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Study of spectral and photometric variability of the asynchronous polar BY Camelopardalis (H 0538+608)

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Abstract. Results of synchronous time–resolved spectroscopic and photometric observations of the peculiar polar BY Cam at high state of brightness ($14\overset{m}{.}2 - 15\overset{m}{.}6$) obtained with the 6 m telescope of the SAO using the TV scanner and the photometer NEPh in February 1990 and March 1991 are presented. From 117 spectra with a mean temporal resolution of 300 s and a spectral resolution of about 2 Å in the wavelength range 3900–5000 Å an analysis of variability of equivalent widths, central intensities, half-widths and radial velocities of the hydrogen and HeII 4686 Å emission lines has been performed. The analysis has shown the presence of significant variations of the parameters of lines depending on the phase of the spin period of the white dwarf and on the photometric state (flaring or pulsating) of the system. The mean equivalent width of the line HeII 4686 Å increased by a factor of 1.5 in the flaring state as compared with the pulsating state. The radial velocity curves measured from the broad components of the emission lines HeII 4686 Å, H_β, H_γ were approximated by least-squares sinusoids. In the pulsating state, they showed pronounced departures from a sinusoid, which are about 1.4 times of the amplitude of the sinusoid. The observed variability may be indicative of changes in the geometry of accretion on a time scale of 20–40 minutes. In the pulsating state the narrow emission line components disappear for a short time around the phases associated with a photometric minimum whose duration differs and is of 20 minutes for the Balmer lines, 15 minutes for HeI 4471 Å and 5 minutes for HeII 4686 Å. The half-widths of the Balmer lines in the pulsating state vary with a quasiperiod approximately equal to a quarter of the white dwarf spin period, which is not observed in the flaring state. Possible causes of the revealed spectral and photometric variations are discussed.

Key words: accretion – stars: individual: BY Cam – stars: binaries: general – stars: cataclysmic variables – X-rays: stars

1. Introduction

The AM Herculis type stars (polars) are a subclass of cataclysmic variables consisting, according to the standard model (Liebert & Stockman, 1985), of a white dwarf with a strong magnetic field (primary) and a low-mass dwarf (secondary) filling its Roche lobe. The magnetic field affects the gas stream motion from the secondary component, channelling it to the magnetic poles of the white dwarf. The spectral range of the energy liberated in the polar regions of the white dwarf is very wide: from the hard X-rays to the far infrared region. A characteristic distinction of polars is the strong proper linear and circular polarization of their optical radiation (Tapia, 1977). Reviews of properties and observational data of AM Her type systems are presented by Cropper (1990) and Vojkhanskaya (1990).

The X-ray source H0538+608 was discovered as a result of the programme of optical identification of X-ray sources carried out by the orbiting observatory HEAO 1 and the specialized satellite Uhuru (Forman et al., 1978; Wood et al., 1984). After the circular polarization had been revealed, the source was ranked among polars (Remillard et al., 1986).

Two brightness states are observed in the system: high ($\approx 14^m - 15^m$) and low ($\approx 17\overset{m}{.}5$) (Szkody et al., 1990; Mason et al., 1989; Silber et al., 1992; Andronov et al., 1992; Silber, 1995). The X-ray-to-optical flux ratio in H 0538+608 is one of the highest in polars

(Remillard et al., 1986; Kallman et al., 1993).

Spectra obtained in the ultraviolet region have shown that the NV 1240 Å and CIV 1550 Å line intensity ratio in H 0538+608 reaches 10–20, whereas it equals 0.3 in other polars (Bonnet-Bidaud & Mouchet, 1987). This spectral property can be best explained by the anomalous content of the CNO-cycle elements. This anomalous composition is characteristic of Novae after the burst (Bonnet-Bidaud & Mouchet, 1987). However, Silber et al. (1992) noticed no bursts in BY Cam on the archive plates. The difference between its chemical composition and solar can be explained by the chemical composition of the secondary companion whose outer layers have been lost during evolution (Mouchet et al., 1991).

The VLA observations gave an upper limit of the radio radiation of this magnetic cataclysmic variable (Mason et al., 1996).

Cropper et al. (1989) detected cyclotron bands in the BY Cam spectrum and estimated from them the magnetic field strength at the poles as 40.8 ± 1.5 MG.

From the analysis of radial velocities of the narrow component of the H_α line, the orbital period of the system was found to be $3^h\!.373 \pm 0^h\!.005$ (Silber et al., 1992). This period differs from the spin period of the white dwarf by about 1% (8.5σ) (Mason et al., 1989, hereinafter MLS). The analysis of radial velocities measured from the narrow components of H_β and H_γ confirmed the asynchronous rotation of the white dwarf with respect to the orbital period (Bonnet-Bidaud et al., 1992; Mouchet et al., 1997). BY Cam is a second polar with asynchronous rotation of the white dwarf with respect to the orbital motion. The first polar of this type is V1500 Cyg, (Nova Cygni 1975), in which synchronization of the white dwarf rotation and the orbital motion is expected to occur on a time scale of 200-300 yr (Schmidt & Stockman, 1990; Katz, 1991; Pavlenko & Pel't, 1991). A third object, RX J1940.1-1025, has recently been discovered in which, contrary to the two previous ones, the period derived from radial velocities of the narrow emission line component turned out to be shorter than the spin period of the white dwarf (Friedrich et al., 1996). The time of synchronization of the white dwarf roration with the orbital motion for BY Cam was estimated to be about 1200 years (Piirola et al., 1994). Systems of BY Cam type are important objects for studying the nature of synchronization in polars.

Concurrent spectral and photometric observations are of interest from the point of view of studying the nature of the object. In the paper we present the results of the investigations of the variability of the emission line profiles. Behaviour of equivalent widths W_λ, central intensities R_c, emission line half-widths and radial velocities of the broad components of the hydrogen and HeII 4686 Å lines in respect to the phase of the spin period of the white dwarf and the revealed spectral variability in combination with the photometric variations of the system are analysed. This paper is an extension of the study of this peculiar system (Bonnet-Bidaud et al., 1992; Mouchet et al., 1997).

2. Observations

Simultaneous spectral and photometrical observations of BY Cam were made at the Special Astrophysical Observatory in February 1990 and March 1991. The spectral observations were performed with the 1000-channel TV spectrophotometer (Somova et al., 1982; Drabek et al., 1986; Afanasiev et al., 1991) installed in the secondary focus N1 on the spectrograph SP-124 of the 6 m telescope. Using the diffraction grating B2 (1200 gr/mm, providing a dispersion of 50 Å/mm (1 Å/channel) and a spectral resolution of about 2 Å), we recorded spectra at 3800–4900 ÅÅ on February 25, 1990 and at 4000–5100 ÅÅ on other dates. The wavelength calibration of the spectra was done using a He-Ar-Ne lamp. Depending on the seeing, the diaphragm of the spectrograph was $2''$ and $3''$. The data were registered in a frame-by-frame mode (Somov, 1986).

The photometric measurements were performed with the photometer NEPh installed at the secondary focus N1 (Vikul'ev et al., 1991). When deriving a light curve in the B band with a temporal resolution of 0.1 s, 50 % of the light was recorded with the photometer, while the other half was recorded with a scanner for spectral investigations. The photometer diaphragm was $12''$. The standard star 3C147 F ($13^m\!.8$) was used for the UBVR (Johnson) measurements (Neizvestny, 1995). The log of observations is given in Table 1. To calculate the phases, we used ephemeris (MLS) T(0)=HJD2446586.2559417($\pm$ 0.000001) + 0.1384238O2E($\pm$ 0.00000058) (midpoint of the sharp drop in circular polarization), with the spin period of the white dwarf $3^h\!.322171 \pm 0^h\!.000014$.

A new ephemeris for BY Cam (Piirola et al., 1994) appeared later, T(0)=HJD2446138.8202($\pm$15) + 0.13878415($\pm$14)E (transit of the positive circular polarization), where a new estimate of the spin period of the white dwarf, $3^h\!.3308196 \pm 0^h\!.0000034$, was given. We also use this ephemeris in our further phase computations. The phases calculated from this ephemeris are presented in the text in brackets, following the phases obtained from the ephemeris of Mason et al. (1989).

The processing of the observational data was performed by the standard technique using the programmes written in the algorithmic language SIPRAN (Somov, 1986).

Table 1: *Log of observations*

Date	Spectroscopy Start (UT)	Spectroscopy End (UT)	Photometry Start (UT)	Photometry End (UT)	V
25.02.90	17:39	19:04	17:40	20:46	14.6
	19:51	20:41			
10.03.91	16:32	17:42	16:44	21:10	15.0–15.6
	17:49	18:49			
	18:57	20:01			
	20:05	21:06			
12.03.91	16:39	17:39	16:43	20:13	14.2–14.9
	17:44	18:16			
	18:21	19:33			
	19:38	20:23			

3. Photometry

3.1. Light curves

The photometry results have already been reported in our paper (Mouchet et al., 1997). The system's brightness in the V band for the 3 dates of observations are tabulated in Table 1, from which it can be seen that the system was at high state of brightness, $14\overset{m}{.}2 - 15\overset{m}{.}6$. The light curves in the B band (with a resolution of 25.6 s) for the three above mentioned dates are displayed in Fig. 1. They demonstrate two activity levels of the system. The large variability amplitude of the light curves on February 25, 1990 and March 12, 1991 (Fig. 1a,c) points to the "flaring state" (FS) of BY Cam and on March 10, 1991 (Fig. 1b) the light curve indicates a level of activity close to the "pulsating state" (PS) (Mouchet et al., 1997). These states had been revealed earlier in the X-ray range (Ishida et al., 1991) and in the optical range (Silber et al., 1992). The arrows in Fig. 1 mark the minima of the light curves. The first arrow in Fig. 1a (February 25, 1990) falls at phase $\approx 0.4(0.9)$, i.e. it is located near the possible primary eclipse. In Fig. 1b (March 10, 1991) the arrow (referred as Min II in the following) is close to phase $\approx 1.0(1.5)$.

