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A new model of the eclipsing system RZ Ophiuchi

L.B.G. Knee[1,*], C.D. Scarfe[1,], M. Mayor[2], B.W. Baldwin[3,***], and S.J. Meatheringham[4]**

[1] Climenhaga Observatory, Physics Department, University of Victoria, Victoria, B.C., V8W 2Y2, Canada
[2] Observatoire de Genève, CH-1290 Sauverny, Switzerland
[3] Fanshawe College, London, Ontario, Canada
[4] Mt. Stromlo and Siding Spring Observatories, Private Bag, Woden P.O., A.C.T. 2606, Australia

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Summary. Multicolour photometric observations of the 1984 primary eclipse of the binary system RZ Ophiuchi have been obtained and analysed. The ratio of the radii of the two components has been determined using the effective temperature and bolometric correction of each star, derived from its observed spectral classification and photometric colours, and a solution for the orbital inclination and the radius of each star made using this value. The solution supports the "detached model" favoured by Baldwin and by Forbes and Scarfe, in which neither star fills its critical surface. The photometric results were combined with a new radial velocity solution for the system, and physical parameters determined. It appears that RZ Oph may be an example of a system in a short-lived phase of "Case C" mass exchange.

Key words: eclipsing binary – spectroscopic binary – stellar dimensions – stellar evolution

1. Introduction

The nature of the long-period eclipsing binary RZ Oph remains uncertain despite the publication of the first detailed study of the system by Baldwin (1976, 1978) and of an alternative model by Smak (1981). The problem arises mostly from lack of coverage of the eclipse light curve, and from the very small ratio of the stellar radii ($k < 0.2$) and high inclination ($i > 75°$). As a result the light curve solution is indeterminate with respect to k, i and the fractional radius of the larger star, r_g, and it is necessary to fix the value of one of these parameters in advance (Forbes and Scarfe 1984).

Baldwin chose to assume $i = 90°$, and found that this implied that neither stellar component filled its critical Roche lobe. This left unexplained the highly-evolved state of the less massive cool secondary star, which has probably undergone considerable mass transfer to the much smaller but more massive primary. To judge by the extensive circumstellar disk surrounding the primary (Hiltner 1946, Baldwin 1978) this process may still continue.

This evolutionary puzzle may be avoided if one assumes, as Smak did, that the secondary fills its critical surface. This process fixes r_g, which is as arbitrary an assumption as fixing i, and requires the adoption of the preliminary and uncertain mass ratio found by Baldwin. Thus it would be highly advantageous to determine one element independently of the shape of the eclipse light curves. Forbes and Scarfe suggested that k be determined by calibration of the effective temperatures and bolometric corrections for each star, and noted that the data then available favoured a value of k closer to that obtained from the light curve via Baldwin's assumption than via Smak's.

The results of an international campaign to obtain and analyse photometric observations of the 1984 June primary eclipse of RZ Oph are presented below. These results are combined with a new radial velocity solution based primarily on observations with CORAVEL (Baranne et al., 1979) to yield the most complete picture of the system yet produced.

Photopolarimetric observations of the eclipse were obtained by J.C. Kemp, D.J. Kraus and G.D. Henson at Pine Mountain Observatory. Details of their equipment and observing procedures are given by Kemp and Barbour (1981). These observations are to be discussed elsewhere.

2. The photometric observations

Each partial phase of primary eclipse has a duration of about thirty hours, and the eclipse is total for nine days. In order to obtain sufficient coverage of the partial phases during one eclipse it is necessary to observe from several geographic longitudes. A network of collaborating observers was established for this purpose. BV observations were obtained at Pine Mountain Observatory, Oregon (LBGK), and UBV observations at Osservatorio di Catania, Sicily (BWB), Siding Spring Observatory, New South Wales (SJM), and Lick Observatory, California (CDS – partial phases only). *UBVRI* observations were obtained in totality and outside eclipse at Climenhaga Observatory, Victoria, B.C. (LBGK and J.M.V. Gagné).

The observations were made differentially, using BD + 6°3917 as the comparison star and BD + 6°3918 as the check star, following Baldwin (1978), Olson and Hickey (1983) and Forbes and Scarfe (1984). They were transformed to the UBVRI system of Landolt (1973, 1983) by means of observations of standard stars in the nearby Selected Areas 109, 110 and 111 (Landolt 1983).

