Light curve solutions of 50 eclipsing binaries with circular orbits in the Small Magellanic Cloud

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Abstract. In this paper we present the global parameters of 50 eclipsing binaries with circular orbits in the Small Magellanic Cloud, obtained by light curve solutions. The statistical analysis of the results leads us to the following conclusions: (a) The majority of the investigated eclipsing stars are close binaries which components almost or wholly fill their Roche lobes; (b) The majority of these components are hot stars; (c) About 60 % of the secondaries are larger than the primaries; (d) 1/3 of the investigated binaries were modeled by semidetached configurations and 2/3 by detached configurations; (e) 30 % of the stars in our sample are Algols.

Key words: Stars: eclipsing – Stars: modeling – Stars: individual: SMC – Stars:

Решения на кривите на блясъка на 50 затъмнителни двойни звезди с кръгови орбити в Малкия Магеланов облак

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В тази статия ние представяме глобалните параметри на 50 заъмнителни двойни звезди с кръгови орбити в Малкия Магеланов облак, намерени чрез решения на кривите на блясъка. Статистическият анализ на резултатите ни води до следните заключения: (a) Мнозинството от изследваните затъмнителни звезди са тесни двойки, компонентите на които почти или изцяло изпълват обемите на Рош; (b) Мнозинството от тези компоненти са горещи звезди; (c) Около 60 % от вторичните звезди са по-големи от първичните; (d) 1/3 от изследваните двойни звазди се моделират като полуразделени конфигурации и 2/3 като разделени конфигурации; (e) 30 % от зездите в нашата извадка са Алголи.

Introduction

The study of eclipsing binaries is very important for the modern astrophysics because these stars are one of the most useful sources of information about the stellar parameters (radii, masses, temperatures, luminosities, stellar composition) and consequently provide empirical tests for the theory of the stellar evolution.

The investigation of eclipsing binaries in large and homogenous sample gives a possibility to improve the empirical statistical relations between the stellar parameters. The microlensing projects EROS (Grison et al. 1995), MACHO (Alcock et al. 1997) and OGLE (Udalski et al. 1998, 2000) monitored millions of stars in the Magellanic Clouds during the last years. The huge photometric database is available not only for microlensing studies but also for individual and statistical investigations of detected variable stars.

The first OGLE catalogue contains about 1500 eclipsing stars found in the central 2.4 square degree area of the SMC brighter than $I = 20^m$ with periods from 0.3 to 250 days. The next catalogue of variable stars in the Magellanic Clouds found in 1997-2000 (Zebrun et al. 2001) covers about 7 square degrees of the sky. The basic star parameters in this catalogue are: orbital period P; HJD for the primary maximum (T-2450000); zero epoch (phase 0) corresponding to the deeper eclipse; I-band brightness at maximum; I-band amplitude (depth of the primary minimum); phase of the secondary eclipse; depth of the secondary eclipse in I-band; I, B and V brightness at maximum; B-V and V-I colors; type of eclipsing star. Typically, there are about 400 data points in I-band and about 30 points in V and B band for each variable star in the OGLE catalogs. The errors of the magnitude measurements are: 0.005^m for the brightest stars ($I < 15^m$) and 0.08^m for stars with $15^m < I < 19^m$.

The study of the detected eclipsing stars in SMC from the second OGLE catalogue is very meaningful because it is reasonably complete and allows further statistical analysis. We began to study the eclipsing binaries in SMC in order to get their global parameters by simultaneous fitting of the I,B,V data. This paper presents the results from the light curve solutions of the first 50 eclipsing stars with circular orbits in SMC.

1 Procedure of light curve solution

The determination of the global star parameters is based on the light curve solution, i.e. searching for a best fit of observational photometric data and family of synthetic light curves built on certain star model and guess stellar parameters. The objective criterion for the best fit is the least squares method. This quality of data requires specific procedure for the light curve solutions of the OGLE catalogue.