The first arrow in Fig. 1c is at phase $\approx 0.13(0.63)$, the second at $\approx 0.8(1.3)$, the third at $\approx 1.0(1.5)$ and the fourth at $\approx 1.15(1.65)$. Now in the text we will pay attention to spectral variations near these phases. The time interval between the minima at phases $\approx 0.13(0.63)$ and $\approx 1.15(1.65)$ is 3.3422 hours, which, within our measurement errors, is consistent with the white dwarf spin period measured by Piirola et al. (1994).

3.2. Short-period brightness variations. Search for quasi-periodical oscillations

The flickering had been detected earlier in many AM Herculis type systems. In the similar asynchronous system V 1500 Cyg, Kemp et al. (1977) observed a low-amplitude flickering with a characteristic time of 2 minutes and over 10 minutes. Kaluzny and Chlebowski (1988) noted oscillations in the same system in the B band with an amplitude of about $0\overset{m}{.}2$ and a characteristic time of 4 minutes. Pavlenko (1992) also revealed short-period brightness variations of V 1500 Cyg with periods of 26 minutes and 5 minutes.

We should like to emphasize that for the light curve of March 10, 1991 in the PS of the system the maximum amplitude fluctuations occur at phases 0.9–0.12(1.4–1.7) and 1.35–1.5(1.85–2.0) which are located near the possible eclipses (Min I and Min II). The minimum fluctuations fall within 0.5–0.6(1.0–1.1), 0.8–0.9(1.3–1.4) and 1.75–1.85(2.25–2.35).

Remillard et al. (1986) showed that variations in light curves of BY Cam with a characteristic time of 5 minutes in the optical and X-ray ranges are correlated. As a result of search for periodicity in the light curves in the interval between 6 and 40 minutes, Silber et al. (1997) found variations at 10 and 15 minutes.

We studied quasiperiodic oscillations (QPO) in a number of AM Her systems (Bonnet-Bidaud et al., 1991, 1996; Somova et al., 1992). Fourier analysis of our BY Cam light curves in the B band shows variations on a time scale from a few minutes to tens of minutes. So on March 12, 1991, when the system was in the FS, large-amplitude (up to 50 %) variations in the range of periods 300 to 400 s were observed. The variations occurred at orbital period phases $\phi = 0.1$–$0.4(0.6$–$0.9)$. In the FS of the system on February 25, 1990 oscillations with a period of about 500 s were observed. On February 25, 1990 and March 12, 1991 the variations do not show considerable power excess in the indicated periods. This may suggest that they are not coherent.

An example of the power spectrum of the oscillations in the light curves of BY Cam of March 10, 1991 when it was in the PS is displayed in Fig. 2. A peak

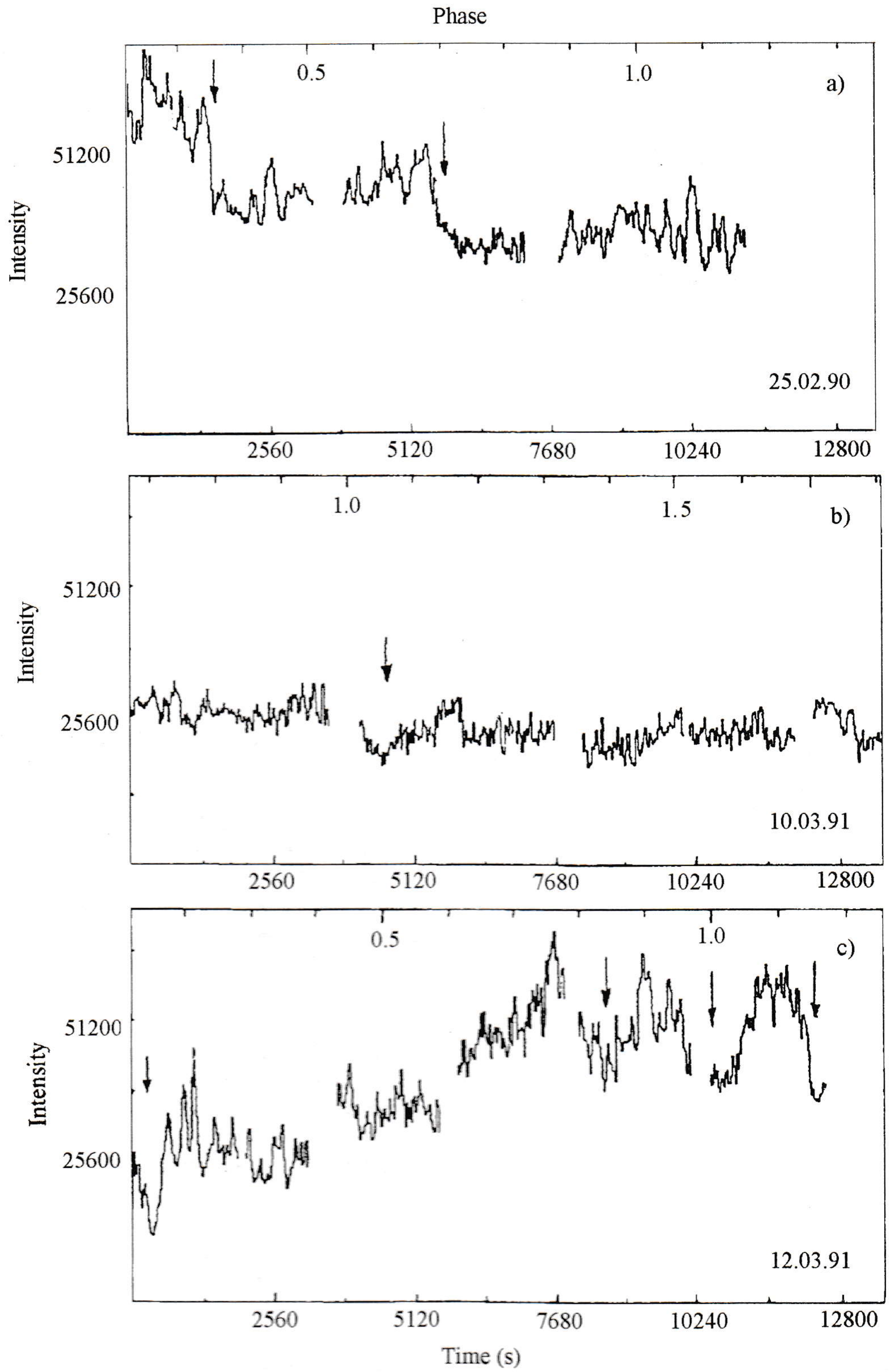

Figure 1: *Light curves of BY Cam in B band for three dates. Phases reported on top of figure are calculated using ephemeris from Mason et al. (1989).*

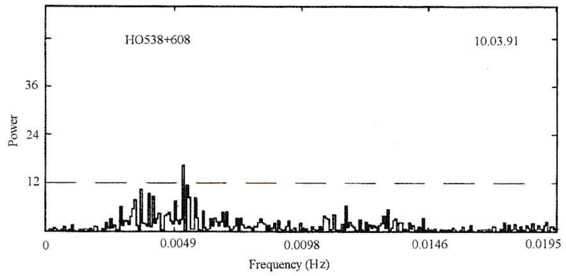

Figure 2: *Power spectrum of the light curve in B band for March 10, 1991. The dashed line indicates the* 6σ *level.*

corresponding to 3-minute quasiperiodic oscillations is visible. On March 12, 1991 QPO with an amplitude up to 40% and characteristic time of about 30 min were observed at phases $\phi = 0.7$–$1.1(1.2$–$1.6)$. Similar quasiperiodic oscillations were, apparently, observed by Silber et al. (1992) and Pavlenko et al. (1996).

4. Spectroscopy

4.1. Long term variability

The general view of the integral spectrum of BY Cam of February 25, 1990 is shown in Fig. 3. The spectrum is seen to be represented (as is the case with polars in a high state of brightness) by emission lines of hydrogen, HeII 4686 Å and HeII 4541 Å, the lines of HeI, and the blend CIII-NIII 4640–4650 Å. In Table 2 are listed the mean values of equivalent widths W_λ, central relative intensities R_c, half-widths (FWHM) of February 25, 1990, March 10, 1991, and March 12, 1991 derived from a set of these parameters from 5-minute spectra. The root-mean-square deviations from the mean value per night are given in brackets.

The nightly mean W_λ of HeII 4686 Å in the FS, i.e. on February 25, 1990 and March 12, 1991, are (Table 2) 43 Å and 46 Å, respectively, which is about 1.5 times as high as in the PS on March 10, 1991 (31 Å). This is an interesting long term variation.

