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Spectroscopic and photometric observations of the short-period RS CVn-type star CG Cyg*

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Abstract. Spectroscopic observations around the H_α line and *BVR* photometry of the eclipsing short-period RS CVn-star CG Cyg are presented. The solutions of the radial velocity curves and the light curves yielded the following masses and radii of the star components: $M_1 = 0.97\ M_\odot$, $M_2 = 0.80\ M_\odot$, $R_1 = 1.00\ R_\odot$, $R_2 = 0.83\ R_\odot$. The measured rotational broadenings of the observed lines correspond to equatorial velocities $V_1 = 80$ km s^{-1} and $V_2 = 66$ km s^{-1}. The distortions of our multicolor light curve were reproduced by two cool spots on the primary star. The strong absorption feature between the spectral lines of the two stars was explained by extended structure around the mass center of the system. The H_α emission line of the secondary star in the August spectra was attributed to a prolonged flare of this star.

Key words. stars: activity – binaries: eclipsing – binaries: spectroscopic – stars: chromospheres – stars: individual: CG Cyg – stars: starspots

1. Introduction

The high level of activity of the RS CVn-stars is attributed to the deep convective zone and the fast rotation of their components which drives the dynamo mechanism.

The eclipsing binary star CG Cyg (G9+K3) is a member of the subgroup of short-period RS CVn systems (with orbital periods less than a day). Their components are MS stars while long-period RS CVn binaries consist of giant/subgiant+MS star. The components of the short-period RS CVn's are relatively close to filling the Roche lobes and exhibit different signs of magnetic activity. Investigations in different spectral ranges indicate coronal and chromospheric activity as a general characteristic of these binary systems. Starspot models have been invoked in order to explain the irregularities of their light curves although some of the observed features can be explained by extinction effects of extra-photospheric extended structures.

The eclipses of the star CG Cyg were discovered by Williams (1922). The observations since that time (Yu 1923; Milone et al. 1979; Jassur 1980; Sowell et al. 1987; Naftilan et al. 1987; Bedford et al. 1987; Dapergolas et al. 1989a, 1994; Zeilik et al. 1989, 1991, etc.) have shown that the light curve of CG Cyg is variable (with different depths of the eclipses and different slopes in both quadratures). Small-scale "bumps" are observed sometimes on the shoulders of the light curve (Jassur 1980; Zeilik et al. 1982; Beckert et al. 1989; Dapergolas et al. 1991).

Bedford et al. (1987) detected a depression at the orbital phase 0.3 (a "third minimum") and suggested the presence of circumstellar material located in the orbital plane. Short time flare-like eruptions were observed also around this orbital phase.

Milone & Ziebarth (1974) noted a decrease of the orbital period after 1967. The variability of the orbital period was confirmed later by other authors (Zeilik et al. 1982; Dapergolas et al. 1989b, 1992; Hall 1991). Sowell et al. (1987) noted that the mean light level outside of the eclipses increased by 15% during 1967-1980.

The observed infrared excess of CG Cyg (Milone 1975; Bedford et al. 1987) was attributed to circumsystem material (Davies et al. 1987). The star also presents a UV excess (Naftilan & Milone 1985).

Naftilan & Milone (1979) detected a third emission component in the CaII H and K lines near the quadrature and suggested that it originated from gas concentrated in the L_1 point or in a shell around the whole system. Lazaro & Arevalo (1997) found an H_α emission excess from both stars of CG Cyg. They established that the total H_α and H_β emission excesses change during the orbital cycle, which implies surface inhomogeneous emission. The ratio of the emission excesses of the H_β and

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H_α line is typical for plage-like structures (Lazaro & Arevalo 1997).

The star CG Cyg is well-studied photometrically but there are only two radial velocity solutions (Popper 1994; Naftilan & Milone 1985) with quite different values. This leads to a poor determination of the global parameters of the system. We observed this binary in order to obtain a new radial velocity solution and to investigate the photometric and spectral appearances of its activity.

2. Observations

Our multicolor photometry of CG Cyg was obtained during 4 nights at the beginning of August 1998 by a two-channel photometer mounted on the 60-cm telescope (Kreiner et al. 1993) of the Mt. Suhora Observatory. The telescope is equipped with an autoguider (Krzesinski & Wojcik 1993). We used as a comparison star BD+34° 4220. A calibration of the channels and observation of the check star BD+34° 4213 (Sp K2, $V = 6\overset{\mathrm{m}}{.}6$) was made every night. The integration times were 10 s in the V and R colors and 15 s in the B color. The errors of the individual points do not exceed $0\overset{\mathrm{m}}{.}01$.

The data were phased according to the ephemeris (Kreiner et al. 2001)

$$\mathrm{HJD(MinI)} = 2439425.1176 + 0.631143114 * E \qquad (1)$$

and Fig. 1 presents the complete light curve.

CG Cyg was also observed in the spectral range around the H_α line with resolution 0.19 Å/pixel on two consecutive nights in May 2001 (spectral range 6500–6700 Å) and two consecutive nights in August 2001 (spectral range 6470–6670 Å). We used a CCD camera Photometrics AT200 with SITe SI003AB 1024 × 1024 pixel mounted on the Coude spectrograph (grating $B\&L632/14.7°$) of the 2-m telescope of the National Astronomical Observatory at Rozhen (Bulgaria). The seeing during the observations did not exceed 2 arcsec ($FWHM$). The exposure time was 20 min and the S/N ratio around 60-90. The bias frames and flat-field integrations were obtained at the beginning and end of each night. All stellar integrations were alternated with Th-Ar comparison source exposures. The data were reduced in a standard way (bias substraction, flat-field division and wave-length calibration) using the software packages PCIPS (Smirnov et al. 1992) and Rewia (Borkowski 1988).

