Circumstellar Variations and Microflaring in FK Comae Berenices: Time-Resolved Balmer Line Spectroscopy

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Abstract:
We present results from the analysis of spectra of the fast rotating giant FK Comae Berenices, obtained with the recently commissioned ESA–MUSICOS spectrograph at the INT and with the Aurélie spectrograph at the OHP. The Balmer lines broad emission is modelled as arising from structures extending up to 4 stellar radii. The absorption is modelled due to the presence of a shell of cold and dense gas (solar-like filaments), near the corotation radius, covering about 20% of the stellar disc. The extended emission is believed to arise in giant structures reminiscent of active loops or prominences. Time-resolved H\textalpha{} emission spectroscopy indicates that these structures undergo continuous microflaring. Based on data sets from May and November 1996 and May and June 1997, we describe different time scales for variability, from yearly rise of activity to hourly microflares.

1. Introduction
FK Comae Berenices, HD117555, is a rapidly rotating, active G-type giant. This star is apparently single but has an extreme rotational velocity, 162±3.5 km s\textsuperscript{-1}, near breakup (Huenemoerder et al. 1993), and a rotational period of 2.4 days (Bopp & Stencil 1981). The spectral type of FK Com is usually considered as G5 II, but other sources give a spectral type as late as G8 III (Rucinsky 1981), the difficulty in the classification due to its fast rotation and spectral oddities.

FK Comae exhibits an H\textalpha{} emission feature, very broad and erratically variable (Merril 1948). The profiles show a central absorption superimposed to the broad emission, giving a double peaked appearance (Ramsey, Nations, & Barden 1981), usually asymmetric.

\textsuperscript{1}Based on observations with the ESA–MUSICOS spectrograph at the 2.5 m Isaac Newton Telescope, ING Observatory, Spain and with the Aurélie spectrograph at the 1.52 m Coudé Telescope, Observatoire de Haute-Provence, France
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Also striking are the resemblances in the spectral and photometric signatures of FK Com and late type close binaries as the RS CVn systems. Not only do they have abnormal Ca II H & K (Bildeman 1954) and Hα emissions, they are also radio (Bopp & Stencil 1981) and X-ray (Hughes & Mclean 1987) emitters, due to an active corona. FK Com and the RS CVn stars also present a quasi-sinusoidal optical light curve (Holtzman & Nations 1984). These similarities indicate an enhanced type of solar-like activity.

We discuss new spectroscopic observations of FK Com. The Balmer absorption and emission are analysed in the frame of extended structures, confined in corotation with the star. The absorption component is interpreted to be due to the obscurations by the star and by a near-stellar shell of cool gas. The emission is attributed to giant structures similar to extended loops filled with material at large height, or active prominences. We discuss the first evidences for continuous microflaring with 1h time scale in the Hα profiles, both in the INT data and the recently obtained OHP data.

2. Observations at the INT and OHP

The first set of data was obtained in May 96 with the 2.5 m Isaac Newton Telescope, at the Observatorio del Roque de los Muchachos, La Palma, Spain, during the commissioning campaign of the (fiber-fed) ESA–MUSICOS spectrograph. This instrument is similar to the MUSICOS prototype, described in detail in Baudrand & Böhm (1992). The specific performances and experimental set-up of instrument on INT are given in Foing et al. (1997). The resolving power of these spectra is $R = 23,000$, in the range 4700 to 8100 Å. To this set we added some more spectra obtained with the same instrument in Nov. 96 and May 97, with slightly higher resolution, $R = 32,000$, in the range 4400 to 10000 Å. For the data reduction of the INT data, we used the MIDAS Nov. 94 echelle reduction package.

In addition to these INT observations, we obtained in June 97 data from the Observatoire de Haute Provence, in France. We used the Aurélie spectrograph at the 1.52 m coudé telescope, with spectral range 6530 to 6600 Å and a resolving power of 30,000.

3. Adjustment of the Photospheric Profiles

As long as the line profile has the same shape over the stellar disc, a rotationally broadened flux profile can be obtained by convolving the flux profile of a non-rotating star with the rotational profile of the observed star (Gray 1976). As a template, we used κ Hercules (HD 145001), a G8 III type star. We have artificially broadened the spectrum of this low activity star to simulate the rotational broadening visible in the spectra of FK Com. After normalization, these spectra were subtracted from the ones of the giant star (Oliveira et al. 1997a,b).
4. Balmer Lines Circumstellar Emission

The difference spectrum shows an emission extending up to $\sim 780$ km s$^{-1}$ in H$\alpha$. We modelled the wings of the H$\alpha$ and H$\beta$ profiles by assuming an effectively thin, corotating emission and a 3D gaussian distribution of the source around the star (Fig. 1, dotted line). The performed numerical integration of such 3D distribution represents well the observed wings profile, but differs strongly for the central absorption of the profiles, within $\sim \pm 1.3 v \sin i$. This analysis is described in more detail in Oliveira et al. (1997a,b).

