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TT Hydrae—Confirmation of Popper's mass-ratio

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Abstract. UBV light curves of TT Hydrae, obtained by Kulkarni and Abhyankar (1978) were analysed using the Wilson-Devinney synthetic light curve method. A mass-ratio of 0.269, derived spectroscopically by Popper (1982) was used for this analysis. The theoretical curves derived from this analyses are found to fit the observed light curves satisfactorily, thus confirming the mass-ratio of 0.269 obtained by Popper instead of the value of 0.142 reported by Etzel (1988). Improved absolute elements are obtained using the results of the present analysis.

Key words : Algol type binary—mass-ratio—absolute elements—evolution

1. Introduction

Algol type binaries are semi-detached systems in the frame work of Kopal's (1959) classification scheme. These systems provide interesting examples of stellar evolution as a consequence of mass loss and mass transfer. The main sequence nature of the hotter members of the Algol type binaries has been generally accepted. However, from a study of 18 binaries, Kopal (1959) showed that the cooler components of these systems, although clearly known to be sub-giants, did not appear to fill their Roche-lobes. He grouped such systems under the label "undersize" sub-giants, TT Hya being one of them. However Hall (1974, 1975) questioned the existence of "under-sized sub-giants". Many of the above systems where better observations have become available and improved techniques of analysis have been used, the subgiant secondaries have been shown not to be "undersized". In the case of TT Hya, Etzel (1988) found its secondary component to be overfilling its lobe.

Kulkarni & Abhyankar (1981, hereafter referred to as KA 81) solved their own UBV light curves (Kulkarni & Abhyankar 1978, hereafter referred to as KA 78) of TT Hya using the Russel-Merrill (1952) method and concluded that, for the spectroscopic mass-ratio of 0.269 (Popper 1979), the derived fractional radius of the secondary cool component $r_c = 0.2438$, when compared to the size of its Roche-lobe $r_c^* = 0.264$ (Plavec and Kratochvil 1964) makes it a detached system. Etzel (1988, here after referred to as EL 88) had also analysed the observations of KA 78 using Wood's WINK programme. In his analysis, Etzel obtained a mass-ratio of 0.142 and $r_c = 0.2431$. Since for this mass-ratio, the size of the secondary

Roche-lobe is $r_c^* = 0.2192$ (Plavec & Kratochvil 1964), the indication is that the secondary component of TT Hya is over filling its Roche lobe. There is also a large difference between Popper's spectroscopic mass-ratio and Etzel's photometric mass-ratio.

In order to verify whether the spectroscopic mass-ratio of 0.269 is consistent with the photometric data, we have reanalysed the UBV light curves of KA 78 using Wilson-Devinney (W-D) (1971) synthetic light curve method and give the results of these analyses.

2. Analysis

From their published (KA 78) UBV observations, Kulkarni (1979) formed 140 normal points in Yellow, 137 in Blue and 141 in Ultraviolet pass bands for his analysis using the Russell-Merrill (1952) method. They are given in tables 1a-1c. We used these normal points for deriving the elements of the binary system using the W-D method with code-5 applicable to semi-detached systems. The preliminary elements used for this analysis are given in column 2 of table 2. Here the parameters $T_{e,h}$ (temperature of the hot component), $T_{e,c}$ (temperature of the cool component), x_h and x_c (limb darkening co-efficients of the hot and cool components) are taken from EL 88; q, the mass-ratio is taken from Popper (1982) and the remaining elements are from KA 81. The albedo coefficients, A_h and A_c for the hot and cool components are kept constant at 1.0 and 0.5 respectively. As the variation of G_h and G_c (gravity darkening coefficients of the hot and cool component) did not change the final results, they are kept constant at 0.25 and 0.08 respectively. According to the principles of the W-D method we adjusted the following elements: the inclination i, the surface potential Ω_h, 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 seemed to have negligible effect on the derived elements. A sufficient number of runs of the DC programme (code-5 for semi-detached systems) was made till the sum of the residuals $\Sigma W(O-c)^2$ showed a minimum and the corrections to the parameters became smaller than their probable errors. In order to check the internal consistency of the results (Popper 1984) separate solutions were also made for each of the UBV light curves.

The results obtained from the solution of the individual light curves are given in columns 3, 4 and 5 of table 2. From these results one can notice that the U solution gave a slightly higher temperature for the primary and secondary components. Since both KA 81 and EL 88 reported the presence of peculiarities in the U light curve, a combined solution is effected first for the B and V pass bands, the results of which are given in column 6 of table 2. Using the parameters obtained in the combined B and V analysis, as initial parameters, another solution was made for the combined UBV light curves. The results obtained from this analysis are given in column 7 of table 2. One can notice that this solution gave $l_3 = 0.0237$ in the U passband alone which is not present in individual solutions. It can also be seen that the results obtained from the individual as well as the combined solutions are consistent.

As a result of all these analyses, it is found that the average value of the mass-ratio $q = m_2/m_1$ is 0.2966. This value is closer to Popper's (1982) spectroscopic mass-ratio of 0.269 and not to Etzel's (1988) photometric mass-ratio of 0.142.

