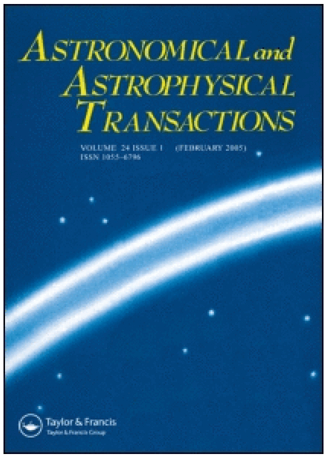

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Prediction of the component mass ratios for W UMa-type contact binary systems

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PREDICTION OF THE COMPONENT MASS RATIOS FOR W UMa-TYPE CONTACT BINARY SYSTEMS

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A new approach to the estimation of component mass ratios for close binary systems is suggested. 225 magnitudes of mass ratios for W UMa-type contact binaries, unobserved by spectroscopic methods, are restored by the ZET statistical method. 204 magnitudes of the spectral classes of the main components for this type of system are defined in an analogous way. The evolutionary types of some stars are specified as a matter of record. The efficiency of the ZET method for predicting these characteristics of W UMa-type contact systems is shown.

KEY WORDS Binary stars, contact binary stars, component mass ratios, ZET method

The mass ratio $q = M_2/M_1$ of the less massive to the more massive component is one of the important characteristics of W UMa-type contact binary systems. But sufficiently reliable values of q can be found only for a few contact systems with certain elements of their spectroscopic orbit. Mass ratios, obtained by the method of synthesis of theoretical light curves, are often far from the truth for other systems. This fact is due to asymmetry in the observed light curve and variance in the curve from night to night and from season to season for contact binary systems. Approximate estimation of mass ratios and other characteristics of eclipsing variable stars were made using individual orbital elements of stars and statistical relations such as mass–radius, mass–luminosity, etc. (Svechnikov and Kuznetsova, 1990). But the q values and other parameters obtained turned out to be inaccurate or even erroneous for many systems. This fact is due to the approximate character of the statistical dependencies and the lack of or unreliability of orbital elements for contact binaries. This is the reason for a new theoretical approach applied to estimate the mass ratios of W UMa-type contact systems. In this paper the mass ratios $q = M_2/M_1$ and the spectra of the more massive component Sp_1 for W UMa-type contact binary systems are computed by the ZET statistical method (Zagorujko *et al.*, 1985; Svirskaya and Voronova, 1993). Svechnikov's method unlike not only individual orbital elements of star are used to predict uncertain q value by the ZET method. Analogous elements (including the certain

q values) of some of these types of systems are also used to determine the uncertain mass ratios. They are the elements most similar to the orbital elements of the investigated star. So, unlike other statistical methods the individual approach to predicting the missing data is the characteristic feature of the ZET method. This is the reason for the sufficiently high prediction accuracy of this method.

The ZET algorithm is intended to predict uncertain elements in empirical "object–property" tables with dimension $M \times N$ and to verify the table or part of it. The rows (objects) of these tables have numbers $1, 2, \ldots, i, \ldots, M$ and the columns (properties) have numbers $1, 2, \ldots, j, \ldots, N$. The local linearity principle is the fundamental assumption of the ZET algorithm. The idea of the local linearity principle is the following. If property j of object i is unknown, the columns and rows most similar to row i and/or column j are selected from the table to predict the unknown element a_{ij}. Prediction of the element a_{ij} is carried out under the assumption of linear dependence between rows and/or columns of the formed submatrix. First element a_{ij} is predicted on the basis of the hypothesis of the linear dependence of the columns j and k. Linear regression coefficients b_{jk} and c_{jk} are obtained, using the certain elements of the j and k columns. Then the approximate value a_{ij}^k is computed as:

$$a_{ij}^k = b_{jk} a_{ik} + c_{jk}.$$

Prediction of the element a_{ij} on the basis of the remaining p columns which have no gaps in row i are carried out in an analogous way. The obtained approximate values of a_{ij} are averaged:

