Astron. Astrophys. 331, 224–230 (1998)

ASTRONOMY AND ASTROPHYSICS

IUE high-resolution observations of the symbiotic star CH Cygni: confirmation of the triple-star model*

A. Skopal[1,2,**], **M.F. Bode**[3], **H.M. Lloyd**[3], **and H. Drechsel**[1]

[1] Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstr. 7, D-96049 Bamberg, Germany
[2] Astronomický ústav Slovenskej akadémie vied, SK-059 60 Tatranská Lomnica, Slovakia
[3] Astrophysics Research Institute, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

Received 4 August 1997 / Accepted 30 October 1997

Abstract. We present and analyse ultraviolet high-resolution spectra of CH Cyg taken during the whole period of the International Ultraviolet Exploler (IUE) mission. Our analysis of the observed variation in the line spectrum confirms a triple-star model recently suggested for CH Cyg.

Radial velocities of emission lines, which are subject to eclipse in the symbiotic pair are placed at antiphase to those of the neutral metal absorptions from the infrared/optical spectrum. This is direct evidence for the orbital motion of the hot component in the inner binary of the triple system.

Variation in the line profiles of highly ionized elements and Ly α also supports the triple-star nature of CH Cyg. Fluxes in the SiIV, SiII and AlIII lines decreased considerably during the eclipse. Circumstellar emission in Ly α is produced by the radiation of the hot star. The central part of its profile ($\sim$1216–1220 Å) remains unchanged during the eclipse, it arises at larger distances from the star. This implies that the hot component radiation was, in fact, practically constant during this time, and thus its observed considerable decline had to be caused only by the eclipse. The outer parts of the Ly α profile extend up to $\pm 2\,200\,\mathrm{km\,s^{-1}}$, they are subject to eclipse, and thus reflect a high velocity outflow originating from the central star.

Key words: binaries: symbiotic – stars: individual: CH Cygni – ultraviolet: stars

1. Introduction

The symbiotic star CH Cyg is a very intensively investigated object. During its recorded symbiotic period from 1963, a vast amount of multifrequency observations have been carried out. In spite of this, a high level of variability in all the observed parameters makes the system very difficult to understand. Detailed theoretical modelling failed in the case of CH Cyg to support the basic model assumed to work in most other symbiotic systems (Kenyon & Webbink 1984; Mürset et al. 1991). A single-star model had been accepted for about 20 years by some authors until the 1980's (e.g. Hack et al. 1982), when a regular variation in radial velocities (RV) of about 5 700 days was revealed, and the binary nature for CH Cyg was suggested (Yamashita & Maehara 1979; Tomov & Luud 1984; Skopal, Mikolajewski & Biernikowicz 1989).

A new avenue in the investigation of the nature of CH Cyg was explored by Hinkle et al. (1993) who suggested a triple-star model on the basis of accurate RVs from the infrared spectrum. Their model consists of an inner binary (the symbiotic pair) as the short (756-day) period component, and an unseen G-K dwarf revolving around the symbiotic binary on a 14.5-year period orbit. Further, they state that the system cannot be eclipsing. Direct support for the triple-star model, but with some modifications, was given by Skopal et al. (1996a). They showed that CH Cyg is an *eclipsing* system, and, instead of the unseen G-K dwarf, there is another giant star in the system in the long-period orbit. Such a configuration means that we cannot observe the RV curves for both giants separately, as their line profiles are blended (Skopal 1997). The need to confirm our triple-star model is emphasised by recent contributions in which some phenomena are still discussed in terms of the binary nature of CH Cyg (Leedjärv & Mikolajewski 1995; Tomov et al. 1996; Munari et al. 1996; Mikolajewski, Tomov & Mikolajewska, 1997).

The main aim of this paper therefore is to give an additional exploration of the triple-star model based on the analysis of the high-resolution ultraviolet spectroscopy carried out by the IUE satellite. We demonstrate that the variations in the RVs as well as in the line profiles of emission lines which are subject to eclipse support perfectly our proposed triple-star configuration for CH Cyg.