The temperature of 10430°K (column 7 of table 2) for the hotter component and the derived colours of $(B-V) = 0.014$ and $(U-B) = -0.047$ gave an average spectral type of B 9.5 V for this component which agrees well with that derived by EL 88.

Table 1a. TT Hya : Normal points in yellow

S. No.	Phase	ΔV	N
1	0.0007	1.752	5
2	0.0022	1.741	7
3	0.0034	1.738	6
4	0.0049	1.732	6
5	0.0060	1.724	4
6	0.0076	1.719	4
7	0.0089	1.725	6
8	0.0104	1.727	6
9	0.0119	1.732	4
10	0.0133	1.715	3
11	0.0147	1.707	2
12	0.0162	1.702	3
13	0.0179	1.688	2
14	0.0189	1.590	3
15	0.0201	1.511	4
16	0.0214	1.421	6
17	0.0299	1.298	6
18	0.0242	1.195	4
19	0.0258	1.068	5
20	0.0270	0.986	6
21	0.0285	0.884	8
22	0.0229	0.758	8
23	0.0314	0.663	10
24	0.0327	0.575	5
25	0.0340	0.521	7
26	0.0381	0.449	5
27	0.0366	0.392	6
28	0.0353	0.330	7
29	0.0395	0.247	5
30	0.0411	0.189	8
31	0.0425	0.137	4
32	0.0435	0.125	5
33	0.0452	0.097	6
34	0.0465	0.065	6
35	0.0479	0.050	5
36	0.0494	0.026	5
37	0.0508	0.019	4
38	0.0522	0.012	2
39	0.0538	0.004	2
40	0.0570	0.011	6
41	0.0620	0.012	5
42	0.1104	–0.011	9
43	0.1175	–0.030	8
44	0.1249	–0.030	22
45	0.1308	–0.032	25
46	0.1358	–0.039	23
47	0.1416	–0.038	19
48	0.1491	–0.046	13
49	0.2110	–0.079	5
50	0.2434	–0.072	6
51	0.2754	–0.067	4
52	0.2821	–0.070	6
53	0.2906	–0.082	11
54	0.2966	–0.078	6
55	0.3020	–0.079	4
56	0.3364	–0.065	4
57	0.3567	–0.069	9
58	0.3890	–0.062	8
59	0.3956	–0.041	11
60	0.4210	–0.031	6
61	0.4544	–0.025	4
62	0.4614	–0.008	5
63	0.4712	+0.033	2
64	0.4748	0.032	7
65	0.4807	0.022	10
66	0.4892	0.030	6
67	0.5061	0.061	3
68	0.5099	0.033	5
69	0.5126	0.035	5
70	0.5154	0.039	8
71	0.5184	0.020	6
72	0.5208	0.025	4
73	0.5238	0.029	3
74	0.5266	0.028	6
75	0.5309	0.001	7
76	0.5345	0.002	4
77	0.5385	0.010	7
78	0.5422	0.008	2
79	0.5496	–0.009	3
80	0.5581	0.002	3
81	0.5653	–0.013	2
82	0.5728	–0.031	3
83	0.5787	–0.025	5
84	0.5836	–0.039	9
85	0.6439	–0.064	2
86	0.6520	–0.057	6
87	0.6600	–0.069	9
89	0.6677	–0.055	4
89	0.6712	–0.051	8
90	0.7036	–0.053	2
91	0.7094	–0.055	3
92	0.7196	–0.053	2
93	0.7246	–0.074	4
94	0.7312	–0.065	5
95	0.7350	–0.055	2
96	0.8134	–0.062	4
97	0.8192	–0.046	4
98	0.8301	–0.052	3
99	0.8656	–0.040	3
100	0.8693	–0.038	10
101	0.8776	–0.016	18
102	0.8875	–0.026	6
103	0.8899	–0.022	5
104	0.8928	–0.027	7
105	0.8956	–0.012	9
106	0.8987	–0.022	7
107	0.9013	–0.015	6
108	0.9038	–0.018	8
109	0.9096	–0.013	3
110	0.9232	–0.011	4
111	0.9271	–0.014	2
112	0.9557	0.106	1
113	0.9616	0.296	1
114	0.9625	0.373	2
115	0.9637	0.425	1
116	0.9643	0.466	3
117	0.9657	0.541	3
118	0.9685	0.726	5
119	0.9701	0.822	6
120	0.9717	0.926	5
121	0.9731	1.043	3
122	0.9742	1.153	5
123	0.9756	1.228	5
124	0.9771	1.293	7
125	0.9783	1.400	5
126	0.9798	1.568	7
127	0.9812	1.668	8
128	0.9826	1.693	6
129	0.9839	1.718	8
130	0.9853	1.723	11
131	0.9870	1.713	8
132	0.9885	1.730	10
133	0.9896	1.732	8
134	0.9908	1.737	11
135	0.9922	1.739	9
136	0.9937	1.732	8
137	0.9951	1.736	9
138	0.9965	1.743	9
139	0.9980	1.745	9
140	0.9995	1.745	6