Wyithe & Wilson (2001, 2002) obtained solutions of the I curves of the brightest eclipsing stars in SMC from the first OGLE catalogue (Udalski et al. 1998) with an automated version of the WD program. They fixed the following parameters of the detached binaries: q=1; T_2=10000 K (arbitrary choice because only relative temperatures T_1 and T_2 matter for single-band light curves); black-body radiation law; limb-darkening coefficients 0.32 and 0.18 for logarithmic limb-darkening law ($I/I_0 = 1-x(1-\mu)$-y$\ln\mu$); exponent in gravity brightening 1; bolometric albedo 1; longitude of periastron 0 or π; third light 0. Wyithe & Wilson (2001) adjusted inclination i, primary temperature T_1, primary luminosity L_1, potentials ω_1 and ω_2, eccentricity e. For the semidetached binaries Wyithe & Wilson (2002) fixed the same parameters as those for the detached binaries and adjusted i, T_1, L_1, q and ω_1. Our procedure for the light curve solution of the OGLE eclipsing binaries in SMC differs from that of Wyithe & Wilson (2001, 2002) and escapes the most of their simplifications and bases on simultaneous fitting of the I,B,V data. It consists of two parts, a subjective stage in which intuition and numerical experiments are used to get reasonable close fit, and an objective stage in which a programmed algorithm leads iteratively to the final solution.

1.1 Preliminary light curve solution on the basis of empirical relations

We obtained preliminary light curve solutions on the basis of the following empirical relations between the global star parameters:

(a) determination of the temperature T_1 of the primary star by the empirical relation T/(B-V);

(b) calculation of the temperature T_2 of the secondary star by the empirical relation $T_2 = T_1(1-l_2)^{1/4}(1-l_1)^{-1/4}$ where l_1 and l_2 are the depths of the two minima in I color (this rule holds for both partial and complete eclipses but only for circular orbits);

(c) calculation of the mass ratio q for MS stars by the empirical statistical relation $q = (T_2/T_1)^{1.67}$;

(d) calculation of the ratio of relative radii by the raw empirical statistical relation $r_2/r_1 = q^{0.75}$.

1.2 Initial light curve solution

We used the code Binary Maker 3 (Bradstreet & Steelman 2004) for fast initial light curve solution because this code (further BM3) allows immediately to see the effect of changing of each parameter on the synthetic light curve. The visualization is very useful and handy tool at this stage of trials and errors.

We made synthetic light curves by BM3 using the values of the star parameters obtained by the empirical relations as well as the guessed value of the orbital inclination i and the values of the limb-darkening coefficients, gravitation darkening coefficients and

reflection coefficients appropriate to the star temperatures. The star parameters r_2, r_1, T_2, q, i were varied in order to get a better coincidence between the synthetic curve and the observational points. The fit quality was estimated visually as well as by the sum of the residuals calculated by BM3.

In fact at this stage we search for a best fit between the synthetic and observed light curves in I color because it is impossible to find some precise solutions of the poor B and V data. However it turned out that in the most cases the V and B synthetic curves built by BM3 and corresponding to the parameters of the I light curve solution reproduced very well the V and B observational points. In the rest rare cases small corrections of the normalization levels of the V and B observed curves were enough to reach a better coincidence in V and B color. These corrections leaded in turn to corrections of the color indices, the primary's temperature and consequently to repeating of the whole BM3 procedure varying the parameters in narrow ranges around the initial I best fit. Thus, we use V and B data points only for small corrections of the star parameters obtained by the I curve solution.

1.3 Final light curve solution

We used the code DC (Differential Corrections) for improvement of the initial light curve solution and estimation of parameter uncertainties using the method of differential corrections. The code DC needs a good starting approximation to the light curve solution (Wilson & Devinney 1971, Wilson 1992, Wilson & Van Hamme 2003). DC has a capability to make simultaneous multicolor light curve solutions. The code DC makes objective iteration for parameter adjustment by the least squares criterion non-automatically but by personal monitoring. The number of iterations depends on quality of the fit reached in the stage of the BM3 solution. The output DC file contains the obtained corrections of the starting values of the varied parameters, the new values of the varied parameters and their errors, as well as the sum of the residuals for the three curves corresponding to the best fit.