Send offprint requests to: C.D. Scarfe

* Guest Observer, Pine Mountain Observatory, University of Oregon, Eugene, Oregon, U.S.A. Present address: Observatorio ja Astrofysiiken Laboratorio, Helsingin Yliopisto, Tähtitorninmäki, SF-00130 Helsinki, Finland

** Guest Observer, Lick Observatory, University of California, Santa Cruz, California, U.S.A., and Dominion Astrophysical Observatory, Victoria, B.C., Canada

*** Guest Observer, Osservatorio di Catania, Catania, Italy

Table 1. Comparison and check stars

Star	comparison	check
BD	+6°3917	+6°3918
V	9.412 ± 0.001	9.272 ± 0.001
$U-B$	0.261 ± 0.002	1.266 ± 0.002
$B-V$	0.659 ± 0.001	1.253 ± 0.001
$V-R$	0.341 ± 0.004	0.650 ± 0.006
$R-I$	0.254 ± 0.007	0.505 ± 0.019
R.V. (km s^{-1})	−26.1 ± 0.2	−7.9 ± 0.1

The colours of RZ Oph change substantially during eclipse; hence care was taken to ensure that the selected standard stars covered a large range of colour, in order to provide transformations that were reliable over such a range. The reductions followed the procedures of Hardie (1962). A complete discussion of the observing program, observational methods and reductions is given by Knee (1985).

The comparison and check star observations were numerous enough to permit accurate determinations of the mean magnitudes and colours, which are listed in Table 1. The colours of these stars correspond to those of unreddened giants of spectral types GO and K3 respectively, in agreement with the results of Olson and Hickey (1983).

The data for RZ Oph from individual observers were combined into normal points, each of which is a mean of five to ten individual observations, except during partial phases when as few as two observations were combined into some normal points; these normal points are listed in Table 2. The r.m.s. uncertainties of typical normal points are 0.021, 0.010 and 0.006 mag in U, B and V respectively. The Pine Mountain and Lick observations during partial phases agree well with each other, but those from Siding Spring at closely adjacent phases do not. This will be discussed below.

Table 2. Photometric normal points

HJD-2445800	U	$O-C_U$	B	$O-C_B$	V	$O-C_V$	Observer
63.5916	11.606	−0.119	10.932	−0.058	9.880	−0.020	B
.8778					9.915	0.015	K
.8951			10.947	−0.043			K
.9109					9.915	0.015	K
.9238			10.989	−0.001			K
.9330					9.838	−0.062	K
64.4501	11.690	−0.035	10.998	0.008	9.913	0.013	B
.4771	11.562	−0.163	10.918	−0.072	9.860	−0.040	B
.5052	11.669	−0.056	10.949	−0.041	9.891	−0.009	B
.5356	11.646	−0.079	10.966	−0.024	9.911	0.011	B
.5637	11.614	−0.111	10.956	−0.034	9.888	−0.012	B
65.20	11.80	−0.074	11.15	0.102	9.92	0.008	M
.22	11.95	0.069	11.16	0.100	9.99	0.074	M
.7168	12.554	0.051	11.538	0.002	10.086	−0.021	S
.7503			11.558	−0.034			K
.7519	12.545	−0.054	11.581	−0.013	10.109	−0.012	S
.7765			11.663	0.052			K
.7744	12.602	−0.033	11.636	−0.001	10.135	−0.005	S
.7885					10.122	−0.023	K
.8165			11.716	0.022			K
.8441					10.165	−0.005	K
.8545			11.736	−0.020			K
.8710					10.186	−0.003	K
.8724	12.802	−0.014	11.769	−0.021	10.182	−0.008	S
.8840					10.188	−0.006	K
.8938			11.819	−0.002			K
.9061			11.821	−0.013			K
.9123	12.878	−0.065	11.842	−0.016	10.205	−0.008	S
.9232					10.220	0.002	K
.9330			11.863	−0.022			K
.9383	12.975	−0.023	11.860	−0.033	10.232	−0.002	S
.9711	13.107	−0.001	11.906	−0.031	10.247	−0.004	S
66.12	13.54	0.044	12.08	−0.110	10.33	−0.014	M
.15	13.49	−0.123	12.22	−0.021	10.39	0.036	M
.4789	13.987	−0.040	12.366	−0.026	10.454	−0.027	B
.5083	13.853	−0.174	12.345	−0.047	10.434	−0.047	B

Observers: B = B.W. Baldwin, K = L.B.G. Knee, M = S.J. Meatheringham, S = C.D. Scarfe

Table 2 (continued)