Table 1b. TT Hya : Normal points in blue

S No	Phase	ΔB	N	S. No.	Phase	ΔB	N	S. No.	Phase	ΔB	N
1	0.0007	2.472	6	51	0.2753	–0.143	4	101	0.8929	–0.152	7
2	0.0021	2.459	5	52	0.2841	–0.188	3	102	0.8955	–0.129	8
3	0.0032	2.455	7	53	0.2908	–0.182	12	103	0.8984	–0.137	6
4	0.0048	2.449	6	54	0.2968	–0.176	6	104	0.9012	–0.143	10
5	0.0058	2.450	4	55	0.3020	–0.172	5	105	0.9038	–0.151	7
6	0.0076	2.434	5	56	0.3366	–0.163	4	106	0.9098	–0.135	4
7	0.0089	2.437	5	57	0.3568	–0.176	9	107	0.9228	–0.116	3
8	0.0104	2.438	7	58	0.3891	–0.170	8	108	0.9265	–0.130	3
9	0.0120	2.436	4	59	0.3954	–0.164	12	109	0.9558	+0.181	1
10	0.0136	2.438	4	60	0.4208	–0.144	6	110	0.9623	0.330	3
11	0.0159	2.385	3	61	0.4601	–0.127	9	111	0.9638	0.373	1
12	0.0175	2.371	2	62	0.4713	–0.101	2	112	0.9644	0.428	3
13	0.0191	2.118	4	63	0.4749	–0.130	7	113	0.9658	0.519	3
14	0.0202	1.980	4	64	0.4809	–0.118	10	114	0.9679	0.689	1
15	0.0215	1.783	6	65	0.4885	–0.123	6	115	0.9688	0.778	4
16	0.0229	1.602	5	66	0.5062	–0.107	3	116	0.9702	0.885	6
17	0.0242	1.425	5	67	0.5100	–0.136	5	117	0.9715	1.046	5
18	0.0259	1.234	4	68	0.5127	–0.136	5	118	0.9730	1.155	4
19	0.0270	1.100	7	69	0.5155	–0.114	8	119	0.9744	1.310	6
20	0.0286	0.952	8	70	0.5183	–0.127	5	120	0.9755	1.483	4
21	0.0300	0.786	7	71	0.5208	–0.135	4	121	0.9769	1.646	7
22	0.0314	0.694	10	72	0.5257	–0.121	9	122	0.9783	1.863	8
23	0.0327	0.586	7	73	0.5306	–0.136	8	123	0.9800	2.142	5
24	0.0339	0.478	6	74	0.5348	–0.126	5	124	0.9813	2.335	5
25	0.0353	0.376	6	75	0.5383	–0.137	8	125	0.9827	2.384	6
26	0.0367	0.302	6	76	0.5423	–0.121	2	126	0.9840	2.399	8
27	0.0380	0.237	5	77	0.5496	–0.142	3	127	0.9853	2.415	10
28	0.0395	0.164	7	78	0.5584	–0.137	3	128	0.9870	2.415	8
29	0.0410	0.097	5	79	0.5623	–0.136	2	129	0.9884	2.426	8
30	0.0422	0.030	5	80	0.5730	–0.156	3	130	0.9895	2.439	11
31	0.0435	0.010	3	81	0.5813	–0.149	14	131	0.9908	2.438	10
32	0.0450	–0.048	5	82	0.6448	–0.169	3	132	0.9923	2.458	10
33	0.0464	–0.069	8	83	0.6522	–0.169	6	133	0.9938	2.445	7
34	0.0480	–0.099	5	84	0.6606	–0.160	11	134	0.9952	2.447	10
35	0.0494	–0.103	4	85	0.6675	–0.151	6	135	0.9966	2.446	7
36	0.0507	–0.125	5	86	0.6721	–0.151	8	136	0.9979	2.443	8
37	0.0518	–0.139	2	87	0.7034	–0.157	2	137	0.9993	2.457	5
38	0.0537	–0.144	1	88	0.7091	–0.161	3				
39	0.0542	–0.139	1	89	0.7194	–0.150	3				
40	0.0592	–0.132	11	90	0.7252	–0.157	3				
41	0.1100	–0.125	7	91	0.7312	–0.143	4				
42	0.1173	–0.130	5	92	0.7351	–0.145	2				
43	0.1246	–0.146	25	93	0.8136	–0.162	4				
44	0.1309	–0.143	20	94	0.8193	–0.145	4				
45	0.1358	–0.154	23	95	0.8303	–0.141	3				
46	0.1418	–0.150	20	96	0.8634	–0.166	2				
47	0.1473	–0.166	10	97	0.8685	–0.143	8				
48	0.1512	–0.147	3	98	0.8762	–0.133	20				
49	0.2121	–0.177	7	99	0.8874	–0.147	7				
50	0.2435	–0.164	6	100	0.8900	–0.139	5				

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Table 1c. TT Hya : Normal points in ultraviolet

