EM Cygni: a study of its eclipse timings

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EM Cygni is a Z Cam-subtype eclipsing dwarf nova. Its orbital period variations were reported in the past but the results were in conflict to each other while other studies allowed the possibility of no period variation. In this study we report accurate new times of minima of this eclipsing binary and update its $O-C$ diagram. We also estimate the mass transfer rate in EM Cygni system and conclude that the mass transfer is far from the critical value. The mass transfer rate determined from the eclipse timings is in agreement with the spectroscopically determined value.

1 Introduction

Dwarf novae are binary stars consisting of a white dwarf and a red dwarf in which some mass is transferred from the red dwarf component onto the white dwarf. Depending mainly on the mass transfer rate and the magnetic field of the white dwarf they produce outbursts caused by instabilities in the accretion disk. In the case of weak magnetic field of the white dwarf the main factor which governs the frequency and amplitude of the outbursts is the mass transfer rate. There is a critical value of the mass transfer rate and it was investigated by Shafter et al. (1986). According to their results, if the mass transfer rate is higher than this critical value there are no dwarf nova eruptions (we have a nova-like variable) and if the mass transfer rate is below it we have a dwarf nova. If the mass transfer is nearly equal to the critical value we have a Z Cam-type variable (see Shafter et al. 1986, 2005). (For details on dwarf novae and the processes in them see Warner 1995).

In the General Catalogue of Variable Stars (Samus et al. 2004) sixteen eclipsing dwarf novae were listed. These objects are important because the period can easily and precisely be measured due to the eclipsing nature and this allows to demonstrate so far small astrophysical effects as mass transfer rate. The careful analysis of the eclipse timings can reveal small orbital period changes which cannot be followed by radial velocity studies. For details on the eclipse geometry in dwarf novae see Smak (1994).

The subject of this study is EM Cygni which is the only known eclipsing Z Cam-subtype dwarf nova. Therefore the precise determination of its mass transfer rate is extremely important. Its eclipses were discovered by Mumford and Krzeminski (1969) and this allows to determine its mass transfer rate. Pringle (1975) and Mumford (1980) stated that the eclipse period of EM Cyg is decreasing. In contradiction with these results, Beuermann & Pakull (1984) concluded that there is no evidence for period change in EM Cyg. Herczeg (1987) also investigated the period of EM Cygni and found weak evidence for period change but he concluded that more observations are needed. It is worthy to mention that the period decrease rate determined by Pringle (1975) was in the order of $10^{-12}$ days/cycle while Mumford’s (1980) value is in the order of $10^{-11}$ days/cycle. These rather contradictory results may originate from the fact that the precision of minimum times obtained before 1984 (Beuermann and Pakull 1984 estimated their accuracy to be 0.0008 days) could be compared to the expected width of the $O-C$ in such a small period variation. If the time-coverage of the minimum observations would be longer, this effect can be avoided because the accumulated period variations are larger in the $O-C$ than its intrinsic scatter.

Since 1984 more than 25000 revolutions have occurred and the corresponding $O-C$ value – assuming $10^{-12}$ days decreasing in every cycle – reaches $-0.0036$ days. Twenty-one years after the latest published photoelectric minimum in any refereed journal we decided to observe EM Cygni because the accumulation of the small continuous period changes can be sufficient for deciding whether the EM Cygni’s period is variable or not. This is very important from the point of view of understanding the mass transfer mechanism in cataclysmic variables.

Our aim was twofold. First, we wanted to solve the question of period change of EM Cyg with new observations. Secondly, we wanted to calculate the mass transfer rate from the observed period change if such a change is present.
2 Observations

EM Cyg was observed at the Konkoly Observatory on four nights (in Cousins I-band) and at the Baja Astronomical Observatory on two nights (in V-band) to obtain precise light curves. The observations were carried out with the 1m RCC telescope of the Konkoly Observatory located at the Piszkestető Mountain Station at 964 meters above the sea level and with the 50cm robotic telescope of the Baja Astronomical Observatory.