In addition to the H_α line there are several lines in the observed ranges that show orbital variability. They are FeI 6678 Å, FeI 6593 Å and CaI 6494 Å. An appropriate Fourier noise filter was applied to the weaker lines of FeI in order to remove the high-frequency noise. This procedure causes some smoothing of the profiles without loss of their main details (Gray 1992).

Figure 2 presents the whole spectra around the second quadrature from the May and August run while the detailed profiles of the investigated lines are shown in Figs. 3–6 together with the corresponding orbital phases.

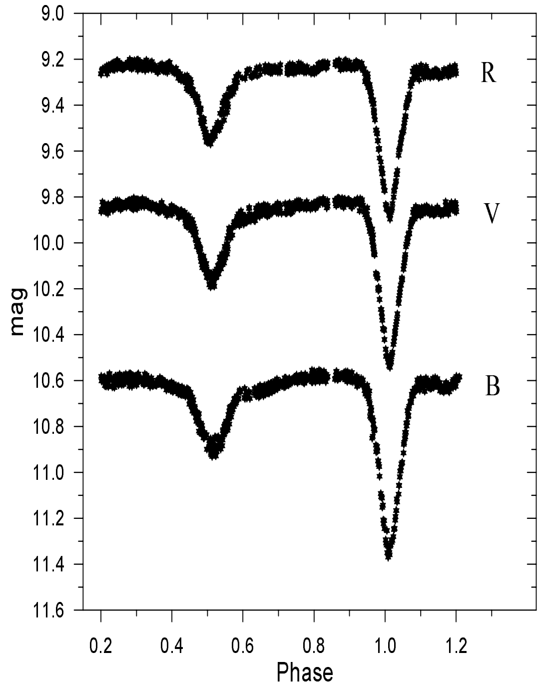

Fig. 1. Light curve of CG Cyg from August 1998.

3. Analysis of the spectral data

3.1. Orbital variability of the spectral lines

The analysis of the orbital variability of the spectra yields information about the dominant sources of the spectral lines as well as about the locations of the active regions in the binary systems.

We observed CG Cyg around the H_α line because it is a spectroscopic indicator of chromospheric activity (Zarro & Rogers 1983; Herbig 1985; Frasca & Catalano 1994; Fernandez-Figueroa et al. 1994; Strassmeier et al. 1990).

Figure 2 shows the apparent difference in the spectra of CG Cyg from our two runs; below we describe their characteristics in detail.

3.1.1. May spectra

The most important peculiarity of the May spectra is the presence of a third absorption feature T (Figs. 3a,b) between the spectral profiles of the two stars. It is visible both in the H_α and FeI 6678 line with almost equal $FWHM$ (around 1 Å). The depth of the third absorption feature changes during the orbital cycle and is comparable to the depths of the stellar spectral profiles. Taking into account the high resolving power of our spectra (0.19 Å/pixel) and their S/N, these characteristics of the third absorption feature mean that it represents a real structure in the spectra of CG Cyg. Because the wavelength position of the third absorption feature hardly changes during the orbital cycle we assume that it originates from cool matter around the mass center of the binary system.

We also observed a third absorption feature between the spectral lines of the two star components of the short-period

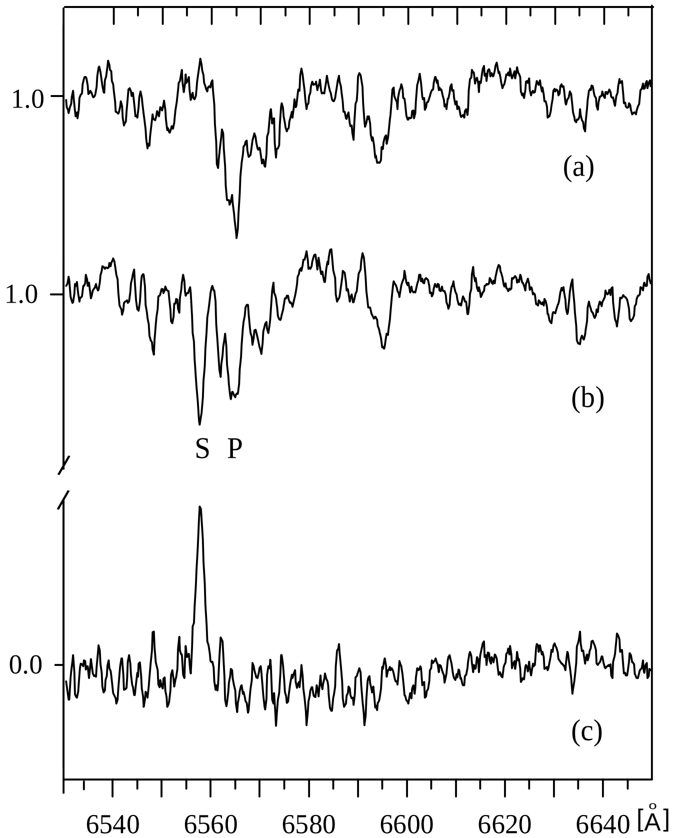

Fig. 2. **a)** Spectrum of CG Cyg at phase 0.73 from August; **b)** Spectrum at phase 0.74 from May; **c)** Their difference after an appropriate alignment in wavelength. (Notes: The scale of the y-axis of the three spectra is the same; P and S marks the positions of the H_α profiles of the primary and secondary star).

