Decrease in the orbital period of dwarf nova OY Carinae

J. G. Greenhill, K. M. Hill, S. Dieters, K. Fienberg, M. Howlett, A. Meijers, A. Munro, C. Senkeil
School of Mathematics and Physics, University of Tasmania, Private bag 37, GPO Hobart, Tasmania 7001, Australia

Draft: 10 July 2006

ABSTRACT
We have measured the orbital light curve of dwarf nova OY Carinae on 8 separate nights between 1997 September and 2005 December. The measurements were made in white light using CCD photometers on the Mt Canopus 1 m telescope. The time of eclipse in 2005 December was 168 ± 5 s earlier than that predicted by the Wood et al. (1989) ephemeris. Using the times of eclipse from our measurements and the compilation of published measurements by Pratt et al. (1999) we find that the observational data are inconsistent with a constant period and indicate that the orbital period is decreasing by 5 ± 1 × 10^{-12} s/s. This is too fast to be explained by gravitational radiation emission alone. It is possible that the change is cyclic with a period ∼ 35 years and fractional period change ∆P/P = 2.6 × 10^{-7}. This is probably due to solar-cycle magnetic activity in the secondary. There are also large systematic deviations, with a time-scale of years, from a sinusoidal modulation.

Key words: binaries: close – stars: evolution – stars:dwarf novae – stars:individual:OY Car – gravitational waves – stars:magnetic fields

1 INTRODUCTION
OY Car is an eclipsing dwarf nova of the SU UMa class. It contains a Roche lobe filling secondary transferring matter via an accretion disc onto a white dwarf. The matter flow onto the disc is via a well defined stream giving rise to a hot spot on the disc. The orbital period is ∼ 91 minutes (Vogt et al. 1981); below the period gap for cataclysmic variables. The light curve shows evidence of eclipses of both the white dwarf and of the hot spot by the secondary.

It is generally believed that cataclysmic variables below the period gap can lose angular momentum only by emission of gravitational radiation (see e.g. Ritter and Kolb 1992). This is a slow process with characteristic time-scale P/P-dot ∼ 10^{10} yr. Many such systems, however, have long term mass transfer rates (and hence angular momentum loss rates) as much as 6 times the rate predicted by gravitational radiation emission suggesting that magnetic braking can occur even in systems with fully convective secondaries (Warner 1995).

Many CVs exhibit quasi-periodic variations in their orbital period and/or optical lightcurves. This cyclic behaviour is thought to be caused by solar-cycle-type magnetic activity in the secondary star (Warner et al. 1988; Applegate 1992; Richman, Applegate & Paterson 1994). Typical magnetic cycle periods are in the range 4 to 30 years (Baptista et al. 2003). There is increasing evidence that this activity occurs even in CVs below the period gap with fully convective companion stars (Ak, Ozkan & Mattei (2001) and references therein). For example the SU UMa star, Z Cha, has a ∼ 107 minute orbital period which shows fractional changes, δP/P ∼ 4.4 × 10^{-7} in a 28 yr cycle (Baptista et al. 2002). The fractional cyclic changes in the shorter orbital period CVs are, however, systematically smaller than those in the longer period systems above the period gap (Baptista et al 2003). Strictly periodic changes in the orbital period can also be caused by a third body in the system causing the centre of mass of the CV to move in and out of the plane of the sky but we are not aware of any published evidence for such systems.

Several ephemerides for OY Car have been published (Vogt et al. 1981; Cook 1985; Wood et al. 1989). The ephemeris by Cook (1985) included a second order term suggesting that the orbital period was decreasing. A later ephemeris (Wood et al. 1989) and a recent study by Pratt et al. (1999) using data gathered over 19 years show, however, that there was, at that time, no evidence for a decreasing period.

In this paper we describe eclipse timing measurements of OY Car made between 1997 September and 2005 December. We use these data in conjunction with the data measured and collated by Pratt et al. (1999) to show that the ephemeris is now inconsistent with a linear function and that the orbital period is decreasing.
2 OBSERVATIONS

The observations described in this paper were made using the 1-m telescope at the University of Tasmania Mt. Canopus Observatory. An SBIG ST6 CCD camera was used for the data taken in 1997. All other observations were made using an STe 512 x 512 pixel, thinned, backside illuminated CCD with Leach controller and CICADA operating software. A journal of observations is given in Table 1. Exposure times were 20 s for the ST6 camera and 10 or 15 s with the STe camera. The chip readout time was typically 3 s and the cameras were set in repeated exposure mode so that continuous coverage, with sampling interval 13 to 23 s, was obtained for at least one orbital cycle on each night. A clear filter was used in all cases.

