Photometric elements of the eclipsing binaries ZZ Cru, RU Gru and DT Lup from multicolour light curves

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Abstract. Multicolour photoelectric observations of the eclipsing binaries ZZ Cru, RU Gru and DT Lup obtained in 1965 and 1968 using Walraven ULBV filters are presented. Photometric elements of the binaries, determined by Wilson-Devinney's code, classify ZZ Cru as a semi-detached, RU Gru as a detached and DT Lup as an almost detached system. Application of the Horák's limb-darkening scan technique for computation of photometric elements is given for these binaries.

Key words: eclipsing binaries - photometry - photometric elements

1. Introduction

In 1965-78, the third author (CJvH) created a program for obtaining multicolour photoelectric light curves of 18 eclipsing variables observed in the southern hemisphere using the 0.9 m telescope of the Leiden Southern Station in South-Africa. Observationally neglected eclipsing binaries with orbital periods in the range 1-2 days were chosen. The program was applied during a full moon, when the sky was too bright for OB stars photometry.

The aim of this paper is to present four-band Walraven ULBV observations of the eclipsing binaries ZZ Cru, RU Gru and DT Lup as a part of the program

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mentioned above. The original observations of these binaries may be obtained from authors upon request. We employed 1992 version of Wilson-Devinney's (1971, 1973) code to calculate photometric elements of the binaries in question. These results are compared with photometric elements found by Horák's method.

2. Walraven multicolour photometry

2.1. Observations

Our ULBV photoelectric observations were taken using the Walraven five-colour photometer (Walraven & Walraven, 1960) attached to the 0.9 m light collector of the Leiden Southern Station near Hartebeespoortdam, South Africa. The effective wavelengths and band-widths of Walraven filters are as follows: W (327 nm, 15 nm), U (367 nm, 26 nm), L (390 nm, 29 nm), B (429.5 nm, 42 nm), V (545 nm, 85 nm). The observations of ZZ Cru (HD 105055, CPD-62 2575), RU Gru (HD 212725, CPD-37 9201) and DT Lup (HD 128087, CPD-50 7071) presented here were taken in 1965 and 1968, respectively. The journal of observations is shown in Table 1.

Table 1. Journal of photometric observations. All observations of ZZ Cru and RU Gru were performed in 1965 while observations of DT Lup in 1968

Date	HJD_{mean} 2 400 000+	Phases
	ZZ Cru	
Mar 16	38836.4586	0.008 - 0.214
Mar 19	38839.4894	0.672 - 0.822
Mar 20	38840.3635	0.179 - 0.253
Apr 11	38862.3566	0.015 - 0.037
Apr 18	38869.3282	0.754 - 0.786
May 8	38889.3248	0.443 - 0.573
May 12	38893.2912	0.587 - 0.690
May 17	39898.3583	0.299 - 0.420
May 18	38899.3949	0.874 - 0.956
May 20	38901.3265	0.883 - 0.023
May 22	38903.3164	0.964 - 0.079
May 31	38912.3110	0.791 - 0.913
Jun 3	38915.2188	0.399 - 0.428
Jul 10	38952.2496	0.275 - 0.323
Jul 14	38956.2318	0.424 - 0.452
Jul 16	38958.2497	0.493 - 0.550
	RU Gru	
Jun 19	38930.5464	0.662 - 0.703
Jun 20	38931.5348	0.182 - 0.240
Jun 2	38944.4866	0.017 - 0.076
Jul 6	38948.4492	0.117 - 0.161
Jul 18	38960.4578	0.437 - 0.528
Jul 22	38964.5284	0.602 - 0.664
Jul 23	38965.4210	0.074 - 0.135
Jul 24	38966.4600	0.622 - 0.685
Jul 27	38969.4134	0.209 - 0.218
Aug 1	38974.4501	0.824 - 0.924
Aug 3	38976.4935	0.901 - 0.006
Aug 19	38992.3624	0.309 - 0.362
Aug 21	38994.4566	0.375 - 0.508
Sep 27	39031.4369	0.932 - 0.020
Sep 29	39033.3809	0.967 - 0.038
	DT Lup	
Mar 31	39947.4708	0.477 - 0.642
Apr 9	39956.4487	0.714 - 0.762
Apr 20	39966.5714	0.680 - 0.728
Apr 21	39968.4289	0.876 - 0.089
Apr 30	39977.3060	0.046 - 0.137
May 6	39983.3906	0.174 - 0.384
May 17	39994.3101	0.737 - 0.850
May 18	39995.3239	0.415 - 0.568

The magnitudes and colour indices of the comparison stars in Johnson and normalized Walraven system (see Section 2.2) are shown in Table 2.

Table 2. The comparison stars used and their magnitudes in Johnson (subscript J) and normalized Walraven system (subscript W)

star	comparison		V_J	$(B-V)_J$	$(L-B)_W$	$(U-B)_W$	$(W-U)_W$
ZZ Cru	HD104934	CPD-62 2569	9.81	0.017	-0.201	-0.498	-0.082
RU Gru	HD212787	CPD-38 8401	9.77	-0.042	-0.001	0.000	-0.010
DT Lup	HD128134	CPD-50 7078	9.98	-0.066	-0.203	-0.463	-0.116

The light curves of the eclipsing variables using the ephemerides given in Section 3 are shown in Fig. 1.

2.2. Transformation from the Walraven to the Johnson system and normalization

Observations taken by the Walraven 5-colour photometer were usually expressed in logarithms of intensity, with a zero-point for the colour indices originally derived from a single star. This is a bit different from the usual practice of adjusting the visual brightness to the magnitude scale and equaling the colour index zero point to the colours of an unreddened A0 V star as in the international UBV system of Johnson. Fortunately it is easy to transform Walraven V colour and the (V-B) colour index to the corresponding Johnson's values. The formulae for this transformation are given as follows:

$$\begin{aligned} V_J &= -2.5V_W - 0.155(V-B)_W + 6.874 \\ (B-V)_J &= -2.5(B-V)_W - 0.023, \end{aligned} \tag{1}$$

where V_J and $(B\text{-}V)_J$ denote the values in the Johnson system, V_W and B-V_W those in the Walraven system. For the other colour indices of the Walraven photometric system no easily derivable equivalents in the Johnson system can be found.

