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First photometric study of the eclipsing binary PS Persei

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Abstract CCD photometric observations of the eclipsing binary PS Persei (PS Per) were obtained on two consecutive days in 2009. The 2003 version of the Wilson-Devinney code was used to analyze the first complete light curves in the V and R bands. It is found that PS Per is a short-period Algol-type binary with the less massive component completely filling its inner critical Roche lobe. The mass ratio of $q = 0.518$ and the orbital inclination of $i = 89.86°$ are obtained. In addition, based on all available times of primary light minima, including two new ones, the orbital period has been improved.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual: PS Per

1 INTRODUCTION

The variable was originally found before 1968, but not designated the name "PS Per" until Kukarkin et al. (1968), but photographic and visual times of light minima have been obtained since 1926. Later, photoelectric and CCD times of light minima were published by Šafář & Zejda (2000a,b), Zejda (2002, 2004), Agerer & Hübscher (2003), Diethelm (2005), Hübscher et al. (2006), Zejda et al. (2006), Brát et al. (2009) and Diethelm (2010). However, no complete light curve of the binary system has been made so far for photometric analysis.

In this paper, the first complete light curves in the V and R bands are presented. The absolute physical parameters as well as the orbital period are determined.

2 OBSERVATIONS

New CCD photometric observations of PS Per in the V and R bands were carried out on 2009 November 13 and 14 using the 85-cm telescope at the Xinglong Station of National Astronomical Observatory of China (NAOC), equipped with a primary-focus multicolor CCD photometer. The telescope provides a field of view of about $16.5' \times 16.5'$ at a scale of $0.96''$ per pixel and a limiting magnitude of about 17 mag in the V band (Zhou et al. 2009).

The typical exposure times in the V and R bands were 90 s and 60 s, respectively. The coordinates of the variable, comparison, and check stars are listed in Table 1. The data reduction was performed by using the aperture photometry package IRAF[1] (bias subtraction, flat-field division).

[1] IRAF is developed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Extinction corrections were ignored since the comparison star is very close to the variable one. In total, 445 CCD images in the V band and 446 images in the R band were obtained. Several new times of light minima (see Table 2) were derived from the new observations by using a parabolic fitting method.

The first complete light curves in the V and R bands are obtained, and displayed in the top panel of Figure 1. The new orbital period, revised in the next section, was used to calculate the phase.

Table 1 Coordinates of PS Per and its Comparison and Check Stars

Star	α_{2000} (h m s)	δ_{2000} (° ′ ″)
PS Per	02 39 33.3	45 38 05.5
Comparison	02 39 24.1	45 42 22.1
Check	02 39 22.2	45 43 34.0

Table 2 New CCD Times of Light Minima for PS Per

No.	J.D. (Hel.) (d)	Error (d)	Min.	Filter
1	2455149.2742	±0.0004	I	V
	2455149.2752	±0.0005	I	R
2	2455149.9768	±0.0003	I	V
	2455149.9768	±0.0004	I	R
3	2455150.3267	±0.0004	II	V
	2455150.3265	±0.0004	II	R

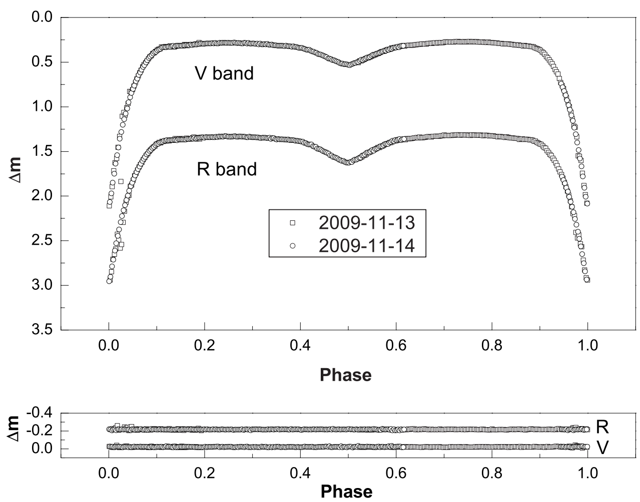

Fig. 1 *Top panel*: the light curves of PS Per in the V and R bands obtained on 2009 November 13 and 14. The points in the R band have been shifted down by 1.0 mag. *Bottom panel*: the differential light curves of the comparison star relative to the check star. The points in the R band have been shifted up by 0.2 mag.

