

The period-luminosity relation for Cepheids derived from multiphase temperature measurements and Cepheids kinematics based on GAIA DR2 data

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Abstract Calibration of the period-luminosity relation (PLR) for Cepheids has always been one of the biggest goals of stellar astronomy. Among a considerable number of different approaches, the Baade-Becker-Wesselink (BBW) method stands in the foreground as one of the most universal and precise methods. We present a new realization of the BBW method which is considered to be the generalization of surface brightness (Barnes & Evans 1976) and Balona (1977) approaches first proposed by Rastorguev & Dambis (2011) and described in Rastorguev et al. (2019). One of the main features of this method is using measured effective temperature variations to determine the main parameters of Cepheid, such as distance, radius, luminosity, colour excess, intrinsic colour. We apply this method to 45 Cepheids of Northern sky, for which multiphase temperature data are available. We take into account the effect of shock waves, whose presence in stellar atmosphere distorts the observational data and the calibrations used in this work. Within 0.0 – 0.87 phase interval we derived PL relation $\langle M_V \rangle_I = -(2.67 \pm 0.17) \cdot \log P - (1.58 \pm 0.16)$. It was used to calculate the distances, rotation curve and kinematical parameters of the sample of 435 Cepheids with GAIA DR2 proper motions.

Key words: stars: variables: Cepheids — stars: fundamental parameters — stars: distance — distance scale

1 INTRODUCTION

In the modern astronomy Cepheids play a particularly important role. PL relation, which was first discovered in 1912, made these objects one of the most reliable standard candles in the context of the extragalactic distance scale calibration. Nowadays obtaining precise PL relation remains one of the priority astronomical goals.

Many different approaches have been proposed in order to solve this task, among which several deserve special attention. One of the most commonly used methods to determine distance is the method of trigonometric parallax, which is inextricably linked to the GAIA mission ([Gaia Collaboration et al. 2018](#)). However, the distances derived with this method are fraught with significant level of uncertainty and systematic errors ([Groenewegen 2018](#)). In comparison with trigonometric parallaxes, the distances obtained for Cepheids in open clusters are more accurate, but limited number of such objects makes PL relation based on Cepheids in open clusters less reliable. The Baade-Becker-Wesselink (BBW; [Baade 1926](#); [Becker 1940](#); [Wesselink 1946](#)) method is thought to be quite effective and universal and comparable to the approaches mentioned above. One of the most well-known implementations of this method is the surface-brightness technique ([Barnes & Evans 1976](#)); including infrared range ([Barnes et al. 2005](#), hereafter **IRSB**); nevertheless it's not the only one.

In our research we focus on another modification of the BBW method, namely maximum-likelihood technique (i.e. light curve modelling), first proposed by [Balona \(1977\)](#) and recently generalized and refined by [Rastorguev & Dambis \(2011\)](#), [Rastorguev et al. \(2013\)](#) (hereafter **RD** version). This modification allows one to determine all the main parameters of Cepheid including mean radius, luminosity, color excess and normal color, as well as apparent distance modulus. Now we present first results of the study that is based on our new approach which uses additionally published multiphase effective temperature measurements (see, for example, catalog [Luck \(2018\)](#)). Here we estimate the luminosities of Cepheids and derive new calibration of the PL relation as described in [Rastorguev et al. \(2019\)](#).

2 OBSERVATIONAL DATA AND SAMPLES OF CEPHEIDS

In this study we use photoelectric and CCD photometry of classical Cepheids from [Berdnikov \(2008\)](#), very accurate radial-velocity measurements published by [Gorynya et al. \(1992, 1996, 1998, 2002\)](#) and effective temperature data from [Luck \(2018\)](#) catalog.

We have selected the data sets according to quality and completeness, but also to ensure that photometric and spectroscopic observational data are as synchronous as possible to prevent any systematic errors in the computed radius value and other parameters owing to evolutionary period changes resulting in phase shifts between the light, color and radial-velocity curves.

The above **RD** calculation algorithm ([Rastorguev et al. 2019](#)) has been conducted for 45 Cepheids. These Cepheids were divided into three samples according to the expected accuracy of the final results. Several factors were taken into account, including the quality of the observational data, its uniformity on the phase curve, the presence of a component (for binary/multiple objects we carried out additional calculations in order to extract the pulsation velocity curve from the radial velocity data and to subtract hot component's radiation from the photometric data), the type of pulsation (overtone or fundamental), the expected position

in the instability strip (in the center or on the edge) and others. The first sample, for which we expect the most precise results, contains 23 Cepheids, the second one includes 10 objects and the rest 12 Cepheids belong to the third sample. The list of Cepheids and sample memberships are given in Table 1.

