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Search for Evolutionary Changes in Cepheid Periods Using the Harvard Plate Collection: NSV 9159

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Abstract—We have obtained 530 photographic magnitude estimates for the long-period classical Cepheid NSV 9159 ($P = 39^{\rm d}$) in the plate collections of the Harvard Observatory and the Sternberg Astronomical Institute. Together with the currently available CCD observations from the ASAS-3 catalog, our data have allowed us to construct an $O-C$ diagram spanning a time interval of 119 years. The $O-C$ diagram has the shape of a parabola, which has made it possible to determine for the first time the quadratic light elements and to calculate the rate of evolutionary decrease in the period, 314.4 ($\pm$7.3) s yr^{-1}, in agreement with the results of theoretical calculations for the second crossing of the instability strip. The available data reduced by the Eddington–Plakidis method do not reveal any noticeable random fluctuations in the period.

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INTRODUCTION

Small changes in periods, including progressive ones, were detected for some of the classical Cepheids (below, the word "classical" is omitted) back in the early 20th century. However, the nature of these progressive changes had remained unknown until the 1960s, when the advent of computers led to a rapid development of the stellar evolution theory that inevitably predicted the existence of continuous slow changes in Cepheid periods.

According to theoretical calculations (see, e.g., Becker 1985), a star leaving the main sequence moves toward the red supergiants, while its evolutionary track enters the so-called instability strip and can cross it (sometimes incompletely) one, three, or five times; each time the star begins to pulsate and becomes a Cepheid. Since the track is not parallel to the constant-period lines, the pulsation period increases when the star moves from left to right in the instability strip (the first, third, or fifth crossing) or decreases when it moves from right to left (the second or fourth crossing); in this case, the data points on the $O-C$ diagram should lie along a nearly parabolic curve. Theoretical calculations show that in an observing time of the order of a century, the period changes for Cepheids with periods of 5–6 days even for the second and third (slowest) crossings of the instability strip reach such a value that the evolutionary pattern of behavior of the $O-C$ residuals becomes easily detectable (Fernie 1990; Berdnikov et al. 2000). If, however, the star becomes a Cepheid during other crossings of the instability strip and/or has a longer period, then the progressive changes in its period should be detectable in a time interval of only a few decades.

Our experience has shown, however, that there can be no "pure" parabolas on the $O-C$ diagram: cyclic and/or irregular variations in the $O-C$ residuals are superimposed on them; these variations can have such a large amplitude that they become dominant and (sometimes completely) mask the evolutionary changes even in a time interval of more than a century and even for Cepheids with periods longer than 50 days (Mahmoud and Szabados 1980; Berdnikov 1994; Berdnikov et al. 2004, 2007). Therefore, when the period variability for any Cepheid is studied, the longest possible time interval should be covered with observations.

The necessary observations can be found in the literature for a hundred, as a rule, brightest and long-discovered Cepheids. However, for the remaining six hundred known Cepheids, such data can be obtained

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Table 1. Observational material for NSV 9159

Data source	Number of observations	Type of observations	JD interval
Harvard	474	Photographic (PG)	2 411 172–2 447 770
SAI	56	Photographic (PG)	2 445 844–2 449 893
Shajn (1934b)	28	Photographic (PG)	2 420 296–2 427 278
ASAS-3	415	CCD (V band)	2 451 940–2 454 648

only from old photographic plates available in the archives of many astronomical observatories. The richest and oldest collection of such plates is stored at the Harvard Observatory (USA); its numerous stations have regularly photographed the whole sky since the 1880s. The magnitude estimates obtained in the Harvard plate collection supplemented with other photometric data, including currently available ones, allow the $O-C$ diagrams to be constructed in the longest possible time interval.

The detection of parabolas on the $O-C$ diagrams allows the rates of observed evolutionary changes in periods to be calculated. By comparing them with the theoretical rates calculated for different crossings of the instability strip, we can identify the crossing number. In the immediate future, this will make it possible to construct the period–luminosity relation for each individual crossing, which, in turn, will lead to a more accurate determination of Cepheid distances.

Since 2000, we have regularly performed photographic observations of Cepheids using plates from the Harvard collection. The results of studying the period variability for seven stars of this type have been published to date: T Ant (Turner and Berdnikov 2003), VY Car, WZ Car, and GH Car (Berdnikov and Turner 2004), V1496 Aql (Berdnikov et al. 2004), GY Sge (Berdnikov et al. 2007), and CG Cas (Turner et al. 2008). In this paper, we study the behavior of the period for the classical Cepheid NSV 9159.

