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The dwarf nova Z Chamaeleontis – I. Photometry

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Summary. High-speed photometric observations of the dwarf nova Z Cha are presented. The eclipse light curves clearly show the presence of two eclipsed objects which are identified with the white dwarf, and the bright spot on the edge of the accretion disk. The mid-point of the white dwarf eclipse yields a precise eclipse timing, an order of magnitude more accurate than is possible in any other eruptive binary system. The white dwarf eclipse duration has been used to derive a relationship between q and i. The bright spot is found to be variable in brightness on both long and short time-scales and also varies in position.

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Introduction

The dwarf nova Z Chamaeleontis, discovered to be an eclipsing binary by Mumford (1969, 1971), is a particularly important system as it is the only dwarf nova in which the white dwarf is known to be eclipsed by its companion star. It thus provides a unique opportunity to study the accretion processes in dwarf nova systems, and the changes which take place during outbursts.

Warner (1974) obtained photometric observations of the star during quiescence and at outburst, which clearly showed that the outburst was due to a substantial brightening of the accretion disk. Bath *et al.* (1974) have discussed these observations in terms of a model for the dwarf nova outburst.

This paper (Paper I) presents high-speed photometric observations of Z Cha in its quiescent state. Paper II (Rayne & Whelan, in preparation) will discuss spectroscopic observations of Z Cha obtained with the Anglo-Australian Telescope. In Paper III the photometric and spectroscopic observations will be interpreted in terms of a detailed model for the Z Cha binary system.

Observations

The observations were obtained with the 30-inch telescope of the South African Astronomical Observatory, Sutherland, using the University of Cape Town high-speed photo-

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Table 1. Journal of observations.

Date	UT start	UT finish
1977 November 15/16	00 16 40	01 30 20
1977 December 9/10	22 26 50	01 43 00
1977 December 11/12	00 20 53	01 00 30
1977 December 17/18	23 03 30	01 48 30

meter. Five-second integrations in white light were obtained using an Amperex 56DVP photomultiplier. Observations were obtained on four nights during 1977 November and December. The times of observation are listed in Table 1.

Z Cha was in its quiescent state at the times of all the observations, the previous recorded outburst being a supermaximum on JD 2443367 (1977 August 11) (F. M. Bateson, private communication).

Figs 1 and 2 show the light curves obtained on the nights of December 9/10 and 17/18 on both of which two eclipses were observed. These are plotted at a time resolution of 10 s, in the form of count rates with sky brightness subtracted, and corrected for extinction. The light curves show the same general form as those obtained by Warner (1974) with a hump followed by a deep eclipse.

Eclipse light curves

In Figs 3 and 4 the light curves of the six observed eclipses are plotted on an expanded scale. It can be seen that in all cases there is a standstill on the decline lasting about 80 s. This feature was also noted by Warner (1974) but in his data the standstills are much shorter, lasting about 20 s. In some of the light curves it is also clear that the rise occurs in two stages, separated by a much longer standstill. This is best seen in the November 15/16