$$a_{ij}^{\text{col}} = \frac{\sum\limits_{k=1}^{p} a_{ij}^k Q_{kj}}{\sum\limits_{k=1}^{p} Q_{kj}},$$

where Q_{kj} is the k column weight, proportional to the linearity degree and the mutual occupancy of columns j and k. So

$$Q_{kj} = |r_{kj}|^{\alpha} L_{kj},$$

where r_{kj} is the coefficient of linear correlation and L_{kj} is the number of non-empty pairs of elements of columns j and k.

The individual parameter α is chosen for each gap (α ranges from 1 to 15). Predicting all the certain elements of containing cap column is carried out to determine the parameter α. The average relative error of predicting these elements for each value α is calculated. The minimum of this error is the criterion for the choice of the parameter α. Prediction by rows is fulfilled in an analogous way. If the average relative error, δ_j of predicting all the certain elements of column j is less than the corresponding error, δ_i of predicting all the certain elements of row i, then the prediction by columns a_{ij}^{col} is chosen as a final value of a_{ij}, and this error is chosen as the prediction error. If $\delta_i < \delta_j$, then $a_{ij} = a_{ij}^{\text{row}}$.

Five characteristics of stars listed by Svechnikov and Kuznetsova (1990), available for predicting the mass ratio and independent of it, were used to restore the

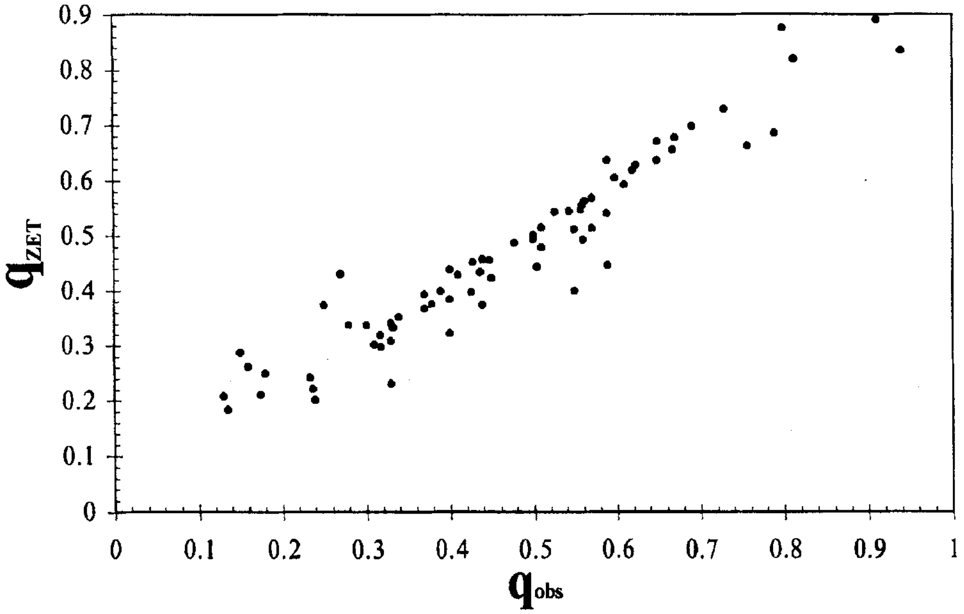

Figure 1 Comparison of observed mass ratios q_{obs} with those calculated by the ZET method.