3 ORBITAL PERIOD STUDY

All available times of primary light minima found in the literature were collected and listed in Table 3, which also includes the data in the database of Kreiner (2004) about eclipsing binaries. For my two-band light minima, a mean time of light minimum is given. The $O-C$ values of all minimum times are computed with the ephemeris given by Kreiner et al. (2001)

$$\mathrm{Min\ I} = 2424527.2165 + 0^{\mathrm{d}}.70217968 \times E, \quad (1)$$

and are listed in the fifth column of Table 3. The corresponding $O-C$ diagram, Figure 2, shows that the data are distributed around a straight line. So, a linear ephemeris was used to fit the $O-C$ values. The photographic and visual data show a large deviation from the straight line for their low quality. In the fitting process, a weight of 10 is used for photoelectric and CCD data, and 1 for photographic and visual data. The CCD times, 2451841.3121 and 2452213.4662, have a weight of 1 because of their large errors. A least-squares fit to the data gave the following ephemeris:

$$\mathrm{Min\ I} = 2424527.2163 + 0^{\mathrm{d}}.70217977 \times E. \quad (2)$$

The new ephemeris is plotted in Figure 2 with a solid line. The residuals with respect to Equation (2) are listed in the sixth column of Table 3.

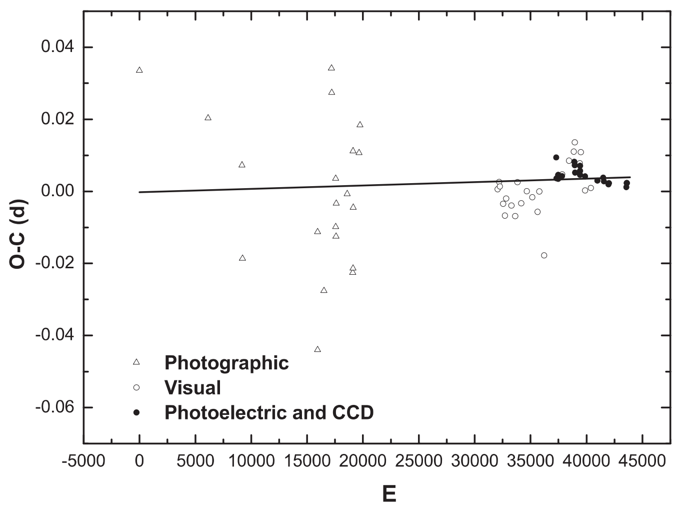

Fig. 2 $O-C$ diagrams. The solid line is calculated with the new ephemeris in Eq. (2).

4 PHOTOMETRIC SOLUTIONS WITH THE WILSON-DEVINNEY METHOD

The light curves were analyzed using the 2003 version of the Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1979, 1990). Since the spectral type of PS Per is F5, an effective temperature of $T_1 = 6750\,\mathrm{K}$ is assumed for the primary component. Assuming the photospheric surface of the binary star is convective, gravity-darkening coefficients ($g_1 = g_2 = 0.320$) and bolometric albedo ($A_1 = A_2 = 0.5$) were used. According to the tables of van Hamme (1993), the limb-darkening coefficients 0.506 for the V band ($x_{1V} = 0.506$) and 0.414 for the R band ($x_{1R} = 0.414$) were adopted.

