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B[e] Star CI Cam: Eighteen Years of Research

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Abstract. We present the results of extensive spectroscopic and photometric observations of CI Cam performed after its outburst in April 1998. The outburst was interpreted as a thermonuclear runaway of hydrogen on the surface of a white dwarf (WD). We detected variations of both the brightness and the He II 4686 Å line radial velocity with a period of $19^{d}.400 \pm 0^{d}.015$ due to orbital motion of the WD. The rapid brightness variations on a timescale of hours is explained by pulsations of a B4 III–V[e] star. In 2012, the system entered an active state with the stronger He II line and with the brightness increased by 0.4 mag. We observed a slow low-amplitude drift in the velocity of Fe II and [N II] emission lines which we explained by the orbital motion of the B[e] star + WD system along with all its gaseous environment around a third companion invisible in the spectra. The active phase of the B[e] star might have been initiated by a close approach of the binary and the third companion in 2007.

CI Cam was first described as an emission-line B-type star by Merrill et al. (1932), and cataloged as MWC 84 (Merrill & Burwell 1933). It was included in the General Catalog of Variable Stars (GCVS) after an optical and IR photometric investigation by Bergner et al. (1995), who detected brightness variations with an amplitude of 0.4 mag in the *V* band. In April 1998, CI Cam was identified as a source of a transient event observed in X–rays (Smith et al. 1998; Belloni et al. 1999) as well as in other domains of the electromagnetic spectrum. In the optical spectra, ejecta were observed at radial velocities of ~1200 km s^{-1}. The evolution of the radio remnant was described by Mioduszewski & Rupen (2004) as "a shock ploughing into a dense circumstellar medium". Orlandini et al. (2000) and Ishida et al. (2004) interpreted the event as a thermonuclear runaway of hydrogen on the surface of a white dwarf (WD). The WD was detected by the spectroscopic method in a single spectral line, He II 4686 Å, whose radial velocity varied with an amplitude of ~500 km s^{-1} and a period of 19.407 days (Barsukova et al.

2006). The brightness variations with this period showed a full amplitude of 0.032 mag in the *V* band. These discoveries characterize the object as a peculiar classical nova with a massive hot companion. The explosion occurred in a dense medium (therefore the source was strong in γ–rays). A hydrogen shell at the surface of the companion was accumulated from the material of the circumstellar disk and wind. At the peak of the outburst the star became brighter by at least 3.5 mag in the *R*–band, when the contribution of the exploded WD to the total brightness was a few units of 10^{38} erg s^{-1} (assuming a distance of 1.1–1.7 kpc), which is typical of classical novae.

We follow this unique object since April 1998. We have performed multicolor UBVR photometry on 586 nights and the optical *V*–band monitoring on 69 nights. The entire set of photometric observations is available online[1]. We also obtained ~200 medium-resolution spectra (R = 350–1000), and 30 high-resolution optical spectra (R = 13000–60000). Information about the telescopes and spectroscopic instruments used in our observations of CI Cam, and a table of all measurements of the He II line radial velocities and equivalent widths (see Sect. 2) are available online[2].

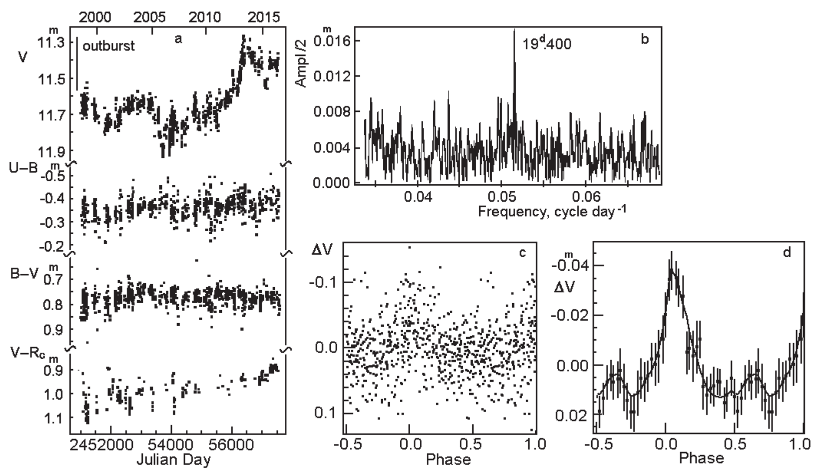

Figure 1. a: *V*–band light curve, $U-B$, $B-V$, and $V-R_c$ color-index curves of CI Cam shown for the data taken after the 1998 outburst. b: Deeming (1975) power spectrum plotted for the residuals of the averaged *V*–band light curve. c: the *V*–band light curve plotted versus phase of 19^d.400 period. d: the average *V*–band light curve versus phase of the same period.