3 RESULTS AND DISCUSSION

Obtaining PR relation allows one to identify the overtone Cepheids. These objects are shifted towards lower period values on the PR diagram. Among the Cepheids studied in the present work seven objects have been suspected to be overtone pulsators based their positions on period-radius and period-luminosity diagrams, namely BE Mon, DL Cas, DT Cyg, FF Aql, RS Ori, SU Cyg and Y Lac. The periods of these stars were shifted by a $\Delta \log P^d \approx +0.15$ to fit the fundamental period. All suspected overtone pulsators were included to the third sample, meaning the parameters estimated for these Cepheids are less reliable.

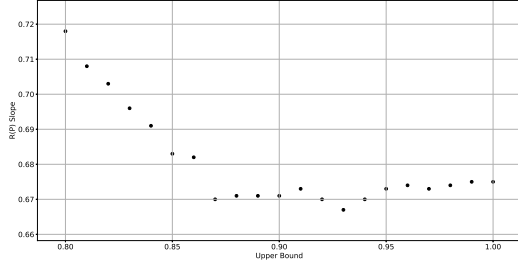


Fig. 1 Slope of the PR relations versus upper phase constraint

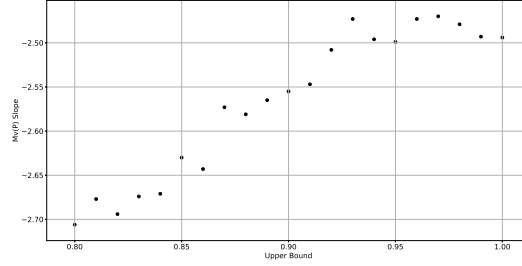


Fig. 2 Slope of PL relations versus upper phase constraint

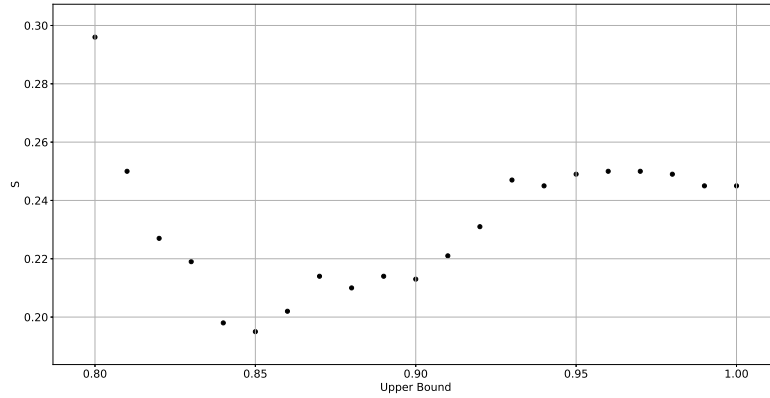


Fig. 3 Standard deviation from linear PL relation versus upper phase constraint

As is known, at the moments of time, corresponding to the upper phases of pulsation (near $\varphi \approx 1.0$), shock waves can arise in stellar atmosphere. These shock waves change the physical conditions in the environment and produce asymmetric line profiles in the spectrum which leads to the mismatch between the

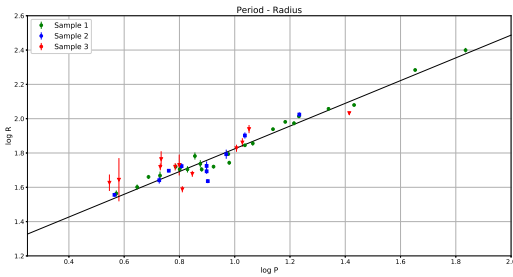
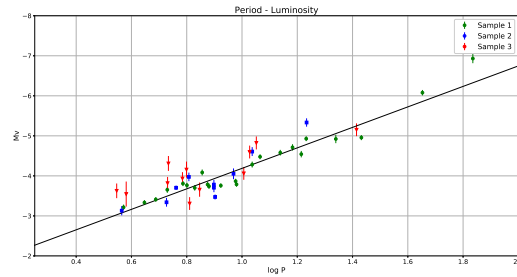
Table 1 Parameters of 45 Cepheids with [0, 0.87] phase interval

