On the accretion disc properties in eclipsing dwarf nova EM Cyg

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Abstract In this paper we analyzed the behavior of the unusual dwarf nova EM Cyg using the data obtained in April-October, 2007 in Vyhorlat observatory (Slovak Republic) and in September, 2006 in Crimean Astrophysical Observatory (Ukraine). During our observations EM Cyg has shown outbursts in every 15-40 days. Because on the light curves of EM Cyg the partial eclipse of an accretion disc is observed we applied the eclipse mapping technique to reconstruct the temperature distribution in eclipsed parts of the disc. Calculations of the accretion rate in the system were made for the quiescent and the outburst states of activity for different distances.

Keywords accretion, accretion discs - binaries: close - binaries: eclipsing - stars: dwarf novae - stars: individual: EM Cygni - cataclysmic variables.

1 Introduction

EM Cyg is an eclipsing dwarf nova which has relatively long orbital period ($P_{orb} = 6^{h}.98$). Dwarf novae are evolved binary stars, where the Roche lobe-filling red dwarf component accretes matter onto the white dwarf component. Loosing angular momentum, matter forms an accretion disc. Such systems produce outbursts, caused by instabilities in the disc.

EM Cyg was discovered by Hoffmeister in 1928. Mumford & Krzeminski (1969) investigated instabilities on the eclipse light curves and noted, that they reflect instabilities in accretion disc. Stiening et al. (1982) detected rapid oscillations on light curves with typical time scale of 14.6 and 16.5 seconds. Brady & Herczeg (1977), using long-term photographic observations found outburst cycle to be 24-25 days and noted the seasonal changes of the light curve and the outburst cycle.

Because EM Cyg shows standstills (North et al. 2000), it is classified as Z Cam type star. So EM Cyg is the only eclipsing dwarf nova among Z Cam type stars.

Using radial velocities, Robinson (1974) estimated masses to be 0.7 $M_{\odot}$ and 0.9 $M_{\odot}$ for the white dwarf and the red dwarf respectively. These parameters corresponded to the thermal-timescale mass transfer in the system, and were doubtful. Stover et al. (1981) found that the orbital inclination of the system is about 63° and the mass relation close to results obtained by Robinson (1974).

North et al. (2000) found that the spectrum of EM Cyg in the range 6230-6650 Å is contaminated by light from a K2-5V star (in addition to the K-type mass donor star). The K2-5V star contributes approximately 16 % of the light from the system in that band and, if not taken into account, has a considerable effect upon radial velocity measurements of the mass donor star. The revised value of the mass ratio, combined with the orbital inclination $i = 67^\circ$, leads to the masses of 0.99$M_{\odot}$ and 1.12$M_{\odot}$ for the mass donor and white dwarf respectively.

Recent more precise measurements of the third star light by Welsh et al. (2007) showed that masses to be $M_{wd} = 1.0M_{\odot}$ and $M_{rd} = 0.77M_{\odot}$.

There are several too different estimates of the distance to EM Cyg. From ellipsoidal variations in the infrared band, Jameson et al. (1981) found secondary
s spectral type to be K2V and the distance to the system to be 320 pc. Bailey [1981] using K magnitudes of Jameson et al. [1981] determined the possible distance to be in the range 285–429 pc with most probable value of about 352 pc. But Stiening et al. [1982], using private communication of Stover suggests 400 pc in his calculations.

Taking into account the light of the third star, Welsh et al. [2003] supposed the distance to be 450–500 pc.

Winter and Sion (2003) found 411 parsecs using the MEADE DSI PRO CCD camera in R band with 15 sec exposure and using the Pupava telescope (d=280 mm, Newton system) with the MEADE DSI PRO CCD camera in R band with 30 sec exposure in Vyhorlat observatory (Slovak Republic) during May-November, 2007 (Fig.1, see online database [http://var.kozmos.sk]). The quantity of observational runs are 8 for Crimean data and 61 for Slovakian data.

CCD images were processed with C-Munipack package [Hroch 1998], including flatfielding and debiasing. The procedure of the “artificial” mean weighted moments we determined using the method of ”asymptotic parabola” [Andronov & Marsakova 2006] (Table 1). To achieve a higher accuracy with period determination, we used 30 moments of minima obtained from Misselt (1996), we calculated transformation coefficients for converting the magnitudes from the instrumental systems of Pupava telescope: $m-m_0 = -0.027(0.012) + 0.98(0.024) \cdot (V_0-R_0)$.

