MODEL OF FeII EMISSION LINES IN THE SYMBIOTIC STAR CH Cygni

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ABSTRACT. A model of the emission regions of the circumstellar mass of the symbiotic star CH Cygni is presented. The complicated structure of the profiles of the FeII emission lines at the time of maximum activity (1981 - 1984), as well as of their parameters (relative intensity and radial velocity) is explained by the existence of three independent emission regions in the system:
1. Extreme parts of the accretion disk-envelope, 2. stellar wind of the cool M giant in the vicinity of the hot component, 3. "hot spot".

1. INTRODUCTION

The characteristic feature of activity of the symbiotic star CH Cygni were three outbursts, sporadically observed since 1963. The blue continuum as well as the emission components of the spectral lines of all elements were enhanced strongly during this period. The optical emission spectrum was characterized by lines HI, FeII and [FeII] . The most recent outburst was the strongest and lasted from 1977 to 1986. The star's brightness increased suddenly to about $7^{m}_{.}5$ and continued to grow gradually, for the last time in the summer of 1981 up to $5^{m}_{.}5$ in the U-filter. It retained this value until August 1984 (e.g., Luud et al., 1986). The rapid and irregular variability of all photometric and spectrophotometric parameters, and of the radial velocities of spectral lines was typical (e.g., Hack et al., 1986, 1988; Skopal et al., 1989).

Considerable attention of the astronomers was concentrated on the sudden decrease of the star's brightness by $1\overset{m}{.}0 - 1\overset{m}{.}5$ in the summer of 1984 (e.g., Mikolajewski and Tomov, 1986), on the radio burst and the bipolarly expanding outbursts observed since 1984 (Taylor et al., 1985), on the detection of soft X-rays in May 1985 (e.g., Leahy and Taylor, 1986) and on observing the minimum in the U light curve in 1985, corresponding to the eclipsing of the hot active component by the cool giant (Mikolajewski et al., 1987).

Our present knowledge indicates that the symbiotic star CH Cygni is an eclipsing binary consisting of a red giant M6III and a white dwarf. Intermittent mass transfer probably occurs between the components. The manner of mass transfer nor its interaction with the compact component have been explained satisfactorily. A considerable effort has recently been made to determine the elements of the spectroscopic orbit. The elements used in this study are identical with those used by Skopal et al. (1989): $P = 5700$ days, $e = 0.50$, $\omega_c = 139^{o}$, $\gamma = -57.7$ km/s, T_0 = JD 2 445 059, $K_{cool} = 4.9$ km/s, $K_{hot} = -16$ km/s.

The complicated profiles of the spectral lines in the maximum of the activity phase (1981-1984) and their rapid changes reflected the complicated evolution of the circumstellar mass in the system. Its basic probable behaviour was qualitatively analysed by Skopal et al. (1989). They found, e.g., that the resultant profile of the FeII emission lines in this interval could be explained by the existence of several independent emission regions in the circumstellar mass of CH Cygni.

The purpose of this paper is to present a quantitative model of the resultant profile of the FeII emission lines, to determine its basic parameters, i.e. radial velocities and relative intensities, and their comparison with the values observed at the time of the activity maximum of CH Cygni (1981-1984).

2. MODEL OF THE EMISSION REGIONS

The following have been taken as the main emission regions for which the model has been constructed: 1. The extreme parts of the accretion disk-envelope around the hot component, 2. The stellar wind of the cool M giant in the vicinity of the hot component of CH Cygni, 3. The region of collision of the mass transferred from the cool component with the accretion disk-envelope, the so-called "hot spot". The radiation contributions of the separate regions depend on the degree of evolution of the circumstellar mass during the outbursts, on the instantaneous interaction of the binary and its phases. Therefore, the action of these regions in time must be estimated with regard to the evolution of the outburst. The evolution of the blue continuum (Fig. 5a) and of the envelope spectrum provided us with guidance in this matter. The 1977 outburst led to the generation of the accretion disk-envelope around the compact component of CH Cygni as the basic source of UV radiation and radiation in the optical region (up to ≈ 500 nm) of the spectrum. Its existence may naturally be assumed during the whole activity period. Consequently, the contributions of its emission components were calculated for the outburst period as a whole. An enhancement in the interaction of the binary's components may be expected as of 1979, when an absorption envelope spectrum began to form (e.g., Rodriguez, 1986); a further enhancement of the blue continuum also occured in 1980 (Fig. 5a). The contribution of radiation from the stellar wind round the hot component (region 2) is, therefore, assumed as of this period. It has been included in the model since JD 2 444 500 (September 1980). The contribution of the "hot spot" (region 3) has been included in the model since the most recent enhancement of the blue continuum in the summer of 1981, when a strong absorption envelope spectrum developed together with significant changes in the spectral line profiles (e.g., Wallerstein, 1983). This has been incorporated since JD 2 444 771.

