J. Astrophys. Astr. (1994) **15,** 165–178

Orbital Elements and Evolutionary Nature of the Long Period RS CVn Type Eclipsing Binary RZ Eridani

P. Vivekananda Rao, M. B. K. Sarma & B. V. N. S. Prakash Rao *Centre for Advanced Study in Astronomy, Osmania University, Hyderabad 500 007*

Received 1993 May 20; accepted 1994 March 31

Abstract. Light curves of the long period RS CVn type eclipsing binary RZ Eri, obtained during the period 1976–1979 with the 1.2 m telescope of the Japal–Rangapur Observatory are analysed, using Wilson–Devinney method, by fixing the two parameters T_h (7400°K) and q(0.963), resulting in the following absolute elements: $A = 72.5 \pm 1.4R_\odot$, $R_h = 2.84 \pm 0.12R_\odot$, $R_c = 6.94 \pm 0.20R_\odot$, $M_{\text{bol, h}} = 1.35 \pm 0.28$, $M_{\text{bol ,c}}= 1.41 \pm 0.28$, $m_h = 1.69 \pm 0.06m_\odot$ and $m_c= 1.63 \pm 0.13m_\odot$. The presence of humps and dips of varying amplitudes at a few phases in the normal UBV light curves is explained as due to residual distortion wave. The derived (B-V) and (U-B) colours of both the components appear to have been reddened to an extent of $0^m.20$ in (B-V) and $0^m.16$ in (U-B) colours. This reddening is attributed to the presence of an envelope around the system, the material of which might have come from the loss of mass experienced by the evolving cooler component. Taking into consideration the dereddened colours and temperatures of the components, spectral types of *F*0 IV for the primary and G 5–8 III–IV for the secondary component were derived. The fractional radii of 0.039 and 0.096 of the two components, when compared with the radii of their critical Roche lobes of 0.378 and 0.372 suggest that these components are well within their critical sizes. From the position of the components on the. isochrones and the evolutionary tracks of stars of Pop I composition computed by Maeder & Meynet, it is concluded that the evolution of the components of RZ Eri is abnormal. This system is found to be situated at a distance of 185 pc, with an age of about 2.5×10^9yrs.

Key words: Eclipsing binaries, orbital elements, evolution—long period RS CVn stars—stars, individual.

1. Introduction

RZ Eridani (RZ Eri) (BD-10°993, HD 30050) is a relatively bright ($m_v = 7.7$) Algol type binary with a long period of $39^d.3$. Cesco & Sahade (1945) found Ca II *H* and *K* emission lines in the spectrum of the secondary component. This was confirmed by Joy & Wilson (1949) and Bidelman (1954). Later, Popper (1962), Gronbech (1975) and Eggen (1978) classified the primary component of this system to be an *A*5-*F*5 or Am type star and the secondary to be either a *G*8 or a *K* type giant. Popper (1976,

1982) obtained spectra of this system and improved the spectroscopic orbital elements of Cesco & Sahade (1945).

Based on its known characteristics, Hall (1976) included RZ Eri in the long-period RS CVn group. Caton & Oliver (1979) obtained the photoelectric light curve of the system and observed the following features:

(a) Absence of secondary minimum.
(b) No significant distortion wave.
(c) No significant change in period.

The light curves obtained later by Caton (1986) showed a distortion wave of a few hundredth of a magnitude in total amplitude. According to him, there was a possible presence of secondary eclipse near phase 0.67. Popper (1988) and Burki *et al.* (1992) confirmed the presence of the secondary eclipse at this phase.

Studies of RZ Eri in X-rays were reported by Walter & Bowyer (1981) and in radio radiation by Gibson (1979), Hjellming & Gibson (1979) and Paredes *et al.* (1987).

In order to improve our knowledge of this system, its absolute elements and evolutionary nature, we observed RZ Eri during 1976–1979 observing seasons. The preliminary results were already reported by Vivekananda Rao *et al.* (1988). In the following we give a detailed report on the results of our study of this system.

2. Observations

We observed the system RZ Eri in UBV passbands (Johnson system) during 1976–1979 observing seasons. The stars BD – $10^0$999 and – $10^0$994 were used as comparison and check stars respectively. These observations were made using an unrefrigerated EMI 6256B photomultiplier attached to the 1.2 m reflecting telescope of the Japal–Rangapur Observatory. The photocurrent was amplified by means of a GR 1230A DC amplifier and was recorded on a Honeywell Brown chart recorder. The observations of the comparison star were used for determining the nightly extinction coefficients. The rms error Δm (check-comparison) was found to be $\pm\ 0^m.01$ in V and $\pm\ 0^m.02$ in B and U, which indicated that the comparison star was constant in brightness within these errors during the period of our observations. All the observations were corrected for atmospheric extinction. The instrumental differential magnitudes Δm (variable comparison) were transformed to the Johnson and Morgan standard UBV system using the transformation coefficients obtained from the observations of an adequate number of standard stars, in each season on two nights. The transformation relations given by Hardie (1962) were used. The average standard magnitudes of the comparison star, during 19761979, were found to be $V = 9^m.08 \pm 0.01$, $B = 9^m.74 \pm 0.02$ and $U = 9^m.83 \pm 0.02$. The individual standardised observations in the form HJD versus ΔV, ΔB, and ΔU were published elsewhere (Vivekananda Rao & Sarma 1986).

