THE CORRELATIONS BETWEEN THE PARAMETERS OF THE SHARPNESS OF THE LIGHT CURVE AND PERIOD FOR MIRAS

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Abstract: We have considered the dependence of the sharpness of the mean light curves of Mira-type stars on the period. The correlation coefficients and regression lines have been calculated. We have derived the variations of the mean light curve depend on variations of the ascending branch versus period only.

INTRODUCTION

The study of the variations of the light curves of the Mira-type stars is the main aim of this work.
Earlier, the deviations of the shape of the light curve from the mean one for Miras were explained by the influence of the molecular band abundance only. However, at present time, different investigations show the real variations of the shape of the light curve, which are connected to the difference of the physical conditions and the evolutionary stages of the stars at the AGB.
The asymmetry of the light curve may be owed to a power of the shock wave from the stellar pulsation (Vardya, 1987). The results of investigation of the hump duration (Kudashkina, 1994) indicate a connection to the variations of the ascending branch and the shock wave too. Moreover, the shape of the light curve can give information about the mode of the stellar pulsations, if to use it together with the color index curves, as it is was proposed by the authors (Dawson, 1988) for 60 objects.
Clearly, the stars with the stable pulsations will have a most stable shape of the light curve. In those stars, the pulsating zone is localized and is separated from the convective zone. Also, there are no helium flashes in those stars. The light curves of those stars have no strong variations from cycle to cycle.
We have introduced new parameters for characteristics of the light curve (Kudashkina, 1996). Here we consider the sharpness of the light curve only.

Database and mathematical methods

The amateur databases of the AFOEV (ftp://cdsarc.u-strasbg.fr/pub/afoev), VSOLJ (http://www.kusastro.kyoto-u.ac.jp/vsnet/VSOLJ) and AAVSO (Mattei, 1979) were used for our investigations of LPVs. The programs used for data reduction of these observations were described by (Andronov, 1994; Andronov and Marsakova 2006).
The AAVSO light curves of Miras (time interval is 1000 days) were digitized to obtain the values with a 10^d step. These data were fitted by a trigonometric polynomial

$$m(t) = a_0 - \sum_{k=1}^{s} r_k \cos 2\pi k \frac{(t-t_k)}{P}, \qquad (1)$$

where r_k are semi-amplitudes and t_k are initial epochs for the brightness maximum (minimum magnitude) of the wave with a period P_k=P/k. The value of the main period was corrected by using the method of differential corrections. The computer program FOUR-M (1) was used. The phases of the individual waves are computed as $\varphi_k = FLOAT\left(k\frac{(t_k - T_0)}{P}\right)$, where T_0 is the initial epoch and FLOAT(x)=x-INT(x) is a decimal part of *x* defined in the range from 0 to 1.
The mean curves of Miras and the tables of their parameters obtained from the AAVSO data are given in the article by (Kudashkina, 1996).
Below we list some of the parameters:
P - the period of the light variation;
r_1 - amplitude of the wave with a frequency f_1;
f="M-m" - the asymmetry of the light curve defined as the ratio of the duration of the ascending branch to the period;
m_i - $\frac{dm(t)}{dt}$ - the maximal slope of ascending branch;

m_d - $\frac{dm(t)}{dt}$ - the maximal slope of descending branch;

t_i - $\frac{dt}{dm}$ - the characteristic time of the increase of brightness (ascending branch) by 1^m;

t_d - $\frac{dt}{dm}$ - the characteristic time of the decrease of brightness (descending branch) by 1^m.

m_{is} - $\frac{\left(\frac{dm}{dt}\right)_{curve}}{\left(\frac{dm}{dt}\right)_{\sin}}$, where $\left(\frac{dm}{dt}\right)_{\sin} = \pi \frac{m_{\min} - m_{\max}}{P}$ - for ascending branch;

m_{ds} - the same for the descending branch.

Results

For the analysis, we have used the values of the parameters given in the table 3. The following regression relationships have been obtained:

lg m_i = (-0.56 ± 0.16) lg P + (0.12 ± 0.40), (2)
lg m_d = (-0.91 ± 0.10) lg P - (0.90 ± 0.24), (3)
lg t_d = (0.83 ± 0.10) lg P - (0.73 ± 0.25), (4)
lg t_i = (0.53 ± 0.15) lg P - (0.10 ± 0.36), (5)
lg t_i = (0.59 ± 0.07) lg P - (0.22 ± 0.15) (6)

W And is not included in equations (2) and (3), because this star have extremally large amplitude. X Oph is not included to equation (3) because this binary star is far from other stars on the graphic. The relationship (6) is derived without small-amplitude stars. For details, see subsection 3.
The correlation coefficients for these relationships are given in the table 1.