The Walraven colour indices, expressed in magnitudes, have been normalized to zero for unreddened A0 V stars, as is the usual practice in stellar photometry. To obtain the correction terms, seven stars were used from the listing of Walraven & Walraven (1977) which had an A0 V classification in the Michigan revision of the HD spectral types (Houk & Cowley, 1975; Houk, 1978). The photometric quantities were corrected for interstellar reddening in a manner described by Walraven & Walraven (1960). The resulting normalized colour indices, denoted here by $(L\text{-}B)_W$, $(U\text{-}B)_W$ and $(W\text{-}U)_W$, can be derived from the corresponding values in the instrumental Walraven system by the following expressions:

$$\begin{aligned} (L-B)_W &= -2.5(L-B) - 0.379 \\ (U-B)_W &= -2.5(U-B) - 1.005 \\ (W-U)_W &= -2.5(W-U) - 0.223. \end{aligned} \tag{2}$$

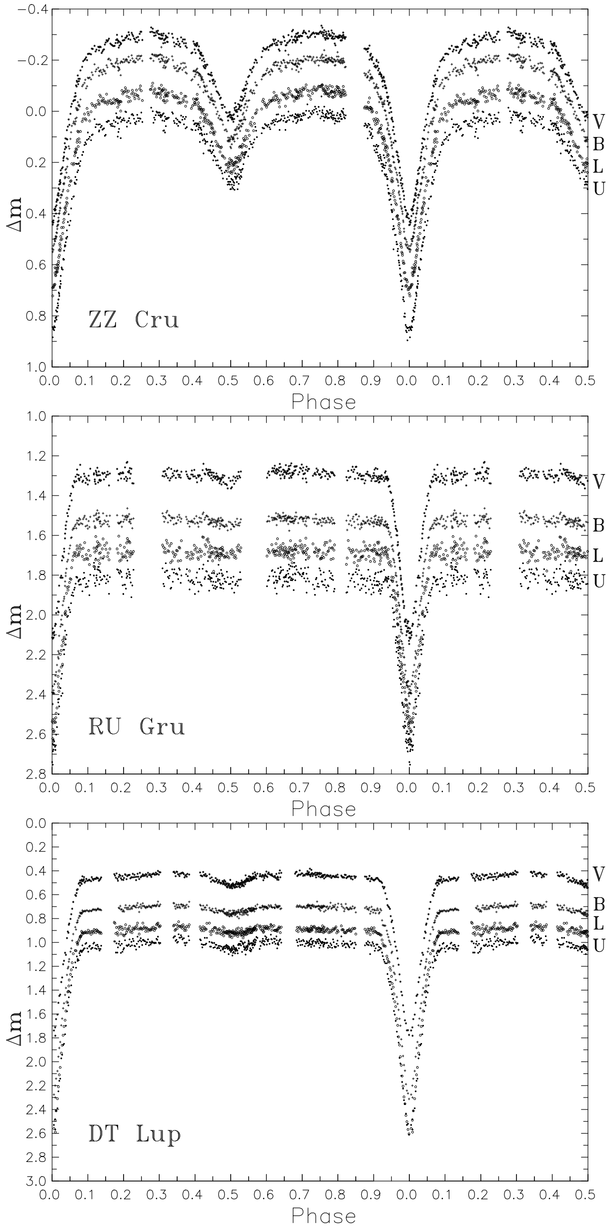

Figure 1. Walraven ULBV light curves of ZZ Cru, RU Gru and DT Lup. The magnitude scales are valid for U filter. The other light curves are shifted for clarity.

It must be noted, however, that due to malfunctioning of the beam-splitter in the Walraven photometer for the seasons 1965-69, the $(L\text{-}B)_W$ colour index is not reliable. It has been corrected tentatively by the addition of a term equal to 0.013 mag.

3. Basic information about the observed objects

3.1. ZZ Crucis

The eclipsing binary ZZ Cru (sp. type B8, $m_{Max} = 9.6$ mag, $m_{Min\ I} = 10.1$ mag, $m_{Min\ II} = 9.8$ mag, P = 1.862 days) was discovered by Oosterhoff (1933), who also determined the period and published a light curve. The system was also studied by Alden (1936) and Gaposhkin (1953). A new ephemeris was derived by using the older epochs of minimum brightness with those found from the present investigation (Table 3). The weights 1 and 5 were used for minima times determined from photographic and photoelectric observations, respectively. A least-squares weighted solution resulted in the following ephemeris:

$$\begin{array}{lll} Min\ I = HJD\ \ 2\,423\,916.401 & +1.8621862 & \times E \\ \qquad\qquad\qquad\qquad\quad \pm 8 & \quad \pm 16 & \end{array} \tag{3}$$

It is remarkable that the light curve of ZZ Cru observed by Oosterhoff (1933) and Gaposhkin (1953) indicates that the maximum preceding the primary minimum is brighter than the maximum following it. This effect is not seen in our light curves. Both maxima are almost of equal brightness.

3.2. RU Gruis

The eclipsing binary RU Gru (sp. type A0, $m_{Max} = 11.3$ mag, $m_{Min\ I} = 11.7$ mag, $m_{Min\ II} = 11.35$ mag, P = 1.893 days) was discovered as a variable star by Hoffmeister (1949). Hoffmeister (1956) published its Algol-type light curve, gave the four epochs of minimum brightness found from photographic observations and determined the ephemeris: Min I = HJD 2 434 546.648 + 1.89664 ×E. Our minima times (Table 3) were used to determine the period 1.893162 ± 0.000006 days. This value enabled us to calculate the epochs of older minima. A least-squares weighted solution resulted in the following ephemeris:

$$\begin{array}{lll} Min\ I = HJD\ \ 2\,434\,546.665 & +1.893127 & \times E. \\ \qquad\qquad\qquad\qquad\quad \pm 5 & \quad \pm 2 & \end{array} \tag{4}$$

The resulting ephemeris is shorter than originally quoted by Hoffmeister (1956). The observed light curve shows a very shallow secondary minimum, well detected only in the V passband (Fig. 1).

3.3. DT Lupi

The eclipsing binary DT Lup (sp. type A0, $m_{Max} = 9.8$ mag, $m_{Min\ I} = 11.7$ mag, $m_{Min\ II} = 9.9$ mag, P = 1.453 days) was discovered by Hoffmeister (1943). A least-squares weighted solution for seven minima times found from photographic observations along with the time of minimum found by us (Table 3) resulted in the following ephemeris:

$$\begin{array}{lll} Min\ I = HJD & 2\,427\,897.643 & +1.4530891\ \times E. \\ & \qquad \pm 3 & \qquad \pm 6 \end{array} \qquad (5)$$

Table 3. Times of minimum (JD_{hel} - 2 400 000) light used for the least squares solutions

Epoch	JD_{hel}	Ref.	Epoch	JD_{hel}	Ref.
	ZZ Cru		8048	38903.2753	5
0	23916.417	1		**RU Gru**	
15	23944.331	1	0	34546.630	3
23	23959.281	1	1	34548.549	3
30	23972.260	1	10	34565.611	3
45	24000.210	1	11	34567.520	3
203	24294.385	1	2323	38944.3982	5
204	24296.228	1	2340	38976.5816	5
400	24661.248	1	2369	39031.4837	5
408	24676.208	1	2370	39033.3766	5
799	25404.226	1		**DT Lup**	
806	25417.368	1	0	27897.629	4
1749	27173.360	2	260	28275.443	4
1757	27188.307	2	525	28660.517	4
1764	27201.258	2	527	28663.410	4
1764	27201.301	2	529	28666.342	4
1764	27201.340	2	584	28746.252	4
2171	27959.220	2	604	28775.320	4
8047	38901.4135	5	8307	39968.4544	5

References: 1 - Oosterhoff (1933), 2 - Alden (1936), 3 - Hoffmeister (1956), 4 - Hoffmeister (1943), 5 - this paper

