Astron. Astrophys. 338, 139–150 (1998)

ASTRONOMY AND ASTROPHYSICS

A spectroscopic study of the long-period binary star WY Geminorum

Laurits Leedjärv

Tartu Observatory, Tõravere, EE 2444, Estonia (leed@aai.ee)

Received 30 January 1998 / Accepted 10 June 1998

Abstract. The long-period VV Cephei type binary star WY Gem, consisting of a M2 supergiant and an early B type main-sequence star, has been monitored spectroscopically on the 1.5-meter telescope of Tartu Observatory from 1984 to 1997. The Hα emission line has undergone significant variations, with equivalent width decreasing from a value of about 20 Å in 1980s down to 3–5 Å in 1996–1997. Strong emission lines of Fe II, present in 1985, have almost vanished by now. At the same time, the forbidden emission lines of [Fe II] and [S II] have not changed remarkably. Radial velocities of the M2 supergiant have been measured, and together with the data available from literature, they are used for deriving approximate orbital elements of WY Gem. Although the observational data have large scatter, it is likely that WY Gem has a long-period ($P \approx 64$ yr), very eccentric orbit ($e = 0.61$), with periastron passage occuring in 1983. Such elements are confirmed by the variations of the emission lines of Hα and Fe II, as well as by photometric observations. Near the time of periastron passage, the hot (B type) star probably accretes some amount of the supergiant's wind, and even an accretion disk could be formed. The observed Hα profiles, in principle, are consistent with those computed as arising in a rotating disk. The extent of the disk has decreased since 1984.

Key words: stars: binaries: spectroscopic – stars: individual: WY Gem – stars: supergiants

1. Introduction

WY Geminorum = HD 42 474 = BD +23°1243 belongs to a not numerous class of stars referred to as VV Cephei type (Cowley 1969) or syncretic (Buss & Snow 1988) binaries. These stars consist of a M (or late K) type supergiant and a hot companion (usually a B type main-sequence star). The visual spectrum is characterized by the presence of Hα and [Fe II] emission lines. Frequently the stars also show weaker emission in other Balmer lines as well as in those of Fe II, [S II], [O I], [Ni II] and other species, particularly in the near-ultraviolet spectral region (Cowley 1969). Radio flux from ionized gas detected from several VV Cep type binaries (Altenhoff et al. 1994; Hjellming 1985), and ultraviolet circumstellar outflow line profiles (Che et al. 1983) indicate that the hot star secondary orbits inside the stellar wind of the M star primary.

In a very general way, the VV Cep stars are similar to symbiotic stars, both showing K or M type absorption spectrum on which are superimposed emission lines and a hot continuum. A more detailed examination, however, reveals marked differences – for example, red giants in the symbiotic binaries are of a luminosity class III, whereas the VV Cep binaries contain supergiants of a luminosity class at least Ib. Symbiotic spectra exhibit emission lines from species of much higher stages of ionization than the spectra of the VV Cep stars, in which mostly only emission lines of singly-ionized metals are observed (according to Bidelman & Stephenson (1956), FR Sct has shown emission lines of [Fe III] and [O III], too). Considering the evolutionary status, the VV Cep stars are more similar to the ζ Aurigae type binaries, which have K supergiant primaries and orbital periods of several years (Buss & Snow 1988). The latter, however, do not show the characteristic emission lines of [Fe II].

The orbital periods of the VV Cep stars typically span several decades, in many cases $P \geq 40$ yr (Buss & Snow 1988), with the visual binary α Sco being the extreme case ($P \geq 800$ yr). Due to large orbital separations, the individual stars in most VV Cep type systems resemble isolated stars of similar spectral classes and probably evolve quite independently. In specific cases, however, mass transfer and accretion could be possible. The prototype star VV Cep itself serves as an example of such phenomena. But Buss & Snow (1988) have also found that VV Cep is peculiar in several aspects, and that it does not represent well other members of the class.

Existence of emission lines in the spectrum of WY Gem was first pointed out by Humason (1922). The spectral type of the supergiant has been mostly referred to as M2epIab (Bidelman 1954; Lee 1970). White & Wing (1978), however, propose a luminosity class Ib, and Humphreys (1978), on the other hand, Ia. The hot companion probably is of spectral class B2V (Wawrukiewicz & Lee 1974) or B2III (Buss & Snow 1988). But as the latter authors point out, the luminosity classes of the hot components of the VV Cep type stars could be overestimated due to large circumstellar absorption, therefore a main sequence star can be considered as a more realistic case.

Cowley (1969, 1970) has found that the hot component of WY Gem likely undergoes eclipses by the extended atmosphere of the M supergiant. Taking into account a long duration of the eclipse in 1960s (as compared to VV Cep) and other considerations, she has suggested for WY Gem an orbital period in excess of 40 years, possibly even near 80 years.

WY Gem has been spectroscopically monitored at the Tartu Observatory since 1984. The present paper is devoted to the analysis of the thirteen years' observations, which together with other data available, have allowed us to derive some basic properties of the binary system. After describing the observations and their reduction in Sect. 2, the analysis of various spectral features is given in Sect. 3. Sect. 4 deals with the orbital elements of the binary system, and Sect. 5 concerns the question about eclipses in the WY Gem system. In Sect. 6 we discuss the nature of the hot component, and Sect. 7 concludes the discussion of WY Gem.

2. Observations

Spectroscopic observations of WY Gem at the Tartu Observatory have been carried out since 1984, using the 1.5-meter telescope equipped with a Cassegrain grating spectrograph ASP-32. Until 1994 the spectra have been recorded on photographic plates. During observing season 1994/95 the Santa Barbara Instruments Group Peltier cooled CCD camera ST-6 was attached to the same spectrograph. This red-sensitive camera could be used for obtaining the spectra of WY Gem in the Hα region only. Since the beginning of 1996 the spectrograph has been equipped with the CCD camera HPC-1 from SpectraSource Instruments (1024x1024 chip by Tektronix). Higher sensitivity of this camera has allowed us to register the Hα spectra of WY Gem at higher dispersion (about 12 Åmm^{-1}) than before. Table 1 gives the log of the observations.

The photographic spectra have been digitized on a microdensitometer PDS, and further processed in a usual way, using the calibration spectrum taken on the same plate. Preliminary reduction of the CCD spectra has been performed with the ESO software package MIDAS. This reduction includes flat-fielding and subtraction of the dark frame and the sky background. The spectrum of a star usually occupies 6–12 rows in the CCD frame. The values of each pixel in those rows have been divided by the weights obtained from the cross-section of the spectrum. The final one-dimensional spectrum is computed as a median value of those weighted rows, thereby excluding random noises.

Further reduction of both photographic and CCD spectra has been performed using the program package KASPEK, developed and modified by Annuk (1986) at the Tartu Observatory. For a wavelength calibration, the spectrum of a Ne-Ar hollow cathode lamp has been recorded together with all the stellar spectra. The wavelength-calibrated spectra have been filtered for reducing the noise, and finally, normalized to the continuum. The KASPEK package has been used also for measurements of radial velocities (RV), equivalent widths (EW) and other quantities from the normalized spectra.