HJD-2445800	U	$O-C_U$	B	$O-C_B$	V	$O-C_V$	Observer
66.5348	13.924	−0.103	12.356	−0.036	10.450	−0.031	B
.5685	13.913	−0.114	12.348	−0.044	10.451	−0.030	B
.5845	13.911	−0.116	12.333	−0.059	10.468	−0.013	B
.8240			12.410	0.018			K
.8330					10.474	−0.007	K
.8615			12.381	−0.011			K
.8708					10.478	−0.003	K
.8970			12.384	−0.008			K
.9139					10.482	0.001	K
.9153			12.314	−0.078			K
67.4912	13.983	−0.044	12.425	0.033	10.476	−0.005	B
.5190	14.018	−0.009	12.373	−0.019	10.472	−0.009	B
.5448	14.088	0.061	12.380	−0.012	10.483	0.002	B
.5700	14.123	0.096	12.405	0.013	10.481	0.000	B
68.5203	13.998	−0.029	12.393	0.001	10.484	0.003	B
.5492	14.026	−0.001	12.413	0.021	10.485	0.004	B
.5726	14.010	−0.017	12.417	0.025	10.484	0.003	B
.7893			12.460	0.068	10.470	−0.011	K
.8258			12.407	0.015	10.453	−0.028	K
.9420			12.391	−0.001	10.500	0.019	K
70.7820					10.490	0.009	K
.8051					10.499	0.018	K
.8292			12.395	0.004			K
.8597			12.399	0.007			K
72.8225			12.389	−0.003	10.492	0.011	K
74.4826	13.982	−0.045	12.442	0.050	10.521	0.040	B
.98	14.22	0.193	12.45	0.058	10.47	−0.011	M
75.09	13.61	−0.417	12.45	0.058	10.51	0.029	M
.3992	14.024	−0.003	12.387	−0.005	10.488	0.007	B
.4525	13.896	−0.131	12.401	0.009	10.486	0.005	B
.5083	13.862	−0.165	12.396	0.004	10.490	0.009	B
.5234	13.784	−0.243	12.402	0.010	10.494	0.013	B
.5691	13.911	−0.116	12.390	−0.002	10.482	0.001	B
.7621			12.349	−0.043	10.474	−0.007	K
.7986			12.368	−0.024	10.507	0.026	K
76.22	13.57	−0.061	12.21	−0.088	10.42	0.042	M
.7170	12.421	−0.025	11.472	−0.016	10.082	−0.002	S
.7233			11.462	−0.018	10.077	−0.004	K
.7432	12.370	−0.048	11.440	−0.025	10.075	0.002	S
.7602			11.432	−0.007	10.069	0.009	K
.7715	12.330	−0.029	11.410	−0.020	10.059	0.004	S
.7978			11.400	0.007	10.040	−0.007	K
.8448					10.026	−0.002	K
.8474			11.333	0.006			K
.8557	12.158	−0.070	11.320	0.001	10.018	−0.005	S
.8778					10.012	0.000	K
.8861			11.290	−0.007			K
.8899			11.274	−0.006	10.000	−0.007	S
.8948	12.102	−0.090					S
.9111					9.988	−0.008	K
.9194			11.240	−0.010			K
.9204			11.246	−0.003	9.983	−0.007	S
.9360	12.025	−0.106					S
.9444					9.968	−0.013	K
.9461			11.224	−0.011	9.970	−0.009	S
.9468			11.218	0.014			K

Table 2 (continued)

HJD-2445800	U	$O-C_U$	B	$O-C_B$	V	$O-C_V$	Observer
76.9751	11.996	−0.100	11.211	0.008	9.968	−0.004	S
77.10	11.95	0.000	11.19	0.091	10.03	0.096	M
.16	11.90	−0.009	11.16	0.094	10.03	0.110	M
.19	11.88	−0.007	11.12	0.067	10.02	0.105	M
.22	11.78	−0.085	11.11	0.065	9.97	0.061	M
.3943	11.773	0.002	11.009	0.019	9.917	0.017	B
.4216	11.763	0.002	11.008	0.018	9.911	0.011	B
.4453	11.748	0.000	11.001	0.011	9.911	0.011	B
.4724	11.746	0.006	10.992	0.002	9.906	0.006	B
.4995	11.720	−0.018	10.992	0.002	9.908	0.008	B
.5138	11.720	−0.015	10.989	−0.001	9.914	0.014	B
.5546	11.704	−0.021	10.986	−0.004	9.909	0.009	B
.5708	11.687	−0.038	10.968	−0.022	9.894	−0.006	B
.7602			10.940	−0.050	9.886	−0.014	K
.7986					9.870	−0.030	K
.8007			10.938	−0.052			K
.8302					9.864	−0.036	K
.8386			10.937	−0.053			K
.8639					9.883	−0.017	K
78.4078	11.577	−0.148	10.915	−0.075	9.866	−0.034	B
.4961	11.594	−0.131	10.942	−0.048	9.883	−0.017	B
.5721	11.563	−0.162	10.925	−0.065	9.867	−0.033	B
80.4477	11.567	−0.158	10.915	−0.075	9.854	−0.046	B
.5053	11.558	−0.167	10.908	−0.082	9.847	−0.053	B
108.8607			10.921	−0.069	9.861	−0.039	K
120.7914			10.926	−0.064	9.857	−0.043	K
133.7045			10.916	−0.074	9.832	−0.068	K

The time of mid-eclipse was found to be HJD 2445871.2 ± 0.2, in agreement with the ephemeris of Forbes and Scarfe. The normal points during and close to partial phases, folded about this time, are plotted in Figs. 1, 2, and 3.