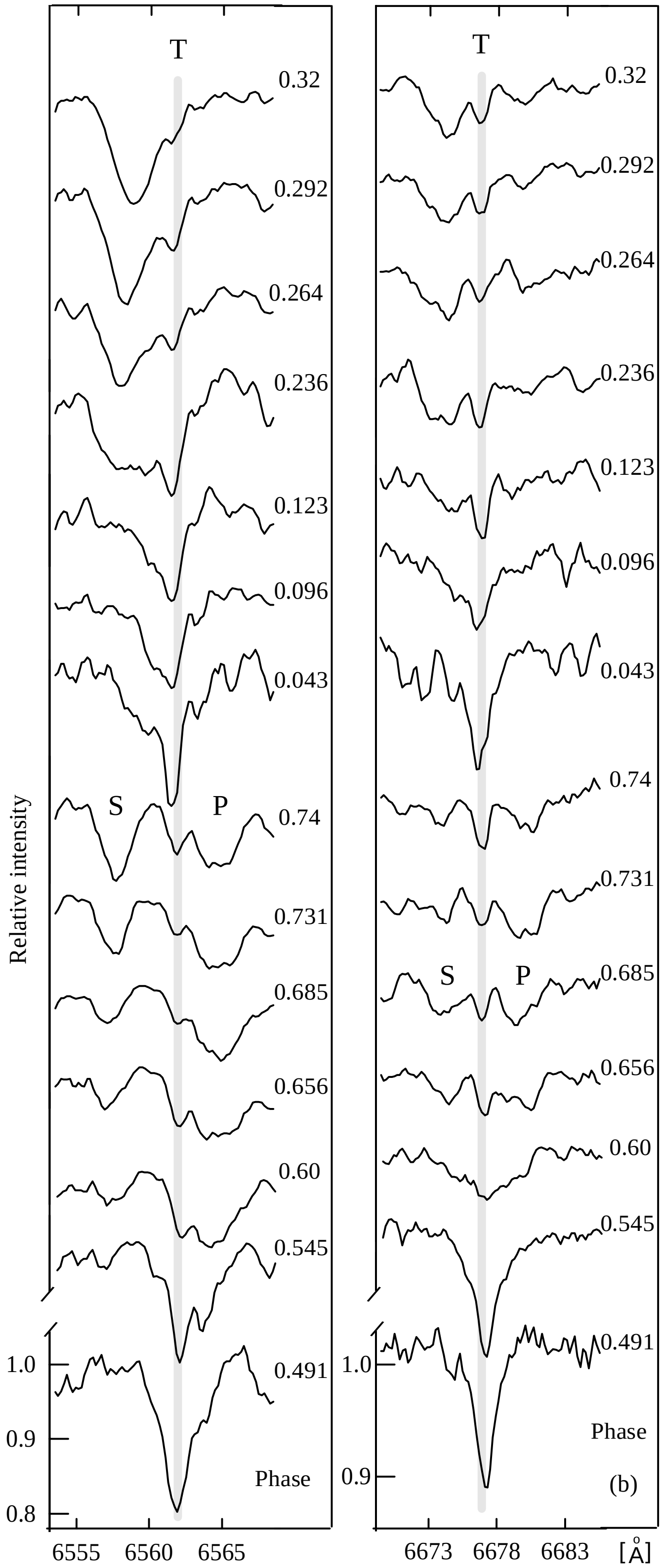

Fig. 3. H_α **a)** and FeI 6678 **b)** profiles of CG Cyg from May 2001 with the third absorption feature T.

RS CVn system ER Vul (Kjurkchieva et al. 2003) but it was weaker than that in the spectra of CG Cyg.

The profiles of the H_α and FeI 6678 lines change considerably during the orbital cycle (Fig. 3). The H_α line of the secondary star is invisible at most orbital phases but has a depth almost equal to that of the primary star at phases 0.73–0.74. This orbital variability is probably due to inhomogeneous chromospheric emission that fills its profiles. The observations of Lazaro & Arevalo (1997) also show that the H_α emission excess is much higher around the first quadrature than at the second one.

The FeI 6678 line of the secondary star is visible at almost all phases out the eclipses. Its profiles are deeper around the second quadrature than around the first one. We found the same trend of the orbital variability of the spectral lines for other short-period RS CVn-stars we observed: XY UMa, SV Cam and RT And. This phenomenon was called "second quadrature effect" (Kjurkchieva et al. 2002).

3.1.2. August spectra

The most important characteristic of the August spectra is that the H_α line of the secondary star is in emission. This behavior is best visible in Fig. 2c showing the difference between August and May spectra around the second quadrature. The relative increase of the H_α emission of the secondary star corresponds to $EW = 0.195$ Å at this phase. The arrows in Fig. 4 indicate the H_α line of the secondary star at the phases when it is in emission above the continuum level. We assume that this