It can be seen from Table 2 that the mean equivalent widths of the Balmer lines H_β and H_γ change from date to date, which is, in our opinion, also a remarkable long term variability. For the spectra acquired on March, 1991 the H_β/H_γ equivalent width ratio is higher than on February, 1990. The Balmer lines at the bases in the spectra of BY Cam turned out to be broader than in a number of other polars. The width varies with orbital period phase from 2500 to 3500 km/s. In contrast to the Balmer lines, the HeII 4686 Å line width at the base changes from 1500 to 2500 km/s depending on the spin period phase.

4.2. Line profiles

From the frame-by-frame records spectra with an exposure of 300 s each were formed. 26 spectra were taken on February 25, 1990, 50 on March 10, 1991 and 41 spectra on March 12, 1991. All these data are uniform in the way of recording and processing.

The H_β, H_γ and HeII 4686 Å emission line profiles reduced and normalized to the continuum according to the MSL spin period phase of the white dwarf on February 25, 1990 are presented in Fig. 4a. Fig. 4b shows the profiles of H_γ, HeI 4471 Å, HeII 4686 Å and H_β of March 10, 1991. The profiles of the same lines of March 12, 1991 are displayed in Fig. 4c. It can be seen from the figures that these 5-minute profiles demonstrate strong variations and the presence of several components in both the Balmer and the helium lines. From Fig. 4a, b, c an obvious variability of line profiles depending on the phase of the white dwarf axial rotation period of each date can be seen and strong variations from date to date are detected.

We pay special attention to the variation of the line profiles around the minimum on March 10, 1991, when the system was pulsating. It is clear from Fig. 4b that the Balmer line profiles in the PS become low-contrast for 20 minutes at phases 1.01–1.08(1.51–1.58). The same situation is observed for HeI 4471 Å at phases 1.03–1.08(1.53–1.58) for 15 minutes, while for HeII 4686 Å at phase 1.03(1.53) this state lasts for about 5 minutes. This implies that the time of the possible eclipse of the regions where the emission peaks for different lines in the PS form is different: from 5 minutes for HeII 4686 Å to 20 minutes for Balmer lines.

It is illustrated in Fig. 4c that on March 12, 1991 the Balmer lines HeI 4471 Å and HeII 4686 Å were weak for 5 minutes at phase 0.127(0.627). At phase 1.152(1.652) the emission lines are also seen to reduce in intensity, and shifted by 0.025 in phase. A sudden broadening of H_γ occurred at phase 1.127(1.63). This is well visible in Figs. 4c and 5i.

The 5-minute weakening in brightness on March 12, 1991 at phases $\approx 0.13(0.63)$ and $\approx 1.15(1.65)$ (Fig. 1c) is coincident in phase with the above mentioned changes in the spectra of BY Cam. Such a behaviour of the line profiles gives ground to believe that there occur possible secondary eclipses at these phases. An analysis of the behaviour of the H_β and HeII 4686 Å line profiles in the spectra of BY Cam with a resolution of 500 s is available in the paper by Mouchet et al. (1997).

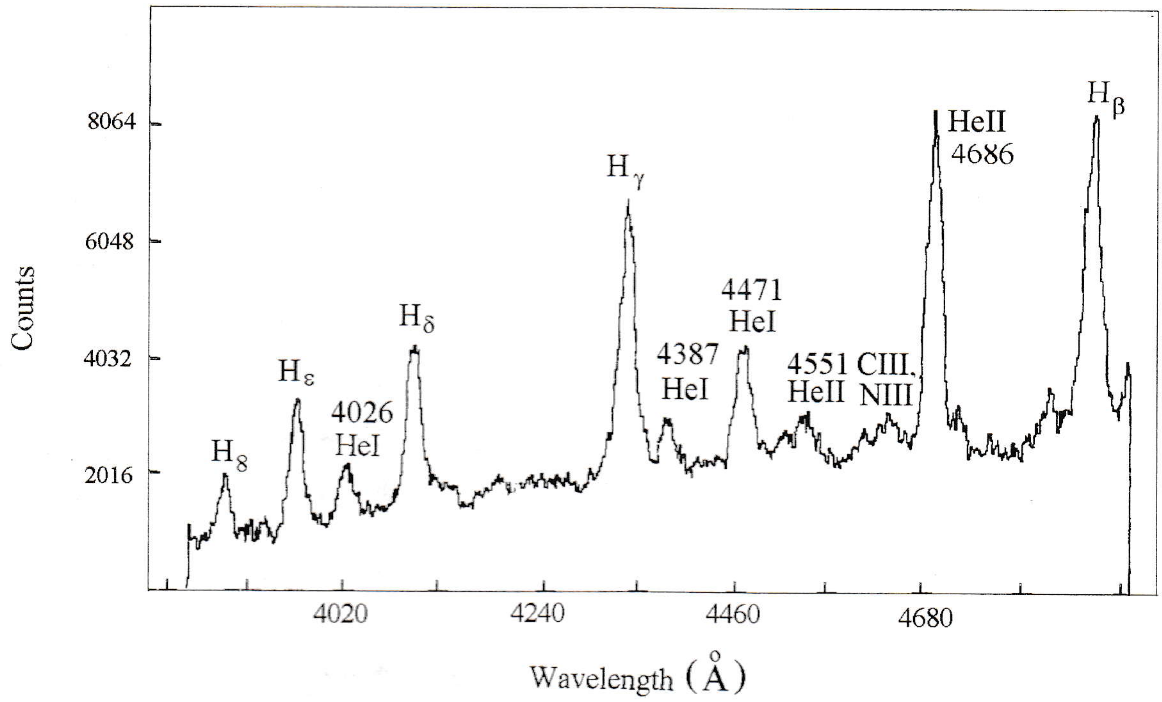

Figure 3: *The integral spectrum of BY Cam, obtained on February 25, 1990. The exposure time was 10928 s.*

Table 2: *Mean spectrophotometric parameters of emission lines*

Date	Line	EW (Å)	R_c	FWHM (Å)
25.02.90	$H\beta$	31.7 (9.2)	1.6 (0.5)	18.3 (5.4)
	$H\gamma$	52.5 (8.7)	2.4 (0.5)	20.5 (2.8)
	$H\delta$	33.4 (6.2)	2.0 (0.4)	17.1 (4.0)
	HeII 4686Å	42.8 (9.2)	2.4 (0.6)	18.6 (3.6)
	HeI 4471Å	22.1 (4.6)	1.2 (0.3)	18.7 (4.9)
10.03.91	$H\beta$	45.8(17.9)	2.62(1.1)	16.75(6.5)
	$H\gamma$	41.2(15.2)	2.57(1.0)	14.62(4.5)
	HeII4686	31.5(10.9)	2.44(1.2)	12.32(4.3)
	HeI4471	19.1 (6.7)	1.4(0.5)	12.7(5.2)
12.03.91	$H\beta$	44.9 (16.4)	3.1 (1.2)	12.8(4.2)
	$H\gamma$	40.2 (11.1)	2.9 (0.9)	13.1(3.5)
	HeII4686	46.2 (17.4)	4.1 (1.6)	10.5(2.7)
	HeI4471	17.6 (8.4)	1.6 (0.6)	11.4(4.0)

4.3. Phase variations of equivalent widths, central intensities and half-widths of emission lines

The present paper contains the results of investigation into the behaviour of spectrophotometric parameters of the Balmer lines, HeII 4686 Å and HeI 4471 Å without dividing them into components. We have measured their equivalent widths W_λ, central intensities and FWHM. The measurement techniques were described earlier by Kopylov et al. (1986). Typical errors in the determination of emission line parameters are presented therein too. The equivalent width measurement errors for lines with $W_\lambda \approx 20$ Å are $\approx 5\,\%$, for central intensities $\approx 5\,\%$ and for half-widths $\approx 4\,\%$. This implies that the measurement errors do not exceed the size of the symbol these parameters are labeled by in the figures.

In Fig. 5 we present the variation curves of W_λ, R_c and FWHM for the Balmer lines, HeI 4471 Å and HeII 4686 Å, depending on the phase of the white dwarf spin period of February 25, 1990 (Fig. 5a,b,c),

