INFLUENCE OF SHOCK WAVES ON THE LIGHT CURVES OF LONG-PERIOD VARIABLES

L. S. Kudashkina[1], G. M. Rudnitskij[2]
[1] Astronomical Observatory, Odessa State University
T.G.Shevchenko Park, Odessa 270014, Ukraine
e-mail: root@astro.odessa.ua
[2] Sternberg Astronomical Institute, Moscow State University
13 Universitetskij prospekt, Moscow 119899 Russia
e-mail: gmr@sai.msu.su

ABSTRACT. The shapes of light curves of Mira-type variable stars is analyzed. It is shown that some features of the light curves may be explained by passage of shock waves in the stars' atmospheres. In particular, it is noted that "steps" of the ascending branches of the light curves have very similar durations (of the order of 0.1 stellar period) for a big number of miras. This time span is just approximately the time of propagation of shock waves through stars' atmospheres. The numerical simulation of shock wave propagation support the above suggestion and yield time scales that fit the observed light curve features.

Key words: Stars: Miras, light curves, stellar atmospheres, shock waves.

For long-period variables, the shape of light curves is determined to a considerable extent by influence of shock waves, which propagate in the star's atmosphere and in the inner layers of the circumstellar envelope during each cycle of the stellar variability. Of interest are also some peculiarities of the light curves: "humps", "steps" on the ascending branch and – as an extreme case – double maxima. It can be said that the "normal", stable state of a long-period variable is the minimum light, whereas the shock waves, caused by stellar pulsations, move the star from this state to the "excited" state, which is connected with the light maximum. The increase of brightness in the visible and infrared is in the first turn due to an increase of temperature of the photospheric layers that are responsible for the stellar continuum in the visual.

In order to investigate the influence of shock waves on the light curves, we constructed a numerical model of propagation of a shock in mira's atmosphere. We accounted for the effects of ionization of gas and for dissociation of molecular hydrogen on the shock front. We assumed the shock to be spherical. The initial radius was $\sim 3 \cdot 10^{13}$ cm. Then, with a fixed step in time (10^5–10^6 s), we computed the gas physical parameters for the current shock radius. According to Willson (1976), we assumed that the shock velocity falls with growing radius as $D = D_0(r_0/r)^\alpha$; from empirical data, $\alpha = 1$. Here D is the current shock velocity, D_0 – its initial value at $r = r_0$. We varied D_0 between 20 and 100 km s^{-1}. We assumed also the postshock ionization and dissociation to be determined by Saha-type equations.

We solved by the iteration method the system of equations for the quantities

$$\begin{aligned} z &= \frac{p_2}{p_1} = \frac{2\gamma_1 \mathrm{M}^2}{\gamma_2+1}\left[1+\frac{(\gamma_2^2-1)\,q}{2D^2}\right], \\ \frac{T_2}{T_1} &= \frac{2\gamma_1(\gamma_2-1)\,\mu_2\mathrm{M}^2}{(\gamma_2+1)^2\,\mu_1}\times \\ &\quad\times\left[1-\frac{(3-\gamma_2)(\gamma_2+1)\,q}{2D^2}\right], \end{aligned} \qquad (1)$$

where q is the energy spent for ionization and dissociation, M is the Mach number, γ – the adiabatic index, μ – the molecular we-

Table 1: Characteristics of individual stars. Notes: Gr. – group of periods (I – $P < 200^d$; II – $200^d < P < 300^d$; III – $300^d < P < 400^d$; IV – $P > 400^d$); f – asymmetry of the light curve; T – duration of the hump; ′ – the period was redetermined.

