PHOTOMETRIC ELEMENTS AND EVOLUTIONARY STATUS OF ECLIPSING BINARY DI PEGASI

U. S. CHAUBEY
Uttar Pradesh State Observatory, Naini Tal, India

(Received 29 May, 1981)

Abstract. The light curves of eclipsing binary DI Pegasi in *U*, *B*, and *V* filters have been presented and discussed. Photometric elements of the system have been determined. Using the colour indices, we estimate absolute dimensions and discuss the evolutionary status of the system.

1. Introduction

The eclipsing nature of DI Pegasi was discovered by Jensch (1934). Binnendijk (1973) observed this star photoelectrically in *B* and *V* filters and discussed its photometric peculiarities. There has been no radial velocity study done. The only published light curve solution is that of S. M. Rucinski based on Kruszewski's observations taken with polarizing photometer (Rucinski, 1967). He discussed a third light ($L_3 = 24\%$ in V) present in the system. In this paper we have examined the *UBV* photometric observations of this binary star, obtained in October and December 1979 to investigate the photoelectric orbital elements and to study the evolutionary status of the system.

Throughout this paper subscript '*h*' refers the hotter star which is eclipsed at primary minimum. Subscript '*c*' refers to the cooler star which is eclipsed at secondary minimum.

2. Observations

Photometry of DI Peg was carried out with 104 cm telescope of Uttar Pradesh State Observatory. The telescope was equipped with a EMI 6094S photomultiplier, thermoelectrically cooled to −20°C and *UBV* filters of Johnson and Morgan. During October to December 1979, 111 three colour observations of variable star were obtained. The comparison star was BD + 14°5004, which is less than half degree from the variable. For all observations, a diaphragm 15 arc sec in diameter was used to exclude a nearby companion of magnitude 14 (visual estimate).

The variable was observed alternately with the comparison star, generally two observations of the variable were made between two observations of the comparison star. In general, each observation of variable star consisted of a sequence of deflections taken in a symmetric *VBUUBV* pattern, so that all three colours could refer to one time. The comparison star was observed in a simple *UBV*

Astrophysics and Space Science **81** (1982) 283–293. 0004–640X/82/0812–0283$01.65.

pattern. After correcting for atmospheric extinction, all the observations were transformed to the standard *UBV* system.

The individual observations, in differential form, are listed in Table I, wherein the phases have been computed with the ephemeris

$$\text{JD(Hel)} = 2\,444\,164.3545 + 0\overset{\text{d}}{.}711\,818\,2\,E. \tag{1}$$

In the above, epoch is the time of primary minimum light observed by us and period is also computed by us. The method of determining the period is given in Section 3. The differential magnitude ΔU, ΔB, and ΔV in the sense DI Peg minus BD + 14°5004 are plotted in Figure 1.

TABLE I
Observed differential magnitudes of DI Pegasi

JD(Hel) 2 444 000 +	Phase	ΔU	ΔB	ΔV
164.0674	0.602	−1.349	−0.801	−0.404
.0814	0.616	−1.348	−0.795	−0.410
.0934	0.648	−1.352	−0.798	−0.408
.1044	0.659	−1.350	−0.799	−0.404
.1184	0.673	−1.346	−0.779	−0.406
.1304	0.685	−1.348	−0.750	−0.405
.1519	0.715	−1.356	−0.784	−0.411
.1595	0.726	−1.364	−0.800	−0.418
1696	0.740	−1.376	−0.755	−0.423
1793	0.754	−1.331	−0.820	−0.429
.2002	0.783	−1.346	−0.843	−0.451
.2102	0.797	−1.335	−0.828	−0.431
.2234	0.816	−1.346	−0.835	−0.431
.2338	0.830	−1.341	−0.828	−0.398
.2498	0.853	−1.272	−0.786	−0.395
.2592	0.866	−1.260	−0.775	−0.379
.2703	0.881	−1.261	−0.783	−0.393
.2776	0.892	−1.260	−0.769	−0.390
.2898	0.909	−1.263	−0.708	−0.340
.2998	0.923	−1.209	−0.655	−0.278
.3095	0.937	−1.120	−0.571	−0.182
.3116	0.939	−1.043	−0.516	−0.161
.3148	0.944	−0.963	−0.478	−0.130
.3241	0.950	−0.939	−0.421	−0.059
.3283	0.963	−0.784	−0.273	+0.081
.3356	0.973	−0.543	−0.046	+0.241
.3397	0.979	−0.430	+0.061	+0.351
.3429	0.984	−0.403	+0.129	+0.436
.3522	0.997	−0.091	+0.357	+0.630
.3547	0.000	−0.069	+0.368	+0.644
.3568	0.003	−0.074	+0.352	+0.617
.3588	0.006	−0.164	−0.316	+0.585
.3609	0.009	−0.217	+0.260	+0.530
.3710	0.023	−0.487	−0.031	+0.487
.3804	0.036	−0.720	−0.252	+0.091