To run DC is necessary to choose which parameters will be varied and their increments (it is recommended they to be around 1 % of the starting value of the corresponding parameter). Taking into account the quality of the OGLE data we chose the following increments for the varied parameters: 50 K for the temperature of the secondary star T_2; 0.5^0 for the orbital inclination i; 0.005 for the relative star radii r_i; 0.02 for the mass ratio q; 10^0 for the latitude of the spot; 5^0 for the spot longitude; 1^0 and for the angular spot radius; 0.02 for the relative spot temperature $k = T^{sp}/T^{st}$.

2 Analysis of the results

We have chosen to model those eclipsing stars in SMC which B and V data have enough points into the eclipses. In opposite case the light curve solution is undetermined, especially for the secondary star temperature.

Table 1 presents the values of the global parameters obtained by our light curve solutions of 50 eclipsing stars in SMC with circular orbits and Fig. 1 illustrates fits for one detached (D) and one semidetached (SD) binary. The symbols $SD1$ and $SD2$ in the Table 1 mean respectively that the primary and secondary star fills-in its Roche lobe. The symbol " $*$ " means that the stellar model requires solution with spot. The first four columns of Table 1 show respectively the star number, type of obtained configuration; orbital period (in days); out-of-eclipse magnitude in I color. The last columns present the values of the fitted parameters: temperatures of both components T_1 and T_2; photometric mass ratio q; relative radii of the components r_1 and r_2.

The statistical analysis of the obtained results for our sample of 50 eclipsing binary systems in SMC leads to the following conclusions:

1) The temperatures of the primary components are in the range 4000-34000 K with maxima at 13000 K and 19000 K (Fig. 2 - left panel). This result is in correspondence