1. Multicolor Photometry and Photometric Monitoring

New multicolor photometry demonstrates slow brightness variability in the range 11.26–11.93 mag in the *V* band (Fig. 1a). Since 2007, the brightness of the object increased gradually, reached a maximum in 2013 April, and has been decreasing slowly by ~0.15 mag until now. There were flashes and dips on shorter timescales and a more

[1]http://www.vgoranskij.net/cicam.all

[2]http://jet.sao.ru/~bars/spectra/cicam/midres.dat

rapid variability within 0.25 mag. Color-indices showed no significant variations except for $V - R_c$, which decreased by 0.2 mag during the 2013 maximum and later. The orbital wave is easily detectable in the UBV bands with the Fourier transform method (Deeming 1975) after removal of the main trend of the slow brightness changes. The power spectrum plotted for the V–band data is shown in Fig. 1b. The improved period value is $19^{d}.400 \pm 0^{d}.015$. In the light curve plotted for the residuals versus phase, the orbital changes are clearly visible (Fig. 1c). The average light curve has an asymmetric shape with a narrow peak near zero phase with an amplitude of 0.05 mag and a weak secondary peak at the phase 0.6.

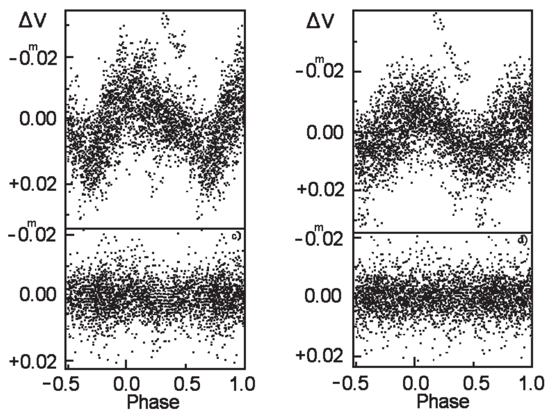

Figure 2. Main pulsation components extracted from the V–band light curve of CI Cam. The component with with the $0^{d}.4152$ period is plotted in the upper left panel, and the one with the $0^{d}.2667$ period is plotted in the upper right panel. The light curves of the check star GSC 3723.0080 folded with the same periods are plotted in the lower panels.

Additionally, periodic variations were detected on a timescale of hours (Barsukova & Goranskij 2009; Goranskij & Barsukova 2009). The dominant waves have the periods of $0^{d}.2667, 0^{d}.4152$ and amplitudes of 0.016 mag and 0.020 mag, respectively, (Fig. 2) were interpreted as double-mode radial pulsations with a 3:2 resonance related to the B[e] star itself. Few additional low-amplitude waves were extracted and treated as being due to interaction. These short-period pulsations exclude membership of CI Cam in the sgB[e] group, and confirm a B4 III–V[e] spectral type (Barsukova et al. 2002).

2. Medium- and High-Resolution Spectroscopy

The He II line became nearly twice as strong in the active state, when the star reached its maximum brightness. It has been easily detected in almost all spectra since 2012, while its appearance before the brightening was a rare case. The period of the radial velocity variations remained the same, $19^{d}.407$ days, but the radial velocity curve shape has changed significantly (Fig. 3). The radial velocity amplitude decreased by nearly a factor of two, so that the velocity of the motion away from the observer stayed the same, while the velocity toward the observer decreased and exhibited a larger scatter. Figure 3 shows two boundary orbital solutions for the radial velocity curve found with the *Console* package (Meschiari et al. 2009) and corresponding shapes of the orbits. The orbital eccentricity determined using an averaged velocity curve is 0.27, $K = 169$ km s^{-1}, periastron longitude $\omega = 270°$, $a \cdot \sin i = 0.6$ AU. The systemic γ–velocity determined with these solutions changes between $\gamma_1 = 0$ and $\gamma_2 = -80$ km s^{-1} and is about -24 km s^{-1} for the average curve. The variability of the radial velocity curve suggests that the He II line forms not only in the accretion disk of the WD, but also in a gaseous stream in its vicinity. The visibility of this stream depends on the orbital phase.

