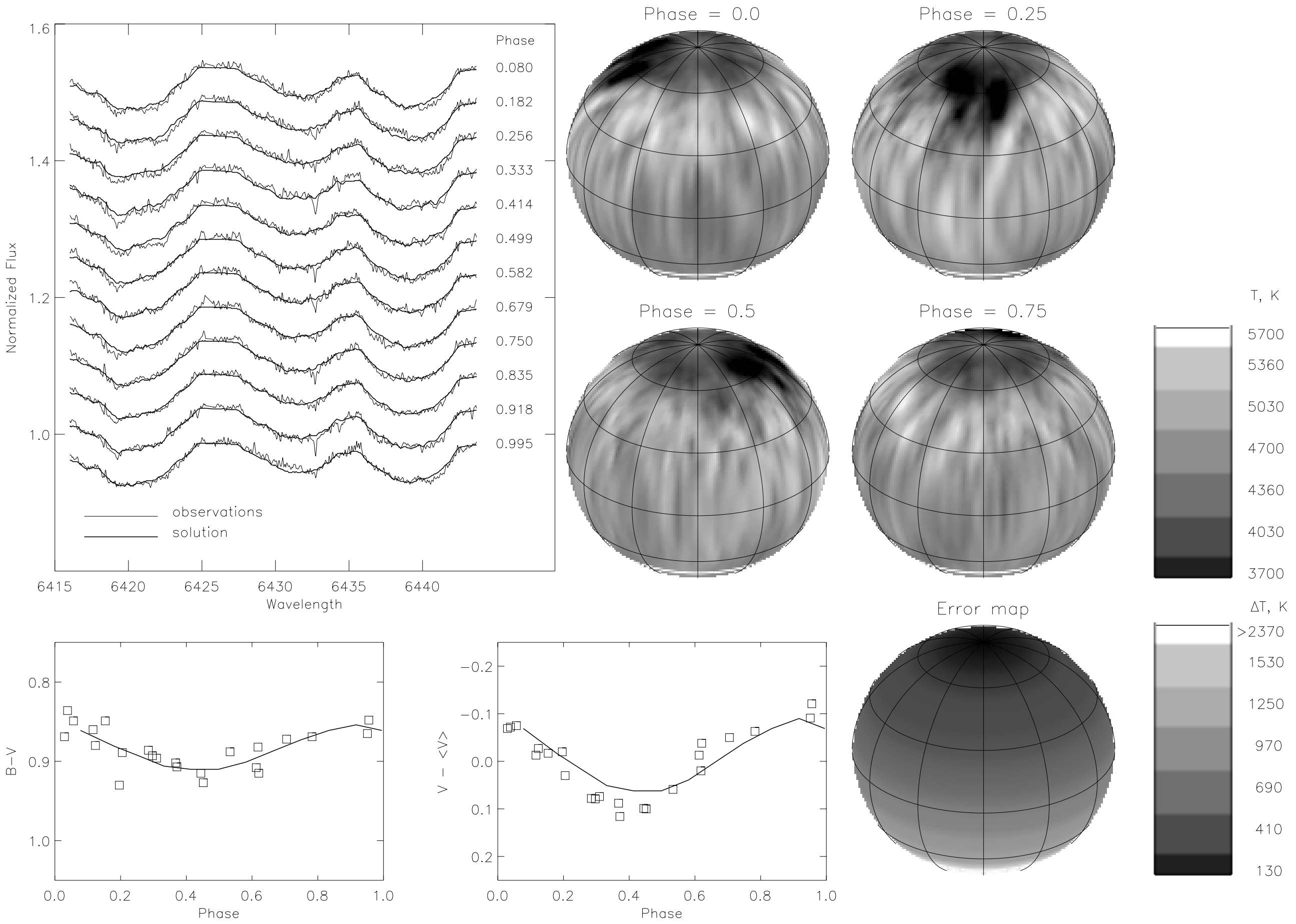

Fig. 3. The image of FK Com obtained with the Occamian approach from the 6416–6444 Å region (Map 3). The image is shown with a coordinate grid of 30°. Other notations are as in Fig. 1.

deduced from the Fisher information matrix shows a decrease of the accuracy towards lower latitudes (error map in Fig. 3). Thus, the higher latitudes show more real structures than the lower latitudes, and this is true for any approach.

