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OBSERVATION OF AN Hα OUTBURST IN THE Be STAR HR 4123

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ABSTRACT

During routine monitoring of the Be star HR 4123 during the year 1987–1988, a burst of Hα emission was observed on 1987 May 11. The increase was observed on 1987 May 9 and lasted until 1987 June 7, peaking to an equivalent width of 31.6 Å on 1987 May 11. This short-term burst is interpreted as due to the presence of a compact object in binary motion around the Be star, which accretes the matter ejected by the Be star to give out X-rays, which in turn produce ionization in the gas to give out the Hα emission. The broad line at 6577.5 Å observed to accompany Hα emission during the burst is suggested to be emission from dielectronic recombination from C III ions in a C II region around the H II region formed by the X-radiation.

Subject headings: stars: Be — stars: binaries — stars: emission-line — stars: individual

I. INTRODUCTION

Be stars are known to show variable line emission (Doazan 1982). The appearance and disappearance of Hα emission on time scales of years are also well observed. Some Be stars like μ Cen seem to show episodes of Hα emission enhancement lasting several months. We report here such an enhancement for the Be star HR 4123 during 1987 May–June and also a broad emission at 6577.5 Å. HR 4123 (HD 91120) is a shell star. It is designated as a spectroscopic binary in the Bright Star Catalogue (Hoffleit and Jaschek 1982) and in the Radial Velocity Catalogue (Wilson 1963). The radial velocities determined at different epochs show large variations (Abt 1970), but to our knowledge no binary periodicity has been determined.

The observational details and results are given in § II, and the origin of the Hα enhancement is discussed in § III. The origin of the broad emission at 6577.5 Å is considered in § IV, and finally in § V we present a summary.

II. OBSERVATIONAL DETAILS AND RESULTS

Five spectrograms in the Hα region were obtained on five night between 1987 April 30 and 1988 January 2 using a grating spectrometer of 1800 grooves mm^{-1} and a 170 mm camera, at the Cassegrain focus of the 1.02 m reflector of Vainu Bappu Observatory, India. The spectrograms were obtained on 09802 emulsion with a reciprocal dispersion of 27 Å mm^{-1} at 6563 Å, and they were digitized using a PDS-1010 M microdensitometer, at a speed of 2 mm s^{-1}, using a spacing interval of 5 μm. The transformation to intensities was done with the help of calibration plates obtained using an auxiliary calibration spectrograph. The RESPECT software package (Prabhu, Anupama, and Giridhar 1987) was used for all the reductions (smoothing by a low-pass filter and cutoff frequency ~10 cycles mm^{-1}) using the VAX 11/780 computer. The wavelength calibration was performed by fitting a third-order polynomial to the measured positions of about 20–30 laboratory comparison lines (Fe + Ar or Fe + Ne hollow cathode source). With this dispersion curve we rebinned the stellar spectra in equidistant wavelength steps. The obtained measuring accuracy in the wavelength scale is of the order of ±0.05 to ±0.10 Å. Finally, we normalized the spectra by dividing by a spline fit to manually selected continuum points. Figure 1 shows the Hα profiles of HD 91120 obtained on five nights between 1987 April 30 and 1988 January 2. The main finding from our observations is a substantial increase of the total emission strength of Hα within just two days, from May 9 to May 11. A result which was reported for the first time in Be stars, the detection of emission around 6578 Å (Baade *et al.* 1988), is also seen in our spectrum of May 11. In addition to the above-mentioned observations, the following details are worth mentioning:

1. Hα profiles of HD 91120 which were obtained by Andrillat and Fehrenbach (1982) in 1980 show two emission components superposed on the broad photospheric absorption [equivalent width of the emission components, $W(\alpha) = 5.1$ Å]. Our Hα profiles of April 30 and January 2 are almost identical with the profiles of Andrillat and Fehrenbach (1982). Broad photospheric absorption is also present in the Hα profiles of May 9 and June 7, but the total emission strengths are different from the earlier ones (see Fig. 1 and Table 1). No photospheric absorption feature is seen in the Hα profile of May 11.

2. Peak emission intensities of Hα profiles increased from $1.91 I_c$ (May 9) to $5.11 I_c$ (May 11) and then decreased to $1.88 I_c$ (June 7). But the emission intensities are almost equal on 1987 30 April and 1988 January 2.

3. The equivalent width of the Hα line [$W(\alpha)$] increased from 10.11 Å (May 9) to 31.55 Å (May 11) and then decreased to 10.34 Å (June 7). $W(\alpha)$ values of the Hα profiles of April 30 and January 2 are almost equal (Table 1).

4. Before 1987 May 11, the peak separation ($\Delta V_{\rm peak}$) of the two emission components is 4.3 Å; after May 11, the $\Delta V_{\rm peak}$ values are 3.5 Å (1987 June 7) and 3.96 Å (1988 January 2); but the peak on May 11, however, there is almost no well-defined red component (the Hα profile is highly asymmetric).

