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Letter to the Editor

The Eclipsing Dwarf Nova OY Carinae: Ephemeris and Physical Parameters[*]

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Summary:

Eighteen eclipse light curves of OY Car in quiescent state and one during early rise to an outburst are analysed. They show totality phases for primary (white dwarf and/or central part of the disc) and hot spot. A very precise orbital period of 0.0631209247 d could be derived from the eclipses of the primary. An analysis of the eclipse geometry revealed the basic physical parameters of OY Car, in particular an orbital inclination $i=79°\pm2°$, stellar masses $M_1=0.95\pm0.15\ M_\odot$ and $M_2 = 0.14\pm0.05\ M_\odot$, stellar radii, binary separation, as well as size and location of the hot spot. These results are compared to similar investigations on Z Cha, HT Cas and other ultra-short period dwarf novae, which all agree in relatively large primary masses ($\sim 1\ M_\odot$). Therefore, the well-known period gap between 2 and 3h is not due to a discontinuity in the mass function of white dwarfs. The hot spot location in quiescent state undergoes certain variations due to changes in the orientation of the gas stream, while the radius of the disc remains essentially constant.

Key words: cataclysmic variables - dwarf novae - eclipsing binaries.

I - Introduction

The dwarf nova OY Car (=S 6302) was detected by Hoffmeister (1963) already in 1959. However, it remained essentially unobserved for twenty years. A first photoelectric monitoring (Vogt, 1979a) immediately revealed deep eclipses which repeat with a period of only 91 minutes and which show similar characteristics to those of Z Cha. For several years, Z Cha was considered the only known dwarf nova which displays a total eclipse of the most luminous radiation source in a cataclysmic binary system: a primary (white dwarf and central disc) and a hot spot (cf. Warner, 1974). The recent detection of similar properties for OY Car, as well as for HT Cas (Patterson, 1979) offers the opportunity to study model parameters of ultra-short period cataclysmic binaries ($P < 2^h$) in more detail.

The first photoelectric observations of OY Car were obtained during rise and maximum of an outburst. The ephemeris given by Vogt (1979a) is based only on the partial eclipses observable at outburst and, therefore, of very low accuracy. Subsequently, we collected several eclipse observations in quiescent state, spread over more than one year. We give an accurate ephemeris in this Letter; furthermore, we report characteristics of the eclipse light curve which permit to derive important parameters of primary and secondary components, as well as of the hot spot.

II - Eclipse Light Curve and Ephemeris

The light curve of OY Car in quiescence closely resembles that of Z Cha as shown by Bailey (1979). A pronounced hump with maximum at phase ∿0.75 is present in each cycle, interrupted by the eclipse in its descending branch. A typical eclipse light curve of OY Car is shown in Fig. 1. Six moments of contact are present in all eclipses at quiescence and were denominated as T_1 to T_6 in Fig. 1. We interpret these times, in analogy to Bailey's (1979) discussion of Z Cha, as the beginning and end of the primary ingress (T_1 and T_2 resp.), of the hot spot ingress (T_3 and T_4 resp.), and of the primary egress (T_5 and T_6 resp.). As reference for an accurate ephemeris we use the eclipse center of the white dwarf primary (cf. Sec. 3), i.e. the moment

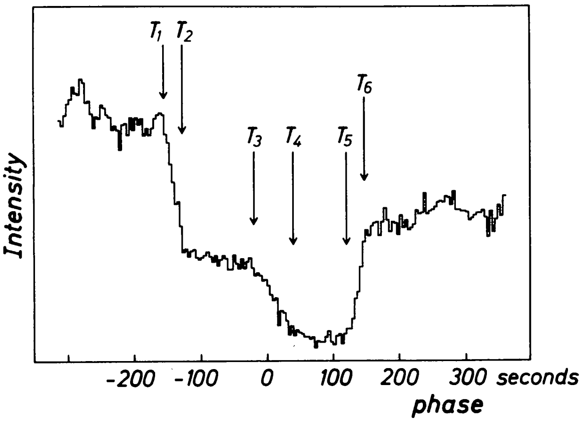

Fig. 1. *Typical eclipse light curve of OY Car (E=6639). The contact times T_1 to T_6 (see text) are indicated.*

