CYCLE–TO–CYCLE VARIATIONS OF THE SYMBIOTIC BINARY R AQR

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ABSTRACT. The observations of R Aqr from the AFOEV database are analyzed. The corrected value of the period $P = 387.509 \pm 0.029^{d}$ was determined from a 5–th order trigonometric polynomial fit with a corresponding initial epoch for the maximum $T_0 = 2444733.76 \pm 0.93^{d}$ and asymmetry $A = 0.409 \pm 0.011$. The cycle–to–cycle variations of the phase curve are present which are studied by using "running parabolae", "running sines", "asymptotic parabolae" and "linear fit" approximations. The range of variations is $5.7 - 8.0^{m}$ (brightness at maximum), $10.6 - 12.3^{m}$ (brightness at minimum), $7.1 - 34.1$ days/mag (slope of the ascending branch at $m = 9^{m}$), $25.7 - 44.6$ days/mag (slope of the descending branch at $m = 9^{m}$). The corresponding full amplitudes of the phase variations are 0.069, 0.136, 0.120, 0.256, respectively. The most stable in phase is the maximum, for which no secular period variations detected, but a secondary cycle of $P_2 = 3955 \pm 50^{d}$ and amplitude $(0.032 \pm 0.005)P$ may be suggested. The characteristics of the individual cycles are tabulated.

Key words: Stars: Binary, Pulsating, Symbiotic, R Aqr

Introduction

R Aqr exhibits characteristics of many types of astrophysical objects in the same system. This is a symbiotic binary with a composite spectrum. One of the components is a Mira–type variable. The star is a prototype of the subclass of symbiotic binaries the light variations of which are characteristic for a long–periodic variable. Other subclasses are Z And with a number of small ($\approx 3^{m}$) year–scale outbursts and AG Peg with outbursts of an amplitude $\approx 4^{m}$ lasting dozens of years (cf. Boyarchuk 1983). The system is surrounded by a planetary nebula, the central part of which is highly variable in radio wavelength and shows jet–like structures. It is also a X–ray source (cf. reviews by Kenyon (1986), Friedjung (1993)). This is the only symbiotic showing detectable SiO maser emission (Lepine et al. 1978). The light curve shows Mira–type variability with a mean period $P = 386.96^{d}$ and initial epoch $T_0 = 2442398$ (GCVS IV, Kholopov et al. 1985).

This work continues our study of symbiotic variables with Mira–type components. Previous results were published by Chinarova et al. (1994), Hric et al. (1994) and Chinarova (1995). The part of the AFOEV light curve of R Aqr and its brief analysis were published by Skopal et al. (1992).

Observations

The observations were obtained by the members of the AFOEV in 1935–1996 (JD 2428088–50096) and are stored in the AFOEV database (Schweitzer 1996). From all data we deleted "not sure" values and estimates "fainter than", thus 1521 data points remained. The most numerous data were obtained by the observers: M.Duruy ($n = 150$), P.Vedrenne (130), A.Mizser (94), B.Thouet (83). We thank the amateur astronomers who contributed to these data.

The total range of the brightness variations is $5^{m}\!.5 - 12^{m}\!.5$ with a sample mean $8^{m}\!.32$ and a r.m.s. deviation $1^{m}\!.45$. The time light curve is shown in Fig. 1. It exhibits well pronounced Mira–type variations with apparent cycle–to–cycle changes.

Analysis: Multiharmonic Fits

For the trigonometric polynomial fit we have used the computer code FOUR–N (Andronov 1994). The degree s was determined by using the Fischer's test. The probability P_r that one more harmonic will have amplitude statistically distinct from zero was computed for each number of harmonics. Its limiting value was set to 0.005. The general characteristics of the fits dependent on s were computed: where σ_n is a biased r.m.s. deviation of the observations from the fit, i.e. $\sigma_n^2 = \frac{1}{n}\Sigma(O - C)^2$, for the unbiased value $\sigma_*^2 = \frac{1}{n-2m-1}\Sigma(O - C)^2$, σ_s is a r.m.s. value of the standard error of the fit averaged through the period P, L_p characterizes the probability P_r, i.e.