The detector of the 1m RCC telescope was an 1340×1300 pixels electronically cooled (T_{CCD} = −40°C) CCD camera manufactured by the Roper Scientific Ins. The exposure time was between 5-15 seconds depending on sky-conditions. The readout-time was only two seconds therefore the duty cycle was very favourable. All frames were bias-subtracted. Dark correction was not applied because a negligible dark current was measured for this exposure time. Flat-field correction was also done using dome flats. The detector of the 50cm robotic telescope was an Apogee ALTAU16 4kx4k CCD camera with a field of view of 42 × 42 arcminutes. Bias, dark and flat-field corrections were applied. To determine the raw magnitudes of stars in the frames, aperture photometry was performed using the IRAF/DAOPHOT package (Stetson 1990). We selected a comparison star and a check star in the frames and they showed a sufficient stability in each colour (standard deviation of their magnitude differences is 0.003 magnitudes (1m RCC) and 0.007 magnitudes (50cm robotic telescope), respectively). Then differential photometry was done defining the variable’s brightness as Δm = m_{var} − m_{comp}. No standard transformation was applied.

3 Analysis of the O − C diagram

3.1 Source of data

Times of eclipses were collected from the following sources. 29 minima times were taken from Mumford & Krzeminski (1969); two from Mumford (1974); one from Mumford (1975); three from Mumford (1980). One time of minimum was observed by Beuermann & Pakull (1984). These are all the published minima in any refereed journal and none has been published since them.

Beuermann & Pakull (1984) determined two times of minima from the Figure 1 of Jameson et al. (1981). Of course, this method does not yield an accurate minimum time, but we followed them and concluded that around JD 2444105 – when the observations of Jameson et al. (1981) were carried out – the O − C value was about −0.0065 days (against the ephemeris of Mumford & Krzeminski 1969). (At this time the cycle number E was close to 21390.) We assign a one-tenth weight to this value.

We also found two amateur minimum observations on the homepage of ’The Astronomer’ (www.theastronomer.org). One of them cannot be used for a minimum time estimation but the other one – reproduced in Figure 1 – was inspected and a fitting resulted a usable minimum time. We denoted the reference of this minimum time as ’Anonymous’ in Table 1.

New and reliable minima times were determined from our light curves with the Kwee-van Woerden (1956) method which means that the descending and the ascending branches of the minimum are reflected to a certain time value and it searches for the time which yields the minimum difference between the original and the reflected curves. These moments of minima are presented in Table 1. Errors of the times of minima can be estimated as follows: 0.0008 days before 1980, 0.0001-0.0004 after that. These errors are smaller than the observed scatter of 0.002 days seen in Figure 4 (which shows the O − C diagram). The possible explanation of this can be due to the intrinsic variations of the location of the hot spot in the system. Note that the eclipses in EM Cyg are not total but grazing ones. Some of our minimum observations are presented in Figures 2-3.

| HJED   | Reference | HJED   | Reference |
|--------|-----------|--------|-----------|
| 37882.8603 | 1 | 39230.9335 | 1 |
| 37883.7321 | 1 | 39293.7704 | 1 |
| 37906.7130 | 1 | 39767.6624 | 1 |
| 37911.6603 | 1 | 39769.6971 | 1 |
| 37936.6778 | 1 | 40006.7886 | 1 |
| 37966.6413 | 1 | 40007.9534 | 1 |
| 37968.6778 | 1 | 40008.8263 | 1 |
| 37996.6048 | 1 | 41980.6054 | 2 |
| 38174.9335 | 1 | 41982.6435 | 2 |
| 38345.6984 | 1 | 42515.8792 | 3 |
| 38348.6058 | 1 | 43776.6771 | 4 |
| 38496.9701 | 1 | 43778.7146 | 4 |
| 38561.5523 | 1 | 43780.7508 | 4 |
| 38562.4242 | 1 | 45257.4091 | 5 |
| 38624.3885 | 1 | 50692.4613 | 6 |
| 38674.7156 | 1 | 53650.4266 | 7 |
| 38675.5883 | 1 | 53709.1873 | 7 |
| 38676.7513 | 1 | 53984.3938 | 7 |
| 38878.9343 | 1 | 53989.3343 | 7 |
| 38883.8795 | 1 | 53990.5006 | 7 |
| 39052.6043 | 1 | 53991.3676 | 7 |
| 39054.6428 | 1 | 53993.4088 | 7 |