Table 1. The correlation coefficients for the relationships.

Relationship	ρ	ρ/σ_ρ	N
lg m_i — lg P (2)	-0.41	-3.42	61
lg m_d — lg P (3)	-0.77	-9.20	61
lg t_d — lg P (4)	0.73	8.11	61
lg t_i — lg P (5)	0.42	3.60	62
lg t_i — lg P (6)	0.85	8.84	32

Remarks: ρ is the correlation coefficient, σ_ρ is it's error estimate, N is the number of stars.

1. The relation "lg m_i - lg P"

The parameter m_i is the value of the sharpness of the ascending branch of the mean light curve at the point of the maximal sharpness. The significant distinction of the modules of the coefficient at lg P in the equation (2) points to existence statistical dependence between the slope of the ascending branch on the period for the majority of the stars. See fig. (1).
The group of the eight stars stand out for the others. They will be discussed in the subsection 3.

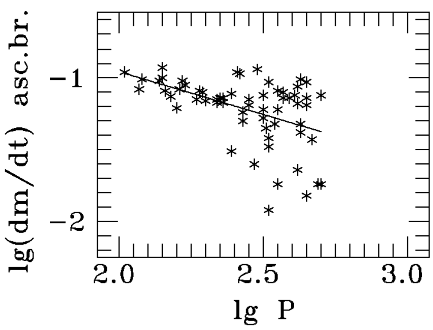

Fig. (1). The relationship between the sharpness of the ascending branch and period in the logarithmic aspect.

2. The relation "lg m_d - lg P"

The absolute value of the coefficient of the slope regression line of relationship (3) is close to 1 (0.91±0.10). It means, that the variation of the slope of the descending branch does not depend statistically on the period. In other words, the amplitude of the descending branch does not show any strong dependence on the period. This relationship may be explained as trivial. See fig. (2).

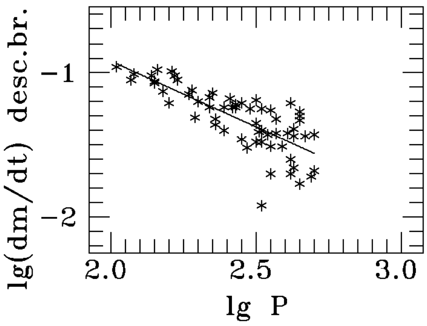

Fig. (2). The relationship between the sharpness of the descending branch and period is trivial.

3. The relation "lg t_i - lg P"

The coefficient of the slope of the regression line of relationship (4) differs from unity also significantly. It means, that the increasing of brightness by 1^m depends statistically on the period for the majority of stars. See fig. (3).

The group of the eight stars stands out in respect to the others. These stars are listed in table 2, part 1. The general property of these stars separating them from others is a very small amplitude. If to exclude from the consideration the stars from the table 2, part 1, then the graphic will look as in the figure 4. Now, we see the 18 stars, for which the value of the increasing of the brightness by 1^m is constant with period. One third of them are S-Miras.

Among others, prevail the stars of the late spectral subtype. As t_i is a time in days, it may be supposed that the characteristic time of the increase of the brightness does not depend on any photometric parameter, including the period and is constant for Miras approaching to the final stage of their evolution. For earlier Miras is the clear dependence t_i on the amplitude of the brightness. Note, the correlation coefficient between Δm_V (amplitude of the brightness) and t_i is equal to 0.60 ($\rho\backslash\sigma_\rho = 5.6$), and between r_1 and t_i equals 0.67 ($\rho\backslash\sigma_\rho = 7.0$).

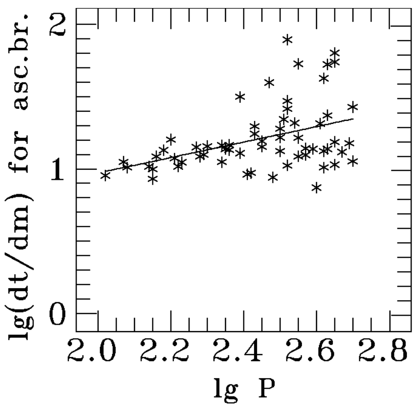

Fig. (3). The relationship between the characteristic time of the increase of the brightness by 1^m on the period in the logarithmic aspect.