Star	P, days	Gr.	Sp. (latest)	f	lg (T/P)	T/P	lg$[\Delta P/P]$
R Hor	407.6	IV	M8eII-III	0.40	−0.844	0.1431	
U Aur	408.09	IV	M9e	0.39	−0.845	0.1429	
S Scl	362.57	III	M9e (Tc)	0.48	−1.002	0.0996	
V Cyg	421.27	IV	C7.4e	0.46	−1.005	0.0989	
S Cep	502.34	IV	C7.4e	0.55	−0.864	0.1369	−1.498′
T Cep	388.14	III	M8.8e	0.54	−0.915	0.1217	
R Cas	443.88	IV	M10e	0.40	−1.111	0.0774	−1.506′
W Peg	345.5	III	M8e	0.46	−0.919	0.1206	
RU Tau	544.6	IV	M6.5	0.62	−0.845	0.1428	
V Cam	503.16	IV	M7e	0.31	−0.973	0.1063	−1.433
χ Cyg	421.54	IV	S10.4e(MS)	0.41	−1.167	0.0681	
R Aur	448.10	IV	M9.5e	0.51	−0.874	0.1336	−1.686
Y Cep	322.57	III	M8.2e	0.40	−1.124	0.0752	
W And	399.24	III	M10(S9.2e)	0.42	−0.923	0.1193	−2.076′
o Cet	333.47	III	M9e	0.38	−1.036	0.0921	−2.347′
RR Cep	384.18	III	M8.8e	0.41	−0.862	0.1374	
RT Oph	426.34	IV	M7e(C)	0.36	−1.107	0.0782	
U Her	415.69	IV	M9.5e	0.40	−1.019	0.0958	−1.627′
NP Her	448	IV	C6.3e	0.5	−1.003	0.0992	
RU Her	484.83	IV	M9	0.43	−0.941	0.1146	
U Ser	237.50	II	M6e	0.48	−0.591	0.2563	
W Cas	417.98	IV	C7.1e	0.46	−0.891	0.1286	−1.444′
T Phe	281.79	II	M5e	0.37	−0.973	0.1065	
R Cam	270.22	II	S8.7e	0.45	−0.727	0.1876	
RS Her	219.70	II	M8:	0.47	−0.919	0.1206	
VZ Cas	169.24	I	M3e	0.46	−0.985	0.1034	
RS UMa	258.97	II	M6e	0.42	−1.178	0.0664	
R Vir	145.95	I	M8.5e(III)	0.50	−1.204	0.0625	−2.678′
TU And	318.36	III	M5e	0.48	−1.140	0.0725	−2.301′
R Leo	313.67	III	M9.5eIII	0.43	−1.307	0.0493	−1.921′
U CMi	422.03	IV	M4e	0.52	−0.768	0.1707	−1.706′
X Cas	441.94	IV	C5.4e	0.55	−0.658	0.2200	−1.345′
T Cas	465.35	IV	M9.0e	0.56	−0.894	0.1275	−1.336′
R UMa	301.53	III	M9e	0.39	−1.342	0.0455	−3.523′
T Cam	374.80	III	S8.5e	0.47	−1.135	0.0732	−2.367′
T UMi	316.74	III	M6e	0.45	−1.313	0.0486	−1.281′
S Umi	225.87	II	S5.9e	0.47		0.2117	
R Aqr	386.96	III	M8.5e	0.42		0.1236	
X UMa	249.04	II	M4e	0.43		0.0524	
S Leo	190.16	I	M6e:	0.47		0.1829	
T Lyn	406.0	IV	C7.1e(N0e)	0.47		0.1071	
U Lyn	433.6	IV	M9.5:e	0.42		0.1604	
SZ Aur	454.04	IV	M8e	0.46		0.2394	