Table I (continued)

JD(Hel) 2 444 000 +	Phase	ΔU	ΔB	ΔV
164.3916	0.052	−0.943	−0.465	−0.105
.3935	0.055	−0.972	−0.474	−0.123
165.1677	0.140	−1.290	−0.780	−0.382
.1722	0.149	−1.316	−0.788	−0.391
.1777	0.157	−1.335	−0.817	−0.426
.1859	0.168	−1.336	−0.813	−0.434
.1911	0.175	−1.349	−0.826	−0.442
.1991	0.187	−1.343	−0.837	−0.460
.2047	0.194	−1.370	−0.841	−0.458
.2297	0.230	−1.375	−0.838	−0.460
.2401	0.244	−1.372	−0.830	−0.410
.2456	0.252	−1.369	−0.826	−0.451
.2536	0.263	−1.366	−0.842	−0.469
.2790	0.299	−1.400	−0.839	−0.460
.2890	0.313	−1.380	−0.817	−0.455
.2974	0.325	−1.391	−0.840	−0.459
.3067	0.338	−1.375	−0.846	−0.452
.3120	0.345	−1.357	−0.853	−0.449
.3203	0.357	−1.365	−0.828	−0.426
.3247	0.363	−1.365	−0.835	−0.441
.3283	0.368	−1.351	−0.840	−0.429
.3338	0.376	−1.343	−0.799	−0.418
.3418	0.387	−1.362	−0.808	−0.386
.3436	0.390	−1.360	−0.799	−0.413
.3490	0.397	−1.349	−0.814	−0.424
.3505	0.399	−1.346	−0.800	−0.382
.3526	0.402	−1.309	−0.780	−0.378
.3602	0.413	−1.296	−0.785	−0.360
.3616	0.415	−1.287	−0.781	−0.354
.3679	0.424	−1.277	−0.748	−0.318
.3696	0.426	−1.254	−0.739	−0.319
219.1424	0.969	−0.497	−0.284	+0.196
.1518	0.982	−0.322	+0.084	−0.343
.1533	0.984	−0.274	+0.132	−0.381
.1605	0.994	−0.070	+0.308	−0.537
.1618	0.996	−0.003	+0.345	−0.571
.1660	0.002	+0.044	+0.420	−0.633
.1673	0.004	+0.029	+0.410	+0.643
.1684	0.006	+0.008	+0.380	+0.612
.1698	0.008	−0.008	+0.348	+0.585
.1785	0.020	−0.248	+0.145	+0.433
.1800	0.022	−0.285	+0.118	+0.410
.1829	0.026	−0.328	+0.081	+0.382
.1921	0.039	−0.631	−0.218	+0.096
.1936	0.041	−0.662	−0.245	+0.082
.2018	0.052	−0.849	−0.396	−0.067
.2035	0.055	−0.878	−0.444	−0.092
.2136	0.069	−1.005	−0.580	−0.175
.2148	0.071	−1.022	−0.586	−0.231
.2236	0.083	−1.126	−0.654	−0.243

Table I (continued)