5. Discussion

5.1. Spot properties and evolution

Using different methods for the inversion allows us to study the effects of the different algorithms on the result. The images for 1995 obtained with the Tikhonov regularization (Map 2) and the Occamian approach (Map 3) show a similar spot structure with the same mean latitudes and longitudes. The temperature scales of the images are also similar, and the spot contrast of about 1200–1400 K is supported by the comparison with the photometry as well. Since the local line profile calculations, stellar parameters, models, and the observations were the same for both methods, and S/N of the observations was high enough, the significance of the formal assumptions and details of the algorithms appear to be reduced. Therefore, using the Tikhonov regularization for the 1994 observations with the same other inputs seems to be sufficient for studying the spot evolution between the years 1994 and 1995.

The latitudes where the spots are seen are about 60°-70°. This is in accordance with numerous results of surface imaging of rapidly rotating stars of different types. Nevertheless, surface imaging of FK Com-type stars by different authors gave contradictory results. The image of FK Com by Piskunov et al. (1994) showed a large equatorial spot with moderate contrast (ΔT=350 K). Similarly, imaging of HD 32918 revealed an equatorial belt of spots (Piskunov et al. 1990). The same kind of differences can be seen in the images of the third FK Com-type star HD 199178 (Vogt 1988, Strassmeier 1996, Hackman et al. 1999). Strassmeier (1996) showed that the dominating latitude of the spots is very sensitive to the microturbulence and oscillator strengths chosen for the line modelling. The extremely large rotational velocities of the stars require especially careful line modelling. The absence of numerous small, high contrast, randomly distributed spots in our images can be considered as indication of a proper modelling of the line profiles.

The coolest regions in the images for both years have a very similar structure and are situated at the same latitudes. The regions are seen near the phases 0.1 and 0.3 in 1994 and 1995, respectively. The high resolution and S/N of our spectroscopic observations allowed resolving two spots with mean latitudes of about 70°and 60°. This structure is well repeated in both seasons. It seems that the coolest region in both maps is the same feature, it has just moved about 0.2 in phase between the summers of 1994 and 1995. The distance between the two spots in the active region appears to increase by 0.04 in phase during a year, which could be interpreted as to be caused by differential rotation. There is also some similarity between the spots at phase 0.25 in 1994 and at 0.45 in 1995. They have the same latitude of about 60° and similar location relative to the coolest region. Again, if it is the same feature in both seasons, then it has moved about 0.2 in phase during a year. Other cool features seen in the maps seem to have no counterparts, even if we account for the +0.2 shift in phase.

Summarizing the above discussion, one can notice that the spots at the latitude of 60° shifted 0.18 in phase, while the spot at 70° shifted 0.23 in phase during about a year from August 1994 to July 1995. If this behaviour is interpreted as being caused by differential rotation it implies that in the polar region the higher latitudes rotate faster than the lower ones. Of course, more images are needed to confirm such a rotation. Having new observations, we intend to continue the study of the star and trace the evolution of the spots more thoroughly. Nevertheless, comparison of the present images of FK Com with the published photometric observations can help us understand the so-called "flip-flop" effect.