The image reduction and analysis was carried out using MIDAS and the DoPHOT profile fitting photometry system. The images were dark subtracted, flat-fielded and trimmed before calling a Midas control language procedure which carried out DoPHOT photometry on each image and generated a table of magnitudes of OY Car relative to its bright neighbour ~ 0.4 arc-minutes to the NW. Details of the eclipse portion of a typical light curve are shown in Fig 1.

3 RESULTS

3.1 Eclipse timing

Eight moments of contact are present in all eclipses in the quiescent state. We follow the definitions of Bailey (1979) where $T_1$ and $T_2$ correspond to the beginning and end of the primary ingress, $T_5$ and $T_6$ are the corresponding times of egress and $T_3$ and $T_4$ are the times of hot spot ingress. The eclipse centre of the white dwarf primary is given by

$$T_0 = 0.25(T_1 + T_3 + T_5 + T_6)$$

To the measured time we must add half the exposure times used on each night. In order to compare with published ephemerides, the measured times were converted to heliocentric times (HJD) and then to Terrestrial Dynamic Time. For each eclipse light curve, the resulting Heliocentric Julian Ephemeris Date (HJED) is listed in Table 1.

3.2 Comparison with published ephemerides.

We compare our eclipse times with predictions from the ephemeris of Wood et al (1989)

$$HJED = (2,443,993.553839 \pm 9) + (0.0631209239 \pm 5)E$$

where $E$ is the cycle number. The values of $E$ and the differences (O-C) between observed and predicted eclipse times are listed in Table 1.

We combine our results with the compilation of previous measurements in Pratt et al. (1999). The variation of O-C with cycle number $E$ since 1979 is illustrated in Fig 2. For the sake of simplicity we have plotted only single points representing the means (and error in the mean) where data from this compilation were closely spaced in time. In this analysis we have assumed equal precision for each measurement with weighting proportional to the number of measurements contributing to each mean.

The data are clearly inconsistent with the assumption of a constant period. The solid line represents the best fitting second order polynomial for all the measurements.

$$O-C = -6.6 \pm 2.6 + (9.0 \pm 1.4 \times 10^{-4}) E - (1.3 \pm 0.1 \times 10^{-8}) E^2$$

The quadratic term is significant at the 12σ level indicating a period evolution time-scale of $3.7 \times 10^7$. Cook (1985) found evidence at the 3.5σ level for a period evolution time-scale of $2.1 \times 10^7$ yr but later measurements (Wood et al. 1989) were

Table 1. Journal of observations and eclipse timing (O-C in seconds) relative to the ephemeris of Wood et al. 1989.

| Date    | HJED         | Cycle No. | O-C    |
|---------|--------------|-----------|--------|
| 28.08.97 | 2450689.04220 | 106074    | -49±11 |
| 28.09.97 | 2450720.16079 | 106567    | -47±14 |
| 06.09.01 | 2452159.00124 | 129362    | -135±26|
| 02.10.03 | 2452912.98043 | 141307    | -156±10|
| 23.12.03 | 2452997.05749 | 142639    | -156±10|
| 22.05.04 | 2453147.91661 | 145029    | -147±9 |
| 17.01.05 | 2453388.09108 | 148834    | -163±5 |
| 17.01.05 | 2453988.15424 | 145835    | -159±7 |
| 11.12.05 | 2453716.131680| 154031    | -168±5 |
| 11.12.05 | 2453716.194089| 154032    | -164±5 |
not consistent with his predictions. We note however that, with the passage of time, the quadratic term is becoming increasingly dominant so that the constant period hypothesis can be excluded with a high level of confidence.

The fit is poor with $\chi^2/dof = 9.4$ for 63 degrees of freedom. There are also highly significant systematic deviations with time-scales of years. We have investigated the possibility that changes in the shape and duration of the eclipse light curve might cause these systematic deviations. The mean duration (centre of ingress to egress) for our measurements is $276.9 \pm 6.0$ s - not significantly different from the value $274.7 \pm 3.4$ s reported by Vogt et al. (1981). Similar durations are also evident in the light curves published by Cook (1985), Wood et al. (1989) and Pratt et al. (1999). Neither is there any significant variation in the duration of the ingress and egress. The phase and duration of hotspot eclipses is much more variable but this cannot affect the white dwarf eclipse timing. Hence we conclude that changes in the eclipse light curve do not contribute to the observed changes in orbital period.