Send offprint requests to: A. Skopal

* Based on observations by the *International Ultraviolet Explorer* satellite taken at the Villafranca Satellite Tracking Station of the European Space Agency

** Visiting Astronomer, Liverpool John Moores University

Table 1. Journal of high-resolution IUE spectra of CH Cyg used in this paper

Spectrum	Disp.	Date			Spectrum	Disp.	Date			Spectrum	Disp.	Date		
		YY	MM	DD			YY	MM	DD			YY	MM	DD
SWP 03479	H	78	11	28	SWP 27252	H	85	12	12	SWP 52656	H	94	10	25
SWP 08940	H	80	5	6	SWP 27958	H	86	3	20	SWP 52990	H	94	12	5
SWP 09984	H	80	9	1	SWP 28011	H	86	3	24	SWP 54255	H	95	3	30
SWP 10878	H	80	12	23	SWP 39521	H	90	8	23	SWP 54256	H	95	3	30
SWP 15638	H	81	12	3	SWP 39971	H	90	10	27	SWP 54475	H	95	4	20
SWP 22057	H	84	1	20	SWP 41156	H	91	3	22	SWP 54801	H	95	5	31
SWP 24955	H	85	1	23	SWP 44617	H	92	5	7	SWP 55345	H	95	7	22
SWP 25833	H	85	5	2	SWP 47070	H	93	2	28	SWP 55901	H	95	9	11
SWP 26024	H	85	5	27	SWP 49035	H	93	10	29	SWP 56144	H	95	11	2
SWP 26218	H	85	6	21	SWP 52404	H	94	10	14	SWP 56288	H	95	12	13

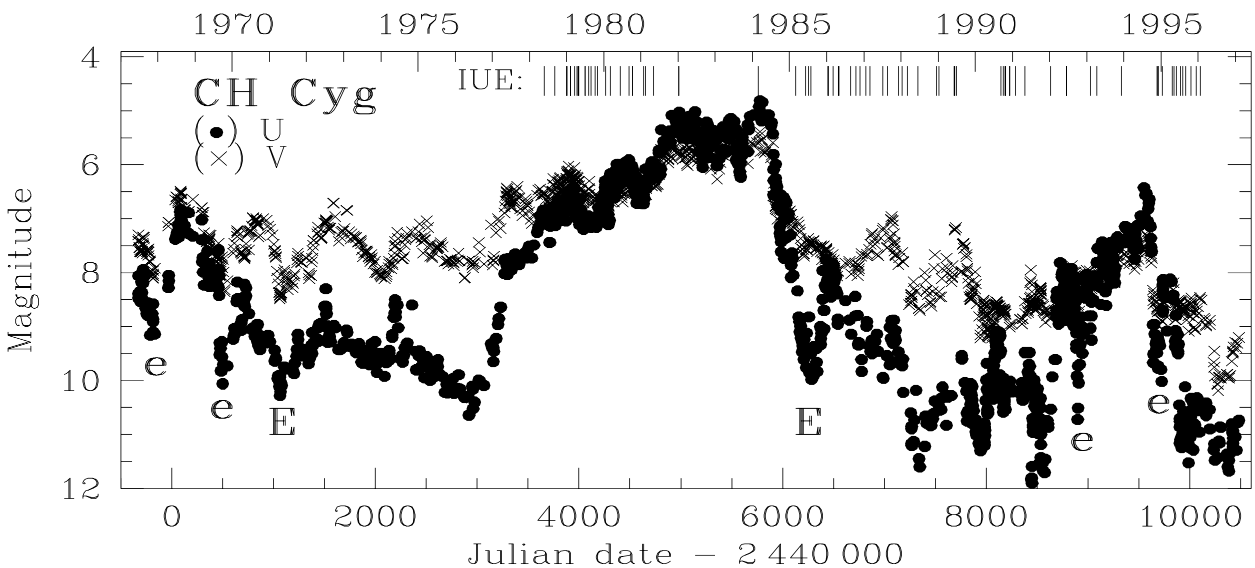

Fig. 1. The U and V light curves of CH Cyg covering the period 1967 – 1996. The eclipses in the long (14.5-year) period orbit are marked by **E** and those in the short (756-day) period symbiotic pair by **e**. The IUE shifts are marked at the top by vertical bars

2. Observations

This paper is based almost exclusively on high-resolution UV observations carried out using the IUE satellite during its operational period from 1978 – 1995. There are 49 LWP and 36 SWP high-resolution spectra on the list of the VILSPA archive. Corresponding satellite shifts are marked along the light curve of CH Cyg in Fig. 1. We sorted the data in time – with respect to CH Cyg activity, and in wavelength – with respect to the most prominent spectral lines (Sect. 3). The IUE observations cover the following different stages of CH Cyg:

(i) The maximum of the star's brightness (monitored by IUE from 1978 to mid-1984).

(ii) The return of CH Cyg to quiescence (mid-1984 to 1986).

(iii) The quiescent phase (1987 to 1991).

(iv) The 1992 active phase (1992 to 1995 March 30).

(v) The present quiescence (first and last observations were made on 1995 May 31 and 1995 December 13, respectively).