3.2 The O − C diagram

The Julian Heliocentric Ephemeris Date (HJED) is free from the varying rotation of Earth. Since we need as high precision as we can reach we transformed all HJD values of the observed minima into HJED ones. Then linear and quadratic fits yield the following ephemeris:

\[ T_{\text{cl}}(\text{HJED}) = 2437882.8606(3) + 0.29090912(1) \times E(1) \]
Csizmadia et al.: EM Cygni: a study of its eclipse timings

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Fig. 1 The minimum observations of EM Cyg reproduced from the homepage of The Astronomer.

Fig. 2 The I-band light curve of EM Cyg obtained by us at JD 2 453 650.

Fig. 3 The I-band light curve of EM Cyg obtained by us at JD 2 453 709.

Fig. 4 $O - C$ diagram of EM Cyg. The 'expected' is the theoretically expected $O - C$ curve calculated from the theory (Eq. (8) of Shafter et al. 1986) assuming conservative case. The 'upper limit' curve shows the maximum possible period variation (see text).

and

$$T_{ecl}(\text{HJED}) = 2437882.8606(3) + 0.29090911(4) \times E - \frac{1}{2} \cdot 10^{-14} \times E^2$$

(2)

The numbers in the parentheses show the errors in the last digits.

We also calculated the corresponding $\chi^2$ values for both fits and found that in case of the linear fit $\chi^2 = 1.99$ while in case of quadratic fit it is $\chi^2 = 1.98$. So the introduction of a quadratic term does not improve significantly the fit. However, a simple least-squares regression could be very sensitive to the distribution of data points and of errors. Therefore we determined the value of maximum possible quadratic term in another way. We calculated the $O - C$ values within a parameter-space (in the form $T_{ecl} = T_0 + AE + BE^2$ where $E$ is the cycle number, and $T_0 = 2 437 882.8590...2 437 882.8622$, step size: 0.0001 days, $A = 0.29090910...0.29090915$, step size: $2.4 \times 10^{-8}$ days, $B = -1.5 \times 10^{-12}...1.5 \times 10^{-12}$, step size: $10^{-15}$ days) and we found that the corresponding $\chi^2$ value of the $O - C$ values are minimal at $T_0 = 2 437 882.8598$, $A = 0.29090914$, $B = -9.8 \times 10^{-14}$. This corresponds to $\dot{P}/P < 2.32 \times 10^{-12}$ 1/days. A Monte Carlo simulation was also used to estimate the upper limit because in this way we could study how the errors may yield an apparent quadratic term. At the epochs of the observed $O - C$ curve, 1000 $O - C$ values were simulated for each epoch with random errors. The mean of these errors was as mentioned in the previous section and they were assumed to be normally distributed. Then we had 1000 $O - C$ curves and all of them were fitted by a parabola. The average of the quadratic terms yielded $< B >= -8.0 \times 10^{-14}$ days. This is similar to the result of the previous attempt. Therefore the value of $2.32 \times 10^{-12}$ 1/days was accepted as the absolute value of the upper limit for the period decrease.
For comparison, we plotted the $O-C$ diagram of EM Cygni calculated by the linear ephemeris together with the theoretically expected one in Figure 4. The maximum possible period variation is also shown in Figure 4 which was calculated from the above determined upper limit of $\dot{P}$. Comparing our ephemeris to the previously determined ones (see Section 1) one can see that our result is close to the one of Beuermann and Pakull (1984): we found no evidence of period variation. We cannot confirm the results of Pringle (1975) and Mumford (1980) who found definite period decrease.