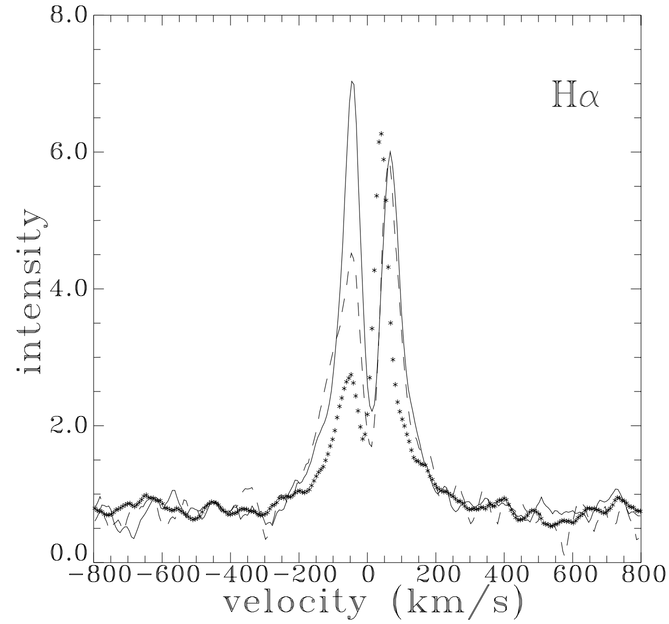

Fig. 1. Some examples of the Hα profile in the spectrum of WY Gem. Solid line: April 7, 1984; dashed line: April 15, 1985; asterisks: April 3, 1993

3. Analysis of the spectra

3.1. The Hα line

The most prominent spectral features of the VV Cep type stars, different from those of single M supergiants, are the emission lines of Hα and [Fe II]. In the spectrum of WY Gem, besides Hα, emission in several other Balmer lines has been detected also, at least temporarily. This was first noted by Humason (1922). According to Cowley (1995, personal communication), emission in the higher members of the Balmer series has become considerably weaker in 1930s, and was not present in 1940s and 1950s. In 1960s, the Balmer lines have demonstrated sharp shell absorption components (Cowley 1970).

Unfortunately, there is no historical information about the behaviour of Hα in the spectrum of WY Gem available. During the time interval from 1984 to 1997, covered by our observations, Hα has been a double-peaked emission line, but remarkable variations of the EW and the intensities of the emission peaks have taken place. A few examples of the profile can be seen in Fig. 1.

In 1984, the violet emission peak of Hα was stronger than the red one, resulting in the ratio $V/R > 1$, while for all the remaining time $V/R < 1$. The minimum value $V/R = 0.385$ was observed in October 1993. During 1995–1997 V/R has retained values 0.6–0.7. Such a profile of Hα is different from that in the spectrum of the prototype star VV Cep, which out of the eclipse of the hot component, always shows $V/R > 1$ (Wright 1977; Hack et al. 1992).

The overall intensity of the Hα emission line has decreased during the whole time of our observations. Fig. 2 shows the behaviour of the EW as well as of the ratio V/R with time.

Table 1. Spectroscopic observations of WY Gem at the Tartu Observatory

Date	JD (2 400 000+)	$\lambda\lambda$ (Å)	Disp. (Å/mm)	Exp. (min)
Photographic spectra				
84/04/07	45 798.37	6100–6700	28	200
84/04/21	45 812.35	6100–6700	28	150
85/02/06	46 103.52	3850–4800	37	180
85/02/09	46 106.50	3850–4800	37	190
85/04/15	46 171.38	6100–6700	28	112
87/03/09	46 864.45	6100–6700	28	120
87/03/15	46 870.40	6100–6700	28	170
88/01/27	47 188.44	6100–6700	28	100
89/10/23	47 823.54	6100–6700	28	175
90/03/29	47 980.38	6100–6700	28	110
90/04/14	47 996.34	6100–6700	28	135
91/12/14	48 605.41	4200–5000	37	130
92/01/25	48 647.44	4200–5000	37	110
92/01/29	48 651.46	4200–5000	37	120
92/10/07	48 903.48	6100–6700	28	120
92/12/27	48 984.51	6100–6700	28	105
93/01/23	49 011.51	6100–6700	28	120
93/02/25	49 044.38	6100–6700	28	110
93/03/22	49 069.38	6100–6700	28	120
93/04/03	49 081.33	6100–6700	28	120
93/10/25	49 286.47	6100–6700	28	112
93/12/15	49 337.50	6100–6700	28	105
94/02/08	49 392.31	6100–6700	28	116
94/02/16	49 400.37	6100–6700	28	125
94/02/27	49 411.41	6100–6700	28	110
94/03/01	49 413.41	3920–4900	37	160
94/03/21	49 433.36	3920–4900	37	160
94/03/28	49 440.31	3920–4900	37	176
CCD-camera ST-6				
94/10/07	49 633.51	6500–6700	28	10
94/10/22	49 648.64	6500–6700	28	10
95/01/03	49 721.33	6500–6700	28	10
95/01/04	49 722.44	6500–6700	28	10
95/01/17	49 735.29	6500–6700	28	10
95/01/18	49 736.26	6500–6700	28	10
95/01/19	49 737.30	6500–6700	28	10
95/01/20	49 738.38	6500–6700	28	10
95/01/21	49 739.36	6500–6700	28	10
95/02/28	49 777.47	6500–6700	28	20
95/03/11	49 788.29	6500–6700	28	10
95/03/30	49 807.37	6500–6700	28	10
CCD-camera HPC-1				
96/01/08	50 091.46	6200–6750	28	10
96/01/24	50 107.42	6200–6750	28	10
96/01/31	50 114.34	6300–6850	28	10
96/02/08	50 122.27	6300–6850	28	5
96/02/11	50 125.29	3700–5500	86	15
96/02/11	50 125.32	6300–6850	28	10
96/02/18	50 132.34	6300–6850	28	5
96/02/18	50 132.38	3700–5500	86	10
96/02/28	50 142.43	6300–6850	28	10
96/03/03	50 146.44	6250–6800	28	10
96/03/09	50 152.39	6300–6850	28	10
96/03/13	50 156.39	6300–6850	28	5
96/03/17	50 160.39	6250–6800	28	5
96/03/19	50 162.40	6300–6850	28	5
96/03/20	50 163.41	6300–6850	28	5
96/03/21	50 164.40	6300–6850	28	5
96/03/22	50 165.42	6300–6850	28	5
96/04/03	50 177.35	6300–6850	28	5
96/04/06	50 180.38	6250–6800	28	5
96/04/09	50 183.41	6300–6850	28	4
96/04/13	50 187.30	6300–6850	28	5
96/04/13	50 187.32	6380–6650	12	10
96/10/10	50 367.45	6420–6700	12	10
96/10/16	50 373.46	6420–6700	12	10
96/11/08	50 396.50	6300–6850	28	10
96/11/10	50 398.44	6420–6700	12	10
96/11/14	50 402.43	6420–6700	12	10
96/11/15	50 403.45	6420–6700	12	10
96/12/19	50 437.42	6380–6650	12	10
96/12/30	50 448.27	6300–6850	28	10
97/01/14	50 463.33	6380–6650	12	10
97/01/16	50 465.36	6380–6650	12	10
97/01/25	50 474.41	4080–4920	37	20
97/02/01	50 481.37	6380–6650	12	10
97/02/16	50 496.27	6300–6850	28	10
97/02/16	50 496.29	6380–6650	12	15
97/03/05	50 513.44	6300–6850	28	10
97/03/08	50 516.41	4080–4920	37	20
97/03/08	50 516.44	6380–6650	12	10
97/03/20	50 528.39	6300–6850	28	10
97/04/02	50 541.41	6300–6850	28	10
97/04/06	50 545.40	6380–6650	12	15
97/04/16	50 555.38	6380–6650	12	10
97/04/27	50 566.35	6380–6650	12	15
97/09/03	50 694.56	6380–6650	12	10
97/09/15	50 706.55	6380–6650	12	10
97/09/23	50 714.56	6380–6650	12	10
97/09/24	50 715.55	6380–6650	12	10
97/09/24	50 715.56	4200–5050	37	20
97/09/27	50 718.51	6380–6650	12	15
97/10/26	50 747.57	6380–6650	12	10
97/11/04	50 756.57	6380–6650	12	10

Demonstrating minor variations around the value 20 Å during 1980s, the EW of Hα has decreased more than twice by the beginning of 1990s. In the most recent spectra (1996–1997) the EW has varied mostly between 3 and 5 Å.

