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Multi-Ring Structure of the Eclipsing Disk in EE Cep – Possible Planets?

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Abstract. The photometric and spectroscopic observational campaign organized for the 2008/9 eclipse of EE Cep revealed features, which indicate that the eclipsing disk in the EE Cep system has a multi-ring structure. We suggest that the gaps in the disk can be related to the possible planet formation.

1. Introduction

The eclipses of the 11th magnitude star EE Cep have been observed with a period of 5.6 yr from the early 1950-ies. Their depths change in a wide range from about $0^{m}_{\cdot}5$ to $2^{m}_{\cdot}0$ (see Graczyk et al. 2003), however all of them show the same features: they are almost gray and have the same asymmetric shape (descending branch of every eclipse has longer duration than the ascending one). In all eclipses it is possible to distinguish five phases (shown in Fig. 1): ingress (1–2) and egress (3–4), respectively preceded and followed by the extended atmospheric parts (1_a–1 and 4–4_a), and the slope-bottom transit (2–3). The most plausible explanation of the observed photometric behavior was proposed by Mikołajewski & Graczyk (1999). They suggested that the secondary consists of a dark disk, with opaque interior and semi-transparent exterior, around a low luminosity central object. The inclination of the disk to the line of sight and the tilt of its cross-section to the direction of motion are changed by precession. This causes the changes in the depth and the duration of the eclipses. A significant impact parameter is responsible for the observed asymmetry of the eclipses. This model can explain the shallow ($0^{m}_{\cdot}6$), flat-bottomed eclipse observed in 1969 if we assume a nearly edge-on and non-tilted projection of the disk.

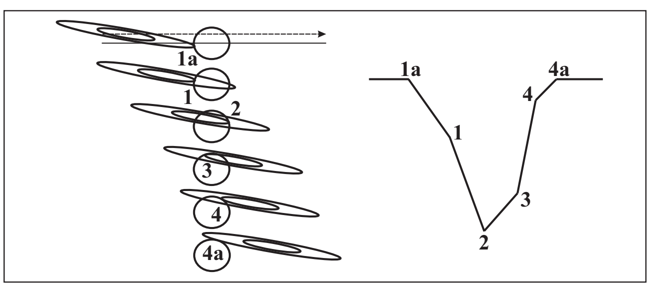

Figure 1. A schematic illustration of the eclipses in the EE Cep system. The contact times ($1_a, 1, 2, 3, 4, 4_a$) distinguished in the light curve (right) refer to characteristic configuration of the disk and the star during the eclipse (left).

2. The 2003 eclipse

An observational campaign organized during the 2003 eclipse (Mikołajewski et al. 2003), brought very good quality photometric $UBV(RI)_C$ data with a dense time coverage. For the first time it was possible to analyze the color evolution during the eclipse and not only their amplitudes. The preliminary photometric results of this campaign were described by Mikołajewski et al. (2005a). The eclipse turned out to be quite shallow and in accordance with expectations almost gray. The eclipse achieved depths from about $0^{\rm m}.5$ in $I_{\rm C}$ to $0^{\rm m}.7$ in U passbands. In Fig. 2, the B light curve and the color indices are presented. Each point represents the average of all measurements obtained in a given passband during a single night. The color indices from the 2003 eclipse show two blue maxima, about nine days before and after the mid-eclipse. Simultaneously, weak maxima in the B light curve are clearly visible.

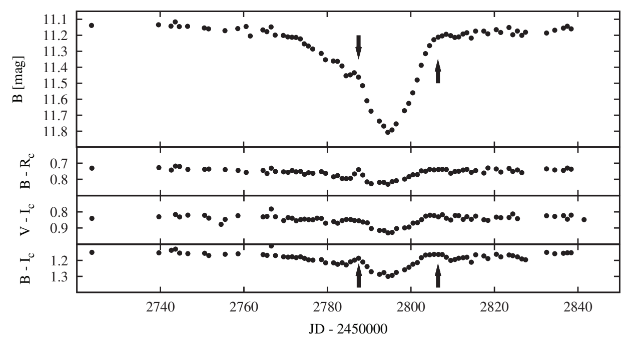

Figure 2. The 2003 eclipse. The B light curve (top) and three color indices (bottom) are presented. Arrows denote times of blue maxima.

3. The gapped disk model

The blue maxima observed in the color indices can be understood if we assume that a hot star, rotationally darkened at the equator and brightened at the poles, is eclipsed by a disk divided into two parts by a gap (Fig. 3). The spectra obtained in 2003 indicate indeed that the hot component is a rapidly rotating Be star (Mikołajewski et al. 2005b). A comparison of the Balmer absorption lines in the spectrum of EE Cep with theoretical profiles gives $v \sin i \approx 350$ km/s (see Gałan et al. 2008), which implies strong equatorial darkening. The difference between the polar and the equatorial temperatures can reach even 5-6 $\cdot 10^3$ K.