5.2. The "flip-flop" effect

Although, the first photometric observations of FK Com have been published in 1966, regular observations have started only in 1980. We combine all available observations from that time in Fig. 4, considering phases of photometric minima calculated with the ephemeris given by Eq. (1). The data are from Jetsu et al. (1993), Jetsu et al. (1994b), Strassmeier et al. (1997), and references therein. From the photometry one can see that the minimum is moving between the two active longitudes found by Jetsu et al. The periods are indeed different for different epochs, as Strassmeier et al. found, and they are between the two extreme values: $2\overset{\mathrm{d}}{.}39596$ and $2\overset{\mathrm{d}}{.}40470$, as determined from Fig. 4. The period of $2\overset{\mathrm{d}}{.}4002466$ found by Jetsu et al. is believed to correspond to the mean rotational period of the star, and deviations from it show the internal motion of the spots on the stellar surface. As seen from Fig. 4, the occupation of a given active longitude lasts about 1–2 years, and moving to the other longitude also takes about 1–2 years. One can notice that there is a possible cycle in action of the active longitudes. The data by Strassmeier et al. show a distinct decrease in the phase of the minimum from 1.0 to 0.4 in 1993–1995, which was preceded by an increase of the phase from 0.4 to 1.1 during 1990–1993. The estimated length of the cycle of 6.5 years reasonably fits the earlier observations of 1966–1990 as well. With such a cycle one can expect that during 1996–1998 the minimum should have moved from 0.4 to 1.0, again upwards. The question is, whether spots migrate themselves across the stellar surface or their areas evolve in a certain way resulting in the shifting of the minimum. The former means that spots with large life-times (more than six years) can have their own motions in both directions, towards the stellar rotation and also in the opposite direction. The latter means that two active longitudes are periodically active, and the migration of the minimum is only the visible effect of spotted area evolution. Then, the life-times of the spots are not certain because of their permanent evolution. The answer can be found in a set of surface images of the star.

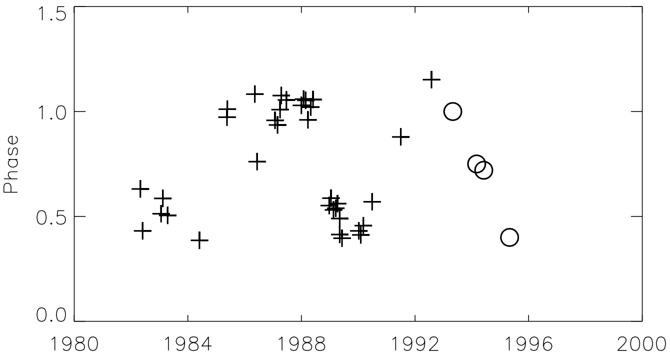

Fig. 4. The photometric minima of FK Com. Crosses are data from Jetsu et al. (1993), Jetsu et al. (1994b), and circles are data from Strassmeier et al. (1997).

From the present surface images it is clear that the photometric minimum is caused by a combination of the active regions rather than one separate spot. The spot structure is noticed to survive for 11 months and move about +0.2 in phase during that time. We found that the simultaneous photometry for the year 1995 is well reproduced by the maps, while the non-simultaneous photometry for the year 1994 cannot be fitted well enough. Having available photometric observations obtained between April and June 1994 and between March and June 1995, so on average 70 days before and 250 days after our spectra, we plot them together with the calculated curve in Fig. 5. As can be seen the earlier light curve shows the minimum at the phase 0.75, and the later one has the minimum at 0.4, which was steadily observed during the first half of 1995. The curve calculated from the map shows the main minimum near the phase 0.75 and a secondary minimum at the phase 0.25, both minima are weaker than in the observations. It seems that Map 1 presents the star at some intermediate stage when the activity is switching from one active longitude to the other: the active region at the phase 0.75 becomes weaker and the one at 0.25 takes over. At the same time spots are moving in phase. Such a behaviour implies that both effects, spot migration and evolution of their areas, are responsible for the periodic phase shifts of the light curve minima shown in Fig. 4. Note that originally only spot migration was supposed for "flip-flops". Probably, the differential rotation could play some role in the specific evolution of the active regions as well.

Similar structures and a similar behaviour have recently been found for the RS CVn-type binary star II Peg also studied with surface imaging (Berdyugina et al. 1998b). Two active longitudes have been revealed from the images, which were seen in photometric observations as well. They existed on the surface at least seven years, and the larger active region evolved from one active longitude to the other within about one year,