JD(Hel) 2 444 000 +	Phase	ΔU	ΔB	ΔV
219.2252	0.085	−1.134	−0.664	−0.259
.2325	0.096	−1.191	−0.757	−0.329
.2338	0.097	−1.211	−0.763	−0.332
220.1723	0.416	−1.297	−0.747	−0.405
.1790	0.425	−1.332	−0.780	−0.380
.1868	0.436	−1.305	−0.768	−0.350
.1883	0.438	−1.298	−0.750	−0.345
.1945	0.447	−1.296	−0.748	−0.325
.2098	0.469	−1.276	−0.693	−0.303
.2171	0.479	−1.258	−0.658	−0.274
.2184	0.481	−1.228	−0.660	−0.270
.2269	0.493	−1.241	−0.666	−0.270
.2282	0.494	−1.250	−0.653	−0.238
.2337	0.502	−1.224	−0.660	−0.288
.2440	0.517	−1.276	−0.686	−0.276
.2535	0.530	−1.228	−0.702	−0.350
.2605	0.539	−1.290	−0.709	−0.357
.2618	0.542	−1.296	−0.710	−0.363

3. Determination of Orbital Period

From the observations listed in Table I two primary minima were determined using the method of chord bisection. These times of primary minimum light are listed in Table II alongwith other photoelectric primary minima available in the literature.

In order to determine the period, we have calculated the O – C values of the observed minima from the ephemeris of Rucinski (1967)

$$M(E) = 2\,437\,522.3946 + 0\overset{d}{.}711\,817\,5\;E\;. \tag{2}$$

These O – C values are plotted against phase in Figure 2, which shows that orbital period of the system suddenly decreased some time in February 1969. After this, period has been gradually increasing. Method of least squares has been adopted to fit the parabola through the points (times of minima onward February 1969) which gives $P = 0\overset{d}{.}711\,818\,2$ at the our observational time.

4. Light Curves

Figure 1 shows the *UBV* light curves of DI Peg. The observed magnitudes of the system at various phases are given in Table III, which shows that luminosity at phase $0\overset{P}{.}25$ is greater than the luminosity at phase $0\overset{P}{.}75$ in all the *UBV* filters. This phenomenon may be due either to gas stream absorption or to electron

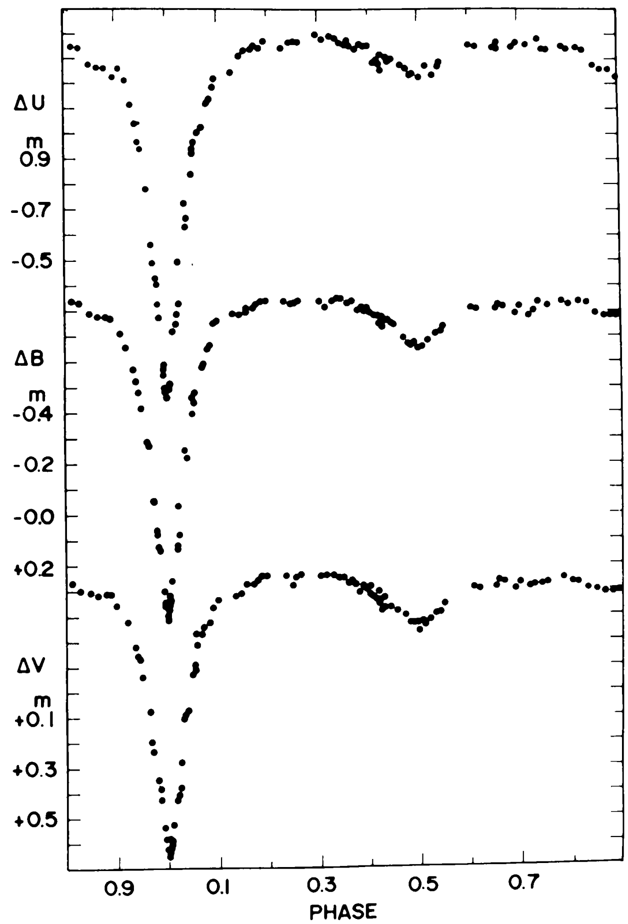

Fig. 1. The light curves of DI Pegasi in *U*, *B*, and *V* filters.