$$T_0 = \frac{1}{4}\,(T_1 + T_2 + T_5 + T_6) \tag{1}$$

(cf. Bailey, 1979). The resulting times of mid-eclipse are listed in Table 1. A linear least-squares fit of 18 eclipse observations in quiescence reveals the ephemeris

$$\text{HJD (mid-ecl.)} = 244\ 3993.\underset{\pm 11}{553241} + 0\overset{d}{.}\underset{\pm 22}{0631209247}\ E \tag{2}$$

with a standard deviation of only ±1.9 seconds. The first observation (E=0) was not used when deriving (2)

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[*] Based on observations obtained at the European Southern Observatory, La Silla, and at the Carnegie Southern Observatory, Las Campanas, Chile

Table 1 : Eclipse observations of OY Car

E	T_0 (HJD-2440000)	O - C (10^{-5}d)	Telescope and Instrument (1)	Time resolution (2) (s)
0 3)	3993.55324	0	a	3
776	4042.53507	-1	a	10
807	4044.49183	0	a	10
808	4044.55492	-3	a	10
823	4045.50178	+2	a	10
3282	4200.71614	+2	b	5
3283	4200.77926	+2	b	5
3346	4204.75588	+3	a	2
3585	4219.84175	-1	c	10
3600	4220.78854	-3	c	10
3616	4221.79850	0	d	10
3711	4227.79501	+2	d	5
5594	4346.65170	+1	e	3
5608 4)	4347.53537	-2	e	3
6607	4410.59318	-1	e	4
6621	4411.47690	+2	e	3.2
6622	4411.54003	+3	e	3.2
6623	4411.60310	-3	e	3.2
6639	4412.61304	-2	e	2

Remarks

(1) Telescope and Instrument: All observations without filter , with a blue-sensitive multiplier (EMI 6256), except under c (Johnson V-band).

a) ESO 1m tel. single channel photometer
b) ESO 1m tel. double channel polarimeter
c) CARSO 2.5m tel. two channel photometer
d) CARSO 1m tel. single channel photometer
e) DANISH 1.5m tel. modified Roden photometer

(2) In some cases a higher time resolution was used (down to 400 ms); the original data were averaged afterwards.

(3) $\sim 1^{m}$ above minimum on a rising branch to a short eruption.

(4) Affected by thin cirrus clouds.

Table 2 : Characteristics of the Eclipse Light Curve

	quiescence (E=776-6639)				rise to outburst (E = 0)	
	Δt (s)	$\sigma_{\Delta t}$	Δm (mag)	$\sigma_{\Delta m}$	Δt (s)	Δ m
T_1	-152.6	5.2	-0.48	0.12	-149	-0.30
T_2	-121.5	3.8	0.29	0.13	-124	0.10
T_3	- 28.6	9.0	0.57	0.15	- 38	0.28
T_4	+ 28.6	13.4	1.77	0.25	+ 21	0.66
T_5	+121.2	5.5	1.79	0.31	+121	0.66
T_6	+154.1	5.1	(0)	-	+152	(0)

because it corresponds to an early stage in the rise to an outburst.

Table 2 contains the mean phases of the contact times (with respect to T_0) and the mean magnitude differences relative to phase T_6. The values of σ refer to the standard deviation of a single eclipse observation from the general average. This scatter is mainly caused by real variations and not by uncertainties in the measurement procedure. In particular, the duration of ingress and egress of the primary varies between 21 and 52s, that of the hot spot between 42 and 79s. Also the phase of mid-ingress of the hot spot shows significant variations between -16 and +15s. On the other hand, the width of the primary eclipse (time interval between mid-ingress and mid-egress) is nearly constant (274.7±3.4s). The large scatter in magnitudes is also real. The eclipse minima at T_5 vary from $1\overset{m}{.}48$ to $2\overset{m}{.}47$ in quiescence and indicate a quite strong variability in the eclipse amplitude. It may be worth mentioning that the contact phases of the eclipse observed during early rise (E=0) are still undisturbed and coincide with those of the quiescent state while the eclipse amplitude is already drastically reduced (in the magnitude scale).