The profile of the FeII emission line, generated in each radiation region, has been approximated by a Gauss curve. The resultant profile $\psi(\lambda,t)$ is their sum:

$$\psi(\lambda,t) = \sum_{i=1}^{3} (I_i(t)/(\sigma_i\sqrt{2\pi}))\ \exp\left[-(\lambda-a_i(t))^2/2\sigma_i^2\right] \tag{1}$$

The index "i" indicates the radiation region as given at the beginning of this section. The values of the relative intensities, $I_i(t)$, depend on the evolution of the emission regions and on the instantaneous interaction of the system, $I_3(t)$, moreover, also on the binary phase. The shifts $a_i(t)$ (i.e. radial velocities) are only phase-dependent and the halfwidth σ_i in the model are constant.

Region 1 has been determined as $I_1(t)$ = const. = 0.1. This value was found by modelling the profiles of the activity maximum period (1981-1984) in which a strong absorption envelope spectrum was also observed. It is evident that $I_1(t)$ depends on the optical properties of the accretion disk-envelope: for example, at the beginning of the outburst, when an intensive emission spectrum was observed nearly exclusively (e.g., Rodriguez, 1986b; Hack et al., 1982) the disk-envelope was optically thin and probably the dominant radiation region in the system. At this time, the value $I_1(t)$ was evidently larger than 0.1. The value $\sigma_1 = 0.2$ was derived from the model, and the shift $a_1(t)$ at wavelength λ_0 is given by the orbital motion of the hot component:

$$a_1(t) = \lambda_0(RV_{orb}(t) + \gamma + K)/c \tag{2}$$

$RV_{orb}(t)$ is the radial component of the instantaneous velocity in orbit, γ is the velocity of the centre of gravity of the system relative to the Sun, and constant K = -5 km/s was determined from observations (e.g., Hack et al., 1986; Skopal et al., 1989). The cause of the shift could be attributed to the slow rotation of the distant emission parts of the disk-envelope and to a certain degree of asymmetry of the emission regions to the absorption; c is the speed of light.

Region 2 has been determined as $I_2(t) = 0.25$ as derived from the model, and $\sigma_2 = 0.2$ as estimated from the 1981 spectrograms, when the contribution of this radiation region should have been dominant according to this model. The shift $a_2(t)$ depends on the phase and velocity of the stellar wind in the vicinity of the hot component. The stellar wind is represented by vector W blowing from the cool to the hot component. Consequently,

$$(3) \qquad a_2(t) = \lambda_0(W\cos\varphi(t) + \gamma)/c$$

Phase $\varphi = \omega_c + \nu + \frac{1}{2}\pi$, ν is the proper anomaly and ω_c the length of the periastron of the cool component. The value of vector W was taken to be 13 km/s.

The radiation of Region 3 is generated by the collision ionisation of the accretion disk-envelope with the particles of the stellar wind. The instantaneous value $I_3(t)$ depends on the phase angle φ and on the density of the "hot spot" radiation. Let f_ν is the radiation flux per unit surface of the "hot spot" perpendicular to its surface. The overall radiation flux of the "hot spot" is then $F_\nu(t) = \int_s f_\nu \cos\alpha \, ds$, where $\cos\alpha = \sin\vartheta \sin\varepsilon$ is the direction cosine of the "hot spot" surface element $ds = r^2 \sin\vartheta \, d\vartheta \, d\varepsilon$ to direction of observation, $r, \vartheta, \varepsilon$ are usual spherical coordinates and s is the visible part of the "hot spot" (Fig. 1). If we put $I_3(t) = F_\nu(t)$, we arrive at

$$(4) \qquad I_3(t) = 2 f_\nu r_*^2 \int_{\vartheta=0}^{\pi/2} \int_{\omega=0}^{\varepsilon_0} \sin^2\vartheta \sin\varepsilon \, d\vartheta \, d\varepsilon = \frac{1}{2}\pi f_\nu r_*^2 (1 - \cos\varepsilon_0) \quad .$$