5. On 1987 April 30 and May 9 and 1988 January 2, the V/R ratio of the two emission components is almost equal to unity. But this value is definitely greater than unity on 1987 June 7.

6. A broad and strong emission line has been observed around 6577.5 Å on May 11.

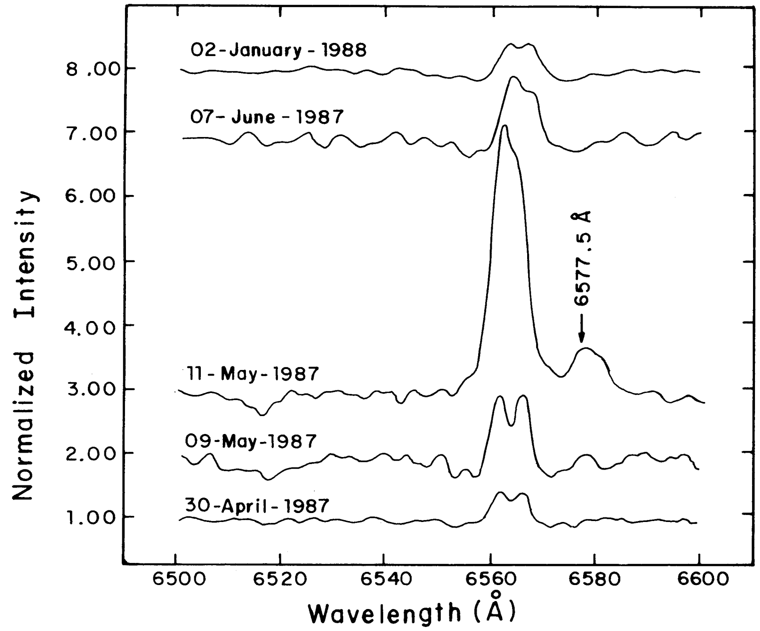

FIG. 1.—Spectra of HD 91120 in the Hα region. Dates of observations are given at the left.

III. ORIGIN OF THE Hα ENHANCEMENT

Hα outbursts similar to that in HR 4123 were seen earlier in μ Cen by Peters (1986) and by Baade *et al.* (1988). The increase in the equivalent width took place in a few days and lasted about a month. Peters and Baade *et al.* suggested that the outbursts are due to expulsion of material of the order of 10^{-11} $M_\odot$. The Lyman continuum from the B2 IV star presumably ionizes the gas to lead to the Hα emission.

The luminosity in Hα emission during the outburst of HR 4123 is estimated to be about 2×10^{32} ergs s^{-1}, corresponding to the equivalent width of 31.6 Å and an assumed spectral type of B9. In this estimation the stellar background radiation intensity is taken from Kurucz (1979) for the assumed spectral type surface temperature ~13,000 K. The suggestion of Peters (1986) that the outburst is due to expulsion of additional material alone cannot work in this case, because the spectral type of HR 4123 is B9 and the Lyman continuum is not enough to provide the required ionization (see Apparao and Tarafdar 1987). We have calculated that the Lyman continuum radiation of the star has to be enhanced by a factor of about 10^4 to explain the observed Hα emission. To our knowledge, models for such large enhancement on a short time scale of months have not been proposed, even though models using nonradial pulsations and magnetic fields have been discussed for the emission of gas (see the papers in Slettebak and Snow 1987 and also Apparao, Antia, and Chitre 1987) from Be stars and its enhancement. Here we proposed that the enhancement of radiation comes from a companion to the B9 star which is a compact star (neutron star or white dwarf). We suggest that when the newly expelled gas, during its expansion, passes the compact star, X-ray emission takes place as a result of accretion of matter on to the compact star. The X-rays ionize the gas, resulting in the enhanced Hα emission. The decay of the Hα emission occurs when the gas envelope during expansion passes over the compact object.

We have calculated that the Hα emission of 2×10^{32} ergs s^{-1} can occur if the X-ray luminosity is about 3×10^{34} ergs s^{-1} with a bremsstrahlung spectrum of temperature 3 keV and a hydrogen density of 10^{12} cm^{-3}. Such outbursts of X-ray fluxes have been observed in X Per and other objects which are known to contain a compact object (White *et al.* 1982). The nature of the outburst, that is, an increase and gradual decrease of Hα emission, indicates that the gas density in the ejected envelope has a maximum and a falling density on either side. If an expansion velocity of about 10 km s^{-1} is assumed, which is usual in Be stars, the width of the ejected envelope, using the duration of the outburst, is about 10^{12} cm.