III - Physical Parameters

The Roche model of cataclysmic binaries gives a well known relation between the relative radius of the secondary R_2/A (in units of the separation A between the mass centers) and the mass ratio $q=M_1/M_2$. This relation (calculated with Paczynski's (1971) approximation), can be compared to expected radii of main sequence secondaries according to the theoretical mass-radius relation of the lower main sequence (Grossmann et al, 1974) which is in good agreement with the empirical relation for unevolved visual binaries of low mass given by Lacy (1977). We derive $M_2 = 0.14\ M_\odot$ for the secondary of OY Car, if it is a main sequence star.

The observed width of the primary eclipse reveals a unique relation between q and the orbital inclination i (e.g. (8) in Ritter, 1980b), which is shown in the upper margin of Fig. 2. Fig. 2 contains the observed relative radius R_1/A of the primary based on the mean duration (32.0s) of its ingress and egress (cf.(16) in Ritter, 1980b). This is compared to the expected R_1/A values for white dwarfs between 0.6 and 1.1 $M_\odot$ whose radii obey the mass-radius relation of Kippenhahn and Thomas (1965), while A is given by the third Kepler

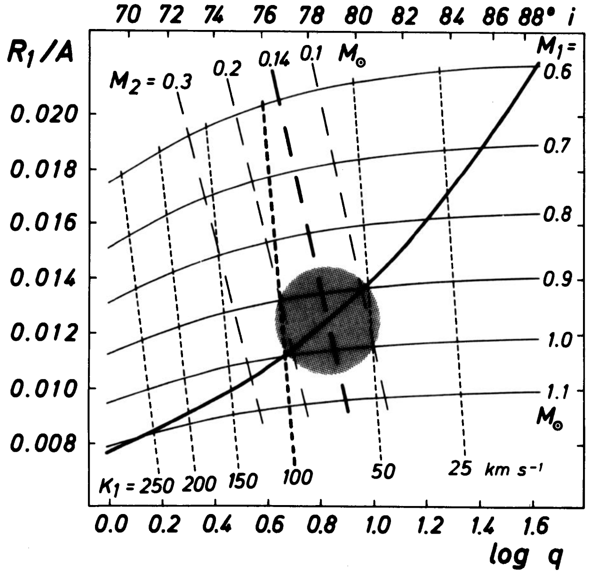

Fig. 2. *Radius R_1 of the primary (in units of the binary separation A), as derived from ingress/egress duration and eclipse width, vs. mass ratio q (broad solid line). The upper scale denotes the orbital inclination i as derived from the width of the primary eclipse. The narrow solid lines refer to relative radii as expected for various white dwarfs (with $0.6 \leq M_1 \leq 1.1 M_\odot$) which obey the mass-radius relation of Kippenhahn and Thomas (1965). Secondary masses M_2 between 0.1 and 0.3 $M_\odot$ are shown as long dashes, the main sequence case $M_2=0.14\ M_\odot$) is indicated broader. The shortly-dashed lines correspond to radial velocity semi-amplitudes K_1 of the primary, between 25 and 250 km s^{-1}; a broader dashed line indicates Bailey's (1980) value (K_1 = 100 km s^{-1}). The most probable physical parameters of OY Car are expected within the grey area.*

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law. Lines of constant secondary masses between 0.1 and 0.3 $M_\odot$, and of expected radial velocity semi-amplitudes K_1 of the primary (cf.(10) in Warner, 1976) are shown as well. The observed R_1/A line coincides with the main sequence status of the secondary ($M_2 = 0.14$ $M_\odot$) for a white dwarf with $M_1 = 0.95$ $M_\odot$; Bailey's (1980) $K_1 \approx$ 100 km/s corresponds to $M_1 = 1.0$ $M_\odot$. We conclude that mass ratios q=4 ... 7 and a primary with ∿ 1 $M_\odot$ are in closest agreement with the available observational data of OY Car.