4. Multicolour light-curve analysis

4.1. Wilson-Devinney method

The photometric elements of ZZ Cru, RU Gru and DT Lup were determined using the normal points listed in Tables 9, 10 and 11, respectively. Particular numbers of individual points included into one normal point were used as weights. We employed a well-known method of Wilson and Devinney (1971, 1973) upgraded in 1992 (Wilson). At first the mode 2 (with no constraints on the surface potentials) for detached systems was applied. A synchronous rotation, zero eccentricity and blackbody radiation were assumed. Temperatures of the primary components, the mass ratios as well as other input parameters for all three systems were accepted from Brancewicz & Dworak (1980). In order to decrease the number of free parameters, we assumed theoretically predicted values of limb darkening as given by Grygar et al. (1972). The values of gravitational darkening and bolometric albedo were taken from Rucinski (1993). With these assumptions, all ULBV light curves were solved simultaneously. The differential corrections code was run until the output corrections were smaller than the probable errors σ of the elements. Two sets of solutions were obtained. The first one with fixed zero third light, the second one with relaxed third light. The differential corrections converged rather slowly. We had to perform more than 10 steps.

We also tried to check mass ratios q published by Brancewicz & Dworak (1980). These values are not very reliable because of unavailable spectroscopic data. Therefore, we sought the optimum value of q (in the least square sense) for systems ZZ Cru and DT Lup by scanning this parameter in the range of plausible values.

The resulting photometric elements (for an optimum value of q) for zero and relaxed third light and their probable errors are given in Tables 4 and 5, respectively. The computed third light for ZZ Cru was close to zero. The fits corresponding to the elements in Table 4 (ZZ Cru) and Table 5 (RU Gru and DT Lup) are shown in Fig. 2.

We have solved the ULBV light curves for ZZ Cru with an assumption of the zero third light for several fixed values for the mass ratio (q = 0.20 - 0.65). The sum of squares reached a minimum of about q = 0.25, which results in a semi-detached configuration and significantly differs from q = 0.61 given by Brancewicz & Dworak (1980).

As is seen in Fig. 1, the system RU Gru is the only obvious detached system of the three discussed in this paper. The quality of the light curve of RU Gru is rather poor as the star is the faintest of all three systems, the secondary minimum is visible only in V colour and some phases are not observed at all (0.24 - 0.30 and 0.53 - 0.60). The light curve of this binary has the largest scatter of the three objects. It reaches about 0.1 mag in U filter. The system is detached, so there is little information about the mass ratio q in its light curve. Therefore we assumed that q = 0.74 as given by Brancewicz & Dworak (1980). The computed third light is the largest of all three systems. This effect could be partly caused by insufficient information contained in its light curve and possible existence of a third body in the system. In the solution for the zero third light $r_1 > r_2$ while $r_2 > r_1$ for the relaxed third light.

In the case of DT Lup, we have solved the ULBV light curves for several fixed values of the mass ratio (q = 0.37 - 0.51) assuming a zero third light. The sum of squares reached a minimum value of about q = 0.45 (close to q = 0.44 from Brancewicz & Dworak, 1980). It varied only 4% over the whole interval of q. The WD solution shows that the system is almost detached (larger component almost fills in its corresponding Roche lobe). It is interesting to note

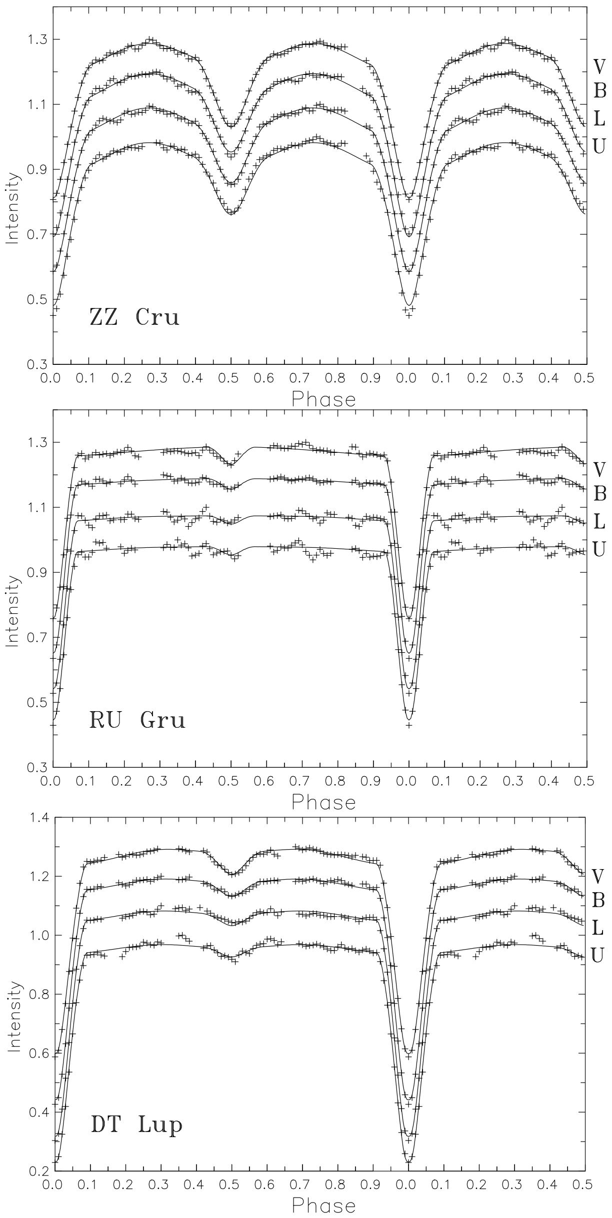

Figure 2. Normal points and the best fits of ZZ Cru, RU Gru and DT Lup for the relaxed third light

Table 4. Photometric elements and their probable errors σ for fixed zero third light (i - inclination; $q = m_2/m_1$ - mass ratio; Ω_1, Ω_2 - surface potentials; r_1, r_2 - volume mean fractional radii calculated from the surface potentials; T_1, T_2 - polar temperatures; L_1, L_2 - luminosities of the components). $\sum w(O-C)^2$ is weighted sum of squares of residuals for all four light curves. Parameters not adjusted in the solution are denoted by a superscript "a".