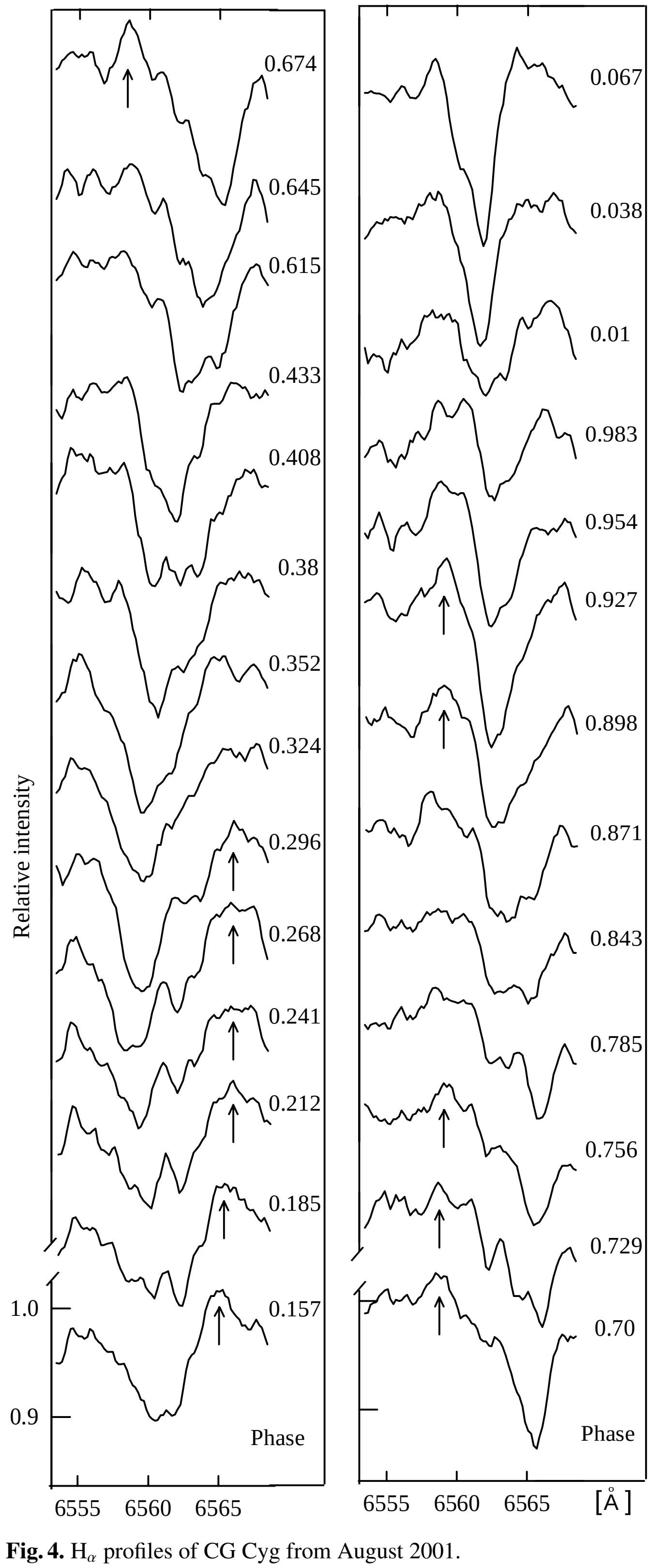

Fig. 4. H_α profiles of CG Cyg from August 2001.

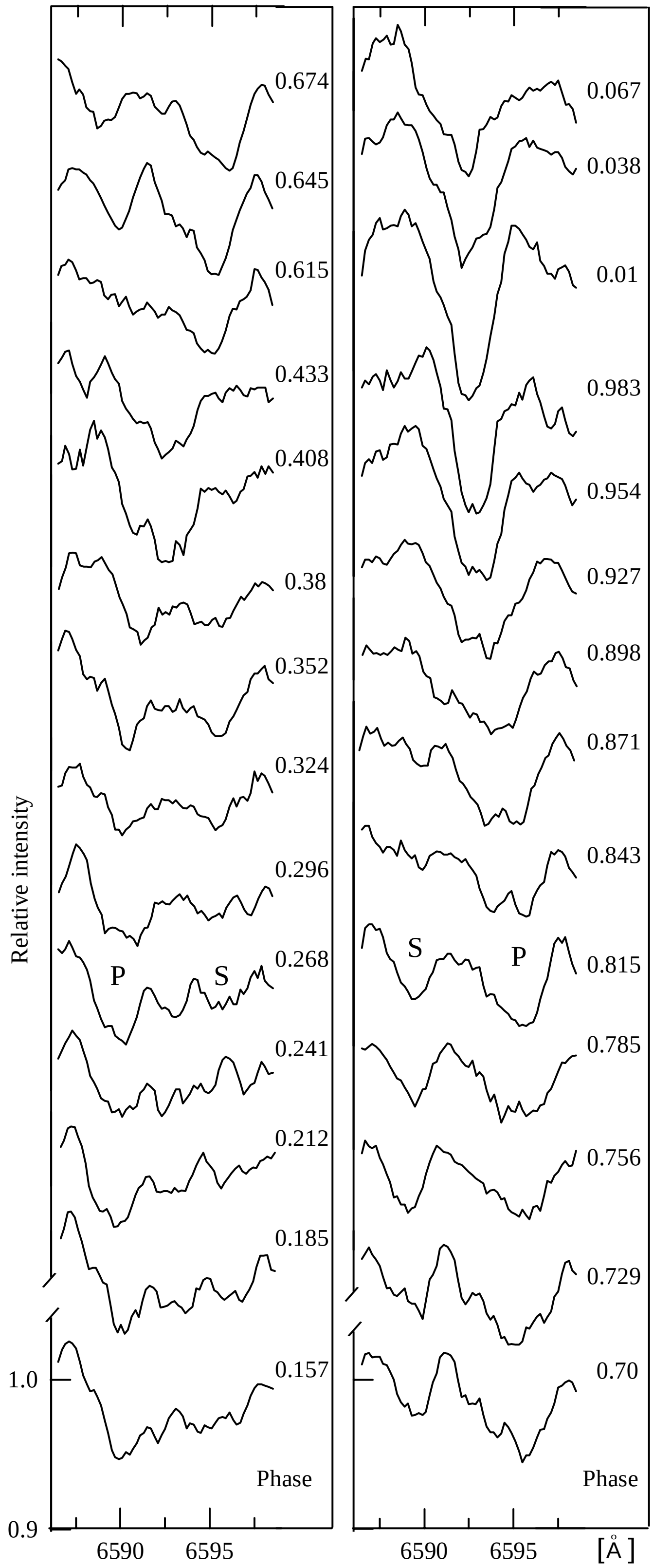

Fig. 5. FeI 6593 profiles of CG Cyg from August 2001.

emission is the reason for the small depth of the H_α profile just in the middle of the primary eclipse (phase 0.01, Fig. 4).