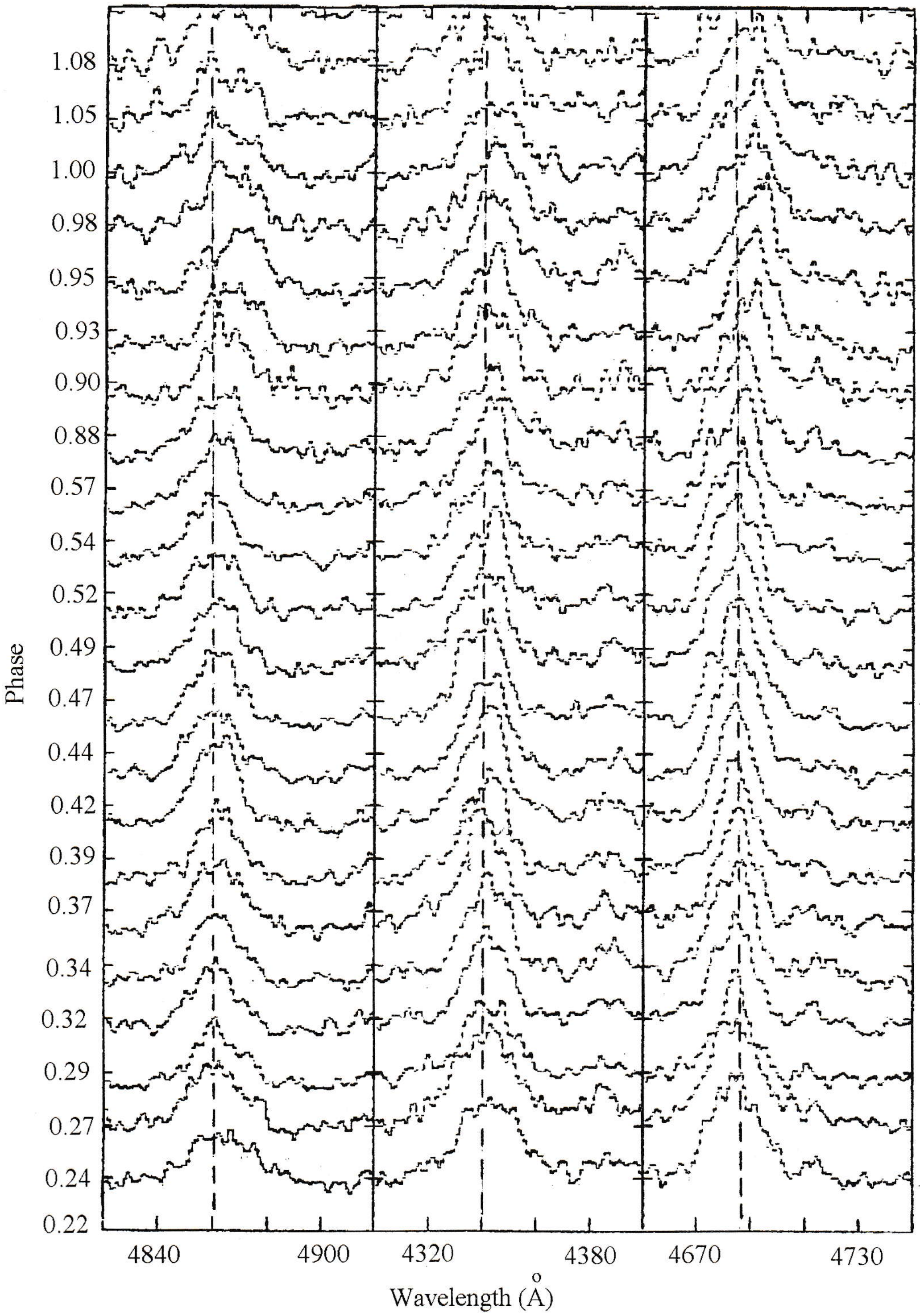

Figure 4: *a. Normalized to the continuum* Hβ, Hγ *and HeII 4686 Å profiles, obtained on February 25, 1990. The phases were calculated using the ephemeris from Mason et al. (1989). They are shown at the Y axis. The dashed line indicates the laboratory position of the wavelengths for these lines. One wavelength scale unit has 20 Å.*

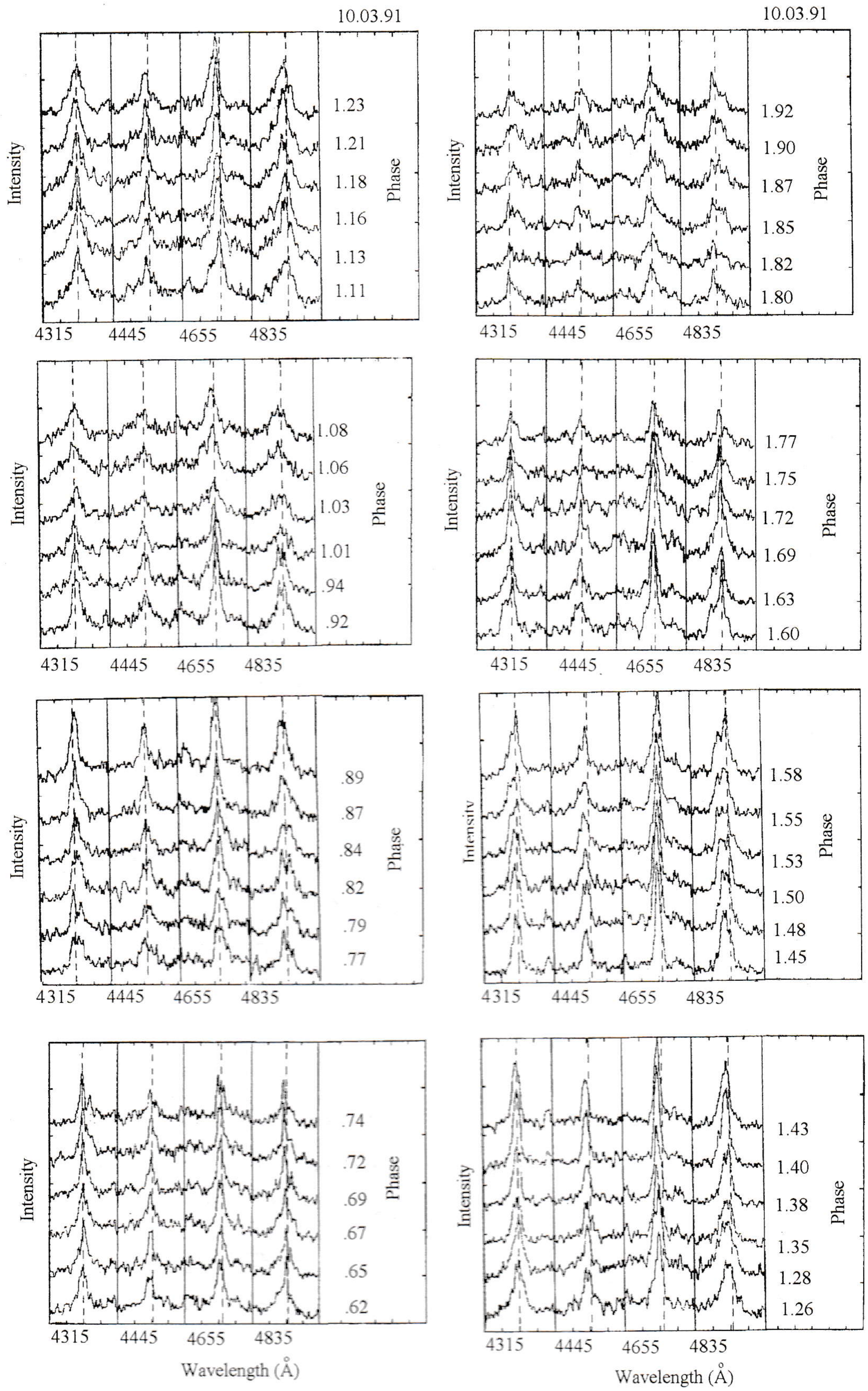

Figure 4: *b-c. Normalized to the continuum* Hγ, *HeI 4471Å, HeII 4686 Å and* Hβ *profiles for March 10 and 12 1991, respectively. Phases are represented right at the Y axis from the bottom upwords. The dashed lines show the laboratory wavelengths for these lines. One wavelength scale unit has 20 Å.*

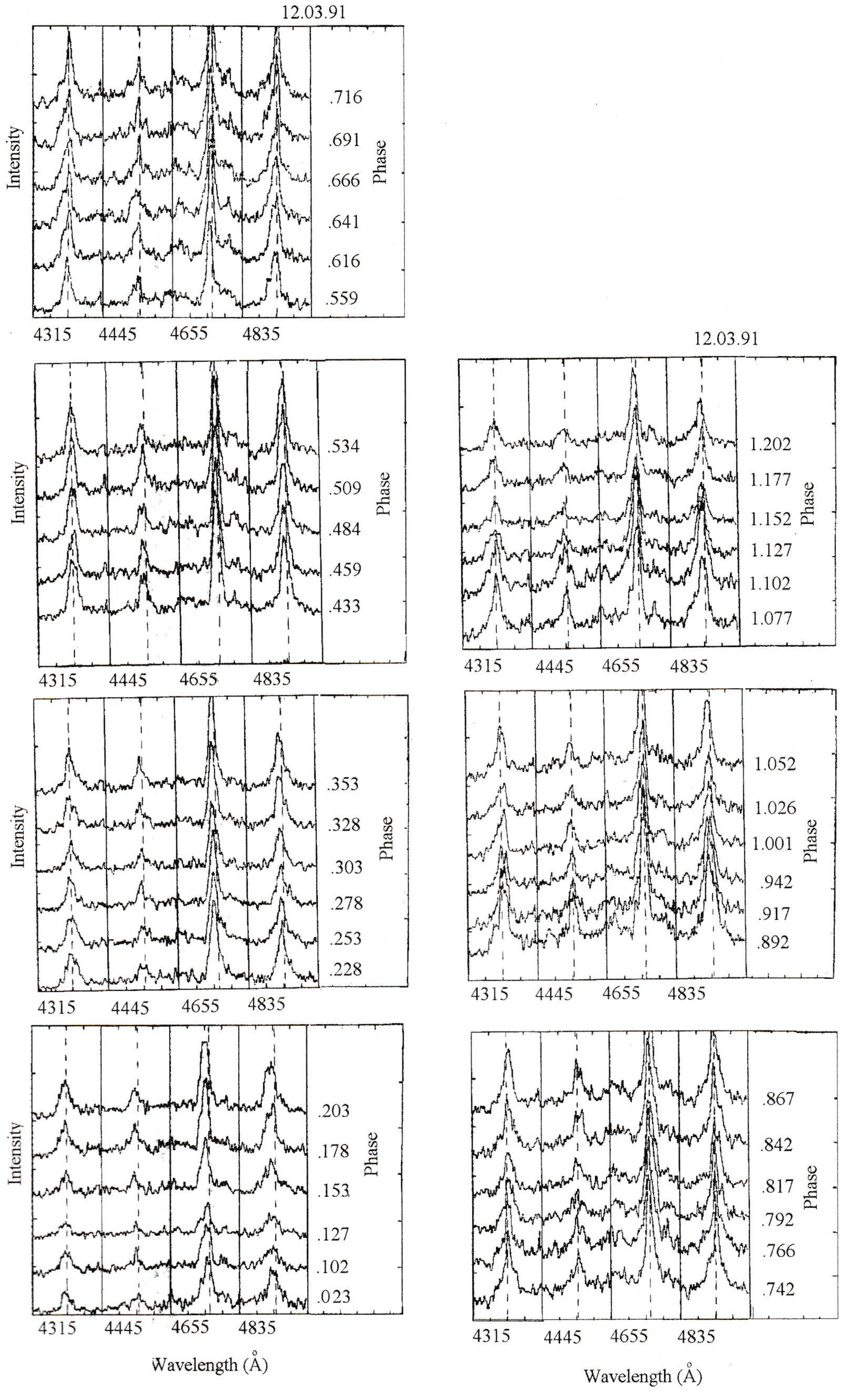
12.03.91
Intensity
Phase
.716
.691
.666
.641
.616
.559
4315 4445 4655 4835
.534
.509
.484
.459
.433
4315 4445 4655 4835
.353
.328
.303
.278
.253
.228
4315 4445 4655 4835
.203
.178
.153
.127
.102
.023
4315 4445 4655 4835
Wavelength (Å)
12.03.91
1.202
1.177
1.152
1.127
1.102
1.077
4315 4445 4655 4835
1.052
1.026
1.001
.942
.917
.892
4315 4445 4655 4835
.867
.842
.817
.792
.766
.742
4315 4445 4655 4835
Wavelength (Å)

