RAPID SIMULTANEOUS OBSERVATIONS OF Fe II AND BALMER EMISSION LINES OF X OPH

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Abstract. Sudden brightening of Fe II and Balmer (Hβ and Hα) lines of X Oph was observed on 28–29 May, 1986. Equivalent width of Fe II and Hβ lines increased by a factor of two and that for Hα line by a factor of four, during the brigtening phase of the star. This brightening phenomena has been explained in the framework of 'Coronal Radiative Instability'.

1. Introduction

Non-supergiant early-type stars with Balmer emission lines in their spectra, including also Oe and Be-shell stars may be defined as Be stars (Slettebak, 1979). Extended gaseous envelopes surrounding the atmospheres of the central star are radiating the emission lines. For many Be stars the extended gaseous envelopes around it may completely disappear, leaving a normal absorption-line B-type star, until some time later on a new envelope developes again (Slettebak, 1979; Underhill and Doazan, 1982; Kogure and Hirata, 1982). Most of the studied Be stars are rapid rotators and irregularly variable both sepectroscopically and in magnitude.

In spite of large efforts in understanding the physical origin, geometry, dynamics, and spectral and photometric variations of Be stars envelopes, so far no general agreement has been achieved.

Recent high-resolution and high signal-to-noise ratio, spectroscopic studies of Hα and Fe II emission lines for 24 bright southern Be stars by Hanuschik (1986, 1987) suggest that Hα profile is composed of two components, a relatively broad strong primary (dense inner most disk) and a narrow weak secondary (low-density outer region). Fe II emission lines (symmetric double peak – class 1 and asymmetric single peak – class 2) do not indicate the two-component structure like Hα profiles. Broad asymmetric Hα profiles with a sharp peak either on the blue or on the red side of four pole-on Be stars (k CMa, δ Cen, HR 3237, and X Oph) do not indicate the present two-component structure of the envelope. Fe II profiles of X Oph suggest that this star may be classified as an intermediate case between class 1 and class 2. Both Hα and Fe II emission profiles of X Oph indicate the presence of strong radial motions superimposed to rotation in its envelope (Hanuschik, 1986, 1987). With the present knowledge it is difficult to understand the emission-line profiles of X Oph in the framework of an equatorial disk model, if self-absorption in the disk is to play an important role. Thus, to understand the geometry and dynamics of the peculiar envelope of X Oph, rapid simultaneous observations of Balmer (Hβ and Hα) and Fe II emission lines have been obtained on several

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nights between 1985 and 1987. The present paper presents the results of 28–29 May, 1986 when the peak emissions as well as equivalent widths of envelope lines (Balmer and Fe II lines) increased suddenly. Study of this type of sudden envelope brightening may throw certain important information about Be phenomenon.

2. Observations and Reductions

Rapid simultaneous observations of Balmer (Hβ and Hα) and Fe II lines of X Oph were obtained on several nights between 1985 and 1987. Sudden brightening of X Oph was observed on 28 May, 1986. Spectrograms were obtained at the Cassegrain focus of the 102 cm reflector of Vainu Bappu Observatory, Kavalur, with the help of the Carl-Zeiss UAG Spectrograph, with a grating of 651 grooves mm^{-1} and a 170 mm camera over a wavelength range 4600–6700 Å at a reciprocal dispersion of 82 Å mm^{-1}. Kodak 09802 emulsion was employed. All plates were calibrated for relative intensity with an auxiliary calibration spectrograph.

The spectrograms were digitized using PDS-1010M microdensitometer at a speed of 2 mm s^{-1}, with sampling interval of 5 μm. Reductions of all the spectrograms were done using RESPECT software package (Prabhu *et al.*, 1987). Smoothing by low-pass filter (cut-off frequency 10 cycles mm^{-1}), conversion of density to intensity scale and wavelength scale fixation using laboratory comparison spectrum (Fe + Ar hollow cathode source) were done interactivity using RESPECT.