The H_α profiles of the primary star have an emission core with an *EW* around 0.15 Å at the phases 0.18–0.21, 0.65, 0.73, 0.81–0.84. The first and last of them are almost symmetric relative to the primary eclipse. We found the same behavior of the H_α line of the primary star of the short-period RS CVn-stars RT And (Kjurkchieva et al. 2001) and SV Cam (Kjurkchieva et al. 2002).

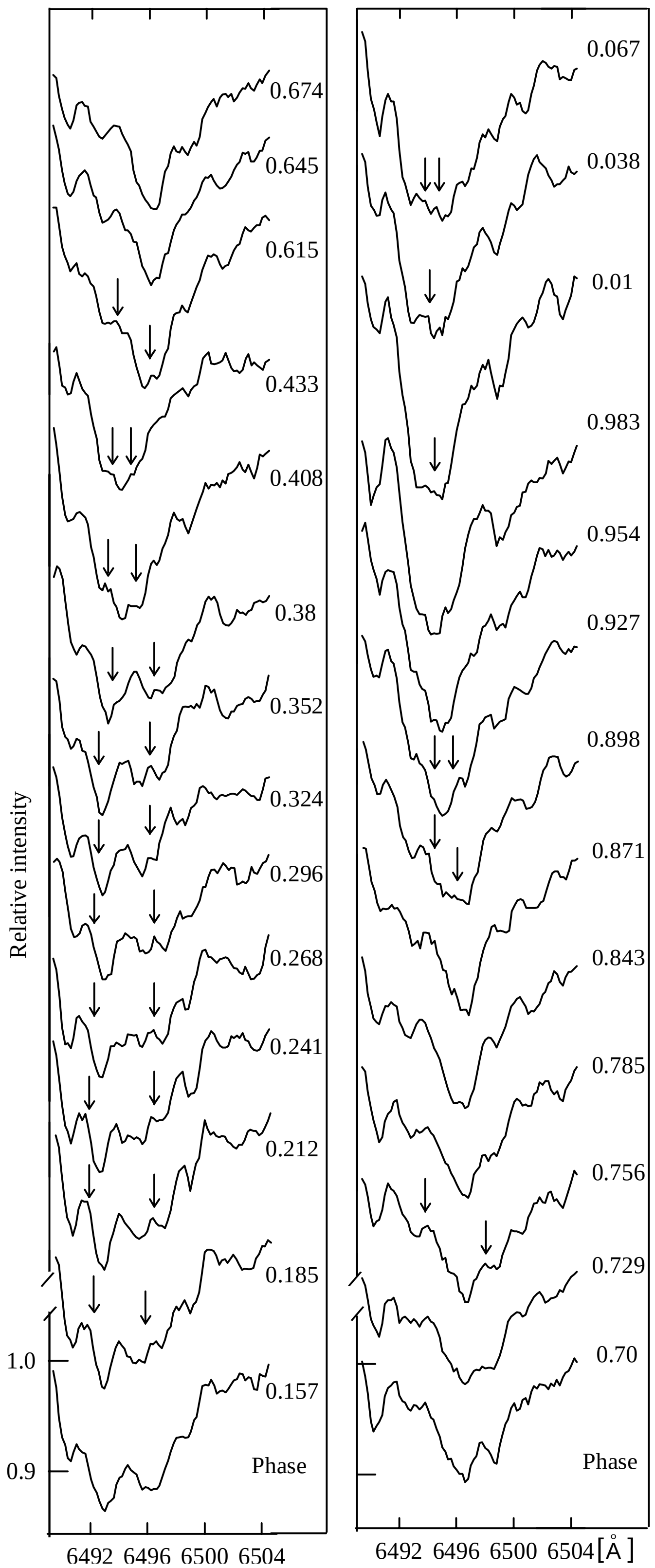

Fig. 6. CaI 6494 profiles of CG Cyg from August 2001.

The third absorption feature in the H_α line is also visible in the August spectra but it is wider and has a more complex shape than in the May spectra (Fig. 4).

The absorption profiles of the FeI 6593 line from the two stars (Fig. 5) are visible at most phases. The profiles of the secondary star are considerably deeper around the second quadrature than around the first one, which is another confirmation of the "second quadrature effect". In contrast to H_α the FeI 6593 line is deepest in the middle of the primary eclipse (phase 0.01). The third absorption feature between the two star profiles of FeI 6593 is quite wide and its depth is almost equal to that of the profile of the secondary star in the phase range 0.16–0.27.

Due to the detected emission cores of the CaI 6494 line in the spectra of the short-period RS CVn-star ER Vul (Kjurkchieva et al. 2003) we proposed that this line should be considered as an optical indicator of chromospheric activity of late stars. To check this proposition for CG Cyg we included this line in the spectral range of the August observations. Figure 6 shows the orbital variability of the CaI 6494 line of CG Cyg. Emission cores of its profiles are visible at some phases (marked by arrows) but they are not so apparent as in the spectra of ER Vul. Probably this is due to the smearing effect of the third wide absorbing feature in the CG Cyg spectra.

We attribute the fact that the H_α line is shallowest just in the middle of the primary eclipse while the CaI 6494 and FeI 6593 lines are deepest there to the H_α emission of the secondary star.

3.2. Radial velocity solution

The measurement of the lines of short-period RS CVn stars is difficult for several reasons. First, the lines arising from each component are rotationally broadened and blended with the surrounding metal lines of itself and its companion star. Second, the profiles are distorted by the presence of emission or absorption features on or between the profiles of the two stars. All these complications apply in the case of CG Cyg.

In order to measure the radial velocities we fitted the spectral profiles by Gaussians (for the procedure see Kjurkchieva et al. 2002). The mean errors of the individual measurements of the radial velocity were quite big due to the reasons mentioned above: around 35 km s^{-1} for the primary star and 42 km s^{-1} for the secondary. The measured radial velocities are given in Table 1 and shown in Fig. 7 where the values of the FeI line are phase-shifted by 0.015 to avoid superposing the data.