uncertain q values: the spectral class of the more massive component Sp_1, the mass and absolute bolometric magnitude of the more massive component M_1 and M_{1b}, the value of the orbital semi-major axis A and the value of orbital inclination i. A table with the six parameters q, Sp_1, M_{1b}, M_1, A, i for 295 KW-type stars according to Svechnikov's classification (Svechnikov *et al.*, 1980) was compiled. The spectroscopic mass ratios were chosen as the certain q value. These mass ratios (altogether 70 values) and the corresponding available characteristics were taken from Svechnikov (1986), Webbink (1991) and from a number of articles (Rainger *et al.*, 1992; Lin Qing-yao *et al.*, 1991; Wang You-ru and Lu Wen xian, 1990; Bakos *et al.*, 1990; Yang Yu-lan *et al.*, 1991; Samec *et al.*, 1991; Hrivnak, Brucc, 1991; Rainger *et al.*, 1990; Hrivnak, 1990; Lapasset and Gomez, 1990; Kaluzny *et al.*, 1989; Linell *et al.*, 1989). Gaps were placed instead of the remaining q values.

All the certain elements of the first column were verified under a 5 × 5 submatrix. The average error of verification was 11.8%. This result shows the expediency of using the ZET method for the restoration of uncertain mass ratios for W UMa-type systems. The comparison of the observed mass ratios with those predicted by the ZET method under various submatrices was also carried out. The result is shown in the Figure 1. As seen in the Figure 1, the observed and calculated (by the ZET method) q values are close to each other and lie near to the line coming out from the coordinate beginning at 45° to the axis of the abscissae. This fact also shows the expediency of using the ZET method to solve the given problem.

Table 1. Comparison of mass ratios q_{ZET}, calculated by the ZET method, with mass ratios q_{S_ν} from Svechnikov and Kuznetsova (1990)

Star	q_{S_ν}	q_{ZET}	*Prediction error* (%)	*Relative error* (%)
EP And	0.50	0.26	0.7	95.5
GZ And	0.62	0.49	0.4	25.7
HU And	0.62	0.59	0.6	4.3
IM And	0.60	0.57	0.6	5.7
LO And	0.49	0.26	0.2	86.3
SW Ant	0.50	0.37	1.1	33.8
WZ Ant	0.32	0.25	1.0	26.7
AS Aps	0.56	0.48	2.5	15.5
GU Aps	0.33	0.23	2.6	45.2
GY Aps	0.50	0.41	1.6	23.0
IR Aps	0.50	0.41	1.5	20.8
IU Aps	0.58	0.56	2.0	3.7
IY Aps	0.52	0.41	2.0	25.4
KT Aps	0.46	0.51	0.1	10.2
LN Aps	0.31	0.55	1.1	43.4
AT Aqr	0.59	0.50	2.2	16.9
V417 Aql	0.48	0.72	1.9	33.3
V723 Aql	0.42	0.29	1.0	46.4
V784 Aql	0.39	0.38	1.3	3.1
V891 Aql	0.41	0.34	3.4	19.7
V956 Aql	0.46	0.28	1.9	66.8
V1341 Aql	0.59	0.48	1.5	23.5
V651 Ara	0.62	0.60	1.1	3.1
V653 Ara	0.70	0.64	0.3	9.6
V659 Ara	0.60	0.56	1.2	7.7
V702 Ara	0.42	0.52	0.6	19.5
V781 Ara	0.54	0.54	0.4	0.3
V791 Ara	0.46	0.40	1.7	15.3
AH Aur	0.60	0.57	0.9	6.1
TU Boo	0.54	0.40	0.9	33.4
TZ Boo	0.40	0.47	2.0	14.8
XY Boo	0.40	0.45	0.8	11.1
AR Boo	0.41	0.52	0.7	20.9
CK Boo	0.52	0.53	0.9	1.9
RV CVn	0.82	0.35	1.6	134.9
BI CVn	0.50	0.67	0.2	24.9
TU CMi	0.42	0.20	0.6	115.0

Actually, when predicting 225 uncertain q values on the basis of this table, 218 magnitudes were restored with an error of about 5%, and 7 magnitudes with an error of about 10%. The obtained values of $q(q_{\mathrm{ZET}})$ and a comparison of these values with mass-ratios q_{S_ν} from Svechnikov and Kuznetsova (1990) are given in Table 1. As seen from Table 1 the obtained data are essentially in accordance with the results published in a recent paper. The predicted mass ratios differ from the approximately estimated q values by less than 10% for almost 1/3 of the stars. The value differences shown are between 10% and 30% for more than 1/3 of the stars. The difference between q_{ZET} and q_{S_ν} is more than 30% for almost 1/3 of the stars.