		ZZ Cru		RU Gru		DT Lup	
Element			σ		σ		σ
i [°]		82.78	0.08	81.41	0.07	80.56	0.11
q		0.25^a	–	0.74^a	–	0.45^a	–
Ω_1		3.1570	0.0027	5.3265	0.0264	4.8843	0.0383
Ω_2		2.3529^a	–	4.7433	0.0100	2.7937	0.0058
r_1		0.3504	0.0004	0.2194	0.0019	0.2268	0.0020
r_2		0.2667^a	–	0.2063	0.0006	0.3083	0.0014
T_1 [K]		11170^a	–	9620^a	–	10050^a	–
T_2 [K]		8670	16	4228	120	5117	24
L_1	V	0.7820	0.0004	0.9755	0.0001	0.8784	0.0003
	B	0.8079	0.0004	0.9900	<0.0001	0.9316	0.0002
	L	0.8197	0.0003	0.9935	<0.0001	0.9488	0.0001
	U	0.8275	0.0003	0.9952	<0.0001	0.9581	0.0001
L_2	V	0.2180	0.0004	0.0245	0.0001	0.1216	0.0003
	B	0.1921	0.0004	0.0100	<0.0001	0.0684	0.0002
	L	0.1803	0.0003	0.0065	<0.0001	0.0512	0.0001
	U	0.1725	0.0003	0.0048	<0.0001	0.0419	0.0001
$\sum w(O-C)^2$		0.2122	–	0.2468	–	0.1753	–

that the value of q is positively correlated with T_2 and negatively correlated with inclination i.

The calculated third light for RU Gru and DT Lup can hardly be distinguished from appropriate changes in the orbital inclination because the influence of both parameters on the shape of the light curve is highly correlated. The inclination angle of RU Gru and DT Lup is about 5 degrees lower for the fixed zero third light, than for the relaxed third light. The sums of squares of residuals for the solutions with the non-zero third light are understandably lower due to four additional parameters being relaxed.

The 2D outlines and 3D surfaces of all three binaries using the photometric elements given in Table 4 (ZZ Cru) and Table 5 (RU Gru and DT Lup) plotted by Binary Maker 2.0 (Bradstreet, 1993) are shown in Fig. 3.

4.2. Limb-darkening scan technique

In the seventies, the first author (TBH) developed a novel way of computing the elements of eclipsing binaries called the limb-darkening scan technique (henceforth LDST) (Horák, 1975). His computer code MINISCAN written for the main-frame computers enabled the separate and independent analysis of the light curves of an eclipsing binary in different colours. The LDST seeks the

Table 5. Photometric elements and their probable errors σ for relaxed third light L_3.

		RU Gru		DT Lup	
Element			σ		σ
i [°]		86.15	1.02	85.32	0.70
q		0.74^a	–	0.45^a	–
Ω_1		6.3009	0.0680	4.9363	0.0320
Ω_2		4.2421	0.0226	2.7813	0.0031
r_1		0.1804	0.0021	0.2242	0.0017
r_2		0.2406	0.0019	0.3114	0.0008
T_1 [K]		9620^a	–	10050^a	–
T_2 [K]		4788	81	4993	22
L_1	V	0.6457	0.0130	0.7254	0.0114
	B	0.6694	0.0120	0.7858	0.0122
	L	0.6799	0.0110	0.8093	0.0126
	U	0.6832	0.0106	0.8038	0.0119
L_2	V	0.0676	0.0033	0.0925	0.0030
	B	0.0344	0.0022	0.0515	0.0018
	L	0.0247	0.0015	0.0384	0.0013
	U	0.0196	0.0010	0.0306	0.0011
L_3	V	0.2867	0.0120	0.1821	0.0108
	B	0.2962	0.0105	0.1627	0.0119
	L	0.2954	0.0102	0.1523	0.0124
	U	0.2972	0.0102	0.1656	0.0117
$\sum w(O-C)^2$		0.2032	–	0.1265	–

best fit elements for equidistant values of limb-darkening coefficients u in the range from 0 to 1. The same value of u is assumed for both stars i.e. $u_1 = u_2$. If it is the case then the temperatures of both stars are comparable and this assumption is naturally valid. Conversely, the contribution of the light of the secondary component is small therefore the value of u_2 is unimportant. The elements corresponding to the minimum of the sum $(O-C)^2$ are then considered to be the solution. The advantage of the LDST is that it does not require any initial approximation. Since this method uses the sphere-sphere model after the rectification of the light curve, it is useful only for detached binaries with moderately deformed components.

Horák's method was applied to compute the elements for two southern binaries RW CrA and HO Tel of the third author's list (Grygar & Horák, 1980). After having this positive experience, the first three authors planned to employ the same procedure for further element calculations, then started working jointly on the project in the eighties. For various reasons the project proceeded slowly but was terminated suddenly due to the untimely death of Dr. T. B. Horák (* May 26, 1939) on January 27, 1991. The data and computational code written by him were inadvertently erased from the obsolete main-frame computer in Bratislava and the punched cards were lost or destroyed before we were able to convert all the material into a better format. However, during sorting of Dr. Horák's archive we have recently found computer printer outputs with photometric elements of ZZ Cru, RU Gru and DT Lup found by the LDST.

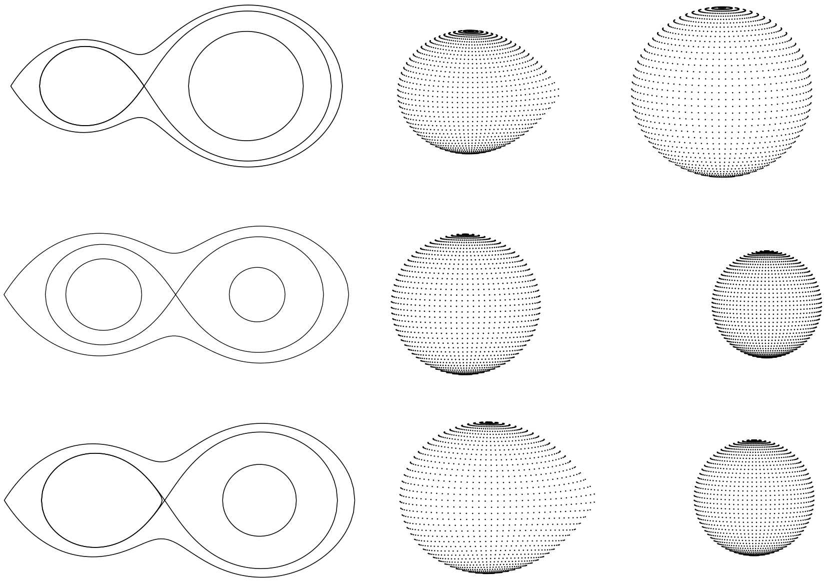

Figure 3. 2D outlines and 3D surfaces of ZZ Cru, RU Gru and DT Lup (from top) corresponding to the best fits for phase 0.75

At first, the normal points were formed with maximum phase spacings $\Delta\theta$ within a single normal point of 4° for ZZ Cru, 2° for RU Gru and 1° for DT Lup. Thereafter, a harmonic analysis of the light curves outside of the eclipses was made up to the second terms. The rectification formula was given in Horák (1975). Fourier coefficients of the light curves outside the eclipses determined by an external angle θ_e are found in Table 6.

As the Horák's method restricts the solutions to the sphere-sphere model, the proximity effects were removed by their extrapolation into the minima. After their removal, the LDST was applied to fit the data.

In the case of ZZ Cru, the LDST for the zero third light met no numerical difficulties and it converged rapidly in all colours to the elements given in Table 7. The mean geometrical elements $i = 82.6 \pm 0.5°$, $r_1 = 0.347 \pm 0.003$, $r_2 = 0.266 \pm 0.002$ are in agreement (within the errors) with the elements found by the WD's code (Table 4).