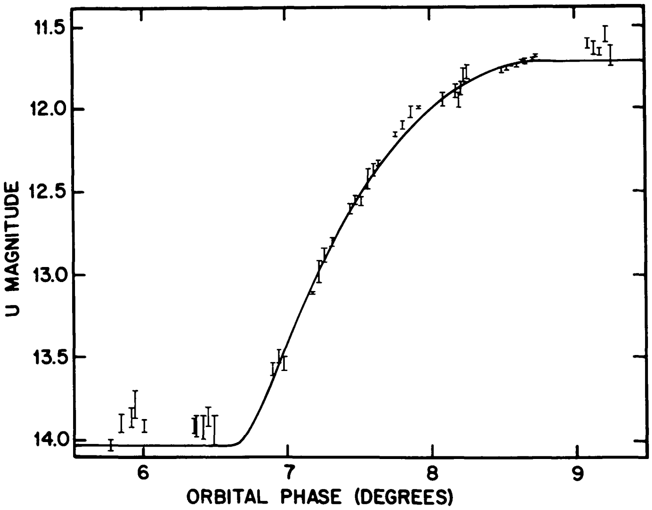

Fig. 1. Photometric normal points in the U band during and close to partial eclipse. The curve represents the elements from Table 5. The error bars represent the standard deviation of a single observation and are centred on the mean for each normal point

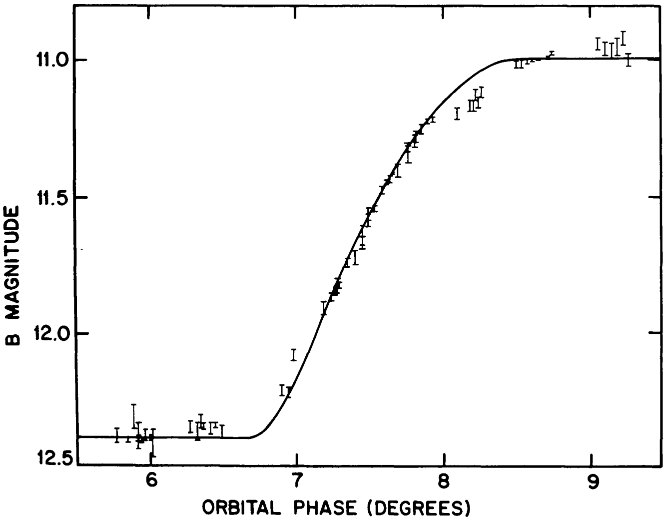

Fig. 2. Same as Fig. 1 for B observations

3. Colours of the components

The determination of the magnitudes and colours of each stellar component of RZ Oph from the eclipse depths is complicated by the presence of the disk, which contributes a small but appreciable amount to the system's light, and probably accounts for the

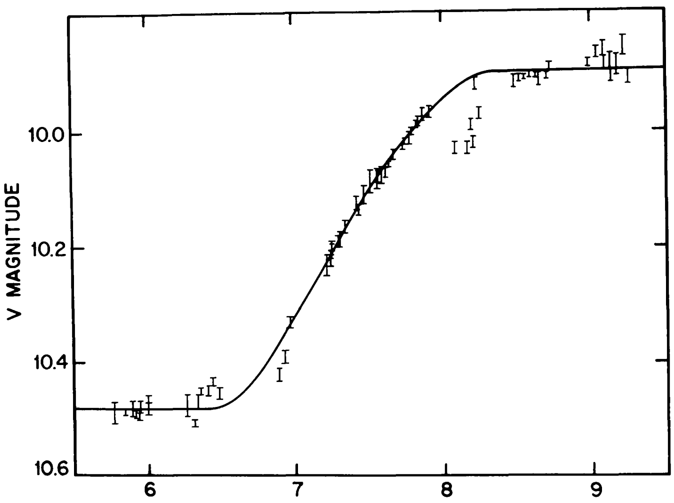

Fig. 3. Same as Fig. 1 for V observations

small variations observed outside eclipse (Olson and Hickey 1983, Olson 1984). These variations occur on time scales comparable to the orbital period; hence there should be negligible variation during the relatively short duration of the stellar eclipse.

However the eclipse of the disk needs some further consideration. During most of totality the brightest part of the disk will also be hidden behind the secondary, so its contribution is reduced and the light remaining should be essentially that of the secondary star. Just outside the external contacts however, the visible fraction of the disk is less than at any other out-of-eclipse phase but is changing rapidly. Thus the light of the two stars alone is thus most closely represented by the brightness observed very close in time to these contacts. Using the disk brightness estimates of Olson and Hickey it was found, moreover, that disk contamination should have no significant effect on the stellar colours. Thus the magnitudes and colours of each component were derived from the mean magnitudes during totality and just outside the external contacts.