3. Solution of the light curves

3.1 *Period fixation and formation of normal points*

From our observations, the following two primary minimal times were obtained:

HJD(Pri. Min) = 2443574.0830 and 2443888.3618.

Fitting these times and the other times of minima available in the literature up to 1979 to a linear relation, we obtained the following improved ephemeris:

$$\text{HJD(Pri. Min)} = 244{,}3888.3618 + 39^{d}.\,2824660 \tag{1}$$

and used this for calculating the phases of all our observations. From an (O-C) diagram we found that the period of the system remained constant during 1906 to 1979. Using the observations available upto 1989, Burki *et al.* (1992) derived a slightly longer period of $39^{d}.28254$, but this will not affect the phases of our observations calculated from the ephemeris at (1).

The light curves of RS CVn systems are usually affected by a distortion wave and its effect has to be removed before solving them for elements. The nature of the wave in RZ Eri is not well established. Caton & Oliver (1979) did not find any distortion wave in their 1977–1978 observations. However, a distortion wave of a few hundredth of a magnitude in total amplitude was found by Caton (1986) in his observations of 1978–1979. Burki *et al.* (1992) reported that out of all their observations between November 1977 and April 1989 they could find a well described variability for a safe removal of the effects of the spots only in their 1987–1988 observations. They had also stated that the nature of the spots, whether bright or dark, was also not known. Thus our knowledge about the nature of the distortion wave in RZ Eri is very limited.

Since the period of RZ Eri is quite long ($39^{d}.3$) we could not observe a complete light curve in any one observing season during 1976–1979, thus making it difficult for us to find the nature of the wave and correct our light curves, before solving them for elements. However, assuming that by combining the observations of the three seasons, the wave effects, if any, will be averaged out and that the solution of these curves will give average elements of the secondary component which is found to be responsible for the wave (Burki *et al.* 1992). Accordingly, we formed normal points by combining all our observations according to their phases.

As the slope of the light curves, Δm versus phase, varied rapidly during the primary eclipse, to represent the observations faithfully, as far as possible, we grouped together points within a phase range of about $0^{P}.001$ (0°.5) to form a normal point in the eclipse region whereas outside the eclipses, points within a phase range of about $0^{p}.003$ (1°) were grouped together. About 155 normal points were formed in this manner for each of the U, B, V pass bands. These normal points are plotted in Figs. 1a and 1b as filled circles.

3.2 *Light curve solution by Wilson—Devinney method*

3.2.a *Methodology and initial solution*: Out of the presently existing synthetic binary light curve methods Wilson-Devinney (1971) method (hereafter referred to as W-D method) is regarded as more reliable and is widely used. Hence we used this method for obtaining the elements of RZ Eri. Initially, from a preliminary analysis of UBV light curves of this system by Kopal's method (1959), we ascertained that the primary eclipse is an occultation and the system is detached. This conclusion is in conformity with the findings of Popper (1988) and Burki *et al.* (1992).

For initiating the W-D method, one needs reliable preliminary elements. As Kopal's

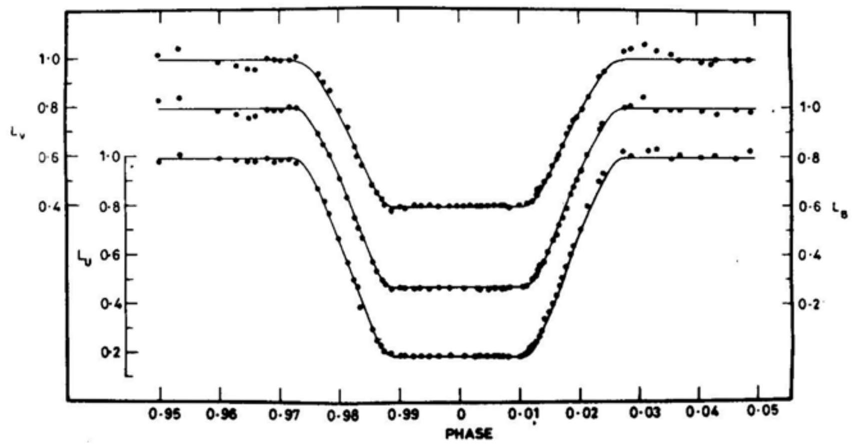

Figure 1a. RZ Eri: Light curves in V, B and U passbands during $0^p.95$ to $0^p.05$. Filled circles represent observations (normals) and solid lines represent the theoretical curves obtained from WD solution with fixed parameters of T_h (7400°K) and q (0.963).