As the spectra during periods (i), (ii) and (iii) do not display significant variations and also some of them have been previously published, we use here only the best representative samples. However, for the period of the recent 1992-95 active phase and the following quiescent period, we present practically all the available IUE observations. During this period the CH Cyg spectrum underwent more significant variations (in part caused by eclipses) and also most of the spectra have not yet been published. Finally, we note that we use only the SWP spectra, because the LWP spectra do not contain any more important information with respect to the main aim of our contribution. Also some of them were previously published by Persic, Hack & Selvelli (1984) and by Skopal et al. (1996b).

A journal of high-resolution SWP spectra used in the current contribution is given in Table 1.

3. Evolution in the line spectrum

The most prominent emission lines in the UV spectrum during the active phases of CH Cyg between autumn 1984 and spring 1995 were lines of Ly α, Si IV 1402.77, O I 1304.86, 1306.02, N I 1411.95, 1494.68, 1742.73, 1745.25, O III 1666.15,

Table 2. Radial velocities of emission lines which are subject to eclipse

N	Spectrum	Date	Julian date	phase*	RV_{obs}	$RV_{Ly\,\alpha}$	RV_{orb}	RV_{corr}	Note
1	SWP 03479	28/11/78	43841.374	0.293	-55.5	-28.8	-60.3	8.3	OI, 1
2	SWP 08940	6/5/80	44367.127	0.988	-33.4	17.9	-52.4	-24.2	OI
3	SWP 09984	1/9/80	44485.229	0.144	-43.3	-1.3	-50.5	-16.8	OI
4	SWP 10878	23/12/80	44597.767	0.293	-5.9	32.5	-48.7	-15.0	OI
5	SWP 15638	3/12/81	44942.200	0.749	-23.0	9.5	-43.5	-14.3	OI, 2?
6	SWP 22057	20/1/84	45721.112	0.779	7.0	18.5	-43.8	7.0	OI
7	SWP 24955	23/1/85	46088.991	0.266	-17.8	18.7	-53.4	-8.4	OI,SiIV,SiII,AlIII
8	SWP 25833	2/5/85	46187.535	0.396	-36.8	2.5	-56.3	-8.3	OI,SiIV,SiII,AlIII
9	SWP 26024	27/5/85	46213.272	0.430	-25.9	16.5	-57.0	-10.7	OI,SiII,AlIII
10	SWP 26218	21/6/85	46238.067	0.463	-20.0	17.8	-57.7	-5.4	OI,SiII,AlIII
11	SWP 27252	12/12/85	46411.678	0.693	-5.3	16.5	-62.4	15.3	OI
12	SWP 27958	20/3/86	46509.525	0.822	-28.8	6.2	-64.7	4.4	OI
13	SWP 28011	24/3/86	46513.688	0.828	-20.8	2.4	-64.8	16.3	OI
14	SWP 39521	23/8/90	48127.294	0.962	-23.5	0.9	-71.1	21.4	OI
15	SWP 39971	27/10/90	48192.119	0.048	-48.0	2.9	-70.6	-5.6	3, SiIII],CIII]
16	SWP 41156	22/3/91	48338.088	0.241	-70.7	-5.9	-69.4	-20.7	3, SiIII],CIII]
17	SWP 44617	7/5/92	48750.909	0.787	-35.0	-12.4	-65.2	17.3	OI
18	SWP 47070	28/2/93	49046.526	0.178	-30.0	5.4	-61.6	0.9	OI, 2
19	SWP 49035	29/10/93	49289.923	0.500	-17.5	-6.9	-58.2	22.3	OI, 2
20	SWP 52404	14/10/94	49640.288	0.963	-84.6	-55.7	-52.8	-1.4	OI
21	SWP 52656	25/10/94	49650.635	0.977	-36.2	-6.9	-52.6	-2.0	OI
22	SWP 52990	5/12/94	49691.973	0.032	-80.6	-43.9	-52.0	-10.0	OI
23	SWP 54256	30/3/95	49806.764	0.184	-26.5	15.3	-50.1	-17.0	OI
24	SWP 54475	20/4/95	49828.479	0.212	-33.1	3.9	-49.8	-12.5	OI
25	SWP 54801	31/5/95	49868.567	0.265	-31.7	5.4	-49.1	-13.3	OI
26	SWP 55345	22/7/95	49921.357	0.335		14.1			3
27	SWP 55901	11/9/95	49971.220	0.401	-0.5	27.6	-47.5	-5.9	OI
28	SWP 56144	2/11/95	50024.450	0.471	1.6	23.7	-46.6	-0.8	OI
29	SWP 56288	13/12/95	50064.600	0.525	-6.5	16.8	-46.0	-2.6	OI

