EE Cep eclipse in 2014 - an international observational campaign

D. Pieńkowski[1], C. Gałan[2], T. Tomov[3], P. Wychudzki[3], M. Mikołajewski[3], K. Gazeas[4], B. Staels[5], S. Zoła[6], B. Dębski[6], E. Kuligowska[6], D. Dimitrov[7], D. Kjurkchieva[8], D. Marchev[8], A. Armiński[9], I. Miller[10], Z. Kołaczkowski[11], D. Możdzierski[11], E. Zahajkiewicz[11], P. Bruś[11], A. Pigulski[11], T. Smela[12], E. Conseil, D. Boyd[13], G. Conidis[14], I. Plauchu-Frayn[15], T. Arranz Heras[16], M. Kardasis[17], M. Biskupski[12], R. Kneip, L. Hambálek[18], T. Pribulla[18], E. Kundra[18], J. Nedoroščík[18], J. Lopatovský[18], Z. Garai[18], D. Rodriguez[19], F. Dubois[20], L. Logie[20], A. Capetillo Blanco, P. Kankiewicz[21], E. Świerczyński[3], M. Martignoni[22], I. Sergey[23], J. Kare Tandem Qvam[24], E. Semkov[7], Sunay Ibryamov[7], Stoyanka Peneva[7], J. -L. Gonzalez Carballo[25], J. Ribeiro, S. Dean[26], G. Apostolovska[26-27], Z. Donchev[7], L. Corp[27-28], P. McDonald, M. Rodriguez[29], A. Sanchez[30], K. Wiersema[31]

[1] Warsaw University Observatory, Al. Ujazdowskie 4, PL-00-478, Warszawa, Poland; [2] NCAC PAS, Warsaw, Poland; [3] Nicolaus Copernicus University, Toruń, Poland; [4] Department of Astrophysics, Astronomy and Mechanics, National and Kapodistrian University of Athens, Zografos, Athens, Greece; [5] Sonoita Research Observatory/AAVSO, USA; [6] Astronomical Observatory, Jagiellonian University, Krakow, Poland; [7] Institute of Astronomy and National Astronomical Observatory, BAS, Sofia, Bulgaria; [8] Department of Physics, Shumen University, Shumen, Bulgaria; [9] AAVSO, Cambridge, USA; [10] Furzehill House, Ilston, Swansea, SA2 7LE, UK; [11] Astronomical Institute of the Wroclaw Univeristy, Wrocław, Poland; [12] PTMA, Szczecin, Poland; [13] West Challow Observatory, Oxfordshire, UK; [14] Department of Physics and Astronomy, York University, Toronto, Ontario, Canada; [15] Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, Ensenada, B.C., Mexico; [16] Observatorio Astronómico "Las Pegueras", NAVAS DE ORO (Segovia), Spain; [17] Hellenic Amateur Astronomy Association; [18] Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica, Slovak Republic; [19] Guadarrama Observatory, MPC458; [20] Astrolab Iris, Zillebeke Belgium; [21] Institute of Physics, Astrophysics Division, Jan Kochanowski University, Kielce, Poland; [22] Stazione Astronomica Betelgeuse, Magnago, Milano, Italy; [23] Private Observatory near Maladziechna, Belarus; [24] Horten VGS, Norway; [25] Cerro del Viento Observatory (MPC I84); [26] AstroCamp Observatory, Nerpio, Spain (MPC I89); [26] [27] Institute of Physics, Faculty of Science, Ss. Cyril and Methodius University, Skopje, FYROM, Macedonia; [28] Groupe Européen d'Observations Stellaires (GEOS), Bailleau l'Evêque, France; [29] Private Observatory in Madrit-Ventila; [30] Gualba Observatory, Spain; [31] Department of Physics and Astronomy, University of Leicester, UK.

The 11-th magnitude star EE Cep is a member of rare class of binary systems in which the eclipses are caused by a dark, dusty disk surrounding the orbiting companion. The precursor of this group is the extremely long-period (27 yr) ε Aur (see Guinan & Dewarf 2002). For a long time these both remained uniques, however, in the recent years new candidates emerge and their number is still increasing (eg. Garrido et al. 2016; Rattenbury et al. 2015; and references in Gałan et al. 2014). Studies of EE Cep system are of great importance because of its well documented a long history of eclipses showing very unusual behaviour, for over 13 orbital epochs.