S. No.	Phase	ΔU	N	S. No.	Phase	ΔU	N	S. No.	Phase	ΔU	N
1	0.0006	2.957	4	5	0 2437	–0.205	6	101	0.8810	–0.195	22
2	0.0022	2.947	4	52	0.2752	–0.213	4	102	0.8901	–0.208	5
3	0 0033	2.930	5	53	0 2824	–0.230	6	103	0.8930	–0.207	7
4	0 0050	2.929	4	54	0.2912	–0.259	10	101	0.8956	–0.196	8
5	0.0060	2.916	2	55	0.2969	–0.250	6	105	0.8985	–0.198	4
6	0.0075	2.914	2	56	0 3021	–0.249	5	106	0.9012	–0.197	12
7	0 0090	2.896	4	57	0.3364	–0 214	3	107	0.9042	–0.217	9
8	0.0106	2.887	4	58	0.3571	–0.229	7	108	0 9096	–0 197	3
9	0.0124	2.925	1	59	0.3980	–0.229	7	109	0 9229	–0 179	3
10	0 0131	2.909	1	60	0.3954	–0.233	12	110	0 9260	–0.184	2
11	0.0143	2.927	1	61	0.4207	–0.233	6	111	0 9279	–0.186	1
12	0 0162	2.853	1	62	0.4557	–0.208	3	112	0.9559	+0.213	1
13	0.0178	2.766	1	63	0.4609	–0.219	4	113	0.9619	0 277	1
14	0 0191	2.445	2	64	0.4714	–0 185	2	114	0.9628	0 312	2
15	0.0198	2.309	3	65	0.4751	–0 231	7	115	0 9639	0.368	1
16	0.0214	1 942	4	66	0.4812	–0 215	9	116	0 9646	0.427	3
17	0.0227	1.678	5	67	0.4877	–0.229	4	117	0 9659	0.512	3
18	0.0249	1.454	6	68	0.5063	–0.193	3	118	0.9680	0 686	1
19	0.0258	1.247	2	69	0.5100	–0.201	4	119	0.9687	0.753	3
20	0 0271	1.101	8	70	0.5126	–0 230	6	120	0.9702	0.897	7
21	0 0287	0.914	7	71	0.5155	–0.213	7	121	0 9715	1.033	5
22	0 0300	0 787	8	72	0.5180	–0.187	7	122	0.9730	1.190	7
23	0 0303	0.653	8	73	0.5208	–0.201	5	123	0 9745	1.385	4
24	0.0326	0 545	8	74	0.5240	–0.211	3	124	0.9755	1.535	5
25	0.0339	0 428	7	75	0.5267	–0.217	5	125	0 9770	1.762	6
26	0.0354	0.313	6	76	0 5304	–0.222	11	126	0.9784	2.017	8
27	0.0368	0.255	6	77	0.5351	–0.207	3	127	0.9799	2 360	5
28	0.0382	0.177	6	78	0 5385	–0.211	8	128	0.9810	2.613	7
29	0 0397	0 094	6	79	0.5424	–0.235	2	129	0.9826	2 732	7
30	0.0410	0.022	4	80	0.5497	–0.233	3	130	0 9840	2.786	7
31	0.0422	–0.003	7	81	0.5586	–0.205	3	131	0 9854	2.808	8
32	0 0436	–0.080	5	82	0.5667	–0 206	2	132	0 9869	2.794	4
33	0.0451	–0.110	5	83	0.5776	–0 217	7	133	0 9882	2 845	5
34	0.0465	–0.114	7	84	0.5838	–0.241	9	134	0.9895	2.860	9
35	0 482	–0.132	5	85	0 6454	–0 213	4	135	0.9909	2.867	7
36	0.0495	–0 157	4	86	0.6518	–0 217	5	136	0.9924	2.903	6
37	0.0508	–0.161	5	87	0.6603	–0.206	11	137	0 9936	2 860	3
38	0.0519	–0.190	2	88	0.6666	–0.206	7	138	0.9952	2 897	8
39	0.0533	–0 197	2	89	0.6719	–0.199	9	139	0 9967	2 899	6
40	0.0543	–0.183	1	90	0 7032	–0.199	2	140	0 9980	2.909	5
41	0.0594	–0.183	11	91	0.7088	–0.202	3	141	0.9993	2 927	4
42	0.1117	–0.191	4	92	0.7201	–0.197	3				
43	0.1170	–0.198	5	93	0.7251	–0.208	3				
44	0 1256	–0 218	13	94	0 7314	–0.202	5				
45	0 1309	–0.198	12	95	0 7352	–0.211	2				
46	0.1359	–0 221	15	96	0.8137	–0.197	4				
47	0.1417	–0.208	15	97	0.8194	–0 217	4				
48	0.1453	–0.232	11	98	0 8305	–0 210	3				
49	0.1513	–0 194	3	99	0.8655	–0.244	2				
50	0.2118	–0.202	6	100	0.8697	–0 207	13				