Table 1. Continued

Star	$q_{S\nu}$	q_{ZET}	*Prediction error* (%)	*Relative error* (%)
TX CMi	0.37	0.38	2.9	3.1
AO Cam	0.60	0.54	1.9	10.7
BS Car	0.60	0.57	1.1	6.1
IR Car	0.46	0.55	0.5	16.3
IS Car	0.62	0.43	0.3	42.8
BS Cas	0.44	0.36	0.8	20.6
EY Cas	0.50	0.56	1.4	11.4
MR Cas	0.52	0.41	1.5	27.1
MT Cas	0.56	0.41	0.7	35.0
V480 Cas	0.50	0.44	1.9	13.2
V520 Cas	0.48	0.61	2.2	20.7
AS Cen	0.66	0.49	3.5	33.4
MV Cen	0.54	0.60	0.3	9.6
OP Cen	0.44	0.45	1.3	2.1
V349 Cen	0.43	0.38	1.5	12.9
V356 Cen	0.58	0.44	4.3	32.7
V508 Cen	0.48	0.57	1.6	15.6
V565 Cen	0.46	0.57	2.7	18.7
V594 Cen	0.56	0.43	0.5	28.8
V609 Cen	0.44	0.50	1.9	12.0
V615 Cen	0.39	0.27	2.1	42.2
V625 Cen	0.44	0.50	3.1	12.7
V677 Cen	0.59	0.62	1.6	4.3
V759 Cen	0.39	0.43	4.6	8.4
BE Cep	0.41	0.33	0.1	25.1
EP Cep	0.53	0.52	0.9	1.6
ES Cep	0.40	0.52	4.2	23.5
CG Cha	0.43	0.35	1.6	23.1
CH Cha	0.54	0.27	1.5	100.2
CX Cha	0.39	0.46	1.1	15.8
CY Cha	0.62	0.43	0.8	44.9
RW Com	0.40	0.57	5.5	29.8
SS Com	0.40	0.20	0.4	98.7
AQ Com	0.62	0.61	3.8	1.3
DD Com	0.54	0.55	2.3	1.3
EY Com	0.53	0.47	0.9	13.3
AY CrA	0.48	0.61	1.0	21.5
BG CrA	0.50	0.29	5.0	73.9
CR CrA	0.35	0.23	2.3	50.0
V465 CrA	0.44	0.25	0.5	74.5
V501 CrA	0.39	0.23	2.5	70.0
V571 CrA	0.42	0.23	0.7	83.4
V577 CrA	0.41	0.34	2.0	21.3
V634 CrA	0.59	0.58	0.6	1.1
W CrV	0.36	0.37	2.4	2.1
SX CrV	0.59	0.54	4.9	9.5
TW Cru	0.50	0.26	1.2	90.3
NU Cyg	0.62	0.62	1.8	0.1
NZ Cyg	0.39	0.26	0.3	48.6
PY Cyg	0.56	0.56	1.1	0.0
QU Cyg	0.55	0.45	2.7	21.7