Moments of minima determined by the previous investigators too [Mumford & Krzeminski 1969; Mumford 1974, 1975, 1980; Beuermann & Pakull 1984; Csizmadia et al. 2008]. The improved elements are

$$ T = -2437882.86059(33) + 0.290990919984 d \cdot E \quad (1) $$

From Fig.1, one can see that the typical interval between outbursts is about 25 days. Duration of outburst is approximately equal to the time interval between them.

Individual light curves show significant flickering which deforms the partial eclipse shape.

On the individual light curves the effect of the presence of a bright hot spot in accretion disc is presented. The hump before the eclipses is well visible, and the as-

| Table 1 | 28 heliocentric moments of minima of EM Cyg (HJD-240000). (1) - Crimean data, (2) - Slovakian data |
|---------|---------------------------------------------------------------------------------------------------|
| 53947.444111 | 54269.482122 | 54328.535272 | 53953.407271 | 54272.388222 | 54331.447822 | 53954.419051 | 54299.440922 | 54336.390642 |
| 53960.386411 | 54314.570702 | 54339.296492 | 53961.408541 | 54315.544002 | 54357.334542 | 54240.387782 | 54319.516212 | 54361.406792 |
| 54242.423102 | 54320.385852 | 54364.316802 | 54256.386352 | 54321.551142 | 54366.351362 | 54258.430002 | 54322.425262 |
| 54267.443402 | 54327.367562 |

Fig. 1 Long term light curve of EM Cyg, obtained in 2007 in Vyhorlat observatory (Humenne, Slovak Republic).
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Fig. 2 Averaged light curves for two different states of the brightness of the system, the eclipse model fits and the residuals.

cending branch of the eclipse light curve is longer, than the descending one.

The strong flickering and variability with time-scales from several minutes to dozen percents of the orbital period are presented on the light curves.

To investigate the typical patterns on the orbital light curves of EM Cyg and to diminish the flickering distortions, all phase curves were divided onto two groups, depending on the activity state of the system. Within each group the average detrended light curves were calculated (Fig. 2).

There is well pronounced secondary eclipse on a phase 0.5 on the light curve both in the outburst and the quiescent states. This eclipse occurs when the secondary (red dwarf) star is behind the white dwarf and the disc. Our data shows that the amplitudes of the secondary minima in the quiescent and the outburst states are constant. Thus, an occulting media has the same properties in both states because the secondary star has the constant luminosity expected.

The shape of quiescent state light curve is typical for the systems with significant ellipsoidality effect.

3 Eclipse mapping of EM Cyg

Light curves of the partial eclipse of accretion disc in EM Cyg allow us to reconstruct the temperature distribution in the eclipsed parts of accretion disc using the eclipse mapping technique (Horne 1985). If we use the system parameters, determined by North et al. (2000) and Welsh et al. (2007) \( (i = 67^\circ, M_{rd} = 0.77, M_{wd} = 1.0) \), one can see that there is no eclipse of the white dwarf in the system (see Fig. 3 in Robinson (1974)). The eclipse light curves become more sensitive to the accretion disc structure fluctuations in such situation. To minimize the influence of accretion disc non-uniformity, we used the averaged light curves for the outburst and the quiescent activity states of EM Cyg, presented in the Fig. 2.

Our model takes into account radiation of the eclipsed part of the accretion disc, the donor star light with ellipsoidality and gravitation darkening effects and the constant term, wich includes the radiation from the uneclipsed part of accretion disc and the third star light. So, we cannot resolve the third star light fraction in the constant radiation parameter but the eclipse mapping results are independent from the presence of any additional constant sources.

Our eclipse mapping technique (Halevin 2007) based on genetic algorithm fitting of the light curves with the model, where brightness distribution in two-dimensional accretion disc is modeled by the set of points. The density of such points is proportional to the brightness of the selected area of accretion disc. The advantage of this method is the smaller number of free parameters of the model than in the classical eclipse mapping techniques are used.

To model of the donor star radiation we suggested that it fills the Roche lobe and use the gravity darkening parameter \( \beta \) to be 1. The reflection effect was neglected because it is expected to be small in a late-type companion.

The maps of the eclipsing part of accretion disc for the quiescent and the outburst states have been calculated using the system parameters, presented in Table 2. To build the map of accretion disc we used the model with 200 radiating points.

The fits and the residuals one can see in Fig. 2. In the quiescent state we see well pronounced pre-eclipse lump, corresponded to the hot spot in accretion disc, where ballistic flow coincides with the disc.