Fig. 3 presents the radial velocities of the components of Hα. Besides more or less occasional variations, there seems to be a slight tendency of decreasing the difference between the velocities of the red and violet emission components dur-

Table 2. Peak intensities, equivalent widths and radial velocities of the emission lines in the spectrum of WY Gem. The data have been averaged over time intervals indicated in the first and second rows. In the third row, number of averaged spectra is given

Spectral line	Year Dates n	1985 Feb. 06–09 2	1991/92 Dec. 14–Jan. 29 3	1994 Mar. 01–28 3	1996 Feb. 11–18 2	1997 Jan. 25–Sept. 23 3
Fe II λ4178	$I_{\max}$	1.60	–	1.13	1.08:	1.10:
	EW(Å)	0.88	–	0.20	*	*
Fe II λ4233	$I_{\max}$	2.15	*	1.20	–	1.06:
	EW(Å)	1.48	*	0.17	–	*
Fe II λ4583	$I_{\max}$	1.75	*	1.16:	–	–
	EW(Å)	1.40	*	*	–	–
[Fe ii] λ4244	$I_{\max}$	2.35	–	2.83	1.35	1.58
	EW(Å)	1.98	–	2.66	1.65	2.24
[Fe ii] λ4276	$I_{\max}$	1.60	1.42	1.75	1.15	1.28
	EW(Å)	0.79	0.42	0.88	0.58:	0.84
[Fe ii] λ4287	$I_{\max}$	2.30	1.77	2.88	1.33	1.64
	EW(Å)	1.41	0.83	2.25	1.39	1.85
[Fe ii] λ4319	$I_{\max}$	1.27	1.27	1.47	1.19	1.22
	EW(Å)	0.33:	0.32	0.44	1.00:	0.85
[Fe ii] λ4413	$I_{\max}$	1.70	1.56	1.75	–	1.28:
	EW(Å)	0.82	0.78	0.84	–	*
[Fe ii] λ4452	$I_{\max}$	1.45	1.32	1.46	–	1.19
	EW(Å)	0.55	0.34	0.50	–	0.31
[S ii] λ4068	$I_{\max}$	1.39	–	1.38	–	–
	EW(Å)	0.49	–	0.45	–	–
$v_{\rm r}$(Fe ii mean)	kms^{-1}	+24.7	–	+31.1	+28.9:	–
$v_{\rm r}$([Fe ii] mean)	kms^{-1}	+28.2	+21.2	+23.2	+25.0:	+22.9
$v_{\rm r}$([S ii] λ4068)	kms^{-1}	+34.6	–	+19.4	+9.4:	–

Asterisks (*) denote the cases when the line is visible in the spectrum, but not reliably measurable. Dashes (–) mean that the spectrum does not cover a given wavelength region, or the line is not identified. Data marked with colon (:) are uncertain.

ing the whole observational period. Even more remarkable is the decreasing of the difference between the velocities of the absorption and of the violet emission component, being lowest around JD 2 449 000 (1992–1994). This episode coincides with the lowest values of V/R observed. Such a correlation is quite natural, as weakening of the violet emission component can be considered as an apparent shift of the absorption component towards shorter wavelengths. But the reason for such variations remains unclear.

3.2. Other emission lines

In the blue-region spectrum of WY Gem, the most prominent emission lines are those of [Fe II]. Also, the emission line of [S II] λ 4068 Å is present in all our spectra covering the wavelength region shortward of 4080 Å. Emission lines of Fe II were strong in the spectra obtained in February 1985, with the strongest lines at λ 4233 Å and λ 4583 Å. Those and other emission lines of Fe II have become considerably weaker by March 1994 and almost disappeared by February 1996.

Fig. 4 presents a few examples of the blue-region spectrum of WY Gem. In Table 2 one can find a compilation of data on the emission lines of Fe II, [Fe II] and [S II]. The intensities and EW of those lines do not show significant differences on short time scales. The variations over years, however, are quite remarkable. So, we have averaged individual observations over the time periods, as indicated in Table 2. In the third row of the table caption the number of averaged spectra is given. One should note that, although the photographic spectra in 1985–1994 and the CCD spectra in 1997 have been recorded at the same dispersion, spectral resolution of the CCD spectra is somewhat lower than that of the photographic spectra. This difference may to some extent be responsible for the lower central intensities of the emission lines measured from the CCD spectra. Two spectra from 1996 are low-dispersion spectra (about 86 Åmm^{-1}) and actually are not comparable to the remaining ones.

Also given in Table 2 are RV, measured from the emission lines of Fe II (mean value), [Fe II] (mean value) and [S II] λ 4068 Å. The scatter of the velocities of individual lines is quite large, especially in the case of the CCD spectra. Errors of the given mean values are usually 10–15 kms^{-1}. Provided the error limits, one could conclude from Table 2 that RV of the emission lines essentially do not vary during the period from 1985 to 1997. Velocities of the forbidden lines, perhaps, have been slightly higher in 1985, than over the remaining time.

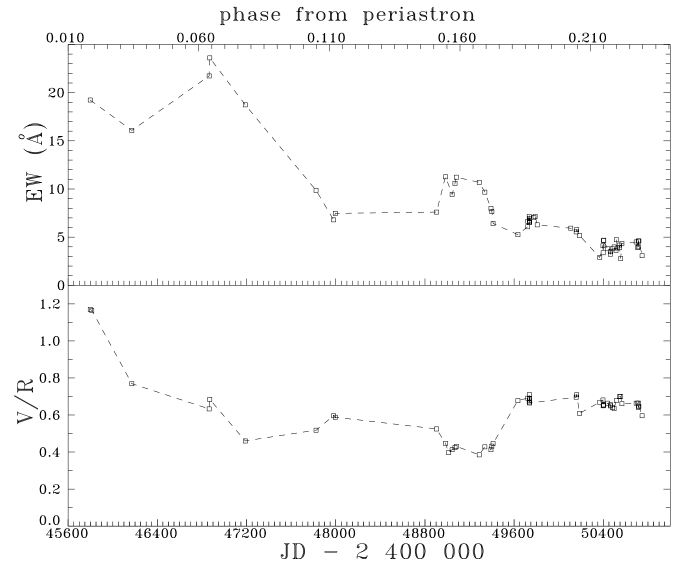

Fig. 2. Equivalent width and ratio of the emission peak intensities of the Hα line in the spectrum of WY Gem. Phase from periastron is calculated according to the orbital elements discussed in Sect. 4

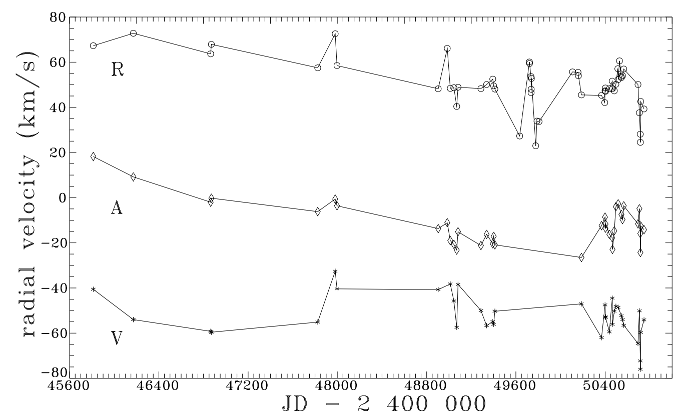

Fig. 3. Radial velocities of the components of Hα in the spectrum of WY Gem. R stands for the red emission component, A – absorption component, V – violet emission component