The observational errors are insignificant compared to the uncertainties which arise in the interpretation of the eclipsed object. In principle, a comparison of the observed R_1/A values with the theoretical mass-radius relation is only valid if the primary is actually a normal white dwarf. In this case, we always should observe identical ingress and egress durations. However, their large scatter of more than a factor 2 could be an indication that the primary radius is variable, i.e. that the eclipsed body is actually the small, luminous central part of the disc in which the white dwarf is embedded. In this case, the observed R_1 is larger than the white dwarf radius; so derived M_1 values are lower mass limits.

A second correction should arise in reducing the observed ingress and egress phases to the true geometrical phases of contact: A spherical or elliptical object with limb darkening will produce a gently rounded light curve near the contacts. Our straight-line approximation will, therefore, tend to underestimate the duration of ingress and egress. Patterson (1979) applied a correction of 24% in a similar case (HT Cas). Such a correction would move the observed R_1/A relation in Fig. 2 towards 24% larger radii, i.e. to $M_1 \approx 0.8$ $M_\odot$ for $M_2 = 0.14$ $M_\odot$. Fortunately, both uncertainties partly compensate each other. Therefore, we hesitate to apply any correction and consider the situation as displayed in Fig. 2 as the best approximation to reality.

Table 3 : Physical Parameters of OY Car

i	=	79°	±	2°
M_1	=	0.95	±	0.15 $M_\odot$
M_2	=	0.14	±	0.05 $M_\odot$
A	=	(4.8	±	0.3) 10^{10} cm
R_1	=	(6.0	±	1.5) 10^{8} cm
R_2	=	(1.10	±	0.15) 10^{10} cm
d_{HS}/A	=	0.327	±	0.002
R_{HS}/A	=	0.019	±	0.006
α	=	33°	±	4°

The physical parameters of OY Car are listed in Table 3; their errors reflect mainly the uncertainties in the interpretation. In addition, the radius R_{HS} of the hot spot, its distance d_{HS} to the primary (in units of A) and its position angle α were derived. For this purpose, the phase of egress of the hot spot is needed. This feature is not always clearly seen in the light curve; however, 8 eclipses with a fairly well observed egress give an average of +419±3s for this phase. We used the geometry described by Ritter(1980b). The error range given for the hot spot parameter reflects the observed variations in phase and duration of the hot spot ingress.