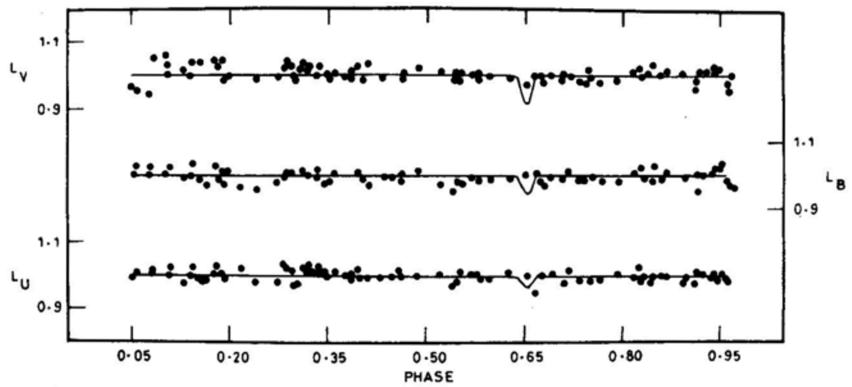

Figure 1b. RZ Eri: Same as Fig. la for $0^p.05$ to $0^p.95$.

method gave discordant parameters in U passband compared to those of B and V, we used the elements given by Popper (1988) and Burki *et al.* (1992) as initial parameters for the WD method and these are given in column 2 of Table 1. A plot of the preliminary theoretical light curves obtained with WD method showed a phase shift of about 0.09 with respect to the observed curve and hence a correction was applied to this effect. According to the principles of WD method, initially we adjusted the following parameters: the inclination i, the surface potentials Ω_h and Ω_c, the mass ratio q, the relative monochromatic luminosity L_h, the temperatures $T_{e,h}$ and $T_{e,c}$ and the third light, l_3. The limb darkening coefficients x_h and x_c, and gravity darkening exponents G_h and G_c were also adjusted but the choice of these coefficients seemed to have negligible effect on the derived elements of RZ Eri. Sufficient number of runs of the DC programme (code 2 for detached systems) was made till the sum of the residuals $\Sigma w(\text{O-C})^2$ showed a minimum and the corrections to the parameters became smaller than their probable errors. In order to check the internal consistency of the

Table 1. RZ Eri: Elements derived from the combined solution (all parameters varied).

Element 1	Initial parameters 2	Combined UBV solution 3
e	0.352	0.3496 ± 0.0236
ω	312°.1	$312°.11 \pm 3°.0$
P shift	0.0914	0.0914
$T_{e,h}$(°K)	7400	8530 ± 87
$T_{e,c}$(°K)	4790	4970 ± 62
Ω_h	26.6968	26.6508 ± 0.0130
Ω_c	12.4647	12.4350 ± 0.0171
q	0.9643	1.05924 ± 0.00157
i^0	89.3	89.280 ± 0.07
$L_h/L_h + L_c$	V = 0.5952 B = 0.7356 U = 0.8388	0.6029 ± 0.0190 0.7204 ± 0.0200 0.7970 ± 0.0230
$L_c/L_h + L_c$	V B U	0.3971 ± 0.0200 0.2796 ± 0.0200 0.1780 ± 0.0220
$l_3/L_h + L_c + l_3$	0	0.0250 ± 0.0004
r_h(pole)		0.0400 ± 0.0009
r_h(point)	.0385	0.0400 ± 0.0010
r_h(side)		0.0400 ± 0.0010
r_h(back)		0.0400 ± 0.0010
r_c(pole)		0.0965 ± 0.0010
r_c(point)		0.0971 ± 0.0012
r_c(side)	0.0939	0.0966 ± 0.0012
r_c(back)		0.0970 ± 0.0014
x_h	V = 0.60 B = 0.54 U = 0.50	0.582 ± 0.02 0.557 ± 0.02 0.530 ± 0.03
x_c	V = 0.80 B = 0.96 U = 0.99	0.778 ± 0.03 0.931 ± 0.03 0.990 ± 0.04
$A_h = A_c$	1.0	1.0
$G_h = G_c$	1.0	1.0

results (Popper 1984) separate solutions were made for each of the U, B and V light curves and for the combined set, by keeping all parameters as unknown. These solutions were found to be in close agreement. In column 3 of Table 1, we give the results of the combined solution only.

3.2.b *Reddening of the colours*: Using the derived luminosities (Table 1, column 3) and the differential magnitudes of $\Delta V = -1^m.312$, $\Delta B = -1^m.308$ and $\Delta U = -1^m.112$, corresponding to unit luminosity at maximum light at quadrature, we derived the magnitudes and colours of the individual components. These values are:

	Hot component	Cool component
V	8.317	8.771
B-V	0.471	1.045
U-B	0.176	0.776

The values of V = $9^m.08$, B = $9^m.74$ and U = $9^m.83$ for the comparison star were used in these calculations (section 2). Assuming no interstellar reddening (r = 185 pc and b = – 33°) the above derived value of (B-V) for the hotter star corresponds to spectral type of *F*7 (Allen 1976). However, the (U-B) colour for such a star should be about 0.04 (Allen 1976). Hence its derived (U-B) value of 0.18 suggests a reddening of 0.14 in this colour. Similarly, the (B-V) colour of 1.04 of the secondary component should correspond to a (U-B) of 0.84. Hence its derived (U-B) value of 0.78 suggests it to be 'bluer'. A similar conclusion was arrived at by Popper (1988). As interstellar reddening seems to be negligible, this reddening in the colours might have arisen from gases existing around the system probably in the form of an envelope. From the studies of RZ Eri in Geneva colour system, Burki *et al.* (1992) suggested the presence of an envelope around this system which contributed a colour excess, *E*(B-V) of $0^m.20$ for both the components. If we assume the nature of the material in the envelope to be similar to that of the interstellar matter, *E*(B-V) = $0^m.20$ should correspond to *E*(U-B) = $0^m.16$ (Allen 1976). Adopting these values to the colours of both the components of RZ Eri, one gets the following unreddened colours:

	Hot component	Cool component
$(B\text{-}V)_0$	0.271	0.845
$(U\text{-}B)_0$	0.016	0.616

The above corrected $(B\text{-}V)_0$ colour of the primary corresponds to a temperature of 7400° (*F*0*V*) (Allen 1976), while $(U\text{-}B)_0$ colour gives a temperature of 6600°. However, since the primary component was found to have metallic line characteristics (Morgan in Cesco & Sahade 1945), one cannot give much weight to the (U-B) colour in fixing the temperature or spectral type as the (U-B) in such stars is a function of both temperature and metallicity. Hence giving full weight to the corrected (B-V) colour of 0.27, the temperature of the primary is fixed as 7400°K.

As discussed above, since our U, B, V observations were reddened due to the circum-stellar envelope, they should first be corrected for this effect before analysing them for elements. In order to achieve this, we reanalysed the normal light curves, assumed to be free of the distortion wave, by keeping the parameter ' T_h' as fixed at a value of 7400°K instead of treating it as an unknown parameter.

3.2.C *Fixation of mass-ratio for the analysis:* A reanalysis of the yellow light curve with the parameter 'T_h' fixed at 7400°K and with the remaining parameters as unknown, yielded again a mass-ratio of 1.06, the same as that obtained from the analysis where all the parameters were treated as unknown (column 3, Table 1). This indicates that $m_2 > m_1$. Popper (1988) published radial velocity curves of both the components and spectroscopic elements of RZ Eri. From these studies, a mass-ratio of 0.963 was derived, indicating that $m_2 < m_1$. According to Burki *et al.* (1992) the possibility that the most evolved component of RZ Eri, in reality, to be also the most massive i.e., $m_2 > m_1$, by at least one-tenth of a solar mass, does exist.

In order to see how best the spectroscopic data of Popper (1988) fit the theoretical RV curves with the mass ratio 1.06, we computed theoretical radial velocity curves with WD method for the mass-ratios of 1.06 and 0.963 using V_0 = 43.2 km/sec and $A/R_\odot$ =72.5 as given by Popper (1988) and e = 0.3496, ω = 312°.11 and i = 89°.28 derived from light curve analysis (Table 1). A plot of these curves is shown in Fig. 2. Here the dashed lines represent the theoretical radial velocity curves of RZ Eri for a mass ratio of 1.06 and those with continuous lines represent the same for a mass ratio of 0.963. The As represent the observations of Popper (1988) for the primary, hot component and the points represent his observations obtained from absorption lines for the secondary, cool component. The circled points represent the radial velocities of the Ca II emission lines. The phases are the same as those of the light curves. It is clear from Fig. 2 that the observations fit the radial velocity curves with m_2/m_1 =0.963 much better than they fit the curves with m_2/m_1 = 1.06.

As is evident from the above, since the spectroscopic mass-ratio of 0.963 is a better value compared to the derived photometric mass-ratio of 1.06, we reanalysed the

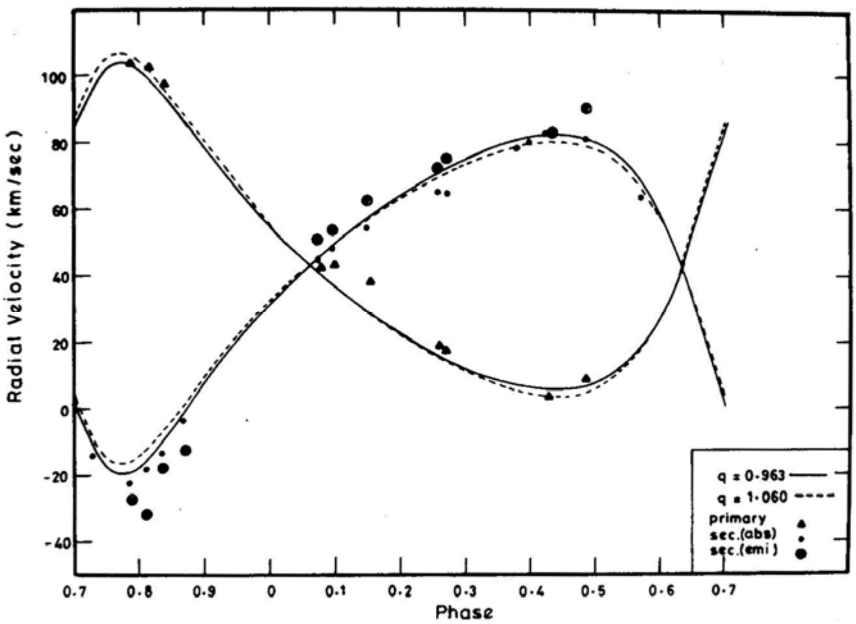

Figure 2. RZ Eri: A plot of phase versus theoretical radial velocities computed by the W-D synthetic method using V_0 = 43.2 km/sec, $A = 72.5R_\odot$, e = 0.3496, ω = 312°.11 and i = 89^0.28. The phases are according to the ephemeris at equation (1) section 3.1.