4 Discussion

4.1 Conservative case

Since we could only give an upper limit for the period variation only, we could guess the maximum possible mass transfer rate in the system. Assuming a conservative case (i.e. the angular momentum and total mass remains constant in the system) the mass transfer rate can be related to the period change via

\[ \frac{1}{P^2} \frac{dP}{dt} = -3 \left( \frac{1}{q} - q \right) \frac{1}{M_1 + M_2} \frac{dM_2}{dt} \]  

(e.g. Thomas 1977) where $t$ refers to time, $q$ is the mass ratio and $M_2$ is the mass of the donor star. Accepting $q = 0.88$ and $M_1 = 1.12 M_\odot$, $M_2 = 0.99 M_\odot$ (North et al. 2000) and $P^{-1}dP/dt = 2.32 \cdot 10^{-12}$ we have $dM_2/dt = 2 \cdot 10^{-9} M_\odot/yr$. This is an upper limit for the mass transfer rate.

From the study of the far-ultraviolet spectrum of EM Cygni, Winter & Sion (2003) found that the mass transfer rate in EM Cyg is between $3.2 \cdot 10^{-11}$ and $1.1 \cdot 10^{-10}$ solar mass per year. Our upper limit is higher than their upper value and is not in contradiction with their results. Therefore the agreement between the spectroscopically observed mass transfer rate and the one derived from eclipse timings is good.

We compared the result to the theoretical expectations. Shafter et al. (1986) investigated the value of the critical mass transfer rate for different values of orbital periods and white dwarf masses. Accepting $M_1 = 1.12 M_\odot$ for the white dwarf in EM Cyg (North et al. 2000) and taking into account that EM Cyg has an orbital period of 6.96 hours, Eq. (8) of Shafter et al. (1986) yields $dM_{crit}/dt = 1.2 \cdot 10^{-8} M_\odot/yr$. If the mass transfer is conservative in EM Cyg, this system is far from this limit. In summary, the mass transfer rate is lower by an order than the theoretically expected value.

4.2 Non-conservative case

In EM Cyg the mass is transferred from the less massive component to the more massive one yielding a period increase. In non-conservative mass transfer there are several mechanisms which decrease the period. Therefore, in total, the result can be a nearly constant as well as a decreasing period! In this case the period variation depends on the mass transfer rate as well as the angular momentum ($J$) variations:

\[ \frac{\dot{P}}{P} = \frac{3}{J} \left( \frac{2+3q}{1+q} \frac{M_1}{M_2} - \frac{3+2q}{1+q} \frac{M_2}{M_1} \right) \]  

(4)

(see Warner 1995). Assuming that $M_2 = -M_1$ we have

\[ \frac{\dot{P}}{P} = \frac{3}{J} \frac{1-q^2}{q(1+q)} \frac{M_1}{M_2} \]  

(5)

We observed nearly zero period variation so we can determine what angular momentum loss is required to neutralize the period increase caused by the mass transfer. For this purpose we set $\dot{P} = 0$ and $M_1$ was chosen as the critical value. With $q = 0.88$, $M_1 = 1.12 M_\odot$ and $M_2 = 1.2 \cdot 10^{-8} M_\odot/yr$ we get that $\frac{1}{J}$ are to be $-4.63 \cdot 10^{-17} s^{-1}$ in order to reduce the period variation to zero.

The system can loss mass via stellar wind. Assuming that the secondary loses $10^{-14}$ solar mass per year via stellar wind (which is a similar value to the one of the Sun) and all this mass isotropically leaves the system, this leads $\dot{M}/P = -2.4 \cdot 10^{-18} \text{day}^{-1}$. (we used the formula given in Batten 1973, p.95). This is too low to explain the missing period variation.

The rotational period of a rotating star decreasing, if the star loses mass by stellar wind (Iben, Fujimoto & MacDonald 1992). Due to the spin-orbit coupling this reduces the total angular momentum of the system. From Warner’s (1995) Eq. (9.13b) we know that

\[ \dot{J}_{rot} = -1.2 \cdot 10^{14} \left( \frac{k_2}{0.1} \right)^2 P_{orb}^{31/12} (h) \text{dyncm} \]  

(6)

In this relation $k_2$ is the gyroradius of the secondary. Assuming $k_2 = 0.1$ we have $\dot{J}/J = -2.25 \cdot 10^{-16} s^{-1}$ due to this rotational angular momentum loss. This seems to be too high to explain the constancy of the period.