IV - Discussion

OY Car is -appart from the special case WZ Sge- the dwarf nova with the shortest known orbital period. We derived the basic physical parameters of both binary components. The relatively large primary mass of about solar unity and the large mass ratio seem to be common properties of most ultra-short period cataclysmic binaries so far studied: Smak's (1979) analysis of Warner's (1974) and Bailey's (1979) data reveals a mass ratio q=4 ... 9 for Z Cha, implying a primary with $\gtrsim 1$ $M_\odot$ if the secondary is a main sequence star. Applying our method of Section 3 to Z Cha we derive $M_1 = 0.85$ $M_\odot$ and $M_2 = 0.17$ $M_\odot$ when using $K_1 = 87$ km/s (Vogt, 1979b). HT Cas has $M_1 > 0.8$ $M_\odot$ (Patterson, 1979), EX Hya $M_1 = 1.4$ $M_\odot$ and $M_2 = 0.19$ $M_\odot$ (Breysacher and Vogt, 1980). The two non-eclipsing ultra-short period dwarf novae VW Hyi and WX Hyi also have primary mases ∿ 0.8 $M_\odot$ and large mass ratios of $q \approx 6$ (Schoembs and Vogt, 1980).The extended line wings of VW Hyi in outburst imply a maximal rotation velocity of the disc of $v_d . \sin i = 3500$ km s^{-1} which is only compatible with primary masses $M_1 \gtrsim 0.8$ $M_\odot$. Since these studies were carried out independently by various authors applying different methods, their concordant results $M_1 \approx 1$ $M_\odot$ and $4 < q < 9$ for all ultrashort period dwarf novae (with the possible exception WZ Sge) deserve certain confidence. Only Ritter's (1980a, 1980b) parameters of OY Car and Z Cha do not agree with those of other authors; he derived $1.6 < q < 2.5$ and $0.3 < M_1 < 0.35$ for these dwarf novae. Since his input parameters are essentially the same (although of lower accuracy: he used only one eclipse light curve in either case), his method has to account for the large difference in the binary parameters. Indeed, he assumed that the separation of the doubled peaks in the Balmer emission line profile is identical to the projected rotation velocity of the outer rim of the disc. However, the emission line doubling of Z Cha and OY Car at least partly arise from a narrow central absorption which is superimposed on the broad Balmer emission. The absorption centers of Hβ, Hγ and Hδ reach levels at or below the continuum for both stars; Hε - H 11 of Z Cha appear only in absorption because the emission seems to be of steeper decrement (Whelan et al, 1979; Vogt, 1979b; unpublished data of R.S. and N.V.).The observed line profiles apparently do not exhibit the disc rotation in a unique way; this impedes to derive reliable binary parameters from the emission peak separation.

The large primary masses of ultra-short period cataclysmic binaries contradict Webbink's (1979) hypothesis that the observed period gap between 2^h and 3^h reflects the mass discontinuity between helium white dwarfs ($0.18 \leq M_1 \leq 0.46$ $M_\odot$) and carbon-oxygen white dwarfs ($0.56 \leq M_1 \leq 1.4$ $M_\odot$). Since the primary masses of many cataclysmic binaries turn out to be near one solar mass, a different mechanism has to account for the period gap.

In addition to the binary parameters of OY Car we derived also some properties of the hot spot. Its ingress occurs significantly later in OY Car than in Z Cha (Smak, 1979) and HT Cas (Patterson, 1979). OY Car reveals a more extended standstill between T_2 and T_3, possibly a consequence of the shorter orbital period which implies a relatively larger size of the disc. The hot spot ingress phase of OY Car is variable, but our analysis showed that these variations are entirely due to changes of the position angle α while the distance d_{HS} between hot spot and primary mass center turned out to be constant within less than 1% (cf. Tab. 3). Apparently, the orientation of the gas stream from L_1 shows certain variations while the disc radius remains constant.

A puzzling effect, already reported by Patterson (1979) for HT Cas, is also present in our data of OY Car: we often observe a strong flickering immediately after the white dwarf's egress, at a phase in which the hot spot is supposed to be still eclipsed. Is the white dwarf the cause of this flickering? Or does it arise in the central part of the disc, which seems to be very luminous and of similar size as the white dwarf itself?

Further work on OY Car presently is being carried out by the authors. This concerns the relative luminosities of primary, secondary, disc and hot spot at quiescence, based on eclipse and hump light curves in different colours, including the infrared. Spectroscopic and polarimetric data in quiescent state are being analysed. Photoelectric high speed photometry during a normal outburst (April/May 1979) revealed partial eclipses and low-amplitude flickering. Extensive photoelectric UBVRI photometry during the supermaximum of January 1980 shows that width and depth of the eclipse in eruption state depends on band-pass and on the time elapsed after the start of the outburst. Superhumps with a period of 0.0646 d and with variable amplitude (due to interaction with the eclipse light curves) were also found. Although OY Car had been overlooked for twenty years, it soon will advance to one of the best studied dwarf novae in the SU UMa sub-group.

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