5. Model of the Near-Stellar Shell of Absorption

The central absorption is slightly broader than $2v \sin i$. Therefore, it cannot be attributed only to the effect of obscuration from the star itself. We attribute this extra effect to the existence of a near-stellar shell of absorbing material. The presence of this shell also contributes to another extra absorption, as it absorbs the background photospheric profile by a factor $\varepsilon$. This contribution is subtracted from the computed model profile. The resulting profile is compared with the difference spectrum and the best computed parameters are given in Fig. 1.

The fractional depression of the line profiles is approximately the same in these two Balmer lines, indicating possibly an optically thick absorption. Under this assumption, $\varepsilon$ gives us an estimate of the fraction of the stellar disc obscured by the near-stellar shell; according to this model we have a disc coverage of about 23%.

The residues, after this axisymmetric model contribution is removed, have an H$\alpha$/H$\beta$ flux ratio of the order of 4, indicating an optically thicker source than the extended emission. Their projected velocities are within $\pm v \sin i$. They could be interpreted as inhomogeneous active regions at or near the stellar surface and denser than the circumstellar environment. They account for $\sim 10\%$ of the total emission.

Our axisymmetric model, based on simple assumptions, fits the observed Balmer features, for the May 96 low activity epoch. The results hold if we consider an homologous contraction of the geometry along the rotation axis, accounting for the surface ellipsoidal distorted shape (to be elaborated in future work). However, the circumstellar shells may be even more distorted than the stellar surface flattening, that we calculated to be of about 1/3. At other epochs, Nov. 96 and May 97, of higher activity, stronger asymmetry and variability are present.

6. Time Scales for FK Com Variability

Time variability of the H$\alpha$ profile has been reported in the past. Welty et al. (1993) analysed in detail the V/R peak ratio variations (refer to them for the definition) of this profile over a long period of time, even though stressing that no fundamental properties can be measured by this ratio, due to the observed multiple component character. The referred variations are then attributed to “localised” prominence-like structures, superposed to a more distributed com-
Figure 1. The Hα (top) and Hβ (bottom) average difference spectra, as well as the gaussian profiles (dotted line), fitting the wings of the extended emission. The obscuration by the star and the absorption by the near-stellar shell are displayed (dashed line). Finally, the extra absorption ε of the background photospheric profile is included in the model (full line) (Oliveira et al. 1997a,b).

ponent. They also establish these transient structures would last more than one week.

6.1. Yearly Time Scale Variations

In our INT May 96 data, the typical value of the V/R ratio is of the order of 0.96, giving us, by comparison with the literature, an indication of an axisymmetric distribution. When we compare equivalent width measurements of all our data sets, this corresponds also to a low activity level. The lower equivalent width measurements correspond to May 96 and the highest to May 97 (equivalent width of the Hα emission profile of 2.2 and 5.9 Å respectively). If we assume a global stability of the underlying emission and even though an exact trend cannot be derived, we are inclined to conclude that from the first to the last INT set, we observed an “average” rise in the activity, after one year.

6.2. Active Region Rotation, Gradual Evolution, and Flaring

The variations we observe in the shape of the multiple profile from one rotational period to another, seem to agree with the effect of active circumstellar structures persistent over a few rotations, even though a much better time-sequence is needed to be conclusive.

Within the data set series, some interesting points can be noticed. Our Nov. 96 observations tend to confirm a “one dominant emitting blob” situation, based on the change in the symmetry of the profile, as was suggested by Welty
et al. (1993), but nothing similar could be concluded from the other data sets. In the last INT set of data, a very fast (8% in phase) inversion in the V/R ratio occurs, that cannot be explained only by the periodic variations due to the corotating structures transiting the stellar disc. This quick enhancement could be caused by some excitation phenomena in the loop large scale structure. The spectra from 16th May 97 are suggestive of a large flare, when compared with spectra obtained at similar phase before and after this event, as there is a rise in the Hα equivalent width from 5 to 11 Å approximately.