Table 2. RZ Eri: Summary of elements derived from W-D method (T_h and q fixed).

Element 1	V Solution 2	B Solution 3	U Solution 4	Combined UBV solution 5
e	0.3496 ± 0.0236	0.3496 ± 0.0236	0.3496 ± 0.0236	0.3496 ± 0.0236
ω	312.11 ± 3.00	312.11 ± 3.00	312.11 ± 3.00	312.11 ± 3.00
P shift	0.0914	0.0914	0.0914	0.0914
$^*T_{e,h}$(°K)	7400	7400	7400	7400
$T_{e,c}$(°K)	4663 ± 52	4585 ± 50	4745 ± 60	4670 ± 60
$^*q$	0.963	0.963	0.963	0.963
$i°$	89.70 ± 0.06	89.50 ± 0.07	89.58 ± 0.07	89.61 ± 0.07
$\frac{L_h}{L_h + L_c}$	0.5993 ± 0.0200	0.7231 ± 0.0200	0.8075 ± 0.0230	$V = 0.6040 \pm 0.0190$ $B = 0.7177 \pm 0.0200$ $U = 0.8132 \pm 0.0230$
$\frac{L_c}{L_h + L_c}$	0.4007 ± 0.0200	0.2769 ± 0.0200	0.1925 ± 0.0220	$V = 0.3960 \pm 0.0200$ $B = 0.2823 \pm 0.0200$ $U = 0.1868 \pm 0.0220$
l_3	0	0	0	0
r_h(pole)	0.0393 ± 0.0010	0.0388 ± 0.0010	0.0393 ± 0.0022	0.0391 ± 0.0009
r_h(point)	0.0393 ± 0.0010	0.0389 ± 0.0010	0.0393 ± 0.0023	0.0391 ± 0.0010
r_h(side)	0.0393 ± 0.0011	0.0388 ± 0.0011	0.0393 ± 0.0026	0.0391 ± 0.0010
r_h(back)	0.0393 ± 0.0011	0.0389 ± 0.0011	0.0393 ± 0.0025	0.0391 ± 0.0010
r_c(pole)	0.0950 ± 0.0010	0.0958 ± 0.0009	0.0957 ± 0.0017	0.0955 ± 0.0010
r_c(point)	0.0956 ± 0.0012	0.0965 ± 0.0011	0.0963 ± 0.0020	0.0962 ± 0.0012
r_c(side)	0.0951 ± 0.0014	0.0959 ± 0.0012	0.0957 ± 0.0022	0.0956 ± 0.0012
r_c(back)	0.0955 ± 0.0019	0.0964 ± 0.0014	0.0962 ± 0.0026	0.0961 ± 0.0014
x_h	0.600 ± 0.020	0.535 ± 0.020	0.501 ± 0.030	$V = 0.600 \pm 0.02$ $B = 0.535 \pm 0.02$ $U = 0.501 \pm 0.03$
x_c	0.810 ± 0.030	0.960 ± 0.030	0.990 ± 0.040	$V = 0.810 \pm 0.03$ $B = 0.960 \pm 0.03$ $U = 0.990 \pm 0.04$
$^*A_h = A_c$	1.0	1.0	1.0	1.0
$^*G_h = G_c$	1.0	1.0	1.0	1.0

* Fixed parameters.

light curves by keeping the parameter $q(m_2/m_1 = 0.963)$ also as fixed parameter along with T_h (7400°K). It is expected that analysis of the light curves with fixed T_h and q at known values should yield most reliable elements.

3.2.d *Results of the reanalysis of the light curves with T_h and q fixed:* As discussed above, we reanalysed the normal UBV light curves by keeping T_h (7400°K) and q(0.963) as fixed parameters in the W-D method. These results, for individual as well as for the combined set, are given in Table 2. It is interesting to note that the third light, l_3, which is present only in the U pass band of the solution of the combined set given in column 3, Table 1, is not present in Table 2 in any of the solutions. The theoretical light curves computed with the elements derived from the combined solution (Table 2, column 5) are shown as solid lines in Figs, la and 1b. The fit of the theoretical curves to the observed normal points is quite satisfactory.