The variability of EE Cep was discovered in 1952 (E=0) by Romano (1956) and soon confirmed by Weber (1956). The eclipsing nature of these minima was established after observations of three subsequent events in 1958, 1964 and 1969 (Meinunger 1973). So far all consecutive, primary eclipses were observed with P_{orb} = 5.6 yr, but have never been noticed any traces of the secondary eclipse. Three last eclipses, since 2003 (E=9), were studied in the framework of wide international campaigns, and here we present the results of the last one carried out in 2014 (E = 11).

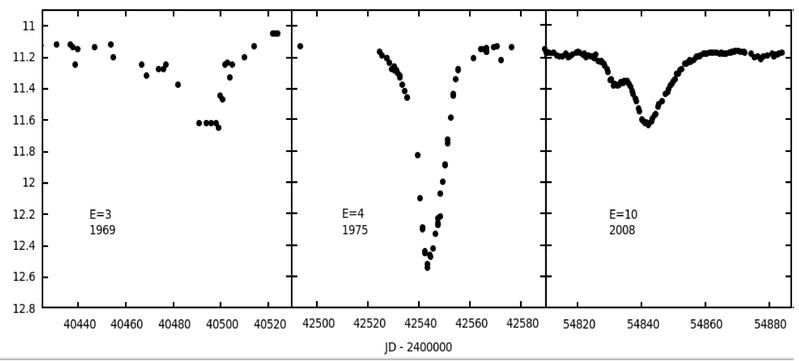

Fig. 1. Representative light curves of eclipses. *Left:* unique, the only flat bottomed eclipse observed in 1969 (m_{pg} band). *Center:* deep eclipse from 1975 (*B* band). *Right:* shallow eclipse from 2008/9 (*B* band).

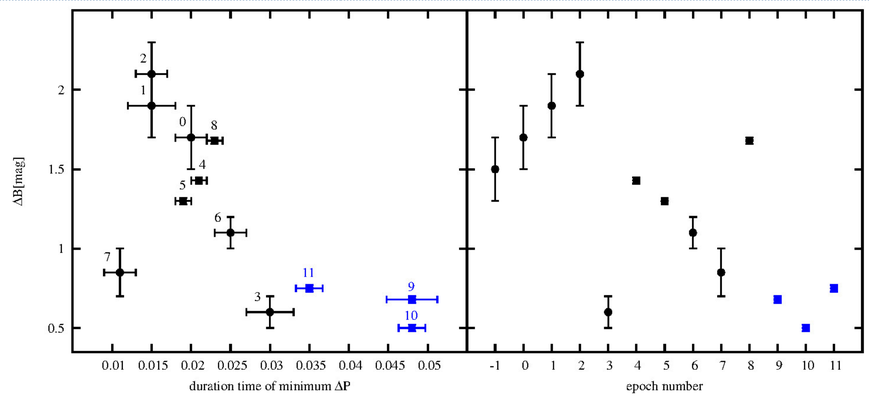

Fig. 2. *Left:* The depth-duration relation (each eclipse is signed by its epoch number). *Right:* Time dependence relation for the depth of the eclipses.

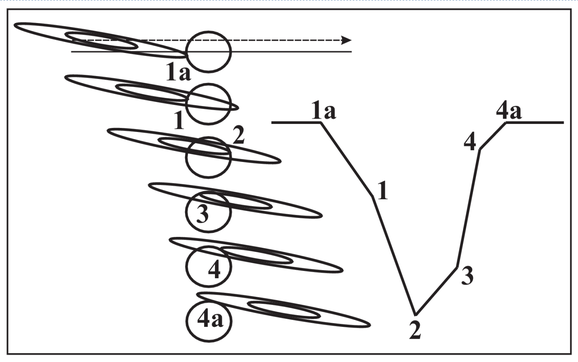

Fig. 3. Schematic representation of the eclipses geometry in the EE Cep system (Gałan et al. 2012).