Table 2. TT Hya : Results obtaıned by varying all the parameters

Parameter	Prelıminary values	*V*	*B*	*U*	*V* and *B* combined	*V*, *B* and *U* combined
1	2	3	4	5	6	7
T_h °K	9500	10,864	10,770	11,036	10,525	10,430 ± 47
T_c °K	4674	3,930	3,930	4,265	3,930	3,915 ± 59
Ω_h		13.6861	14 1075	13 9576	13 3805	13.5189 ± 0.015
Ω_c		2 4539	2.4532	2.4585	2.4701	2.4581
q	0.269	0.2944	0.2941	0.2965	0 3018	0.2963 ± 0.0020
$i°$	83.74	80.739	80.680	80.665	80.722	80.791 ± 0 08
pole		0 0747	0 0724	0.0732	0.0764	0 0756 ± 0.0014
r_h point	0.093	0.0747	0.0724	0 0732	0.0765	0.0757 ± 0 0015
side		0.0747	0.0724	0.0732	0.0765	0.0756 ± 0.0016
back		0.0747	0.0724	0 0732	0.0765	0.0757 ± 0.0015
pole		0.2598	0 2597	0.2603	0.2616	0 2603 ± 0.0016
r_c point		0 3774	0.3777	0 3780	0 3797	0.3780 ± 0.0019
side	0 2438	0 2705	0 2704	0 2710	0.2724	0.2710 ± 0.0016
back		0 3032	0.3031	0 3037	0 3051	0 3037 ± 0 0017
V	0.7682				*V* 0.7679	0.7671 ± 0.022
L_h *B*	0.8858	0 7722	0.8923	0 9323	*B* 0.8958	0 8945 ± 0.021
U	0.9100				*U* —	0 9395 ± 0.024
V	0 2318	0 2278	0 1077	0 0677	*V* 0.2321	0.2339
L_c *B*	0 1142				*B* 0.1042	0.1055
U	0.0900				*U* —	0.0368
l_3	—	0	0	0	0	*V* 0
						B 0
						U 0.0237 ± 0 0006
V	0.43	0 386	0.511	0 486	*V* 0.386	0 386 ± 0 020
x_h *B*	0.52				*B* 0.511	0 511 ± 0.020
U	0 48				*U* —	0.486 ± 0.030
V	0 71	0 833	0 893	0 900	*V* 0.833	0.833 ± 0 030
x_c *B*	0.89				*B* 0.893	0.893 ± 0.030
U	0.89				*U* —	0 900 ± 0.040

Since the analysis of the light curves yielded a photometric mass-ratio of 0.297 which is closer to the spectroscopic mass-ratio of 0.269 (Popper 1982), we have made another analysis of the light curves by keeping T_h and q fixed at 10430° and 0.269 respectively. The values of x_h(V = 0.386, B = 0.511 and U = 0.386) and x_c (V = 0.833, B = 0.983 and U = 0.833), obtained in the previous analyses were also fixed. The remaining parameters viz. Ω_h, L_h, T_c and i are varied as per the principles of the W-D method. As mentioned earlier, A_h (1.0), A_c (0.5), G_h (0.25) and G_c (0.08) were also not varied.

Table 3. TT Hya · Results obtained by keeping T_h (10,430°) and q (0 269) as fixed parameters

Parameter	V	B	U	V, B and U combined
1	2	3	4	5
T_h °K	10,430	10,430	10,430	10,430
T_c °K	3,966	3,993	3,978	4,000 ± 56
Ω_h	13.5279	13.5451	13 5362	13.5057 ± 0 013
Ω_c	2 3897	2.4258	2 4077	V 2 4131 B 2.3967 U 2.3904
q	0.269	0.269	0.269	0.269
$i°$	80 975	81 069	81.125	81 157 ± 0.06
pole	0 0754	0.0755	0.0755	0 0755 ± 0.0009
r_h point	0.0754	0 0755	0 0755	0.0756 ± 0.0010
side	0.754	0 0756	0.0755	0.0756 ± 0.0008
back	0 0754	0 0755	0.0755	0 0756 ± 0.0009
pole	0.2530	0 2538	0.2536	0.2533 ± 0.0016
r_c point	0.3682	0.3692	0.3688	0 3688 ± 0 0018
side	0 2633	0.2641	0.2639	0.2637 ± 0.0016
back	0.2959	0 2966	0.2965	0.2964 ± 0.0018
L_h	0 7643	0.8942	0.9339	V 0 7664 ± 0.021 B 0.8898 ± 0 019 U 0.9363 ± 0.022
L_c	0.2357	0.1058	0 0429	V 0.2336 B 0.1102 U 0.0401
l_3	0	0	0 0232	V 0 B 0 U 0 0236 ± 0.0007
x_h	0.386	0.511	0.386	V 0.386 B 0.511 U 0.386
x_c	0.833	0.893	0.833	V 0 833 B 0.893 U 0.833

As before, the analysis is made first for the individual and then for the combined light curves. These results are given in columns 2, 3, 4 and 5 of table 3. In this case, l_3 is present in U pass band for the individual as well as for the combined analysis.

Theoretical curves obtained from the parameters of the combined solution (column 5 of table 3) are shown as solid lines in figures 1(a)-(c). The observed normals are shown as filled circles in this figure. It can be noticed that the theoretical curves fit the observations quite satisfactorily.