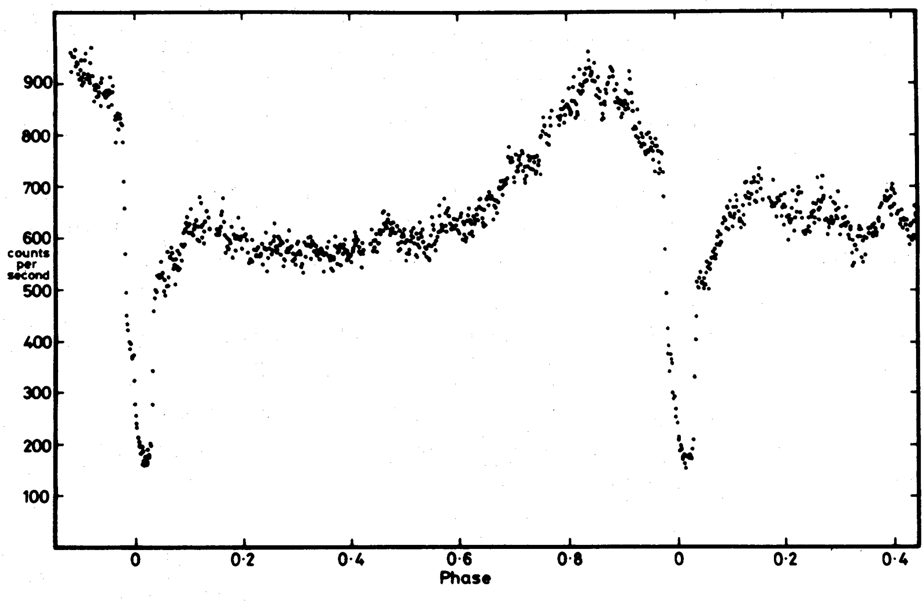

Figure 1. Light curve of Z Cha obtained on 1977 December 9/10. Each point represents the count rate over a 10-s integration, corrected for extinction. Phase is calculated from the revised elements given in this paper.

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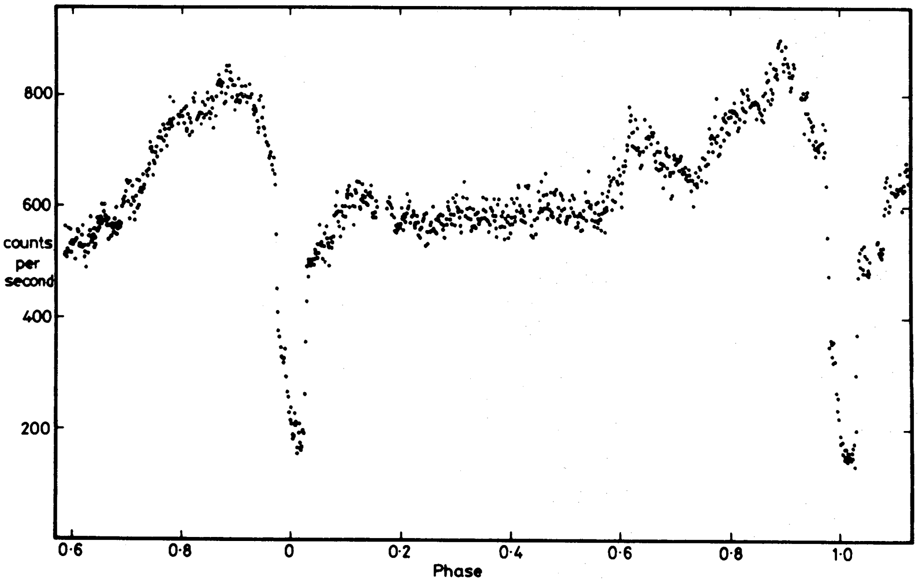

Figure 2. Light curve of Z Cha obtained on 1977 December 17/18. Details as for Fig. 1.