THE TECHNIQUE AND OBSERVATIONAL MATERIAL

To study the Cepheid period variability, we use the universally accepted technique of analyzing the $O-C$ diagrams; the most accurate method for determining the $O-C$ residuals is the method of Hertzsprung (1919), whose computer implementation was described by Berdnikov (1992). To confirm the reality of the detected period changes, it should be shown that the random fluctuations in the pulsation period, if present, are not dominant on the $O-C$ diagram; we search for these random fluctuations using the technique described by Eddington and Plakidis (1929).

NSV 9159 was discovered by Shajn (1934a). She published 28 photographic magnitude estimates (Shajn 1934b) but did not give the variability type. The star 173357-2030.4 in the ASAS-3 catalog (Pojmanski 2002) identified with NSV 9159 was classified as a classical Cepheid with a period of 38.517803 days only almost 70 years later.

To construct the $O-C$ diagram for the Cepheid NSV 9159, we used the times of maximum light determined from the photographic observations that we obtained in the plate collections of the Harvard Observatory and the Sternberg Astronomical Institute (SAI) as well as from the published photographic observations by Shajn (1934b) and the CCD V-band observations from the ASAS-3 catalog (Pojmanski 2002); information about the number of observations is presented in Table 1.

The oldest plate with NSV 9159 was taken at the Harvard Observatory in 1889 and the latest CCD image was obtained in 2008. Consequently, our data span a time span of 119 years.

RESULTS AND DISCUSSION

The results of our reduction of the seasonal light curves for NSV 9159 are presented in Table 2. Columns 1 and 2 give the times of maximum light and their errors; column 3 gives the type of observations (see Table 1); columns 4 and 5 contain the epoch number E and the $O-C$ residual; column 6 and 7 contain the number of observations N and the data source. The data from Table 2 are shown on the $O-C$ diagram (Fig. 1) by the circles with vertical bars, which indicate the limits of the errors in the $O-C$ residuals. For convenience, the $O-C$ residuals in Fig. 1 are expressed in fractions of the period.

Figure 1 shows that the $O-C$ diagram has the shape of a parabola. Using the times of maximum light from Table 2, we obtained the quadratic light elements for NSV 9159:

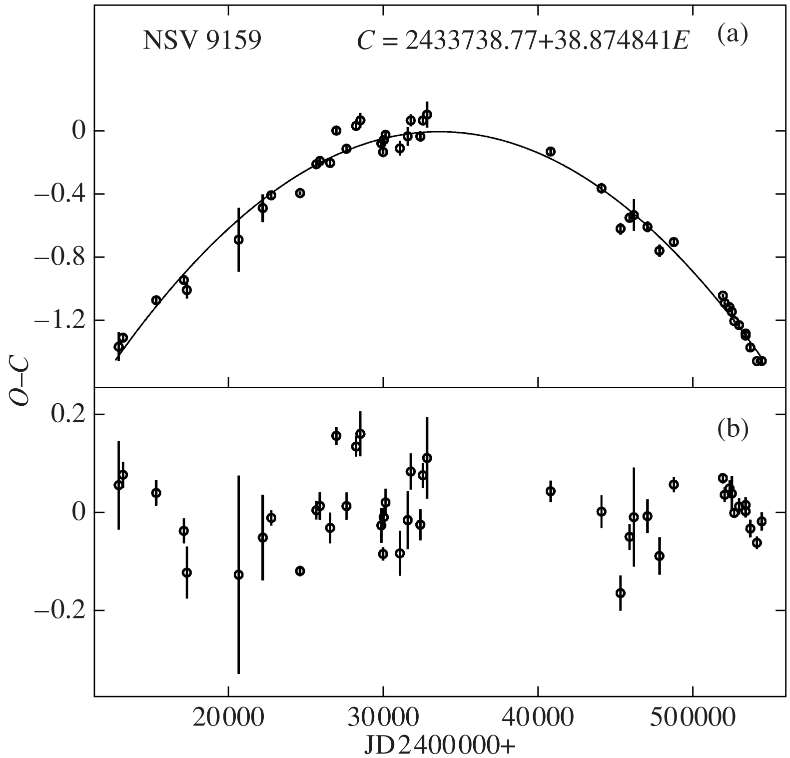

Fig. 1. $O-C$ diagram for NSV 9159 relative to the linear (a) and quadratic (b) light elements (1). The line in Fig. 1a is a parabola with coefficients (1).