IV. THE EMISSION AT 6577.5Å

In this section we examine the origin of the 6577.5 Å emission. The energy in this line at the maximum, again assuming a

TABLE 1

MEASURED VALUES OF Hα AND C I EMISSION PROFILES

DATE OF OBSERVATION	I_{max}/I_c					
	V	R	V/R	$W(\alpha)$ (Å)	$W(6577.45)$ (Å)	ΔV_{peak} (Å)
1987 Apr. 30	1.41	1.42	1	4.84	...	4.33
1987 May 9	1.91	1.92	1	10.11	...	4.34
1987 May 11	5.11		...	31.55	4.94	...
1987 June 6	1.88	1.64	1	10.34	...	3.57
1988 Jan 2	1.40	1.38	1	5.28	...	3.96

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spectral type of B9, Kurucz's (1979) calculation of radiation emitted by a B9 star, and an equivalent width of 4.94 Å, is 3×10^{31} ergs s^{-1}. Baade *et al.* (1988) have observed three broad emission humps around 6575, 6580, and 6587 Å. They suggested that these are the C II lines λλ 6578 and 6583, whose profiles are modified by the rotating emission region to give the observed humps. These are the $3s\ ^2S$–$3p\ ^2P^o$ $J(1/2$–$1/2)$ and $J(1/2$–$3/2)$ transitions. The excitation of the upper level requires 16.33 eV. The upper state can result from excitation of C II either by photons or by collision with electrons. The upper state can also occur due to recombination of C III ions with electrons; the C III ions require 24.38 eV photons for their formation from C II ions. We consider below each of these processes in the case of HR 4123.

First we cnsider the H II region formed by the Lyman continuum of the B9 star. Using a surface temperature of 13,000 K and the Lyman radiation as given by Kurucz (1979), the Hα emission from this region is about 5×10^{28} ergs s^{-1}, corresponding to an $n_e^2 V \approx 2 \times 10^{53}$ (n_e is the electron density and V the volume). Since the B9 star contains a negligible amount of radiation above 24.38 eV, most of the carbon is in the form of C II ions. Therefore, the recombination of C III ions to yield excited C II ions is negligible. Excitation of C II ions by photons to the required level is also negligible, because photons above 16.33 eV are also too few (Kurucz 1979). The excitation of C II ions to the required level is possible by electrons colliding with C II ions. The temperature in the H II region by the B9 star is expected to be close to $T \sim 10^4$ K. In this case the excitation rate is

$$L_{12} = 1.6 \times 10^{-17}\ \mathrm{cm^3\ s^{-1}} .$$

The de-excitation rate is much larger than this value, and therefore the total number of emitted photons from this process is

$$N_{\rm ph} \approx L_{12}\, n_e\, n_{\rm C\,II}\, V ,$$

with $n_{\rm C\,II}$ being the density of C II ions. If we use $n_{\rm C\,II}/n_{\rm H} \approx 3 \times 10^{-4} \approx n_{\rm C\,II}/n_e$, then

$$N_{\rm ph} = L_{12}\, n_e^2\, V \times 3 \times 10^{-4} .$$

Using values from above, $N_{\rm ph} \approx 10^{33}$ and the energy in the infrared photons is about 10^{21} ergs s^{-1}, which is much less than the observed value. The excitation rate cannot be increased to the requisite level unless the temperature is increased to high values inconsistent with that in the H II region. Therefore, we conclude that the C II emission from the H II region formed by the B9 star is not responsible for the observed emission at 6577.5 Å.

We had, in the previous section, considered the H II region formed by X-ray emission from a compact object as the origin of the enhanced Hα emission. We now consider whether the C II emission can occur in this region. The structure of the H II region formed by X-radiation is studied in great detail by Kallman and McCray (1982). It shows that the ion species dominant in the H II region formed by the X-radiation are C III and C IV and a negligible amount of C II. Therefore, the radiation from C II ions excited either by collisions with electrons or by UV radiation, in this region, is small.

The upper state can of course result from recombination of C III ions, which requires 24.38 eV photons for their formation from C II ions. C III and C IV are the dominant ions of carbon in this H II region. The ratio of emission energy in the carbon lines to that in Hα is

$$\frac{E_{\rm C}}{E_{\rm H}} = \frac{\alpha_{\rm C}\, n_{\rm C}\, n_e\, V}{\alpha_{\rm H}\, n_{\rm H}\, n_e\, V} \approx \frac{n_{\rm C}}{n_{\rm H}} \approx 3 \times 10^{-4} .$$

In the above $\alpha_{\rm C}$ and $\alpha_{\rm H}$ are the recombination coefficients; $n_{\rm C}$ and $n_{\rm H}$ are the densities of carbon and hydrogen atoms, n_e is the electron density, and V is the volume of the H II region. The photon energies of the carbon lines and Hα are taken to be approximately equal. Thus the emission from the carbon ions due to the recombination is much less than the observed value.