Table 2 The system parameters of EM Cyg, used in the eclipse models.

| Parameter | value | reference |
|-----------|-------|-----------|
| \( M_{wd} \) | 1.0\( M_\odot \) | Welsh et al. (2007) |
| \( M_{rd} \) | 0.77\( M_\odot \) | Welsh et al. (2007) |
| \( i \) | 67\(^\circ\) | North et al. (2000) |
| \( p \) | 0.290909199 d | see text |
| \( A_R \) | 0.1 kpc\(^{-1}\) | see text |
| \( d \) | 200-500 pc | |
In the quiescent state, the secondary star contributes of about 64 per cent of the light to the total flux from the system and the third star in R band.

The secondary eclipse deep is about 5.3 per cent of the flux from the red dwarf and the width of the eclipse is about 15 per cent of the orbital period. Taking into account low inclination angle, the origin of covering might be ballistic stream or extended above orbital plane gaseous structures.

For our models we used correction for interstellar extinction according Warner (1995) \( E_{B-V} \approx 0.74 E_{B-V} \) and \( A_R \approx 3.0 E_{R-I} \). In the case of \( E_{B-V} = 0.05 \) we have \( A_R \) to be about 0.1 per kiloparsec.

### Table 3

| distance, pc | quiescent | outburst |
|-------------|-----------|----------|
| 200         | \( 1.2 \cdot 10^{-9} \) | \( 5.6 \cdot 10^{-9} \) |
| 300         | \( 2.2 \cdot 10^{-9} \) | \( 1.4 \cdot 10^{-8} \) |
| 400         | \( 3.8 \cdot 10^{-9} \) | \( 3.1 \cdot 10^{-8} \) |
| 500         | \( 6.1 \cdot 10^{-9} \) | \( 6.2 \cdot 10^{-8} \) |

Comparing the temperature distribution with the steady state models, we estimated the mass accretion rate for different distances to the system in the quiescent and in the outburst states both (see Table 3). The mass accretion rate estimates were calculated by minimizing of the mean square deviation of observed temperature values from the steady state temperature distribution for different accretion rates.

### 4 Discussion

Our mass accretion rate estimates are close to values, determined by the previous investigators, if we choose the distance to be about 200 pc. At the same time, the disc becomes ionized according to Warner (1995), critical temperature curve during outburst for the models with distance larger than 300 pc. Distances about 500 pc demand ionized gas state in the disc even for quiescent states, what is improbable. So, using ionization criteria during outburst state, we must accept the distances, ranged between 300 and 400 pc.

Another estimate of the distance we can make using ellipsoidal modulation of the light curve in the quiescent state, where such effect is mostly pronounced. Using mean flux of the secondary from our model, we find that it has \( m_R \approx 13.6 \). If the secondary star having mass to be \( 0.77 M_\odot \) is a normal main sequence star, the spectral class must be K0V. In that case \( m_V = 5.9 \) (Allen 1973), \( V-R = 0.64 \) (Johnson 1966) and the distance must be about 459 pc. At the same time for the system parameters we used, to fill its Roche lobe, the secondary must be slightly evolved. If we use the spectral class value K2V, determined by Jameson et al. (1981) the distance estimate will be 400 pc. This value is the same as determined by Winter & Sion (2003) using the \( M_V \) versus \( P_{orb} \) relation.

The distance of 400 pc in our models corresponds to relatively high accretion rate. Taking into account that the outburst state and the quiescent state have practically equal durations we estimate the mass transfer rate to be about \( 1.7 \cdot 10^{-8} M_\odot / \text{year} \). This value about an order higher than determined by Csizmadia et al. (2008) upper limit \( 2 \cdot 10^{-9} M_\odot / \text{year} \) for conservative mass transfer. To explain observed stability of the orbital period in the case of high mass transfer rate we can take into account of magnetic braking effect. Using relations from Csizmadia et al. (2008) we find that in the case of system parameters from Table 2, the mass transfer rate which can be neutralized by magnetic braking is about \( 2.5 \cdot 10^{-8} M_\odot / \text{year} \). So, magnetic braking of EM Cyg system can explain of the mass transfer rate wich we have found for the case of 400 pc.
distance. Our present result supports the suggestion of Csizmadia et al. (2008) that these two effects neutralize each other and that is why we do not see any observable period variation.

5 Conclusions

In this paper, using large volume of minima timings we specified the orbital period of the system. Our R band light curves in the quiescent state show significant ellipsoidal effect. Firstly for this star we used the eclipse mapping technique of the outer parts of accretion disc. We estimated the mass accretion rate for different distances and showed, that the distance must be in the range between 300 and 400 pc. Using ellipsoidal variability of the secondary star we estimated the distance to be about 400 pc. Also we showed, that the magnetic braking effect can explain of \(1.7 \cdot 10^{-8} M_\odot/\text{year}\) mass transfer rate, which has been found for 400 pc distance.