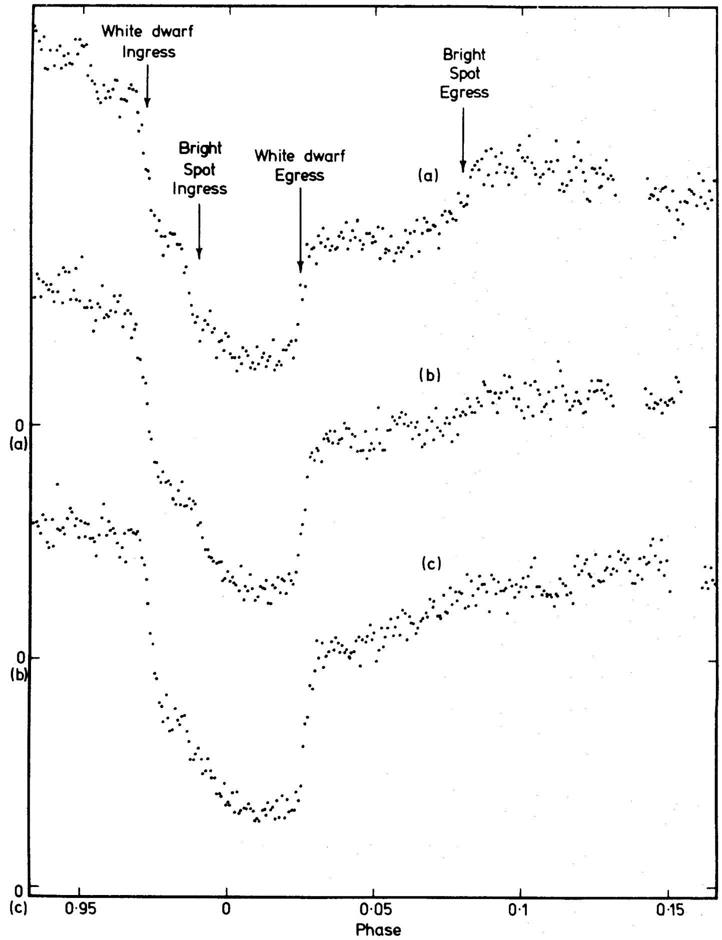

Figure 3. Eclipse light curves of Z Cha observed on: (a) 1977 November 15/16 and (b, c) 1977 December 9/10. Each point represents the count rate for a 5-s integration, corrected for extinction. The phase is calculated from the revised elements given in this paper. The zero level for each curve is indicated and the interpretation of the different stages of the eclipse has been marked on the top curve.

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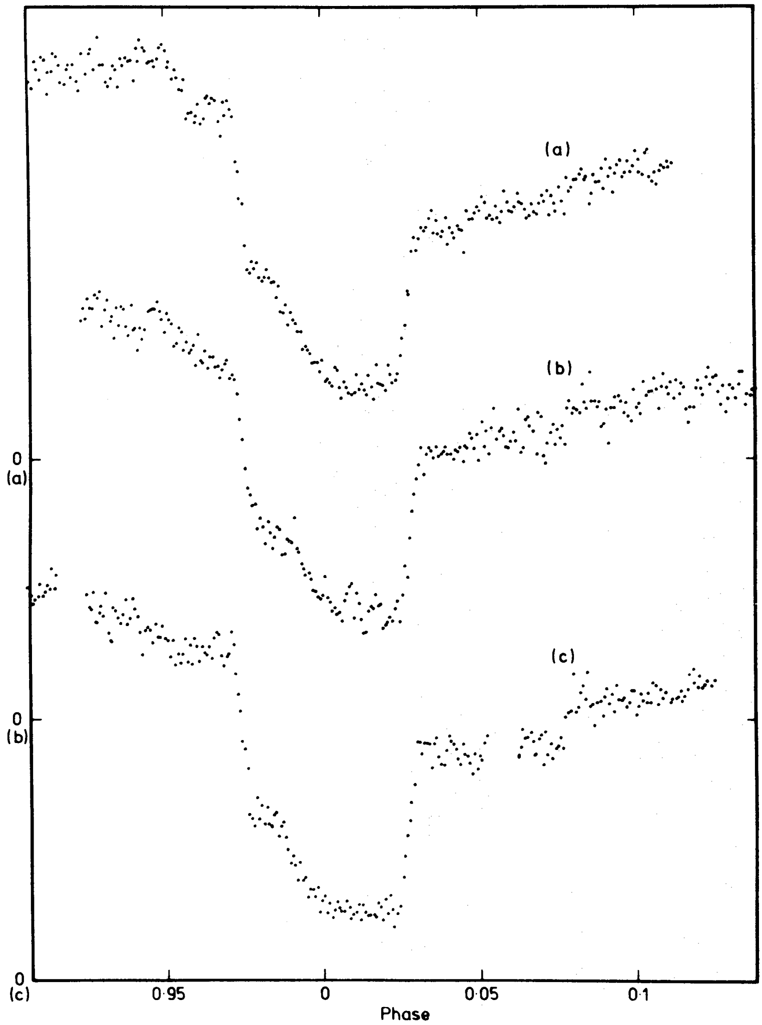