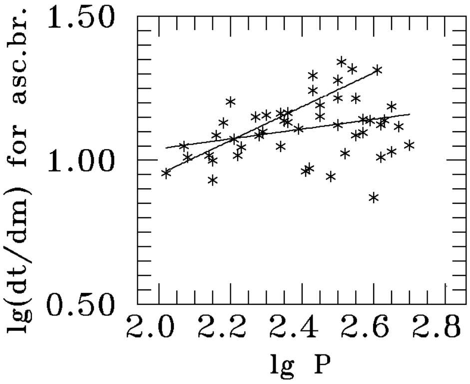

Fig. (4). The relationship is derived for stars except that listed in the table 2, part 1.

4. The relation "lg t_d - lg P"

The coefficient of the slope regression line of this relationship is close to 1 (0.83±0.10). It means that the variation of the time of the light decreasing on 1^m does not depend statistically on the period as the case considered in the section 3.3. This relationship is trivial also. See fig.(5).

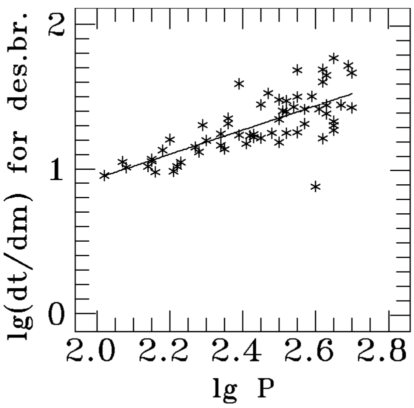

Fig. (5). The relationship between the decrease of the brightness by 1^m on the period is trivial.

5. The relation "lg m_{is} - lg P"

The correlation coefficient for this relationship equals to 0.48±0.11 and the ratio "signal/noise" is equal to 4.26. The number of the stars is 62.

We consider that the parameter m_{is} correlates with the period. It means that, for the larger period, the ascending branch more differs from a sinusoid. (Fig. 6).

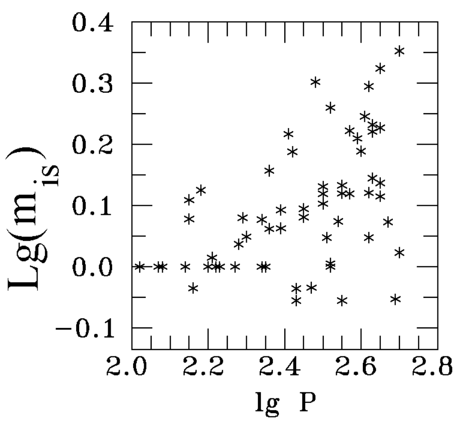

Fig. (6). The relationship has the correlation coefficient ρ =0.48 ($\rho\backslash\sigma_\rho$ = 4.26).

6. The relation "lg m_{ds} - lg P"

This diagram does not show any correlation. (Fig. 7). It is considered once more, that the descending branch varies independently on the period.

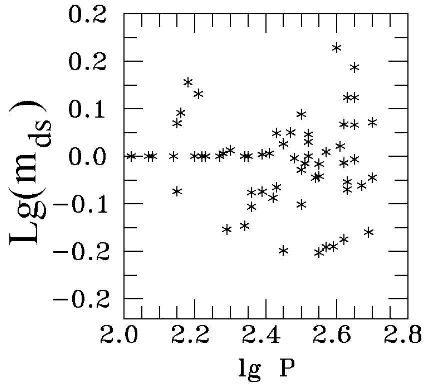

Fig. (7). The diagram does not show the correlation.

7. The phases of the maximal sharpness of the branches of the light curve

On the figures 8 and 9, the phases of the maximal sharpness of the branches are shown versus period. These relationships do not show correlations. Note, that the parameters "phase m_i" and "phase m_d" show no correlations.