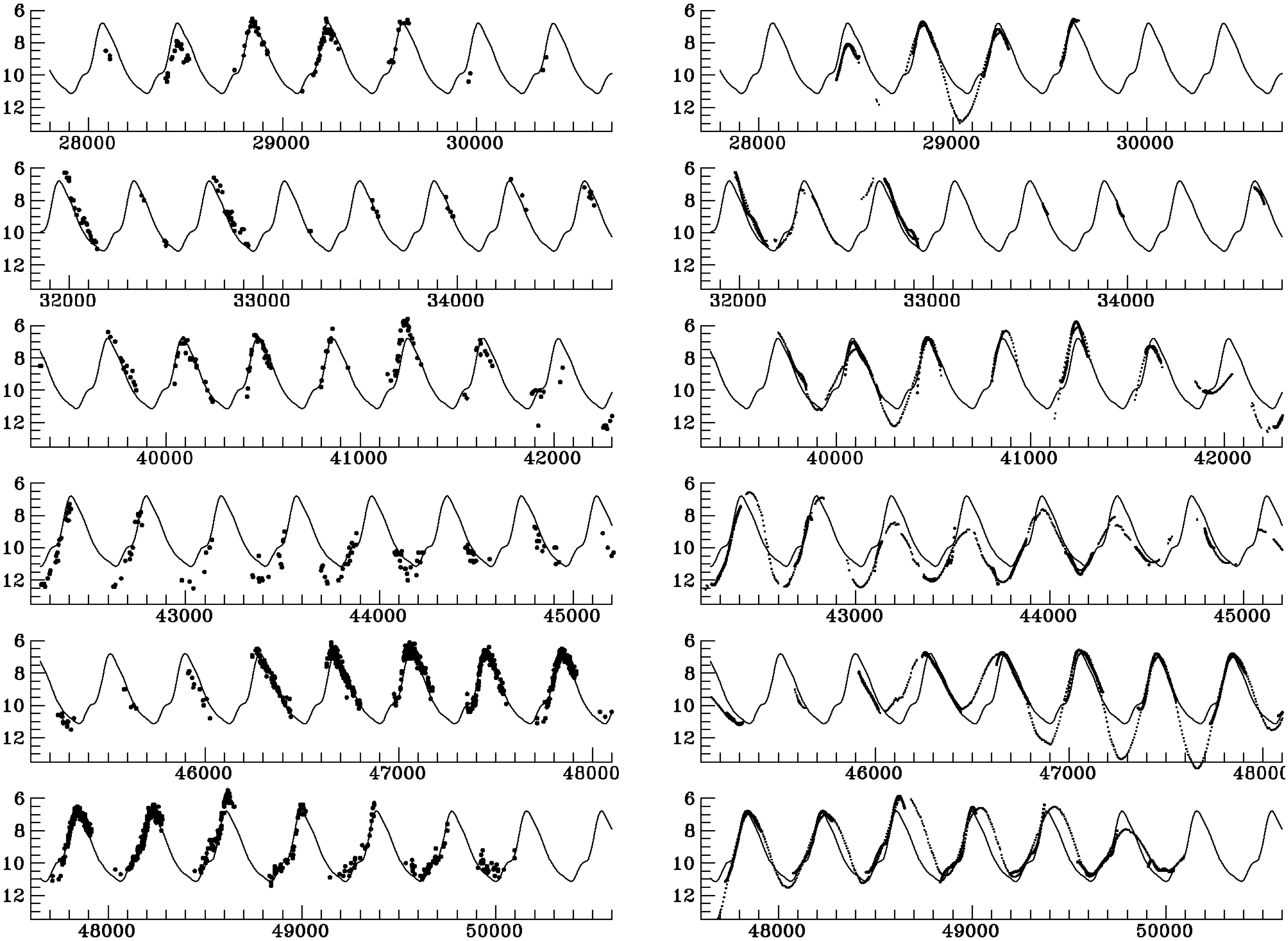

Figure 1. *Left:* Light curve of R Aqr (filled circles); *right:* fits of the light curve of R Aqr: "running parabolae" with $\Delta t = 57^{\rm d}$ (large dots), "running sines" with $\Delta t = P/2 = 193.48^{\rm d}$ (small dots) and the best 5-th order trigonometric polynomial (=4–harmonic fit) (line).

