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# RZ OPHIUCHI: PHOTOMETRIC VARIATIONS AND A DETACHED CONFIGURATION

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## ABSTRACT

A nine-year survey of multicolor intermediate-band photometry of RZ Oph reveals small but significant brightness-change variations outside primary eclipse. Most of these changes cannot be explained by the ellipticity effect of a cool mass losing component which fills its Roche lobe. Instead, this evidence supports recent analyses that have proposed a detached configuration for this binary. Photometric and spectroscopic observations point to the existence of a large accretion disk around the hot mass-gaining star in this binary, implying that mass transfer occurs in this system by some process other than Roche lobe overflow.

## 1. INTRODUCTION

The totally-eclipsing long-period binary RZ Ophiuchi (BD+07°3832; F5 Ib+K5 Ib; $P$=262 days) has been studied for nearly 90 years. Hiltner (1946) first noted H$\beta$ emission in this binary. Baldwin (1978) summarized the early work on this system, and estimated the properties of a large accretion disk around the hotter component. Baldwin suggested that the cool star does not fill its Roche lobe, and ignited a series of investigations in which this question, among others, was debated (Smak 1981; van Paradijs *et al.* 1982; Olson & Hickey 1983; Forbes & Scarfe 1984; Knee *et al.* 1986; Olson 1987, 1989; Zola 1991). The 1988 Algols colloquium in Sidney, B. C., also produced extended discussion of this binary (Batten 1989).

Good observational coverage of a 262-day binary is obviously not easy to achieve, and interpretation is complicated by secular changes in light curves and perhaps other properties. Thanks to Scarfe and collaborators, radial-velocity curves are available for both stars. Photometric solutions are still confused by unknown amounts of time- and phase-dependent continuum disk light, which has left unsettled the question of whether the cool star fills its Roche lobe. Zola (1991) concluded that RZ Oph is truly a semidetached system. The purpose of this current paper is to examine qualitatively the author's multicolor photometry, which calls into question a semidetached status for RZ Oph.

Zola (1991) addressed some of the problems of earlier models. He obtained new, nearly complete, BV observations of RZ Oph from 1988 to 1990 (as short a time as possible), to minimize the influence of intrinsic disk variations. These light curves seemed to exhibit a clearly-defined ellipticity effect. He then calculated a theoretical $V$ light curve using the Wilson–Devinney code (Wilson & Devinney 1971; Wilson 1975) and the detached elements of Knee *et al.* (1986). He concluded that the calculated ellipticity effect was too small to explain his data, even allowing a disk around the hot star. Letting the cool star fill its Roche lobe increased the ellipticity effect, reduced the photometric signature of the accretion disk, and led to better general light-curve fits to his and to Olson's (1987) *Iybv* observations (*u* observations were too distorted to be represented). Zola then added an empirical blackbody model disk to the Wilson–Devinney program, and obtained approximate disk parameters from theoretical light-curve fits to observations. In particular, the model disk then filled only about 60% of the hot-star Roche lobe, while the disk temperature was similar to that obtained by Olson (1987).

The Olson and Zola disk models are roughly limiting cases. In the former, the cool star does not fill its Roche lobe, but the accretion disk around the hot star fills, or slightly overfills, the hot-star lobe. In the latter, the cool star fills its lobe, and the accretion disk does not fill the hot-star lobe. The Zola model avoids some of the physical puzzles of the earlier model, and can invoke lobe overflow to supply mass transfer. It does assume that the ellipticity effect can be identified unambiguously in the observations.

An important part of Zola's approach was to obtain data as rapidly as possible, to avoid changes in disk light. However, a further point in the selection of a model for RZ Oph is the requirement that the ellipticity part of light variations be time independent, and of course decline toward short wavelength, as the distorted cool-star contribution falls. Thus, full confirmation of any model does require extended photometric observations to separate disk and ellipticity effects. These observations should ideally include the near infrared, where the contribution of the cool star is large, and the ellipticity is the most obvious.