These colours were corrected for reddening using $A_v = 0.40$ (Olson and Hickey) and standard reddening relations (Mihalas and Binney, 1981; Taylor, 1986), and correspond well to the colours expected from the spectral classifications (Baldwin, 1978) of F5 Ib and K5 Ib for the primary and secondary respectively, except for the very uncertain $R-I$ index of the primary. The observed magnitudes and colours and the unreddened colours of each component are given in Table 3.

4. The ratio of stellar radii

The indeterminacy of the light curves requires that the value of k be found from the effective temperatures ($T_{\rm eff}$) and bolometric corrections (B.C.) of each component, using

$$M_{\rm bol}({\rm K}) - M_{\rm bol}({\rm F}) = 10 \log \frac{T_{\rm eff}({\rm F})}{T_{\rm eff}({\rm K})} + 5 \log k \quad (1)$$

where for either star, $M_{\rm bol} = M_v + {\rm B.C.}$

Tables of effective temperatures and bolometric corrections as functions of colour indices are scarce and uncertain for supergiants, particularly for late spectral types. For the primary F star, $T_{\rm eff}$ and B.C. were derived from the $B-V$ and $V-R$ colours

Table 3. Magnitudes and colours of RZ Ophiuchi

	primary	secondary
a) Observed		
V	10.856 ± 0.010	10.481 ± 0.002
$U-B$	0.525 ± 0.013	1.635 ± 0.017
$B-V$	0.483 ± 0.011	1.911 ± 0.003
$V-R$	0.305 ± 0.030	1.042 ± 0.006
$R-I$	-0.257 ± 0.139	0.924 ± 0.011
b) Corrected for reddening		
$U-B$	0.43 ± 0.03	1.54 ± 0.03
$B-V$	0.36 ± 0.03	1.79 ± 0.03
$V-R$	0.22 ± 0.05	0.96 ± 0.04
$R-I$	-0.34 ± 0.15	0.84 ± 0.04

Table 4. Temperatures and bolometric corrections

	primary		secondary
$T_{\rm eff}$ (K)	6600 ± 250		3600 ± 200
B.C. (mag)	0.15 ± 0.04		-1.26 ± 0.33
k		0.13 ± 0.03	

and the model atmospheres of Kurucz (1979, 1986). $U-B$ was not used since it is a poor temperature indicator for F stars; nor was the very uncertain $R-I$ colour.

From the photometry of Olson and Hickey, the F star has Strömgren indices $c_1 = 1.4 \pm 0.2$ and $b-y = 0.34 \pm 0.01$. These place it in the supergiant (low gravity) region of Strömgren's (1963) $c_1-(b-y)$ diagram. This supports the F5 Ib classification and indicates that the low-gravity region of Kurucz's tables ($1.0 \leq \log g \leq 2.5$) should be used.

For the secondary K star, $V-R$ and $R-I$ indices were converted to the Johnson system using the transformations of Landolt (1983) and Taylor (1986), and the effective temperature and bolometric corrections were derived from the tables of Johnson (1966) for supergiants. The results for both stars, together with the ratio of radii k derived from them, are given in Table 4. The temperatures agree well with those derived by Forbes and Scarfe, but this is to some extent fortuitous, since the colours are somewhat different.

5. The light-curve solutions

Although the light curves presented here are the most complete yet obtained for the primary eclipse of RZ Oph, they are still preliminary in nature. They lack coverage near the contact points and are complicated by some contamination by disk light. The complex variations in the light curves outside eclipse (Olson 1984) preclude rectification.

As a result, the use of one of the existing sophisticated techniques for light-curve solution was not considered justified. Thus the solutions followed the technique of Russell and Merrill (1952) for totally eclipsing systems, with the ratio of the radii fixed at $k = 0.13$. The limb-darkening coefficient of the eclipsed F star was assumed to be $x = 0.6$ in the V band and $x = 0.8$ in the U and B bands. Only well-determined parts of the light curves were

Table 5. Photometric elements

Band	U	B	V
L_g	0.120 ± 0.002	0.275 ± 0.001	0.586 ± 0.003
r_g	0.137 ± 0.016	0.127 ± 0.015	0.128 ± 0.016
r_s	0.018 ± 0.002	0.017 ± 0.002	0.017 ± 0.002
i	$88.^\circ3 \pm 2.^\circ9$	$90.^\circ0 \pm 3.^\circ3$	$90.^\circ0 \pm 4.^\circ0$
θ_e	$8.^\circ721 \pm 0.^\circ010$	$8.^\circ511 \pm 0.^\circ016$	$8.^\circ375 \pm 0.^\circ011$
θ_i	$6.^\circ618 \pm 0.^\circ026$	$6.^\circ696 \pm 0.^\circ018$	$6.^\circ466 \pm 0.^\circ026$

used in the solutions, and the light at external contact was considered to be adjustable within the limits imposed by the observations near that phase.