TABLE II
Photoelectric times of primary minimum light of DI Pegasi

JD(Hel) 2 400 000.0 +	Cycles	O–C	Reference
37 522.3946	0	0^{d}.0000	Rucinski (1967)
37 527.3776	7	+0.0003	Rucinski (1967)
37 544.4610	31	+0.0001	Rucinski (1967)
39 006.5324	2085	−0.0016	Rucinski (1957)
40 114.8356	3642	+0.0017	Binnendijk (1973)
40 127.6488	3660	+0.0022	Binnendijk (1973)
40 159.6796	3705	+0.0012	Binnendijk (1973)
40 500.6394	4184	+0.0004	Binnendijk (1973)
40 512.7402	4201	−0.0003	Binnendijk (1973)
42 015.4802	6312	−0.0036	Pohl and Kizilirmak (1975)
42 289.4285	6697	−0.0078	Pohl and Kizilirmak (1977)
44 164.3545	9331	−0.0091	Present Study
44 219.1650	9408	−0.0086	Present Study

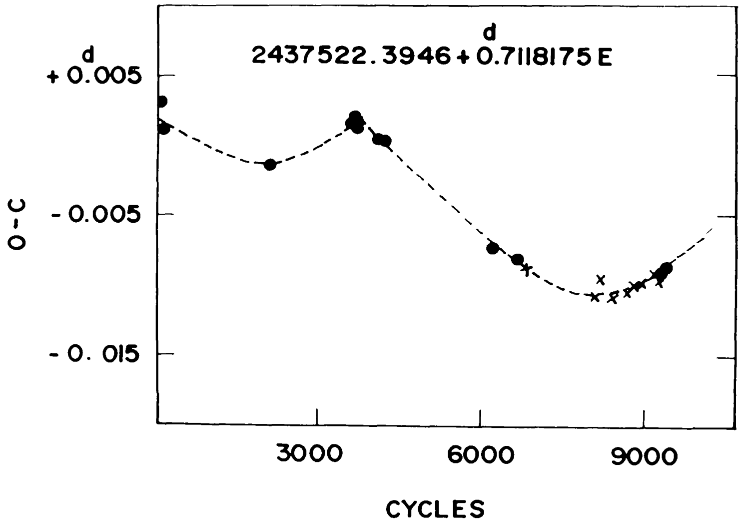

Fig. 2. The O – C curve of DI Pegasi between 1962 to 1979. Filled circles denote the photoelectric minima while crosses denote the visual minima.

scattering (Piotrowski *et al.*, 1974) present in the system. The amount of light loss in the three wavelength regions are such as to imply that the phenomenon is independent of wavelength. Hence, the electron scattering is probably the mechanism.

The most interesting feature that can be seen in the light curves is that the shoulders of the primary minimum are depressed. This phenomenon has already been found in the eclipsing binaries β Per (Guinan *et al.*, 1976), RW Per (Hall and Stuhlinger, 1977), RT Per (Sanwal and Chaubey, 1979). In these binaries the hotter component is surrounded by a disk of circumstellar material which is luminous by scattered light and lies in the plane of the orbit. The reduction in the light is due to the eclipse of disk by the subgiant component before and after the primary component is eclipsed.

TABLE III
Observed *UBV* magnitudes of DI Peg and its comparison star

	U	*B*	*V*
Comparison Star.	11ᵐ33	10ᵐ77	9ᵐ83
DI Peg (Phase 0.0)	11ᵐ35	11ᵐ13	10ᵐ48
DI Peg (Phase 0.25)	9ᵐ95	9ᵐ88	9ᵐ38
DI Peg (Phase 0.5)	10ᵐ12	10ᵐ07	9ᵐ59
DI Peg (Phase 0.75)	9ᵐ99	9ᵐ91	9ᵐ42

5. Rectification

The light outside the eclipse was expressed as the truncated Fourier series

$$I = A_0 + A_1 \cos \theta + A_2 \cos 2\theta + B_1 \sin \theta + B_2 \sin 2\theta \ . \tag{3}$$

The coefficients A_0, A_1, A_2, B_1, and B_2 were determined by a least squares fit using a computer programme. The magnitudes corresponding to unit light in the three colours and the resulting coefficients are given in Table IV.

In order to rectify the light within the eclipse for ellipticity and reflection, we carried out calculations by the equation (Russell and Merrill, 1952)

$$I^r = \frac{I + C_0 + C_1 \cos \theta + C_2 \cos 2\theta}{(A_0 + C_0) + (A_2 + C_2) \cos 2\theta} \ . \tag{4}$$

The C terms here, were calculated with the method given by Binnendijk (1970).