$\star$ according to the ephemeris of inferior conjunction of the giant in the symbiotic pair: $JD_{sp.conj.} = 2\,445\,888(\pm12) + 756(\pm4) \times E$ (Hinkle et al. 1993), RV_{obs} - average RV of measured lines, $RV_{Ly\,\alpha}$ - RV of the geocoronal component of the Ly α line, RV_{orb} - RV of the center of gravity of the symbiotic pair, RV_{corr} - corrected RV: $RV_{corr} = RV_{obs} - RV_{Ly\,\alpha} - RV_{orb} - 25.3$
Notes: 1 - noisy Ly α, 2 - distorted profile, 3 - OI lines not present

SiII 1808.00, 1816.92, AlIII 1854.72, 1862.79, SiIII] 1892.03, CIII] 1908.73 and the MgII 2796, 2803 Å doublet. During the main active phase, 1979 – mid-1984, these lines were fainter (e.g. NI and AlIII), not present (Ly α, SiIV) or in absorption (SiII). Also the HeII 1640 line, which usually dominates the ultraviolet spectrum of symbiotic stars, was very weak and broad, or absent. On return of CH Cyg to quiescence, from 1984 to 1986, the profiles of most of these lines were characterized by a simple emission, but during the recent, 1992-95, active phase they developed complex profiles of P-Cygni type with a broad absorption component. Here, for the sake of simplicity, we present and discuss in more detail only the Ly α, OI and AlIII lines, because they demonstrate best the primary aim of our contribution.

3.1. The OI 1304 and 1306 Ålines

Among all emission lines in the UV spectrum of CH Cyg, the OI lines display the simplest profiles. As they are subject to eclipses in the inner binary (Skopal et al. 1996a), we tried to measure their accurate wavelengths to verify the orbital motion of the hot component in the symbiotic pair. To avoid possible problems with accurate wavelength calibration in the high-resolution spectra, we determined positions of the lines with respect to the geocoronal Ly α component. We estimated the wavelength of the emission core (mostly at $\approx$ 2/3 of the height of the line) graphically and checked it by a numerical method finding the 'light centre' of a line centroid. The line centroid is defined by the profile within the 6 or 10 pixel-wide part of the spectrum centered at the top of the line. In the case of a symmetric profile both methods gave practically the same values. The uncertainty due to these methods is only of a few km s^{-1} of the Ly α and OI lines. A larger uncertainty, up to $\sim$20 km s^{-1}, is caused by a poorer definition of the OI profiles. They were faint on underexposed spectra, during quiescence or in eclipses, and/or affected by activity, mainly in the 1992-95 period. The last point refers to the 1993 spectra (SWP47070 and SWP49035), in which emission cores of OI lines are probably in part absorbed on the violet side. This effect is strongly pronounced in other lines (Sect. 3.2, Fig. 3). As a result of this we measured red-shifted RVs in these spectra (Table 2). In addition to OI lines we also used RVs of AlIII, SiII and SiIV emissions in some specta from the 1984-86 period, and of SiIII] 1892 and CIII] 1909 in the 1990-91 quiescent phase (Table 2, Sect. 3.2), as they are also subject to eclipse and

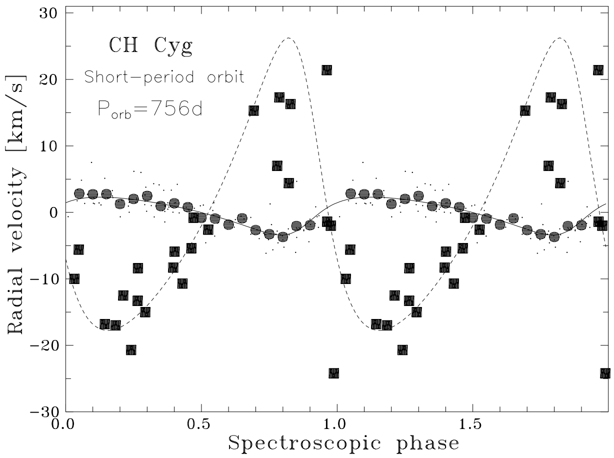

Fig. 2. Short-period RV variations. Full circles are $0.05 \times P_{\rm orb}$ means of the observed RVs of the M giant(dots). The solid line represents the solution of their spectroscopic orbit according to elements published by Hinkle et al. (1993). Squares are RVs of the emission lines in the far-UV spectrum as listed in Table 2 (those annotated by marks 1 and 2 are not plotted). Compared is a theoretical RV-curve of the hot component according to elements from Skopal (1997)

display a simple profile during these epochs (cf. Fig. 3 here; Fig. 3 of Skopal et al. 1996a and Fig. 5 of Skopal et al. 1998). Why these lines – very different in states of ionization – are subject to eclipse, is obviously because of the low luminosity of the source of ionizing radiation and the large volume around the hot star eclipsed by the stellar disk of the giant ($\sim$120 $R_\odot$, Skopal 1997).