Table 3 Times of Primary Light Minima for PS Per

JD (Hel.) (1)	Method (2)	Error (d) (3)	E (4)	$O-C$ (d) (5)	Residuals (6)	Reference (7)
2424527.250	p		0	0.03350	0.03374	MVS No.2
2428834.407	p		6134	0.02034	0.02000	MVS No.2
2430972.531	p		9179	0.00722	0.00660	MVS No.2
2430991.464	p		9206	–0.01863	–0.01925	MVS No.2
2435718.545	p		15938	–0.01124	–0.01249	MVS No.2
2435725.534	p		15948	–0.04404	–0.04529	MVS No.2
2436114.558	p		16502	–0.02758	–0.02888	MVS No.2
2436596.315	p		17188	0.03416	0.03278	MVS No.2
2436603.330	p		17198	0.02736	0.02598	MVS No.2
2436850.460	p		17550	–0.00988	–0.01128	MVS No.2
2436852.580	p		17553	0.00358	0.00217	MVS No.2
2436876.438	p		17587	–0.01253	–0.01393	MVS No.2
2436895.406	p		17614	–0.00338	–0.00479	MVS No.2
2437588.460	p		18601	–0.00073	–0.00223	MVS No.2
2437939.528	p		19101	–0.02257	–0.02412	MVS No.2
2437944.477	p		19108	0.01117	0.00961	MVS No.2
2437946.551	p		19111	–0.02136	–0.02291	MVS No.2
2437970.442	p		19145	–0.00447	–0.00602	MVS No.2
2438321.547	p		19645	0.01069	0.00908	MVS No.2
2438385.453	p		19736	0.01834	0.01672	MVS No.2
2447028.565	v		32045	0.00065	–0.00211	BBSAG No.85
2447118.446	v		32173	0.00266	–0.00011	BBSAG No.86
2447170.406	v		32247	0.00136	–0.00142	BBSAG No.87
2447384.566	v		32552	–0.00344	–0.00625	BBSAG No.89
2447491.294	v		32704	–0.00675	–0.00957	BBSAG No.90
2447566.432	v		32811	–0.00198	–0.00481	BBSAG No.91
2447894.348	v		33278	–0.00389	–0.00677	BBSAG No.94
2448136.597	v		33623	–0.00688	–0.00979	BBSAG No.96
2448283.362	v	0.004	33832	0.00257	–0.00036	BBSAG No.97
2448509.458	v	0.005	34154	–0.00329	–0.00625	BBSAG No.99
2448867.573	v	0.003	34664	0.00007	–0.00294	BBSAG No.102
2449202.511	v	0.004	35141	–0.00163	–0.00468	BBSAG No.104
2449546.575	v	0.006	35631	–0.00568	–0.00878	BBSAG No.107
2449653.312	v	0.003	35783	0.00001	–0.00310	BBSAG No.108
2449945.401	v	0.005	36199	–0.01774	–0.02089	BBSAG No.110
2450713.6127	cc	0.0014	37293	0.00939	0.00612	Šafář & Zejda (2000a)
2450721.3309	cc	0.0008	37304	0.00362	0.00035	BBSAG No.116
2450839.2981	cc	0.0021	37472	0.00463	0.00135	Šafář & Zejda (2000b)
2450841.4035	cc	0.0021	37475	0.00349	0.00021	Šafář & Zejda (2000b)
2451077.3366	cc	0.0006	37811	0.00422	0.00091	BBSAG No.119
2451088.572	v	0.003	37827	0.00474	0.00142	BBSAG No.119
2451515.501	v	0.008	38435	0.00850	0.00513	BBSAG No.121
2451810.419	v	0.005	38855	0.01103	0.00762	BBSAG No.123
2451841.3121	cc	0.0058	38899	0.00823	0.00481	Zejda (2002)
2451876.4201	cc	0.0017	38949	0.00724	0.00382	Zejda (2002)
2451878.533	v	0.008	38952	0.01360	0.01018	BBSAG No.124
2451899.5900	cc	0.0003	38982	0.00521	0.00179	Agerer & Hübscher (2002)
2452190.295	v	0.003	39396	0.00783	0.00437	BBSAG No.126
2452204.3365	cc	0.0010	39416	0.00573	0.00227	BBSAG No.126
2452213.4637	cc	0.0005	39429	0.00460	0.00113	BBSAG No.127