The phases in all the three colours were rectified with the equation

$$\sin^2 \theta^r = \frac{\sin \theta}{1 - z \cos^2 \theta} \ , \tag{5}$$

where oblateness coefficient z was computed with equation

$$Nz = \frac{-4(A_2 - C_2)}{(A_0 - C_0) - (A_2 - C_2)} \ , \tag{6}$$

and $N = 2.2$, 2.6, and 3.2 for $x = 0.4$, 0.6, and 0.8, respectively.

6. Photometric Solutions

In order to get the photometric solutions, it is necessary to eliminate the extralight produced by disk of circumstellar material. For this purpose, we adopt the model illustrated schematically in Figure 3. The circumstellar material is considered to be a ring sufficiently flattened in orbital plane so that its luminous portion has a thickness every where significantly smaller than the diameter of

TABLE IV
Rectification constants
($I = A_0 + A_1 \cos \theta + A_2 \cos 2\theta + B_1 \sin \theta + B_2 \sin 2\theta$)

	U	B	V
$\Delta m = 0^m.0$	$-1^m.36$	$-0^m.83$	$-0^m.44$
A_0	0.9673	0.9661	0.9718
A_1	0.0102	0.0120	0.0093
A_2	0.0273	0.0308	0.0256
B_1	0.0011	0.0016	0.0012
B_2	0.0015	0.0020	0.0011
z	0.038	0.046	0.043
N	3.2	3.0	2.6

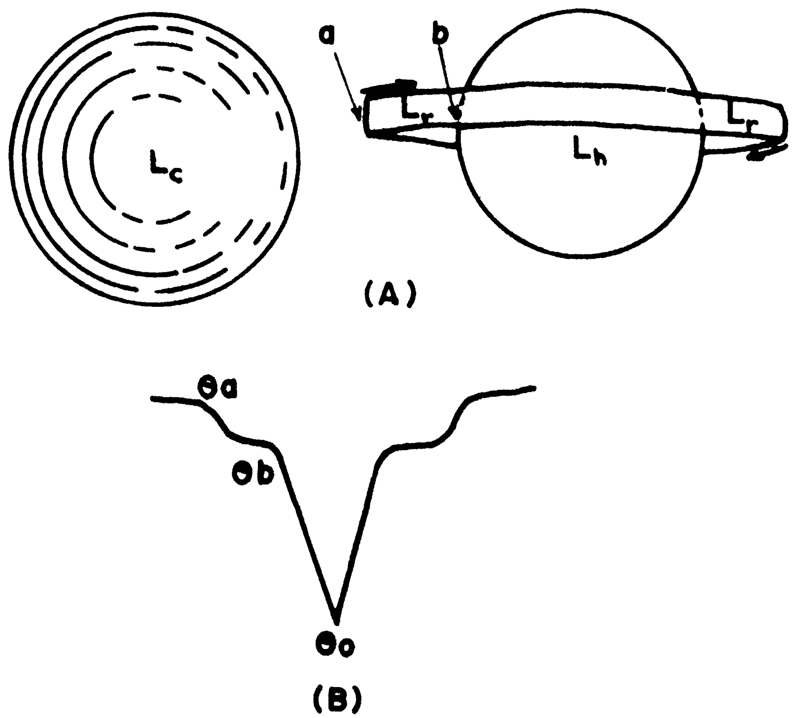

Fig. 3. The representation of model and light curve near the primary minima, proposed to determine the light curve solutions for DI Pegasi. The contact of L_c at 'a' and 'b' in (A) correspond to the phase θ_a and θ_b in (B), respectively.

the hotter star. The two regions L_r, assumed to be equal in intensity, lie on either side of the hotter star. Light, from the portion of the ring seen projected onto the hotter star, is simply included as part of L_h implicitly.