4. Absolute elements

4.1. *Spectral classification*

From the derived luminosities of the combined solution (Table 2) and using the corresponding differential magnitudes for unit luminosity (section 3.2b), the magnitudes and colours of the individual components are derived. These are:

	Hot component	Cool component
V	8.315	8.774
(B-V)	0.477	1.031
(U-B)	0.150	0.735

After applying the reddening correction (section 3.2b), we get

	Hot component	Cool component
$(B\text{-}V)_0$	0.28	0.83
$(U\text{-}B)_0$	− 0.01	0.58

The $(B\text{-}V)_0$ colour of the primary, now corresponds to a spectral type of *F*0 with a temperature of 7400°K (Allen 1976) and is the same as the fixed parameter T_h. This confirms that our analysis with fixed T_h (7400°K) and q (0.963) yielded results akin to the reddening free data. The $(B\text{-}V)_0$ colour of the secondary component corresponds to a spectral type of *G*8 V or *G*5 III whereas its $(U\text{-}B)_0$ colour corresponds to *K*1 V or *G*6 III. A temperature of 4670°K derived for the secondary (Table 2) corresponds to a spectral type of *K*1 V or *G*8 III. Both the colours and temperature yield consistent results. Keeping in view the sizes of the components (section 43), we have adopted *F*0IV and *G*5-*G*8 III-IV as the spectral types of the primary and secondary components respectively. From an earlier preliminary study, Sarma (1985) concluded that this system consisted of an *F*6 V primary and *K*2 IV secondary. Popper (1988) classified the components to be of *F*5 V and *K*2 III or *K*5 V spectral types. Burki *et al.* (1992) classified them as A8–*F*0 IV and *G*8–*K*2 III–IV. Morgan's tentative classification (in Cesco & Sahade 1945) for the primary was *F*5 IV, with a weak *K* line corresponding to type *A*5. In the same paper, Morgan suggested that the spectral type of the secondary was probably a sub-giant class *G*8. Thus our adopted spectral

Table 3. RZ Eri: Element of RZ Eri obtained from different studies.

Parameter method 1	Popper (1988) (a) 2	Burki *et al.* (1992) (b) 3	Present studies (c) 4
Primary radius (r_h)	$0.039 \pm .003$	$0.0385 \pm .0006$	0.0391 ± 0.0010
Secondary radius (r_c)	$0.097 \pm .003$	$0.0938 \pm .0009$	0.0957 ± 0.0013
e	$0.352 \pm .024$	$0.377 \pm .008$	0.3496 ± 0.0236
ω	$312°.1$	$312°.7 \pm 1.2$	$312°.11 \pm 3.00$
$i°$	89.0 ± 1.0	89.31 ± 0.13	89.61 ± 0.07
$q = m_c/m_h$	0.963	0.96*	0.963*
$R_h/R_\odot$	2.83	2.79	2.84 ± 0.12
$R_c/R_\odot$	$7.00 \pm .30$	$6.80 \pm .23$	6.94 ± 0.20
$T_{e,h}$(°K)	—	7390 ± 80	7400*
$T_{e,c}$(°K)	—	4790 ± 100	4670 ± 60
Log $L_h/L_\odot$	$1.10 \pm .80$	$1.34 \pm .60$	1.33 ± 0.11
Log $L_c/L_\odot$	$1.26 \pm .50$	$1.32 \pm .07$	1.31 ± 0.11
$m_h/m_\odot$	$1.68 \pm .10$	$1.69 \pm .06$	1.69 ± 0.06
$m_c/m_\odot$	$1.62 \pm .20$	$1.63 \pm .13$	1.63 ± 0.13
$M_{bol,h}$	—	$1.40 \pm .15$	1.35 ± 0.28
$M_{bol,c}$	—	$1.45 \pm .17$	1.41 ± 0.28
$M_{v,h}$	$1.92 \pm .20$	$1.41 \pm .15$	1.36 ± 0.28
$M_{v,c}$	$2.10 \pm .20$	$1.85 \pm .17$	1.82 ± 0.28
Log g_h	$3.75 \pm .09$	—	3.76 ± 0.10
Log g_c	$2.97 \pm .05$	—	2.97 ± 0.06
Spectral type (primary)	*F*5	*A*8-*F*0 IV	*F*0 IV
Spectral type (secondary)	*K*2 III or *K*5 V	*G*8-*K*2 IV–III	*G*5-8 III–IV
Distance (pc)	200	180	185
Age (yr)	—	3.3×10^9	2.5×10^9

(a) – Nelson-Davis-Etzel Programme.
(b) – EBOP Programme (v, b and ⟨m⟩ mean).
(c) – Wilson & Devinney Programme.
* – Assumed.

types of the components of RZ Eri are, in good agreement with those reported from various other studies.

4.2. *Masses of the components*

For any eclipsing system, one can get reliable absolute elements provided it presents total eclipses with both the eclipses present. Also the system should be a double-lined spectroscopic binary whose radial velocity amplitudes are large enough to get an accurate mass-ratio. In the case of RZ Eri, even though the primary eclipse is total and very deep, the secondary eclipse is not present in any of our light curves. As discussed in section 3.2c, the mass-ratio of the system, as derived by Popper (1988) and adopted in the present analysis is 0.963. Combining the values of K_1 and K_2 from Popper with the other required parameters from Table 2 and using relevant equations, we obtained $A/R_\odot$ = 72.50 ± 1.4 and $m_1/m_\odot$ = 1.69 ± 0.06 and $m_2/m_\odot$ = 1.63 ± 0.13.