Constant $\frac{1}{2}\pi f_\nu r_*^2 = 0.5$ was derived from the model, which also applies to $\sigma_3 = 0.3$. The model does not take into account the rotational broadening of the line. The shift function $a_3(t)$, apart from the phase angle, depends on the rotation velocity V_d of the "hot spot". The radial velocity of the radiation regions of the "hot spot" is roughly approximated by its radial component only:

$$(5) \qquad a_3(t) = \lambda_0(V_d \sin\varphi(t) + RV_{orb}(t) + \gamma)/c \quad .$$

The magnitude of vector V_d depends on the distance of the "hot spot" from the centre of the disk-envelope. The radial velocities of the emission components of hydrogen lines H_β and H_γ were used to determine the rotation velocity V_d: from 62.7 to 54.0 km/s (Skopal et al., 1989). All the computations were made using the value V_d = 60 km/s.

3. RESULTS AND DISCUSSION

Apart from profile (1), also its parameters were computed: the maximum (i.e. line intensity) and shift (i.e. radial velocity). Each model profile was divided in height V by a line parallel with the dispersion. The radial velocity was then

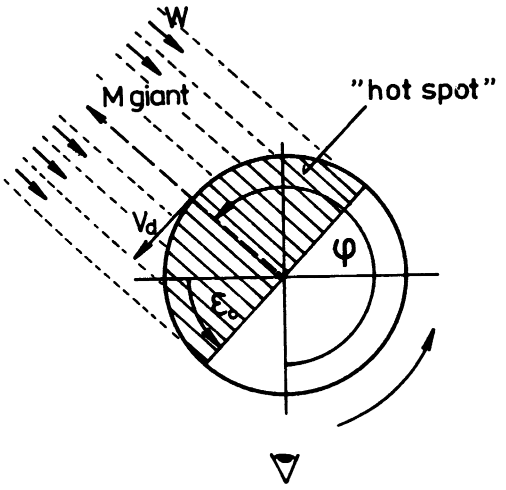

Fig. 1. Schematic picture of the "hot spot"▨. Its position depends on the phase angle φ. The mass transferred from the cold to the hot component is denoted by ⋱ and represented by the vector W. Vector V_d represents the rotational velocity of the "hot spot".

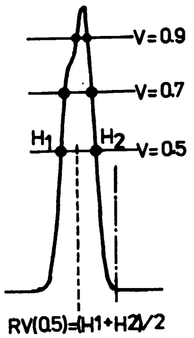

Fig. 2. Radial velocity of the spectral line was calculated from the points of intersection H1, H2 of the profile with the dispersion parallel line in high V. Example of the modeling profile of FeII 423.3 nm line from August 16 1982 is at the picture: RV (0.5) = -75.9 km/s, RV (0.7) = -73.6 km/s and RV (0.9) = -63.7 km/s.

determined from their points of intersection (Fig. 2). This calculation of the radial velocities also reflects the various methods of measuring spectral lines: measurement of the line peak (V ~ 0.9), or of this core (V ≈ 0.5 - 0.7). The model profiles and intensities were compared directly with those observed at the time of the activity maximum, 1982 - 1984, on the spectrograms from the Toruń University Observatory (Skopal et al., 1989). The results are depicted in Figs 3 and 4. The model of the radial velocity curve of the FeII emission lines was computed for the whole period of the last activity phase. In Fig. 5b these curves have been depicted for V = 0.5, 0.7 and 0.9. The curves not smooth. The discontinuity at phase 0.69 is caused by "switching on" the stellar wind. The halfwidths of the profiles of the separate radiation regions are quite small. The resultant profile is, therefore, very sensitive to their mutual position. More pronounced changes in the resultant profile occured as of phase 0.8. The deep minimum of radial velocities of the FeII emission lines, observed between phases 0.8 and 0.9, was generated, as regards this model, mostly due to the existence of the "hot spot". The latter increases its observed area with increasing phase; this also applies to its radiation contribution. Its radial velocity decreases at the same time. As observed, the intensity of the emission line increased substantially and was displaced towards longer wavelengths as of the end of 1983. The disagreement of the line width

