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LETTER

Letter to the Editor

Properties and nature of Be stars

XX. Binary nature and orbital elements of γ Cas

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Abstract. An analysis of accurate radial velocities (RVs) of the Be star γ Cas from 295 Reticon spectrograms secured between October 1993 and May 2000 allowed us to prewhiten the RVs for the long-term changes and to obtain the first orbital RV curve of this star. The orbital period is $203\overset{\mathrm{d}}{.}59$ and the orbit has an eccentricity of 0.26. The orbital motion is detectable even in the published velocities, based on photographic spectra. This implies that γ Cas is a primary component of a spectroscopic binary. The secondary has a mass of about 1 $\mathrm{M}_\odot$, appropriate for a white dwarf or a neutron star, but it could also be a normal late-type dwarf. The ultimate solution of the dispute whether the observed X-ray emission is associated with the secondary or with the primary will need further dedicated studies.

Key words: stars: binaries: spectroscopic – stars: emission-line, Be – stars: individual: γ Cas

1. Introduction

The Be star γ Cas (27 Cas, HD 5394, HR 264, ADS 782A) is a member of a visual multiple system – see also Gontcharov et al. (2000) who discovered a new companion, closer than ADS 782B. It is the very first Be star known, discovered by Secchi (1867). It exhibits spectral and light variations on several distinct time scales. History of its pronounced long-term spectral and light variations was summarized, e.g., by Doazan et al. (1983) or Telting & Kaper (1994). It underwent two consecutive shell phases in 1935-36 and 1939-40, followed by a relatively short phase when it appeared as a normal B star. When the Balmer emission lines are present, they exhibit cyclic long-term V/R and radial-velocity changes. In 1976, Jernigan (1976) and Mason et al. (1976) reported that γ Cas is the optical counterpart of the X-ray source MX0053+60. However, the attempts to detect the orbital motion of γ Cas (on the assumption that γ Cas is a binary with a compact companion), led to negative results - see Cowley et al. (1976) and Jarad et al. (1989). There is also evidence of rapid spectral changes of γ Cas in the form of line-asymmetry and RV variations on a characteristic time scale of $0\overset{\mathrm{d}}{.}7$ – see Hutchings (1970) and Jarad et al. (1989) – and in the form of travelling sub-features returning every about $0\overset{\mathrm{d}}{.}8$ to the line centre – see Ninkov et al. (1983), Yang et al. (1988), Horaguchi et al. (1994) and Smith (1995). Later, Smith et al. (1998) found simultaneous but anti-correlated UV and X-ray light changes with a period of $1\overset{\mathrm{d}}{.}123$ which they identified with the rotational period of γ Cas. Note, however, that Harmanec (1999), searching for such a period only in a close neighbourhood of the $1\overset{\mathrm{d}}{.}123$ period, found a significantly different period of $1\overset{\mathrm{d}}{.}15655 \pm 0\overset{\mathrm{d}}{.}00012$ from the Hipparcos H_p band photometry. The complex nature of rapid line-profile changes of the UV Si IV lines was demonstrated by Smith & Robinson (1999).

There are currently two competing interpretations of the nature of the observed X-ray emission: one is the accretion of the wind from γ Cas onto a putative white-dwarf companion and the other one is that it originates from some physical processes in the outer atmosphere of γ Cas itself. Arguments for and against these two hypotheses are best summarized in recent studies by Kubo et al. (1998) and Robinson & Smith (2000).

Realizing that there had been no attempt to search for the orbital motion of γ Cas in electronic spectra, we have been collecting Reticon spectrograms of γ Cas since 1993. Here, we report the first results.