There is actually not enough data for making further conclusions about the long-term behaviour of the intensities of the forbidden lines. Monitoring over even still longer time interval would be necessary to address the problem of possible variations of the forbidden lines. In the case of the prototype star VV Cep, Hack et al. (1992) have found that both permitted and forbidden emission lines of Fe II are clearly associated with the M supergiant. This result disagrees with many previous studies. In a recent paper, Kawabata & Saitō (1997) again have found no essential variations of the [Fe II], [Ni II] and [Cu II] emission lines in the spectra of VV Cep obtained between 1976 and 1984. For another star Boss 1985 = KQ Pup, Cowley (1965) has found no significant variations of the forbidden lines between 1918 and 1964, while the permitted Fe II emissions are strongly correlated with the 27-year orbital period. Actually, the Fe II emission lines have been strong only during one third of the orbital period, for some years before and after the periastron passage. This fact should be kept in mind while discussing possible period and other orbital elements of WY Gem.

3.3. Radial velocities of the M2 supergiant

The time interval covered by our observations forms a small fraction of the proposed orbital period for WY Gem (up to 80 years). However, we have measured RV of the M2 supergiant in the WY Gem system, in order to use them together with the data available in the literature for deriving at least approximate orbital elements of the binary system. For the photographic spectra about 40 most likely unblended absorption lines in the spectral region 6100–6700 Å were selected from the tables by Moore (1945) and from the proposed list of lines for VV Cep by Wright (1977). Several of these lines, however, appear to be blended, or for some other reason yielded RV systematically deviating from the mean value by majority of the lines. Finally, depending on the quality of the spectrogram, about 15–30 lines belonging to Fe I, V I, Ti I, Ca I, Co I and Cr I were used for the RV measurements from the red-region spectra. In the blue spectral region, about 10–15 absorption lines of neutral metals were used for the same purpose.

Measurements of RV from the CCD spectra actually do not differ from those from the photographic spectra, except the fact that our CCD spectra, in general, have lower spectral resolution than the photographic ones. This, especially, concerns the spectra obtained in the observing season 1994/95 with the camera ST-6, which has pixel size 23x27 μm. The small field of the camera (375x242 pixels) together with poor resolution has allowed us to select only 6–8 lines for RV measurements. Those lines usually have shown large scatter of individual velocities. Thus, those RV are considered as the least reliable ones. Better sensitivity and wider linear extension of the camera HPC-1 have allowed us to record the spectra of WY Gem in a longer wavelength interval at a higher dispersion, and we could use about 10–14 good quality lines for the RV measurements.

RV have been measured, using the parabolic approximation of the line profile, or the method of bisector. Intrinsic errors of the measurement of one spectrum are usually 1–6 kms^{-1} for the photographic and the HPC-1 spectra, and about 10 kms^{-1} or more for the ST-6 spectra. A few spectra, however, have yielded radial velocities differing from most of the remaining values by 15–20 kms^{-1}. We have considered such differences as erroneous and excluded those spectra from further use. Table 3 lists the heliocentric RV of the M2 supergiant together with their mean errors.

4. Orbital elements of the binary system

There are no orbital elements of WY Gem available in the literature. Fortunately, several measurements of RV of the M2 supergiant, dating back to 1922, have been published. Cowley (1995) has communicated us a set of unpublished measurements made mostly from the plates of Lick, Kitt Peak and Flagstaff observatories. Unfortunately, those data are available only as a plot.

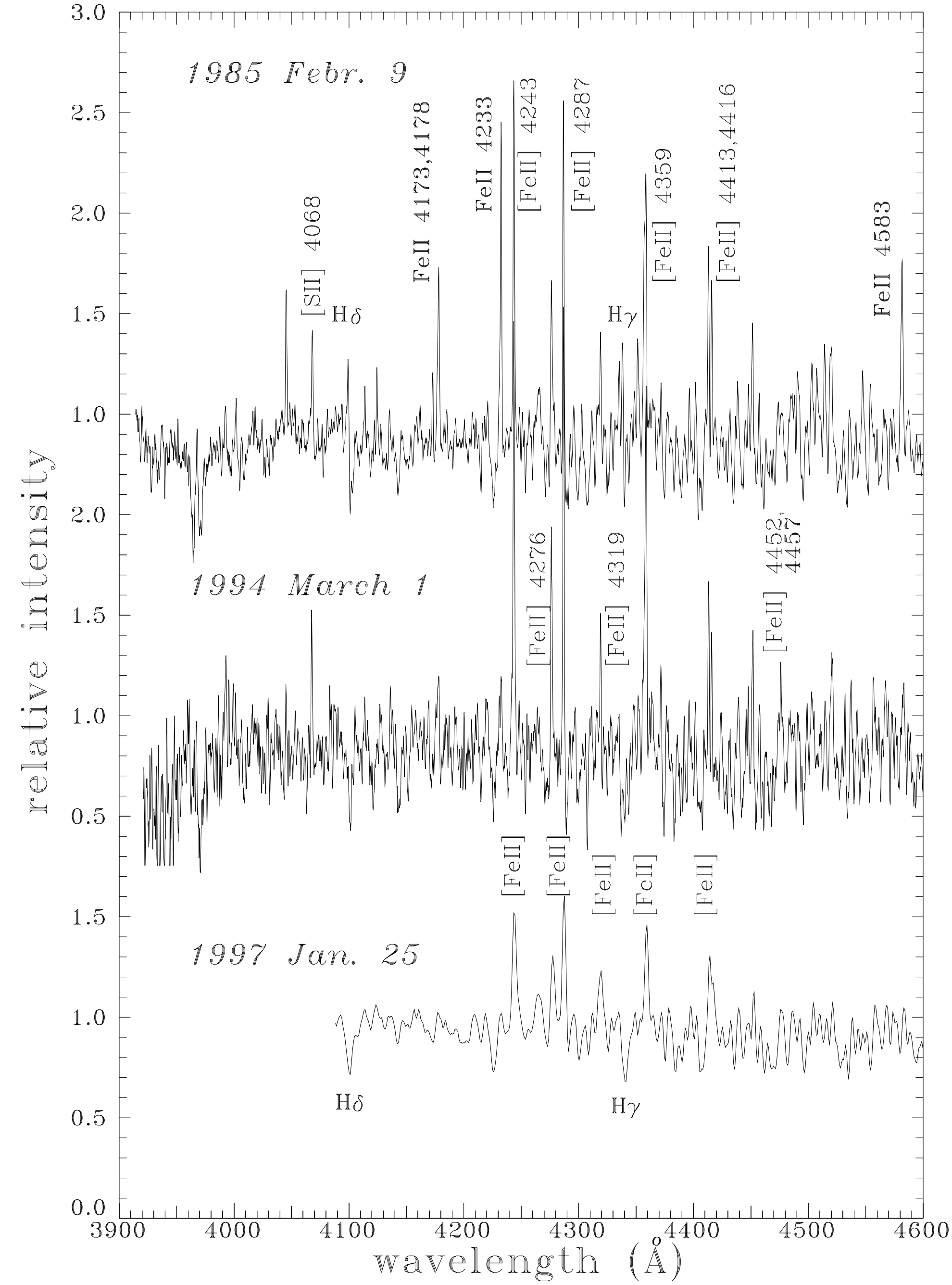

Fig. 4. Some examples of the blue-region spectrum of WY Gem. Note that emission lines of Fe II and H have almost disappeared between 1985 and 1994 while the forbidden lines of [Fe II] show no variations

Thus, the accuracy of these velocities as well as of dates is low. The same concerns the paper by Burki & Mayor (1983), from which some approximate data for the period 1979–1982 could be obtained (however, those velocities occured to be very important when deriving orbital elements). Two data points measured by CORAVEL have been received from Samus (1996) as a private communication. Table 4 lists all the collected RV for WY Gem.