$$\begin{aligned} \max\mathrm{JD_{hel}} &= 2433738.77(\pm 0.67) \\ &+ 38\overset{\mathrm{d}}{.}87484\ (\pm 0.00137)E \\ &- 0.19367 \times 10^{-3}(\pm 0.44928 \times 10^{-5})E^2. \end{aligned} \tag{1}$$

The linear part of these elements was used to calculate the $O-C$ residuals in the fifth column of Table 2. We used elements (1) to draw the parabola in Fig. 1a. Figure 1b shows the deviations from this parabola, which are in the form of waves, possibly, with a cycle of about 20 000 days in length.

We analyzed the deviations from elements (1) for the presence of random fluctuations in the pulsation period using the method suggested by Eddington and Plakidis (1929). For this purpose, we calculated the differences $a(r)$ between the observed (O) and calculated (C) times of all r brightness maxima from Table 2 to determine the accumulated phase delays $u(x) = a(r + x) - a(r)$ between the maxima separated by x cycles. According to Eddington and Plakidis (1929), the average $\langle u(x)\rangle$ for the absolute values of all accumulated delays should be related to the random fluctuation in period e by

$$\langle u(x)\rangle^2 = 2a^2 + xe^2, \tag{2}$$

where a characterizes the random errors in the measured times of maximum light.

The results of our calculations presented in Fig. 2 reveal no random fluctuations in the period of NSV 9159: in general, the diagram is dominated by the scatter. There is only a faint hint of a linear trend of $\langle u(x)\rangle^2$ for a cycle difference $x < 50$. However, in this case, a formal fitting of Eq. (2) gives here a solution in the form

$$\langle u(x)\rangle^2 = -0.748(\pm 0.139) + 0.292(\pm 0.005)x,$$

where the negative a^2, just as the value of 0.54 ± 0.07 for e, which is considerably higher than the predicted $e \simeq 0.16 \pm 0.15$ for a pulsating star with the period $P = 39^{\mathrm{d}}$ (Turner and Berdnikov 2001), indicates that this solution is not realistic. Thus, our data provide no evidence for the existence of noticeable random period fluctuations, i.e., the parabola on the $O-C$ diagram (Fig. 1) reflects the real evolutionary changes in the period.

The quadratic term of elements (1) makes it possible to calculate the rate of evolutionary decrease in the period: 314.4 ($\pm$7.3) s yr^{-1}, in agreement with the theoretical calculations for the second crossing of the instability strip (Berdnikov et al. 2000; Turner et al. 2006).

It should be noted that our results are based on specific standard light curves. Therefore, we give