Unfortunately, a relatively cool disk around the hotter component can mimic ellipticity, through partial eclipses of the disk by the cool star near primary eclipse, and partial eclipses of the cool star by the disk around secondary eclipse. In this paper, I review briefly nine years of five-color intermediate-band *uvbyI*(Kron) photometry of RZ Oph, and trace qualitatively many light-curve changes outside primary eclipse. These data suggest that light changes produced by circumstellar material contribute significantly to out-of-eclipse light variations, hampering efforts to extract the true ellipticity, and to decide about cool-star lobe filling. RZ Oph is an important system that bears on the

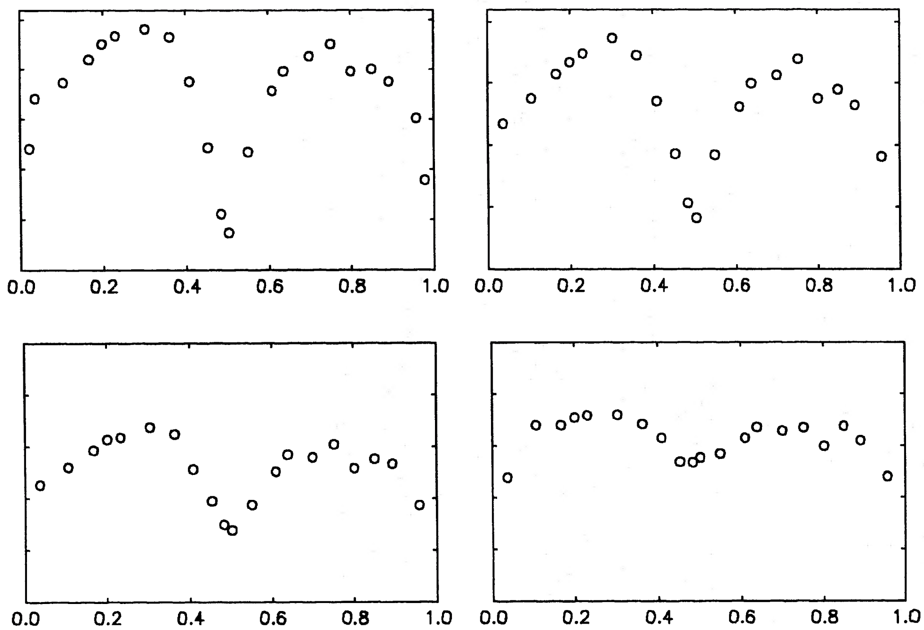


FIG. 1. Binned observations (variable-comparison magnitude plotted against orbital phase) of all RZ Oph data (1982–1991). Top panels: *I* and *y*; bottom panels: *b* and *v*. Tick marks on the vertical axes are at 0.05 mag intervals. See Fig. 2 for *u* observations.

question of whether significant mass transfer can occur if the cool mass losing star fails to fill its Roche lobe.

### 2. OBSERVATIONS AND GLOBAL SUMMARY

The author's nine years of differential photometry of RZ Oph, discussed in this paper, was obtained with the Prairie 1 m reflector at the Mount Laguna Observatory. Observational procedures are described in Olson & Stoehr (1986) and Olson (1987). No significant variations were noted in the comparison star (HD 173400=BD +06°3917). The same photometer, photomultiplier (cooled RCA 31034A-02), and filter set were used in all observations, and there is no indication that the differential photometric system changed detectably in this time. Observations in all filters yielded photon statistical errors smaller than 0.01 mag, and most observations were made under good-to-excellent observing conditions. It was impossible to obtain complete coverage of primary eclipse, because of the short duration of ingress and egress. These data will be placed in file no. 266E of the IAU Commission 27 Archive (Schmidt 1992), when photometric analyses of all long-period eclipsing systems in the author's and P. B. Etzel's program are finished.

A global view of all of the author's *Iybv* data is shown in Fig. 1. Here, data are grouped into bins of phase width 0.05 outside eclipses and 0.02 in the broad depression around phase 0.5, which for simplicity will be called "secondary eclipse" (though it is much broader than the true stellar eclipse). Magnitude differences (RZ Oph-comparison) are plotted, and tick marks on all vertical axes mark 0.05 mag intervals.