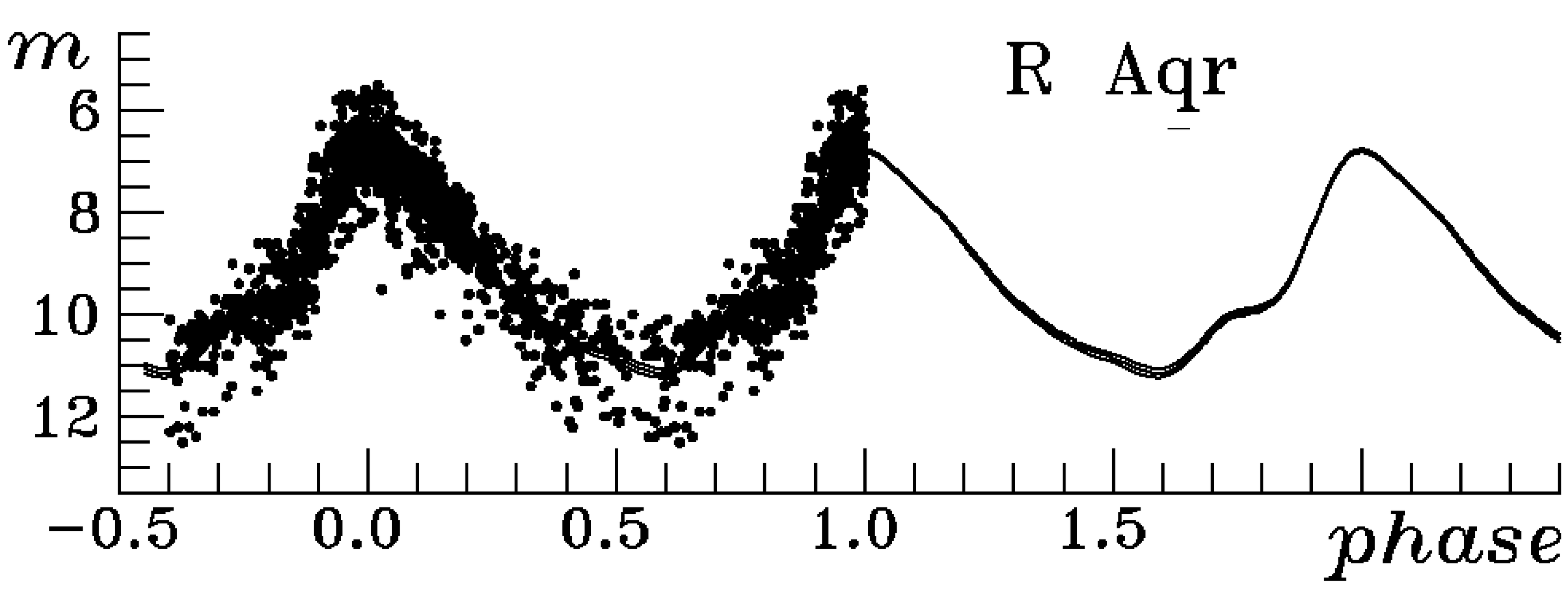

Figure 2. Phase light curve of R Aqr (filled circles) and its 4–harmonic fit (lines $m(\phi)$, $m(\phi) \pm \sigma(\phi)$).

Table 1. Parameters of the harmonics for the best 5–th order trigonometric polynomial fit.

r_j	ϕ_{0j}	r_j/r_1	$\phi_{0j} - j \cdot \phi_{01}$
1.920±0.028	0.045±0.002	1.000±0.000	0.000±0.000
0.394±0.028	0.044±0.010	0.205±0.016	-0.048±0.012
0.211±0.026	0.043±0.020	0.110±0.014	-0.092±0.021
0.196±0.026	-0.107±0.022	0.102±0.014	-0.288±0.023
0.085±0.024	-0.267±0.042	0.044±0.012	-0.493±0.044

Table 2.