CHARACTERISTICS of THE ECLIPSES. The most striking feature of the EE Cep minima are large changes of their depth across a wide range of about 0.5 to 2.0 magnitudes. **Fig. 1.** shows the representative light curves of three minima: i) typical example of deep minimum observed in 1975 (E = 4) in the frame of the first campaign using photoelectric detectors (Meinunger 1975), ii) the shallowest so far eclipse observed in 2008/9 (E = 10), and iii) the exceptional eclipse with flat bottom during its central part in 1969 (E = 3). It is clearly visible that the changes in the depth are accompanied with variations of the total eclipses duration. The analysis of the depth-duration relation for the eclipses up to 1997 (E = 8) was performed by Graczyk et al. (2003) and it is reproduced here in **Fig. 2.** with inclusion of three newest eclipses (blue points). All so far eclipses characterise with similar assymetry – the descending branches have longer duration times than ascending branches. It is possible to distinguish in light curves five repeatable phases (**Fig. 3**): sloped-bottom transit during the central part of the eclipse (2 – 3) is preceded and followed by the real ingress (1 – 2) and egress (3 – 4), respectively, and two atmospheric wings (1a – 1 and 4 – 4a) caused by semitransparent external parts of the eclipsing body. Multicolor observations, including R and I bands, that are collected since 1997 (Mikołajewski & Graczyk 1999) showed that the contribution of the secondary component in the optical range is negligible. Very small color variations during the eclipses constitute the very strong argument against that the eclipsing component could be a giant star.

THE PRECESSING DISK MODEL. To explain this unusual behavior Mikołajewski & Graczyk (1999) suggested that the eclipses of the primary are caused by a dark, relatively thick disk, opaque in its interior and semitransparent in exterior around an invisible secondary component: it could be a low-mass single star or super-jupiter planet, or a close binary. In such a model the differences between the particular eclipses can be understood if the disc has varying inclination to the line of sight during different eclipses, for example due to precession. The unique flat bottom eclipse, observed in 1969 (E = 3), can be explained by a nearly edge-on and non-tilted projection of the disk. The photometric and sepctroscopic results of two campaigns for the eclipses in 2003 and 2008/9 (Mikołajewski et al. 2005ab; Gałan et al. 2010), complemented by the historical light curves (Graczyk et al. 2003) were used to perform numerical modelling of the system. The best solution was obtained for the eclipses caused by a disk, precessing with period $P_{prec} \sim 11-12 P_{orb}$ (Gałan et al. 2012). According to prediction of this model the eclipse in 2014 (E =11) should achieve large depth close to 2 mag. Analysis of the high resolution spectra confirmed that the priamry component is B5III star rotating at very high speed (350 km/s) what cause inhomogeneous temperature and fluxe distribution on its surface due to Von Zeipel effect. Non-simultanous eclipses of the hot, polar regions of the star, can explain clear „bumps" observed in the light curves and color indices during shallow eclipses. Smaller, the second order effects detectable in the light and color curves of such high quality could be related to multi-ring structure of the disk. Gałan et al. (2010) speculated that possibly planets could be responsible for their formation.