Figure 4: *c*.

March 10, 1991 (Fig. 5d,e,f), and March 12, 1991 (Fig. 5g,h,i). It can be seen from the figures that the parameters change their values depending on the phase. The curves look different for different dates.

On February 25, 1990, for instance, the maxima in the curves $W_\lambda - \phi$, $R_c - \phi$ for all the lines in the FS fall at phase $\approx 0.4(0.9)$ (Fig. 5a,b). This coincides with the phase of the first minimum in the light curve of this date (Fig. 1a).

In the PS of the system on March 10, 1991 the maxima of the curves $W_\lambda - \phi$, $R_c - \phi$ for the Balmer lines are at phase $\approx$ 1.4(1.9) (Fig. 5 d, e). The extremum in the curve $W_\lambda - \phi$ for HeII 4686 Å on the same date is somewhat shifted towards phases 1.45–1.5(1.25–2.0) as compared to the Balmer lines, while the peak in the R_c curve falls at phase 1.45(1.95) and is located near the main minimum (Min I). When looking at the light curve of this date (Fig. 1b), one can see that expected weakening in the object's brightness at Min I is absent. Similar results derived in November 1990 were given by Piirola et al. (1994).

On March 12, 1991 the maximum of the curves $W_\lambda - \phi$ and $R_c - \phi$ for the Balmer lines, HeI 4471 Å and HeII 4686 Å moved to phase $\approx$ 0.3(0.8). Great differences in the shape of the curves from night to night are visible.

Fig. 5 (c,f,i) shows the behaviour of the half-widths of the lines H_β, H_γ, H_δ, HeII 4686 Å and HeI 4471 Å of February 25, 1990; H_β, H_γ and HeII 4686 Å of March 10, 1991; and for the same lines of March 12, 1991 versus the spin period of the white dwarf.

It follows from Fig. 5f that the maxima of the H_β and H_γ Balmer line half-widths in the PS on March 10, 1991 are visible at intervals of a quarter of the spin period of the white dwarf, the half-width maximum of the line H_β being at phases $\approx$ 0.8(1.3), 1.0(1.5), 1.25(1.75), 1.5(2.0), 1.85(2.35). The behaviour of the H_γ line half-width is basically correlated with that of H_β, some differences can, however, be seen (Fig. 5f).

Half-widths of H_β and H_γ lines of March 12, 1991 and February 25, 1990 obtained in the FS differ from those obtained in the PS and there is no recurrence of their behaviour from date to date (Fig. 5 i, c).

The phase dependence of the HeII 4686 Å line half-width variations on March 10 suggests that its behaviour is clearly different from those of the Balmer lines. It can be seen from Fig. 5f that the maxima of its half-widths fall at phases 1.05(1.55) and 1.9(2.4). Its half-widths of March 12 in the FS behave somewhat different (Fig. 5i) than those of March 10 in the PS (Fig. 5f). The maxima of its half-width of March 10 in the PS are at $\approx$ 0.1(0.6) and 0.8(1.3). Attention is attracted by the weakening of the half-widths of H_β, H_γ and HeII 4686 Å on March 12 near phases 0.7–0.75(1.2–1.25) when all the lines become the most narrow. In the March 12 light curve (Fig. 1c) near phase 0.85(1.35) we see a minimum. These spectral and photometric changes are likely to be interrelated.

4.4. Emission line radial velocities

The true location of emission line forming regions in polars has thus far been a subject of discussions. It has been shown in the papers of many authors that the narrow peak and broad line represent different regions. The broad line component is deemed to be formed in the accretion column region and therefore represents rotation of the white dwarf, while the narrow peak may arise on the red dwarf side facing the white dwarf as a consequence of X-ray heating and hence represents the orbital period of the system.

Emission lines in the BY Cam spectrum have a more complex structure as compared with other polars. In (MLS) the spectra of BY Cam were obtained during one orbital cycle. The authors detected as many as four components (narrow, broad, high-velocity and asymmetric) in the H_β and H_γ emission line profiles. Silber et al. (1992) studied the H_α line for 6 nights and showed that the profiles of this line are chiefly composed of two components.

The complex and variable line profiles in BY Cam make analysis of radial velocities rather complicated. In the given paper radial velocities are measured from the centre of gravity and line peak. The resultant accuracy of radial velocity determination is ±25 km/s. For weak lines this error may be twice as high. The data obtained were approximated by the least-squares fit of the curve

$$V(\phi) = K \sin(2\pi(\phi - \phi_0)) + \gamma, \tag{1}$$

where V is the radial velocity, γ is the gamma velocity, ϕ is the white dwarf spin period phase (MLS ephemeris), K is the half-amplitude of the radial velocity curve. The measurements of radial velocity parameters for a number of emission lines in the spectrum of BY Cam are listed in Table 3, as well as the parameter errors, given in brackets. Also in this table, the σ parameter is equal to the root-mean-square deviations (km/s) of all measurements from a sinusoid. In the separate column of the table, the way of emission line radial velocity measurement is indicated: CGR — from the centre of gravity of a line, PIC — from the line peak. It can be seen from Table 3 that on February 25 HeII 4686 Å has minimum departure from the sinusoid. For illustration we display in Fig. 6 the radial velocity curves for this line measured from the line peak and the centre of gravity on this date. It is seen that the radial velocity curves of the narrow and broad components are practically in phase but have different amplitudes and gamma velocities.

The March 10 and 12 radial velocity curves measured for H_β, H_γ and HeII 4686 Å from the centre

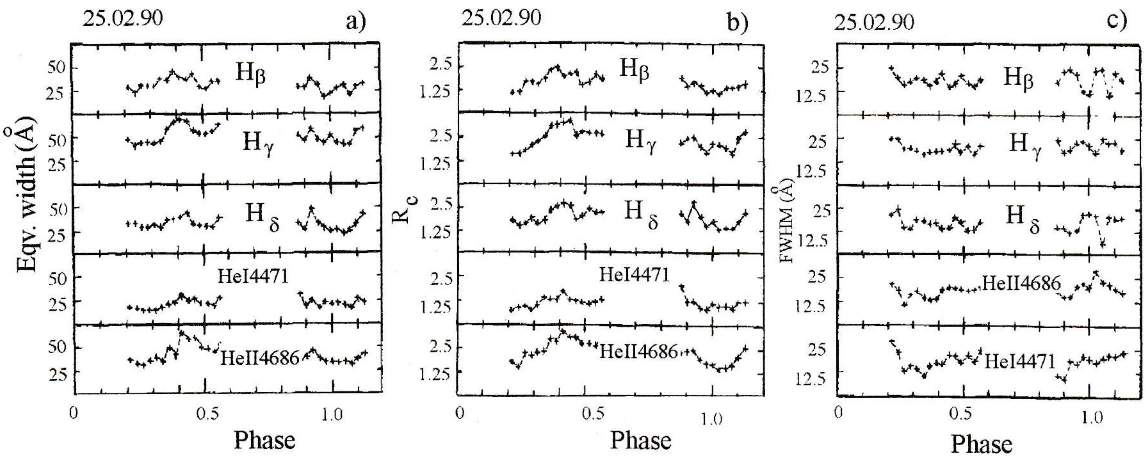

Figure 5: *Curves of spectrophotometric parameters of emission lines: equivalent widths W_λ, relative intensities R_c, and FWHM over the rotation period of the white dwarf are presented. The phases were calculated using the ephemeris from Mason et al. (1989). a–c — for February 25, 1990; d–f — for March 10, 1991. In Fig. 5f the scale for* Hβ *is given on the right; g–i — for March 12, 1991.*