Event	n	ϕ	$\sigma[\phi]$	$\sigma_n[\phi]$	V	σ[V]	σ_n[V]
Max	16	0.001	0.020	0.005	6.61	0.40	0.10
Min	7	0.594	0.045	0.019	11.04	0.70	0.28
Incl	22	0.878	0.021	0.005	16.71	6.32	1.38
Decl	19	0.223	0.043	0.010	38.43	3.89	0.92

$P_r = 10^{-L_p}$; "max" and "min" are extreme values of the fit; $A = (t_{max} - t_{min})/P$ is asymmetry and Δm is the amplitude. One may note that σ_n is monotonously decreasing with s, whereas σ_* as nearly at "standstill" for $s \geq 4$. The value of σ_s increases with s what is usually expected for relatively low signal/noise ratio. The period's estimates are the same within errors for $s \geq 2$, the extreme values of the brightness, amplitude and asymmetry are close for $s \geq 4$. This indicates that the results are rather stable and $s = 5$ is a realistic value although the contribution of the 5-th wave (=4-th harmonic) is much smaller than of the other ones. This fit is shown by a solid line in Fig. 1. The mean epoch for maximum ($6.^{m}78 \pm 0.^{m}03$) is JD $2444733.76 \pm 0.^{d}93$, minimum ($11.^{m}15 \pm 0.^{m}09$) JD $2444575.1 \pm 4.^{d}0$. The asymmetry $A = 0.409 \pm 0.011$ coincides with the value $A = 0.42$ listed in the GCVS, despite the best fit period value $P = 387.^{d}509 \pm 0.^{d}029$ significantly differs from that $386.^{d}96$ listed in GCVS. One may note an apparent hump at the ascending branch. It is not seen in all individual cycles, but is statistically significant at the mean phase curve shown in Fig. 2.

The extreme slopes of the fit occur at the phases computed in respect to the maximum are $\phi = -0.098$ (ascending branch, $dt/dm = 15.4 \pm 0.5$ days/mag) and $\phi = 0.217$ (descending branch, $dt/dm = 30.6 \pm 2.5$ days/mag). The ratio of the slope to that expected for the sine with the same period and full amplitude is $B = 1.84 \pm 0.06$ and $B = 0.92 \pm 0.08$, respectively.

However, there are cycle–to–cycle changes of the phase curve shape. Moreover, one may suggest that the magnitude at minimum was distinctly fainter by 1.5^{m} at JD 2442200–44200 than in the later dates. This agrees with the earlier light curve published by Mattei and Allen (1979) where one may see a time interval JD 2425600–27200 when the amplitude was ≈ 4 times fainter than in other years. However, there are large observational gaps preventing more detailed study of this phenomenon.

The Fourier coefficients for the light curves of pulsating variables were studied for Cepheids by Kukarkin and Parenago (1937) and recently in a number of observational and theoretical papers for RR Lyr–type stars (e.g. Antonello 1994, Kovacs et al. 1986 and references therein) and Mira–type objects (Chinarova 1995, Kudashkina and Andronov 1996). In Table 1 are listed the following parameters of individual harmonics: j the number of trial harmonic, r_j is semi-amplitude, ϕ_{0j} is phase of the maximum of the harmonic in respect to the maximum of the fit. Amplitudes and phases relative to the first harmonic and their standard errors are computed by using the formulae by Petersen (1986). Please note that our definition ϕ_{0j} (phase at which the maximum occurs) differs from that of Petersen (1986) by sign. All phase shifts are reduced to the interval (−0.5,0.5).

Analysis: Individual Cycles: Methods

The period of the star is close to 1 year, its declination is low. Thus there are significant gaps in observations and the individual cycles are not fitted completely. As an attempt to solve this problem, we have used several fitting routines. They are listed below.