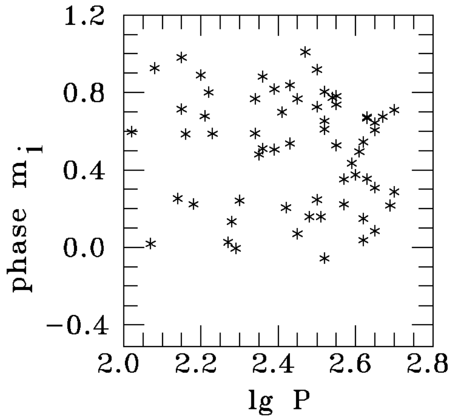

Fig. (8). The relationship of the phase of maximal sharpness of the ascending branch relative to the phase of the maximum brightness versus period.

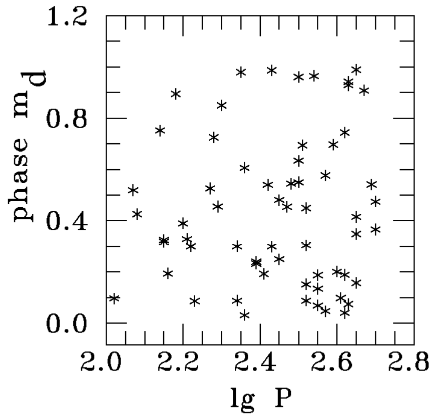

Fig. (9). The relationship of the phase of maximal sharpness of the descending branch relative to the phase of the maximum brightness versus period.

8. The relation "asymmetry - period"

The classical asymmetry f=(M-m)/P shows no correlation with period. (Fig 10). However, the parameter f correlates with 11 other parameters, which are listed in the article by (Kudashkina, 1996; Kudashkina, 1997).

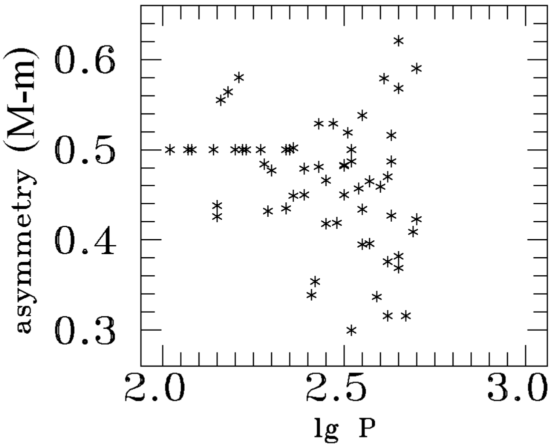

Fig. (10). The relationship of the classical asymmetry versus period.

Table 2 (part 1). The small-amplitude stars.

N	Star	Period, d	Sp.type	Δm_V	m_i	t_i
1	Y Per	247.1	C4.3e(R4e)	2.01	.031	31
2	BG Cyg	292.2	M7e-M8e	2.55	.025	33
3	X Oph	327.7	M5e-M9e	1.34	.012	78
4	V Aur	353.7	C6.2e(N3e)	2.40	.018	53
5	W Cas	417.7	C7.1e	2.81	.023	42
6	X Cas	441.9	C5.4e(N1e)	1.71	.015	63
7	U Cyg	484.5	C7.2e-C9.2(N)	3.30	.018	53
8	S Cep	503.5	C7.4e(N8e)	2.77	.018	55

Table 2 (part 2). The late-spectral type stars.

N	Star	Period, d	Sp.type	Δm_V	m_i	t_i
1	T UMa	257.0	M4IIIe-M7e	5.41	.109	9
2	RS UMa	261.1	M4e-M6e	5.76	.106	9
3	R UMa	301.5	M3e-M9e	5.46	.114	9
4	T UMi	316.7	M4e-M6e	5.63	.075	13
5	o Cet	333.5	M5e-M9e	5.52	.094	11
6	R Ser	353.6	M5IIIe-M9e	6.81	.082	12
7	R Gem	368.9	S2.9e-S8.9e	6.46	.072	14
8	T Cam	374.8	S4.7e-S8.5e	5.74	.080	12
9	U Ori	385.6	M6e-M9.5e	5.51	.072	14
10	W And	399.2	S6.1e-S9.2e	11.0	.134	7
11	U Aur	410.5	M7e-M9e	5.66	.076	13
12	U Her	414.9	M6.5e-M9.5e	4.45	.066	15
13	χ Cyg	421.5	S6.2e-S10.4e	8.99	.088	11
14	R And	426.2	S3.5e-S8.8e	7.78	.097	10
15	R Cyg	443.8	S3.9e-S6.9e	6.73	.065	15
16	R Cas	443.9	M6e-M10e	6.25	.093	11
17	R Aur	448.0	M6.5e-M9.5e	6.14	.072	14
18	V Cam	503.5	M7e	5.37	.075	13

Remarks: The Spectral types are from GCVS (Khopolov, 1985), other data are from (Kudashkina, 1996).