Figure 4. Eclipse light curves of Z Cha observed on: (a) 1977 December 11/12 and (b, c) 1977 December 17/18. Details as for Fig. 3.

light curve. These features can also be seen in the eclipse observed by Warner (1974) on 1972 April 11.

The eclipse behaviour can be understood by assuming that there are two eclipsed objects which we will refer to as object A and object B. The initial sharp drop (at about phase 0.97) is caused by object A going into eclipse. Following the standstill object B goes into eclipse (phase ~ 0.99) and the slower fall indicates that it is larger than A. The initial rise (phase ~ 0.03) is clearly the emergence of object A as it closely matches the initial fall. After a longer standstill object B emerges from eclipse (phase ~ 0.08). This emergence is not always clearly seen.

The eclipse of object A shows no significant variation in duration (defined from the mid-point of the fall to the mid-point of the rise) as shown in Table 2. It also occurs at a precisely constant phase of the binary period as will be shown in the next section. On the other hand the eclipse of object B is somewhat variable in phase as can be seen in Table 2 where the mid-point times of rise and fall are given in seconds relative to the centre of the A eclipse. Object B also varies in brightness both in the long term (Table 5) and during each eclipse.

In terms of the standard binary model of dwarf nova systems (e.g. Warner 1976; Robinson 1976) it is natural to interpret object A as the white dwarf, and object B as the

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Table 2. Times in seconds relative to centre of white dwarf eclipse.

Eclipse	Object A (white dwarf)	Object B (bright spot)			
	Duration	Fall	Centre	Rise	Duration
1977 November 15/16	343	−72	222.5	517	589
December 9/10 1	342	−44	241	526	570
December 9/10 2	345	−42	–	–	–
December 11/12	345	−43	–	–	–
December 17/18 1	345	−28	232.5	493	521
December 17/18 2	345	−52	220.5	493	545
1972 April 11*	346	−78	211.5	501	579

* From Warner (1974).

bright spot which forms where the stream of material from the secondary impacts on the accretion disk around the white dwarf. The observed duration of the ingress and egress of the object A eclipse is 40 s. With the typical separation of such a short-period binary system this indicates a radius of order 10^9 cm – just that expected for a white dwarf. It is not clear whether the radiation actually comes from the white dwarf, or from the central parts of the disk which can have a brightness distribution highly concentrated towards the centre (Bath *et al.* 1974). This point will be discussed in Paper III and for the present we will refer to the object as the white dwarf.

Z Cha is, then, the only eruptive binary system in which we clearly see the eclipse of an object of white dwarf dimensions. In other eclipsing systems which have been studied the eclipse is either of the bright spot alone, as in U Gem (Warner & Nather 1971; Smak 1971) or is principally of the accretion disk as in UX UMa (Nather & Robinson 1974). In either case the light curve is very different to that of Z Cha.

Eclipse timings

Previous determinations of the elements (Mumford 1971; Warner 1974) have used times of eclipse minima. This is unsatisfactory since the time of minimum will be altered by the movement in phase of the bright spot eclipse relative to the white dwarf eclipse. This movement clearly occurs as can be seen from the data in Table 2 and indicates that the bright spot is not fixed in position. In particular there appear to have been substantial changes between the observations of Warner (1974) and those presented here. We note that this effect could give rise to spurious period changes in those systems in which only the bright

Table 3. Eclipse timings.