4.3. *Sizes and luminosities*

Using the values of A, r_h, r_c, T_h and T_c (Table 2) for the primary and secondary components we obtained their sizes, luminosities, bolometric and visual absolute magnitudes. These values, with their errors, are:

	Hot component	Cool component
Radius $R/R_\odot$	2.84 ± 0.12	6.94 ± 0.20
Log $L/L_\odot$	1.33 ± 0.11	1.31 ± 0.11
M_{bol}	1.35 ± 0.28	1.41 ± 0.28
M_v	1.36 ± 0.28	1.82 ± 0.28

The bolometric corrections are from Popper (1980). For comparison, the elements of RZ Eri as derived by us, Popper (1988) and Burki *et al.* (1992) are given in Table 3.

Assuming an absorption of $A_v = 0^m.6$ for the material of the envelope and with negligible space absorption, the distance of RZ Eri is found to be 185 ± 0.5 pc.

5. Evolutionary nature

With a view of studying the evolutionary status of the components of RZ Eri, we used the evolutionary tracks computed by Maeder & Meynet (1988) for stars of Pop I composition. These evolutionary tracks for stars of initial mass of 1.7 and 2.0 in solar units are shown as solid lines in Fig. 3 which is a plot of log $L/L_\odot$versus log T_e. In the same diagram, the dashed lines represent the isochrones for ages of 2.5 and 3.0 billion years. These isochrones were obtained by interpolation between the evolutionary tracks of Maeder & Meynet (1988) based on points of corresponding evolutionary status. It can be seen that the evolutionary nature of the primary and the secondary are different. The secondary component which is of smaller mass is in an advanced phase of evolution (sub-giant) and is presently on its way to a rapid expansion. The primary component with a slightly higher mass is still in the main sequence phase. The secondary component with a mass of 1.63 ± 0.13$m_\odot$, fits the evolutionary path of a star of mass 1.7 $m_\odot$, whereas the primary component with a mass of 1.69 ± 0.06 $m_\odot$ fits the evolutionary track of a star of mass 2.0$m_\odot$. Comparing the general properties of 22 RS CVn binaries, Montesinos *et al.* (1988) separated them into three groups, of which the third group consisted of binaries with abnormal evolution. Systems like SS Boo, CG Cyg, WW Dra, Z Her, AR Lac, TY

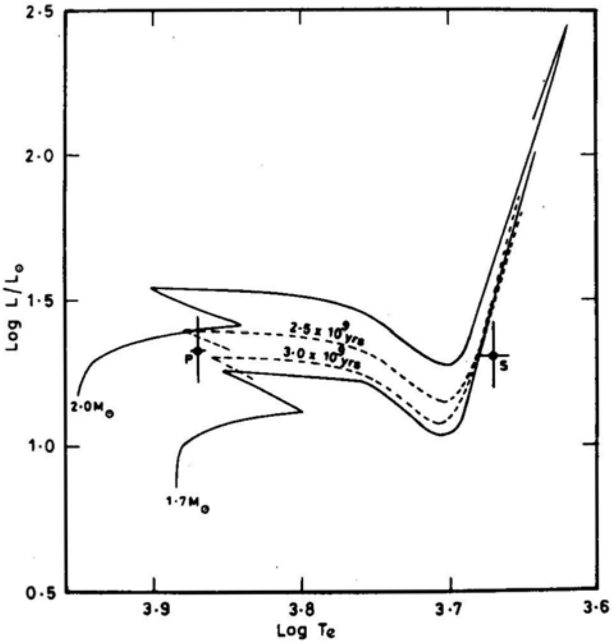

Figure 3. RZ Eri: Location of the primary (P) and secondary (S) components in the log $L/L_\odot$ vs. log T_e diagram. The evolutionary tracks (continuous line) are by Maeder & Meynet (1988). The lines (dotted) of equal ages are also noted.

Pyx, RZ Cnc, AR Mon and RZ Eri were placed in this group. The last three members were further noted to be more conspicuous than the remaining ones. The evolution of these systems is abnormal in the sense that either the more massive stars of the system have the smallest radii or, components with similar masses show a large difference between their radii. In addition to this abnormality, we now find that in RZ Eri the primary component appears to follow an evolutionary track of a slightly higher mass. For a clear understanding of this phenomenon, high quality spectroscopic and photometric studies in as many pass-bands as possible are desirable. Theoretical studies based on computations of stellar evolution including mass transfer in binaries having components with equal masses and dissimilar composition (e.g. metallicity) are needed.

From Fig. 3 one can notice that both the primary and secondary components fit the isochrone of 2.5×10^9 years. Hence it is concluded that the age of RZ Eri is about $2.5 \pm 0.1 \times 10^9$ years.