Table 1. Global parameters of 50 eclipsing stars in SMC

Star number	Configuration	Period [d]	I [mag]	T_1 [K]	T_2 [K]	q	i [^{0}]	r_1	r_2
7	D	1.25	17.150	23850	20050	0.98	64.8	0.300	0.280
11	SD2	2.66	17.810	19700	12200	0.26	79.9	0.250	0.290
13	SD2*	3.82	16.425	31100	17400	0.35	75.2	0.173	0.317
14	SD2*	2.45	17.392	24000	16000	0.35	83.6	0.188	0.317
15	D	1.65	18.525	17150	16350	0.87	83.0	0.230	0.210
16	SD2	6.22	18.720	7300	6250	0.60	79.6	0.230	0.360
17	SD2	3.80	19.258	12650	7150	0.18	83.2	0.150	0.267
18	D	1.52	17.859	16350	16050	0.89	80.2	0.255	0.236
20	D	1.45	17.173	26500	22050	0.74	70.6	0.290	0.250
25	SD2*	2.46	16.283	33350	20650	0.46	87.0	0.250	0.339
26	D	0.55	18.517	15400	12750	0.87	75.7	0.390	0.330
35	D	0.89	17.899	19600	18700	0.60	64.6	0.410	0.300
38	SD2	1.98	16.500	31200	18900	0.67	83.0	0.270	0.370
41	SD1	0.86	17.300	28900	22600	0.70	81.3	0.437	0.325
44	D*	50.32	17.154	7900	5180	0.85	85.2	0.120	0.080
45	SD2*	11.90	18.799	5350	5250	0.35	79.7	0.215	0.317
52	D	1.72	17.336	18850	18700	0.99	85.0	0.292	0.293
53	D	142.04	16.592	7550	5700	0.60	87.4	0.125	0.090
65	D	5.51	19.100	11800	7100	0.85	88.5	0.260	0.212
71	D	0.91	17.140	9300	6600	0.71	66.5	0.311	0.230
73	D	0.62	17.696	12150	11850	0.89	66.4	0.334	0.321
74	SD2*	6.33	16.599	13600	8050	0.28	77.4	0.160	0.299
78	D	1.34	17.620	18000	17350	1.00	78.3	0.322	0.300
89	D	1.91	17.278	27500	15000	0.27	65.7	0.339	0.225
90	D	6.39	17.520	18750	16950	0.91	82.6	0.125	0.115
100	SD1	1.19	16.510	22050	12500	0.21	58.9	0.548	0.211
107	D	2.53	17.885	10450	10350	0.92	80.7	0.198	0.191
112	D	15.93	17.800	19300	17900	0.80	87.5	0.075	0.060
114	SD2	1.57	17.200	16700	12600	0.70	73.3	0.400	0.374
116	D	0.87	18.144	12550	8750	0.35	65.5	0.481	0.326
122	D	1.94	17.770	15450	15050	0.90	77.1	0.265	0.195
140	D	0.95	17.947	14650	13450	1.00	86.6	0.331	0.274
165	SD2	16.90	16.870	10950	5400	0.15	86.0	0.205	0.255
176	D*	1.28	17.548	18400	19000	1.00	75.6	0.259	0.260
177	SD2	16.90	16.875	11550	5700	0.22	83.8	0.179	0.281
186	D	0.95	17.840	9950	9850	0.87	70.3	0.346	0.330
194	D	109.35	16.590	5600	5300	0.80	81.8	0.120	0.110
205	D	16.60	17.845	17750	17050	0.98	87.9	0.070	0.070
207	SD2	2.85	18.490	13000	6700	0.45	81.7	0.250	0.337
229	SD2	0.56	18.710	9100	9050	0.88	82.0	0.350	0.394
259	D	1.27	17.919	10400	8100	0.56	78.8	0.310	0.361
277	D	1.11	16.990	15600	14200	1.00	79.4	0.330	0.300
278	SD2*	1.40	18.287	12400	9800	0.62	86.2	0.342	0.363
298	D	1.16	17.797	18250	17700	1.00	78.2	0.294	0.270
332	D	3.32	17.425	13900	8450	0.30	86.0	0.201	0.300
352	D	0.99	18.712	9600	7000	0.64	80.2	0.345	0.253
366	D	0.97	18.293	12700	12250	0.86	74.2	0.391	0.330
389	D	1.25	16.067	27000	25500	0.70	71.8	0.263	0.228
395	D	1.17	18.225	12000	10700	0.60	76.4	0.280	0.240
396	D	1.95	16.325	27450	17750	0.59	72.0	0.340	0.209

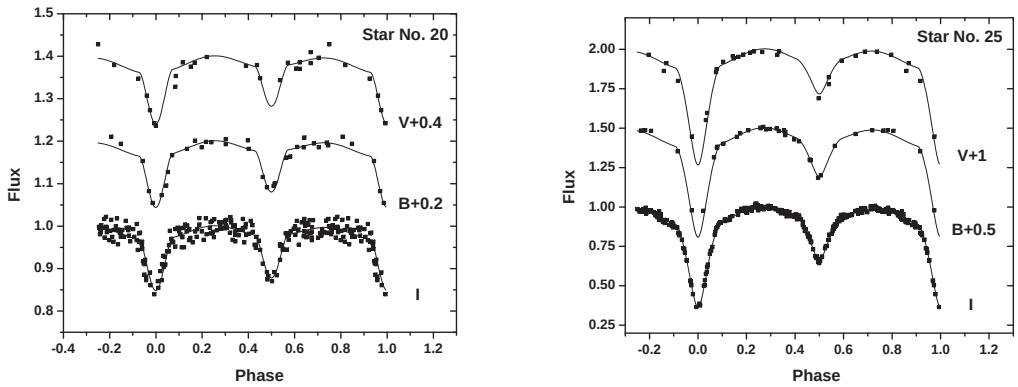

Fig. 1. Illustration of light curve solutions of detached binary (left panel) and semidetached binary (right panel).

with the expectation the stars in SMC to be primarily of types O and B (from the colors reported by Udalski et al. 1998);

