CI Cam and the Nature of B[e] Phenomenon

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Abstract. As a result of photometric and spectral monitoring, CI Cam was classified as B4 III-V[e]. The distance to the object was calculated as 1.1–1.9 kpc. Its binarity was discovered with the orbital period of 19.404 days. Spectral signs of the presence a third component in the system were found. Double-mode pulsations of the B-type component were observed, and disappearance of the high-frequency mode in the active state was recorded. Arguments are presented against the classification of CI Cam as a supergiant.

Keywords: stars: emission-line, B[e]; stars: individual: CI Cam

DOI:10.26119/978-5-6045062-0-2_2020_90

The term "B[e] phenomenon" represents a group of hot stars with emission lines of hydrogen, helium, with permitted and forbidden emissions of ionized iron and some other elements, and with strong infrared excess. This group includes stars of different types at various stages of evolution. The star CI Cam (MWC 84, IRAS 04156+5552), an optical counterpart of the X-ray transient XTE J0421+560, flared up in 1998 in all wavelength ranges and was intensively observed by us since the outburst. It shows all the characteristics of the B[e] star. CI Cam is a member of the new subgroup of nonsupergiant dust-forming B[e] stars (FS CMa stars) (Miroshnichenko 2007). Based on the BTA spectrum with a high signal-to-noise ratio on the wings of high-order hydrogen absorption lines, CI Cam was classified as a B4 III-V star. The spectra contain He II 4686 Å line, which changes its position in the spectrum regularly with a period of 19.4 days with a maximum amplitude of 400 km s^{-1} and is likely to form near the compact component. The same period 19.4 days was also found in photometric data (Barsukova et al. 2006). Despite 22 years of research in different wavelength ranges, the nature of this object remains controversial.

From 1998 to 2020, we obtained about 10000 multicolor photoelectric and CCD observations for this object in the optical range. Additionally, 247 spectra of medium spectral resolution and several tens of spectra with high resolution were obtained. We have updated the system's orbital period of 19.4041 $\pm$0.0002 days. The light curve with this period is shown in Fig. 1a. It was obtained after removing the slow trends. There, the average light curve is shown, too, the amplitude of the orbital variability is $0^m.05$. The He II 4686 Å emission line is visible and measured in 217 spectra. The radial-velocity curve in this line converted with an orbital period of 19.404 days is shown in Fig. 1b.

The orbit of the system is elliptical with an eccentricity of 0.49. Judging by the large amplitude of the line-of-sight velocity and the absence of any traces of the orbital period in the lines of the B star, the mass of the component – the source of He II is very small. A dynamic estimate of the mass of B[e] star gives a lower limit of 8.9 or 7 $M_\odot$. The height of the periastron above the center of the B[e] star gives an upper limit on the radius of the main component at 34 $R_\odot$. Since the radii of supergiants are 34 – 46 $R_\odot$, the main component of CI Cam can be a supergiant only in the case of a small orbital inclination. The radius of a B4 III-V-type star can be in the range of 3.6 – 5.9 $R_\odot$. So, the spectral type we have determined does not contradict the orbital elements at any angles of inclination of the orbit. The absolute magnitude of the star B4 III-V can be within $-1^m.2$ and $-2^m.3$, hence the distance to CI Cam, calculated with the accepted interstellar reddening value, is 1.1 – 1.9 kpc, which surprisingly coincides with the result of the GAIA DR1 satellite.

Positions of all permitted ionized iron lines and the forbidden [NII] line in the high resolution spectra change slowly with time, but this shifts do not correlate with the phase of the orbital period of 19.4 days. For eight years, their radial velocity has changed by 13.5 km s^{-1} (Goranskij et al. 2017). In 2008, the radial velocity trend of these emissions was reversed. It is difficult to imagine the constant acceleration of a large circumstellar nebula. We assume the presence of a third component in the system, which is not detected in the spectrum, but affects the B[e] star along with its environment. There are sufficient solutions for the triple system with orbital periods greater than 160 years and with an eccentricity of 0.6.

CI Cam demonstrates different types of optical variability on a time scale from several years to microvariability over one night. Photometric observations in 2006 revealed double-mode pulsations of the star B4 III-V[e] (Goranskij & Barsukova 2009) (Fig. 2). At the same time, in the high-resolution spectra, a rapid variability of the profile of the weak He I line 4713 Å was recorded, during which the classic P Cyg profile changed to the inverse one, what happens as a result of pulsations. Two waves dominated with the ratio of periods close to whole