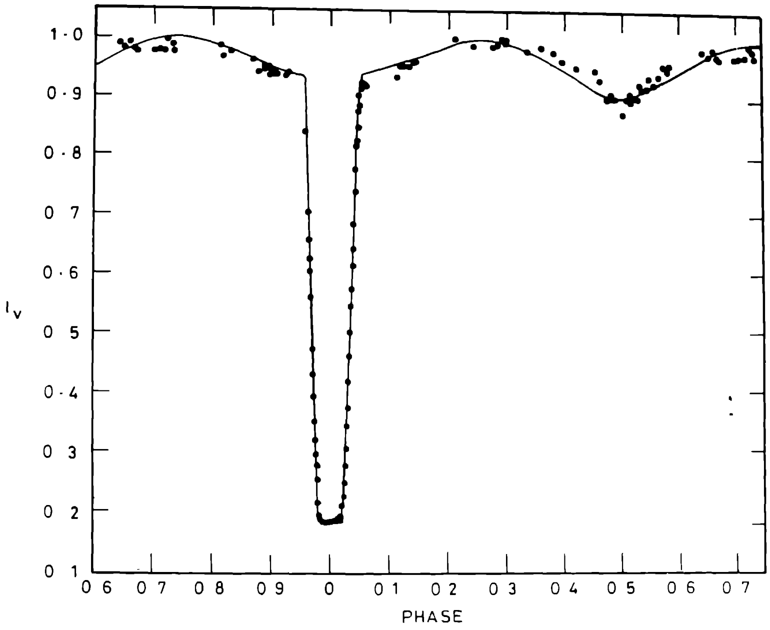

Figure 1(a). TT Hya : Light curve in yellow. Solid line represents theoretical curve obtained from the parameters of the combined solution given in column 5 of table 3. Filled circles represent the observed normals

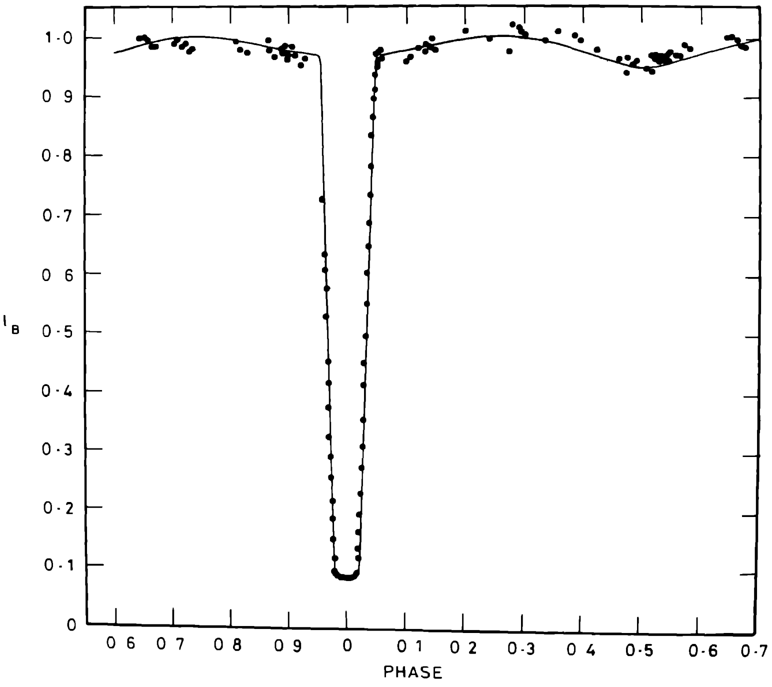

Figure 1(b). Same as figure 1(a) for blue.

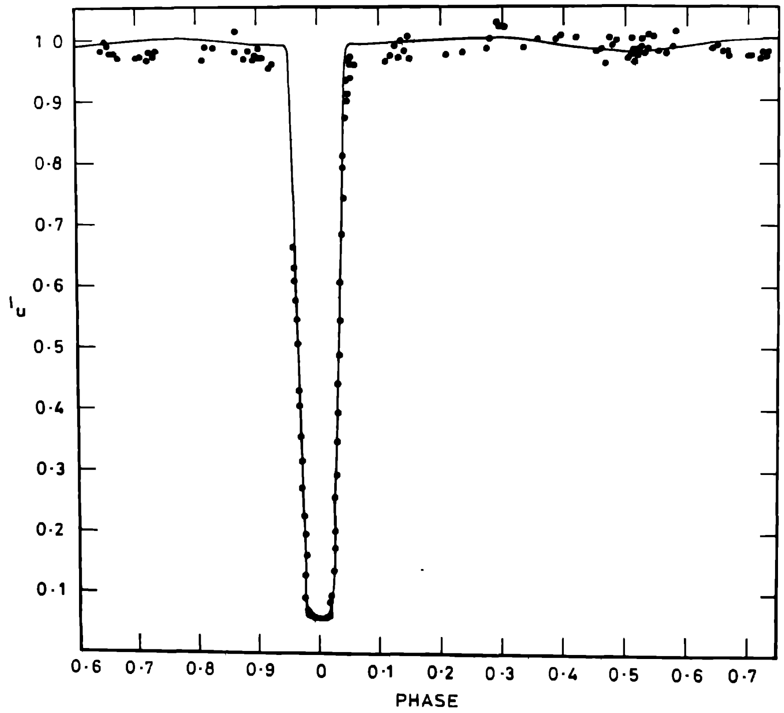

Figure 1(c). Same as figure 1(a) for U.

3. Spectral types and absolute elements

Using the parameters obtained from the present analysis, spectral types and improved absolute elements of the components of TT Hydrae are derived.