On casual inspection, these light curves give the impression of ellipticity. One signature of the cool star is clear: the depth of secondary eclipse decreases monotonically from *I* to *v* (but deepens again in *u*: see Fig. 2). This wavelength-dependent feature of these light curves is well represented by the Zola models in *y*, *b*, and *v*, but is rather poorly represented in *I*. However, if we omit data in the phase range $\approx$0.45 to 0.55, then this impression changes. The *I*, *y*, and *b* curves can, in fact, be brought into nearly perfect registration by only relative vertical shifts. This behavior certainly does not reflect an ellipticity effect, which should decline rapidly through this wavelength range. Some other, presumably circumstellar, effects dominate these light variations, and in the *I* to *b* range yield nearly identical relative light changes. A significant asymmetry between quadrature lights [the O'Connell (1951) effect] is also present, and is of nearly the same size in *I*, *y*, and *b* data. Both the light variations and the O'Connell effect are smaller in *v*, but increase again in *u*, as shown in Fig. 2. This behavior also cannot be explained by an ellipticity effect.

### 3. DISCUSSION OF LIGHT-CURVE VARIATIONS

The character of out-of-eclipse variations changed significantly between 1987 and 1989. *Iybv* data are plotted in Figs. 3 and 4, for intervals (1982 to 1986) and (1989 to 1991), respectively (vertical tick marks again mark 0.05 mag steps). Symbols represent running normals containing up to six individual observations (where an observation is a single 10 s integration except in *u*, where typically three integrations were averaged to give a mean with about 1% photon noise). Nightly variations, also noted by Zola, are present in these data and increase toward short wavelength, becoming very large at some times in *u* (Fig. 2).

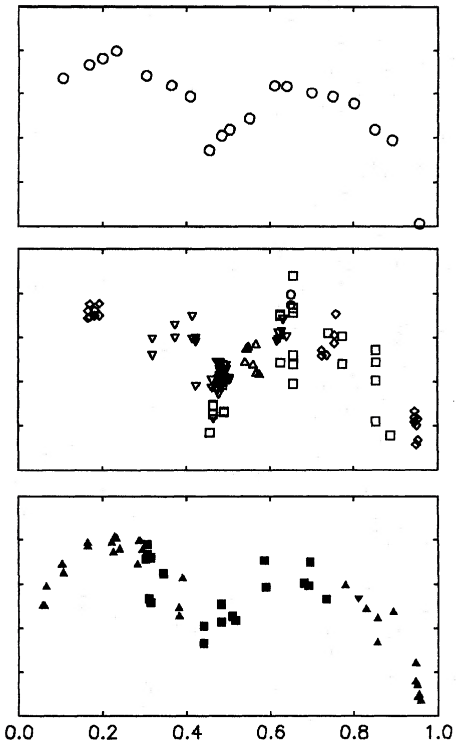


FIG. 2. Ultraviolet observations of RZ Oph. Top panel, all binned data; middle panel, six-point running normals of 1982 to 1986 data; bottom panel, six-point running normals of 1989 to 1991 data. Vertical tick marks are all at 0.05 mag intervals. In the lower two panels, different symbols represent different years.

Relatively large asymmetries are present in the (1982 to 1986) data shown in Fig. 3. Light variations between phases 0.1 to 0.4, and 0.6 to 0.9, are not the mirror images of symmetrical light curves. The former do decrease toward shorter wavelength; once again, the sharp declines from phase $\approx 0.75$ to first contact of primary eclipse near phase 0.975 are nearly identical in $I$, $y$, and $b$; are smaller in $v$; and are larger in $u$. Possibly the changes between phases 0.1 and 0.4 *do* come mainly from ellipticity, as proposed in Olson (1987; Fig. 1). However, the light declines after phase 0.75 cannot be explained by ellipticity, and seem more likely to be caused by a partial eclipse of the disk by the cool star, as Olson assumed. Moreover, there are small but real light differences in succeeding orbital cycles just prior to first stellar contact of primary eclipse, probably arising from changes in the disk.

An asymmetry also occurs in the shape of secondary eclipse, which is significantly skewed at all wavelengths by a depressed egress, or a raised ingress, branch. By reflecting the descending $I$ light near phase 0.45 around phase 0.5 (i.e., from phase 0.45 to 0.55), a light asymmetry of about 0.05 mag results. This amount is a significant fraction of the entire variation outside primary eclipse. Such asymmetries also cannot be explained by the ellipticity effect.