An inspection of Figure 3 reveals that between θ_a and θ_b (actually rectified contact angle θ_a and θ_b) the light loss is simply due to the eclipse of L_r by the cooler star while between θ_b and θ_0 (rectified contact angle θ_b and θ_0) the light loss is due to the eclipse, of the hotter star plus the portion of the ring projected onto it, by the cooler star. In other words, between these phases (θ_b to θ_0) any major part of the ring is not being occulted. Therefore it is possible to fix $\alpha = 0.0$ at $I^r(\theta_b)$ and to solve the light curve for geometrical elements with the help of the tables of eclipse of Russell and Merrill (1950).

The limb darkening coefficients used in these calculations were $x_h = 0.6$, 0.7, and 0.8, respectively, in V, B, and U filters. To deal with B light curve interpolation between the $x = 0.6$ and $x = 0.8$ tables of Russell and Merrill (1950) was done. The solution thus obtained for DI Peg in all three filters U, B, and V are listed in Table V.

The orbital solution gives two rather large components and their surface brightness unequal, suggests that binary star DI Peg is a semidetached binary system. The variable period (having upward parabolic O – C curve) and existence of gaseous disk around the primary component give an additional evidence

TABLE V
Photometric orbital solutions of DI Pegasi

	U	B	V
x_h	0.80	0.70	0.60
k	0.99	0.98	0.98
θ	37°.5	37°.8	38°.0
α_0	0.895	0.946	0.937
r_h	0.310	0.313	0.316
r_c	0.306	0.307	0.309
L_h	0.657	0.722	0.705
L_c	0.133	0.170	0.169
L_r	0.105	0.054	0.063
i	82°.5	82°.7	82°.3
J_c/J_h	0.198	0.227	0.194

for the semidetached model for the system in which cooler star has filled up its Roche lobe.

7. Absolute Dimensions and Evolutionary Status

The absolute dimensions of DI Peg are of course impossible to determine directly because no radial velocity observations are available. But absolute dimensions can be estimated by assuming that the hotter star obeys the mass-luminosity relation.

A plot of the colour indices of the primary star, in colour-colour diagram suggests that the hotter star is either a heavily reddened B8 V star or a little reddened F3 V star. Neither of these is consistent with the K0: classification of BD. However the latter is in good agreement with the F3 to F5: classification of Rucinski (1967).

If the hotter star has an effective temperature corresponding to a spectral type of F3 V, we compute the absolute dimensions with the aid of expression (cf., Hall, 1974)

$$R_h = 215 r_h \{M_h (1+q) P^2\}^{1/3} \tag{7}$$

and

$$\log R_h = 7.48 - 2 \log T_h + 1.94 \log M_h \ , \tag{8}$$

where

T = the effective temperature;
R = the radius in solar units;
M = the mass in solar units;
P = the period in years; and
q = the mass ratio, which is a function of fractional radius of the cooler star, r_c.

In our calculations, effective temperature of the hotter star has been estimated from Allen (1973). The mass ratio, q has been estimated from Kopal (1959). The resulting absolute dimensions are given in Table VI.

TABLE VI
Absolute dimensions of DI Pegasi

Semi-major axis of the orbit: $A = 4.36\ R_\odot$	
Masses: $M_h = 1.48\ M_\odot$;	$M_c = 0.70\ M_\odot$
Radii $R_h = 1.34\ R_\odot$;	$R_c = 1.37\ R_\odot$

In order to study the evolutionary status of the components, we have plotted their masses against their radii in Figure 4, which also shows the various mass-radius relations of a single star at its various evolutionary stages in H–R diagram. The positions of the components indicate that primary component lies on the main-sequence in H–R diagram and secondary lies above the Main-Sequence i.e., in subgiant phase.

The ratio of the surface brightnesses of the both stars allow us to estimate the spectral type of the cooler star. Using the effective temperature scale given by Allen (1973), we obtained the spectral type of the secondary star as K3.