Therefore, when the hot polar area appears in the gap the blue maxima are observed. In Fig. 3 two eclipse models are presented: with a solid disk and with a disk having a gap. The first model gives quite a good fit to the light curve and the global color changes, but it does not explain in details the color evolution during the eclipse. The disk model with a circular gap fits the observed color changes quite well. It was not possible to obtain a good fit to the light and color curves simultaneously, most likely because the assumed formula for the density of the disk was too simple.

4. The 2008/9 eclipse

The fruitful observational campaign in 2003 did not provide answers to a number of questions: (i) is the Be star (primary) in the EE Cep system indeed eclipsed by a dark, precessing disk? (ii) does the gap in the disk really exist? (iii) what is the nature of the central body surrounded by the disk and what is its contribution to the total flux? An excellent opportunity for answering these questions came with the next eclipse,

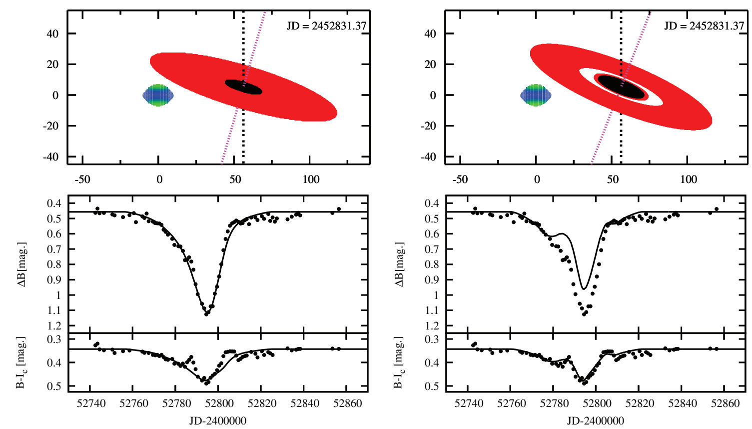

Figure 3. Modeling the eclipse of a fast rotating Be star by a solid disk (left) and by a disk with a gap (right). A flat, circular disk with the r^{-2} density profile has been assumed. *Top:* the system projection in the plane of the sky. The polar (hot) and the equatorial (cool) areas of the star are shown by changing shades. The inner (opaque) and the outer (semi-transparent) areas of the disk are shown by dark and light shades, respectively. The sizes are expressed in the solar radii. *Middle:* The B light curve (points) from Mikołajewski et al. (2005a) fitted with synthetic curves (lines). *Bottom:* The $B - I_C$ color index from the 2003 eclipse (points) together with the synthetic fits (lines).

which took place at the turn of 2008, with a minimum occuring on January 10, 2009. The invitation to the observational campaign was announced in a short paper in *IBVS* (Gałan et al. 2008).

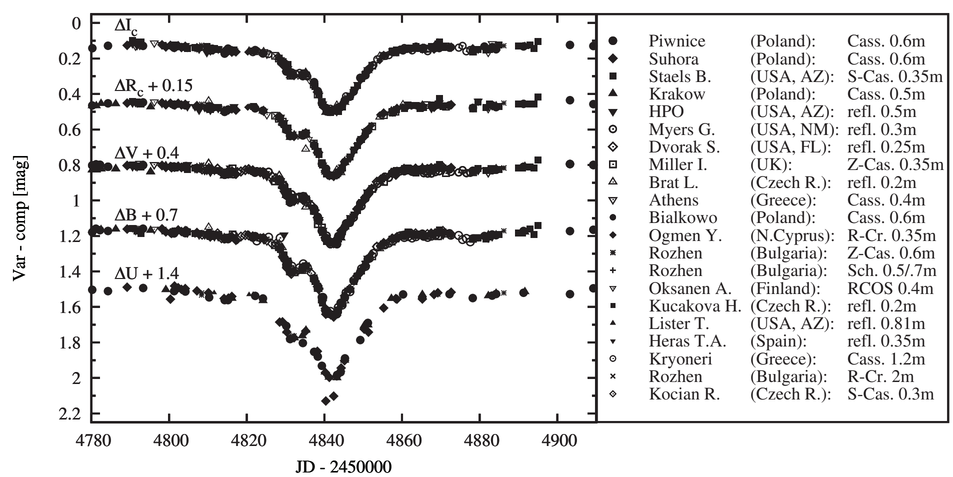

Figure 4. The $UBV(RI)_C$ photometry obtained during 2008/9 eclipse using 21 telescopes located in Europe and North America.

The strong interest among observers, who took part in the observations, resulted in a large amount of the collected data. The $UBV(RI)_C$ light curves presented in Fig. 4

are composed of more than 1600 individual data points in total! Surprisingly, the last eclipse with depths $\sim 0\overset{m}{.}5$ in U and nearly $\sim 0\overset{m}{.}4$ in I_C passbands, turned out to be the shallowest in the observing history of EE Cep. In Fig. 5, we present the B light curve and the color indices. Each point represents the average of all measurements obtained in a given filter during the first and second part of a particular Julian day. The accuracy of the photometry is excellent, reaching a few mmag. The features observed during the previous eclipse, including the two blue maxima, occur also in the 2008/9 eclipse.