The results of the two sinusoidal fits of the radial velocity data are: $K_1 = 134.5 \pm 1.1$ km s^{-1}; $K_2 = 164.5 \pm 2.7$ km s^{-1}. Our K_1 and K_2 values are close to those of Popper (1994) of 137 km s^{-1} and 159.3 km s^{-1} and quite different from those of Naftilan & Milone (1985) who obtained $K_1 = K_2 = 125$ km s^{-1}.

Using our values of K_1 and K_2 and the value of the orbital inclination $i = 83°$ determined photometrically (next section) we obtained for the masses of the star components of CG Cyg the values $M_1 = 0.97 \pm 0.04\ M_\odot$ and $M_2 = 0.8 \pm 0.03\ M_\odot$. These values are close to those of Popper (1994): $M_1 = 0.94\ M_\odot$ and $M_2 = 0.81\ M_\odot$.

On the basis of our radial velocity solution and relative star radii $r_1 = 0.267$ and $r_2 = 0.216$ obtained by the light curve solution (next section) we calculated the absolute star radii $R_1 = 1.00 \pm 0.03\ R_\odot$ and $R_2 = 0.83 \pm 0.03\ R_\odot$ ($k = R_2/R_1 =$

Table 1. Measured radial velocities in km s^{-1}.

phase	$RV_1(H_\alpha)$	$RV_2(H_\alpha)$	RV_1(FeI)	RV_2(FeI)
0.615	40		51	
0.645	63		60	−181
0.674	67		70	
0.700	72		74	−190
0.729	77	−220	74	−199
0.756	81	−220		−203
0.785			79	−199
0.815			74	−194
0.843			65	
0.871			51	
0.898			38	
0.157			−165	106
0.185	−156		−176	97
0.212	−175		−185	110
0.241	−184		−190	
0.268	−184		−183	115
0.296	−179		−176	101
0.324	−174		−165	97
0.352			−153	92
0.380			−142	88

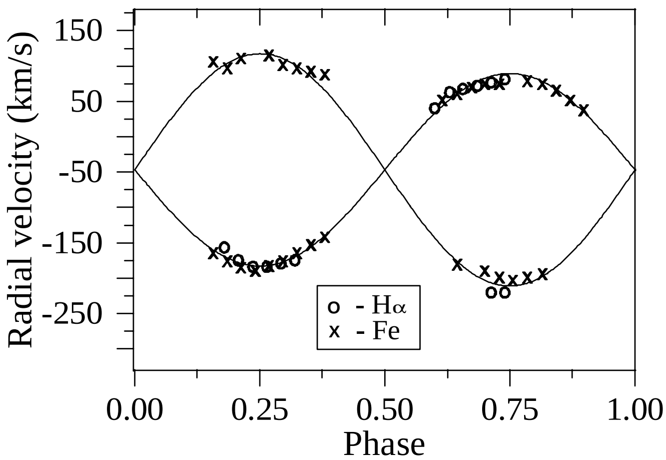

Fig. 7. Radial velocity curves of CG Cyg.

0.83). The radii of the star components corresponding to their masses on the mass-radius relation for MS stars are $R_1 = 0.98\ R_\odot$ and $R_2 = 0.83\ R_\odot$. This means that the two components of CG Cyg almost obey the mass-radius relation for MS stars, i.e. they are MS stars.

We determined the rotational broadenings of the observed lines of the two components by fitting them with 6th-order polynomials (see Kjurkchieva et al. 2002). The measured values (around 3.5 Å for the primary star and 2.9 Å for the secondary star) correspond to equatorial velocities $V_1 = 80 \pm 5$ km s^{-1} and $V_2 = 66 \pm 5$ km s^{-1}. The calculated values ($V_i = 2\pi R_i/P_{\rm rot}$) corresponding to the determined radii are $V_1 = 80.3$ km s^{-1} and $V_2 = 66.2$ km s^{-1}. They are equal to those determined by the measured rotational broadenings of the spectral lines.

Table 2. Global parameters of CG Cyg.

i	q	r_1	r_2	T_1	T_2	$L_1(V)$	Ref
82.8	1	0.241	0.226	5200	4400	0.74	1
83	1	0.238	0.223	5200	4400	0.62	2
82.8	0.53	0.25	0.215	5200	4400	0.7	3
83.3	1	0.24	0.225	5320	4400	0.63	4
82.4	0.8	0.24	0.225	5260	4720	0.7	5
82.6	0.8	0.266	0.221	5200	4400	0.7	6
83	0.38	0.26	0.216	5200	4400	0.72	7
82.1	0.6	0.24	0.228	5200	4400	0.7	8
83	0.82	0.267	0.216	5200	4400	0.78	9

Reference: 1 - Budding & Zelik (1987); 2 - Banks & Budding (1989); 3 - Heckert (1994); 4 - Zeilik et al. (1994) ; 5 - Popper (1994); 6 - Heckert (1996); 7 - Heckert (1998); 8 - Dapergolas et al. (2000); 9 - this paper.

4. Analysis of the photometric data

Our light curve of CG Cyg (Fig. 1) shows the following peculiarities:

(a) the secondary eclipse is asymmetric and distorted;

(b) there is an increasing of the brightness before and after the primary eclipse;

(c) there are narrow light depressions at phases 0.17 and 0.78.

For the light curve modeling we used the standard package of the Wilson-Devinney code version 1996 (Wilson & Devinney 1971; Wilson 1993) and the light fitting technique developed by Budding & Zeilik (1987).