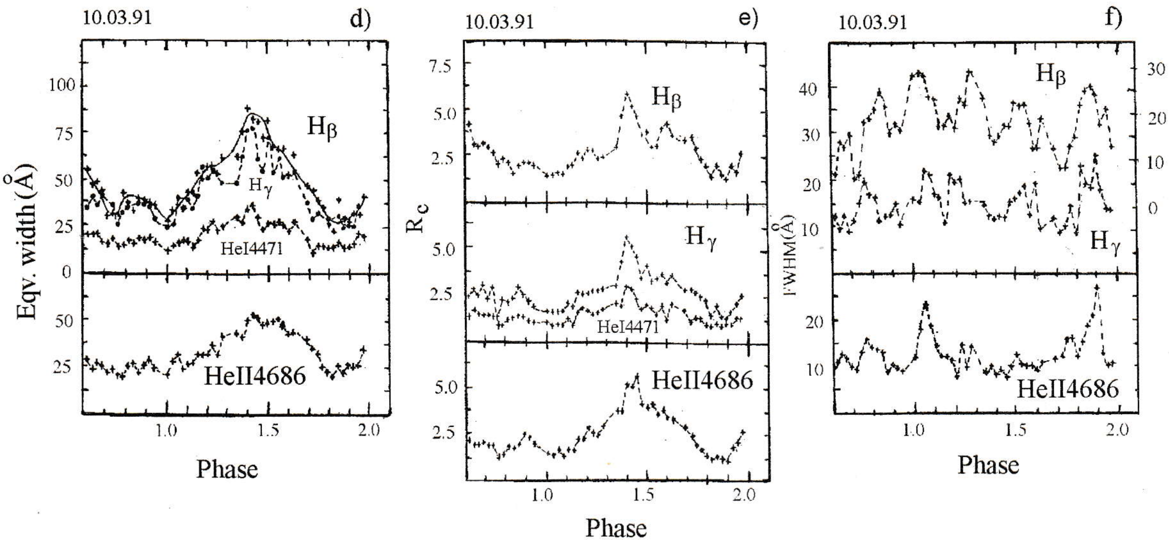

Figure 5: *d–f.*

of gravity are shown in Fig. 7 a–i. The sinusoid fit of the radial velocity measurements on March 10 is shown in Fig. 7 d, e, f and Table 3. Fig. 7 e, f shows that at phases 1.1–1.5 (1.6–2.0) there are deviations from the sinusoid. These deviations are best seen in the radial velocity curves of March 12, when the system was in the FS. They are visible at phases 0.1–0.55 (0.6–1.5) for H$_\beta$ (Fig. 7 i) and 0.1–0.65 (0.6–1.15) for H$_\gamma$ (Fig. 7 h).

The sinusoid fit of the radial velocity measurements for Balmer lines on March 12 gave the largest errors for the three dates of observations, so we do not present them in the table. The radial velocity curves measured from the broad components of the Balmer lines on March 12 (Fig. 7 h, i) are similar to those derived by Silber et al. (1992) in the FS.

The radial velocity curves derived from the broad components of the HeII 4686 Å and Balmer lines of March 10 in the PS were also sinusoid fitted by the least-squares method (Fig. 7 d, e, f). They showed a considerable departure from the sinusoid (by about a factor of 1.4) with respect to the half-amplitude of the sinusoid at phases 1.8–1.9 (2.3–2.4).

It is seen from Figs. 6 and 7 as well as from Table 3 that the parameters of HeII 4686 Å radial velocity curves differ from those of the Balmer lines.

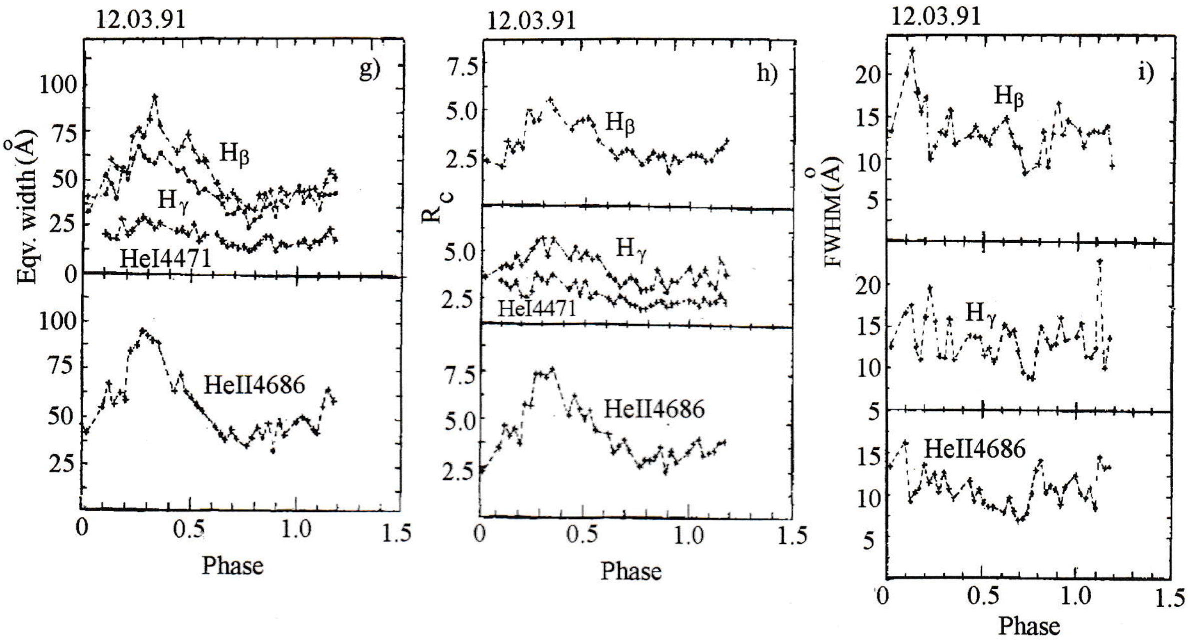

Figure 5: *g–i.*

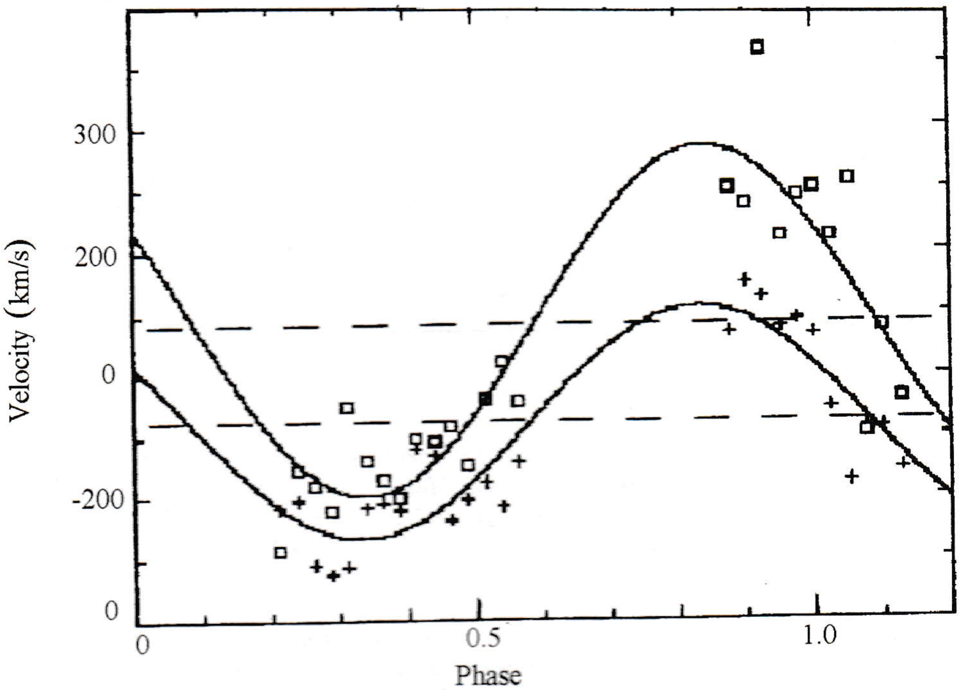

Figure 6: *Radial velocity curves for different components of HeII 4686 Å for the February 25, 1990. (+ – measured from the centre of gravity, □ – from the line peak). The dashed lines show γ-velocities for the radial velocity curve measured from the line peak and centre of gravity. The phases were calculated using the ephemeris from Mason et al. (1989). The parameters of radial velocity curves are given in Table 3.*

Table 3: *Parameters of radial velocity curves*

Line	Method	$K(km/s)$	$\gamma(km/s)$	ϕ_0	$\sigma(km/s)$
25.02.90					
$H\beta + H\gamma$	CGR	93(18)	-82(16)	0.66(0.03)	79
$H\beta$	-"-	103(24)	-77(22)	0.67(0.04)	108
$H\gamma$	-"-	83(23)	-86(20)	0.65(0.04)	101
$H\delta$	-"-	78(29)	-111(26)	0.68(0.06)	128
HeII 4686	-"-	188(14)	-76(11)	0.58(0.01)	57
HeI 4471	-"-	122(21)	-32(19)	0.71(0.03)	94
HeII 4686	PIC	283(22)	87(18)	0.59(0.01)	88
10.03.91					
$H\beta$	CGR	227(21)	-48(17)	0.60(0.01)	85
$H\gamma$	-"-	281(20)	79(17)	0.62(0.01)	82
HeII 4686	-"-	327(29)	-46(24)	0.56(0.01)	118
HeI4471	-"-	230(26)	5(21)	0.63(0.02)	105
HeII 4686	PIC	204(24)	-36(20)	0.62(0.02)	98