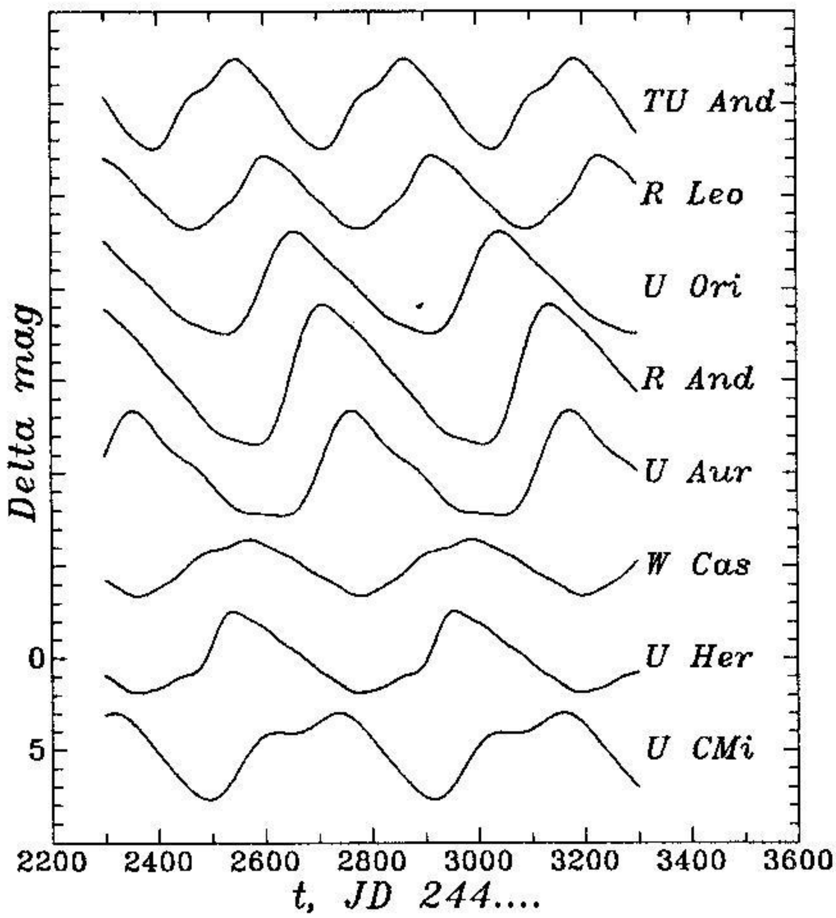

Figure 1: The smoothed light curves of some Mira-type stars with periods $300^d < P < 400^d$. The observations were obtained by the AAVSO members (Mattei et al. 1978). For approximation we have used a program FOUR-N by Andronov (1994) which determines a least squares fit with different number of harmonics.

Table 1 (continued)

Star	P, days	Gr.	Sp. (latest)	f	lg (T/P)	T/P	lg$[\Delta P/P]$
V Del	533.51	IV	M6e	0.42		0.0978	
U Ari	371.13	III	M9.5e	0.40		0.1172	
S CMi	332.94	III	M8e	0.49		0.1045	
R CVn	328.53	III	M9e	0.46		0.1191	
R LMi	372.19	III	M9.0e(Tc:)	0.41		0.0935	

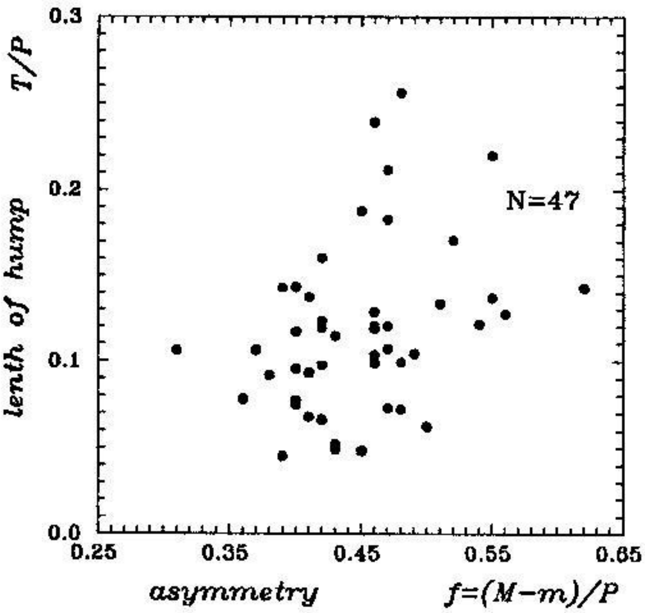

Figure 2: The relationship "duration of the hump - asymmetry". NP Her is not included.

ight. Subscripts 1 and 2 refer to the pre– and postshock gas parameters respectively. Detailed expressions for the quantities, entering the above formulae, can be found in Klimishin (1984). The calculations stopped when the postshock degree of ionization fell to a value $a = N_{H^+}/N_H < 0.001$. As a byproduct, we got also the intensity of the free–free emission of the postshock ionized gas.

The main result of the calculations is the time of the shock propagation in the stellar atmosphere until the moment when the shock loses its capacity to heat the gas to temperature that is sufficient for ionization. This time span is on the average about 1 month (from 20 to 35 days). This value is close to the duration of "humps" and "steps" on the ascending branches of miras' light curves. The subsequent growth of brightness is going on as if by inertia, at the expense of the growing volume of the expanding heated gas. It should be stressed that the relative duration of the noted features, expressed in fractions of the light period, is notably constant for different stars: it is, on the average, ~ 0.1.

The figures present sample light curves and some statistical regularities, which imply the plausibility of the suggested interpretation of the light curves. The table lists the stars used in the statistics.

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