Name	Sample	Binary	Fundamental period (days)	$E(B - V)$ (mag)	$\langle R \rangle$ (R_{\odot})	$\langle M_v \rangle_I$ (mag)	$(m - M)_0$ (mag)
AW Per	3	Yes	6.463	0.58	38.8 ± 1.6	-3.31 ± 0.16	8.94 ± 0.20
BB Her	1	No	7.508	0.40	54.5 ± 2.7	-3.78 ± 0.07	12.54 ± 0.11
BE Mon	3	No	3.811	0.57	44.1 ± 12.8	-3.55 ± 0.31	12.24 ± 0.34
BG Lac	2	No	5.332	0.29	43.8 ± 2.0	-3.34 ± 0.11	11.28 ± 0.13
CD Cyg	1	No	17.074	0.58	103.1 ± 1.9	-4.93 ± 0.06	11.95 ± 0.14
CF Cas	1	No	4.875	0.54	45.8 ± 1.2	-3.41 ± 0.06	12.78 ± 0.13
CV Mon	3	No	5.379	0.69	52.4 ± 2.4	-3.82 ± 0.16	11.84 ± 0.21
Delta Cep	1	Yes	5.366	0.09	46.6 ± 2.5	-3.65 ± 0.08	7.30 ± 0.08
DL Cas	3	Yes	11.268	0.65	87.0 ± 4.8	-4.82 ± 0.16	11.70 ± 0.21
DT Cyg	3	No	3.520	0.04	42.3 ± 4.7	-3.63 ± 0.18	9.28 ± 0.19
Eta Aql	1	No	7.177	0.17	60.6 ± 2.9	-4.09 ± 0.07	7.43 ± 0.08
FF Aql	3	Yes	6.297	0.27	53.7 ± 7.5	-4.16 ± 0.20	8.64 ± 0.21
FM Aql	1	No	6.114	0.69	52.6 ± 1.6	-3.81 ± 0.06	9.81 ± 0.15
FN Aql	1	No	9.482	0.48	62.2 ± 1.3	-3.87 ± 0.06	10.67 ± 0.12
RS Ori	3	No	10.658	0.37	72.7 ± 4.2	-4.60 ± 0.16	11.78 ± 0.18
RT Aur	1	No	3.728	0.06	36.7 ± 1.5	-3.22 ± 0.07	8.47 ± 0.07
RX Aur	1	No	11.624	0.34	71.8 ± 2.2	-4.48 ± 0.06	11.01 ± 0.10
RX Cam	2	Yes	7.912	0.55	53.0 ± 3.2	-3.78 ± 0.12	9.65 ± 0.16
S Sge	1	Yes	8.382	0.17	52.5 ± 1.2	-3.78 ± 0.06	8.82 ± 0.07
S Vul	1	No	68.438	1.15	250.8 ± 7.6	-6.93 ± 0.12	12.10 ± 0.26
SS Sct	2	No	3.671	0.39	36.0 ± 0.9	-3.13 ± 0.12	10.06 ± 0.14
SU Cyg	3	Yes	5.417	0.09	58.1 ± 6.1	-4.30 ± 0.19	10.88 ± 0.19
SV Mon	1	No	15.235	0.30	95.8 ± 1.6	-4.71 ± 0.08	11.99 ± 0.10
SV Vul	1	No	44.969	0.62	192.2 ± 3.1	-6.08 ± 0.07	11.42 ± 0.14
T Mon	1	Yes	27.033	0.31	120.1 ± 1.6	-4.96 ± 0.06	10.10 ± 0.09
T Vul	1	Yes	4.435	0.07	39.9 ± 1.4	-3.33 ± 0.06	8.88 ± 0.07
TT Aql	1	No	13.755	0.59	86.8 ± 1.8	-4.58 ± 0.07	9.76 ± 0.14
U Aql	3	Yes	7.024	0.44	47.7 ± 1.9	-3.66 ± 0.18	8.62 ± 0.20
U Sgr	1	No	6.745	0.46	50.6 ± 2.2	-3.70 ± 0.07	8.89 ± 0.12
U Vul	2	Yes	7.990	0.72	43.3 ± 1.2	-3.47 ± 0.06	8.21 ± 0.16
V500 Sco	2	No	9.317	0.62	62.1 ± 3.8	-4.05 ± 0.13	10.75 ± 0.18
VX Per	2	No	10.885	0.53	79.8 ± 3.3	-4.61 ± 0.11	12.15 ± 0.16
W Gem	2	No	7.914	0.30	49.4 ± 1.7	-3.71 ± 0.11	9.65 ± 0.13
W Sgr	1	Yes	7.595	0.13	50.6 ± 1.5	-3.74 ± 0.07	7.99 ± 0.07
WZ Sgr	1	No	21.850	0.59	114.2 ± 1.9	-4.92 ± 0.11	11.01 ± 0.16
X Cyg	1	No	16.386	0.34	94.0 ± 2.4	-4.54 ± 0.08	9.80 ± 0.11
X Pup	3	No	25.965	0.53	107.8 ± 2.5	-5.15 ± 0.16	11.93 ± 0.19
X Vul	1	No	6.320	0.85	50.7 ± 1.8	-3.76 ± 0.06	9.78 ± 0.18
XX Sgr	2	No	6.424	0.58	52.9 ± 2.0	-3.97 ± 0.11	10.93 ± 0.16
Y Lac	3	No	6.090	0.15	52.5 ± 2.6	-3.94 ± 0.16	12.58 ± 0.16
Y Oph	2	No	17.128	0.78	105.7 ± 3.1	-5.33 ± 0.10	8.92 ± 0.19
Y Sgr	2	No	5.773	0.23	49.7 ± 1.1	-3.70 ± 0.06	8.67 ± 0.07
YZ Sgr	1	No	9.554	0.36	55.4 ± 1.5	-3.79 ± 0.06	9.96 ± 0.09
Z Lac	1	Yes	10.886	0.48	70.0 ± 1.1	-4.28 ± 0.07	11.10 ± 0.12
Zet Gem	3	No	10.150	0.07	67.2 ± 3.2	-4.06 ± 0.16	7.69 ± 0.16