$JD_\odot$	O–C (day)	Reference
2441660.4998	−0.0001	Warner (1974)
660.5742	−0.0002	Warner (1974)
661.5431	+0.0002	Warner (1974)
784.3177	0.0000	Warner (1974)
2443463.53123	0.00000	This paper
487.44550	+0.00001	This paper
487.51997	−0.00002	This paper
489.53148	+0.00001	This paper
495.49142	+0.00001	This paper
495.56589	−0.00002	This paper

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spot eclipse is observed. Significant period changes have been reported in three such systems, EM Cyg and T Aur (Pringle 1975) and U Gem (Arnold, Berg & Duthie 1976).

We therefore adopt as an eclipse timing the centre of the white dwarf eclipse, defined as half-way between the mid-point of the white dwarf ingress and the mid-point of the egress. Table 3 lists timings obtained in this way from the six eclipses presented here, and the four quiescent state eclipses observed by Warner (1974). The latter timings have been estimated from small-scale published light curves and are therefore of somewhat lower accuracy. Unfortunately it is not possible to use the data of Mumford (1971) in the same way as the time resolution is too low to identify the different stages of the eclipse.

Using these 10 eclipses the following revised elements have been derived,

$$T = \mathrm{JD}_{\odot}\, 2440264.68155 + \underset{\pm 36}{0.0744992705}E.$$

The residuals from these elements of the six eclipses presented here are all less than 0.00002 day. This is an order of magnitude greater accuracy than can be achieved with any other eruptive binary system. Z Cha will therefore be an ideal system for investigating period changes when further data are obtained.

Eclipses observed during outburst have been omitted from the above analysis since the structure is clearly different at these times. If the six outburst eclipses observed by Warner (1974) are reduced relative to the above elements, it is found that they all give positive O–Cs with a mean value of 0.00048 (± 0.00012) day. Since the outburst eclipse is thought to be an eclipse of a bright accretion disk centred on the white dwarf (Warner 1974; Bath *et al.* 1974), this indicates that the light distribution in the outburst disk is asymmetric, the trailing edge being brighter. This would be expected due to the presence of the bright spot.

Eclipse duration and the *q*, *i* relation

The secondary in dwarf nova systems is normally assumed to fill its Roche lobe. In this case the observed eclipse duration of the white dwarf defines a unique relation between the mass ratio q and the inclination i.

We approximate the system with a point mass M_1 (representing the white dwarf) and a star of mass M_2 filling its Roche lobe. Taking spherical polar coordinates centred on M_1, the quantity $\Omega(r, \theta, \phi)$ has a constant value Ω_0 on the Roche lobe (Kopal 1959) where

$$\Omega(r, \theta, \phi) = \frac{1}{r} + \frac{1}{q(1 - 2rl + r^2)^{1/2}} - \frac{lr}{q} + \frac{1}{2}\left(\frac{1}{q} + 1\right) r^2(1 - v^2)$$

and

$$q = \frac{M_1}{M_2}$$

$$l = \cos\phi \sin\theta$$

$$v = \cos\theta.$$

If ψ is the observed eclipse half-angle and i is the inclination then the line $\phi = \psi, \theta = i$ is tangential to the Roche lobe at some point $r = r_0$ (where r_0 is close to one). At this point:

$$\Omega(r_0, i, \psi) = \Omega_0$$

$$\frac{\partial\Omega}{\partial r}(r_0, i, \psi) = 0.$$

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Table 4. q, i relation.

$q(=M_1/M_2)$	i (deg)
0.2	61.37
0.5	66.84
0.8	69.67
1.0	71.00
1.2	72.08
1.5	73.38
2.0	75.04
3.0	77.31
5.0	80.13
8.0	82.76
12.0	85.30

This point was determined for a given q and ψ by using the Newton Raphson iteration method varying r and θ alternately. The method was tested by reproducing some of the results tabulated by Chanan, Middleditch & Nelson (1976) and gave good agreement.