6. Discussion

One can notice several humps and dips, with differing amplitudes, at a few phases, in UBV light curves of RZ Eri (Figs. la and lb). These may be the effects of the residual waves that may not have been completely nullified in the process of combining the observations of all the seasons, as expected. However, observed reddening of the (B-V) and (U-B) colours of the components of RZ Eri are explained as due to the presence of an envelope around the system. The material in the envelope might have been expelled from the secondary component of RZ Eri during evolution to its present sub-giant stage. Comparing the observed fractional radii of 0.039 and 0.096 of the primary and secondary components with their radius of the critical Roche lobes of 0.378 and 0.372 respectively, for a mass-ratio of 0.963 (Plavec & Kratochvil 1964), it is found that the components are well within their critical sizes (filling only 10% and 25% respectively). The position of either of the components on the evolutionary tracks (section 5) does not indicate any possibility of a 'Case B' type evolution. However, as the secondary, cooler and bigger component is in an advanced stage of evolution, there may be a mild exchange ($< 5 \times 10^{-11} m_{\odot}$/yr) of mass and mass loss when this component was crossing the H–R gap (Popper & Ulrich 1977) and may be responsible for the envelope detected in the system. The IR excess detected in this system by Busso *et al.* (1990) is a confirmation of a circumstellar shell or envelope around RZ Eri. A similar circumstellar envelope has been detected by Glebocki *et al.* (1986) around λ And. It is interesting to note that both RZ Eri and λ And belong to the long-period group of the RS CVn systems.

Acknowledgements

Our thanks are due to Prof. K. D. Abhyankar for many helpful discussions. Our thanks are also due to the unknown referee for his valuable suggestions. M.B.K.S. wishes to thank the Council of Scientific and Industrial Research, New Delhi, for financial assistance under the Emeritus Scientists Scheme.

References

Allen, C. W. 1976, *Astrophysical Quantities, 3rd edn.,* (London: The Athlone Press) p. 206.
Bidelmann, W. P. 1954, *Astrophys. J. Suppl. Ser.,* **1**, 175.
Burki, G., Kviz, Z., North, P. 1992, *Astr. Astrophys.,* **256**, 463.
Busso, M., Scaltriti, F., Ferrari-Toriolo, M., Origlia, L., Persi, P., Robberto, M., Silvestro, G. 1990, *Mem. Soc. astr. Ital.*,**61**, 77.
Caton, D. B., Oliver, J. P. 1979, *Inf. Bull. Var. Stars,* No. 1665.
Caton, D. B., 1986, *Astr. J.,* **91**, 132.
Cesco, C. U., Sahade, J. 1945, *Aρ. J.,* **101**, 370.
Eggen, O, J. 1978, *Inf. Bull. Var. Stars,* No. 1426.
Gibson, D. M. 1979, in *IAU Symp. 88: Close Binary Stars: Observations and Interpretation,* Eds. M. J. Plavec, D. M. Popper & R. K. Ulrich (Dordrecht: D. Reidel) p. 31.
Glebocki, R., Sikorski, J., Bielicz, E., Krogulec, M. 1986, *Astr. Astrophys.,* **158**, 392.
Gronbech, B. 1975, *Inf. Bull Var. Stars,* No. 1956.
Hall, D. S. 1976, in *IAU Coll. 29: Multiple Periodic Variable Stars, Part I,* Ed. W. S. Fitch, (Dordrecht: D. Reidel).
Hardie, R. H. 1962, in *Astronomical Techniques,* Ed. W. A. Hiltner (University of Chicago Press) p. 178.
Hjellming, R. M., Gibson, G. M. 1979, in *IAU Symp. 88*: *Close Binary Stars: Observations and Interpretation,* Eds M. J. Plavec, D. M. Popper & R. K. Uhich, (Dordrecht: D. Reidel) p. 209.
Joy, A. H., Wilson, R. E. 1949, *Astrophys. J.,* **109**, 231.
Kopal, Z. 1959, *Close Binary Systems* (Chapman and Hall Ltd).
Maeder, A., Meynet, G. 1988, *Astr. Astrophys. Suppl. Ser.,* **76,** 411.

Montesinos, B., Gimenez, A., Fernandez-Figneroa, M. J. 1988, *Mon. Not. R. astr. Soc.*, **232**, 361.
Paredes, J. M., Estalella, R. Rius, A. 1987, *Astr. Astrophys.*, **186,** 178.
Plavec, M., Kratochvil, P. 1964, *Bull. astr. Inst. Csl.*, **15**, 165.
Popper, D. M. 1962, *Publ. astr. Soc. Pacific,* **74,** 129.
Popper, D. M. 1976, *Inf. Bull. Var. Stars*, No. 1083.
Popper, D. M., Ulrich, R. K. 1977, *Astrophys. J.*, **212,** L131.
Popper, D. M. 1980, *A. Rev. astr. Astrophys.*, **18,** 115.
Popper, D. M. 1982, *Publ. astr. Soc. Pacific*, **94,** 945.
Popper, D. M. 1984, *Astr. J.*, **89,** 132.
Popper, D. M. 1988, *Astr. J.*, **96,** 1040.
Sarma, M. B. K. 1985, in *Highlights of Astronomy*, Ed. J. P. Swings, **7,** 443 (Dordrecht: D. Reidel).
Vivekananda Rao, P., Sarma, M. B. K. 1986, *Contr. Nizamiah & Japal-Rangapur Obs.*, No. 18.
Vivekananda Rao, P., Sarma, M. B. K., Prakash Rao, B. V. N. S., 1988, in *IAU Coll. 107: Algols*, Ed. A. H. Batten, (Kluwer Academic Publishers), p. 357.
Walter, F. M., Bowyer, S. 1981, *Astrophys. J.*, **245,** 671.
Wilson, R. E., Devinney, E. J. 1971, *Astrophys. J.*, **166,** 605.