Table 2 The period-luminosity relations in the form $M = a \cdot \log(P) + b$

References	a	b	Method
Groenewegen (2018)	-2.24 ± 0.14	-1.84 ± 0.12	GAIA DR2 trigonometric parallax
Benedict et al. (2007)	-2.43 ± 0.12	-1.62 ± 0.02	HST trigonometric parallax
Present work [0.00; 1.00]	-2.45 ± 0.15	-1.79 ± 0.14	RD
Present work [0.00; 0.87]	-2.60 ± 0.17	-1.58 ± 0.16	RD
Gieren et al. (2018)	-2.62 ± 0.10	-1.37 ± 0.04	IRSB
Storm et al. (2011)	-2.67 ± 0.10	-1.29 ± 0.03	IRSB
Fouqué et al. (2007)	-2.68 ± 0.09	-1.28 ± 0.03	IRSB
Molinaro et al. (2011)	-2.78 ± 0.11	-1.42 ± 0.11	IRSB
Turner et al. (2010)	-2.78 ± 0.12	-1.29 ± 0.10	Membership in open clusters

observational data and the calibrations. Moreover, the propagation of shock waves may be reflected in the change of the projection factor. We therefore need to constrain our data to avoid the distorted observations. Some authors (for example, Storm et al. 2011) exclude phase region [0.8, 1.0] from consideration. We decided to repeat our algorithm for the first sample Cepheids with different upper phase limits and find out which constraint leads to the smallest scatter of individual Cepheids relative to linear PL relation. As shown in Fig. 1 and 2, the choice of constraint decisively affects the obtained PR and PL relations. From our point of view, the optimal restriction for the phase interval is [0.00, 0.87]. This choice doesn't change the slope of PR relation compared to the case without restriction (Fig. 1) and reduces the scatter relative to the linear PL relation (Fig. 3). It is worth noting that the spread of the third sample Cepheids relative to the linear PL dependence has become slightly larger, therefore, we recommend to use the expressions obtained for the combination of the first and the second samples.

**Fig. 4** Period-Radius diagram, corresponding to the optimal phase interval**Fig. 5** Period-Luminosity diagram, corresponding to the optimal phase interval

PR and PL relations are shown in Fig. 4 and 5, respectively. Figures demonstrate that there's a strong correlation between the quality of the sample (the order number in the Table 1) and the scatter relative to linear relationship. Leaving the first two samples and adopting the optimal phase constraint, we obtained the following PR relation: $\log R = (0.67 \pm 0.02) \cdot \log P + (1.15 \pm 0.03)$, in good agreement with other works (for example, Sachkov et al. 1998).

The coefficients of our PL relations and the PL relations from the literature are listed in Table 2. It's clearly seen that in terms of the slope our relations fill the gap between the relations obtained with trigonometric parallaxes and the relations obtained with **IRSB** version of the BBW method, which seems to be quite satisfactory result. The deviation of our relation from the relation [Groenewegen \(2018\)](#) is small in the region of the short period Cepheids and becomes larger as the period increases, which is also expected as the accuracy of trigonometric parallaxes becomes lower for the far located stars, among which there are statistically more bright ones (the latter is explained by selection effects).