Table 2. Times of maximum light for NSV 9159

Max JD	Error, days	Filter	E	$O-C$, days	N	Data source
2 412 926.6	3.5	PG	−534	−53.0	12	This paper (Harvard)
2 413 200.9	1.0	PG	−527	−50.8	6	This paper (Harvard)
2 415 348.3	1.0	PG	−472	−41.6	16	This paper (Harvard)
2 417 141.5	1.0	PG	−426	−36.6	15	This paper (Harvard)
2 417 333.4	2.0	PG	−421	−39.1	6	This paper (Harvard)
2 420 689.1	7.8	PG	−335	−26.6	5	This paper (Harvard)
2 422 251.9	3.4	PG	−295	−18.8	6	Shajn (1934b)
2 422 799.2	0.6	PG	−281	−15.7	9	This paper (Harvard)
2 424 665.8	0.4	PG	−233	−15.1	29	This paper (Harvard)
2 425 722.5	0.7	PG	−206	−8.0	35	This paper (Harvard)
2 425 956.6	1.1	PG	−200	−7.2	11	Shajn (1934b)
2 426 617.0	1.2	PG	−183	−7.7	27	This paper (Harvard)
2 427 013.7	0.7	PG	−173	0.3	11	Shajn (1934b)
2 427 670.1	1.1	PG	−156	−4.2	19	This paper (Harvard)
2 428 297.7	0.8	PG	−140	1.4	20	This paper (Harvard)
2 428 571.2	1.8	PG	−133	2.8	15	This paper (Harvard)
2 429 926.2	1.3	PG	−98	−2.9	19	This paper (Harvard)
2 430 040.6	0.5	PG	−95	−5.0	4	This paper (Harvard)
2 430 082.5	0.7	PG	−94	−2.0	21	This paper (Harvard)
2 430 200.4	1.0	PG	−91	−0.8	34	This paper (Harvard)
2 431 130.1	1.7	PG	−67	−4.1	18	This paper (Harvard)
2 431 638.4	2.3	PG	−54	−1.1	14	This paper (Harvard)
2 431 836.7	1.4	PG	−49	2.8	30	This paper (Harvard)
2 432 454.7	1.2	PG	−33	−1.1	27	This paper (Harvard)
2 432 614.2	1.0	PG	−29	2.8	34	This paper (Harvard)
2 432 887.8	3.2	PG	−22	4.2	11	This paper (Harvard)
2 440 886.9	0.8	PG	184	−4.8	12	This paper (Harvard)
2 444 182.2	1.3	PG	269	−13.9	8	This paper (Harvard)
2 445 416.2	1.4	PG	301	−23.9	10	This paper (Harvard)
2 446 002.0	1.0	PG	316	−21.2	20	This paper (SAI)
2 446 274.8	3.9	PG	323	−20.5	9	This paper (Harvard)
2 447 166.0	1.3	PG	346	−23.4	9	This paper (Harvard)
2 447 937.6	1.5	PG	366	−29.3	15	This paper (SAI)
2 448 872.7	0.6	PG	390	−27.2	21	This paper (SAI)
2 452 047.3	0.4	V	472	−40.4	52	Pojmanski (2002)
2 452 162.0	0.6	V	475	−42.3	8	Pojmanski (2002)
2 452 472.1	0.6	V	483	−43.2	28	Pojmanski (2002)
2 452 626.4	1.4	V	487	−44.4	4	Pojmanski (2002)
2 452 779.6	0.3	V	491	−46.7	67	Pojmanski (2002)
2 453 089.6	0.6	V	499	−47.7	46	Pojmanski (2002)
2 453 514.7	0.5	V	510	−50.2	63	Pojmanski (2002)
2 453 515.2	0.6	V	510	−49.7	21	Pojmanski (2002)
2 453 822.7	0.7	V	518	−53.2	31	Pojmanski (2002)
2 454 247.0	0.5	V	529	−56.6	62	Pojmanski (2002)
2 454 558.0	0.7	V	537	−56.5	34	Pojmanski (2002)