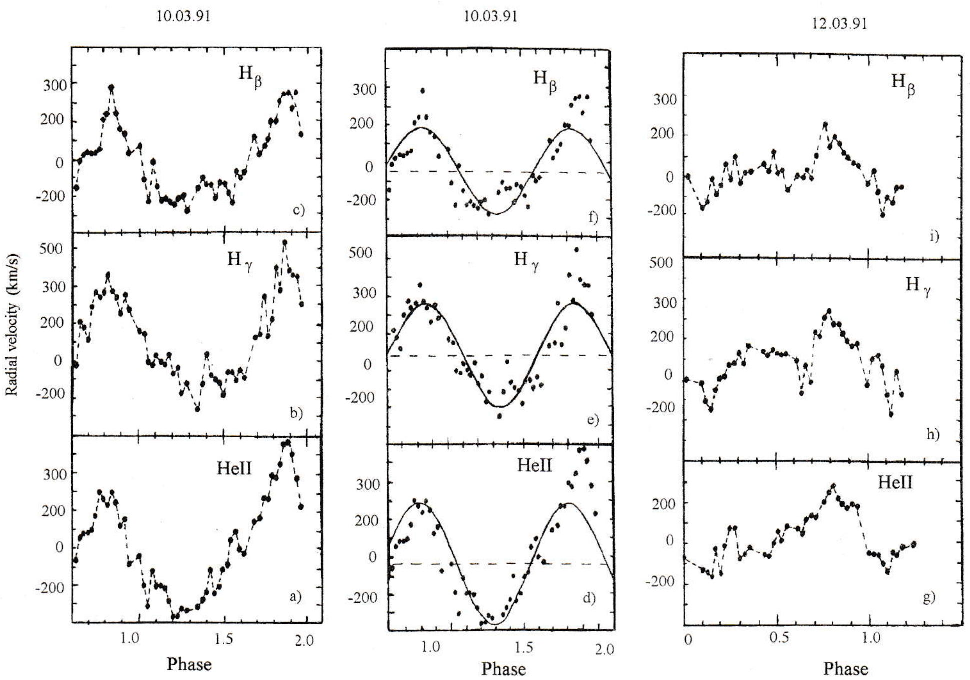

Figure 7: *a-i. Radial velocity curves measured from the broad components of Balmer lines and HeII 4686 Å line. The phases are calculated from the ephemeris from Mason et al. (1989). Left: a) for HeII 4686 Å; b) for* Hγ*; c) for* Hβ*, for March 10, 1991. Middle: d) for HeII 4686 Å; e) for* Hγ*; f) for* Hβ*, for March 10, 1991. The curve parameters are given in Table 3. Right: g) for HeII 4686 Å; h) for* Hγ*; i) for* Hβ*, for March 12, 1991.*

Measurements of radial velocities of different components of the H_β and HeII 4686 Å in BY Cam spectra through fitting by Gaussian (up to 3) are presented in the paper by Mouchet et al. (1997).

5. Discussion

5.1. Beat period of the system

Though the spin and orbital periods of BY Cam are not yet accurately determined (Mouchet et al. 1997), the asynchronism of this system is well established. Using the value of the spin period of the white dwarf in BY Cam obtained by Piirola et al. (1994), we calculated the beat period P_3 on the basis of the relationship

$$P_1{}^{-1} - P_2{}^{-1} = P_3{}^{-1},$$

where P_1 is the polarimetric period (or the spin period of the white dwarf); P_2 is the orbital period of the system. Taking that $P_1 = 3^{\rm h}.33088196$ (Piirola et al., 1994) and $P_2 = 3^{\rm h}.3817$ (Mouchet et al., 1997), $P_3 = 9^{\rm d}.55$. With $P_2 = 3^{\rm h}.3558$ (Zucker et al., 1995) the third period of the system is 21 days. This implies that the value of the beat period is strongly dependent on the orbital period. The matter of accurate determination of the orbital and beat periods for the asynchronous polar BY Cam is still open to question, and the problem is likely to be resolved by new observations covering no less than one beat period.

In a long observing run, lasting for 66 days, a period of 7 days was found (Silber, 1995), and a period of 14 days was suggested by Mason et al. (1995a,b). From the results of ultraviolet spectral observations a period of 14.5±1.5 days was suggested (Mouchet et al., 1997). To determine particularly the beat period of BY Cam, 40–night observations were conducted (Silber et al., 1997). The authors found a period of 7.24 days in the light curves, which is, apparently, half of the beat period. The set of data presented here clearly indicate changes in the accretion geometry very probably related to the beat period, however the time sampling of the observations does not allow to confirm such effect.

5.2. Spectral and photometric variability

Our concurrent spectral and photometric studies have shown BY Cam to be far from being a stationary object. This follows from the B-band light curves (Fig. 1), from the analysis of the emission line profiles in the spectra with a sufficiently high temporal resolution (300 s) (Fig. 4 a, b, c), from the radial velocity measurement data (Fig. 7) and spectrophotometric parameters of emission lines (Fig. 5).

In the X-rays, BY Cam demonstrates a non-typical behaviour with two alternate states:

- pulsating state with short-period variation of brightness, the period is equal to the spin period of the white dwarf;
- flaring state with aperiodic variations in light curves.

Such a behaviour of the system is interpreted by changes in the accretion geometry (Ishida et al., 1991). It follows from the results of our spectral and photometric observations that we observed this polar in two states: flaring on February 25, 1990 and March 12, 1991; and pulsating on March 10, 1991. The fast spectroscopy results point to the fact the accretion geometry is likely to change in this system on a time scale of 20–40 minutes in the pulsating state. This is inferred from the behaviour of the radial velocity curves of the broad components of the HeII 4686 Å and Balmer lines (Fig. 7 d, e, f), where strong (up to 1.4 times) variations in the half-amplitude are observed at phases 1.8–1.9 (2.3–2.4).

The departures from a sinusoid are similar to those visible in the radial velocity curves measured from the broad components of the Balmer lines on March 12, 1991 in the flaring state (Fig. 7). They were also found in the radial velocity curves for the asynchronous system V 1500 Cyg (Kaluzny & Chlebowski, 1988). The authors explain these departures as due to the presence of two-pole accretion in the system.

We have shown that W_λ of the HeII 4686 Å line in our observations is, on average, by a factor of 1.5 larger in the flaring than in the pulsating state. It may be assumed that in the FS, when, as follows from the photometry results, the brightness of BY Cam becomes higher than in the PS (see Table 1), the enhancement of brightness and increase in the equivalent widths and central intensities of the HeII 4686 Å lines may be due to changes in the visibility of the accretion regions.

From quantitative analysis of our spectral and photometric data for BY Cam, significant changes in W_λ, R_c, FWHM and V_r on a time scale of 5–20 minutes have been revealed. Variations in light curves on a shorter time scale (1–3 minutes) in the B band have been found, which follows from the results of our investigations and the paper of Mouchet et al. (1997).

From the data of Ferrario et al. (1989), Ferrario and Wickramasinghe (1990), Somova and Somov (1992), in polars, for the case of one-pole accretion the broad emission line half-widths have been found to vary with orbital period phase, there being two maxima in the phase curves for most geometrical configurations. It is inferred from the analysis of half-widths in the case of BY Cam that accretion of matter occurs in a more intricate manner. The difference between the white dwarf spin period and the orbital period of the system causes "switching" of accretion from one pole to the other (Mouchet et al., 1997). The possibility of two-pole accretion in this system was also discussed earlier (MLS).

The geometry of the accretion stream and shock in the binary system BY Cam must change during a period equal to the beat cycle between the spin period of the white dwarf and the orbital period. This may cause chaotic photometric and spectral variations similar to those found in the Nova 1975 V 1500 Cyg (Stockman et al., 1988).

The average half-width of the emission Balmer lines on March 12, 1991 turned out to be the smallest, about 850 km/s, whereas on March 10, 1991 and on February 25, 1990 it was about 1000 km/s and 1300 km/s, respectively. The average half-width of HeII 4686 Å was smaller than that of the Balmer lines and was equal to ≈650 km/s, ≈760 km/s and ≈1200 km/s on the same dates.

The spectral line profile differences on different dates may be due to accretion gas stream variations caused by the difference between the white dwarf spin period and the orbital period of the system. Emission line profiles, spectrophotometric parameters of these lines, radial velocity curves and light curves of BY Cam show variability according to the phase of the spin period of the white dwarf and obviously from date to date. This may be related to the changes in the accretion structure at different orientations of the magnetic field of the white dwarf. The influence of the magnetic field orientation in a dipole on the accretion rate in close binary systems was discussed by Andronov (1984).

6. Conclusions

Results of the work done are as follows.