Finally, we subtracted the RV of the geocoronal Ly α component, the long-period RV curve of the centre of gravity of the symbiotic pair according to elements recently revised by Skopal (1997), and a residual of 25.3 km s^{-1} of unknown nature. A period search in these data using Stellingwerf's (1978) method of phase minimization indicated significant periods around 760 days. This period is equal to that in the RVs of absorption lines in the 2-3 μm infrared spectrum (Hinkle et al. 1993) and to that in the UBV magnitudes observed during the 1970-77 quiescence (Skopal 1989). In addition, the data phased with the ephemeris for the spectroscopic conjunction of the cool component in the symbiotic pair (Hinkle et al. 1993; Skopal 1995) are placed at antiphase to those of the neutral metal absorptions from the infrared/optical spectrum (Fig. 2). This is a direct indication of the presence of a hot star in the inner binary (supposed to be the symbiotic pair) of the triple CH Cyg system. However, the RVs of emissions in the UV spectrum cannot be used for an accurate determination of the hot component orbital motion, because of other complications of the line profiles in the UV spectrum.

It is of interest to note that a larger deviation of the RVs around the inferior conjunction of the cool component could be associated with rotation of the line-emitting region at its ingress to, and egress from the eclipse (a Struve effect). If it were the case, then the amplitude, $\sim$20 km s^{-1} (Fig. 2), implies

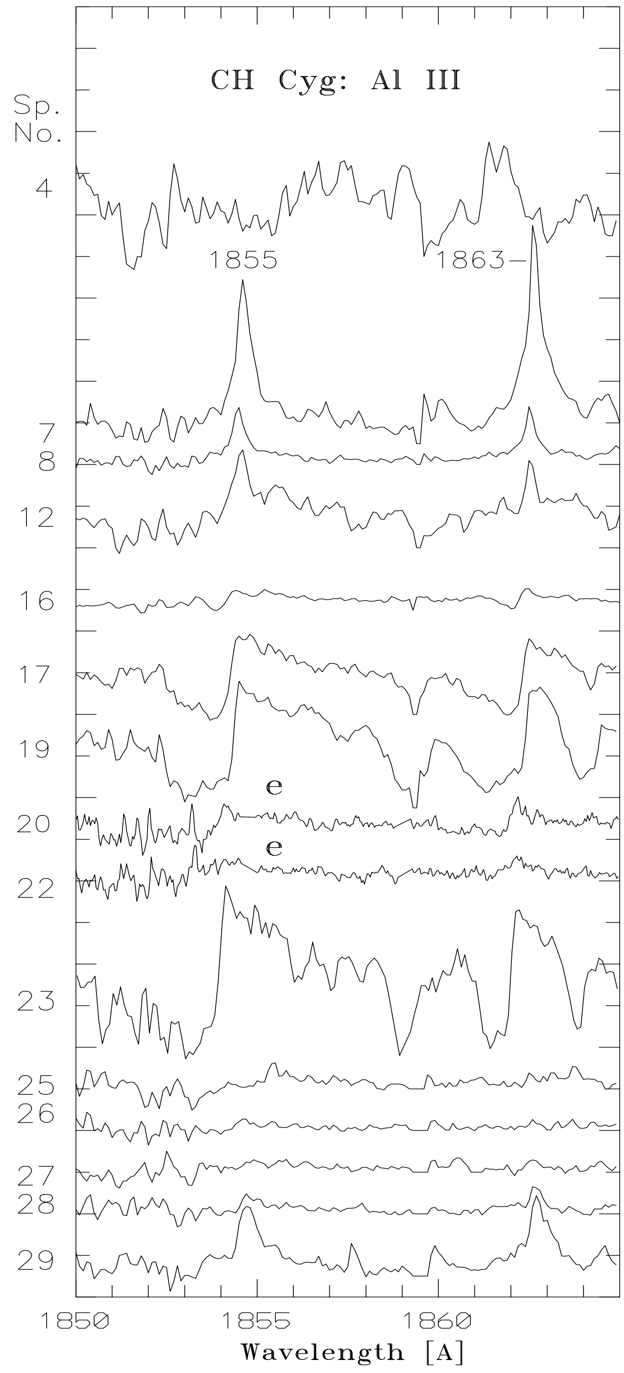

Fig. 3. Evolution in the AlIII profile during the IUE operational lifetime. The number of the spectrum marked at the left margin corresponds to that in the first column in Table 2. Spectra taken during the eclipse in the symbiotic pair are marked by **e**

a localization of the OI emitting region at $\sim 60\,R_{\odot}$ from the central star ($i = 90^{\circ}$ and Keplerian velocity were assumed). This result is in particular agreement with the presence of the OI emissions just at the second contact time (spectrum of 14/10/94) and their disappearance later in mid-eclipse (cf. Fig. 2 of Skopal et al. 1996a).