From the derived luminosities (column 5 of table 3) and the differential magnitudes of $\Delta V = -0.079$, $\Delta B = -0.171$ and $\Delta U = -0.231$, corresponding to unit luminousity at maximum light at quadrature, the magnitudes and colours of the individual components are obtained. These are given below :

	Hot component	Cool component
V	7.549	8.839
$(B - V)$	+0.014	+0.992
$(U - B)$	−0.047	+1.106

The values of $V = 7.339$, $(B - V) = 0.268$ and $(U - B) = 0.069$ of the comparison star, as given by KA 78 are used. Assuming no space reddening ($r = 180$ pc), the value of $(B - V)$ for the hotter star corresponds to a spectral type of AO V while the value of $(U - B)$ corresponds to B9 V and its temperature of 10430°k corresponds to a spectral type of B9 V (Allen 1976). An average of all these values correspond to a spectral type of B9.5 V for the hotter component which agrees completely with that given by EL 88. As for the evolved secondary component, its $(B - V)$ suggests a spectral type of G9 III while its $(U - B)$ colour suggests a spectral type of K2 III. A temperature of 4000°K derived for the secondary gives it a spectral type of K4 III (Allen 1976). An average of the above values gives a spectral type of G9 – K4 III-IV to the secondary component. This spectral type is somewhat later than that of G9 – K1 III-IV derived by Etzel (1988).

Taking the amplitudes of its RV curves as 35 km/sec and 130 km/sec (Popper 1982), and using the parameters given in column 5 of table 3, which gives $A = 22.904\ R_\odot$, we obtained the following absolute elements for TT Hydrae :

$m_h/m_\odot$	2.65
$m_c/m_\odot$	0.71
$R_h/R_\odot$	1.73
$R_c/R_\odot$	6.22

The above absolute elements when combined with the derived temperatures give the following parameters :

$\log L_h/L_\odot$	1.503
$\log L_c/L_\odot$	0.948
$M_{\mathrm{bol,h}}$	0.93
$M_{\mathrm{bol,c}}$	2.32
$M_{\mathrm{V,h}}$	1.26
$M_{\mathrm{V,c}}$	3.29
$\log g_h$	4.384
$\log g_c$	2.704

Since the errors for K_h and K_c are not available, we could not estimate the errors of all the above elements. Table 4 gives a comparison of solution geometries derived by different authors.

4. Discussion

Our analysis of the UBV light curves of TT Hydrae, obtained by KA 78, using the W-D method has given consistent parameters for individual as well as for combined curves. The presence of a third light, l_3 of about 2% in the U pass band might have arisen because of (i) errors due to changes in the effective wavelength during the partial phases, (ii) intrinsically larger errors when compared to the B and V observations, (iii) the well known problem of not being able to match properly the U pass band and finally, (iv) some emission from the circumstellar material, the presence of which was indicated by the spectrophotometric observations of EL 88.

The fit of the theoretical curves obtained from the parameters of the W-D analysis using $q = m_2/m_1 = 0.269$, is quite satisfactory with the observations except (1) in the wings of the secondary eclipse which may be due to comparatively large errors in the observations of the shallow secondary phases, and (2) between the secondary and primary eclipses mainly due to proximity effects. However, from the analysis of the same observations Etzel (1988) concluded that "preliminary WINK solutions for the V and B light curves and separate analysis of their maximum demonstrated that the spectroscopic mass-ratio $q = m_2/m_1 = 0.269$ from Popper's (1982) velocity amplitudes, could not be used to fit the complete curve". From his analysis he derived a mass-ratio of 0.142 and explained the discrepancy in the spectroscopic and photometric mass ratios to the probable non-photospheric origin of the spectral lines of the hotter component which formed the basis for the amplitude of the RV curve of Popper. But as mentioned earlier, the theoretical curves obtained in the present analysis using the W-D method with $q = m_2/m_1 = 0.269$ have fitted the observations quite satisfactorily. The

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Table 4. TT Hya : Comparison of solution geometries

Parameter	(1)	(2)	(3)	(4)
T_h °K	—	9795	10,430	—
T_c °K	—	4853/4666±7	4,000±56	—
$i°$	83.74	84 42±0.04	81 157±0.06	—
$q = m_c/m_h$	0.269 (assumed)	0 142±0 004	0.269 (fixed parameter)	0 269
$m_h/m_\odot$	2 61	2 25	2.65	2.69
$m_c/m_\odot$	0.70	0.41	0.71	0.72
r_h	0 0929	0.0894±0 0004	0.0756±0.0009	—
r_c	0.2438	0.2431±0 0012	0.2711±0 0017	—
$R_h/R_\odot$	2.01	1.90	1 733	—
$R_c/R_\odot$	5 53	5 24/4.48	6 220	—
$M_{bol,h}$	—	0.95	0 93	—
$M_{bol,c}$	—	1 82/2.14	2 32	—
$M_{v,h}$	—	1.17	1.26	—
M_v,c	—	2.22/2 61	3.29	—
Log $L_h/L_\odot$	—	1.50	1.503	—
Log $L_c/L_\odot$	—	1.15/1 02	0.948	—
Log g_h (cgs)	—	4.23	4.38	—
Log g_c (cgs)	—	2.63	2.70	—
d (pc)	—	193 (AV=0)	181 (AV=0)	—