2. Observations and reductions

All 295 spectrograms used here have been obtained in the coudé focus of the Ondřejov 2-m reflector with a Reticon 1872RF detector. They cover the wavelength region from 6280 to 6720 Å

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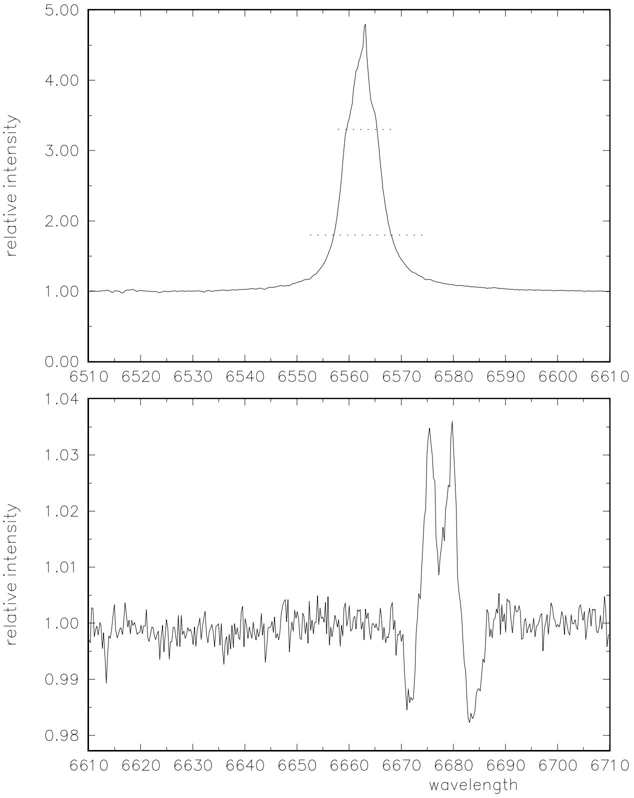

Fig. 1. The Hα and He I 6678 line profiles from an Ondřejov Reticon spectrum of γ Cas obtained on HJD 2449310.1969. Note the different intensity scale at the two panels

and have a linear dispersion of 17.1 Å mm^{-1} (4 pixels per Å). A standard reduction of these spectrograms was carried out using program SPEFO, developed by Dr. J. Horn – see Horn et al. (1996) and Škoda (1996). The zero point of RV scale was corrected through the use of reliable telluric lines. The two strongest lines seen, Hα and He I 6678, from one Reticon spectrum are shown in Fig. 1. We measured RVs of Hα (emission wings) and of He I 6678 line (absorption and emission wings and the shell absorption core) interactively, comparing the direct and reverse images of the profiles. For the Hα profile, we set on the symmetric steep portions of the emission profile (having the relative intensities between the two dotted lines in Fig. 1), taking care to avoid disturbances due to telluric lines. Although the Hα profile is complicated, we found that independent measurements by two of us led to an excellent reproduction of the results, usually within 2 km s^{-1}. All our RV measurements will be published in a follow-up study, devoted to the long-term changes of γ Cas.

3. Analysis of RV changes

Fig. 2 is a plot of RVs of several measured lines vs. time. Large RV changes, typical for long-term variations of Be stars, are clearly visible, the He I shell core having a larger RV amplitude than the emission wings. Our data confirm further lengthening of the cycles, demonstrated already by Telting & Kaper (1994).

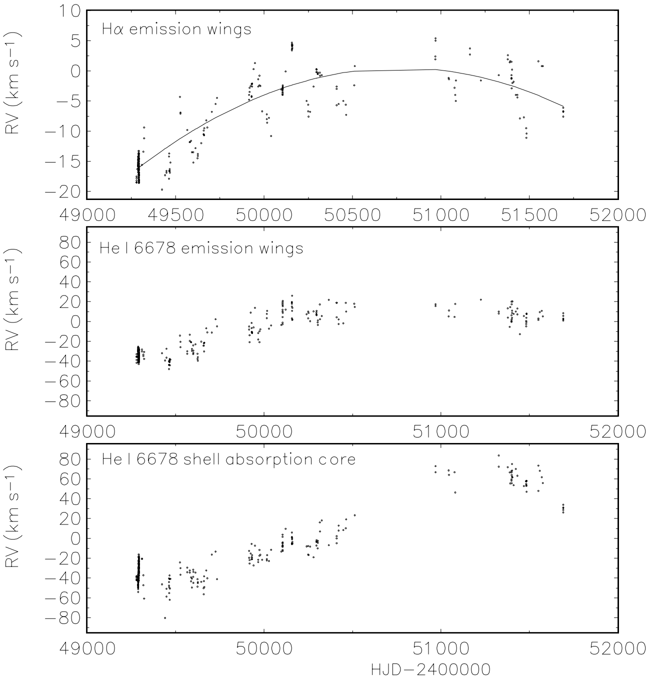

Fig. 2. RVs of several spectral features plotted vs. time: The solid line for Hα emission RVs shows the spline function used to the removal of the long-term changes