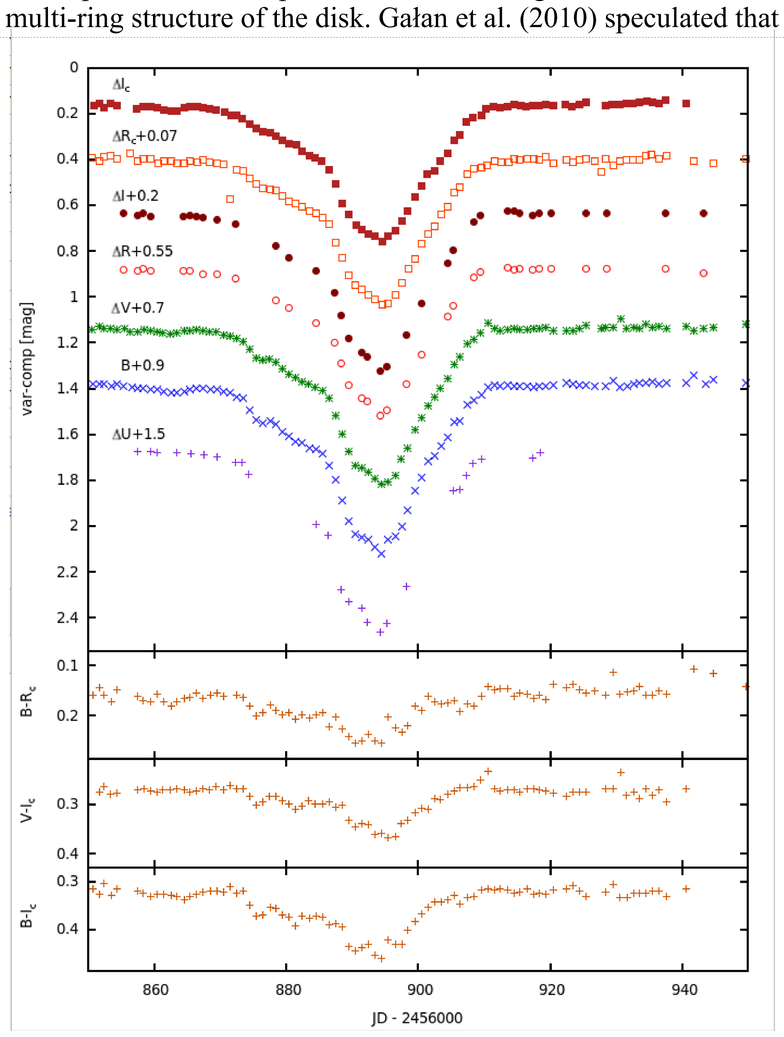

Fig. 4. Photometric variations during 2014 eclipse of EE Cep. *Top*: *U*, *B*, *V*, *R*, R_C, *I*, I_C light curves. *Bottom*: *B*-R_C, *V*-I_C, and *B*-I_C color indices.

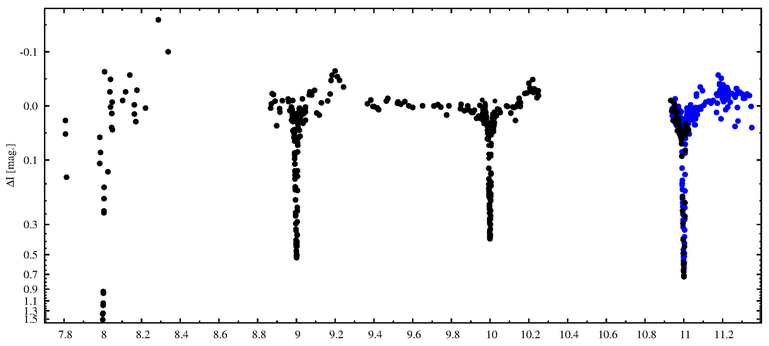

Fig. 7. Differential *I* magnitudes of EE Cep during and around of eclipses at epochs E = 8, 9, 10, and 11. The zero value represents average brightness outside eclipses (phase 0.4-0.8) Blue points show the AAVSO *I*-band light curve after correcting for the differences between photometric systems of particular observers.

OBSERVATIONAL CAMPAIGN 2014

Good enough data can be obtained only through a collective effort in extensive campaigns, like those from the recent years. Gałan et al. (2014) invited for observations of the event in 2014, and obtained wide response of observers using above 30 telescopes located in Europe and North America.

More than 2000 individual photometric measurements were obtained with 27 instruments – most using $UBV(RI)_C$ pass-bands of Johnson-Cousins photometric system and in several cases *RI* filters more close to Johnson's realization of these bands. The photometric data – covering 243 days from 22-th March to 20-th November 2014 – were processed to correct for small differences among photometric systems of individual observatories and the points obtained during the same nights were averaged in single points with the procedure described in details by Pieńkowski et al. (in preparation). The final light curves and color indices are shown in **Fig. 4**.