Table 1. Continued

Star	$q_{S\nu}$	q_{ZET}	*Prediction error* (%)	*Relative error* (%)
V700 Cyg	0.54	0.15	0.7	258.8
V859 Cyg	0.39	0.40	1.1	3.2
V874 Cyg	0.40	0.42	2.8	4.5
V906 Cyg	0.46	0.44	0.3	3.9
V907 Cyg	0.42	0.20	1.3	114.9
V931 Cyg	0.52	0.61	1.7	14.4
V940 Cyg	0.52	0.59	1.8	11.4
V947 Cyg	0.42	0.40	1.5	5.4
V979 Cyg	0.48	0.44	1.8	8.9
V1044 Cyg	0.40	0.35	2.0	12.8
V1191 Cyg	0.58	0.45	1.5	28.2
V1200 Cyg	0.46	0.33	1.5	38.7
V1437 Cyg	0.44	0.26	5.8	68.6
V1902 Cyg	0.45	0.34	0.2	33.8
EW Del	0.46	0.40	0.3	14.0
EX Del	0.45	0.25	0.9	79.2
FR Del	0.42	0.39	1.8	6.4
BV Dra	0.41	0.35	5.5	18.1
BW Dra	0.32	0.48	1.2	33.3
UX Eri	0.44	0.42	1.7	4.0
BL Eri	0.50	0.44	8.4	12.7
AH Gem	0.52	0.75	0.4	30.8
HY Gem	0.50	0.50	1.3	0.4
RV Gru	0.78	0.71	1.3	10.6
BH Gru	0.46	0.40	0.4	15.1
V412 Her	0.48	0.45	1.8	7.0
V426 Her	0.65	0.57	0.7	15.0
V477 Her	0.50	0.46	1.2	7.8
V502 Her	0.35	0.37	0.5	5.0
V513 Her	0.60	0.57	1.8	5.6
V516 Her	0.48	0.29	0.9	65.4
V687 Her	0.52	0.40	1.5	30.6
V718 Her	0.54	0.50	0.4	8.7
SZ Hor	0.48	0.53	1.7	9.9
AE Hya	0.52	0.36	0.7	45.3
AE Hya	0.48	0.34	1.9	41.4
RT Hyi	0.62	0.58	0.6	7.8
EM Lac	0.44	0.26	0.7	67.4
HR Lac	0.46	0.39	1.0	18.1
LU Lac	0.57	0.51	0.9	12.6
BL Leo	0.50	0.57	1.7	11.9
BW Leo	0.56	0.46	0.8	20.8
BZ Leo	0.68	0.64	3.0	6.1
CE Leo	0.60	0.46	1.5	30.2
RT LMi	0.48	0.39	1.0	24.0
VZ Lib	0.46	0.27	0.4	73.0
DG Lup	0.50	0.42	6.8	18.8
FS Lup	0.44	0.34	1.0	28.3
PY Lyr	0.46	0.42	0.9	9.1
V417 Lyr	0.58	0.47	0.9	22.6
V423 Lyr	0.40	0.30	1.2	34.9