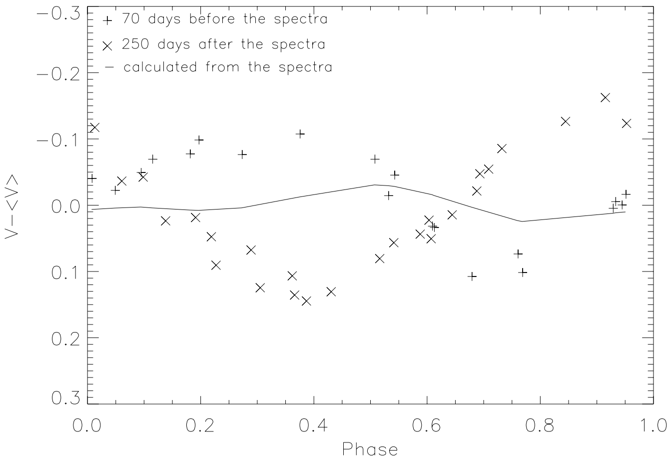

Fig. 5. The behaviour of the light curve during 1994 and early 1995. The solid line is the V curve calculated from the spectra taken in August 1994, pluses are photometric observations from April-June 1994 and squares are photometric observations from March-June 1995 (photometry from Strassmeier et al. 1997).

showing the effect of switching activity between the active longitudes. This effect was mainly caused by spotted area evolution rather than spot migration. Such a behaviour was found to be periodic in II Peg and three other RS CVn-stars (Berdyugina & Tuominen 1998) with cycles of 9–18 years. The structure of two active longitudes and periodical switching of their activity on RS CVn-stars and FK Com appears to be determined by a similar magnetic dynamo acting in the underlying layers of the stars. It is interesting that RS CVn-stars are binaries, while FK Com is probably a single star. However, Bopp & Stencel (1981) and Bopp (1982) suggested that FK Com can be the endproduct of a coalescing process of a close binary system, explaining its fast rotation. If so, then binarity can play some role in establishing the active longitude structure and its behaviour. New surface images of FK Com-stars and other active stars, single and binary, could clarify the situation.

6. Conclusions

With high-resolution and high S/N observations new surface images of FK Com for the years 1994 and 1995 are obtained. The following conclusions can be drawn.

1. The surface maps obtained with the Tikhonov regularization and the Occamian approach are found to be very similar when the same local line profiles, models, stellar parameters and observations are used as inputs for both methods. The main spot structures and the temperature scales of the maps can reproduce the almost simultaneous photometric observations.
2. The comparison between images from 1994 and 1995 shows a strong evidence for a spot group that has survived on the surface of FK Com during the 11 month period and moved about +0.2 in phase in that time. The motion of the two spots within the group suggests the presence of differential rotation with the higher latitudes rotating faster than the lower latitudes.
3. The earlier established “flip-flop” phenomenon is caused by a combination of many spots rather than by one separate group of spots. The spots are moving and evolving in area resulting in the photometric minimum being near the active longitudes.
4. The flipping between the active longitudes is repeated with an average period of 6.5 years, similar to some RS CVn-stars.

Acknowledgements. We thank Lauri Jetsu for providing the photometric observations used in this paper. This research was partly supported by the EC Human Capital and Mobility (Network) grant “Late type stars: activity, magnetism, turbulence” No. ER-BCHRXCT940483. H.K. and T.H. were supported by a grant from the Jenny and Antti Wihuri foundation. The calculations for the inversions were carried out on the Cray C94/128 supercomputer at the Centre for Scientific Computing (Espoo, Finland). Nordic Optical Telescope is operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