In addition to these variations, there is a pattern of apparently *regular* RV changes of the Hα emission wings on a time scale of about 200 days. This prompted us to prewhiten the RVs of the Hα emission for the long-term changes using spline smoothing after Vondrák (1969) and Vondrák (1977) – see the solid line in Fig. 2 – and to analyze the RV residuals for periodicity. It immediately turned out that a very well-defined periodic variation with a period of about 203-204 d is present. (The same is also true about the RV of the He I emission and He shell core which give residual 203-d RV curves in phase with the Hα emission but with a larger scatter because the He line is weak.) It was demonstrated, e.g., by Božić et al. (1995) for the primary of the double-lined Be binary φ Per (and also found for several other known Be binaries) that the steep symmetric parts of the Hα emission wings may be used to the detection of the orbital motion of a Be star. We therefore adopt a working hypothesis that the RV changes of the Hα emission with a period of 203 d reflect the orbital motion of γ Cas.

4. γ Cas as a spectroscopic binary

Using the program FOTEL, developed by Hadrava (1990), we derived the orbital elements using the Hα emission RVs prewhitened for the long-term changes. They are given in the second column of Table 1 and the phase diagram is shown in the upper panel of Fig. 3. The RV curve is defined remarkably well, especially when one considers its small semi-amplitude. To characterize the measuring accuracy and to demonstrate that the variations occur indeed on the time scale of $203\overset{\mathrm{d}}{.}59$ and not