Light curves are systematically different in the (1989 to 1991) observations shown in Fig. 4 (only one night was obtained in 1991, so this set corresponds closely in mean time to Zola's recent observations). Light variations between phases 0.05 and 0.3 steepened since 1986, but even here the change cannot be ascribed to the ellipticity effect. Relative vertical shifts once more bring these light-curve segments into nearly perfect registration in $I$, $y$, and $b$; in $v$ the change is smaller, and in $u$ larger again, but of slightly

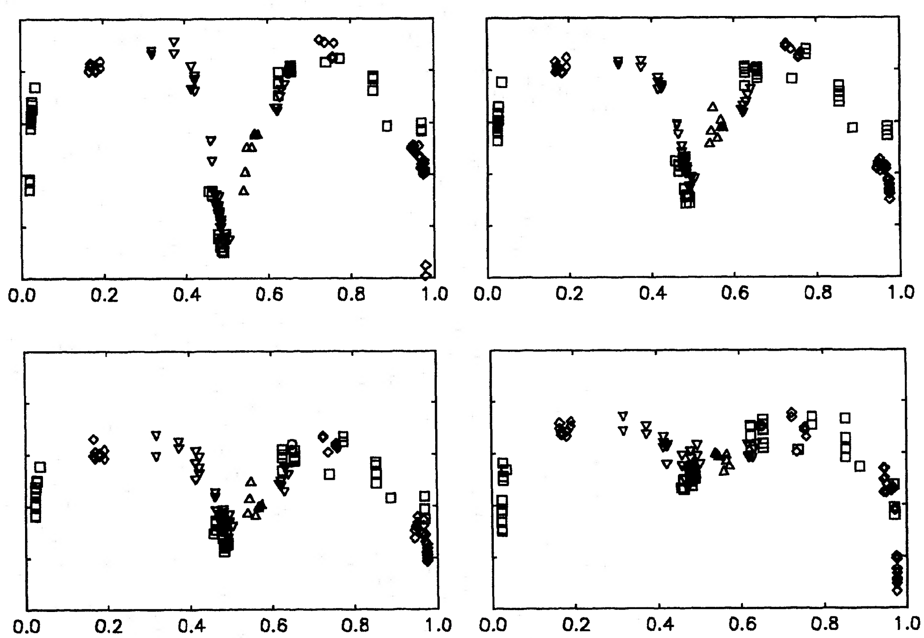


FIG. 3. Six-point running normals of $I$, $y$, $b$, and $v$ observations for 1982 to 1986. Same arrangement as in Fig. 1. See Fig. 2 for $u$ observations. Different symbols are used for different years.

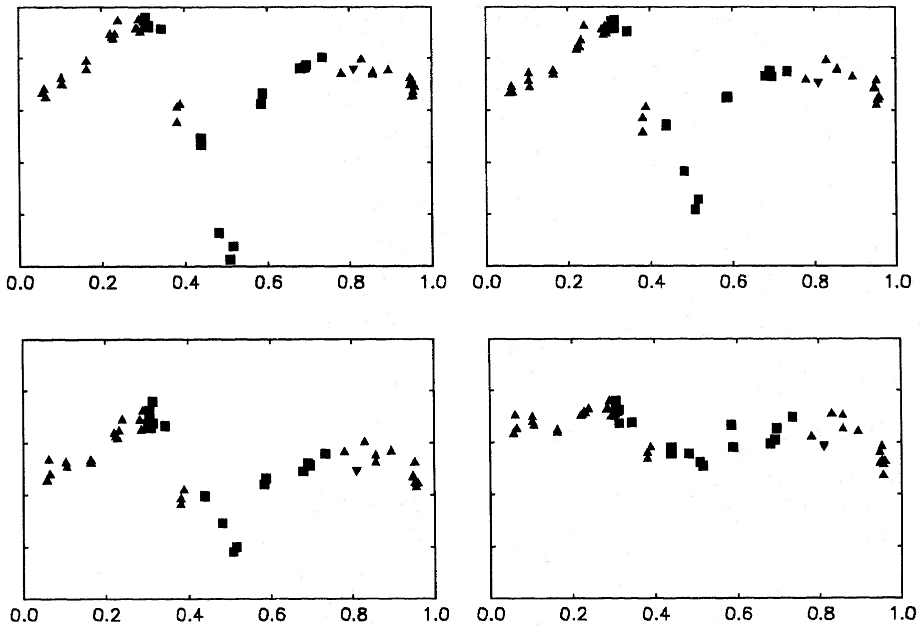


FIG. 4. Six-point running normals of $I$, $y$, $b$, and $v$ observations for 1989 to 1991. Same arrangement as in Fig. 1. Different symbols are used for different years. See Fig. 2 for $u$ observations.