In the case of the detached system RU Gru, the secondary minimum is well detected only in the V passband. Accordingly, Horák's solutions for B,L,U passbands were mutually inconsistent and very uncertain. Therefore, we present a separate solution for the V passband only. The photometric elements found by

Table 6. Fourier coefficients of the light curve outside the eclipses for ZZ Cru ($\theta_e = 39°$, $\Delta\theta = 4°$), RU Gru ($\theta_e = 25°$, $\Delta\theta = 2°$) and DT Lup ($\theta_e = 30°$, $\Delta\theta = 1°$)

	U		L		B		V	
ZZ Cru		σ		σ		σ		σ
A_0	0.9003	0.0023	0.9411	0.0015	0.9648	0.0015	0.9263	0.0012
A_1	-0.0147	0.0028	-0.0104	0.0019	-0.0107	0.0017	-0.0115	0.0015
A_2	-0.0372	0.0033	-0.0374	0.0022	-0.0419	0.0021	0.0419	0.0018
B_1	-0.0037	0.0014	-0.0044	0.0010	0.0009	0.0009	-0.0019	0.0008
B_2	-0.0031	0.0018	-0.0016	0.0012	0.0010	0.0011	-0.0012	0.0009
RU Gru		σ		σ		σ		σ
A_0	0.9195	0.0016	0.9410	0.0013	0.9465	0.0007	0.9436	0.0009
A_1	-0.0083	0.0024	-0.0032	0.0020	-0.0064	0.0010	-0.0087	0.0013
A_2	-0.0065	0.0030	-0.0031	0.0024	-0.0014	0.0013	-0.0048	0.0016
B_1	0.0060	0.0018	0.0009	0.0015	0.0009	0.0008	0.0053	0.0010
B_2	0.0053	0.0018	0.0017	0.0014	0.0021	0.0008	0.0034	0.0009
DT Lup		σ		σ		σ		σ
A_0	0.9773	0.0013	0.9032	0.0009	0.8873	0.0006	0.9397	0.0007
A_1	-0.0315	0.0018	-0.0175	0.0013	-0.0167	0.0009	-0.0203	0.0011
A_2	-0.0023	0.0019	-0.0042	0.0013	-0.0094	0.0009	-0.0124	0.0011
B_1	0.0014	0.0011	0.0039	0.0008	0.0006	0.0006	-0.0004	0.0007
B_2	-0.0074	0.0013	-0.0043	0.0009	-0.0036	0.0007	-0.0036	0.0008

Table 7. Photometric elements of ZZ Cru for the zero third light

	V	B	L	U
i [°]	81.2	82.7	82.7	83.9
r_1	0.353	0.340	0.348	0.346
r_2	0.263	0.262	0.267	0.272
u	0.6	0.0	0.2	0.0
L_1	0.786	0.790	0.803	0.822
L_2	0.214	0.210	0.197	0.178

the LDST for the zero and relaxed third lights (in parenthesis) are as follows: i = 80.3° (85.1°), r_1 = 0.223 (0.175), r_2 = 0.211 (0.243), u = 0.4 (0.6), L_1 = 0.926 (0.527), L_2 = 0.074 (0.069) and L_3 = 0.000 (0.404). The solutions for the zero and relaxed third lights differ considerably and the amount of the relaxed third light is very high. While there is agreement between the geometric elements i, r_1 and r_2 found by the WD's code (Tables 4 and 5) and the LDST, other photometric elements considerably differ. Neither the WD's code nor the LDST is able to distinguish, which solution (with the zero or relaxed third light) reflects reality.

When using the paper outputs of Horák's computations for DT Lup, we found only photometric elements computed under the assumptions of the relaxed third light and the limb-darkening coefficient u = 0 as seen in Table 8.

The average geometrical elements: $i = 84.3 \pm 0.6°$; $r_1 = 0.216 \pm 0.003$; $r_2 = 0.306 \pm 0.002$ are in agreement with elements found by using the WD's code (Table 5) at the 3σ level.

Table 8. Photometric elements of DT Lup for $u = 0$, $L_1 + L_2 + L_3 = 1$

	V	B	L	U
i [°]	82.5	85.0	84.9	84.6
r_1	0.2080	0.2170	0.2198	0.2185
r_2	0.3087	0.3022	0.3040	0.3081
L_1	0.7290	0.7604	0.7876	0.7553
L_2	0.1865	0.1077	0.0888	0.1493
L_3	0.0845	0.1319	0.1236	0.0954

5. Conclusions

It is obvious that multicolour photoelectric light curves for the three systems presented here are superior to all previously published photometric data. Therefore, we may expect that the derived elements should supersede the elements found in current literature. However, we have to be cautious as the mutual comparison of the elements obtained by using two entirely independent approaches clearly shows that the accuracy of the elements is much lower than indicated by their formal errors in the WD's code. Part of the problem stems from rather poor coverage of all phases of some systems. We have found that ZZ Cru is a semi-detached binary with a negligible third light, while DT Lup is an almost detached system with an indeterminate contribution of the third light, showing the complexity of the binary. It is rather surprising that RU Gru as a well-detached system exhibits unexpectedly a large third light, most probably caused by a third body in the system. Good spectroscopy would almost certainly solve the issue. It is apparent that comprehensive photometric and spectroscopic studies of all three systems are quite desirable, particularly for the unequivocal determination of mass ratios q in the systems.

A cross-comparison of Horák's and WD's methods shows that the main virtue of Horák's approach is its independence in choice of starting parameters and a rather rapid convergence. While the geometric elements i, r_1, r_2 found by Horák's method are in good agreement with more sophisticated WD's method, the disagreement in other photometric elements including the amount of the third light is remarkable. It is probably a consequence of using simple spheres as poor approximations for true shapes of stellar components.

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Table 9. Normal points of ZZ Cru