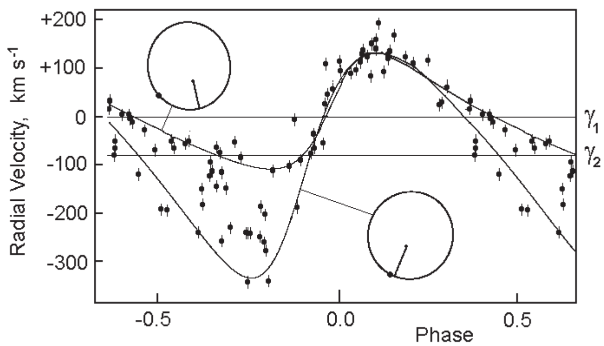

Figure 3. The He II line radial velocity curve folded with the $19\overset{d}{.}4$ orbital period. Only the best-quality spectra were used. The boundary orbital solutions and corresponding systemic velocities (γ_1 and γ_2) are shown by solid lines. The ellipses show the shapes of orbits for these solutions. Lines inside the ellipses show the periastron positions. The dots on the orbital ellipses represent the node line position.

We note that radial velocities of the He II 4686 Å line refer to the narrow Fe II wind emission lines, which have a rectangular shape with sharp edges (see Fig. 4, top left panel). Compared to the narrow lines, the He II line looks wide and structured. However, Barsukova et al. (2007) discovered that in échelle spectra the Fe II lines and even the forbidden [N II] 5754 Å line, associated with gaseous environments, have been slowly changing their positions in the spectrum. This means that the gaseous content as a whole is moving with an acceleration. In this drift, the width of lines measured as FWHM did not vary and remain at about 76 km s^{-1}. The amplitude of this drift was as small as 13.4 km s^{-1} for 7.9 years. The [N II] line has a similar shape and width to the Fe II lines (Fig. 4, at the top right panel), but it showed a different behavior in the 1998 outburst. In the outburst, its flux remained weak and constant, when the fluxes of the Fe II lines grew more than 10 times stronger, and reached a maximum 210 days after the outburst peak, when Fe II lines dropped to a quiescent state (Barsukova et al. 2002). This suggests that the [N II] line forms much farther from the B[e] star than the Fe II lines. Recent échelle spectra show that the radial velocity trend of narrow emissions was reversed. We assume the presence of a third companion, which is unrecognizable in the spectra but affects the B[e] star along with its gaseous environment. It might be an O–type star with weak absorption lines contaminating the B–type spectrum. Certainly, other explanations of this phenomenon can be suggested and tested using the observational data. We present a list of radial velocities of the Fe II and [N II] lines online[3].