An inspection of Figure 2 reveals that after the sudden period decrease around 1969, the orbital period is gradually increasing. This change in period can be explained in terms of Biermann and Hall model (Biermann and Hall, 1973) which

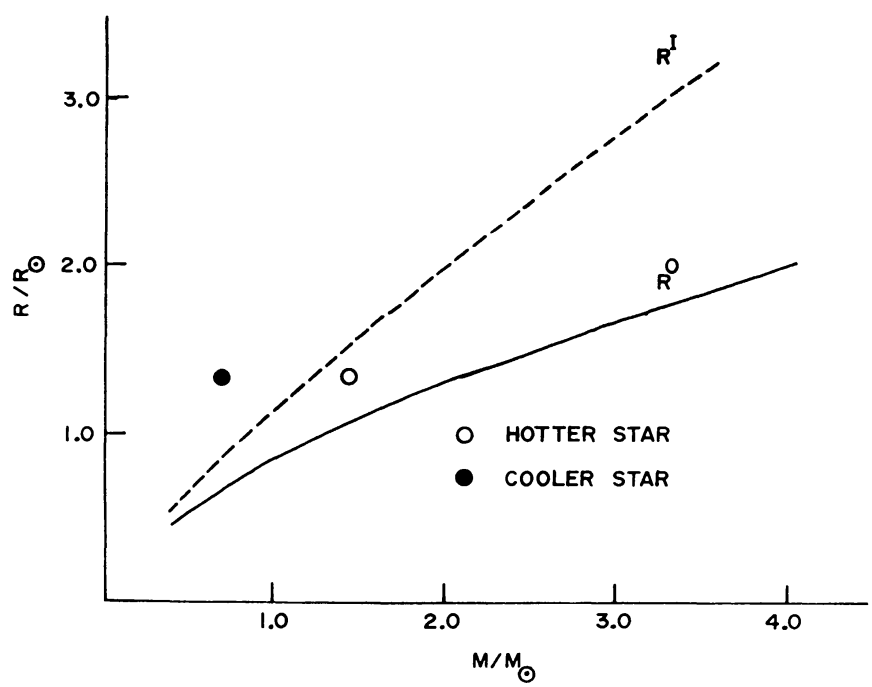

Fig. 4. The distributions of the binary components in the mass radius plane. The solid line and dashed line indicate the mass radius relations for the single star, respectively, at the start of the hydrogen burning in core and at the Chandrasekhar–Schoenberg limit.

suggests that a mass transfer occurs in the system. This model has already been used by us to explain O – C curve and period variability of TV Cas and SW Cyg (Chaubey, 1979, 1980). Using the observed increase in orbital period and absolute elements derived by us, it is found that $3.94 \times 10^{-7} M_\odot$ of mass is transferred from the secondary to the primary star in one year.

Acknowledgements

Thanks are due to Drs S. D. Sinvhal, C. D., Kandpal, and J. B. Srivastava for helpful discussions.

References

Allen, C. W.: 1973, *Astrophysical Quantities*, 3rd edition, Athlone Press, London, p. 206.
Biermann, P. and Hall, D. S.: 1973, *Astron. Astrophys.* **27**, 249.
Binnendijk, L.: 1970, in A. Beer (ed.), *Vistas Astron.* **12**, 230.
Binnendijk, L.: 1973, *Astron. J.* **78**, 97.
Chaubey, U. S.: 1979, *Astrophys. Space Sci.* **60**, 233.
Chaubey, U. S.: 1980, *Astrophys. Space Sci.* **67**, 129.
Guinan, E. F., McCook, G. P., Bachmann, P. J., and Bistline, W. G.: 1976, *Astron. J.* **81**, 57.
Hall, D. S.: 1974, *Acta Astr.* **24**, 215.
Hall, D. S. and Stuhlinger: 1977, *Acta Astr.* **28**, 207.
Jensch, A.: 1934, *Astr. Nachr.* **252**, 395.
Kopal, Z.: 1959, *Close Binary Systems*, Chapman and Hall, London, p. 136.
Piotrowski, S. L., Rucinski, S. M., and Semeniuk, I.: 1974, *Acta. Astr.* **24**, 389.
Pohl, E. and Kizilirmak, A.: 1975, *IAU Inf. Bull. Var. Stars No.* 1358.
Rucinski, S. M.: 1967, *Acta Astron.* **17**, 271.
Russell, H. N. and Merrill, J. E.: 1950, Princeton Univ. Contr. No. 23.
Russell, H. N. and Merrill, J. E.: 1952, Princeton Univ. Contr. No. 26.
Sanwal, B. B. and Chaubey, U. S.: 1979, *Bull Astron. Soc. India* **7**, 118.