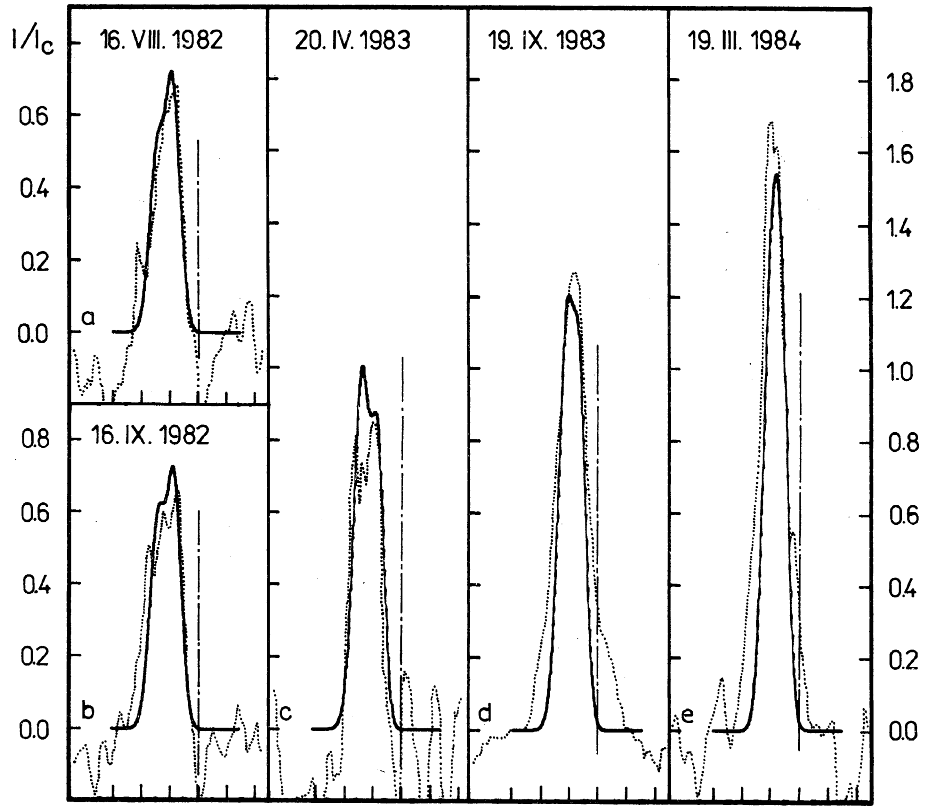

Fig. 3. Calculated (full line) and observed (dotted line) profiles of emission FeII 423.3 nm line.

a) Spectrogram CCS 774c, August 16 1982, RV_{obs}=-70.3 km/s, RV_{model}(V=0.7) = -73.6 km/s.

b) CCS 804d, September 16 1982, RV_{obs}=-80.9 km/s, RV_{model}(V=0.7)=-75.8 km/s.

c) CCS 874a, April 20 1983, RV_{obs}=-94.9 km/s, RV_{model}(V=0.7)=-77.1 km/s.

d) CCS 1016c, September 19 1983, RV_{obs}=-62.8 km/s, RV_{model}(V=0.7)=-73.4 km/s.

e) CCS 1060b, March 19 1984, RV_{obs}=-67.9 km/s, RV_{model}(V=0.7)=-62.2 km/s.

The not-dashed lines represent the radial velocities vr^{hel}= 0. One unit at the x-axis is equal to 0.1 nm.

in 1984 is evidently due to the omisiion of the rotational broadening of the spectral line generated in the "hot spot".

As is known, all spectrophotometric parameters were strongly variable at the time of the outburst. This model does not take these changes into account. It only considers the constant activity of the star. Consequently, the scatter of the measured parameters about the model values may be considerable. Figures 3, 4 and 5b show that the basic trends in the profile changes and, therefore, also in its parameters, i.e. the intensity and radial velocity, can be explained by this model.

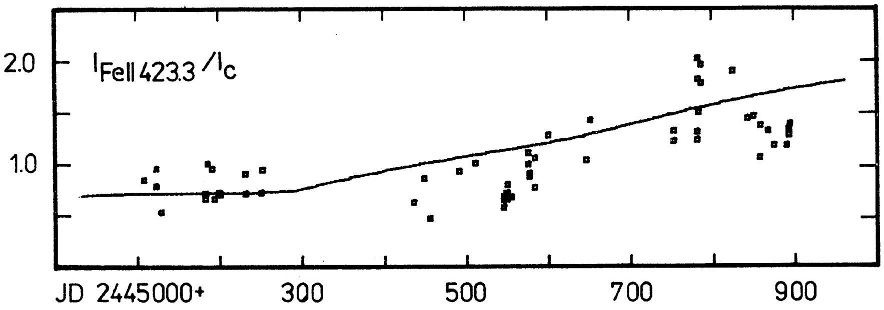

Fig. 4. Changes of intensity of emission line FeII 423.3 nm. I_c is intensity of the local continuum. Full line represents the model and the values were taken from Skopal et al. (1989).