Table 3. Standard V and PG light curves for NSV 9159

Phase	V	PG	Phase	V	PG	Phase	V	PG	Phase	V	PG
0.000	12.959	14.040	0.250	13.207	14.261	0.500	13.542	14.560	0.750	13.640	14.646
0.005	12.959	14.040	0.255	13.215	14.268	0.505	13.548	14.565	0.755	13.625	14.633
0.010	12.960	14.041	0.260	13.222	14.275	0.510	13.555	14.571	0.760	13.610	14.619
0.015	12.961	14.042	0.265	13.230	14.282	0.515	13.562	14.578	0.765	13.595	14.606
0.020	12.963	14.043	0.270	13.238	14.289	0.520	13.569	14.584	0.770	13.578	14.591
0.025	12.965	14.045	0.275	13.246	14.296	0.525	13.576	14.590	0.775	13.561	14.576
0.030	12.967	14.047	0.280	13.254	14.303	0.530	13.584	14.597	0.780	13.543	14.560
0.035	12.970	14.050	0.285	13.262	14.310	0.535	13.591	14.604	0.785	13.525	14.543
0.040	12.973	14.052	0.290	13.270	14.317	0.540	13.599	14.611	0.790	13.506	14.526
0.045	12.977	14.056	0.295	13.278	14.325	0.545	13.606	14.617	0.795	13.487	14.510
0.050	12.980	14.059	0.300	13.286	14.332	0.550	13.614	14.624	0.800	13.468	14.493
0.055	12.984	14.062	0.305	13.294	14.339	0.555	13.622	14.631	0.805	13.448	14.475
0.060	12.988	14.066	0.310	13.302	14.346	0.560	13.630	14.638	0.810	13.428	14.457
0.065	12.992	14.069	0.315	13.310	14.353	0.565	13.638	14.646	0.815	13.408	14.439
0.070	12.997	14.074	0.320	13.317	14.359	0.570	13.646	14.653	0.820	13.388	14.421
0.075	13.001	14.077	0.325	13.325	14.366	0.575	13.654	14.660	0.825	13.367	14.402
0.080	13.006	14.082	0.330	13.333	14.374	0.580	13.662	14.667	0.830	13.347	14.385
0.085	13.011	14.086	0.335	13.341	14.381	0.585	13.670	14.674	0.835	13.327	14.367
0.090	13.016	14.091	0.340	13.348	14.387	0.590	13.678	14.681	0.840	13.307	14.349
0.095	13.021	14.095	0.345	13.355	14.393	0.595	13.685	14.687	0.845	13.287	14.331
0.100	13.026	14.100	0.350	13.363	14.400	0.600	13.693	14.695	0.850	13.267	14.313
0.105	13.031	14.104	0.355	13.370	14.406	0.605	13.700	14.701	0.855	13.248	14.296
0.110	13.036	14.109	0.360	13.377	14.413	0.610	13.707	14.707	0.860	13.229	14.279
0.115	13.041	14.113	0.365	13.384	14.419	0.615	13.713	14.712	0.865	13.210	14.263
0.120	13.046	14.117	0.370	13.391	14.425	0.620	13.719	14.718	0.870	13.192	14.247
0.125	13.051	14.122	0.375	13.397	14.431	0.625	13.725	14.723	0.875	13.174	14.231
0.130	13.057	14.127	0.380	13.404	14.437	0.630	13.731	14.728	0.880	13.157	14.215
0.135	13.062	14.132	0.385	13.410	14.442	0.635	13.736	14.733	0.885	13.141	14.201
0.140	13.067	14.136	0.390	13.416	14.447	0.640	13.740	14.736	0.890	13.125	14.187
0.145	13.073	14.142	0.395	13.422	14.453	0.645	13.744	14.740	0.895	13.109	14.173
0.150	13.078	14.146	0.400	13.428	14.458	0.650	13.747	14.742	0.900	13.095	14.160
0.155	13.084	14.151	0.405	13.434	14.464	0.655	13.749	14.744	0.905	13.081	14.148
0.160	13.089	14.156	0.410	13.440	14.469	0.660	13.751	14.746	0.910	13.068	14.136
0.165	13.095	14.161	0.415	13.445	14.473	0.665	13.752	14.747	0.915	13.055	14.125
0.170	13.101	14.167	0.420	13.451	14.479	0.670	13.752	14.747	0.920	13.044	14.115
0.175	13.107	14.172	0.425	13.457	14.484	0.675	13.752	14.747	0.925	13.033	14.105
0.180	13.113	14.177	0.430	13.462	14.488	0.680	13.751	14.746	0.930	13.023	14.096
0.185	13.119	14.183	0.435	13.467	14.493	0.685	13.749	14.744	0.935	13.013	14.087
0.190	13.125	14.188	0.440	13.473	14.498	0.690	13.746	14.741	0.940	13.005	14.080
0.195	13.131	14.193	0.445	13.478	14.503	0.695	13.742	14.738	0.945	12.997	14.073
0.200	13.137	14.199	0.450	13.484	14.508	0.700	13.737	14.733	0.950	12.990	14.067
0.205	13.144	14.205	0.455	13.489	14.513	0.705	13.731	14.728	0.955	12.984	14.062
0.210	13.150	14.210	0.460	13.495	14.518	0.710	13.725	14.722	0.960	12.978	14.056
0.215	13.157	14.217	0.465	13.500	14.522	0.715	13.717	14.715	0.965	12.974	14.053
0.220	13.164	14.223	0.470	13.506	14.528	0.720	13.709	14.708	0.970	12.970	14.049
0.225	13.171	14.229	0.475	13.512	14.533	0.725	13.699	14.699	0.975	12.966	14.046
0.230	13.178	14.235	0.480	13.517	14.537	0.730	13.689	14.690	0.980	12.964	14.044
0.235	13.185	14.242	0.485	13.523	14.543	0.735	13.678	14.680	0.985	12.962	14.042
0.240	13.192	14.248	0.490	13.529	14.548	0.740	13.666	14.669	0.990	12.960	14.041
0.245	13.200	14.255	0.495	13.536	14.554	0.745	13.653	14.658	0.995	12.959	14.040