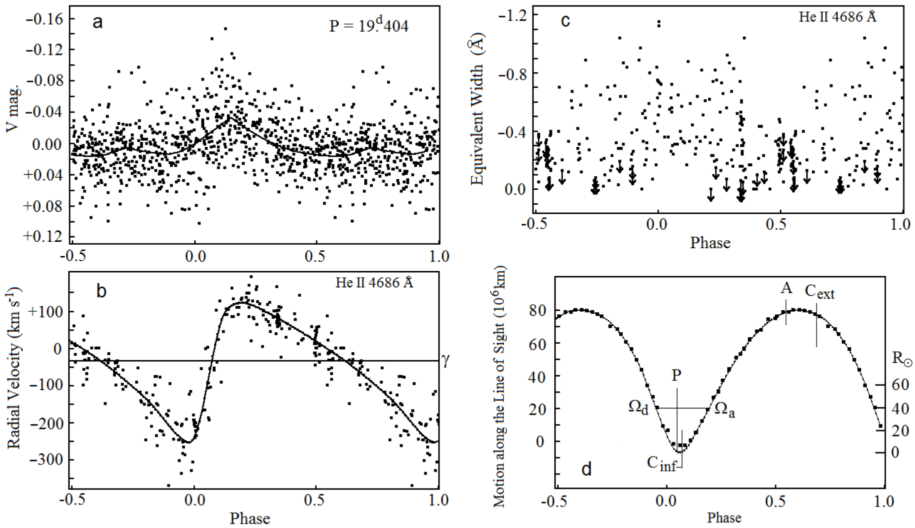

Fig. 1. a) V-band light curve plotted versus phase of orbital ephemeris T = 2458891.468 + 19.404 E (T is an arbitrarily chosen moment). Each point is the average brightness in one night. Total nights 928. Solid line – average light curve. b) The radial velocity curve in the He II 4686 Å line (γ is the systemic velocity equal to –33.5 km s^{-1}). Solid line is the model curve with the fitted orbital elements. c) Equivalent width of He II 4686 Å emission versus orbital phase. The point with the arrow down is the parameter when the line was not visible. There is a noticeable lack of observations of the line with high intensity near phase of 0.5. d) Integral curve that reflects the movement of the He II source along the line of sight in kilometers. Phases are marked on this curve: P - periastron; A - apoastron; Ω_d is the descending node of the orbit; Ω_a is the ascending node. The designations C_{inf} and C_{ext} are the phases of the inferior and exterior conjunction of the compact component with the B type star. The lack of a high intensity of the He II line, as it turned out, relates to the apoastron phase, not to the exterior conjunction. Therefore, this is not an eclipse.

numbers. In this case, as 3 : 2. After brightening in 2013, regular pulsations were found in only one mode with a period of 0.4062 days. The pulsations in the second higher frequency mode disappeared (Goranskij & Barsukova 2018). This change assumes that the pulsations are radial and that the second mode was previously excited by resonance. The pulsations of CI Cam is a unique phenomenon among B[e] stars. It excludes the sgB[e] classification which is popular for this star. B-supergiants do not pulsate at such frequencies. The point is that in the

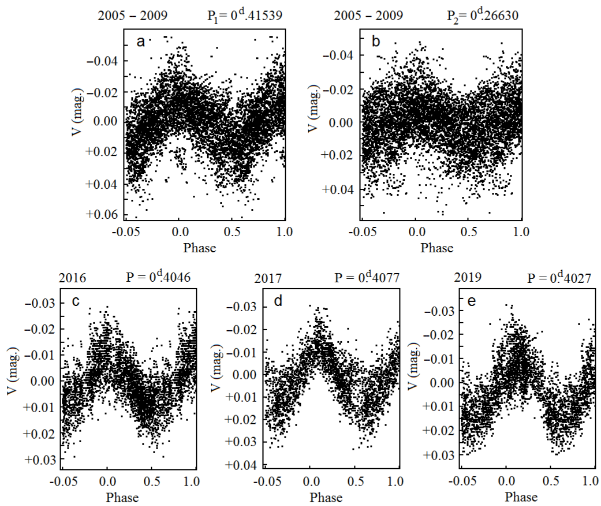

Fig. 2. CI Cam pulsations. Top: the extracted light curves of the first overtone (a), and the second overtone (b) in 2005–2009. Bottom: the first overtone light curve after disappearance of the second overtone in 2016–2019 (c–e).

distribution of B stars by periods (De Cat 2002), CI Cam is located in the gap between pulsating β Cep and SPB (Slowly Pulsating B stars) type stars. These are all main sequence stars, with a mass of $7 - 9$ $M_\odot$ in the gap. Our observations showed a decrease in the pulsation period with increasing brightness.

The medium-resolution spectra revealed the variability of the He II 4686 Å line profile by several times on a scale of 20 minutes. This variability can produce a large scatter of the radial-velocity curve and errors in determination of the orbit. We attribute these rapid changes to the interaction of the He II radiation source with pulsating waves of matter ejected from the main component.

Conclusions. Membership of CI Cam to sgB[e]-type supergiant remains in doubt. We consider the 1998 outburst to be a thermonuclear explosion of hydrogen accumulated on the surface of the white dwarf.

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