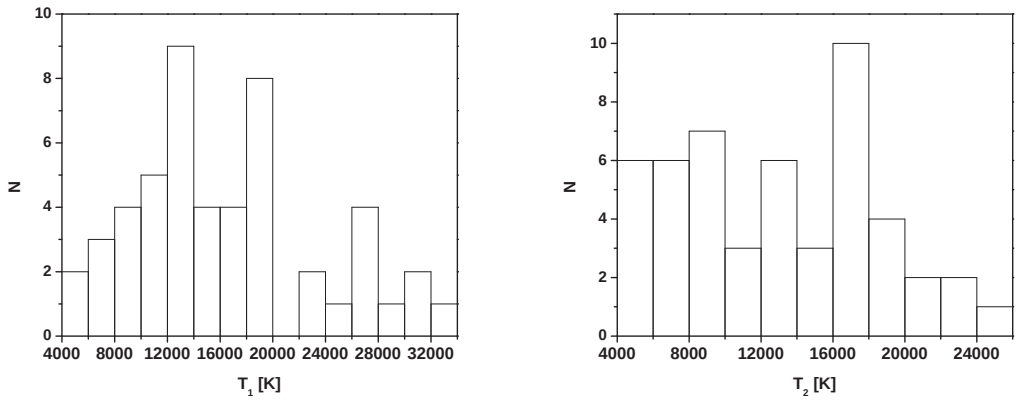

Fig. 2. Distribution of the temperatures of the components T_1 (left panel) and T_2 (right panel).

2) The temperatures of the secondary components are between 4000 K and 26000 K (Fig. 2 - right panel) with maximum at 17000 K, also in correspondence with the expectation the OGLE stars to be hot;

3) The temperature distribution of all 100 stars shows wide maximum at 13000-17000 K (Fig. 3 - left panel);

4) The orbital inclinations of the binaries from our sample are between 55^0 and 90^0 with wide maximum at 75-85^0 (Fig. 3 - right panel);

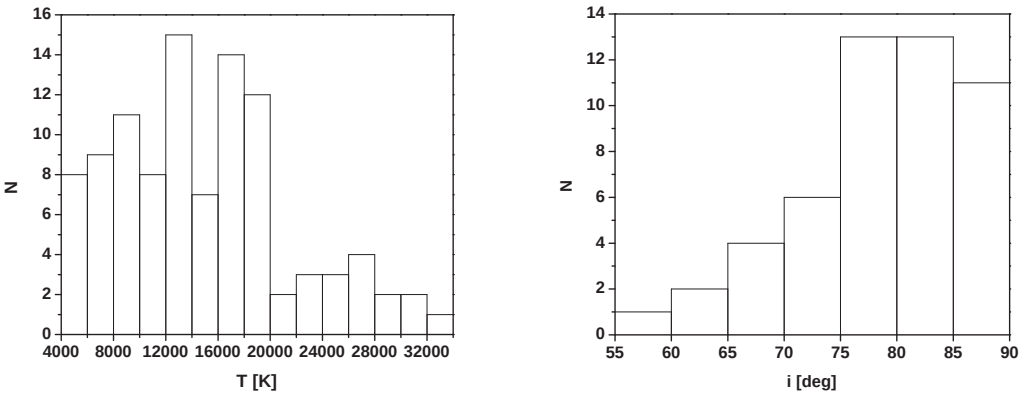

Fig. 3. Distribution of the temperatures T (left panel) and the orbital inclinations i (right panel).

5) The relative radii of the primary components are in the range 0.05-0.55 with maximum at 0.3 (Fig. 4 - left panel). Around 66 % of the primaries in the investigated eclipsing binaries in SMC are close to filling their Roche lobes;