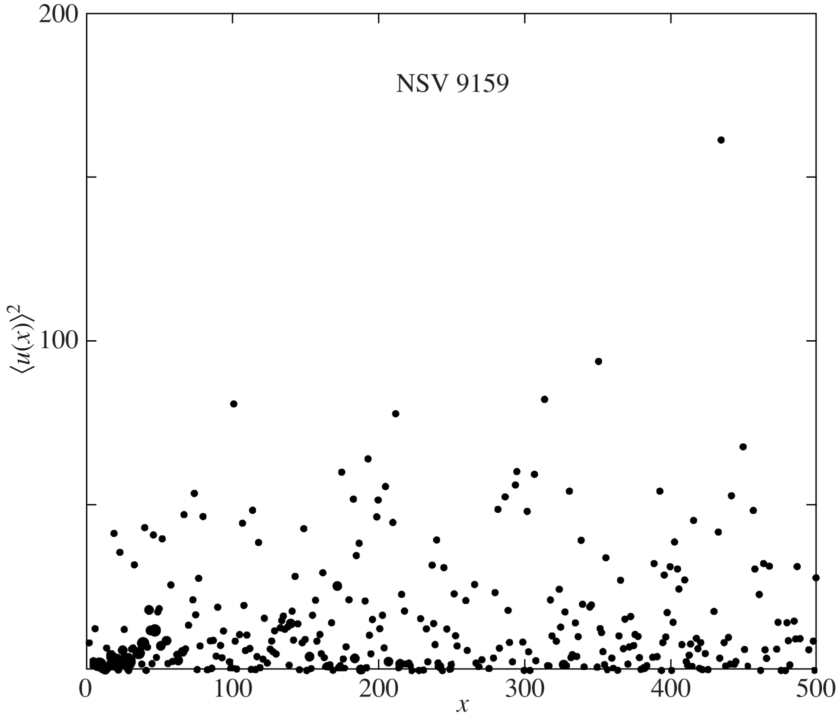

Fig. 2. Square of the accumulated phase delay $\langle u(x)\rangle$ calculated relative to elements (1) versus cycle difference x. The plot is dominated by the scatter, suggesting that there are no random fluctuations in the period of the Cepheid NSV 9159.

them in Table 3 to be used in future studies and to establish a relationship to our data if other standard light curves will be used. Table 3 contains the V and PG magnitudes of NSV 9159 for phases from 0 to 0.995 at 0.005 steps. These standard light curves shown graphically in Fig. 3 were constructed using data from the ASAS-3 catalog (Pojmanski 2002) and our Harvard magnitude estimates.

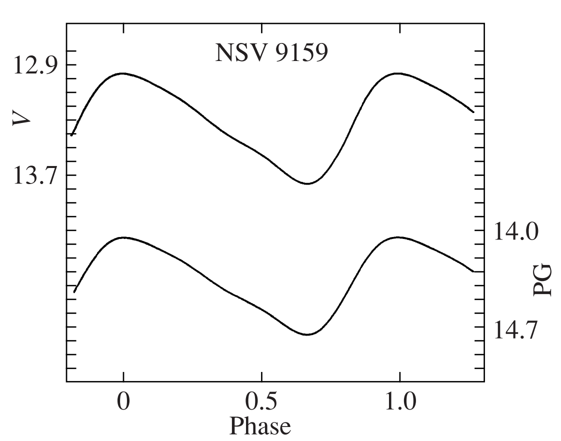

Fig. 3. Standard light curves for NSV 9159.

CONCLUSIONS

By reducing our 530 photographic magnitude estimates for the classical Cepheid NSV 9159 supplemented with available published data, we constructed an $O-C$ diagram spanning a time interval of 119 years, which allowed the quadratic light elements (1) to be determined for the first time. This made it possible to calculate the rate of evolutionary decrease in the period: 314.4 ($\pm$7.3) s yr^{-1}, in agreement with the results of theoretical calculations for the second crossing of the instability strip (Berdnikov et al. 2000; Turner et al. 2006). The available data reduced by the method of Eddington and Plakidis (1929) suggest that there are no random period fluctuations.

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