3.2. The AlIII 1855 and 1863 Å lines

The temporal evolution in the AlIII line profiles is shown in Fig. 3. During the maximum of the star's brightness the AlIII (and also SiIV and SiII) emissions were absent. The main source of the hot component radiation was not capable of ionising a sufficient amount of the AlII (SiIII, SiI) ions, in spite of having its highest total luminosity in the observed symbiotic lifetime of CH Cyg. After the drop in brightness in mid-1984, these lines became visible as simple emissions and were nearly symmetric in profile. During quiescence they disappeared, together with the source of the ionizing radiation. On the other hand, a brightening in the hot continuum was followed by their re-appearance in the spectrum. This is clearly seen in our spectra made during quiescence on 13/12/95, when a short-term brightening in the hot continuum was accompanied by emerging emission lines in the far-UV spectrum (Figs. 3, 4).

During the 1992-95 active phase the AlIII lines developed $\sim 800 - 1\,000\,\mathrm{km\,s^{-1}}$ broad absorption/emission profiles of the P-Cygni type. No central sharp emission was present. During the 1994 eclipse (spectra from 14/10, 25/10 and 5/12/1994) these lines disappeared, and recovered after it, as we recorded on 30/3/95 (Fig. 3). Such behaviour implies that these lines are subject to eclipse in the inner binary. As they had faded considerably already at the beginning of the eclipse (on 14/10/94, close to the t_2 time), this implies that they are created in the proximity of the hot photosphere, closer than the OI lines which were still present as dominant emissions at that time (Skopal et al. 1996a). On the other hand, assuming such natural stratification of the lines with very different states of ionization in the hot star environment, the observed gradual fading in the intensity of these lines could be caused only by gradual eclipsing of the layers in which they originate above the photospere.

3.3. The Ly α line

Evolution in the Ly α profile during the IUE lifetime is shown in Fig. 4. During the maximum, from the first 1978 observations to 1984, no circumstellar Ly α line was evident (see also Selvelli & Hack 1985). Only a sharp emission of geocoronal origin was present. On the 1985-86 spectra, the Ly α line became nearly 20 Å wide with a strong redward-shifted emission. However, during the 1990-91 and also 1995 quiescent phases, the circumstellar Ly α emission practically disappeared together with the hot UV/optical continuum. In the 1992-95 active phase, the Ly α profiles resembled those from the 1985-86 period, but the main emission was a factor of about 2-3 times weaker (Fig. 5). Dependence of the Ly α profile on emission in the hot continuum