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.00	0.4207	34	0.4333	34	0.3877	35	0.2604	34
0.01	0.3802	42	0.3922	42	0.3461	42	0.2109	42
0.02	0.2955	43	0.3015	43	0.2565	43	0.1124	43
0.03	0.2011	39	0.2066	39	0.1566	39	-0.0030	39
0.04	0.1070	29	0.1195	29	0.0576	29	-0.1075	29
0.05	0.0243	28	0.0245	28	-0.0279	27	-0.1931	27
0.06	-0.0458	26	-0.0509	26	-0.1058	25	-0.2871	25
0.07	-0.1024	22	-0.0997	22	-0.1715	21	-0.3682	21
0.08	-0.1599	22	-0.1583	22	-0.2292	21	-0.4217	21
0.09	-0.1943	18	-0.1995	18	-0.2692	18	-0.4587	18
0.10	-0.2170	13	-0.2162	13	-0.2876	13	-0.4878	13
0.11	-0.2344	15	-0.2406	15	-0.3040	15	-0.5126	15
0.12	-0.2457	15	-0.2583	15	-0.3233	15	-0.5310	15
0.13	-0.2418	16	-0.2591	16	-0.3387	16	-0.5441	16
0.14	-0.2447	17	-0.2512	17	-0.3471	17	-0.5288	17
0.15	-0.2624	16	-0.2700	16	-0.3424	16	-0.5379	16
0.16	-0.2706	17	-0.2867	17	-0.3376	17	-0.5472	17
0.17	-0.2668	21	-0.2926	21	-0.3376	21	-0.5577	21
0.18	-0.2684	21	-0.2788	21	-0.3325	21	-0.5530	21
0.19	-0.2729	24	-0.2807	24	-0.3419	24	-0.5551	24
0.20	-0.2778	23	-0.2882	23	-0.3649	23	-0.5638	23
0.21	-0.2926	19	-0.3020	19	-0.3720	19	-0.5705	19
0.22	-0.2966	18	-0.2999	18	-0.3607	18	-0.5687	18
0.23	-0.2837	17	-0.3008	17	-0.3630	17	-0.5689	17
0.24	-0.2841	14	-0.3043	14	-0.3683	14	-0.5661	14
0.25	-0.2964	10	-0.3081	10	-0.3675	10	-0.5726	10
0.26	-0.3053	9	-0.3064	9	-0.3750	9	—	0
0.27	-0.3168	9	-0.3076	9	-0.3890	9	—	0
0.28	-0.3137	13	-0.3134	13	-0.3870	13	—	0
0.29	-0.3052	22	-0.3162	22	-0.3747	22	-0.5865	20
0.30	-0.2949	28	-0.3133	28	-0.3736	28	-0.5856	28
0.31	-0.2860	29	-0.3003	29	-0.3703	29	-0.5687	29
0.32	-0.2847	25	-0.2918	25	-0.3617	25	-0.5609	25
0.33	-0.2864	21	-0.2982	21	-0.3627	21	-0.5748	21
0.34	-0.2793	17	-0.2848	17	-0.3639	17	-0.5731	17
0.35	-0.2658	15	-0.2669	15	-0.3490	15	-0.5599	15
0.36	-0.2718	17	-0.2718	17	-0.3451	17	-0.5641	17
0.37	-0.2679	14	-0.2713	14	-0.3445	14	-0.5615	14
0.38	-0.2493	13	-0.2507	13	-0.3309	13	-0.5419	13
0.39	-0.2485	18	-0.2456	18	-0.3299	18	-0.5430	18
0.40	-0.2547	24	-0.2481	24	-0.3371	24	-0.5464	24
0.41	-0.2432	30	-0.2436	30	-0.3215	30	-0.5346	30
0.42	-0.2111	31	-0.2181	31	-0.2934	31	-0.5095	31
0.43	-0.1762	30	-0.1865	30	-0.2743	30	-0.4811	30
0.44	-0.1484	25	-0.1591	25	-0.2534	25	-0.4663	25
0.45	-0.1215	23	-0.1369	23	-0.2249	23	-0.4394	23
0.46	-0.0914	22	-0.1088	22	-0.1866	22	-0.4097	22
0.47	-0.0509	17	-0.0733	17	-0.1526	17	-0.3763	17
0.48	-0.0143	21	-0.0439	21	-0.1203	21	-0.3563	21
0.49	0.0089	27	-0.0001	27	-0.0932	27	-0.3319	27

Table 9. Normal points of ZZ Cru (continued)

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.50	0.0201	31	0.0141	31	-0.0870	31	-0.3180	31
0.51	0.0102	37	-0.0004	37	-0.0899	37	-0.3234	37
0.52	-0.0107	39	-0.0273	39	-0.1102	39	-0.3376	34
0.53	-0.0387	38	-0.0573	38	-0.1381	38	-0.3689	30
0.54	-0.0839	33	-0.0982	33	-0.1760	33	-0.4141	25
0.55	-0.1290	28	-0.1455	28	-0.2170	28	-0.4545	20
0.56	-0.1696	19	-0.1798	19	-0.2552	19	-0.4752	16
0.57	-0.1924	12	-0.1968	12	-0.2819	12	-0.5050	12
0.58	-0.2150	12	-0.2207	12	-0.3166	12	-0.5268	12
0.59	-0.2336	12	-0.2378	12	-0.3264	12	-0.5327	12
0.60	-0.2442	15	-0.2500	15	-0.3283	15	-0.5406	15
0.61	-0.2558	18	-0.2588	18	-0.3357	18	-0.5448	18
0.62	-0.2673	19	-0.2744	19	-0.3524	19	-0.5592	19
0.63	-0.2624	19	-0.2828	19	-0.3536	19	-0.5656	19
0.64	-0.2638	20	-0.2830	20	-0.3596	20	-0.5654	20
0.65	-0.2679	18	-0.2863	18	-0.3630	18	-0.5628	18
0.66	-0.2758	21	-0.2897	21	-0.3564	18	-0.5695	18
0.67	-0.2851	28	-0.2874	28	-0.3648	25	-0.5775	25
0.68	-0.2894	30	-0.2825	30	-0.3624	27	-0.5764	27
0.69	-0.2893	30	-0.2846	30	-0.3669	27	-0.5755	27
0.70	-0.2990	27	-0.2940	27	-0.3782	27	-0.5818	27
0.71	-0.3011	20	-0.3065	20	-0.3836	20	-0.5904	20
0.72	-0.2989	16	-0.3097	16	-0.3727	16	-0.5932	16
0.73	-0.3006	16	-0.3045	16	-0.3734	16	-0.5967	16
0.74	-0.3061	19	-0.2982	19	-0.3919	19	-0.6059	19
0.75	-0.3104	24	-0.3043	24	-0.3952	24	-0.6001	24
0.76	-0.3042	28	-0.3059	28	-0.3871	28	-0.5903	28
0.77	-0.2955	32	-0.3025	32	-0.3768	32	-0.5861	32
0.78	-0.2935	33	-0.2962	33	-0.3725	33	-0.5835	33
0.79	-0.2908	32	-0.2993	32	-0.3767	32	-0.5756	32
0.80	-0.2863	33	-0.3004	33	-0.3767	33	-0.5741	33
0.81	-0.2915	26	-0.2993	26	-0.3762	26	-0.5845	26
0.82	-0.2909	18	—	0	-0.3721	18	-0.5833	18
0.87	—	0	-0.2587	9	—	0	—	0
0.88	-0.2431	16	-0.2425	16	-0.3195	16	-0.5402	16
0.89	-0.2212	22	-0.2355	22	-0.3134	22	-0.5211	22
0.90	-0.1982	28	-0.2161	28	-0.2869	28	-0.4843	28
0.91	-0.1744	30	-0.1820	30	-0.2546	30	-0.4428	30
0.92	-0.1487	34	-0.1547	34	-0.2223	34	-0.4158	34
0.93	-0.1063	37	-0.1093	37	-0.1807	37	-0.3787	37
0.94	-0.0543	36	-0.0459	36	-0.1243	36	-0.3185	36
0.95	0.0247	35	0.0367	35	-0.0404	35	-0.2122	35
0.96	0.1104	33	0.1155	33	0.0505	33	-0.1179	33
0.97	0.2011	33	0.1999	33	0.1419	33	-0.0243	33
0.98	0.2961	33	0.3072	33	0.2573	33	0.1054	33
0.99	0.3849	36	0.4001	36	0.3558	26	0.2202	36