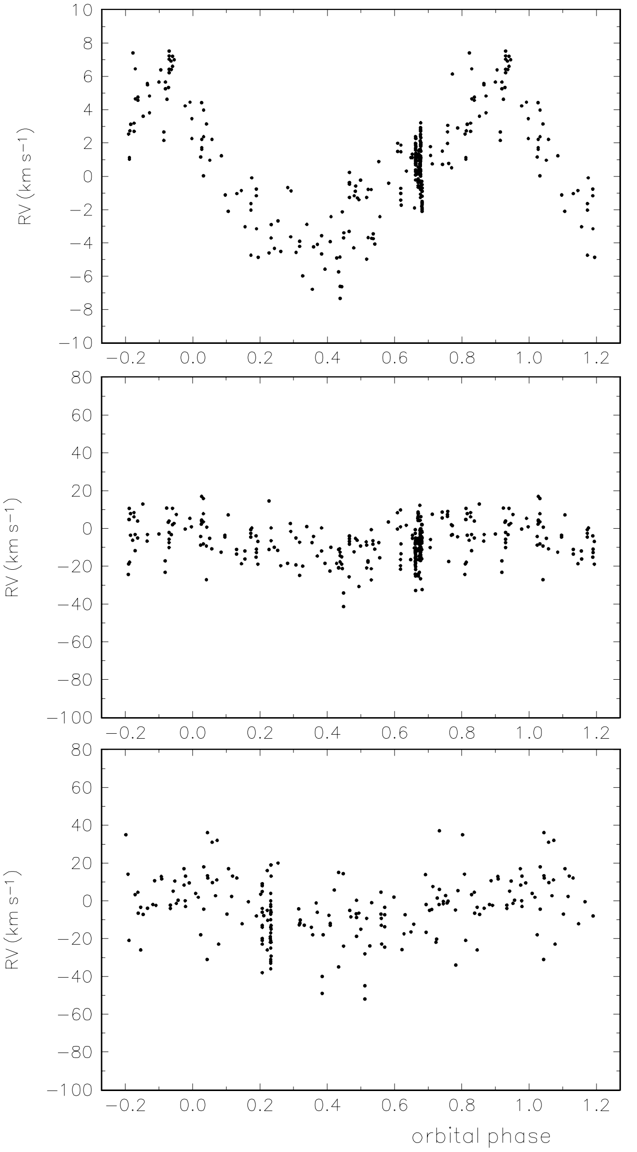

Fig. 3. Orbital RVs curves of γ Cas plotted with the ephemeris derived from the Hα emission RVs: $T_{\rm peri.}$ = HJD 2450578.7 + $203^{\rm d}.59\times E$. From top to bottom: Hα emission wings, broad absorption wings of the He I 6678 line from Ondřejov spectra, and absorption RVs from the photographic spectra published by Cowley et al. (1976) and Jarad et al. (1989)

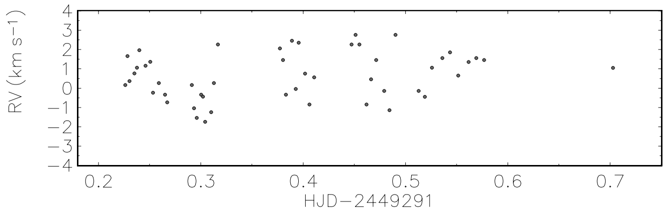

Fig. 4. RV residuals of the Hα emission velocities from the longest night series of observations plotted vs. time. No trend indicative of rapid changes is seen

Table 1. Orbital solutions for the Ondřejov Reticon velocities of Hα emission wings prewhitened for long-term changes, He I 6678 absorption wings and absorption RVs from photographic spectra. Separate systemic velocities were derived for the RVs by Cowley et al. (1976) (C) and Jarad et al. (1989) (J). All epochs are in HJD-2400000, K_1, γ and rms error per 1 observation are in km s^{-1}, No. is the number of RVs

Element	Hα emission	He I 6678 abs.	photogr.
P (d)	$203^{\rm d}.59\pm0.29$	$203^{\rm d}.59$ fixed	203.62±0.15
$T_{\rm peri.}$	50578.7±4.2	50576±16	38391±18
$T_{\rm upper\,c.}$	50592.8	50599.8	38401
$T_{\rm lower\,c.}$	50513.9	50528.8	38319
e	0.260 ±0.035	0.260 fixed	0.260 fixed
ω (°)	47.9±8.0	23±27	57±37
K_1	4.68±0.25	7.0±1.5	11.0±2.0
γ	–	-7.38±0.64	-3.3±1.0 C
			-8.4±2.7 J
rms	1.455	8.946	14.13
No.	272	280	169

on a time scale close to 1 day, we plot, in Fig. 4, the Hα emission RVs vs. time for our longest night series. Only some scatter but no systematic trend can be seen there. We also derived orbital solutions for our He I 6678 absorption-wing RVs and for published RVs. There is a large scatter around the phase curve and one would be hesitant to accept this result without the evidence from the Hα emission RVs but the curves are in phase and all orbital elements mutually agree within the limits of their errors – cf. Fig. 3. A significant part of the scatter may be due to the sub-features moving accross the line profiles which affect the blue and red wing differently at different times. It is also encouraging to see that a free convergency of the period for RVs from photographic spectra (which span 16000 days) leads to a value very similar to that derived from the Reticon data only. RVs of the wings of He I emission and of its shell absorption core, prewhitened for the long-term changes, also follow the 203.6-d period in phase with Hα emission and give semiamplitudes of 7.7 ±1.2 km s^{-1} and 7.5 ±1.2 km s^{-1}, respectively. A consistent detection of a truly periodic RV variation in several spectral lines, originating in different parts of the photosphere and the Be envelope, constitutes a rather solid proof of binary nature of γ Cas.