Table 1. Continued

Star	q_{Sp}	q_{ZET}	*Prediction error* (%)	*Relative error* (%)
V431 Lyr	0.45	0.28	1.0	60.1
UZ Mic	0.50	0.43	0.9	16.9
AH Mic	0.44	0.47	0.7	6.6
V396 Mon	0.46	0.25	1.1	81.5
V524 Mon	0.70	0.66	0.1	6.4
TW Mus	0.42	0.27	1.2	55.8
BE Mus	0.54	0.41	0.2	31.4
GN Mus	0.30	0.30	0.6	1.5
SV Nor	0.32	0.36	1.3	9.9
GX Nor	0.70	0.83	0.9	16.1
BK Oct	0.50	0.44	1.9	13.8
V878 Oph	0.43	0.40	2.1	8.4
V938 Oph	0.55	0.44	2.1	25.7
V940 Oph	0.42	0.42	0.5	0.4
V943 Oph	0.47	0.56	4.7	16.8
V945 Oph	0.56	0.44	0.7	28.1
V947 Oph	0.52	0.49	1.3	5.4
V954 Oph	0.76	0.54	1.2	40.3
V963 Oph	0.70	0.60	3.8	16.9
V1022 Oph	0.80	0.63	1.2	27.4
V1120 Oph	0.54	0.59	0.6	9.2
V1305 Oph	0.34	0.27	1.2	23.7
V1811 Oph	0.40	0.27	0.7	47.1
FZ Ori	0.50	0.72	1.4	30.2
BF Pav	0.58	0.49	0.6	18.1
HP Pav	0.58	0.49	0.3	18.6
HY Pav	0.43	0.43	1.3	1.1
LR Pav	0.42	0.39	1.4	7.3
LT Pav	0.45	0.43	0.9	4.3
LY Pav	0.30	0.34	1.6	12.9
MS Pav	0.48	0.49	0.7	2.5
GW Peg	0.40	0.24	0.2	64.7
V364 Per	0.40	0.51	1.1	21.7
V432 Per	0.48	0.43	1.0	12.1
YZ Phe	0.60	0.53	0.9	13.3
X PsA	0.41	0.36	2.6	14.0
AF Pup	0.38	0.42	1.3	9.9
AY Pup	0.30	0.30	1.2	0.2
DS Pup	0.37	0.35	0.6	5.4
GY Pup	0.25	0.42	2.4	40.4
GZ Pup	0.65	0.53	1.1	21.6
EI Sge	0.36	0.33	1.1	8.4
V431 Sgr	0.62	0.63	4.1	1.9
V496 Sgr	0.74	0.56	6.2	32.1
V497 Sgr	0.58	0.52	0.7	12.1
V743 Sgr	0.32	0.56	4.1	43.2
V779 Sgr	0.50	0.23	0.6	118.3
V902 Sgr	0.62	0.42	2.5	47.1
V985 Sgr	0.47	0.74	0.2	36.1
V1000 Sgr	0.45	0.25	3.1	79.2
V1002 Sgr	0.50	0.49	1.2	2.8

Table 1. Continued

Star	$q_{S\nu}$	q_{ZET}	*Prediction error* (%)	*Relative error* (%)
V1026 Sgr	0.40	0.24	0.9	67.6
V1068 Sgr	0.40	0.48	1.7	16.4
V1723 Sgr	0.60	0.58	1.9	3.1
V3501 Sgr	0.52	0.54	0.4	3.4
CF Sco	0.72	0.51	1.4	40.1
V412 Sco	0.52	0.49	2.0	7.0
V625 Sco	0.44	0.29	0.7	49.2
V821 Sco	0.60	0.44	1.0	35.3
V842 Sco	0.70	0.46	7.0	52.4
SZ Scl	0.48	0.43	0.8	12.1
DE Sct	0.58	0.38	1.3	52.3
DL Sct	0.64	0.42	1.4	51.2
EK Sct	0.65	0.25	3.4	159.7
FG Sct	0.70	0.77	3.4	9.4
DG Ser	0.60	0.68	1.8	11.8
CU Tau	0.38	0.43	0.2	11.0
EQ Tau	0.40	0.45	1.5	10.7
V778 Tau	0.32	0.16	0.8	94.6
AB Tel	0.60	0.51	1.0	16.6
NN Tel	0.37	0.24	1.1	55.7
NP Tel	0.40	0.40	0.8	0.2
AS TrA	0.38	0.47	1.0	18.7
IW TrA	0.56	0.54	1.1	3.8
UY UMa	0.35	0.37	0.4	6.6
BM UMa	0.70	0.75	1.5	7.2
RZ UMi	0.46	0.46	2.5	0.3
BO Vel	0.40	0.46	1.1	13.5
BP Vel	0.68	0.70	0.8	2.6
BT Vel	0.56	0.49	1.7	14.9
FM Vel	0.38	0.29	0.6	31.3
AW Vir	0.39	0.31	1.5	26.8
GR Vir	0.46	0.44	3.5	5.4
HS Vul	0.43	0.45	0.4	5.0
KN Vul	0.39	0.52	1.4	24.9
NO Vul	0.39	0.32	1.0	23.3

Note. Prediction error is the least of the average relative errors of predicting all the certain elements of gap containing column and row. The relative error is the error of predicting the mass ratios by the ZET method q_{ZET} in comparison with the mass ratios $q_{S\nu}$ from Svechnikov and Kuznetsova (1990): $\Delta = \frac{|q_{ZET} - q_{S\nu}|}{q_{ZET}} \cdot 100\%$.