3. Results

3.1. Fe II EMISSION LINES

Five spectra of X Oph for different observing time (from bottom to top with increasing UT) in the spectral region 5000–5400 Å are presented in Figure 1 which shows the strong Fe II emission lines. Each spectrum has been normalized to local stellar continuum. Table I contains the observed peak intensities (I_p/I_c) and equivalent widths of different Fe II emission lines (5169, 5198, and 5316 Å) with their standard deviation

TABLE I

Observed results of strong Fe II emission lines of X Oph in the spectral region 5000–5400 Å

Mean UT of observation	5169		5197.58		5316.61	
	$I_p/I_c \pm 0.05$	$W(5169) \pm 0.36$ (Å)	$I_p/I_c \pm 0.04$	$W(5198) \pm 0.11$ (Å)	$I_p/I_c \pm 0.04$	$W(5317) \pm 0.14$ (Å)
18 : 42	1.20	1.52	1.09	0.87	1.17	1.11
18 : 47	1.22	1.24	1.10	1.07	1.23	1.04
18 : 53	1.30	2.04	1.11	1.11	1.23	1.27
19 : 00	1.33	1.96	1.15	0.85	1.27	1.38
19 : 06	1.24	2.07	1.12	0.96	1.18	1.06

values. Spectra of X Oph which were observed before and after 28–29 May, 1986, have not been shown here but they have been used to compare with the results of 28–29 May, 1986. The following general properties of these emission lines can be derived from inspection of Figure 1 and Table I.