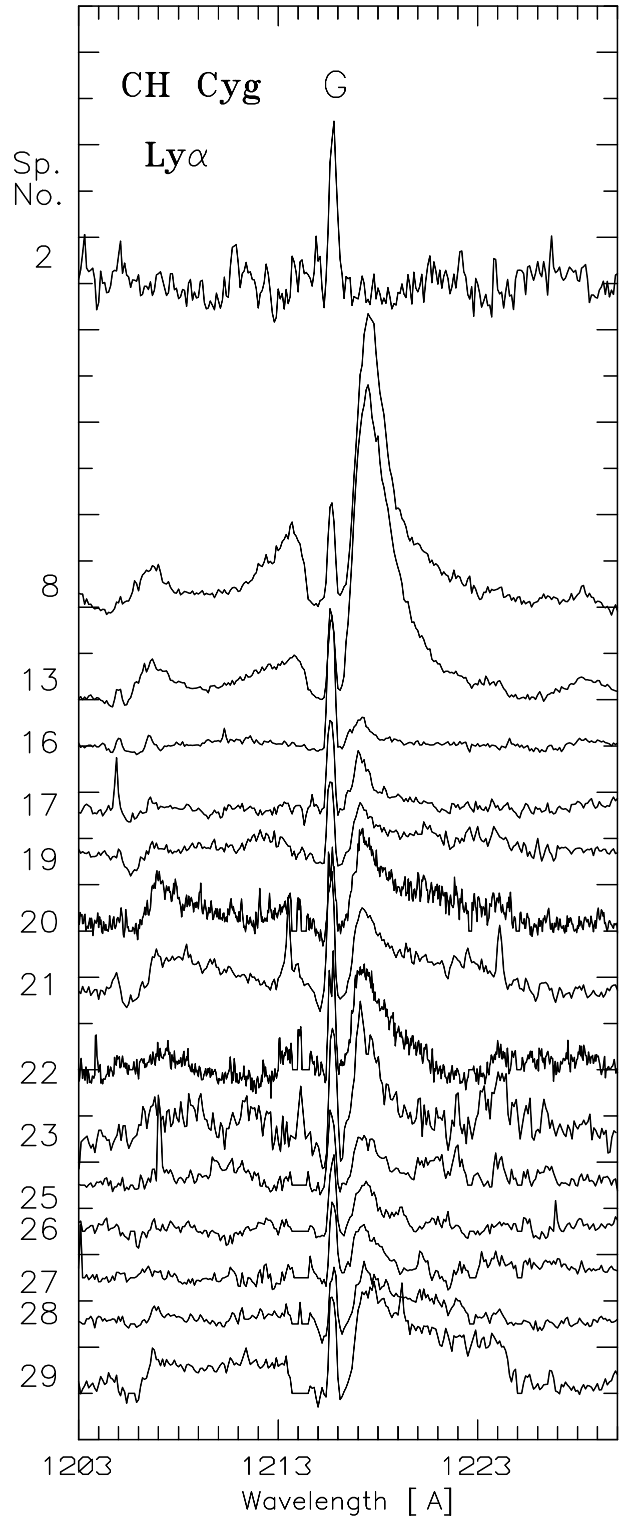

Fig. 4. As Fig. 3, but for Ly α

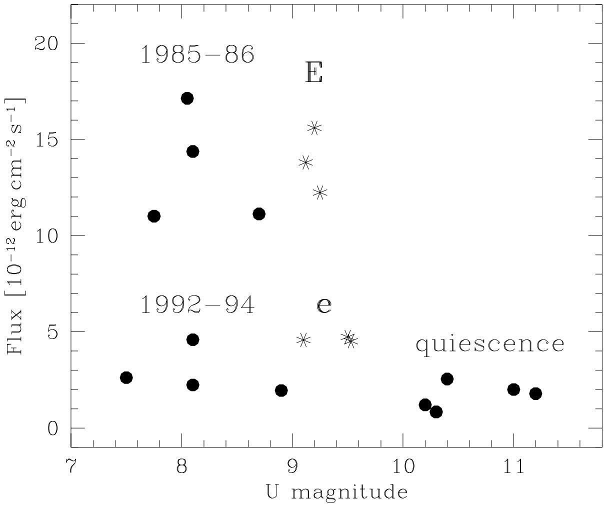

Fig. 5. Ly α fluxes between λ1216 and 1220Å from the available spectra as a function of the U magnitude. Asterisks denote those observed during eclipses, in 1985 (**E**) and 1994 (**e**) - cf. Fig. 1. They indicate the continued activity of the hot star, although we observed a considerable decrease in fluxes of the hot continuum and some lines during that time

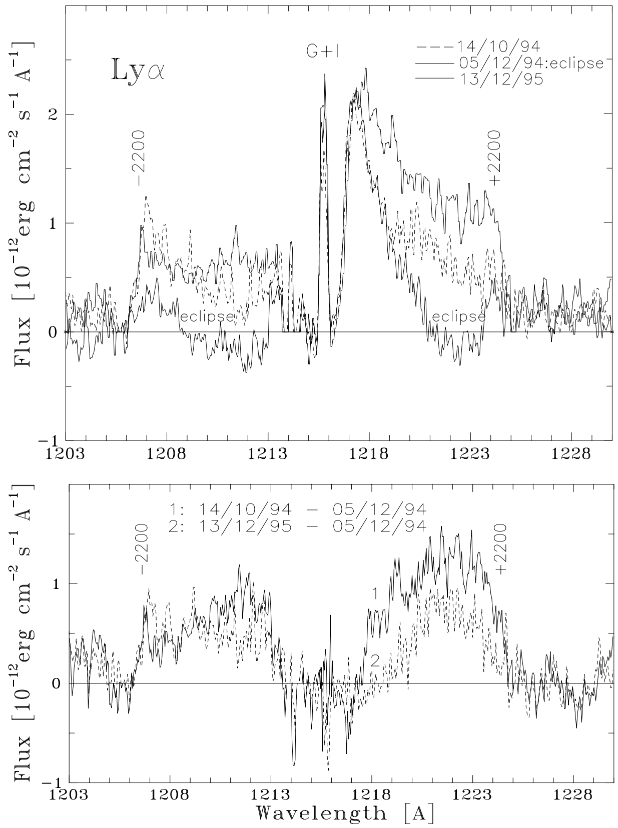

Fig. 6. Top panel: The Ly α profile in selected spectra at the beginning (14/10/94), in (5/12/94) and out (13/12/95) of the eclipse. Bottom panel: Difference spectra of the above mentioned observations

is also evident in our 13/12/95 spectra as described in Sect. 3.2 for the AlIII lines.