RP – Method of "Running Parabolae". It was proposed by Andronov (1990, 1997). To determine the optimal value of the filter half–width Δt we have computed the smoothed values at the times of the original observations and then the "signal/noise" ratio for some range of Δt as described by Andronov (1997). Both the maximum of S/N=17.55 and the unbiased estimate of the r.m.s. deviation of the observations from the fit σ_0 occurred at Δt=57^{d}. The results of the fit are shown in Fig.1 by the large dots. This fit is in excellent agreement with the observations. Owed to large gaps, it was computed only for 1434 data points from 1521. The value $\sigma_0 = 0.24^{m}$ is in reasonable agreement with the accuracy of visual observations. The r.m.s. accuracy of the fit 0.08^{m}. However, the fit was not computed if the number of observations in the subinterval $t_0 - 0.5 \cdot \Delta t, t_0 + 0.5 \cdot \Delta t$ was less than 4 or if all the observations were located from one side of the trial time t_0 or if the accuracy estimate of the smoothed value exceeds 0.5^{m}. Such strong restrictions allow to obtain a good fit, but for the case of R Aqr may not help to receive more complete curve.

RS – Method of "Running Sines". To extend the time interval for running fit one may use periodic function instead of aperiodic parabolae. In our previous paper (Chinarova et al. 1994) we have proposed the method of "running sines" which was applied to the Mira-type component in the symbiotic binary UV Aur. However, the curve is asymmetric, the statistically significant degree of the trigonometric polynomial is $s = 5$ thus one may suggest to extend the method of "running sines" to "running multiharmonic fit", when to compute the value at trial time t_0 one uses the multiharmonic fit in the subinterval $t_0 - 0.5 \cdot \Delta t, t_0 + 0.5 \cdot \Delta t$. In other words, the interval used for fitting has duration equal to the mean period and is centered to trial time t_0. We have tried to apply this method for $s = 1$ and $s = 2$. Although the case $s = 2$ corresponds to better fit at the branches of the light curve well covered by the observations, the uncertainty of the "interpolated" branches far from data is significantly larger and one may see apparent semi-amplitude variations of the light curve. The use of $s = 1$ allows to obtain "true–like" fit at the gaps as well, despite some "minima" of unjustified large depth are seen (e.g. at JD 2446900 and 2 subsequent minima).

AP – Method of "Asymptotic Parabolae". This method is proposed by Andronov (1995) and described in more detail by Marsakova and Andronov

(1996). It was found to be the best for our type of gaped data. It is efficient for the curves with nearly linear ascending and descending branches, the transition between which may be fitted by a parabola. The number of observations used for the fit is larger than that for the "RP" as the transition is shorter than the transition + (ascending + descending) branches, but is more local than "RS" using the whole period.

LF – Linear Fits. As additional "characteristic events" which may be used for study of changes of the period and shape of individual cycles we have computed the times of the crossings of the fit and a constant value (set to $9^{\rm m}$) and the corresponding slopes dt/dm. This is slightly similar to the crossings of the $\gamma-$ value by the radial velocity curve. The parameter dt/dm (the characteristic time in days needed for brightness change by $1^{\rm m}$) was also introduced in the chapter "Multiharmonic fits" for the mean phase curve. Such additional times are more numerous for R Aqr (20 for descending branch, 22 for ascending branch as compared with 16 maxima and 7 minima).

Analysis: Individual Cycles: Results

The characteristics of the maxima and minima obtained by using the "AP" method are listed in Table 3. The "LF" results are listed in Table 4. The time behaviour of the phases of the "four characteristic points", the brightness in the maxima and minima and of the slopes of the descending and ascending branches is shown in Fig. 3.

The phases of crossings $m = 9^{\rm m}$ show apparent parabolic shape which is shown by dashed lines. Obviously, this is only formal approximation, as no secular variations of the shapes may be achieved for the period constant during the observations. However, the estimates of t_i and t_d are independent, thus the seemingly similar parabolic fit is very surprising.