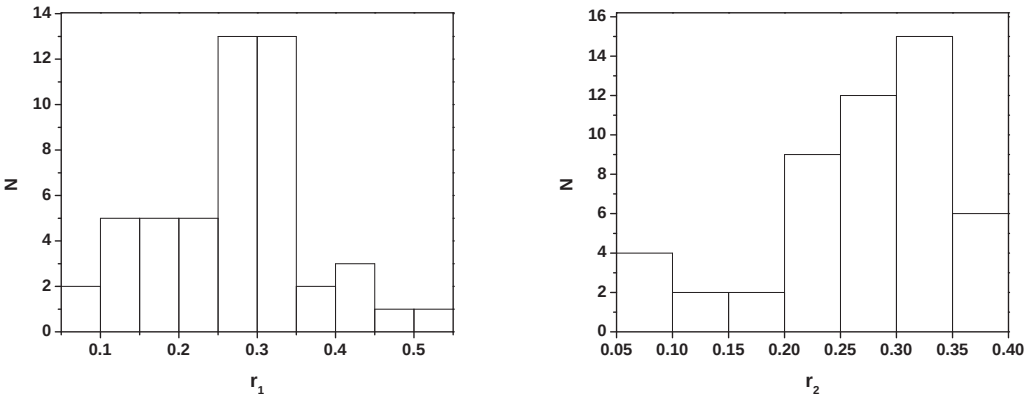

Fig. 4. Distribution of the relative radii of the components r_1 (left panel) and r_2 (right panel).

6) The relative radii of the secondary components are between 0.05 and 0.4 with maximum at 0.3-0.35 (Fig. 4 - right panel);

7) The photometric mass ratio of the binaries varies between 0.1 and 1 with maximum around 0.8-1 (Fig. 5 - left panel).

It turned out that 17 from the all 50 eclipsing light curves of our sample were fitted by semidetached configurations and 33 by detached configurations. This means that around 1/3 of the investigated binaries are SD.

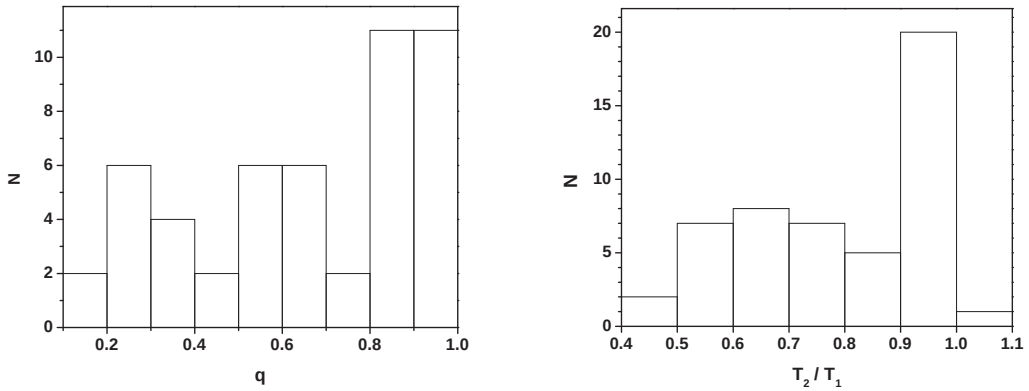

Fig. 5. Distribution of the mass ratios $q = M_2/\mathrm{M}_1$ (left panel) and distribution of T_1/T_2 (right panel).

The statistical analysis of the obtained results separately for the detached (D) and semidetached (SD) binaries from our sample leads to the following conclusions:

1) The temperatures of the primary components of the D systems are in the range 4000-28000 K with maximum at 19000 K while those of SD are in the range 4000-34000 K with maximum at 12000-14000 K;

2) The temperatures of the secondary components of the D systems are between 4000 K and 26000 K with maximum at 17000 K while those of SD are in the range 4000-24000 K with maximum at 8000-10000 K;

3) The temperature distribution of the stars of the D systems has maximum at 16000-17000 K while that of SD has wide maximum at 8000-14000 K;

4) The orbital inclinations of the D binaries lie between 60^0 and 90^0 with wide maximum at 75^0-90^0 while those of SD are in the range 55^0-90^0 with maximum at 80^0-85^0;

5) The relative radii of the primary components of the D binaries are in the range 0.05-0.45 with maximum at 0.3 while those of SD are in the range 0.1-0.55 with maximum at 0.2-0.25;

6) The relative radii of the secondary components of the D binaries are between 0.05 and 0.35 with maximum at 0.2-0.25 while those of SD are between 0.2 and 0.4 with maximum at 0.3;