Discussion

For a detailed classification of Mira-type stars, we propose to use three groups of the parameters: fundamental (P - period, Δm_V - visual amplitude, f - asymmetry); additional (s, r_k, φ_k) and the slopes of the light curve branches (m_i, m_d, t_i, t_d, m_{is}, m_{ds}). The analysis of the correlations between the last group of the parameters and the period has been carried out. It is possible to conclude the following:
(1) The variations of the light curve shape of the Mira-type stars versus period connect with the dependence of the slope of the ascending branch versus period only.

(2) For late spectral subclasses S and O Miras, the asymmetry of the light curve is constant (m_i practically independ on the period).
(3) The sequence of the small-amplitude stars exists. This sequence includes mainly the carbon-rich miras.
Our investigations, including the works (Kudashkina, 1999; Kudashkina, 2003), show that the stars may be subdivided into the groups. Within each group, the stars can be disposed to increasing of the periods. However, we have to take into account the following. The stars of different stellar population have different values of the parameters for the same evolutionary stage. And the difference of the masses also causes uncertainty in the interpretation. Nevertheless, we can choose the spectral type as "zero-mark". Already Keenan (1989) has determined that the spectral type becomes later, while the period increases. It is also the problem. The spectral class of the Miras varies from minimum to maximum on 6 subclasses and more (Terrill, 1969). May one use mean value of the spectral type? Or it is necessary to use only spectral type at minimum? Apparently, the minimum of the brightness is the characteristics of the evolutionary stage for Mira-type star.
Nevertheless, we accept for short period the earlier AGB-stage and the calculating Fourier-coefficients for their light curves attribute to earlier AGB-stars.
Taking into account the results of the works (Kudashkina, 1999; Kudashkina, 2003), we accept that the early-AGB stars have the symmetrical light curve.
Thus, the analysis of the correlation concerning the asymmetry of the light curve of the Mira-type stars indicates the real modifications of the shape of the light curve during the evolution of the star at the AGB.

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Table. The values of the parameters of the sharpness of the mean light curves of Mira-type stars in the place of the most slope.