[3]http://jet.sao.ru/~bars/spectra/cicam/highres.dat

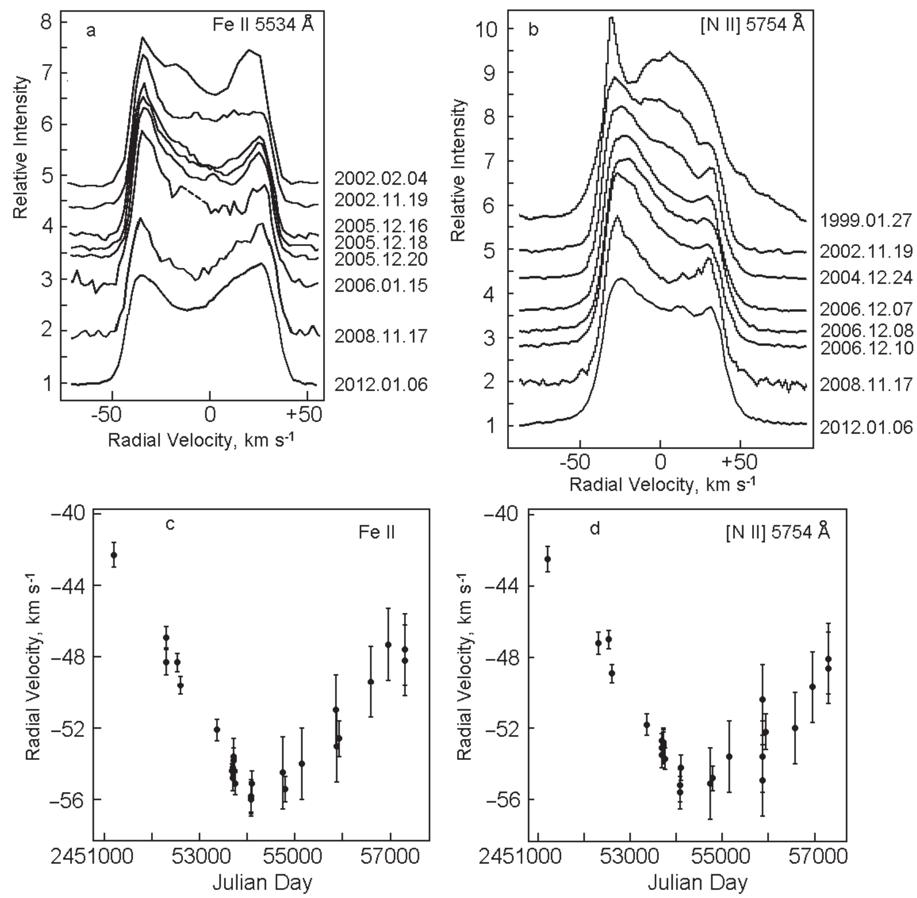

Figure 4. Line profiles and their temporal variations (top). a: Fe II 5534 Å; b: [N II] 5754 Å. The profiles are superimposed for easier comparison. Radial velocity curves of these lines are shown in panels c and d, respectively (bottom). Most spectra were taken at the 6 m telescope with the NES spectrograph (Panchuk et al. 2009).

In this study, we tried to find an orbital solution for the nebular emissions of the B[e] star with the invisible third companion using the same *Console* package. The complexity of such a solution arises from the absence of information about the systemic velocity of the triple system γ_3 because the phases of this radial velocity curve are not yet covered by observations. Using the systemic velocity for the He II line mean velocity curve, $\gamma = -24$ km s^{-1}, we found that satisfactory solutions exist with orbital periods of $P \geq 160$ years. These solutions have an orbital eccentricity in the range 0.47–0.70, and ω between 161 and 183°. Figure 5 shows one of the best solutions with an orbital period of ~220 years (80000 days), $e = 0.62$, $\omega = 158°$, the distance traveled along the line of sight over the period of observations $s \cdot \sin i = 80$ AU. This solution suggests that a close approach occurred between the B[e] star + WD system and the putative third companion in 2007, and the subsequent active state might have been caused by that approach. Nevertheless, the existence of the third companion still remains an open question, and regular high-resolution spectroscopy should be continued.

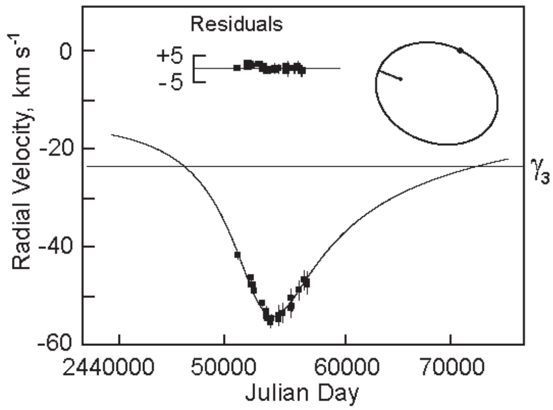

Figure 5. A *Console* solution for the nebular velocity curve with the 220–year orbit.

CI Cam is a unique object that can be used to study the evolution of multiple systems and the B[e] phenomenon. It has probably started as a close binary with 5–8 $M_{\odot}$ components. The more massive and rapidly evolving component transferred its hydrogen-rich envelope onto the less massive companion and became a WD. Also, the mass gainer was far more evolved at that time, and a powerful hydrogen burning developed in a layer in its envelope. The gainer had to receive angular momentum from the accreted mass, which led to an equatorial gas outflow. Close approaches of a third massive companion near the binary system might have caused an accretion process and ellipticity of the WD orbit.

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