The results for each band are given in Table 5; the uncertainties are derived in part from the difference between the adopted values and those from similar solutions with $k = 0.10$ and 0.16, to indicate the effects of the uncertainty in the above determination of k. Residuals of the normal points from this solution are included in Table 2, and the light curves synthesized from it are drawn as continuous curves in Figs. 1, 2, and 3.

The Siding Spring data give large residuals from the fitted curves, especially near external contact. These residuals are of comparable size in B and V, but appear larger in the latter due to the greater scale of the ordinate in Fig. 3 than in Fig. 2. They appear to be smaller in U, but this is largely due to the greater influence of the Siding Spring data on the curve itself, relative to the North American data. The latter are from Lick alone, since no U filter was available at Pine Mountain.

Careful examination of the Siding Spring observing record indicates that the observations were not affected by poor weather, nor to the use of inappropriate extinction coefficients. They thus appear to represent real departures from the model light curves, but only future observations will indicate whether their cause is a permanent feature of the system. The present calculated curves are an attempt to fit all the data obtained during partial phases, and thus yield both large residuals, chiefly for the Siding Spring data, and long sequences of residuals of the same sign for the North American data.

As suggested by Forbes and Scarfe, the eclipse appears to be of longer duration at shorter wavelengths than it is in V. This effect is exaggerated by the fitting of the light curves described above. But if it is real, it may perhaps be due to limb-darkening variations, to disk light, or to an atmospheric eclipse. The values $i = 90.^\circ0 \pm 4.^\circ0$, $r_g = 0.13 \pm 0.02$, $r_s = 0.017 \pm 0.002$ have been obtained by averaging the results of Table 5, and are adopted for the remainder of this paper. Half weight was given to the U results, since this light curve is less well-determined and may be more contaminated by disk light than the others, since it shows greater variation during totality and outside external contact.

6. The radial velocity curves

Baldwin's radial velocity study was preliminary in nature, and suffered from low resolution, uneven phase converage, and possible blending of the lines from each component. An improved spectroscopic solution was thus necessary to permit the absolute parameters of the system to be determined more reliably, as well as to obtain the relative sizes of the critical Roche lobes from the mass ratio.

New radial velocities of both components of RZ Oph have been obtained by one of us (MM) during the period 1977–1984, using the CORAVEL spectrometer (Baranne et al., 1979) on the Geneva 1 m telescope at Observatoire de Haute-Provence. In addition a small number of velocities have been obtained (by CDS) with the radial velocity spectrometer at the Dominion Astrophysical Observatory (Fletcher et al., 1982). Since the correction to the I.A.U. radial velocity system is not well-determined

Table 6. Radial velocities

J.D. 2440000+	Phase	Velocity ($km\,s^{-1}$)	O − C ($km\,s^{-1}$)	Notes
a) K Star				
3401.301	0.322	−25.9	−0.8	C
3696.493	0.449	−53.1	0.1	C
3699.496	0.460	−53.8	0.5	C
3700.485	0.464	−53.8	0.8	C
3711.410	0.506	−54.6	1.4	C
3720.432	0.540	−55.8	−1.6	C
3730.429	0.578	−51.2	−1.7	C
4100.388	0.991	53.7	0.2	C
4113.355	0.040	51.9	0.1	C
4407.535	0.164	25.3	−1.8	C
5171.487	0.080	50.7	3.9	C
5193.386	0.164	26.2	−0.8	C
.395	0.164	25.9	−1.1	C
5582.364	0.649	−33.5	0.2	C
.373	0.649	−33.5	0.2	C
5869.834	0.746	−1.9	0.5	VT
5870.800	0.750	−1.4	−0.2	VT
5887.827	0.815	20.0	−0.6	V
5916.397	0.924	47.5	0.0	C
5942.387	0.023	54.3	1.3	C
6204.936	0.026	50.3	−2.6	V
6264.819	0.254	−2.1	0.6	VB
6299.743	0.388	−42.3	0.6	V
b) F Star				
3698.458	0.456	5.0	−0.4	C
3699.508	0.460	5.9	0.5	C
3711.417	0.506	6.8	1.2	C
3720.437	0.540	6.1	0.7	C
3730.438	0.579	4.1	−0.7	C
3733.361	0.590	5.6	1.1	C
4100.406	0.991	−11.2	−3.2	C
4113.361	0.040	−4.7	3.1	C
5582.364	0.649	1.0	−1.8	C
.373	0.649	−1.6	−4.4	C
5916.397	0.924	−4.3	2.9	C
.406	0.924	−7.3	−0.1	C
5934.816	0.995	−8.9	−0.9	V
5942.400	0.023	−8.8	−0.9	C
5952.400	0.063	−7.2	0.3	V
6204.936	0.026	−5.0	2.9	V
6264.819	0.254	−2.1	−1.1	VB
6299.743	0.388	6.6	2.6	V

C = CORAVEL, V = DAO, B = Lines blended, T = During totality for the recently-installed mask and optical components of the DAO instrument, with which these observations were made, they have been arbitrarily adjusted by $+0.7\,\mathrm{km\,s^{-1}}$ to bring them into agreement with the CORAVEL data.