4. CONCLUSION

This model gives a certain idea of the distribution and evolution of the radiation regions of CH Cygni at the time of its outburst. It was found that, to explain the changes in the profiles of the FeII emission lines, their relative intensities and radial velocities, it was sufficient to assume three independent emission regions: 1. The extreme parts of the accretion disk-envelope around the hot component, 2. The stellar wind of the M giant in the vicinity of the hot component, 3. The region of collision of the mass transfered from the cool component with the accretion disk-envelope, the so-called "hot spot". The model enables the radiation contributions in the FeII lines to be separated and quantified.

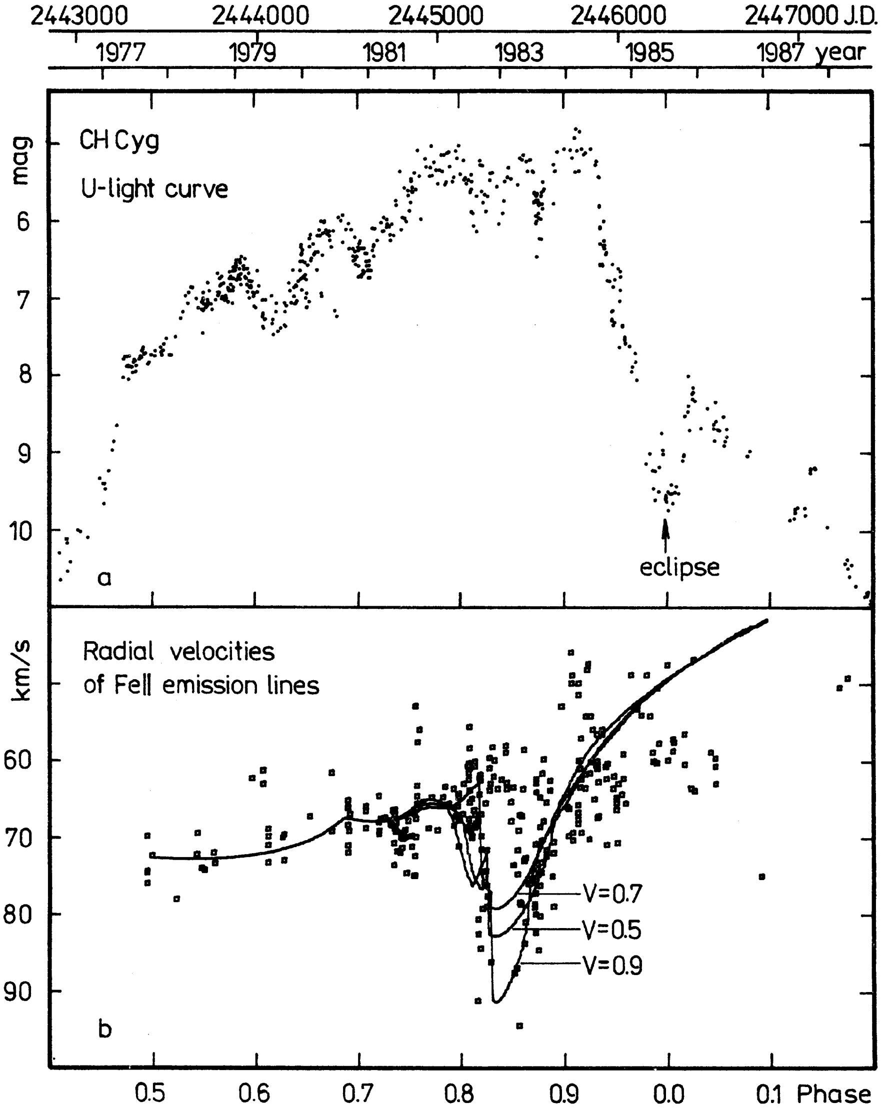

Fig. 5. a) U-light curve of CH Cygni during the period of the last outburst (from the literature).

b) Radial velocities of FeII emission lines (the values from Skopal et al., 1989) and their model computed for three cuts of the spectrum line (V=0.5, 0.7 and 0.9).

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