A comparison of q values calculated by the ZET method and approximately estimated values of q with observed data (Webbink, 1991; Svechnikov, 1986, etc.) was carried out. Results are given in Table 2. As seen from Table 2 the obtained q values are generally a best fit to the observed data in comparison with Svechnikov's data.

The calculated values of q were used instead of the gaps. The spectra of the main component were also predicted in an analogous way. Data from the above mentioned

Table 2. Comparison of observed mass ratios q_{obs} with mass ratios in the ZET method q_{ZET} and mass ratios from Svechnikov and Kuznetsova (1990) $q_{S\nu}$.

Star	q_{obs}	q_{ZET}	$q_{S\nu}$
AB And	0.62	0.62	0.6
AY Aqr	0.59	0.64	0.64
SS Ari	0.33	0.34	0.39
TY Boo	0.44	0.43	0.52
VW Boo	0.43	0.45	0.5
AC Boo	0.28	0.34	0.38
AH Cnc	0.44	0.46	0.5
CW Cas	0.54	0.54	0.56
V523 Cas	0.57	0.57	0.74
V752 Cen	0.32	0.32	0.36
V757 Cen	0.67	0.68	0.64
WZ Cep	0.33	0.33	0.41
EQ Cep	0.41	0.43	0.52
ER Cep	0.65	0.67	0.6
GW Cep	0.37	0.39	0.56
VY Cet	0.56	0.55	0.42
RZ Com	0.48	0.49	0.48
CC Com	0.51	0.51	0.56
FS CrA	0.76	0.66	0.66
LS Del	0.57	0.51	0.48
RW Dor	0.56	0.49	0.6
YY Eri	0.65	0.64	0.56
AK Her	0.23	0.24	0.38
SY Hor	0.56	0.56	0.56
FG Hya	0.13	0.2	0.42
ST Ind	0.24	0.2	0.4
PP Lac	0.33	0.31	0.44
XY Leo	0.79	0.68	0.52
AM Leo	0.43	0.4	0.36
AP Leo	0.3	0.34	0.46
TV Mus	0.14	0.18	0.25
V502 Oph	0.38	0.37	0.46
V566 Oph	0.24	0.22	0.3
V839 Oph	0.59	0.45	0.38
U Peg	0.33	0.33	0.4
BB Peg	0.35	0.35	0.42
AD Phe	0.94	0.83	0.35
RW PsA	0.81	0.83	0.44
HI Pup	0.18	0.25	0.35
AU Ser	0.8	0.87	0.36
Y Sex	0.17	0.21	0.46
AH Tau	0.5	0.44	0.4
AH Vir	0.32	0.3	0.4
AZ Vir	0.5	0.5	0.4

references and spectroscopic data from Svechnikov and Kuznetsova (1990) were also taken as the certain values of Sp_1 (altogether 91 values). Actually, when predicting 204 uncertain Sp_1 values, 198 magnitudes were defined with an error of about 5% and three magnitudes with an error of about 10% and 15%, respectively.

The obtained values of Sp_1 turned out to be similar to the spectra approximately estimated by Svechnikov and Kusnetsova (1990) for the majority of systems, but the difference between the obtained and approximately estimated values of Sp_1 exceeded one spectral class for 1/5 of the systems. The spectra of some of these stars turned out to be earlier than AO. So systems such as GU Aps, AR Boo, OP Cen, AH Cem, V947 Cyg, V431 Lur, DG Lup, V938 Oph, V940 Oph, AF Pup, AY Pup, V842 Sco, perhaps, belong to contact systems of early spectra of primaries (according to Svechnikov's classification).

The obtained results allow us to conclude that the prediction of the mass ratios q and the spectra Sp_1 for W UMa-type systems by the ZET method is possible.

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