different shape (Fig. 2). In the phase range from 0.7 to first contact, $I$, $y$, $b$, and $v$ light curves are depressed near phase 0.7 and "flattened" relative to the (1982 to 1986) set, but $u$ light declines about as rapidly as in the earlier data. The marked changes in light variations outside primary eclipse between Figs. 3 and 4 are perhaps the strongest evidence against an interpretation based largely on the ellipticity effect.

It is now clear why Zola very reasonably interpreted his $V$, $B$ observations as dominated by ellipticity outside primary eclipse. His $V$ and my $y$ observations are very similar. His $B$ observations are at an effective wavelength between my $b$ and $v$, and reflect the decline in light variation between $b$ and $v$ noted above. But the various "parallel" behaviors of the $I$, $y$, and $b$ data under current discussion are evidence against the ellipticity explanation, and in particular against ellipticity as the dominant explanation of the $y$ or $V$ light curves.

Though the (1989 to 1991) data are sparse in secondary eclipse (Fig. 4), this depression does seem to have become more nearly symmetrical, mainly because the ingress branch is fainter in the later data set. Variations in secondary ingress may be correlated with the changes just before primary eclipse, as noted above. If they are a disk effect, then the cause must be located in the leading half of the disk. The secondary eclipse depression nearly disappears in $v$ but returns in $u$, displaced to phase $\approx 0.45$. Only in $u$ do the two data sets appear to agree, perhaps because of the large intrinsic scatter at this wavelength.

While the Zola (1991) interpretation of out-of-eclipse variations, as mostly an ellipticity effect of a lobe-filling cool giant star, would simplify the model of RZ Oph, the above detailed examination of light curves does not seem to support this approach. The case for a semidetached configuration is thereby weakened. The Olson (1987, 1989) analyses used mainly the (1982 to 1986) data in Fig. 3, and interpreted the sharp drop in light between phase 0.75 and first contact (Fig. 3) as a partial eclipse of the disk by the cool star. As already noted, variations in the first half of the light curve during this time may indeed arise mainly from ellipticity. While obvious difficulties remain, this approach still seems to be viable. In the (1989 to 1991) data, a partial disk eclipse may be present after primary eclipse, and systematic light reaches a maximum near phase 0.3.

In addition to dips around primary eclipse, produced mainly by eclipses of the disk by the cool star, secondary eclipse is broadened by partial eclipses of the cool star by the disk. As noted by Olson (1987, 1989), there are major problems in modeling the large size of these light losses; a disk thicker than one set of gravitational stratification seems to be required. Finally, some process must produce the O'Connell effect, which is most prominent in the later data set, particularly in $u$. Near-quadrature light losses are largest at phases when the observer views the following half of the disk and hot star. Perhaps a "diffuse" mass-transferring stream, somewhat similar to those in semidetached binaries, contributes to this asymmetry, by absorbing light from the following half of the hot star and disk.

There is good spectrographic evidence for an accretion disk in RZ Oph during the later set of photometric observations. From 1989 to 1991, strong double-peaked H$\alpha$ emission, characteristic of an accretion disk rotating around the hot star, was continuously present in CCD spectra of RZ Oph obtained at the Mount Laguna Observatory (Etzel & Olson 1992). Absorption in the O I $\lambda$7774 triplet lines increased dramatically around secondary eclipse, where the disk partially eclipses the cool star. This oxygen line extinction is probably associated with the disk continuous extinction that widens secondary eclipse. The photometric evidence discussed in this paper suggests that the accretion disk produces enough continuous emission and extinction to distort the light curves of RZ Oph. As discussed above, these distortions make it very difficult to extract the true ellipticity variations, and to estimate the degree of Roche lobe-filling of the cool star. They present a major challenge to a full understanding of the photometric behavior of this active binary star.

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