7) The mass ratios of the D binaries are in the range 0.2-1.0 with maximum at 0.8-0.9 while those of the SD binaries vary between 0.1 and 0.9 with two maxima at 0.2-0.3 and 0.6-07;

8) The distribution of the ratios T_1/T_2 (Fig. 5 - right panel) of the temperatures of the two components shows that nearly 40 % of the eclipsing binaries have components with equal temperatures;

9) The distribution of the ratio r_2/r_1 of the relative radii of the two components (Fig. 6) shows that nearly 22 % of the binaries have components with equal sizes as well as almost 60 % of them have $r_2/r_1 > 1$.

The orbital periods (Table 1) of the eclipsing binaries from our 50-star sample are short (P<3 days) and medium (3 days<P<7 days). Only 8 binaries have long (7 days<P<15 days) or very-long (P>15 days) periods. The distribution of the orbital periods shows maximum around 1 day and the number of systems falls rapidly with increasing period. According to Udalski et al. (1998) the binaries with short and medium

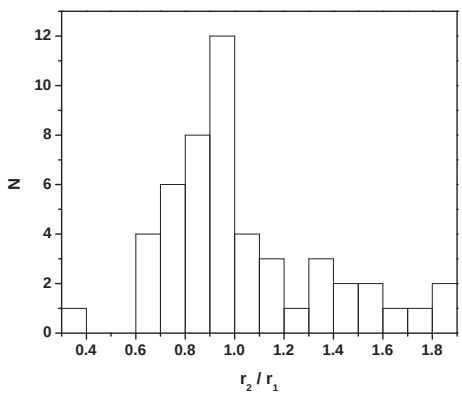

Fig. 6. Distribution of r_2/r_1

periods belong to the young population located in the MS; the long period stars are lower giant branch stars or evolved MS stars while very-long period stars populate upper part of the red giant branch. The number of giant branch eclipsing stars is much smaller than shorter period stars because such wide systems are much more rare. Inclination of orbits of those stars must be much closer to 90^0 than for close binaries. Also, the efficiency of detection for very-long period systems is lower due to smaller number of cycles covered.

The wide maximum at 0.2-0.4 of the distribution of the relative radii r_2 (Fig. 4 - right panel) means that around 80 % are almost or wholly filling their Roche lobes. This result as well as the similar conclusion for r_1 can explain the unexpected maximum of the distribution of the orbital inclinations i in the range 75^0-85^0 by the enhanced presence of semidetached or contact binaries in our sample.

Conclusion

As a result of the light curve solution of 50 eclipsing stars with circular orbits in SMC we determined their temperatures, relative radii, orbital inclinations and photometric mass ratio. The statistical analysis of the obtained global parameters leads us to the following main conclusions:

(1) The most of the investigated eclipsing stars in SMC are close binaries with orbital periods around 1^d;

(2) The most of the components are hot stars with temperatures in the range 8000-20000 K. This result is in correspondence with the known statement that the spectra of the irregular galaxies (as SMC) are similar to the spectra of hot stars;

(3) More than a half of the components are almost or wholly filling their Roche lobes (with $r > 0.2$). For comparison Wyithe & Wilson (2001) found that most of the binaries in SMC have r>0.25;

(4) Nearly 40 % of these eclipsing binaries have components with equal temperatures;

(5) About 60 % of them have $r_2/r_1 > 1$;

(6) We modeled around 1/3 of the investigated binaries in our sample by SD configurations. For comparison Wyithe & Wilson (2001) found detached solutions for 80 % of the investigated eclipsing binaries but concluded that some of them have large components and may be SD;

(7) 30 % of the configurations in our sample are Algols. For comparison Wyithe & Wilson (2001) found that only 20 of total 1459 stars of their sample are classical Algols. They explained this result by the fact that Algols with primaries of spectral types of middle A and later might be too faint for the OGLE limiting magnitudes but B types should be readily observable.

We will continue the study of the eclipsing binaries in Magellanic Clouds because it offers a possibility for high-accuracy investigation of stellar parameters and evolution at low metalicity.

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