The first step of the procedure was to vary the star parameters in order to obtain a fit to those parts of the observed light curve that are mostly unaffected by the presence of spots: the depths and widths of the eclipses as well as the maximum brightness. The only fixed parameter was the mass ratio, the value of which was determined from our spectral data. We used as initial values of our fitting procedure the average values of the star parameters from the previous analyses (Table 2). Varying these parameters by up to ±10% around the initial values by steps of around 1% we obtained a good approximation of our photometric data in all colors for the following values: orbital inclination $i = 83 \pm 0.2°$; relative radius of the primary star $r_1 = 0.267 \pm 0.003$; relative radius of the secondary star $r_2 = 0.216 \pm 0.002$; temperature of the primary star $T_1 = 5200 \pm 50$ K; temperature of the secondary star $T_2 = 4400 \pm 50$ K. The relative light contribution of the primary star in the V color corresponding to these parameters is $L_1(V) = 0.78$.

The goal of the second step of the procedure was to reproduce the distortion curve (the difference of the observed curve and the synthetic curve corresponding to the derived star parameters). The shape of our distortion curve (Fig. 8b) shows it could be reproduced by two cool spots best visible

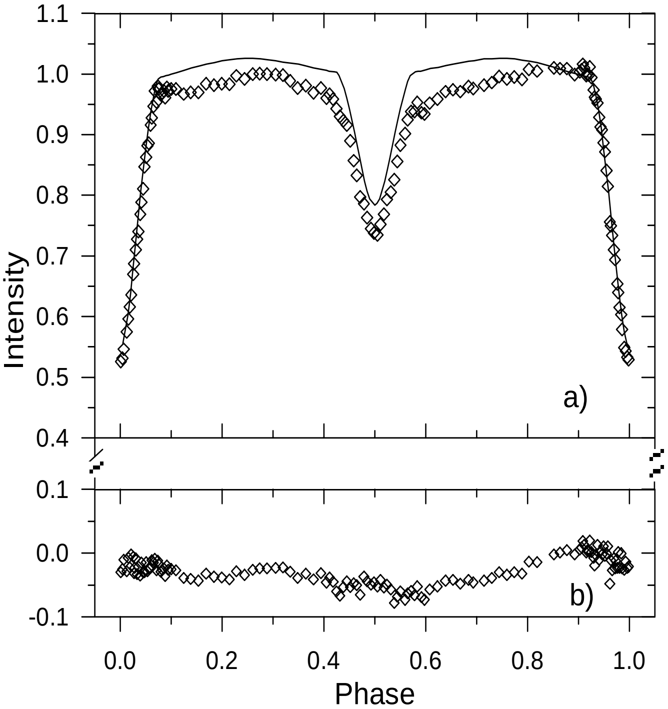

Fig. 8. a) The observed and synthetic "clean" (without spots) V light curve; **b)** their difference, i.e. the distortion curve (the points of the observed curve are averaged in phase bins).

around phases 0.2 and 0.6. Due to the small light contribution of the secondary star (established both by our photometry and spectroscopy) it is reasonably to assume that the spots are on the primary star (if they were on the secondary star their sizes and/or temperature difference with the surrounding photosphere would be unreasonably large).

In order to fit the distortion curve we varied the spot parameters: longitude; colatitude; angular size; spot temperature $T^{\rm sp}$. The obtained values of the spot parameters (*equal* for all colors) are given in Table 3 (the values of the longitude, angular size and colatitude are in arc degrees). The two spots cover 6.4% of the primary star surface and are slightly bigger in size than those obtained by most previous analyses (Table 3) probably due to the approximation of "black" spots ($T^{\rm sp}$ = 0 K) used by the most authors.

Zeilik et al. (1994) performed an analysis of 70 yr photometric data of CG Cyg and established that the large (radii around 20^0) cool spots on the primary star fall into two active longitude belts corresponding to the phases of the quadratures. The analysis of our photometric data confirms this.

The final result of our fitting procedure is shown in Fig. 9.

5. Signs of activity

We assume that the signs of activity in CG Cyg could be divided into two types: first, the presence of structures in the binary outside the star components as a result of some active process and second, photospheric and chromospheric activity of the star components themselves.

Table 3. Spot parameters of CG Cyg in different seasons.

spot number	longitude	angular size	colatitude	$T^{\rm sp}$	Ref.
1	121	21	45	0	1
2	219	12.5	45	0	
1	120	13	38	0	2
1	126	18	45	0	3
2	246	18	45	0	
1	86	15.6	42	4060	4
1	257	9	45	0	5
2	120	6	45	0	
1	260	17	54	0	6
1	103	28	70	0	7
2	216	8	0	0	
1	280	11	59	0	8
1	80	15	90	4260	9
2	200	25	38	4260	

Reference: 1 - Budding & Zeilik (1987); 2 - Heckert & Zeilik (1989) 3 - Banks & Budding (1989); 4 - Beckert et al. (1989); 5 - Heckert (1994); 6 - Heckert (1996); 7 - Heckert (1998); 8 - Dapergolas et al. (2000); 9 - this paper.

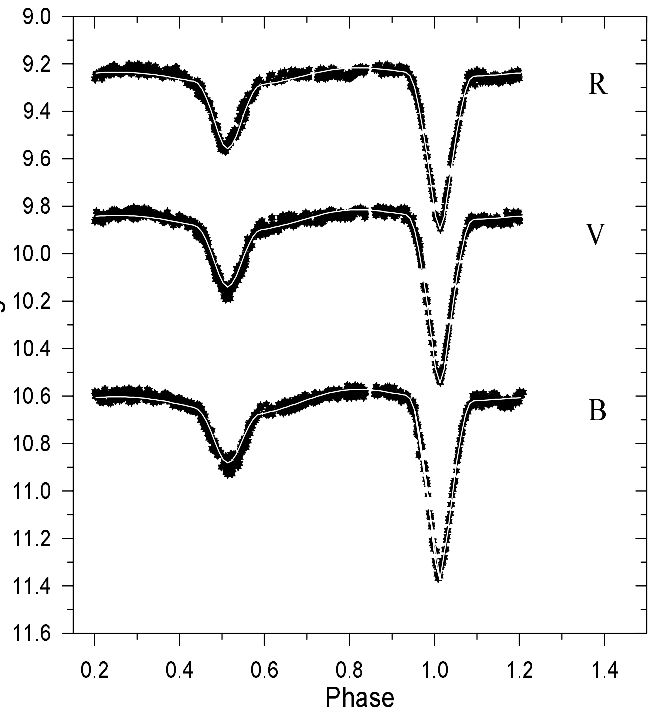

Fig. 9. Light curve approximation.