5. Probable basic physical properties of γ Cas

There is a rather large uncertainty concerning the true effective temperature of γ Cas since the star has strong emission lines all the time since fifties. Perhaps a more probable is the high limit of log $T_{\rm eff}$ = 4.51 derived from line-profile modelling by Hutchings (1970) and from spectrophotometry fits by Goraya (1980). For the often quoted spectral class B0.5 it would be log $T_{\rm eff}$ = 4.46. According to mass vs. log $T_{\rm eff}$ calibration by Harmanec (1988), this range corresponds to masses of 18 and 13 M$_\odot$, respectively, for the primary of γ Cas. Another uncertainty lies in the true value of the amplitude of the orbital

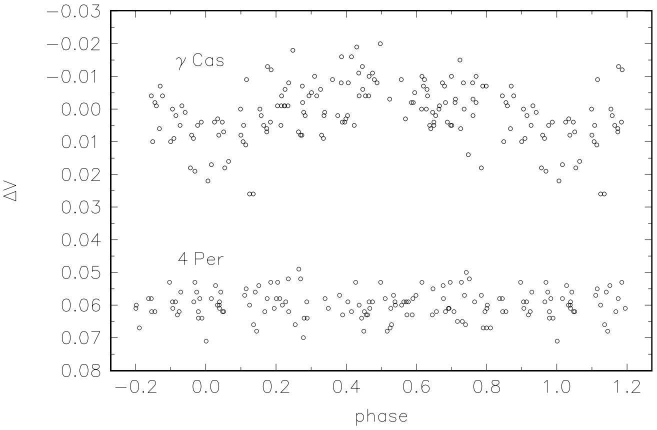

Fig. 5. A plot of Hipparcos photometry, prewhitened for a linear trend, vs. phase of the best-fit short period of $1^{\rm d}.48700$. Phases are calculated from the epoch of minimum light, HJD 2448350.838. To illustrate the noise of Hipparcos photometry, the original H_p photometry of a constant 5-mag. B star 4 Per, suitably shifted in magnitude, is also shown

motion of the primary. While the RV curve based on emission RVs certainly defines well the orbital period, its amplitude may or may not reflect the orbital motion properly. However, it agrees quite well with the RV amplitude of the He I 6678 absorption wings. Note that the interferometric resolution of the Be disk by Quirrenbach et al. (1997) implies an inclination $i > 44°$ if the disk lies in the equatorial plane of the binary and that also Hutchings (1970) arrived at an inclination near about 50°. Using the above range of primary masses, semi-amplitudes between 4.7 and 7 km s^{-1} and a plausible range of orbital inclinations 45° to 90°, one finds the following properties of the system: the mass of the secondary between 0.7 and 1.9 M$_\odot$ and a separation of the binary components between 350 and 400 R$_\odot$ (250 – 300 R$_\odot$ at periastron). The secondary could, therefore, be the long-expected hot compact object but also a late-type star of much lower luminosity than the primary.

6. Discussion

The latest arguments by Robinson & Smith (2000) against the origin of the X-ray emission from an accretion onto a white-dwarf companion appear quite convincing. However, the understanding of the physical processes involved is still far from complete. We mention two possibly relevant items: (i) We found that γ Cas is a binary with a $203^{\rm d}.59$ period and that its orbit is eccentric ($e = 0.26$), similarly as for other Be+X binaries. Other known Be binaries usually have circular orbits. The varying distance between the components should be seen to affect the putative accretion onto the secondary. A search for possible modulation of the X-ray flux with the phase of the orbital period is, therefore, highly desirable. (ii) Considering the importance of the $1^{\rm d}.12$ period for the alternative hypothesis, we re-analyzed good (flag = 0) Hipparcos H_p photometry of γ Cas, prewhitened for a linear trend, over a wider range of possible short periods than Harmanec (1999) did: between $0^{\rm d}.6$ and $5^{\rm d}.0$. The best-fit period is $1^{\rm d}.48700 \pm 0^{\rm d}.00013$, with minimum light at HJD 2448350.838±0.027 – see Fig. 5 which shows the superiority of this period to the period found by Harmanec (1999). The new period is very significantly different from $1^{\rm d}.12$. If real, it could be either a corotation period at some level or a low-order mode of pulsation.

It is, therefore, desirable to carry out further tests of both competing hypotheses.

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