References

Berdyugina S.V., 1991, Izv. Krymsk. Astrofiz. Obs. 83, 102
Berdyugina S.V., 1998, A&A 338, 97
Berdyugina S.V., Tuominen I., 1998, A&A 336, L25
Berdyugina S.V., Jankov S., Ilyin I., Tuominen I., Fekel F.C., 1998a, A&A 334, 863
Berdyugina S.V., Berdyugin A.V., Ilyin I., Tuominen I., 1998b, A&A 340, 437
Bopp B.W., 1982, In: Giampapa M.S., Golub L. (eds.) Proceedings of the Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. SAO Rep No.392, Part 1, p. 207
Bopp B.W., Rucinski S.M., 1981, In: Sugimoto D., Lamb D.G., Schramm D.N. (eds.) Fundamental Problems in the Theory of Stellar Evolution. IAU Symposium 93, Reidel, Dordrecht, p. 177
Bopp B.W., Stencel R.E., 1981, ApJ 247, L131
Bopp B.W., Africano J.L., Stencel R.E., Noah P.V., Klimike A., 1983, ApJ 275, 691
Buser R., Kurucz R.L., 1992, A&A 264, 557
Chugainov P.F., 1966, Inf. Bull. Var. Stars No. 172
Chugainov P.F., 1976, Izv. Krym. Astrofiz. Obs. 54, 89
Cameron A.C., 1982, MNRAS 200, 489
Dorren J.D., Guinan E.F., McCook G.P., 1984, PASP 96, 250
Eggen O.J., Iben I., 1989, AJ 97, 431
Fleming T.A., Gioia I.M., Maccacaro T., Mereghetti S., 1987, AJ 93, 1502
Goncharsky A.V., Stepanov V.V., Khokhlova V.L., Yagola A.G., 1977, Sov. Astron. Letters 3, 147
Gray D.F., 1992, The observation and analysis of stellar photospheres. Cambridge Univ. Press., Cambridge, second edition
Hackman T., Jetsu L., Tuominen I., 1999, A&A, in prep.
Harris H.C., McClure R.D., 1985, PASP 97, 261
Huenemoerder D.P., Ramsey L.W., Buzasi D.L., Nations H.L., 1993, ApJ 404, 316
Ilyin I.V., 1997, Licentiate Dissertation, University of Oulu
Jetsu L., Pelt J., Tuominen I., Nations H.L., 1991, In: Tuominen I., Moss D., Rüdiger G. (eds.), The Sun and Cool Stars: activity, magnetism, dynamos. Proc. IAU Coll. 130, Springer, Heidelberg, p. 381

Jetsu L., Pelt J., Tuominen I., 1993, A&A 278, 449
Jetsu L., Tuominen I., Antov A., et al., 1994a, A&AS 103, 183
Jetsu L., Tuominen I., Grankin K.N., Melnikov S.Yu., Shevchenko V.S., 1994b, A&A 282, L9
Kurucz R.L., 1993, CD No. 13
Kürster M., Dennerl K., 1993, In: Linsky J.F., Serio S. (eds.) Physics of Solar and Stellar Coronae. Kluwer, Dordrecht, p. 443
McCarthy J.K., Ramsey L.W., 1984, ApJ 283, 200
McWilliam A., 1990, ApJS 74, 1075
Merrill P.W., 1948, PASP 95, 376
Piskunov N.E., 1991, In: Tuominen I., Moss D., and Rüdiger G. (eds.) The Sun and Cool Stars: activity, magnetism, dynamos. Proc. IAU Coll. 130, Springer, Heidelberg, p. 309
Piskunov N.E., Tuominen I., Vilhu O., 1990, A&A 230, 363
Piskunov N.E., Huenemoerder D.P., Saar S.H., 1994, In: Caillault J.P. (ed.) Proceedings of the Eighth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. ASPC 64, p. 658
Piskunov N.E., Kupka F., Ryabchikova T.A., Weiss W.W., Jeffery C.S., 1995, A&AS 112, 525
Rucinski S.M., 1981, A&A 104, 260
Rucinski S.M., 1990, PASP 102, 306
Schlegel D.J., Finkbeiner D.P., Davis M., 1998, ApJ 500, 525
Strassmeier K.G., 1996, In: Strassmeier K.G., Linsky J.F. (eds.) Stellar Surface Structure. IAU Symp. 176, Kluwer, Dordrecht, p. 289
Strassmeier K.G., Bartus J., Cutispoto G., Rodono M., 1997, A&AS 125, 11
Terebizh V.Yu., 1995a, Physics–Uspekhi 38, 137 (translated from Uspekhi Fiz. Nauk 165, 143)
Terebizh V.Yu., 1995b, Int. J. Imaging Systems Techn. 6, 358
Terebizh V.Yu., Biryukov V.V., 1994, Astron.&Astrophys. Trans. 6, 37
Vogt S.S., 1988, In: Cayrel de Strobel G., Spite M. (eds.) The impact of very high S/N spectroscopy on stellar physics. IAU Symp. 132, Kluwer, Dordrecht, p. 253
Walter F.M., Basri G.S., 1982, ApJ 260, 735
Walter F.M., Neff J.E., Bopp B.W., Stencel R.E., 1984, In: Baliunas S.L., Hartmann L. (eds.) Proceedings of the Third Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. Springer, New York, p. 279