All the available RV for WY Gem have been used in an attempt to derive orbital period and other elements of the binary system. Of course, it is somewhat dangerous to combine data collected over such a long time interval with different instruments and techniques. Given also large uncertainties of some RV, especially of those obtained from our ST-6 spectra, one cannot have much confidence in any orbital solution.

Fig. 5 displays all the RV from Tables 3 and 4, except those measured from the ST-6 spectra (between JD 2 449 633 and 2 449 807). As already mentioned, those velocities have the largest uncertainties. Several attempts to find orbital solutions with and without those velocities resulted in only minor differences in the orbital elements obtained, and for the sake of clarity we have excluded those velocities from Fig. 5 as well as from calculations of the orbital elements.

Table 3. Radial velocities from the absorption lines of the M2 supergiant in the spectrum of WY Gem measured from observations at the Tartu Observatory

JD 2 400 000+	v_r kms^{-1}	error kms^{-1}	JD 2 400 000+	v_r kms^{-1}	error kms^{-1}
45 812.35	24.1	7.8	50 142.43	13.3	5.4
46 103.52	14.2	3.3	50 152.39	17.4	7.9
46 171.38	29.3	3.8	50 156.39	12.4	4.4
46 864.44	22.8	5.0	50 160.39	12.5	4.4
46 870.40	28.7	4.4	50 187.32	16.8	2.9
47 188.44	11.1	4.0	50 367.45	6.4	6.9
47 980.38	10.8	1.2	50 396.50	6.4	5.8
47 996.34	2.0	3.9	50 398.44	7.7	7.9
48 903.48	13.4	5.5	50 402.43	5.8	7.7
49 011.51	9.1	4.4	50 403.45	7.2	8.4
49 044.37	6.3	3.8	50 437.42	10.1	4.4
49 069.38	9.4	1.9	50 448.27	12.7	7.4
49 081.33	10.7	1.8	50 463.33	3.3	5.9
49 286.47	12.5	2.1	50 465.36	15.7	4.5
49 337.50	10.2	3.4	50 481.37	10.8	2.9
49 392.31	10.1	1.9	50 496.27	11.2	2.4
49 400.37	13.9	2.7	50 496.29	13.9	5.8
49 411.41	10.6	3.6	50 513.44	13.8	6.6
49 433.36	11.3	4.7	50 516.44	11.5	4.3
49 633.55	12.6	10.8	50 528.39	19.2	8.6
49 722.44	27.2	13.1	50 541.41	12.8	5.6
49 735.29	30.0	16.2	50 545.40	10.5	3.0
49 736.28	19.2	14.3	50 555.38	12.6	2.4
49 737.30	22.7	13.9	50 566.35	14.6	3.1
49 739.30	27.6	11.8	50 694.56	10.7	3.3
49 777.47	25.8	16.7	50 706.55	18.9	2.2
49 788.29	16.9	12.3	50 714.56	9.1	5.0
49 807.37	18.8	10.3	50 715.55	9.8	1.8
50 107.42	24.7	11.2	50 718.51	15.5	1.7
50 122.28	15.0	6.6	50 747.57	17.5	9.4
50 132.34	14.5	4.6			

It is evident from Fig. 5 that besides long timescale (decades) variations, the velocities are variable on shorter (about one or few years) timescale. For comparison, the bright supergiant α Orionis, whose spectral class and luminosity are close to those of the cool component of WY Gem is known to show a modulation of brightness and radial velocities with a period of 5.8 years, and possibly also 11 years. Smith et al. (1989) have also found RV variations on a timescale of about 400 days with an amplitude up to 6 kms^{-1}. From the same observations, Dupree et al. (1990) have suggested a period 420 days for α Ori and ascribe this to stellar pulsations in the fundamental mode. De Jager & Eriksson (1992) have found similar period (440 days) in the ultraviolet brightness and RV of α Ori, but they ascribe those variations to gravity waves propagating in the extended photosphere of the supergiant. Our data for WY Gem have not sufficient accuracy and time coverage for detecting similar periodicities, but their presence seems to be likely. Finally, one should note that for the prototype star VV Cep, brightness variations with a period as short as 116 days have been detected (Saitō̄ et al. 1980).

Orbital elements for WY Gem have been estimated by a classical Lehman-Filhés method applied to a least-square fit of the radial velocity curve. This has been performed by the computer code kindly delivered to us by Szczerba (1987) as a personal communication. It is quite apparent from Fig. 5 that orbital periods below 40–50 years are unlikely. The best solution indicated in Fig. 5 as a solid line corresponds to a period $P = 23\,550$ days (about 64.5 years). If the period is really that long, the usual period analysis has not much sense, since the time span of the data is only slightly more than one period. Formally, a period about twice shorter, $12\,900$ days has also shown to be significant. As one can see from Fig. 5, the dashed curve corresponding to that period fits even better the CORAVEL measurements in 1979–1982, but there is no fit between about 1955 and 1970.

Approximate orbital elements for WY Gem are given in Table 5. The errors should be considered as formal only, because of large scatter of the observational points. There are, however, another arguments in favour of the 64-year orbit with large ec-

Table 4. Radial velocities of the M2 supergiant in the WY Gem system available from literature and private communications

JD 2 400 000+	v_r km s^{-1}	Error km s^{-1}	Reference	Remarks
23 071.15	17.1	0.5	Abt 1970	
23 072.21	21.1	1.0	”	
23 090.33	16.4	1.9	”	
26 191	10.0	~ 3.0	Cowley 1995	measured from a plot
26 338.78	15.0	≤ 2.5	Redman 1938	
27 745	7.4	~ 3.0	Cowley 1995	measured from a plot
28 498	8.4	~ 3.0	(private communication)	”
28 513	20.9	~ 3.0	”	”
28 591	14.6	~ 3.0	”	”
33 366	20.8	~ 3.0	”	”
33 443	19.2	~ 3.0	”	”
33 639	18.5	~ 3.0	”	”
33 743	17.1	~ 3.0	”	”
33 927	18.4	~ 3.0	”	”
34 016.5	17.1	?	Babcock 1958	
35 311	22.5	~ 3.0	Cowley 1995	measured from a plot
35 372	20.5	~ 3.0	(private communication)	”
37 094	18.5	~ 3.0	”	”
37 156	20.5	~ 3.0	”	”
37 488	23.9	~ 3.0	”	”
37 580	22.7	~ 3.0	”	”
39 837.5	28.0	2.0	Mammano & Martini 1969	
39 928.5	33.8	3.0	”	
40 070	27.9	~ 3.0	Cowley 1995	measured from a plot
40 302	29.7	~ 3.0	(private communication)	”
40 609	30.5	~ 3.0	”	”
40 732	30.0	~ 3.0	”	”
43 917	37.0	~ 3.0	Burki & Mayor 1983	measured from a plot
44 201	37.2	~ 3.0	”	(CORAVEL)
44 545	40.0	~ 3.0	”	”
44 616	41.6	~ 3.0	”	”
44 660	41.5	~ 3.0	”	”
45 004	47.1	~ 3.0	”	”
45 236	44.3	~ 3.0	”	”
45 262	45.2	~ 3.0	”	”
45 317	44.4	~ 3.0	”	”
48 328.255	11.9	0.5	Samus 1996	CORAVEL
49 252.579	10.9	0.4	(private communication)	”