The H II region due to the X-ray source is embedded in the C II region (Apparao and Tarafdar 1987). We now show that the emission at 6578 Å can be C II emission from the C II region by dielectronic recombination of C III ions formed by the X-radiation "leaking" from the H II region. The dimension of the H II region due to the X-ray source is about 5×10^{10} cm, if we use the luminosity of the X-ray source $L \sim 3 \times 10^{34}$ ergs s^{-1} and the density of gas $n \approx 10^{12}$ cm^{-3} (Kallman and McCray 1982). We assume the gas sphere has a radius r of 10^{12} cm. The C II emission can arise as follows:

$$\underset{1s^2 2s^2 2p^2}{\mathrm{C\ II}} + \text{X-ray} \xrightarrow{-e} \underset{1s 2s^2 2p^2}{\mathrm{C\ III}} \xrightarrow{h\nu} \underset{1s^2 2s^2 2p}{\mathrm{C\ III}}$$

$$\xrightarrow{e} \mathrm{C\ II^*} \xrightarrow{h\nu} \mathrm{C\ II} . \qquad (1)$$

The number density of C III ions n(C III) in the C II region is given by

$$\alpha n(\mathrm{C\ III}) n(e) = n(\mathrm{C\ II})\Gamma , \qquad (2)$$

where α is the recombination coefficient, and $n(e)$ and n(C II) are the densities of electrons and C II ions. Γ is given by

$$\Gamma = F\sigma , \qquad (3)$$

where F is the X-ray photon flux (cm^{-2} s^{-1}) and σ is the cross section for the knocking off of the inner electron of C II (Daltabuit and Cox 1972). The energy in photons at 6578 Å is given by

$$E_{6575} = \alpha n(\mathrm{C\ III}) n(e) h\nu_{\rm I}\, V\ \mathrm{ergs\ s^{-1}} , \qquad (4)$$

where $h\nu_{\rm I}$ is the energy of 6578 Å photons and V is the volume of the C II line emitting region. Using equations (2), (3), and (4),

$$F = \frac{E_{6578}}{n(\mathrm{C\ II}) h\nu_{\rm I}\, V\sigma} . \qquad (5)$$

We use the ratio of the number density of carbon to that of hydrogen as 3×10^{-4}, giving $n(\mathrm{C\ II}) = 3 \times 10^8$ for a density of 10^{12} H atoms cm^{-3}. The energy in X-rays is then

$$E_x = F \times 4\pi R_c^2\, h\nu_x , \qquad (6)$$

where R_c is the dimension of the C II line emitting region and $h\nu_x$ is the energy of the X-ray photons. Using equations (5) and (6), $h\nu_x = 3$ keV, and $R_c \simeq 2 \times 10^{11}$ cm (approximately the distance in which 3 keV photons are substantially absorbed), we find $E_x \sim 2 \times 10^{34}$ ergs s^{-1}. This is approximately the energy escaping the H II region in X-rays. Thus it seems that the C II line emission can arise from the C II region around the X-ray source.

We wish to point out here that lines from C I excitation also occur in this region (λλ6568.7, 6578.8, 6586.2, and 6587.6). These lines can occur in the C II region formed by the B9 star;

however, since in the present case the 6578 Å line emission occurs in association with the Hα emission, this intensity is likely to be smaller than the C II emission.

V. SUMMARY AND DISCUSSION

We have observed an outburst of Hα emission in the Be star HR 4123. To explain this enhanced emission, we need an enhancement of photons from the star with energy greater than the hydrogen ionization potential, by a factor of about 10^4. Such an enhancement does not seem possible for the B9 star on a time scale of a few months. We therefore postulated the existence of a compact star as a binary companion, which, when it accretes matter expelled by the B9 star, gives X-radiation. This X-radiation forms on the H II region, which leads to the enhanced Hα emission. A test of the suggestion of a compact star as a binary companion is of course the observation of X-radiation from HR 4123. It can be looked for with the proposed new X-ray satellites. Another possibility is to look for pulsation in the Hα radiation as is observed in the case of X Per (Mazeh, Treffers, and Vogt 1982; Apparao and Tarafdar 1986).

If the compact object postulated is of mass of about 1 $M_\odot$, and if a mass of about 5 $M_\odot$ for the B9 star is used together with the maximum velocity of about 34 km s^{-1} derived from spectroscopy (Abt 1970) of the B9 star, assuming that the velocity is due to its binary motion, the period of the binary can be estimated to be about 40 days. It will be interesting to determine this period by systematic spectroscopy.

The emission observed at 6577.5 Å can be due to excited C II ions, which are formed in the C II region outside the H II region formed by the X-radiation. The excited C II ions result from dielectronic recombination of C III ions formed by the knocking out of an inner electron by the X-radiation leaking out of the H II region. This explains the occurrence of Hα and C II emission together.

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