Acknowledgements

We thank to anonymous referee for many useful comments. Also we are grateful to I. Andronov, who proposed this star for investigations. We acknowledge with thanks to K. Antoniuk and A. Lomach for their help during observations. We also thank to E. Sion and other colleagues for many fruitful discussions.

![Fig. 3](image-url) Radial brightness temperature distribution in accretion disc for the outburst and the quiescent states for different distances to the system. The dashed lines are theoretical temperature distribution for the steady state flat disc and the thick solid line shows the critical temperature above which gas is in steady accretion regime (Warner 1992).
References

Allen, C.W. 2004. Astrophysical Quantities, 3rd edn, Athlone press, London
Andronov, I. L. & Baklanov, A.V. 2004, Astron. School Rep., 5, 264
Andronov, I. L. & Marsakova, V. I. 2006, JAAVSO, 35, 198
Bailey, J. 1981, Mon. Not. R. Astron. Soc., 197, 31
Bruch, A. & Engel, A. 1994, Astron. Astrophys. Suppl. Ser., 104, 79
Beuermann, K. & Pakull, M. W. 1984, Astron. Astrophys., 136, 250
Brady, R. A. & Herczeg, T. J. 1977, Publ. Astron. Soc. Pac., 89, 71
Cszmadia, Sz., Nagy, Zs., Borkovits, T., Hegedus, T., Biro, I. B. & Kiss, Z. T. 2008, Astronomische Nachrichten, 329, 39
Fernie, 1975, Variable Stars And Stellar Evolution. Editor: L. Plaut. Kluwer Academic Publishers Group (Netherlands)
Godon, P., Sion, E.M., Barrett, P.E. & Szkody, P. 2009, Astrophys. J., 701, 1091
Halevin, A.V. 2007, Odessa Astronomy Publications, 20, 70
Horne, K. 1985, Mon. Not. R. Astron. Soc., 213, 129
Hoffmeister, C. 1928, Astronomische Nachrichten, 233, 33
Hroch, F. 1998, Proceedings of the 29th Conference on Variable Star Research. 7th - 9th November 1997. Brno, Czech Republic, editor J. Dusek and M. Zejda., 30
Jameson, R.F., King, A.R. & Sherrington, M.R. 1981, Mon. Not. R. Astron. Soc., 195, 235
Johnson, H.L., 1966, A.Rev.Astr.Astrophys., 4, 193
Kim, Y.G., Andronov, I.L., Park, S.S. & Jeon, Y.-B. 2005, Astron. Astrophys., 441, 663
La Dous, C. 1991, Astron. Astrophys., 252, 100
Misselt, K.A. 1996, Publ. Astron. Soc. Pac., 108, 146
Mumford, G.S. & Krzeminski, W. 1969, Astrophys. J. Suppl. Ser., 18, 429
Mumford, G.S. 1974, IBVS, 889, 1
Mumford, G.S. 1975, IBVS, 1043, 1
Mumford, G.S. 1980, Astron. J., 85, 748
North, R. C., Marsh, T. R., Moran, C. K. J., Kolb, U., Smith, R. C. & Stehle, R. 2000, Mon. Not. R. Astron. Soc., 313, 383
Robinson, E. L. 1974, Astrophys. J., 193, 191
Stiening, R. F., Dragovan, M. & Hildbrand, R. H. 1982, Publ. Astron. Soc. Pac., 94, 672
Stover, R. J., Robinson, E. L. & Nather, R. E. 1981, Astrophys. J., 248, 696
Verbunt, F. 1987, Astron. Astrophys. Suppl. Ser., 71, 339
Volkhanskaia, N. F., Gnedin, Iu. N., Efinov, Iu. S., Mitrofanov, I. G. & Shakhovskoi, N. M. 1978, Soviet Astronomy Letters, 4, 148
Warner, B. 1995, Cambr. Astrophys. Ser. 28, "Cataclysmic Variable Stars". Cambridge Univ. Press, Cambridge
Welsh, W.F., Froning, C.S., Marsh, T.R., Robinson, E.L. & Wood, P.R. 2005, Publ. Astron. Soc. Pac., 330, 351
Welsh, W.F., Froning, C.S., Marsh, T.R., Reimer, T.W., Robinson, E.L. & Wood, P.R. 2007, Publ. Astron. Soc. Pac., 362, 241
Winter, L. & Sion, E. 2003, Astrophys. J., 582, 352

This manuscript was prepared with the AAS \LaTeX\ macros v5.2.