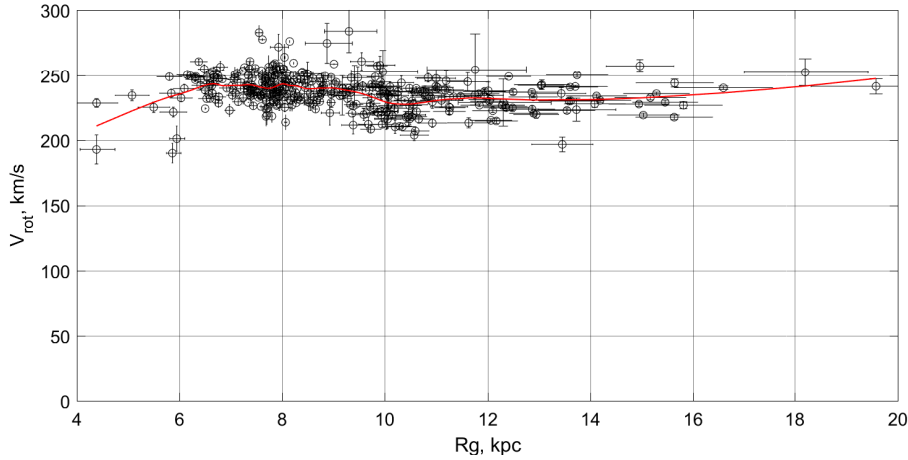


Fig. 6 Rotation curve of the Galactic disk built with statistical-parallax technique using obtained PL relation

To verify our result from completely different kinematical approach we checked the applicability of our **RD** method with statistical-parallax technique ([Rastorguev et al. 2017](#)). We combined flux averaged V magnitudes and the radial velocities from [Mel'nik et al. \(2015\)](#); averaged values of the color excess and the radial velocities from the DDO database ([Fernie et al. 1995](#)); accurate radial velocities and proper motions from GAIA DR2 catalogue ([Gaia Collaboration et al. 2018](#)) and our new PL relation to derive the distances for a large sample of Cepheids and to study their kinematics. The final sample with uniform photometric distances and spatial velocities consists of 435 stars. The calculation of kinematic parameters of the velocity field, which includes differential rotation and small perturbations from four-arm spiral density wave, was carried out by the statistical parallax method, described in all details in [Rastorguev et al. \(2017\)](#).

The distance to the center of the Galaxy was taken to be $R_0 = 8.2$ kpc. As for galactic masers, the best model of the velocity field presumed radial velocity dispersion independent on the galactocentric distance. The kinematic parameters and their statistical errors are listed in Table 3. They include local velocity of the sample (U_0, V_0, W_0) relative to the Sun, radial and vertical velocity dispersion ($\sigma U_0, \sigma W_0$), amplitudes of the velocity perturbations (f_R, f_Θ), the Solar phase angle χ_0 in the spiral pattern and pitch angle i , and also the distance scale factor $P = r_{\text{adopted}}/r_{\text{true}}$. The values of the kinematic parameters are in general agreement with the data on other young objects: masers, OB-stars and open clusters ([Rastorguev et al. 2017](#); [Bobylev & Bajkova 2018a,b, 2019a,b](#)). The value of P determines the ratio of the adopted distance and the “true” distance derived with statistical-parallax technique. Within calculated error the distance scale factor

Table 3 Kinematic parameters obtained with statistical-parallax technique for the final sample of 435 Cepheids (see [Rastorguev et al. 2017](#) for details)

U_0 (km/s)	V_0 (km/s)	W_0 (km/s)	σU_0 (km/s)	σW_0 (km/s)	P
-10.0 ± 1.2	-11.8 ± 0.8	-7.3 ± 1.1	15.8 ± 0.6	8.3 ± 1.0	1.01 ± 0.02
f_R (km/s)	f_Θ (km/s)	χ_0 (deg.)	i (deg.)	ω_0 (km/s/kpc)	ω'_0 (km/s/kpc ²)
-1.9 ± 0.8	1.2 ± 1.5	152 ± 25	-13.6 ± 1.7	29.20 ± 0.40	-3.92 ± 0.05
ω''_0 (km/s/kpc ³)	ω'''_0 (km/s/kpc ⁴)				
0.74 ± 0.03	-0.08 ± 0.01				

is equal to unity which confirms the quality of our PL relation and the absence of some systematic error in its zero-point. Fig. 6 shows the rotation curve of the Galaxy in the galactocentric distance interval from 4 to 20 kpc. The Solar velocity is about 239 ± 4 km/s.

We are thus convinced that new **RD** version of BBW method gives reliable results and in the future it certainly has the potential to become one of the main tools for a distance scales calibration.

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