centricity. As mentioned in Sect. 3.2, the permitted emission lines of Fe II in the spectrum of WY Gem have been strong in 1985, considerably weaker in 1991–1992, and almost disappeared by mid-1990s. According to historical data communicated by Cowley (1995), the same lines have been strong in 1922 and very weak in mid-1930s. For a similar star KQ Pup, Cowley (1965) and Rossi et al. (1992) have found the Fe II emission lines to be strong only for some years before and after the periastron passage. It is difficult to locate exactly the region where the Fe II lines are formed, but it is natural to assume that Fe II lines could be stronger around the periastron passage, as there could be more matter ionized by the radiation of the hot star. Thus, behaviour of the Fe II lines in the WY Gem system is consistent with the periastron passage to have occured in 1983, and the previous one in 1919. At the same time, RV of the forbidden lines are consistent with the derived γ-velocity (22.0 kms^{-1}), assuming that the forbidden lines originate from an extended envelope surrounding the whole system.

Hydrogen Balmer emission lines in the spectra of VV Cep type stars also are known to be stronger around the periastron passage (Cowley 1965, 1969). Variations of the strength of higher members of the Balmer series in the spectra of WY Gem have been similar to those of the Fe II lines (Cowley 1995). Unfortunately, there are no earlier data for the Hα line available, but our observations from 1984 to 1997 seem to support the suggestion of periastron passage to have occured in 1983. As seen in Figs. 1 and 2, EW and intensities of the emission peaks of Hα have secularly decreased since the beginning of

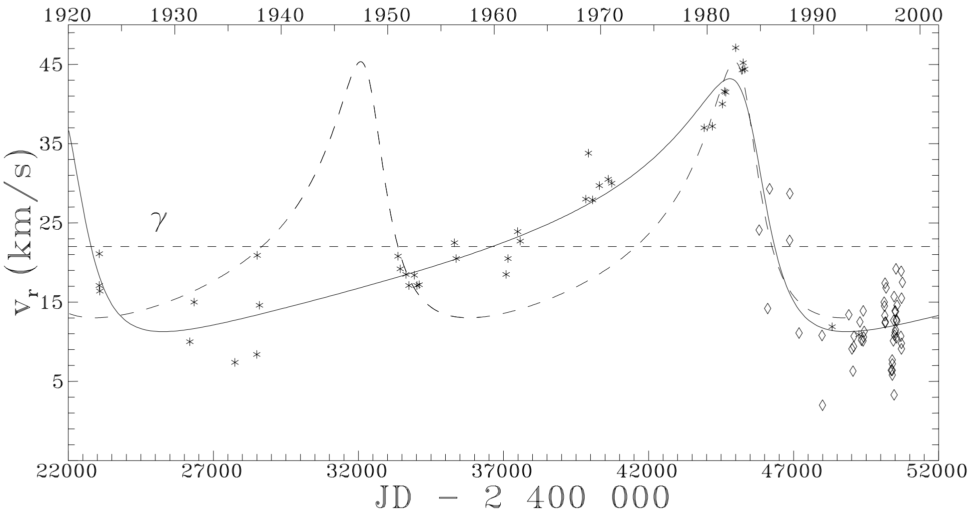

Fig. 5. Radial velocity curve for WY Gem. Diamonds mark observations in the present paper, asterisks those collected from the literature. Solid curve corresponds to the orbital period 23 550 days, dashed curve to the period 12 900 days

Table 5. Orbital elements for WY Gem

Element	Value
Period P (days)	$23\,550 \pm 250$
T_0 (periastron) (JD)	$2\,445\,620 \pm 130$ (Oct 12, 1983)
Semiamplitude K (kms^{-1})	16.0 ± 0.9
Eccentricity e	0.61 ± 0.03
Longitude ω (degr)	57.5 ± 4.5
γ-velocity (kms^{-1})	22.0 ± 0.5
Mass function $f(M)(M_{\odot})$	4.9 ± 0.6
$a \cdot \sin i$ (km)	$(4.09 \pm 0.19) \cdot 10^9$

our observations in April 1984, less than a year after the assumed periastron passage. Large orbital eccentricity ($e = 0.61$) should contribute to the enhancement of the effects of the periastron passage. In VV Cep, on the other hand, the eccentricity is smaller ($e = 0.34$), and the Fe II and Balmer emission lines are observable throughout all the orbital cycle, except during the eclipse of the hot component.

Effects of the periastron passage should be observable also in the ultraviolet spectra. Inspection of the IUE archives showed that only 8 spectra of WY Gem have been obtained, covering the period from December 31, 1978 to January 29, 1980. Such a time interval which does not cover the possible periastron passage time is presumably too short for detecting any significant changes in the UV spectrum. A short description of the UV spectrum of WY Gem will be given in Sect. 6.

5. Is WY Gem an eclipsing system?

Spectroscopic data give no direct information about the orbital inclination i. The prototype star VV Cep is a well-known eclipsing system with $i = 76^{\circ}.7$ (Wright 1977). Total eclipse of its hot component is preceded and followed by an atmospheric eclipse, when the B star shines through the extended atmosphere of the M supergiant. This results in sharp shell absorption lines of ionized metals in the spectrum of VV Cep. Duration of the atmospheric phase of the eclipse has been different in different orbital cycles, very roughly it can be taken as 400 days for both ingress and egress (Saitō et al. 1980).

The spectra of WY Gem taken in 1960 and 1961 contained numerous sharp absorption lines shortward of 3800 Å, belonging mainly to Ti II and Mn II. By the fall of 1968 the shell-type absorptions were extremely pronounced and extended longward at least to Hγ (Cowley 1968, 1970). The shell absorption lines have been weaker again in 1969 and 1970. Cowley (1970) has interpreted those phenomena as early stages of ingress in early 1960s, the totality in 1967 or early 1968, and egress from the eclipse in 1969–1970. Alternatively, the inclination may not be sufficiently large to allow the total eclipse; strengthening of the shell lines could be due to a close, grazing atmospheric eclipse.

The eclipse interpretation of the events in 1960s is consistent with our approximate radial velocity curve, with the eclipse occuring on the rising branch of the velocity curve, preceding the periastron passage. On the other hand, as far as we do not know, whether the eclipse has been a total or an atmospheric one, we cannot derive much information about the inclination i of the orbital plane from this fact. Presumably i should be greater than 60° for atmospheric eclipse to be seen. If we take the mass of the M supergiant equal to 20 $M_{\odot}$, as it has been found for VV Cep (Wright 1977), the mass function $f(M) = 4.9 M_{\odot}$ yields the mass of the hot star in the range from 15 to 20 $M_{\odot}$, depending on the inclination. Such a mass range fits satisfactorily the spectral class early B assumed for the hot component. Of course, one should keep in mind that value of the mass function depends critically on the semiamplitude of the velocities K which is known only approximately.