Table 10. Normal points of RU Gru

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.00	2.1104	19	2.4058	19	2.5682	19	2.4999	19
0.01	2.0351	25	2.3067	25	2.4901	25	2.3964	25
0.02	1.9023	32	2.1524	32	2.3302	32	2.2460	32
0.03	1.7225	26	1.9604	26	2.1333	26	2.0558	26
0.04	1.5509	23	1.7863	23	1.9582	23	1.8793	23
0.05	1.4244	23	1.6458	23	1.8029	23	1.7626	23
0.06	1.3495	21	1.5719	21	1.7264	21	1.6750	21
0.07	1.3052	20	1.5388	20	1.6740	20	1.6329	20
0.08	1.2995	20	1.5242	20	1.6753	20	1.6247	20
0.09	1.3185	19	1.5304	19	1.6903	19	1.6415	19
0.10	1.3117	16	1.5331	16	1.7074	16	1.6412	16
0.11	1.3049	20	1.5411	20	1.7160	20	1.6250	20
0.12	1.2961	22	1.5175	22	1.6848	22	1.5895	22
0.13	1.3047	22	1.5169	22	1.6746	22	1.5934	22
0.14	1.3022	23	1.5230	23	1.6740	23	1.5911	23
0.15	1.2999	16	1.5324	16	1.6718	16	1.6109	16
0.16	1.3062	10	1.5262	10	1.6918	10	—	0
0.17	1.3014	10	—	0	1.6889	10	—	0
0.18	1.2943	10	—	0	—	0	—	0
0.19	1.2952	14	1.5328	14	1.6879	14	1.6057	14
0.20	1.2898	21	1.5193	21	1.6876	21	1.6283	21
0.21	1.2786	21	1.5085	21	1.6689	21	1.6177	21
0.22	1.2904	21	1.5195	21	1.6692	21	1.6108	21
0.23	1.3073	17	1.5337	17	1.6849	17	1.6165	17
0.24	1.3114	10	—	0	1.6868	10	—	0
0.31	1.2965	10	1.5023	10	1.6602	10	1.6092	10
0.32	1.2905	14	1.5056	14	1.6622	14	1.5981	14
0.33	1.2935	17	1.5081	17	1.6798	17	1.6074	17
0.34	1.2907	18	1.5235	18	1.6959	18	1.6083	18
0.35	1.2907	14	1.5226	14	1.6899	14	1.5823	14
0.36	1.2932	13	1.5135	13	1.6782	13	1.6005	13
0.37	1.2972	13	1.5203	13	1.6853	13	1.5954	13
0.38	1.3001	14	1.5292	14	1.7120	14	1.6097	14
0.39	1.2984	16	1.5307	16	1.6982	16	1.6378	16
0.40	1.2968	17	1.5296	17	1.6850	17	1.6343	17
0.41	1.3068	17	1.5268	17	1.6820	17	1.6288	17
0.42	1.2881	18	1.5110	18	1.6601	18	1.6030	18
0.43	1.2765	22	1.5136	22	1.6460	22	1.5949	22
0.44	1.2881	25	1.5262	25	1.6755	25	1.6121	25
0.45	1.2982	30	1.5342	30	1.6943	30	1.6332	30
0.46	1.3098	33	1.5340	33	1.6970	33	1.6275	33
0.47	1.3154	29	1.5340	29	1.6871	29	1.6234	29
0.48	1.3261	26	1.5425	26	1.6921	26	1.6215	26
0.49	1.3350	21	1.5508	21	1.6998	21	1.6202	21
0.50	1.3407	16	1.5503	16	1.6963	16	1.6351	16
0.51	1.3243	16	1.5448	16	1.6891	16	1.6476	16
0.52	1.3012	13	1.5370	13	1.6807	13	1.6366	13
0.61	1.2807	15	1.5171	15	1.6777	15	1.6035	15
0.62	1.2726	23	1.5153	23	1.6753	23	1.6235	23
0.63	1.2739	25	1.5127	25	1.6740	25	1.6183	25

Table 10. Normal points of RU Gru (continued)

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.64	1.2803	31	1.5088	31	1.6714	31	1.6062	31
0.65	1.2824	34	1.5129	34	1.6832	34	1.6102	34
0.66	1.2812	34	1.5206	34	1.6851	34	1.6103	34
0.67	1.2746	34	1.5230	34	1.6839	34	1.6007	34
0.68	1.2751	29	1.5207	29	1.6768	29	1.5927	29
0.69	1.2656	20	1.5157	20	1.6559	20	1.5851	20
0.70	1.2686	17	1.5176	17	1.6578	17	1.5992	17
0.71	1.2615	11	1.5138	11	1.6672	11	1.6218	11
0.72	1.2717	11	1.5119	11	1.6760	11	1.6352	11
0.73	1.2830	14	1.5159	14	1.6849	14	1.6515	14
0.74	1.2880	14	1.5251	14	1.6820	14	1.6346	14
0.75	1.2865	19	1.5292	19	1.7001	19	1.6148	19
0.76	1.2895	19	1.5280	19	1.6901	19	1.6291	19
0.77	1.2897	19	1.5241	19	1.6645	19	1.6357	19
0.78	1.2965	15	1.5268	15	1.6698	15	1.6283	15
0.79	1.2963	10	—	0	1.6702	10	—	0
0.83	1.2974	11	—	0	1.6798	11	—	0
0.84	1.2766	15	1.5275	15	1.6836	15	1.6141	15
0.85	1.2775	16	1.5208	16	1.7081	16	1.6115	16
0.86	1.2986	18	1.5353	18	1.7120	18	1.6195	18
0.87	1.3112	18	1.5406	18	1.6931	18	1.6427	18
0.88	1.3040	18	1.5286	18	1.6767	18	1.6291	18
0.89	1.2990	22	1.5308	22	1.6833	22	1.6416	22
0.90	1.3013	27	1.5302	27	1.6797	27	1.6383	27
0.91	1.3034	28	1.5294	28	1.6814	28	1.6402	28
0.92	1.3101	32	1.5322	32	1.6844	32	1.6363	32
0.93	1.3045	30	1.5374	30	1.6871	30	1.6252	30
0.94	1.3255	28	1.5627	28	1.7029	28	1.6272	28
0.95	1.4032	32	1.6346	32	1.7820	32	1.7140	32
0.96	1.5238	36	1.7593	36	1.9163	36	1.8630	36
0.97	1.6860	41	1.9450	41	2.0943	41	2.0297	41
0.98	1.8776	47	2.1235	47	2.2886	47	2.2230	47
0.99	2.0300	37	2.2810	37	2.4369	37	2.3874	37