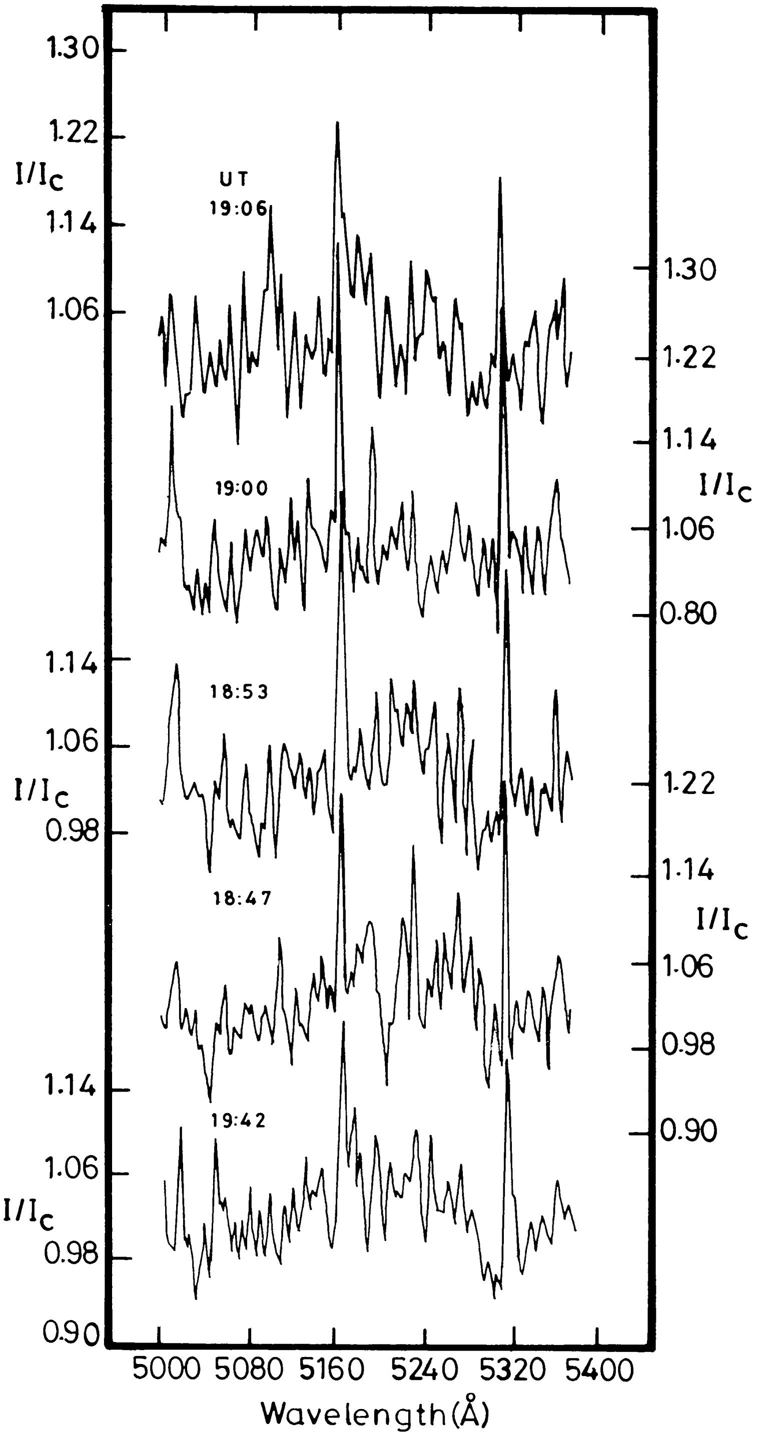

Fig. 1. Spectra of X Oph in the spectral region 5000–5400 Å for different UT. Strong variable emission lines are due to Fe II (mainly 5169, 5198, and 5316 Å) emission.

(1) Peak intensities of all the Fe II emission lines are more stronger on 28–29 May, 1986 than what was observed on other nights.

(2) Weak asymmetries are present in all the Fe II lines which indicates the presence of strong radial motions in the envelope of X Oph.

(3) 5169 and 5316 Å emission lines are stronger than other Fe II emission lines.

(4) Equivalent widths of Fe II emission lines increased by a factor of two during the brightening phase of the envelope of X Oph.

(5) Rapid weak irregular variations of equivalent widths are present in all the Fe II lines. This type of variations indicates the changes in ionization stage at least of iron.