6.3. Microflaring Variations

![Graph showing microflaring variations](image.png)

Figure 2. Time resolved Hα spectra (1st May 96, INT), taken 2 hours apart (above). The difference spectra (below) show variable features, outside the 3σ dispersion, at velocities from approximately −500 to 350 km s\(^{-1}\), indicating that they take place up to 2 stellar radii from the surface.

We arrive now to what we call the micro-flaring time scale. For this analysis we used only data from May 96 and June 97. The first and the last spectra of Hα from May 96 are separated by \(\sim 3\%\) in phase (Fig. 2). Even though the phase coverage is small, the evolution of some variable features can be traced. The spectrum with the highest S/N was used as a reference and subtracted from the other spectra, to enhance the features’ variability. Several variable features are visible at different locations, above the noise (estimated in the range outside the Hα line). They can be interpreted as emission bursts with a time scale of about 1 hour, that could be related to the excitation and recombination of the giant magnetic loop structures around the star. The width of these emission features is approximately 70 to 90 km s\(^{-1}\) and they represent typically 0.8 to 2.7% of the total emission.
The new data obtained at the OHP and their preliminary analysis, in our opinion, confirm and reinforce this microflaring hypothesis (Fig. 3). This data set covers approximately the same phase interval as the previous one. It can be seen that the number and intensity of these short time scale events are larger for this higher average activity level. In Fig. 4, the independent temporal behaviour of these emission bursts is clear. We selected several wavelength locations and plotted the intensity evolution through the time series. No dependence or correlation seems to be present, indicating that these bursts probably occur at all times in different circumstellar active loops, for a typical duration of 1 to 3 hours.

Figure 3. Time resolved OHP/Aurélie spectra in the Hα range (23rd June from 21.3 to 23.2 hours UT). The first and the last spectra show distinct variations in different parts of the observed line profile, clearer than in the INT set. The lower spectra are the difference to the first obtained spectra, and confirm the microflare time variations on the 1h timescale, previously observed in the INT spectra.

7. Interpretation and Perspectives

In FK Com, the physical conditions in the different parts of the chromosphere and corona, allow material to exist in thermal equilibrium either as an X-ray emitting plasma at very high temperatures, or in a denser form at temperatures low enough for hydrogen to recombine, giving origin both to the emission and the absorption observed in the Balmer lines.

As is described in Oliveira et al. 1997b, the activity type of FK Comae displays some strong differences to the solar case. The surface gravity and photospheric scale height are drastically distinct (respectively, \( g \leq 0.025 \sin^2 i \, g_\odot \) and \( H \geq 40 \sin^{-2} i \, H_\odot \)). The low effective gravity creates conditions for ther-
Figure 4. Monochromatic emission time variations at specific wavelengths in the Hα profile (top four lines) and well outside this profile (bottom two constant lines), showing independent variations (OHP data, 23rd June 97). They can be interpreted as independent microflaring events in circumstellar active loops, at different projected distances from axis (0.0, 0.6, 1.2, and 2.0 $R_\star \sin \iota$).

Normal cooling instabilities, near the stellar surface (the keplerian corotation radius is for this star at $R = 1.12 R_\star \sin \iota$). The size of the near-stellar shell of cool gas is then consistent, in our model, with this instability region. Loop structures extending to large height, filled with emitting material and magnetically confined in corotation (Huenemoerder et al. 1993; Welty et al. 1993) are also very likely. This is reminiscent of circumstellar structures observed in RS CVn stars, at times undergoing exceptional flaring (Foing et al. 1994).

We recalled and confirmed evidence for the complexity of the several timescales involved in the FK Com problem, due to the several types of emission components superposed. Adding to this, we investigate a diverse type of emission occurrences. We suggest that fast rotation and loop excitation/reconnection create flares which signatures can be seen in our Hα spectra, as variable emission features. The time scale for loop enhancement and cooling is approximately 1 hour. These microflaring events represent individually $\sim 1.2$ to $2\%$ of the total emission. Thus the total emission can be considered as the superposition of an average of 50 to 85 of these microflaring loops, leading statistically to the broad velocity background emission, with some sporadic dispersion. A larger magnetic reconfiguration of these loops on global scale could lead to the giant flares observed on FK Comae.

Clearly the continuous spectroscopy of FK Comae is required to disentangle these variations in the Balmer lines profiles, due to microflares, flares and rotating quiescent extended structures.
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