The eclipse of the hot component should probably be visible photometrically, too, at least in the ultraviolet. Photometric observations of WY Gem are quite scarce. All the UBVRI data found so far, are presented in Table 6. While variations in the R and I bands are insignificant, one could easily detect a rapid increase in the U brightness between December 1967 and March 1969. Less pronounced variations can be seen in the B and V

Table 6. Photometric UBVRI observations of WY Gem, collected from the literature

JD	Date	U	B	V	R	I	Reference
2 439 833	08.12.67	10.24	9.20	7.38	5.58	4.04	Lee 1970
40 284	03.03.69	9.38	8.89	7.17			Fernie 1972
40 285	04.03.69	9.49	8.98	7.27			”
41 281	25.11.71	9.36	8.94	7.15	5.46	3.95	Wawrukiewicz & Lee 1974
45 789	29.03.84	9.12	8.96	7.27	5.58		Taranova 1986
45 790	30.03.84	9.32	8.95	7.25	5.58		”
48 553	23.10.91	9.32	8.92	7.28	5.45	3.92	Miroshnichenko & Ivanov 1993
48 554	24.10.91	9.38	8.95	7.30	5.46	3.97	”
48 932	05.11.92	9.43	9.01	7.28	5.35	3.98	”

bands at the same time. Such variations again are consistent with an assumption about the eclipse of the hot component in late 1960s and egress from the eclipse in 1969–1970.

There are not enough published photometric observations available from the time after eclipse. Such observations could serve as additional confirmation of the proposed orbital elements, as the rising activity of the hot component around the periastron passage would probably reflect in the ultraviolet brightness. However, P. Kalv from Tallinn Observatory, Estonia has kindly made available for us a set of UBVR observations of WY Gem, made by him from 1984 to 1996. Those preliminary data, although not reduced to the standard Johnson system, show erratic or sometimes semiregular variations by about 0.2 magnitude in the B, V and R bands. But in the U band, in addition to more or less occasional variations there is a secular tendency of decreasing by about 0.4 magnitude from 1984 to 1996. This again supports our conclusion about the periastron passage in 1983. Mass transfer, likely taking place in the WY Gem system around the time of periastron passage, increases the amount of matter near the hot component, giving rise to strengthening of both the emission lines and the near-ultraviolet continuum.

6. Nature of the hot component

Nature of the hot components of VV Cep type stars is still debatable. While it is accepted that the hot component is a B (or late O or early A) type main-sequence star, it is not clear which physical processes could take place in the environment of the hot star and where the emission lines are formed. For VV Cep, a rotating accretion-disk-like envelope around the B star has been proposed (Möllenhoff & Schaifers 1981; Kawabata et al. 1981; Saijo 1981). For KQ Pup, Rossi et al. (1992) have considered a model in which stellar winds from the M supergiant and from the B star are colliding, forming a shock front and an extended turbulent region close to the B star. In the latter, probably the high-ionization UV absorption lines (C IV, Si IV, N V etc.), observed in the IUE spectra of KQ Pup, are formed (Altamore et al. 1982; Rossi et al. 1992). The UV spectrum of WY Gem is dominated by the absorption lines of neutral and singly-ionized species (O I], P I, Si I, Ni I, Fe II, C II, Ni II, Si II, V II etc.), but a few lines from higher ionization stages (P III, Al III, Fe III, O III, Ni III, N IV etc.) also exist (Buss & Snow 1988; Sahade et al. 1984). Also, the resonance doublets of Si IV $\lambda\lambda$ 1393, 1402 Å and C IV $\lambda\lambda$ 1548, 1550 Å are quite strong. But the Fe II emission at λ 1786 Å, present in the spectrum of KQ Pup and a few other VV Cep type stars has not been observed in the IUE spectra of WY Gem. From the above information Buss & Snow (1988) have derived spectral class B2 for the hot component of WY Gem.

Saijo (1981) has modelled the envelope of the hot star in VV Cep as a rotating Keplerian disk. From calculating the Hα profiles and comparing them to the observed ones, he has derived the inner and outer radius of the disk 13 $R_\odot$ and 500 $R_\odot$, respectively. Double-peaked emission profile of Hα in the spectrum of WY Gem may also imply a rotating disk-like structure around the hot star. Orbital period and separation of stars in the WY Gem system are greater than those in VV Cep. Large orbital eccentricity of WY Gem ($e = 0.61$), however, could bring the two stellar components in periastron about as close as in the VV Cep system (1600–1800 $R_\odot$). Radius of the photosphere of the M2 supergiant may approach a similar value, and so some mass transfer to the hot star can be considered possible. On the other hand, Theuns & Jorissen (1993) have shown that formation of an accretion disk would be possible even in the case of wind accretion, if the flow is isothermal. The disk could be asymmetric in this case.

The phenomenon of colliding winds usually is considered to take place in binaries containing O-type or Wolf-Rayet stars (e.g. Gies et al. 1993; Thaller 1997). The same phenomenon, most likely, takes place in symbiotic novae where the primary is a white dwarf undergoing a thermonuclear outburst (Girard & Willson 1987; Mürset et al. 1997). Zamanov (1993) has found that, under certain conditions, winds may interact also in detached binaries like VV Cep type stars. He has elaborated an approximate criterion, allowing one to judge whether accretion from stellar wind or winds' collision could take place. This criterion (formula (3) in Zamanov 1993) contains many quantities which are not known for WY Gem, such as mass loss rates and wind velocities for both the cool and hot star, relative velocity of the stars, etc. However, applying the available mean data for a given spectral and luminosity class together with approximate orbital elements, derived in the present paper, we have found that in the WY Gem system accretion of the M supergiant wind

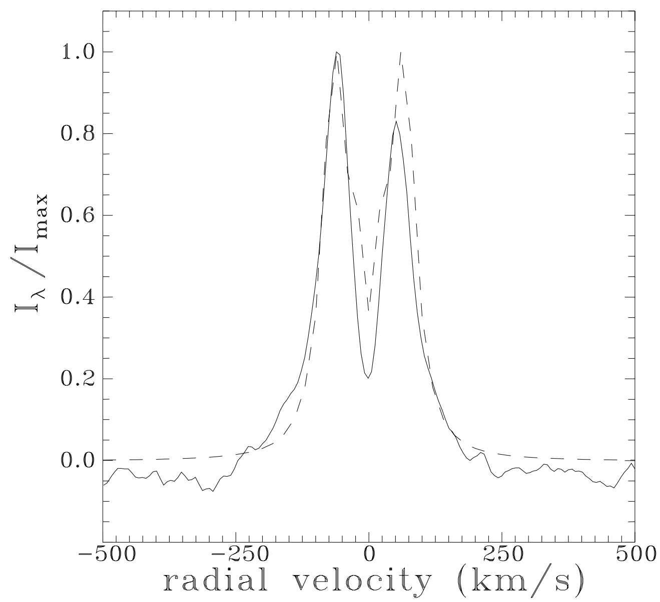

Fig. 6. Comparison of the observed and computed profiles for Hα. Solid line is the observed profile from April 7, 1984. Dashed line is computed (see text) for a model with a mass of central star 14 $M_\odot$, inclination $i = 70°$, and inner and outer radius of the disk 12 and 550 $R_\odot$, respectively

by the B star is more likely than collision of the winds of both stars. The above mentioned difference between the UV spectra of WY Gem and KQ Pup may provide support for this conclusion.

We tend to favour for WY Gem a model in which the B star is accreting matter from the wind of the M supergiant during and around the time of periastron passage. Applying the technique by Saijo (1981) for calculating the Hα profiles arising in a rotating disk yields satisfactory agreement between calculated and observed profiles also for WY Gem. Even better results are obtained, when one calculates Hα profiles by a more elaborate method by Horne & Marsh (1986), which takes into account the geometrical thickness of the disk. Leedjärv et al. (1994) have applied this method to the symbiotic star CH Cyg. By similar calculations, agreement between theoretical and observed Hα profiles can be achieved. One example from a time near the periastron passage is given in Fig. 6.