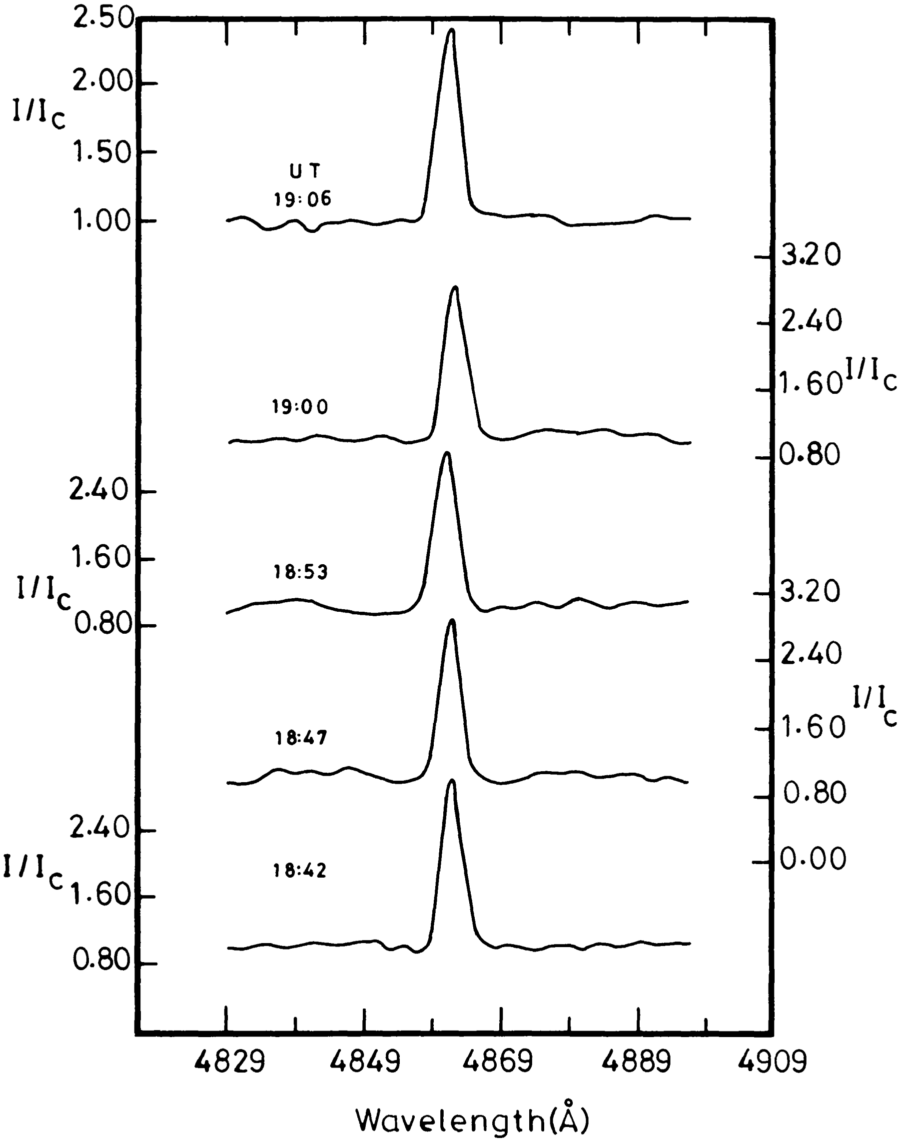

Fig. 2. Hβ profiles of X Oph during its brightening phase.

TABLE II

Emission intensities and equivalent widths of Hβ and Hα lines of X Oph

UT of observation	Hβ		Hα				
	$I_p/I_c \pm 0.21$	$W(\beta)$ (Å)	*VE*	*RE*	*CD*	$W(\alpha)$ (Å)	ΔV_{peak} (Å)
18 : 42	2.98	7.36	20.67	21.18	19.81	159.11	3.29
18 : 47	2.90	7.01	25.26	26.84	24.50	183.79	3.17
18 : 53	2.87	7.76	18.13	20.65	16.67	144.69	3.54
19 : 00	2.84	7.64	22.07	22.57	21.01	179.72	3.24
19 : 06	2.44	6.05	29.92			198.55	>2.0

3.2. BALMER EMISSION LINES

3.2.1. Hβ *Line*

Hβ profiles of X Oph are shown in Figure 2 and sequences of the profiles are the same as in Figure 1. All the Hβ profiles show a single sharp peak emission. Even if the peak separation (ΔV_{peak}) of this line is present but we are unable to detect it with the modest resolution (~ 2 Å) of the spectrograph. According to Dachs *et al.* (1986) this profile has shown a broad top or double peak in 1976 through 1979 with top width or peak separation between 2 and 2.5 Å, while in 1980 through 1982, Hβ emission was always a single sharp peak. So, even if this line had developed double-peak structure in May 1986, the ΔV_{peak} value will be less than 2 Å. Different parameters of this line are presented in Table II. First, through third columns of Table II gives UT of observations, I_p/I_c with its standard deviation and equivalent widths of Hβ [$W(\beta)$], respectively.

Rapid weak irregular variations of $W(\beta)$ is also present in the envelope and nature of variations of the equivalent widths of Hβ and Fe II lines are almost the same. This indicates that Hβ and Fe II lines are formed from the same region of the envelope which has already been suggested by many authors. Another interesting feature of Hβ line is that absorption is present at both wings of the profile. Dust optical depth may be comparable or greater than the line optical depth at the wings of the Hβ profile. So, the absorption features at the wings may be mainly due to the dust absorption.

3.2.2. Hα *Line*

Figure 3 presents the emission profiles of Hα and the order of the profiles are the same as in Figure 1. Listed in Table II are measured values for intensities of the violet (*VE*) and red (*RE*) peak and of the central depression (CD) and for the ratio of violet to red peak intensities [$V/R = (VE - 1)/(RE - 1)$] and equivalent widths [$W(\alpha)$] and their peak separation values (ΔV_{peak}). All the profiles show double-peak structure except the last one (UT = 19 : 06). Most probably the ΔV_{peak} value of the last profile is less than 2 Å. During the brightening phase the ΔV_{peak} values increased when I_p/I_c as well as $W(\alpha)$ decreased and *vice versa.* Also equivalent widths of Hα profiles increased by a factor of four during the brightening phase. Like Hα profiles, strong absorptions are also