Solutions : (1) Kulkarni and Abhyankar (1981) Tables 3 and 5.
(2) Etzel (1988) Tables V and XII.
(3) Present study : combined solution
(4) Popper (1982) Table II.

non-fitting of the observed the theoretical light curves with $q = 0.269$ in the analysis of Etzel and his derived low mass-ratio of 0.142 may be due to (1) his rejecting the observations of some nights (descending branch and into totality) which might have altered the shape and depth of the light curves, and (2) the assumption of a tri-axial ellipsoid in Wood's WINK programme instead of a more correct Roche geometry for the lobes of the components. Hence we attribute the discrepancy in the photometric and spectroscopic mass ratios, as reported by Etzel, to the technique used in his analysis and not to a factual difference. Thus we conclude that the value of the mass-ratio of TT Hydrae is about 0.269 as reported by Popper (1982) and the system is semi-detached with the secondary just filling its critical lobe.

5. Evolution

From their analysis of the TT Hya light curves using the Russell-Merrill method, KA 81 concluded that for a mass-ratio of 0.269 the cool star in this system is in a pre-main sequence stage of evolution and is detached. From their analysis of the same observations using Kopal's (1979) frequency-domain method, Koul and Abhyankar (1982) confirmed the above nature of the secondary component. Later, Abhyankar (1984) concluded that the cool

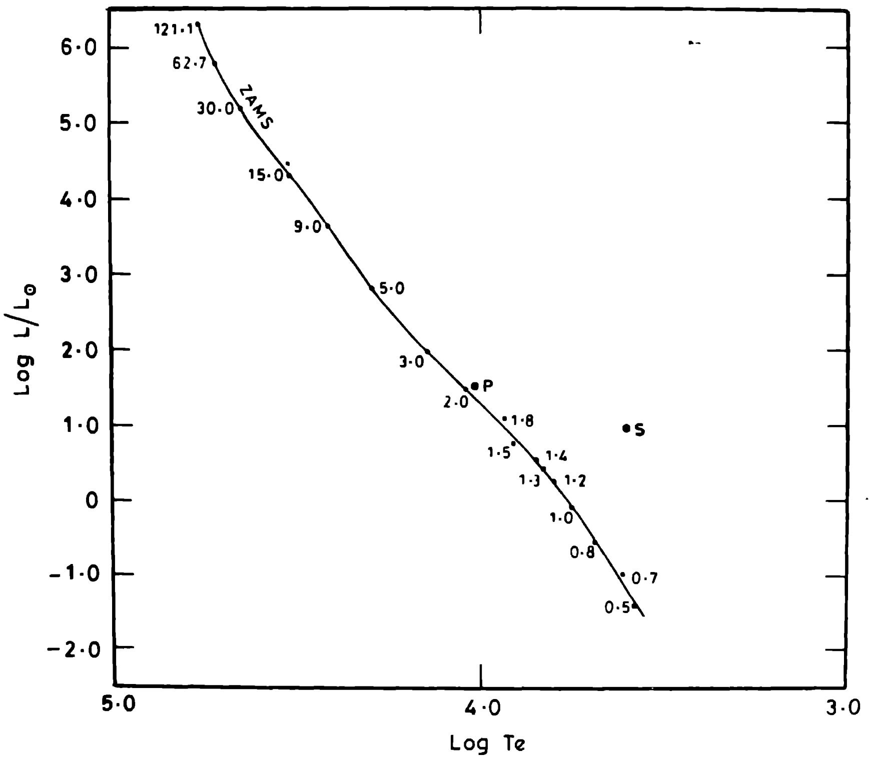

Figure 2. TT Hya : Theoretical zero-age main sequence (ZAMS). The numbers indicate masses of the stars (Cox & Giuli 1968).

sub-giant secondary of TT Hya had definitely lost mass and is not in a pre-main sequence contraction phase. From an analysis of the same observations using Wood's WINK method Etzel (1988) concluded that for the derived mass-ratio of 0.142, TT Hya is a semi-detached system with the secondary cool component over-filling its Roche lobe. From our analysis of the same data using W-D method, we find that for a mass-ratio of 0.269, the secondary is just filling its lobe and hence we conclude that the system TT Hya is semi-detached.

In order to understand the evolutionary status of the components of TT Hya, we have plotted their positions on the Zero Age Main Sequence (ZAMS) (Cox and Giuli 1968), in figure 2. From this plot it is found that, like in all Algol systems, the secondary component, S, is over luminous for its mass due to mass loss during its evolution. From the position of the primary component P, we find that this component is near the ZAMS corresponding to a star of mass 2.0 $m_{\odot}$ while its spectroscopically derived mass is about 2.6 $m_{\odot}$. From this we conclude that the primary is under-luminous and cooler for its mass. This property of the hot component is also noticed by us in the semi-detached system, HU Tau (Parthasarathy *et al.* 1994). Theoretical studies of this property of the hot component will help in understanding the nature of evolution of the mass-gaining components in semi-detached systems.

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