Particular attention is paid here to the Ly α profile. Its variation during the 1992-95 active phase, and mainly *in* and *out* of the 1994 eclipse, provides us with important information about the kinematics and displacement of the circumstellar material in and around the symbiotic pair. The Ly α profile extends from 1206.4 to 1224.5 Å and consists of two – stable and variable – components (Fig. 6, top panel). To demonstrate this better, we subtracted the line profile of mid-eclipse (5/12/94) from those observed just at the beginning of the eclipse (14/10/94) and far later during the short-term brightening on 13/12/95 (Fig. 6, bottom panel).

The stable component of the profile extends from $\sim$1213 to $\sim$1220 Å and consists of a P-Cygni profile with a broad absorption between -360 km s^{-1} and +230 km s^{-1}. We summarize its basic properties as follows: (i) The circumstellar emission in Ly α depends on the star's brightness, i.e. the source of the energy giving rise to it is the radiation of the hot component (Figs. 4, 5). This fact is in contradiction to the previous suggestions that the Ly α line arises in the atmosphere of the red giant in CH Cyg (Selvelli 1988). (ii) During eclipses, in both the outer (in 1985) and the inner (in 1994) orbit, the stable part of the Ly α profile does not vary considerably (Fig. 4, 5, 6 also Fig. 3 of Skopal et al. 1996a). This means that the circumstellar matter emitting in this part of the Ly α profile is not subject to eclipses, but surrounds the whole symbiotic pair. It also implies that the source of the ionizing radiation (i.e. the hot star) remains practically constant during this time, i.e. the considerable decrease in the hot continuum from 1994 October to 1995 January could not be associated with a transient drop in the star's activity. (iii) The broad absorption component does not vary along the orbital cycle of the symbiotic pair. It is very probable that this component is due to interstellar absorption, which, at Ly α, produces a typical very broad absorption feature in the spectrum of hot stars (cf. Heck et al. 1984).

The variable part of the Ly α profile extends up to $\pm$2 200 km s^{-1} (cf. Figs. 4, 6). A major part of this profile is affected by the eclipse, and thus must be emerging from the outflowing material at the vicinity of the hot component (Fig. 6). Thus, by subtracting the line profile from mid-eclipse we can estimate the flux in this part of the Ly α profile as $\sim$10^{-11}erg cm^{-2}s^{-1}. As the spectrum from 5/12/94 is close to mid-eclipse, the giant radius, 123$\pm$4 R$_\odot$ (Skopal 1997) gives an approximate upper limit for the radius of the region producing this part of the Ly α profile. We note here that an asymmetric high velocity gas outflow ($>$2 000 km s^{-1}) was also indicated by broad emission components of Balmer lines occuring in the spectrum on short time scales during the recent active phase (Iijima et al. 1994; Iijima 1996).

In addition to these two components of the Ly α profile, a narrow geocoronal emission (G) is superposed on the profile at $\sim$0 km s^{-1} with respect to the system.

4. Conclusions

Here we summarize the main results of our analysis as follows:

1. RVs of emission lines, which are subject to eclipses in the inner binary of the triple CH Cyg system, are placed at antiphase to the RVs of absorption lines from the infrared/optical spectrum. This result reflects directly the presence of the hot star in the symbiotic pair.
2. A strong decrease in the line fluxes of highly ionized elements as AlIII, SiIV and SiII during the time of the eclipse with respect to those observed out of eclipse, also supports the triple-star configuration of CH Cyg.
3. Radiation from the hot component during activity gives rise to emission in Ly α which arises from material centred around the hot component, and not from the atmosphere of the giant star. The observed flux in the central part of the Ly α profile, between about 1213 and 1220 Å, is not affected by the eclipse, which reflects the constancy of the source of the ionizing radiation during that time. Thus, the decrease in the hot star continuum from 1994 October to 1995 January could not be caused by a 'random' transient decline in the star's activity. This part of the Ly α profile originates from material around the whole symbiotic pair.
4. The outer parts of the Ly α profile, up to velocities of $\pm 2\,200\,\mathrm{km\,s^{-1}}$, indicate a high velocity outflow of material in the vicinity of the hot star.
5. Sudden, irregular variation in emission in both lines and continuum, such as that observed during *quiescence* on 13/12/95, supports a mechanism of sporadic accretion as being responsible for maintaining activity in CH Cyg as previously suggested by Skopal et al. (1996b).

Acknowledgements. This research has been supported by the Alexander von Humboldt foundation, the Royal Society of Great Britain and the Slovak Academy of Sciences Grant No. 1282/96. HML was supported by a PPARC postdoctoral research assistantship.

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