Radial velocity observations have also been obtained with the DAO instrument of the photometric comparison stars. Their radial velocities, which have been adjusted to the CORAVEL system as above, and included in Table 1, show no variation over slightly more than a year. It thus appears likely that they are stable single stars, in agreement with their lack of observed photometric variability.

The data available for a spectroscopic orbital solution are assembled in Table 6. The solution assumed the period to be fixed at 261.9277 days, obtained from the photometric data. An attempt to determine the orbital eccentricity resulted in a value much smaller than its uncertainty. Therefore a circular orbit was adopted, and sine curves fitted by least-squares. The observations of Baldwin, especially those of the K star, show substantial systematic departures from the curves defined by the new data, and were not included in the solution. All the new data were accorded equal weight. The spectroscopic elements are listed in Table 7, and the velocity curves are shown in Fig. 4. We note that the mass ratio, $q = \mathcal{M}_F/\mathcal{M}_K = 8.1 \pm 0.7$, is much larger than that found by Baldwin, and that if the disk eclipse lasts about 42 days (van Paradijs et al., 1982; Kemp, 1984), the radius of the disk is about $110\,R_\odot$.

7. Physical characteristics of the components

The physical parameters of each stellar component have been deduced from the photometric and spectroscopic results discussed above. In Table 8 are given the mass, radius, surface

Table 8. Physical properties

Star	primary	secondary
Mass ($\mathcal{M}_\odot$)	5.65 ± 0.23	0.70 ± 0.06
Radius ($R_\odot$)	5.4 ± 0.6	41 ± 6
$\log g$ (cm/s^2)	3.7 ± 0.1	1.0 ± 0.1
Critical Radius ($R_\odot$)	178 ± 3	70 ± 2
$M_{\rm bol}$	0.5 ± 0.2	-1.3 ± 0.4
M_v	0.3 ± 0.2	0.0 ± 0.5

Table 7. Spectroscopic elements

Period (days)	261.9277 (assumed)
Epoch (nodal passage)	JD 2444102.76 ± 0.36
Systemic Velocity (km/s)	-1.2 ± 0.3
Semiamplitude for K star (km/s)	54.8 ± 0.4
Semiamplitude for F star (km/s)	6.8 ± 0.6
$a_K \sin i$ (a.u.)	$1.32 \pm 0.01 = 284 \pm 2\,R_\odot$
$a_F \sin i$ (a.u.)	$0.16 \pm 0.01 = 34 \pm 2\,R_\odot$
$\mathcal{M}_K \sin^3 i\,(\mathcal{M}_\odot)$	0.70 ± 0.06
$\mathcal{M}_F \sin^3 i\,(\mathcal{M}_\odot)$	5.65 ± 0.23

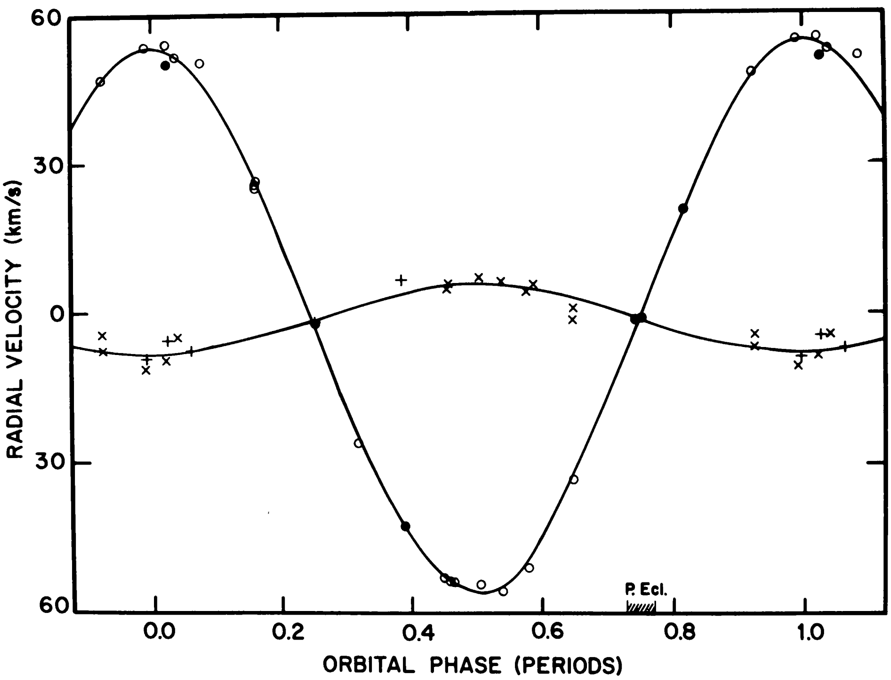

Fig. 4. Radial velocity observations of RZ Ophiuchi as function of phase. Circles represent observations of the K star, open for CORAVEL, filled for D.A.O. For the F star, crosses represent CORAVEL observations and plus signs D.A.O. observations. The curves represent the elements of Table 7