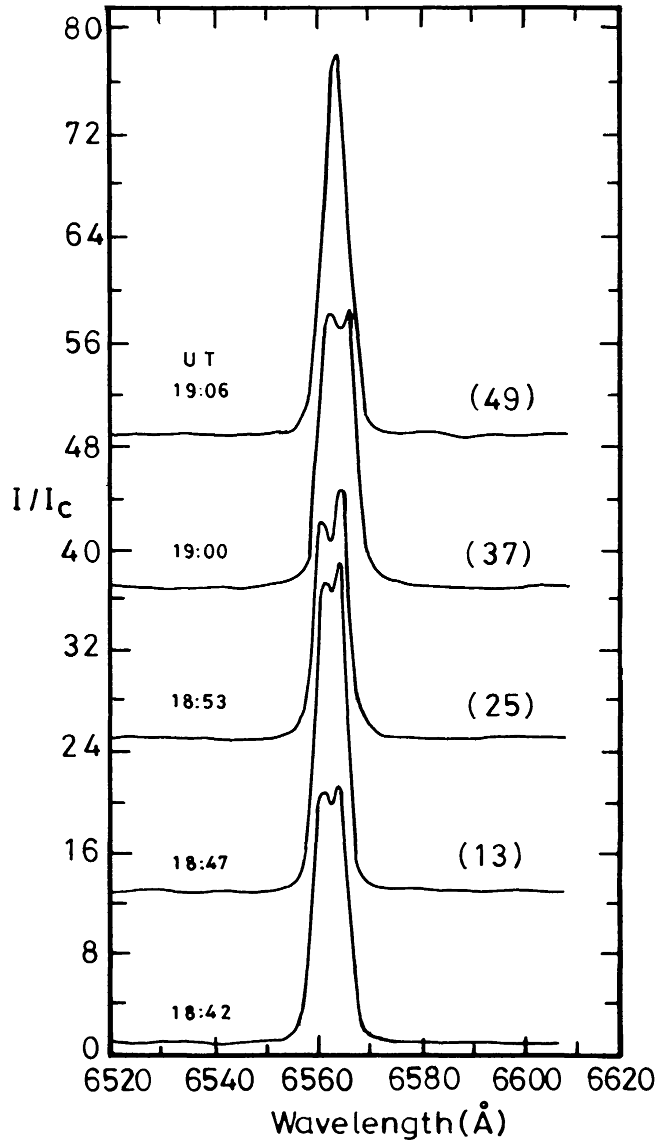

Fig. 3. Hα profiles of X Oph at different observing time.

present at the wings of Hα profiles. This again confirms the presence of dust in the envelope of X Oph.

4. Discussion

From the previous section we find that ΔV_{peak} and I_p/I_c are inversely related and strong turbulence or radial motions, or both, are present in the dusty envelope of X Oph as it was suggested by Hanuschik (1986, 1987). Having these informations in mind, first we shall try to understand the formation process(es) of the double-peak structure of the Hα profile of X Oph and consequently we have to explore the possible mechanisms for sudden envelope brightening.

X Oph is a pole-on Be star with projected rotational velocity ($v \sin i$) equal to 140 km s^{-1}. In order to find out the inclination angle of X Oph, we shall assume that all Be stars are rotating with a uniform rotational velocity at the equator ($v_{\rm eq}$) (Slettebak, 1979, 1982; Kitchin, 1982) and the value of $v_{\rm eq}$ is 450 km s^{-1}. Thus X Oph is seen at low inclination angle ($i \leq 20°$) if it rotates at 450 km s^{-1}.

From the theoretical disk model of Gray and Marlborough (1974) the computed disk radius (R_d) of X Oph in units of stellar radius (R_*) is. 6.3 where R_* equal to 5.8 $R_\odot$. Thus the obscuration of the rear part of the disk by the central star is not possible due to low the inclination angle and the extended disk of X Oph. So, the double-peak structure of Hα profile is not due to obscuration.

Distribution of radial velocities of emitting atoms in the narrow gaseous ring, may also produce a double-peak structure profile (Struve, 1931; Kogure, 1969a, b; Huang, 1972). Usually this happens for very weak double-peak Hα emission line profile which is not the case for X Oph (very strong Hα emission).

Double-peak Hα emission profile of X Oph may be due to Hα emission from very large disk radii where radial velocity dominates over rotational velocity which is very small, superimposed to the strong emission from the inner part of the disk where $v \sin i$ is sufficiently large and the intensity peaks of double-emission lines are shifted towards smaller velocity. Peak separation of Hα profile depends on the relative strength of turbulence or radial motions over rotation. The $\Delta V_{\rm peak}$ value will decrease when a certain fraction of line-broadening by turbulence or radial outflow or inflow dominate over $v \sin i$ value at larger radii.