Next we investigate the possibility that the period is constant with a sinusoidal modulation. In Fig 3 we show a linear fit and residuals. Clearly the linear fit alone is unsatisfactory. We have phase folded the data at the 6.3 year period reported for the quiescent magnitude of OY Car reported by Ak, Ozkan & Mattei (2001) but find no correlation. We then used an iterative process to determine the best sinusoidal fit to the residuals after fixing phase zero at cycle number $= 17,000$ ($JD \sim 2,445,067$). The best fitting period is $2.0 \pm 0.2 \times 10^{5}$ cycles ($35 \pm 3.5$ years) with amplitude $46 \pm 3$ s. The solid line in the lower panel of Fig 2 represents this periodic modulation. The fit is again poor with $\chi^2/dof = 8.1$ for 61 degrees of freedom. Application of the F-test indicates however, that the linear plus sinusoidal model represented in Fig 3 is a better fit than the polynomial model. This is significant at the 99.9% level but, as with the quadratic model, there are highly significant systematic deviations with time-scales of years.
4 DISCUSSION

We consider first the possibility that the decreasing period is due to loss of angular momentum from the system and is not due to some cyclic change. Using the quadrupole general relativity formula for the fractional rate of change in the orbital angular momentum $J/J$ (Livio 1994) and the system parameters for OY Car (Wood et al. 1989) we find $J/J \approx 2.2 \times 10^{-10}$ per year. The observed rate of change is $\sim 2.7 \times 10^{-5}$; almost two orders of magnitude faster than the rate predicted for loss by gravitational radiation.

As already noted the linear plus sinusoid model represented in Fig 3 is a better fit than the quadratic although large non-random residuals remain. The modulation could be due to the presence in the system of a third object - an $M \sim 0.007 M_\odot$ brown dwarf or massive planet with orbital radius $a \sim 9.7$ AU but this is very unlikely since most well observed CVs show cyclical period changes (Baptista et al. 2003 and references therein). It is highly improbable that most CVs are members of triple systems.

The most likely cause is quasi-periodic solar-cycle type magnetic activity in the companion. Magnetic cycles are inherently less regular and this might be the cause of the departures from the model. The fractional period change $\Delta P/P = 2 \pi \Delta (O-C)/P_{mod}$ where $P$ is the orbital period, $P_{mod}$ is the modulation period and $\Delta (O-C)$ is the amplitude of the sinusoidal modulation (Applegate 1992). For OY Car we find $\Delta P/P = 2.6 \times 10^{-7}$, similar to that for other short period CVs (Baptista et al. 2003). Departures from the sinusoidal model are however much larger than those seen in the cyclic modulations of quiescent magnitude for dwarf novae reported by Ak, Ozkan & Mattei (2001). Baptista et al. (2002) observed similar changes in the timing measurements for the SU UMa star Z Cha.

Finally, we present the ephemerides for the quadratic and sinusoidal modulation models. For the quadratic model:

$$HJED = 2.443,993.553813 + 0.0631209343E$$
$$- (1.47 \times 10^{-11}) E^2$$

For the sinusoidal model:

$$HJED = 2.443,993.55406 + 0.0631209126E$$
$$+ (5.3 \times 10^{-4}) \sin \frac{2 \pi (E - 1.7 \times 10^{-4})}{2 \times 10^5}$$

Timing measurements during the next few years should determine which model is valid.

5 CONCLUSIONS

The orbital period of OY Car is decreasing at an average rate of $5 \pm 1 \times 10^{-12}$ s/s. This is $\sim 2$ orders of magnitude too fast to be caused by gravitational radiation emission alone and loss of angular momentum via a stellar wind is considered unlikely.

It is likely that the apparent change is cyclic with a period $P \approx 35 \pm 3.5$ years and fractional period change $\Delta P/P = 2.6 \times 10^{-7}$. This is probably due to solar-cycle type magnetic activity in the secondary. Large irregular deviations from the general trend, with time-scales of years, also occur. Measurements over the next few years will clarify whether the change in period is cyclic or a continuing decrease. We find no evidence for the 6.3 year modulation in quiescent magnitude reported by Ak, Ozkan & Mattei (2001).

6 ACKNOWLEDGEMENTS

We are indebted to Bob Watson for suggesting the project as a research training exercise for third year Physics students and to the referee Pierre Maxted for many helpful suggestions. We gratefully acknowledge financial support for the Mt Canopus Observatory by Mr David Warren.

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