gravity, critical radius, and absolute visual and bolometric magnitudes of each component. The surface gravities were found with the formula

$$\log g_* = \log g_\odot + \log \frac{\mathcal{M}_*}{\mathcal{M}_\odot} - 2\log \frac{R_*}{R_\odot} \quad (2)$$

while M_{bol} and M_v were obtained from

$$M_{\mathrm{bol}*} = M_{\mathrm{V}*} + BC_*$$
$$= M_{\mathrm{bol}\odot} - 5\log(R_*/R_\odot) - 10\log\left(\frac{T_{\mathrm{eff}*}}{T_{\mathrm{eff}\odot}}\right). \quad (3)$$

The approximate formula of Eggleton (1983) was used to calculate the critical radii. Both stars fall well within their critical lobes.

The physical characteristics of the primary appear to be those of a nearly normal F5 giant of luminosity class II–III, despite its super giant spectrum. The derived surface gravity is outside the range used in the original calibration of effective temperature and bolometric correction. However a repetition of this calibration with a gravity appropriate for an F giant results in a value of k agreeing within the uncertainty with that derived previously.

The secondary appears to be a very undermassive K5 giant star of luminosity class III. Its very low surface gravity is consistent with its classification as a supergiant by Baldwin.

The distance to RZ Oph is about 1100 ± 200 pc, from its unreddened V magnitudes and the absolute V magnitudes in Table 8.

8. Evolutionary history of RZ Ophiuchi

The peculiar properties of the cooler star and the substantial amount of circumstellar matter in the system strongly suggest that the present state of RZ Oph is the result of the loss of substantial amounts of matter by the cooler star, which was formerly the more massive component. Much of this matter has presumably been transferred to the hotter star, but some may well have escaped entirely from the system. This mass transfer probably accounts for the circularity of the orbit of RZ Oph, as discussed by Burki and Mayor (1983). These authors also point out that RZ Oph is unusual in being a long-period mass-transfer product in which the mass-losing star is still detectable.

Given the current limitations on the quantitative understanding of evolutionary mass transfer and systemic mass loss it is difficult to determine the past history of a close binary system such as RZ Oph. The present masses however indicate that the original primary must have had a mass at least three times the sun's. Models of "Case B" (mass transfer in the primary's hydrogen shell-burning phase) systems with primaries having masses in the range 3 to 15 $\mathcal{M}_\odot$ (van der Linden 1980) tend to produce a bright main-sequence B star (the mass gainer) and a much fainter helium star. The observed properties of RZ Oph are inconsistent with these models.

However it is not possible to rule out entirely the possibility of Case B evolution if the two components were originally very nearly equal in mass and if little mass was lost from the system. In that case the lower-mass models of Paczyński (1971) may describe the system somewhat better. RZ Oph would then be a system in which the final collapse of the red giant to the white dwarf stage was being observed.

Another possibility is that RZ Oph is an example of Case C (post-helium flash) mass transfer. Few model calculations have yet been published for Case C and only ones that appear to be available for an intermediate mass system are those of Lauterborn (1970). The parameters of the initial system assumed by Lauterborn are quite plausible ones for RZ Oph, and the present appearance of the system corresponds well to his first detached phase, in which the mass-loser is burning only helium in a shell. This stage is more likely to be observed than the second detached phase, during which the mass-loser collapses to a carbon-oxygen white dwarf, because of its longer lifetime. In addition, the observed radius of the mass-loser, and its position in the HR diagram, correspond well to those expected in the first detached phase in Lauterborn's model.

The existence of the circumstellar disk also suggests that the mass-loser has recently become detached for the first time from its critical surface, since the bulk of the mass loss occurs during the first semi-detached phase. Thus a remnant of the mass-transfer disk would more probably be observable in the first detached phase than in the second.

However, estimates of the disk's mass range from about $10^{-9}\mathcal{M}_\odot$ (Baldwin) to $10^{-7}\mathcal{M}_\odot$ (Olson and Hickey). Since cool giants typically lose mass at a rate of about $10^{-6}\mathcal{M}_\odot$ per year, another possible interpretation of the disk is that it is maintained by a wind from the secondary's tenuous outer envelope (Paczyński, 1969).

Thus it appears that the most likely description of RZ Oph is as a system between Roche-lobe filling stages of Case C mass transfer. It may thus be an example of a short-lived phase of close binary evolution, and may indeed be unique among known binaries in this characteristic.

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