The mean characteristics of the parameters obtained by means of "LF" are: standard error of the determination of time $1.46^{\rm d} = 0.0038P$, standard deviation of the brightness from the linear fit $0.235^{\rm m}$ in excellent agreement with the value $0.239^{\rm m}$ estimated from the "RP" fit with optimal value of the filter half-width Δt. The mean slopes are $t_i = 16.8 \pm 1.5^{\rm d}$ and $t_d = 39.6 \pm 1.1^{\rm d}$ for incline and decline, respectively. The value of t_i is close to that obtained from the 4–harmonic fit (15.4 ± 0.5), but t_d differs significantly from 30.6 ± 2.5.

One may introduce the parameter $A_l = t_i/(t_i + t_d)$ equal to the asymmetry if the light curve is composed of the linear ascending and descending branches with zero–length transitions. For R Aqr its mean value is equal to 0.298 ± 0.019. For the 4–harmonic fit $A_l = 0.335 \pm 0.020$, i.e. coinciding with the "LF" value within error estimates. The mean phases and values of the extrema and crossings are listed in Table 2.

Here σ is a r.m.s. deviation from the weighted mean,

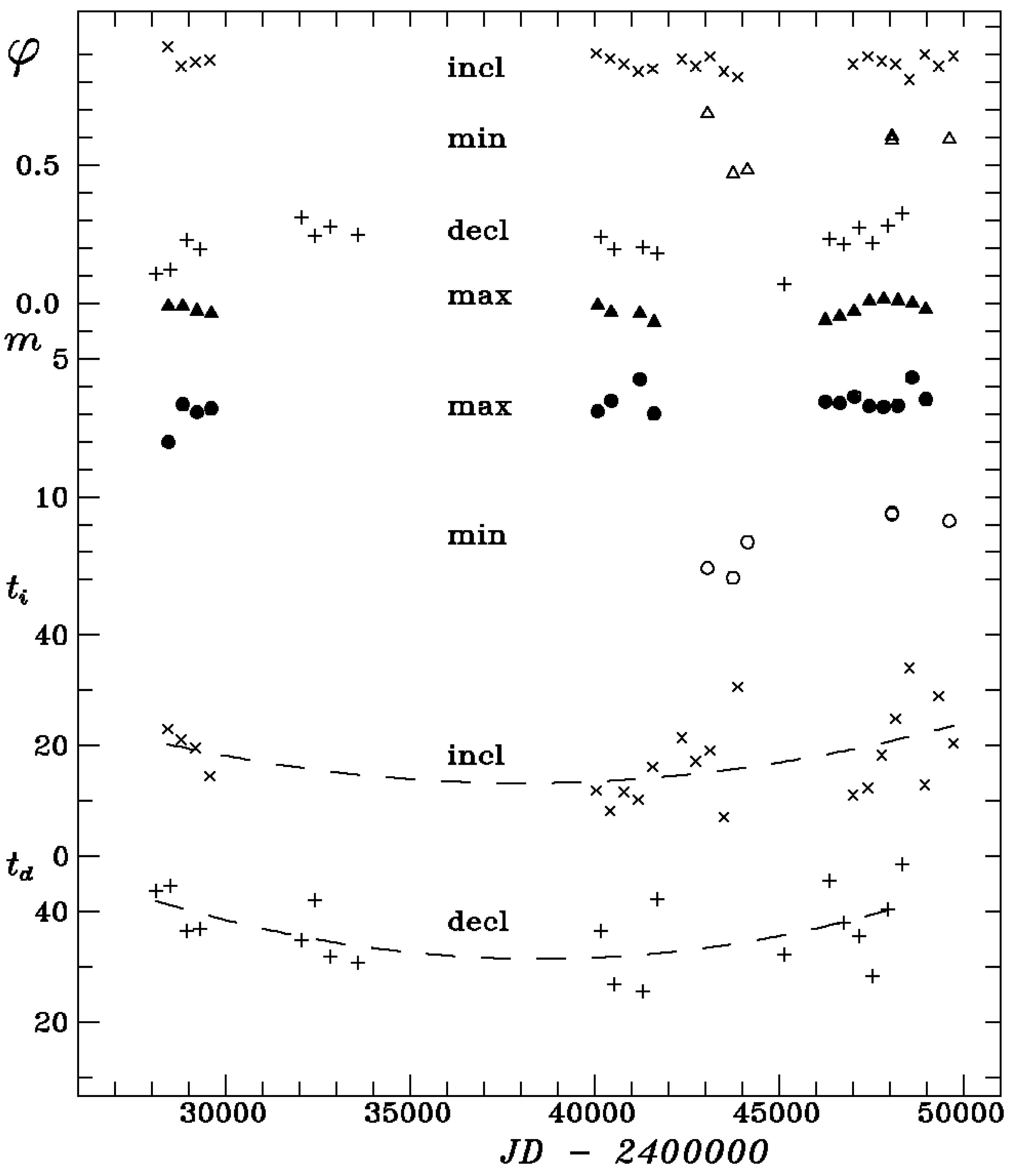

Figure 3. Time dependence of the phases of maxima, minima, crossings of $m = 9^{\rm m}$, brightness of the extrema and slopes dt/dm of the brightness incline (t_i) and decline (t_d) at the crossings.

σ_n corresponds to the standard error of the mean. The parameter V is equal to the magnitude of maximum or minimum and dt/dm for the crossings of $m = 9^{\rm m}$ during incline or decline. One may note that rounding errors of the error estimates may affect the values of the weighted mean and r.m.s. deviations. This may be seen from comparison of the data from this table (values of σ rounded as in Tables 3,4) with that mentioned above with 2 additional digits. However, these differences do not exceed the error estimates. The "unit weight" error σ_0 is also listed.