High-resolution spectra were collected with two spectrograph operating on 2-m Ritchey–Chretien–Coude (RCC) telescope of the Rozhen Observatory, Bulgaria. Two spectra (R ~30000) in the range ~4000-9000Å were obtained with ESpeRo echelle spectrograph (Bonev et al., in preparation). Ten spectra (R ~16000) covering narrow ranges (~200Å) were obtained with Coude spectrograph during 6 night in the period from Apr 4 to Aug 6, 2014. Balmer H_α, H_β and Hγ, and sodium Na I doublet line profiles from these spectra are shown in **Fig. 5**.

Also low-resolution (R ~1000) spectra were collected with several instruments. These give larger set whose comprehensive analysis will be released soon (Pieńkowski et al., in preparation). The evolution of Balmer lines Hα – Hδ in respect to continuum in flux calibrated, low resolution spectra was disussed by Boyd (2014).

PRELIMINARY RESULTS

The obtained light curves show minimum of the eclipse on *JD = 2456894,* which coincides with the minimum calculated with respect to Mikołajewski & Graczyk (1999) ephemeris. The profiles of eclipse in all bands are similar to those from 2003 and 2008/9. In particular there is clear "bump" about ~9 days before photometric minimum in light curve and color indices, and small dip at orbital phase ~-0.015 (**Figs 4** and **6 – *Bottom***). The eclipse reached depths from about $0.^m81$ in *U* to $0.^m61$ in I_C. It is much shallower than expected according to the Gałan's et al. (2012) model. The reason can be too simple the model's assumptions. In particular: i) circularity of the orbit, and ii) very simple the disk density profile. Moreover there was no way to estimate reliable the disk diameter, and it was adopted quite arbitrarily as ~150 R_{sun}. There are indications that the orbit can be eccentric that comes from variations out of the eclipses noted in *I*-band light curve (Gałan et al. 2012). **Fig. 7** shows repeteable brightening in infrared domain with maximum at phase ~0.2. The tentative interpretation can be proximity effects, when components are approaching each other close to periastron passage. In that case, the acceleration in the orbital motion may be an additional reason for the observed eclipse asymmetry and this complication have to be taken into account in the model.

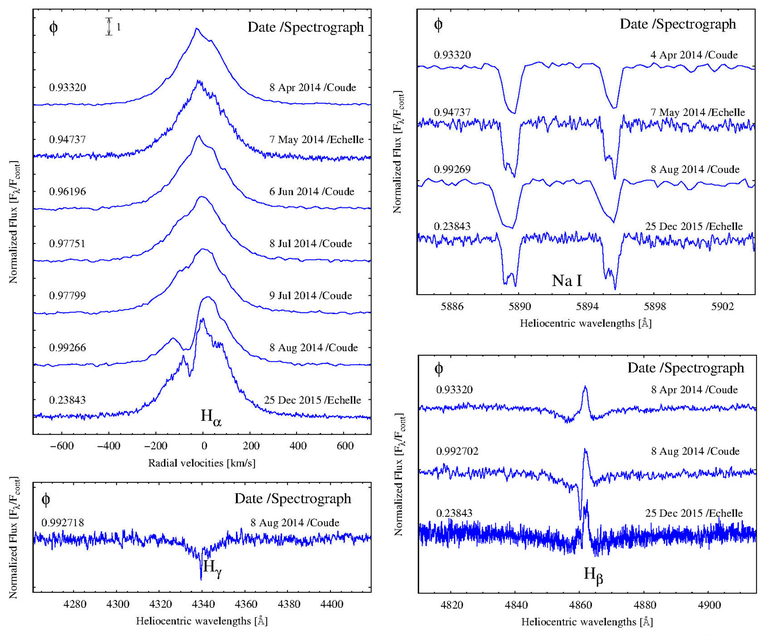

Fig. 5. Balmer H_α, H_β and Hγ, and sodium Na I doublet line profiles in the high resolution spectra obtained during and around of eclipse EE Cep in 2014 (E = 11).