The gravitational radiation is negligible in such systems. The magnetic braking can be a more efficient mechanism. This results in angular momentum loss on the scale of

\[ \dot{J} = -2.52 \cdot 10^{34} P_{orb}^{1.64} (h) \text{dyncm} \]  

(7)

(McDermott & Tamms 1989, Warner 1995). In EM Cygni this yields $\dot{J}/J = -7.57 \cdot 10^{-17} s^{-1}$. This is higher than the required value by a factor of 2, but regarding the rather large uncertainties of magnetic braking theories and the fact that we substitute $\dot{P}/P = 0$ instead of its correct value (which is too low to determine it exactly) one can conclude that this itself could explain the constancy of the period.

To hold up the mass transfer some angular momentum loss is required (Warner 1995). Using Warner’s (1995) Eq. (9.16) we found that this means $\dot{J}/J = -1.2 \cdot 10^{-16} s^{-1}$ which is higher by a factor of 2.6 than required.

One can assume that more than one of these mechanisms are working in this system. But the sum of them is higher than the required value. If the mass transfer rate is
equal to the prediction of Shafter et al. (1986), then the observed constancy of the period can be explained by the magnetic braking itself, and the uncertainty of the estimations allows that we can regard the effects of mass transfer and the magnetic braking to be equal. Also, magnetic braking can be the process which drives the mass-transfer (because its magnitude is in the required range). But in this case Winter & Sion (2003) have been measured too low mass transfer rate.

The mass transfer rate given by Winter & Sion would mean an angular momentum loss rate of \( \dot{J}/J = -2.7 \cdot 10^{-19} \, \text{s}^{-1} \) if the period variation is zero. This is close to the range of the angular momentum loss caused by the assumed value of the secondary’s stellar wind rate (note that this real or accidental agreement does not mean that this should be due to the angular momentum loss caused by stellar wind) but it does not fit the rate of other kind of possible angular momentum loss. With their mass transfer rate the magnetic braking and/or the rotational braking would dominate the right side hand of Eqs. (4-5) and we would observe a large period decrease. One can estimate the period variation rate from their \( \dot{M} \) value. Substituting their mass transfer rate into Eq. (5) and assuming that there is an angular momentum loss from magnetic braking (Eq. 7) we would have \( P/P = -2.0 \cdot 10^{-12} \, \text{days}^{-1} \). From the available minima observations this figure should be excluded.

5 Conclusion

We observed six new times of minima of EM Cygni. We updated its \( O - C \) diagram and found that the period is constant. We found that the upper limit for the period decrease is \( |\dot{P}/P| < 2.3 \cdot 10^{-12} \, \text{days} \).

If the mass transfer is conservative then its rate is far from the theoretically predicted value (Sect. 4.1) but it is in agreement of the spectroscopically determined mass transfer rate of Winter and Sion (2003). (Note that their method was indirect and its reliability depends on e.g. the accuracy of distance therefore this agreement between the two independent determinations give a hint only that the mass transfer is not conservative.) In conservative case the spectroscopically observed mass transfer rate and the one given by present eclipse timing analysis is lower than the theoretically predicted value.

If we assume that the mass transfer occurs in a non-conservative mode and the rate of mass transfer equals to the theoretical predictions of Shafter et al. (1986), we found that the period increase caused by the mass transfer from the secondary to the primary is reduced by the angular momentum loss due to magnetic braking to zero (Sect. 4.2). This explains why we did not observe period variation. It is worthy to mention that in this case the spectroscopic measurement of the mass transfer rate by Winter & Sion (2003) is in contradiction.

Therefore their spectroscopic measurement would exclude the scenario we investigated in Sect. 4.2. If their measurement is right then the mass transfer cannot occur in non-conservative case and this would mean that the accretion disk theory model of dwarf novae may be challenged by the currently available observations.

Since EM Cyg is the only known eclipsing Z Cam subtype dwarf nova its further minima observations are important to refine our results and determine more precisely the difference between the observed and expected mass transfer rates.

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