One may note that the values of $\sigma[\phi]$ are practically equal within pairs (maximum, incline) and (minimum, decline). The asymmetry 0.405 ± 0.049 derived from the mean phases of minima and maxima coincides with that of the 4-harmonic fit within error estimates, but its accuracy is worth than from the fit using all 1521 observations instead of 16+7 extrema.

The periodogram for the phases of maxima (one–harmonic approximation, cf. Andronov 1994) shows the highest peak corresponding to the secondary period $P_2 = 3955 \pm 50^{\rm d}$ and amplitude $(0.032 \pm 0.005)P$. The "false alarm probability" for this peak is $10^{-2.45}$, i.e. this wave may be statistically significant.

Acknowledgements. The research is based on the observations from the AFOEV database. It was partially supported by the Ukrainian State Committee for Science and Technique (DKNT).

Table 3. Characteristics of the maxima and minima.

t_e	n	E	ϕ_e	m_e
Maxima				
28456.9± 3.8	26	-42	-0.004±0.010	8.02±0.10
28843.9± 3.4	22	-41	-0.005±0.009	6.66±0.10
29225.1± 1.8	41	-40	-0.021±0.005	6.94±0.08
29609.1±10.3	10	-39	-0.030±0.027	6.81±0.36
40083.7± 4.5	23	-12	0.000±0.011	6.91±0.12
40460.8± 3.1	28	-11	-0.027±0.008	6.53±0.10
41234.1± 2.3	31	-9	-0.031±0.006	5.75±0.14
41609.4± 5.4	11	-8	-0.063±0.014	7.00±0.25
46262.3± 4.6	76	4	-0.056±0.012	6.57±0.04
46654.9± 3.8	110	5	-0.042±0.010	6.62±0.07
47049.5± 2.4	105	6	-0.024±0.006	6.37±0.06
47452.1± 1.3	124	7	0.015±0.003	6.73±0.06
47841.6± 1.2	178	8	0.020±0.003	6.74±0.05
48227.6± 1.8	153	9	0.016±0.005	6.70±0.07
48611.3± 1.2	61	10	0.006±0.003	5.70±0.07
48989.6± 1.9	21	11	-0.017±0.005	6.47±0.14
Minima				
43063.8±15.8	8	-5	0.691±0.041	12.58±0.65
43755.2± 7.8	22	-3	0.475±0.020	12.93±0.24
44148.0±11.9	20	-2	0.488±0.031	11.63±0.41
48064.9±11.1	50	8	0.596±0.029	10.63±0.13
48070.6± 3.9	179	8	0.611±0.010	10.58±0.81
48070.7± 3.9	179	8	0.611±0.010	10.58±0.82
49616.4± 7.1	23	12	0.600±0.018	10.87±0.11