From Table II it is clearly seen that I_p/I_c or $W(\alpha)$ and $\Delta V_{\rm peak}$ are inversely related. This may be explained in terms of sudden input of mass which is associated with strong radial motions into the envelope. Due to strong radial motions, the $\Delta V_{\rm peak}$ value will decrease and the profile will be broad and mass or number density enhancement will increase I_p/I_c as well as $W(\alpha)$.

Now we have to find out that physical process(es) which has initiated for sudden brightening of envelope lines of X Oph. This we shall discuss below in the framework of 'Coronal Radiative Instability'.

Presence of highly-ionized species, e.g., N V and O VI lines have been found in the ultraviolet spectra of many Be stars (Snow and Marlborough, 1976; Marlborough, 1977; Marlborough and Snow, 1980; Doazan *et al.*, 1980; Dachs, 1980; Heinrichs *et al.*, 1980) which indicate superthermal outflow velocities and the sign of coronal regions with $T_e \sim 10^5$ to 10^6 K in the winds of Be stars. Observed soft and hard X-ray fluxes in certain Be stars, also suggest the presence of coronae with $T_e \sim 10^6$ to 10^7 K. Coronal regions with $T_e \sim 10^5$ to 10^6 K are usually called 'cool coronal regions'. This region consists of two parts: the coronal holes and the quiet corona (Underhill and Doazan, 1982). These two regions differ from corona proper by a factor of 2 in density, while T_e for both lies in the range 1–2 × 10^6 K, the 'hole' being only some 0.3–0.5 × 10^6 K (Vaiana and Rosner, 1978).

Now we shall try to find out the possibility for the formation of radiative instability in a plasma medium like coronal regions. Whether a hydrogen-dominated plasma medium will be thermally unstable or not that will depend mainly on the temperature of the medium. If the temperature of the medium is around (3–5) × 10^5 K, radiative instability may formed there (Field, 1965). Thus we find that the temperature condition for radiative instability is satisfied by the coronal holes region of Be stars. In this region the input energy to the medium and the radiative energy loss (bound-bound, free-free, and bound-free transitions) will try to establish the thermal equilibrium condition and any small temperature perturbation around equilibrium state will decrease the temperature and will increase the density which will lead to the condensation of the medium. Again this will increase the radiative loss and will decrease the internal thermal energy as well as internal pressure of the coronal holes region. As a result of this, further condensation will take place and this process will continue till the radiative instability is formed. Time-scale (T) of this instability may be written as

$$\tau = p/L\,, \tag{1}$$

where $p = \rho RT/\mu$ is the pressure and $L = \chi\rho^2 T^E/m_p^2$ the volumetric radiative loss rate of the medium. Values of χ and E have been obtained from Rosner *et al.* (1978) for the temperature region (3–5) × 10^5 K and the density of the coronal region from Underhill and Doazan (1982). Due to the variations of density of the coronal holes region, the value of τ will change and its approximate value will be around few minutes to an hour. Though we were not able to observe the beginning and end of the brightening phase of X Oph, but it is quite likely that the duration of this phase was very short (may be an hour or so).

Now we have to find out the effect of coronal radiative instability in the envelope of Be stars. Energy released by this process will propagate through the post-coronal transition region and will reach the envelope of Be stars. This in turn will increase the free-free, bound-free, and bound-bound transition rates in the envelope and as a result one may observe sudden enhancement in emission strength of envelope lines (mainly Fe II and Balmer lines) over a time-scale of a few minutes to hours. Thus our present observed results, i.e., sudden enhancement of I_p/I_c and equivalent widths of Balmer (Hβ and Hα) and Fe II lines, may be due to the radiative instability in the coronal holes region of X Oph.

5. Conclusions

From the above study the following conslusion may be drawn.

(1) Significant amount of dust is present in the envelope of X Oph.

(2) Turbulence and strong radial motions play the dominant role for the formation of envelope lines in X Oph.

(3) Double-peak structure of Hα emission profile of X Oph is mainly due to the combined effect of turbulence or radial motions and rotational velocity of X Oph.

(4) Sudden envelope brightening of X Oph may be due to radiative instability in the coronal holes region.

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