One should, however, be aware that fit between the profiles could be formal. We do not know exactly, where the Hα line is formed. It is likely that some additional absorption could take place in the wind of the M supergiant. The Hα absorption line could arise also in the photosphere of the M supergiant. So, we have not paid much attention to precise fitting of the absorption component between the two emission peaks. And, of course, the real Hα line in the spectrum of WY Gem is asymmetric, with the ratio V/R ranging from 0.39 to 1.1. If really, wind accretion takes place, one could consider asymmetric accretion disk, asymmetry of which is depending on the separation of the stellar components.

Recently, Plavec & Smak (1997) have modelled an eccentric accretion disk in the Algol-type binary KU Cyg. In spite of much different orbital separation and nature of stellar components, one cannot exclude somewhat similar configuration to exist in WY Gem. Still we can conclude that physical conditions in the WY Gem system near the periastron passage are similar to those in the prototype system VV Cep, and formation of the accretion disk can be considered possible. Secular weakening of the Hα emission line since 1984 can be considered as an evidence of vanishing the accretion disk after the periastron passage in 1983. More rigorous modelling of the Hα profile, including explanation of the V/R variations remains a future work.

7. Conclusions

Thirteen years of observations together with the other published and unpublished observational data have allowed us to specify some parameters of the long-period binary star WY Gem. Main results of the present work can be drawn up as follows:

1. For the first time, approximate orbital elements of the binary system WY Gem have been found, with $P \approx 64$ yr, $e = 0.61$ and periastron passage time on about JD 2 445 620 (October 1983).
2. Additional confirmation of the proposed orbital elements is obtained from the variations in the emission lines of Hα and Fe II.
3. Forbidden emission lines of [Fe II] and [S II] do not exhibit significant variations over the period of observations, implying their origin in an extended envelope surrounding the whole system.
4. Scarce photometric observations support the orbital elements with periastron passage having occured in 1983. Also, photometric data indicate that the WY Gem system has undergone an eclipse of the hot component in 1960s.
5. Hot component of the WY Gem system most likely is a B2V star which near the time of periastron passage is surrounded by asymmetric accretion disk. Formation of a colliding-winds region is less probable.

The latter conclusion, however, needs further analysis, including modelling of the Hα profiles in the framework of various models with disks or other geometrical configurations. Also, it would be important to have precise radial velocity measurements for WY Gem over a long time span, thus improving the orbital elements, which finally should lead to a better understanding of the basic parameters and the evolutionary status of the VV Cep type stars.

Acknowledgements. The author wishes to remember his late supervisor Prof Lauri Luud (1933–1989) who recommended including WY Gem in the observing program. MSc Alar Puss deserves special thanks for recording many CCD spectra of WY Gem since early 1996. The author thanks Dr Indrek Kolka for obtaining a few spectra, Dr Kalju Annuk for useful advice in the course of processing the spectra and Dr Jaan Pelt for help with the period analysis. Special thanks are due to Prof Anne P. Cowley from Arizona State University for communicating valuable historical information on WY Gem. The author thanks also Dr Peep Kalv from Tallinn Observatory for unpublished photometric observations, Dr Nikolai Samus from Shternberg State Astronomical Institute (Moscow) for providing a few radial velocity measurements by CORAVEL, and finally, Dr Michael Friedjung from Paris Institute of Astrophysics for fruitful discussions and the anonymous referee for useful suggestions. This work has been supported by the Estonian Science Foundation grant No. 827.

References

Abt H. A., 1970, ApJS 19, 387
Altamore A., Giangrande A., Viotti R., 1982, A&AS 49, 511
Altenhoff W. J., Thum C., Wendker H. J., 1994, A&A 281, 161
Annuk K., 1986, Estonian Academy of Sciences, Preprint A-5
Babcock H. W., 1958, ApJS 3, 141
Bidelman W. P., 1954, ApJS 1, 175
Bidelman W. P., Stephenson C. B., 1956, PASP 68, 152
Burki G., Mayor M., 1983, A&A 124, 256
Buss R. H. (Jr.), Snow T. P. (Jr.), 1988, ApJ 335, 331
Che A., Hempe K., Reimers D., 1983, A&A 126, 225
Cowley A. P., 1965, ApJ 142, 299
Cowley A. P., 1968, IAU Circ. 2108
Cowley A. P., 1969, PASP 81, 297
Cowley A. P., 1970, PASP 82, 329
Cowley A. P., 1995, private communication
de Jager C., Eriksson K., 1992, In: de Jager C., Nieuwenhuijzen H. (eds.) Instabilities in Evolved Super- and Hypergiants. North Holland, Amsterdam, p. 117
Dupree A. K., Baliunas S. L., Guinan E. F., Hartmann L., Sonneborn G., 1990, In: Cassiari C., Clementini G. (eds.) Confrontation between Stellar Pulsation and Evolution, PASPC 11, p. 468
Fernie J. D., 1972, PASP 84, 528
Gies D. R., Wiggs M. S., Bagnuolo W. G. (Jr.), 1993, ApJ 403, 752
Girard T., Willson L. A., 1987, A&A 183, 247
Hack M., Engin S., Yilmaz N. et al., 1992, A&AS 95, 589
Hjellming R. M., 1985, In: Hjellming R. M., Gibson D. M. (eds.) Radio Stars. Reidel, Dordrecht, p. 151
Horne K., Marsh T. R., 1986, MNRAS 218, 761
Humason M. L., 1922, PASP 34, 133
Humphreys R., 1978, ApJS 38, 309
Kawabata S., Saijo K., Sato H., Saitō M., 1981, PASJ 33, 177
Kawabata S., Saitō M., 1997, PASJ 49, 101
Lee T. A., 1970, ApJ 162, 217
Leedjärv L., Miko ajewski M., Tomov T., 1994, A&A 287, 543
Mammano A., Martini A., 1969, In: Non-Periodic Phenomena in Variable Stars. IAU Colloq., Budapest, p.415
Miroshnichenko A. S., Ivanov A. S., 1993, SvALett 19, 919
Möllenhoff C., Schaifers K., 1981, A&A 94, 333
Moore C. E., 1945, A Multiplet Table of Astrophysical Interest. Contr. Princeton Univ. Obs. No. 20, Princeton
Mürset U., Wolff B., Jordan S., 1997, A&A 319, 201
Redman O., 1938, Publ. Dom. Obs. Victoria 6, 27
Rossi C., Altamore A., Baratta G. B., Friedjung M., Viotti R., 1992, A&A 256, 133
Sahade J., Brandi E., Fontenla M., 1984, A&AS 56, 17
Saijo K., 1981, PASJ 33, 351
Saitō M., Sato H., Saijo K., Hayasaka T., 1980, PASJ 32, 163
Smak J. I., Plavec M. J., 1997, Acta Astron. 47, 345
Smith M. A., Patten B. A., Goldberg L., 1989, AJ 98, 2233
Taranova O. G., 1986, Astron. Tsirk. 1467, 7 (in Russian)
Thaller M. L., 1997, ApJ 487, 380
Theuns T., Jorissen A., 1993, MNRAS 265, 946
Wawrukiewicz A. S., Lee T. A., 1974, PASP 86, 51
White N. M., Wing R. F., 1978, ApJ 222, 209
Wright K. O., 1977, J.R. Astron. Soc. Can. 77, 152
Zamanov R. K., 1993, Observatory 113, 260