Table 3 – *Continued.*

JD (Hel.) (1)	Method (2)	Error (d) (3)	E (4)	$O-C$ (d) (5)	Residuals (6)	Reference (7)
2452213.4662	cc	0.0070	39429	0.00710	0.00363	Zejda (2004)
2452260.516	v	0.004	39496	0.01086	0.00739	BBSAG No.127
2452524.525	v	0.007	39872	0.00030	–0.00320	Diethelm (2003)
2452531.5507	pe	0.0002	39882	0.00420	0.00069	Agerer & Hübscher (2003)
2452885.446	v	0.002	40386	0.00094	–0.00261	Diethelm (2004)
2453302.5428	cc	0.0010	40980	0.00301	–0.00059	Diethelm (2005)
2453656.4422	cc	0.0003	41484	0.00385	0.00019	Zejda et al. (2006)
2453705.5937	pe	0.0008	41554	0.00278	–0.00088	Hübscher et al. (2006)
2453988.5713	cc	0.0001	41957	0.00197	–0.00172	Brát et al. (2009)
2454019.4675	cc	0.0001	42001	0.00226	–0.00144	Brát et al. (2009)
2455114.8667	cc	0.0006	43561	0.00116	–0.00268	Diethelm (2010)
2455149.2747	cc	0.0003	43610	0.00236	–0.00149	this paper
2455149.9768	cc	0.0003	43611	0.00228	–0.00157	this paper

Notes: In Ref. MVS = Mitteilungen über Veranderliche Sterne; BBSAG = Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft.

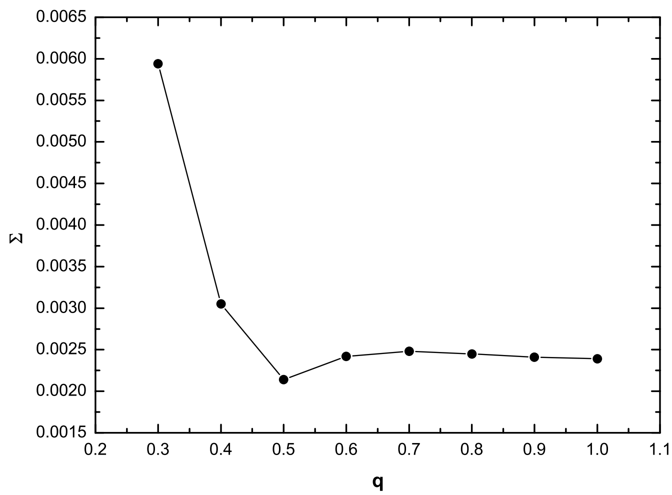

Fig. 3 Relation between Σ (the sum of the squared residuals) and q for PS Per.

Since no mass ratio has been published in the literature, a q-search method was used to determine the mass ratio. Solutions were carried out for a series of values of the mass ratio $q = M_2/M_1$ ($q = 0.3$, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0). Considering the light curves of EB type (EB-type light curve denotes the light curve of Beta Lyrae-type eclipsing systems), mode 2 (detached mode) is assumed. The behavior of the sum of the residuals squared, Σ, as a function of mass ratio q, is plotted in Figure 3, showing that Σ reaches the minimum value near $q = 0.5$. Therefore, the mass ratio was taken as an adjustable parameter and given the initial value of $q = 0.5$. After some differential corrections, the solution converged to mode 5 (semi-detached) and gave the final mass ratio of $q = 0.518$. The derived physical parameters are listed in Table 4. The theoretical light curves computed with the parameters are plotted in Figure 4 as solid line.