Star	lgP	F	m_i	t_i	φ (m_i)	m_d	t_d	φ (m_d)	m_{is}	m_{ds}
RTCyg	2.28	.484±.014	-.082±.003	-12.2±0.5	0.133	.076±.003	13.1±0.5	0.725	1.09±.04	1.01±.04
RVir	2.16	.555±.019	-.082±.006	-12.2±1.0	0.585	.105+.006	9.5±0.6	0.194	.92±.07	1.18±.07
R Vul	2.14	.500±.001	-.096±.004	-10.4±0.5	0.252	.096±.004	10.4±0.5	0.752	1.00±.05	1.00±.05
RZ Sco	2.20	.500±.001	-.062±.003	-16.0±0.7	0.890	.062±.003	16.0±0.7	0.390	1.00±.05	1.00±.05
S Car	2.18	.564±.115	-.074±.007	-13.5±1.2	0.223	.074±.007	13.5±1.2	0.895	1.33±.12	1.33±.12
SS Cas	2.15	.426±.018	-.100±.004	-10.0±0.4	0.981	.089±.004	11.3±0.5	0.324	1.28±.05	1.14±.05
SSHer	2.02	.500±.001	-.110±.005	-9.0±0.4	0.597	.111±.005	9.0±0.4	0.097	1.00±.05	1.00±.05
T Her	2.22	.500±.001	-.096±.002	-10.4±0.2	0.801	.096±.002	10.4±0.2	0.301	1.00±.02	1.00±.02
V Tau	2.23	.500±.001	-.090±.002	-11.1±0.3	0.587	.090±.002	11.1±0.3	0.087	1.00±.03	1.00±.03
W Lyr	2.30	.477±.023	-.069±.004	-14.3±0.9	0.242	.064±.004	15.7±1.1	0.849	1.12±.07	1.02±.07
X Cam	2.15	.438±.017	-.117±.007	-8.5±0.5	0.713	.085±.007	11.7±0.9	0.318	1.19±.07	.87±.07
R Ari	2.27	.500±.001	-.070±.002	-14.1±0.4	0.026	.070±.002	14.1±0.4	0.526	1.00±.03	1.00±.03
RRBoo	2.29	.432±.016	-.079±.005	-12.6±0.7	-0.005	.049±.005	20.1±2.0	0.455	1.20±.07	.75±.07
X Aur	2.21	.580±.024	-.084±.007	-11.8±1.0	0.679	.103±.007	9.6±0.7	0.328	1.04±.09	1.27±.09
SY Her	2.07	.500±.001	-.089±.003	-11.2±0.4	0.019	.089±.003	11.2±0.4	0.519	1.00±.03	1.00±.03
W Pup	2.08	.500±.001	-.097±.005	-10.2±0.5	0.926	.097±.005	10.2±0.5	0.426	1.00±.05	1.00±.05
BG Cyg	2.47	.529±.012	-.025±.001	-39.4±1.9	1.010	.030±.001	33.3±1.1	0.454	.93±.04	1.09±.04
R Aql	2.45	.418±.007	-.064±.002	-15.5±0.4	0.070	.035±.002	27.8±1.3	0.481	1.24±.03	.69±.03
R Boo	2.35	.500±.001	-.073±.001	-13.7±0.2	0.480	.073±.001	13.7±0.2	0.980	1.00±.02	1.00±.02
R Dra	2.39	.450±.009	-.077±.002	-12.9±0.4	0.817	.058±.002	17.1±0.7	0.240	1.16±.04	.87±.04
RS Her	2.34	.500±.001	-.068±.001	-14.6±0.3	0.588	.068±.001	14.6±0.3	0.088	1.00±.02	1.00±.02
RS UMa	2.42	.354±.014	-.106±.004	-9.4±.4	0.205	.058±.004	17.0±1.1	0.540	1.54±.06	.85±.06
R Tri	2.43	.481±.006	-.057±.003	-17.5±1.0	0.838	.058±.003	17.3±1.0	0.299	.88±.05	.89±.05
S Boo	2.43	.529±.011	-.050±.002	-19.7±0.8	0.536	.060±.002	16.6±0.6	0.987	.92±.04	1.09±.04
S UMa	2.36	.502±.013	-.073±.003	-13.5±0.6	0.882	.044±.004	22.3±1.8	0.606	1.43±.07	.87±.07
TU Cyg	2.34	.435±.015	-.089±.005	-11.2±0.7	0.768	.057±.006	17.5±1.8	0.300	1.19±.07	.76±.08
T UMa	2.41	.339±.021	-.109±.006	-9.2±0.5	0.698	.067±.006	14.9±1.3	0.192	1.65±.09	1.01±.09
V Cas	2.36	.449±.010	-.068±.002	-14.6±0.5	0.509	.048±.002	20.5±1.0	0.032	1.15±.04	.82±.04
W Her	2.45	.466±.009	-.070±.002	-14.2±0.4	0.767	.061±.002	16.±0.5	0.250	1.21±.04	1.05±.03
Y Per	2.39	.479±.011	-.031±.002	-31.5±1.8	0.505	.025±.002	38.±2.5	0.233	1.24±.07	1.01±.07
oCet	2.52	.300±.019	-.094±.006	-10.6±0.7	-0.056	.056±.009	17.7±2.8	0.450	1.82±.12	1.09±.17