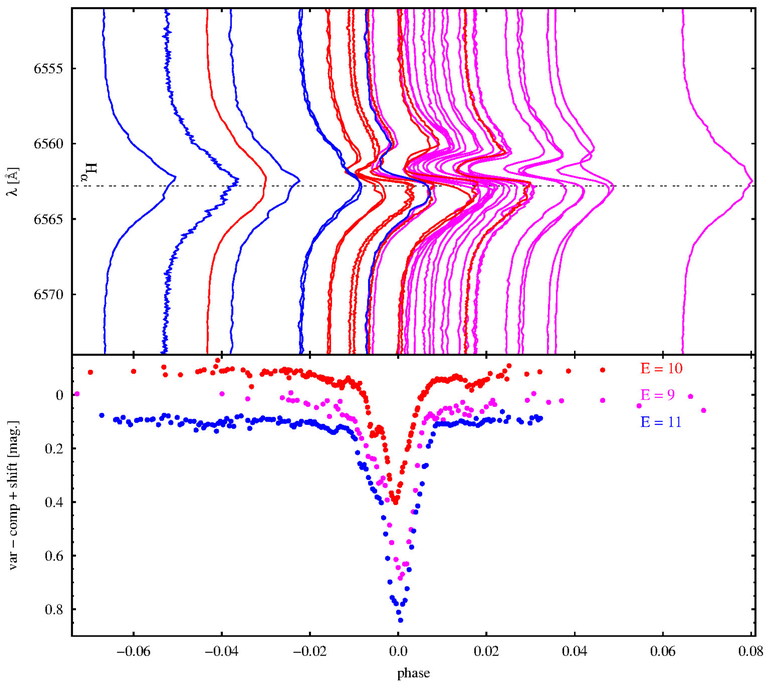

Fig. 6. Evolution of the Hα line profiles (*Top*) and *B* light curves (*Bottom*) during and around of eclipses at epochs E = 9, 10, and 11. Data are folded according to ephemeris by Mikołajewski & Graczyk (1999).

We do not observe significant changes in the Hα line up to Jul 8, and 9, 2014, when the signs of absorption components begin to appear on the blue wings of this emission (**Figs 4** and **6 – *Top***). It falls at the time when small the dip starts to develop in the light curves, which mean the beginning of the photometric eclipse. The new, precise photometric data with dense time coverage enable noticing more subtle changes, and more accurate determination of the eclipse times and their total durations. The shallow eclipses last up to 2.5 – 3.5 months and there is now much less difference with results obtained from spectroscopic observations. The total duration times estimated from the old photometric data seem be underestimated (see **Fig. 2 – *Left***). The Balmer H_α, H_β and Hγ profiles in the spectra obtained deep in the eclipse (Aug 8, 2014) show deep absorption component on their blue wings. Interestingly H_α, and H_β lines in the spectra obtained on Dec 23, 2015 also show absorption component – this is the orbital phase ~0.24 during the brightenings in the *I*-band. The blue-shifted absorption components are visible also in Na I sodium double observed during this phase. Sodium shows developed absorption even at much longer distance in phase than hydrogen (eg. spectrum on May 7, 2014) – similar behaviour of the sodium and potassium lines was observed in phases close to eclipses in ε Aur system (see eg. Tomov et al. 2012; Leadbeater et al. 2012).

References: Boyd D., 2014, arXiv:1412.5127; * Gałan C., et al., 2010, ASPC, 435, 423; Gałan C., et al., 2012, A&A, 544, 53; * Gałan C., et al., 2014, IBVS no 6111; * Garrido H. E., et al., 2016, MNRAS, 457, 1675; * Graczyk D., et al., 2003, A&A, 403, 1089; * Guinan E. F. & Dewarf L. E., 2002, ASPCS, 279, 121; * Leadbeater R., et al., 2012, JAAVSO, 40, 729; * Meinunger L., 1973, MitVS, 6, 89; * Meinunger L., 1975, IBVS No. 965; * Mikołajewski M., & Graczyk D., 1999, MNRAS, 303, 521; * Mikołajewski M., et al., 2005a, Ap&SS, 296, 445; * Mikołajewski M., et al., 2005b, Ap&SS, 296, 451; * Rattenbury N. J., et al., 2015, MNRAS, 447, 31; * Romano G., 1956, Coelum, 24, 135; * Tomov T., et al. 2012, BlgAJ, 18a, 3; * Weber R., 1956, Doc. Des Obs. Circ., No. 9;

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