We found the following observational evidence of activity of the two types in our data:

(1) The strong absorption feature between the stellar lines in our spectra means the presence of matter around the center of mass or near L_1 (they are close for q = 0.82) in the system CG Cyg. Such a structure could be a result of different mechanisms of mass loss from the components;

(2) The narrow depressions of our lightcurve of CG Cyg cannot be reproduced by spots and are probably due to some absorbing structure outside the star components. We found

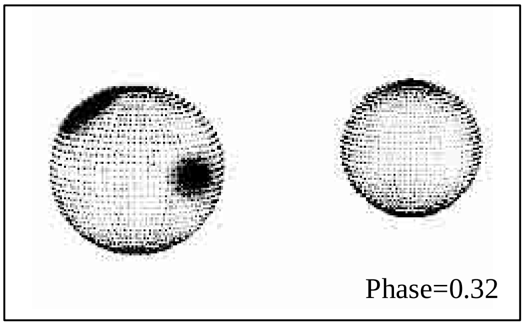

Fig. 10. Sketch of the model star configuration of CG Cyg (at phase 0.32).

similar photometric depressions in three other short-period RS CVn stars: XY UMa (Kjurkchieva et al. 2000a), SV Cam (Kjurkchieva et al. 2000b) and RT And (Kjurkchieva et al. 2001). Such narrow features in the light curves are typical for semi-detached Algol binaries and are attributed to the presence of a gas stream between the two stars (Walter 1973; Arevalo et al. 1995).

(3) The observed "quadrature effect" is similar to the "Struve-Sahade effect" (the lines of the secondaries of O+O binaries are deeper when they move towards the observer). However the reasons for the two effects should be different. The "Struve-Sahade effect" was explained by additional absorption of the zone of collision of the star winds but such strong winds were not observed from the late components of the RS CVn-stars. We assume as a probable reason for the different depths of the spectral lines around the two quadratures the different visibility and correspondingly the different spectral effect of gaseous structure which has a location asymmetric to the line joining the two stars (maybe a gaseous stream between the stars).

(4) The emission cores of the CaI 6494 line of the two stars indicate their chromospheric origin. The emission cores of the H_α line of the primary star at some phases as well as the strong orbital variability of this line for the secondary star could be attributed to inhomogeneous active chromospheres of the two stars;

(5) The H_α emission line of the secondary star in August probably is a sign of a flare event. Although there is no synchronous photometry the higher S/N ratio of our August spectra (compared to that of the May spectra) could be an indirect indicator for an increase of the brightness, i.e. a flare event. Usually H_α flares of RS CVn-stars last several hours (very rarely several days). The flare of CG Cyg in August 2001 observed by us lasted at least two days. Then the wider third absorption in the August spectra may be explained by an enlarging of the region of matter between the star components due to the additional gas ejected during the prolonged flare.

According to the theory of the magnetic dynamo, the dynamo number is roughly inversely proportional to the square of the Rossby number $R_0 = P_{\rm rot}/\tau_{\rm c}$. Following the relation between the turnover time $\tau_{\rm c}$ and the $B-V$ values for dwarf stars (Noyes et al. 1984) and using the $B-V$ values for the primary and secondary star of CG Cyg corresponding to the determined temperatures (Table 2) we calculated the ratio of their Rossby numbers $R_1/R_2 = 1.22$. Thus our spectral data confirm the relation between the activity level and the Rossby number for the late-type stars predicted by dynamo theory as well as the conclusion of Montes et al. (1995) that systems with H_α emission above the continuum are all cooler than 5000 K.

6. Conclusion

The main results of the analysis of our photometric and spectroscopic observations of CG Cyg are as follows:

(1) We re-determined the global parameters of the system (orbital inclination, masses, radii, temperatures and relative luminosities of the two stars) by solutions of the radial velocity curves and the light curves. In addition the equatorial velocities of the two star components were obtained on the basis of the measured rotational broadenings of their spectral lines.

(2) The distortions of our light curve of CG Cyg in all colors were reproduced by two cool spots on the primary star.

(3) The observed strong absorption feature between the lines of the two stars was attributed to the presence of cool matter around the mass center of the binary system.

(4) The H_α emission line of the secondary star was explained by a prolonged flare of this star in August 2001.

(5) The chromospheric activity of the star components is manifested by the emission cores or filled-in profiles of the H_α and CaI 6494 lines.

According to our photometric and spectroscopic observations CG Cyg shows stronger signs of activity (chromospheric excess emission, absorbing matter around the mass center, prolonged flare of the secondary) than the other short-period RS CVn-stars we observed: XY UMa, RT And, SV Cam, ER Vul. This result does not support the expected correlation in which the higher level of activity should correspond to the smaller orbital period, because CG Cyg has the largest period and is the best detached binary between the short-period RS CVn stars mentioned above. This discrepancy could be explained by a weaker differential rotation of the binaries with shorter periods because the dynamo number is proportional both to the rotational angular velocity and to the measure of the differential rotation. There is observational evidence of weak differential rotation of the components of the short-period RS CVn systems (Busso et al. 1985).

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