R Leo	2.50	.450±.009	-.052±.003	-18.9±0.9	0.246	.033±.003	30.0±2.7	0.634	1.32±.06	.83±.07
R Ser	2.55	.434±.013	-.082±.004	-12.2±0.6	0.527	.055±.004	17.9±1.4	0.069	1.36±.07	.92±.07
R UMa	2.48	.419±.011	-.114±.004	-8.8±0.3	0.159	.056±.004	17.7±1.2	0.544	2.00±.07	.99±.07
S CrB	2.55	.395±.010	-.060±.003	-16.4±0.7	0.782	.031±.003	31.4±2.7	0.135	1.32±.06	.69±.06
T Cam	2.57	.465±.006	-.080±.003	-12.5±0.4	0.352	.048±.002	20.4±0.8	0.047	1.67±.05	1.02±.04
TU And	2.50	.483±.010	-.061±.003	-16.4±0.8	0.918	.045±.003	22.0±1.6	0.550	1.27±.06	.95±.07
U Per	2.52	.500±.001	-.034±.001	-29.5±0.6	0.804	.033±.001	29.5±0.6	0.304	1.00±.02	1.0±.02
U UMi	2.52	.487±.006	-.038±.002	-26.0±1.1	0.611	.040±.002	24.9±1.1	0.088	1.01±.04	1.06±.05
V Aur	2.55	.538±.006	-.019±.002	-53.2±4.3	0.738	.020±.001	48.2±3.0	0.188	.88±.07	.97±.06
WAnd	2.60	.459±.011	-.134±.047	-7.4±2.6	0.375	.132±.046	7.5±2.6	0.201	1.54±.54	1.52±.53
W Peg	2.54	.457±.009	-.048±.002	-20.7±1.0	0.774	.037±.003	26.7±2.2	0.964	1.19±.06	.92±.08
X Oph	2.52	.500±.001	-.012±.001	-78.1±1.7	0.652	.013±.001	78.1±1.7	0.152	1.00±.02	1.00±.02
RGem	2.57	.396±.014	-.072±.006	-13.8±1.2	0.222	.038±.006	25.9±4.1	0.576	1.31±.11	.70±.11
TUMi	2.50	.482±.013	-.075±.005	-13.3±0.8	0.726	.065±.005	15.2±1.2	0.961	1.35±.09	1.18±.09
UOri	2.59	.337±.015	-.072±.004	-13.7±0.7	0.434	.031±.002	31.6±2.1	0.697	1.62±.09	.70±.05
SUMi	2.51	.519±.007	-.045±.002	-21.9±1.1	0.159	.039±.002	25.2±1.5	0.694	1.12±.06	.97±.06
VCam	2.70	.376±.008	-.075±.003	-13.3±0.5	0.287	.037±.003	26.4±1.9	0.474	2.25±.08	1.13±.08
χ Cyg	2.62	.423±.008	-.088±.006	-11.3±0.7	0.545	.061±.006	16.2±1.5	0.040	1.32±.09	.92±.09
R And	2.63	.316±.012	-.097±.004	-10.2±0.4	0.354	.041±.005	24.0±2.8	0.941	1.71±.07	.73±.08
R Aur	2.65	.516±.007	-.072±.004	-13.8±0.7	0.643	.054±.003	18.5±0.9	0.157	1.68±.08	1.26±.06
R Cas	2.65	.369±.014	-.093±.006	-10.7±0.7	0.085	.050±.006	20.0±2.4	0.415	2.11±.14	1.13±.14
R Cyg	2.65	.382±.014	-.065±.004	-15.3±0.9	0.605	.047±.004	21.3±1.9	0.348	1.37±.08	.99±.09
S Cep	2.70	.568±.010	-.018±.001	-54.9±3.2	0.710	.021±.001	46.1±2.3	0.366	1.06±.06	1.26±.06
T Cas	2.67	.590±.009	-.037±.002	-26.7±1.5	0.675	.036±.002	27.7±1.6	0.908	1.18±.06	1.14±.06
U Aur	2.61	.316±.039	-.076±.005	-13.1±0.8	0.494	.038±.004	25.8±2.7	0.099	1.76±.11	.89±.09
U CMi	2.63	.579±.005	-.048±.002	-20.5±0.9	0.674	.036±.001	27.6±1.0	0.928	1.39±.06	1.04±.04
U Cyg	2.69	.487±.008	-.018±.002	-52.9±4.8	0.216	.019±.002	51.7±4.5	0.541	.88±.08	.90±.08
U Her	2.62	.409±.011	-.066±.002	-15.0±0.6	0.037	.025±.003	39.9±4.0	0.189	1.97±.07	.74±.07
V Cyg	2.63	.427±.008	-.042±.002	-23.4±0.9	0.667	.022±.002	44.3±3.7	0.075	1.66±.06	.88±.07
W Cas	2.62	.470±.016	-.023±.001	-42.3±2.0	0.150	.020±.001	48.5±2.6	0.743	1.12±.05	.97±.05
X Cas	2.65	.621±.016	-.015±.001	-63.1±4.1	0.308	.017±.001	58.2±3.0	0.989	1.30±.08	1.41±.07