Table 4 Photometric Solutions for PS Per

Parameter	Photometric Element	Error
$g_1 = g_2$	0.32	assumed
$A_1 = A_2$	0.5	assumed
$x_{1\rm bol}$	0.480	assumed
$x_{2\rm bol}$	0.536	assumed
x_{1V}	0.506	assumed
x_{1R}	0.414	assumed
x_{2V}	0.726	assumed
x_{2R}	0.600	assumed
T_1(K)	6750	assumed
q (M_2/M_1)	0.518	0.003
$\Omega_{\rm in} = \Omega_2$	2.8944	–
$\Omega_{\rm out}$	2.5907	–
T_2 (K)	4822	7
i (°)	89.86	0.35
Ω_2	3.590	0.008
r_1 (pole)	0.3229	0.0008
r_1 (side)	0.3317	0.0009
r_1 (back)	0.3402	0.0010
r_2 (pole)	0.3025	0.0004
r_2 (side)	0.3159	0.0005
r_2 (back)	0.3483	0.0005
$\Sigma(O-C)^2$	0.0022	

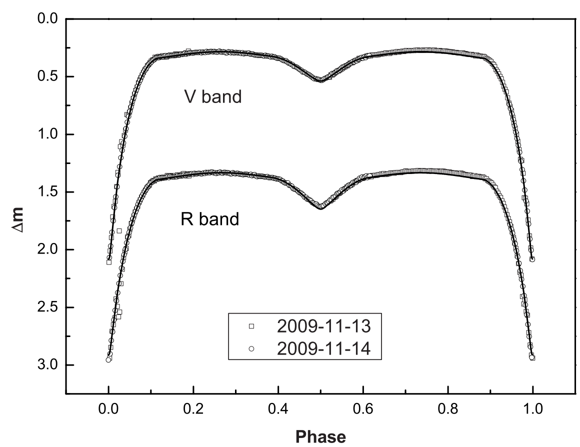

Fig. 4 Same as the top panel of Fig. 1, but the solid curves represent the theoretical light curves computed with the parameters in Table 4.

5 DISCUSSION AND CONCLUSIONS

In this paper, my photometric solution reveals that PS Per is a semi-detached system. The Roche-geometry configuration, where the less massive and cool secondary component fills its inner Roche lobe, permits a dynamical mass transfer from the secondary to the more massive primary star, suggesting a continuous period increase just as in AI Cru (Zhao et al. 2010) and DD Mon (Qian et al. 2009). The orbital period of PS Per, however, does not show continuous increase in this paper. This may be due to the low quality of photographic and visual times, and the short span of photoelectric and CCD times. In order to confirm the mass transfer from the secondary to the primary star, long-term orbital timing data are required.

According to the derived physical parameters listed in Table 4 and the Harmanec's (1988) relation for masses and radii as functions of spectral type, the following orbital parameters can be derived: $M_1 = 1.31\,M_\odot$, $R_1 = 1.39\,R_\odot$, $L_1 = 3.62\,L_\odot$, $M_2 = 0.68\,M_\odot$, $R_2 = 1.35\,R_\odot$, $L_2 = 0.89\,L_\odot$, and $a = 4.19\,R_\odot$. In order to further verify the parameters, spectroscopic observations of the radial velocity curves of both components are needed.

As shown in Figure 1, the secondary maxima of the light curves are slightly higher than the primary maxima. A weak O'Connell effect may arise from a hot spot on the primary component as a result of the impact of the gaseous stream from the cooler, less massive secondary component. Such a hot spot is often seen in other semi-detached binary systems, such as CL Aur (Lee et al. 2010) and KQ Gem (Zhang 2010). Considering the late spectral type and fast rotation of the secondary star, the asymmetry of the light curves can also be attributed to a cool spot on the secondary star caused by magnetic activity. It is a reasonable hypothesis that the magnetic activity makes the light curves show more variability than the impact of the gaseous stream does. So, in order to differentiate the two mechanisms of magnetic activity and impact of the gaseous stream, an investigation of long-term behavior of the light curves is also needed.

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