Table 11. Normal points of DT Lup

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.00	1.7714	14	2.0962	14	2.1849	14	1.9644	14
0.01	1.6890	14	1.9941	14	2.0676	14	1.8741	14
0.02	1.4664	14	1.6932	14	1.7294	14	1.5855	14
0.03	1.2409	16	1.3967	16	1.4130	16	1.3089	16
0.04	1.0143	17	1.1284	17	1.1351	17	1.0427	17
0.05	0.8198	17	0.9038	16	0.8946	16	0.8073	16
0.06	0.6705	19	0.7437	18	0.7213	18	0.6469	18
0.07	0.5609	24	0.6305	21	0.6157	21	0.5443	21
0.08	0.4940	24	0.5626	21	0.5453	21	0.4831	21
0.09	0.4723	24	0.5343	22	0.5124	22	0.4414	22

Table 11. Normal points of DT Lup (continued)

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.10	0.4752	22	0.5339	20	0.5137	20	0.4400	20
0.11	0.4721	17	0.5325	17	0.5125	17	0.4387	17
0.12	0.4675	17	0.5251	17	0.5076	17	0.4316	17
0.13	0.4681	13	0.5235	13	0.5099	13	0.4402	13
0.14	0.4574	9	—	0	—	0	0.4445	9
0.18	0.4458	13	0.5091	7	—	0	—	0
0.19	0.4567	17	0.5160	11	0.5052	17	0.4470	17
0.20	0.4535	19	0.5210	16	0.4993	19	0.4267	19
0.21	0.4473	18	0.5166	18	0.4971	18	0.4113	18
0.22	0.4463	18	0.5081	18	0.4939	18	0.4096	18
0.23	0.4488	19	0.4997	19	0.4850	19	0.4093	19
0.24	0.4475	18	0.4996	18	0.4798	18	0.4058	18
0.25	0.4438	19	0.4986	19	0.4792	19	0.3909	19
0.26	0.4354	19	0.4967	19	0.4820	19	0.3944	19
0.27	0.4340	18	0.5035	18	0.4921	18	0.4004	18
0.28	0.4312	19	0.4969	19	0.4894	19	0.4032	19
0.29	0.4250	16	0.4899	16	0.4712	16	0.3900	16
0.30	—	0	0.4848	11	0.4580	11	0.3942	11
0.34	—	0	—	0	0.4691	10	—	0
0.35	0.4241	15	0.4983	15	0.4661	15	0.3678	15
0.36	0.4267	19	0.4974	18	0.4649	18	0.3651	18
0.37	0.4328	16	0.4945	16	0.4749	16	0.3778	16
0.38	0.4363	11	0.4879	11	0.4703	11	0.3874	11
0.41	—	0	—	0	0.4649	8	—	0
0.42	0.4317	10	0.5115	10	—	0	0.4140	10
0.43	0.4366	15	0.5138	15	0.4777	15	0.4054	15
0.44	0.4556	17	0.5207	17	0.4859	17	0.4039	17
0.45	0.4744	16	0.5337	16	0.4968	16	0.4208	16
0.46	0.4868	20	0.5389	20	0.5018	20	0.4322	20
0.47	0.4899	24	0.5331	24	0.5054	24	0.4461	24
0.48	0.5032	30	0.5434	30	0.5097	30	0.4433	30
0.49	0.5161	37	0.5575	37	0.5163	37	0.4493	37
0.50	0.5257	42	0.5608	42	0.5212	42	0.4575	42
0.51	0.5221	44	0.5571	42	0.5232	42	0.4676	42
0.52	0.5170	44	0.5514	41	0.5179	41	0.4398	41
0.53	0.5065	45	0.5486	42	0.5200	42	0.4254	42
0.54	0.4897	45	0.5421	42	0.5160	42	0.4311	42
0.55	0.4711	46	0.5340	44	0.5066	45	0.4350	45
0.56	0.4571	38	0.5239	37	0.4940	38	0.4154	38
0.57	0.4462	33	0.5174	32	0.4840	33	0.4031	33
0.58	0.4436	28	0.5044	27	0.4796	28	0.3981	28
0.59	0.4450	21	0.5053	21	0.4841	21	0.3965	21
0.60	0.4384	22	0.5038	22	0.4828	22	0.3799	22
0.61	0.4293	22	0.5018	22	0.4693	22	0.3784	22
0.62	0.4452	22	0.5002	22	0.4830	22	0.3844	22
0.63	0.4517	18	0.5021	18	0.4954	18	0.3995	18
0.64	—	0	—	0	0.4814	14	0.3895	14
0.68	0.4172	9	0.5043	7	—	0	—	0
0.69	0.4226	13	0.4980	11	0.4892	11	0.3962	11
0.70	0.4293	21	0.5035	19	0.4901	19	0.4011	19

Table 11. Normal points of DT Lup (continued)

Phase	ΔV	n	ΔB	n	ΔL	n	ΔU	n
0.71	0.4253	25	0.5008	25	0.4962	25	0.4065	25
0.72	0.4210	27	0.4966	26	0.4907	26	0.4044	26
0.73	0.4257	31	0.4945	29	0.4866	29	0.4022	29
0.74	0.4286	33	0.4993	31	0.4879	31	0.3981	31
0.75	0.4333	29	0.5035	27	0.4939	27	0.4035	27
0.76	0.4422	28	0.5122	27	0.4938	27	0.4091	27
0.77	0.4456	24	0.5061	24	0.4993	24	0.4168	24
0.78	0.4467	19	0.5004	19	0.4992	19	0.4231	19
0.79	0.4484	16	0.5034	16	0.4982	16	0.4228	16
0.80	0.4461	16	0.4967	15	—	0	0.4087	16
0.81	0.4466	16	0.5011	15	0.4983	16	0.4004	16
0.82	0.4478	16	0.5106	15	0.5027	16	0.4129	16
0.83	0.4501	17	0.5150	16	0.5052	17	0.4190	17
0.84	0.4555	13	0.5187	13	—	0	0.4150	13
0.85	0.4493	9	—	0	0.5084	9	0.4232	9
0.86	—	0	—	0	0.5177	6	0.4292	6
0.87	0.4548	7	0.5135	7	0.5079	7	0.4211	7
0.88	0.4563	11	0.5139	11	0.5022	11	0.4170	11
0.89	0.4690	15	0.5270	15	0.5016	15	0.4241	15
0.90	0.4685	18	0.5338	18	0.5014	18	0.4331	18
0.91	0.4683	18	0.5265	18	0.5106	18	0.4309	18
0.92	0.4874	17	0.5694	17	0.5536	17	0.4668	17
0.93	0.5605	17	0.6499	17	0.6290	17	0.5469	17
0.94	0.6681	17	0.7383	17	0.7349	17	0.6589	17
0.95	0.8110	16	0.8761	16	0.8898	16	0.8082	16
0.96	0.9819	17	1.0977	17	1.1038	17	1.0078	17
0.97	1.2015	16	1.3730	16	1.3863	16	1.2779	16
0.98	1.4607	15	1.6778	15	1.7222	15	1.5666	15
0.99	1.6720	15	1.9529	15	2.0247	15	1.8318	15

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