- There are considerable variations of spectrophotometric parameters of the Balmer and helium lines depending on the spin period of the white dwarf and from night to night. Phases have been isolated, 0.3–0.5 (0.8–1.0), which the maxima of equivalent widths and central intensities fall at.
- The equivalent width of the HeII 4686 Å line turn out to be on the average by a factor of 1.5 larger in the flaring state than in the pulsating state of the system.
- During the pulsating state the narrow components of the emission lines have been revealed to disappear short time around a minimum brightness phase, whose durations amount to 20 minutes for the Balmer lines, 15 minutes for HeI 4471 Å and 5 minutes for HeII 4686 Å.
- The half-widths of the Balmer lines in the pulsating state vary with a quasiperiod which is approximately equal to a quarter of the white dwarf spin period, which is not observed in the flaring state.
- The radial velocity curves measured from the broad components of the emission lines HeII 4686 Å, H_β, H_γ in the pulsating state show considerable departures from a sinusoid, which are about 1.4 times as high as those of the half-amplitude of the sinusoid at phases 1.8–1.9 (2.3–2.4) during the pulsating state. The observed variability may be indicative of changes in the geometry of accretion on a time scale of 20–40 minutes.

The results obtained may further be used for modelling the structure of accretion in BY Cam.

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References

Afanasiev V.L., Lipovetsky V.A., Mikhailov V.P., Nazarov E. Shapovalova A.I., 1991, Astrofiz. Issled. (Izv. SAO), **31**, 128

Andronov I.L., 1984, Astrofizika, **20**, 165

Andronov I.L., Kolesnikov S. V., Pavlenko E. P., Shakhovskoj N.M., 1992, in: Stellar magnetism, Proceed. of Intern. Meeting, eds.: Yu.V. Glagolevskij, I.I. Romanyuk, S.Petersburg, 158

Bonnet–Bidaud J.M., Mouchet M., 1987, Astron. Astrophys., **188**, 89

Bonnet–Bidaud J.M., Mouchet M., Somov N.N., Somova T.A., 1992, in: Stellar magnetism, Proceed. of Intern. Meeting, eds.: Yu.V. Glagolevskij, I.I. Romanyuk, S.Petersburg, 186

Bonnet-Bidaud J.M., Somova T.A., Somov N.N., 1991, Astron. Astrophys., **251**, L27

Bonnet-Bidaud J.M., Mouchet M., Somova T.A., Somov N.N., 1996, Astron. Astrophys., **306**, 199

Cropper M., Mason K.O., Allington–Smith J.R., Branduardi–Raymont G., Charles P. A., Mittaz J. P. D., Mukai K., Murdin P.G., and Smale A.P., 1989, Mon. Not. R. Astron. Soc., **236**, 29

Cropper M., 1990, Space Sci. Rev., **54**, 195

Drabek S.V., Kopylov I.M., Somov N.N., Somova T.A., 1986, Astrofiz. Issled. (Izv. SAO), **22**, 64

Ferrario L., Wickramasinghe D.T., Tuohy I.R., 1989, Astrophys. J., **341**, 327

Ferrario L., Wickramasinghe D.T., 1990, Astrophys. J., **357**, 582

Forman W., Jones C., Cominsky L., Julien P., Murray S., Peters G., Tananbaum H., Giacconi R., 1978, Astrophys. J. Suppl. Ser., **38**, 357

Friedrich S., Staubert R., Lamer G. et al., 1996, Astron. Astrophys., **306**, 860

Ishida M., Silber A., Bradt H.V., Remillard K., Makishima K., Ohashi T., 1991, Astrophys. J., **367**, 270

Kaluzny J., Chlebowski T., 1988, Astrophys. J., **332**, 287

Kallman T.R., Schlegel E.M., Serlemitsos P.J., Petre R., Marshall F., Jahoda K., Boldt E.A., Holt S.S., Mushotzky R.F., Swank J., Szymkowiak A.E., Kelley R.L., Smale A., Arnaud K., Weaver K., Paerels F.B., 1993, Astrophys. J., **411**, 869

Katz J.I., 1991, Astrophys. J., **374**, L59

Kemp J.C., Sykes M.V., Richard J.R., 1977, Astrophys. J., **211**, 71

Kopylov I.M., Somov N.N., Somova T.A., 1986, Astrofiz. Issled. (Izv. SAO), **22**, 77

Kopylov I.M., Somov N.N., Somova T.A., 1991, Astrofiz. Issled. (Izv. SAO), **31**, 15

Liebert J., Stockman H.S., 1985, In: Cataclysmic Variables and Low Mass X–ray Binaries, ed.: D.Q. Lamb & J. Patterson, Reidel, Dordrecht, 151

Mason P.A., Liebert J.W., Schmidt G.D., 1987, Inf. Bull. Var. Stars, No. **3104**, 1

Mason P.A., Liebert J., Schmidt G.D., 1989, Astrophys. J., **346**, 941 (MLS)

Mason P.A., Chanmugam G., Andronov I.L. et al., 1995a, in: Cataclysmic Variables, Eds.: A. Bianchini, M. Della Valle & M. Orio, Kluwer Academic Publishers, 426

Mason P.A., Andronov I.L., Kolesnikov S.V., Pavlenko E.P., Shakhovskoj N.M., 1995b, in: Proceed. of the Cape Workshop on Magnetic Cataclysmic Variables, eds.: D.A.H. Buckley and B. Warner, A.S.P. Conf. Ser., **85**, 496

Mason P.A., Fisher P.L., Chanmugam G., 1996, Astron.

Astrophys., **310**, 132
Mouchet M., Bonnet–Bidaud J.M., Hameury J.M., 1991, 11th North American Workshop on CVs and LMXBs, ed.: C.W. Mauche, Cambridge University Press, 247
Mouchet M., Bonnet–Bidaud J.M., Somov N.N., Somova T.A., 1997, Astron. Astrophys., **324**, 109
Neizvestny S.I., 1995, in: Photometric systems and standard stars, ed. Moletai Astronomical Observatory, 37
Pavlenko E.P., Pel't Ya., 1991, Astrofizika, **34**, 169
Pavlenko E.P., 1992, Izv. KrAO, **86**, 55
Pavlenko E.P., Shugarov S.Yu., Antipin S.V., Sokolov D.A., Borisov G., Budzinovskaya I., 1996, in: Proceed. of the Keele Conference on Cataclysmic Variables and Related Objects, eds.: A. Evans and J.H. Wood, 217
Piirola V., Coyne G.V., Takalo S.J.L., Larsson S., Vilhu O., 1994, Astron. Astrophys., **283**, 163
Remillard R.A., Brandt H.V., McClintock J.E., Patterson J., 1986, Astrophys. J., **302**, L11
Schmidt G.D., Stockman H.S., 1990, Prepr. Steward Observ., No. 971.
Schwartz D.A., Tapia S., 1986, Astrophys. J., **302**, L11
Silber A.D., Remillard R. A., Brandt H.V., Ohashi T., Ishida M., 1989, Bull. Amer. Astron. Soc., **21**, 715
Silber A., Bradt H., Remillard R.A., Ishida M., Ohashi T., 1991, Bull. Amer. Astron. Soc., **23**, 880
Silber A., Remillard R., Bradt H., Ishida M., Ohashi T., 1990, in: Accretion–Powered Compact Binaries, eds.: C.W. Mauche and F. Cordova, Cambridge, Cambridge University Press, 289
Silber A., Bradt H.V., Ishida M., Ohashi T., Remillard R.A., 1992, Astrophys. J., **389**, 704
Silber A.D., 1995, in: Proceed. of the Cape Workshop on Magnetic Cataclysmic variables, eds.: D. A. H. Buckley and B. Warner, A.S.P. Conf. Ser. **85**, 302
Silber A. D., Szkody P., Hoard D.W., Hammergren M., Morgan J., Fierce E., Olsen K., Mason P.A., Rolleston R., Ruotsalainen R., Pavlenko E.P., Shakhovskoj N.M., Shugarov S., Andronov I.L., Kolesnikov S.V., Taylor T., Schmidt E., 1997, Mon. Not. R. Astron. Soc., **290**, 25
Somov N.N., 1986, Astrofiz. Issled. (Izv. SAO), **22**, 73
Somov N.N., 1988, Thesis, Nizhnij Arkhyz, SAO RAS, 26
Somov N.N., Somova T.A., 1992, Soobshch. Spets. Astrofiz. Obs., **69**, 46
Somova T.A., Somov N.N., Markelov S.V., Nebelitskij V.B., Spiridonova O.I., Fomenko A.F., 1982, in: Instrumentation for Astronomy with Large Optical Telescopes, ed.: C.M. Humphries, Reidel, 283
Somova T.A., Somov N.N., 1992, Soobshch. Spets. Astrofiz. Obs., **69**, 21
Shrader C.R., Remillard R., Silber A., McClintock J.E., Lamb D.Q., 1988, in: A Decade of UV Astronomy with IUE Satellite (ESA SP–281), ed.: E.J. Rolfe (Noordwijk: ESA), **1**, 137
Stockman H.S., Schmidt G.D., Lamb D.Q., 1988, Astrophys. J., **332**, 282
Szkody P., Downes R.A., Mateo M., 1990, Publ. Astr. Soc. Pacific, **102**, 1310
Tapia S., 1977, Astrophys. J., **212**, L125
Vikuliev N., Zinkovskij V., Levitan B., Nazarenko A., Neizvestny S., 1991, Astrofiz. Issled. (Izv. SAO) **33**, 158
Vojkhanskaya N.F., 1990, Astrofiz. Issled. (Izv.SAO), **30**, 3
Wood K. et al., 1984, Astrophys. J. Suppl. Ser., **56**, 507
Zucker D.B., Raymond J.C., Silber A.D., et al., 1995, Astrophys. J., **449**, 310