For the observed eclipse half-angle of 9.61° this yields the relation between q and i tabulated in Table 4. The observed eclipse duration is not possible for values of q greater than 17.36 corresponding to $i = 90°$.

Brightness of white dwarf and bright spot

Using the adopted interpretation of the eclipse light curve it is possible to estimate the relative contributions of the various components to the total light of the system. The minimum of the eclipse gives the contribution of the red secondary star plus any other uneclipsed light in the system. The brightness of the white dwarf can be measured at ingress and at egress. The observed brightness of the bright spot is phase-dependent, this is what causes the hump in the light curve. We can measure its brightness from the height of the hump and from the eclipse ingress and egress. These values (in count/s) are given in Table 5. Because of the presence of flickering, and of photon statistics errors, there is an error of ~ 10 per cent in most of these estimates. A few cases where the error is even greater are indicated by a colon. Table 6 gives the same data for the eclipses from Warner (1974). The count rates are not directly comparable but we can compare the ratios of the different contributions.

From Table 5, the minimum brightnesses for the six eclipses give a mean of 178 count/s with a standard deviation of 10 per cent, in accord with the error estimated above. The

Table 5. Brightness (count/s).

Eclipse		White dwarf		Minimum	Bright spot		
		Ingress	Egress		Hump	Ingress	Egress
1977 November 15/16		340	320	180	390	290	200
December 9/10	1	380	360	160	400	230	70:
December 9/10	2	400	370	180	380	200	–
December 11/12		330	340	180	–	270	–
December 17/18	1	350	340	210	240	180	80:
December 17/18	2	310	320	160	260	200	100:
Mean		352	342	178	334	228	113
Standard deviation		33	20	18	77	44	60

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Table 6. Brightness (count/s).

Eclipse		White dwarf		Minimum	Bright spot		
		Ingress	Egress		Hump	Ingress	Egress
1971 December 8	1	980	1050	430	1300	600	–
December 8	2	1000	1050	410	1200	480	–
December 9		1080	980	400	840	530	–
1972 April 11		1100	1000	180	1150	700	600
Mean		1040	1020	355	1122	578	
Standard deviation		59	36	117	198	95	

brightness of the white dwarf also gives standard deviations of less than 10 per cent. The standard deviation obtained from the egress is less than that from the ingress. This is to be expected as the bright spot is in eclipse at white dwarf egress so there is no flickering at this time.

The data are therefore consistent with both the white dwarf brightness and the minimum brightness remaining constant throughout the six eclipses but variations of up to 20 per cent cannot be ruled out. The ratio white dwarf/minimum averages 1.96 ± 0.10. The same ratio from the three eclipses observed by Warner in 1971 December is somewhat larger at 2.47 ± 0.1; but for Warner's eclipse observed on 1972 April 11 the ratio is 5.8. It can be seen from Table 6 that this is due to a very much lower minimum brightness. It is possible that this arises from incorrect sky subtraction, as the sky brightness will be substantially greater than that of the star at minimum. If it is correct, however, it indicates that the minimum brightness shows long-term variations by at least a factor of 2.

The bright spot shows substantial variations in brightness from night to night, with a total range of nearly a factor of 2. However, in the three cases where two consecutive eclipses were observed on the same night, the two spot brightnesses were the same to within 10 per cent indicating that the time-scale of the variation is longer than the orbital period.

Conclusions

The photometric data on Z Cha can be understood in terms of a model in which most of the light originates from a white dwarf with radius $\sim 10^9$ cm and a bright spot which is variable in both position and brightness on both long and short time-scales. Further discussion in terms of a detailed model for the Z Cha binary system is postponed to Paper III where these data will be discussed in conjunction with spectroscopic observations (Paper II).

Further high time resolution observations of Z Cha will be valuable as they can be used to study period changes, which is possible with much higher accuracy in this system than in any other eruptive binary system.

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