Table 4. Characteristics of the crossings.

t_c	n	E	ϕ_c	dt/dm	σ_0
Descending branch (decline)					
28112.2±5.2	3	-43	0.107±0.013	43.7±14.7	0.127
28505.1±4.2	17	-42	0.120±0.011	44.6±2.4	0.209
28934.7±2.9	16	-41	0.229±0.008	36.5±1.0	0.140
29308.5±6.5	19	-40	0.194±0.017	37.0±4.0	0.169
32066.4±2.4	24	-33	0.311±0.006	34.8±0.3	0.324
32427.5±2.1	5	-32	0.243±0.005	42.1±0.7	0.100
32827.6±2.0	21	-31	0.275±0.005	31.8±0.5	0.262
33591.0±6.2	4	-29	0.245±0.016	30.8±8.5	0.225
40177.1±1.4	11	-12	0.241±0.004	36.5±0.4	0.123
40547.1±4.2	15	-11	0.196±0.011	26.8±2.3	0.207
41324.5±4.3	9	-9	0.202±0.011	25.7±1.7	0.182
41704.3±1.3	5	-8	0.182±0.003	42.3±1.2	0.020
45147.6±3.8	3	1	0.068±0.010	32.3±3.8	0.087
46374.6±1.4	79	4	0.234±0.004	45.5±0.2	0.198
46753.7±1.3	96	5	0.213±0.003	38.1±0.1	0.228
47164.2±2.6	49	6	0.272±0.007	35.6±0.5	0.228
47531.2±1.9	38	7	0.219±0.005	28.3±0.4	0.243
47942.8±3.8	82	8	0.281±0.010	40.3±0.9	0.202
48346.9±5.8	59	9	0.324±0.015	48.5±1.4	0.235
Ascending branch (incline)					
28430.5±1.4	10	-43	0.928±0.004	23.0±0.5	0.179
28790.2±3.4	9	-42	0.856±0.009	21.0±1.5	0.183
29183.5±1.2	19	-41	0.871±0.003	19.6±0.3	0.200
29574.2±2.5	5	-40	0.879±0.007	14.5±1.2	0.204
40046.0±3.1	5	-13	0.903±0.008	11.9±1.6	0.367
40426.7±1.2	8	-12	0.885±0.003	8.3±0.4	0.362
40806.0±1.4	5	-11	0.864±0.004	11.6±0.8	0.239
41183.7±1.6	11	-10	0.839±0.004	10.2±0.5	0.319
41574.8±1.3	3	-9	0.848±0.003	16.2±0.5	0.023
42363.2±1.4	5	-7	0.883±0.004	21.4±0.8	0.146
42740.9±1.7	12	-6	0.857±0.004	17.2±0.5	0.325
43141.4±7.1	5	-5	0.891±0.018	19.1±4.7	0.352
43508.5±2.3	5	-4	0.838±0.006	7.1±1.2	0.383
43888.3±5.4	15	-3	0.818±0.014	30.7±1.8	0.281
47005.6±0.7	22	5	0.863±0.002	11.1±0.2	0.175
47403.9±0.5	39	6	0.891±0.001	12.3±0.1	0.227
47785.3±0.6	52	7	0.875±0.002	18.3±0.1	0.210
48168.3±1.3	46	8	0.863±0.003	24.9±0.4	0.247
48534.6±1.5	62	9	0.808±0.004	34.1±0.2	0.321
48957.4±1.2	14	10	0.899±0.003	12.9±0.3	0.261
49328.3±2.8	11	11	0.857±0.007	29.0±1.9	0.263
49730.5±1.5	4	12	0.894±0.004	20.4±1.3	0.131

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