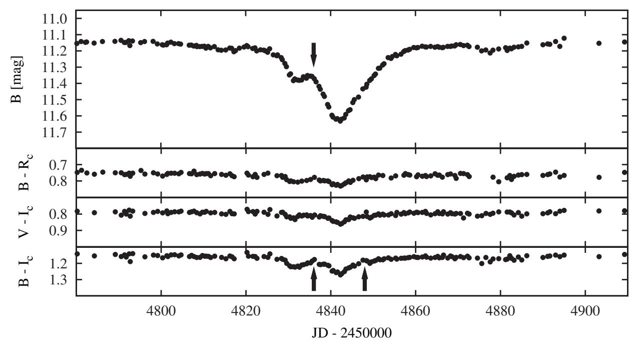

Figure 5. The 2008/9 eclipse. The B light curve (top) and three color indices (bottom) are presented. Arrows denote times of blue maxima.

The bump preceding the minimum, at JD 2454836 (Fig. 4 and 5) is much more pronounced than previously. The differences in the phase and strength of these features can be caused by the changes in the spatial orientation of the disk. The observed variations in the I passband before and after the eclipses during the last decade (Gałan et al. 2008) would give additional support for this idea.

5. Conclusions

A comparison of the photometric and spectroscopic data obtained during the last two eclipses (see Fig. 6) reveals some new characteristics of the eclipsing disk in the EE Cep system. The durations of last two eclipses were longer than we expected (about 90 days), and they both were preceeded and followed by very shallow minima which are perhaps repeatable in each orbital cycle. The 2008/9 campaign results confirmed the existence of a gap in the disk. Additionaly, the data present some indications of the existence of a second, outer gap in the disk. The possible multi-ring structure of the eclipsing disk in EE Cep suggests the existence of some massive bodies that could be responsible for their formation. This means that we may observe signs of planet formation in a circumstellar disk in EE Cep. The results presented here show that the disk in EE Cep system is very similar to the multi-ring structure observed in ε Aurigae (Ferluga 1990).

During the EE Cep eclipses additional components appear in the H_α emission line and in the NaI absorption doublet. Towards the mid-eclipse an absorption component appears and grows in the H_α profile and during the minimum it is very deep and broad. The sodium doublet line profiles evolve during the eclipse and in the minimum multi-component structure with at least two additional absorption components can be seen.

During the shallow minimum at orbital phase 0.017 an additional NaI absorption component was also present, while it was absent soon after the egress. The spectra from the last two eclipses suggest that the absorption lines evolution is the same during each cycle. Unfortunately spectroscopic observations coverage of the last eclipse was very bad. Many more spectroscopic observations during the next eclipse would be needed to understand the nature of EE Cep. Photometry in the infrared *JHK* passbands and the radial velocity variations of the hot component could be invaluable as well.

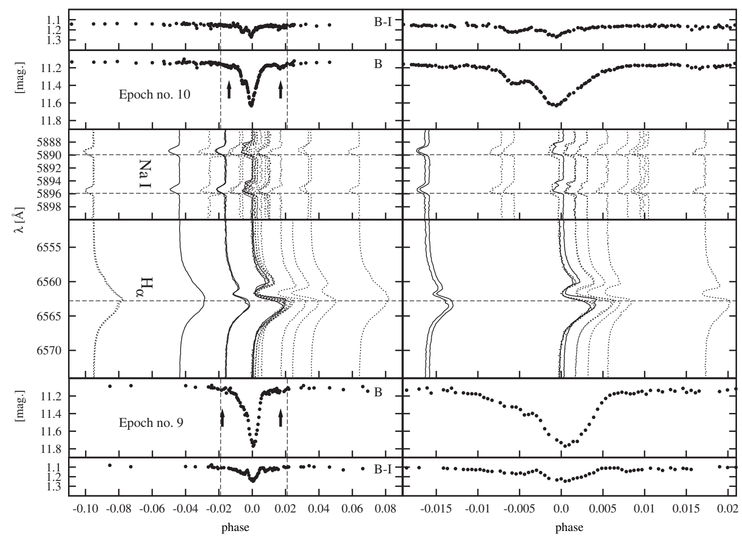

Figure 6. Photometry and spectra from last two eclipses are compared. *Left:* The observations between orbital phase 0.9 and 0.1 are presented. *Right:* An expanded view of 0.04 of orbital phase marked with vertical dashed lines in the left panel is shown. *Top:* Photometry of the 2008/9 eclipse. *Bottom:* Photometry of the 2003 eclipse. The times close to the very shallow minima which occur in both eclipses at phase near of $\pm 0^{p}.017$ are denoted with arrows. *Middle:* The evolution of the NaI absorption and the H_α emission lines. The spectra obtained during and close to the 2003 eclipse are given with dashed lines, while those obtained during the last eclipse, with solid lines. The positions of the continuum levels refer to the orbital phases.

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