CLASSICAL CEPHEIDS AND RR LYRAE STARS AS STANDARD CANDLES

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ABSTRACT

Statistical parallax technique is applied to classical Cepheids with pulsation periods greater than 9 days (this sample is expected to be almost free of first overtone pulsators). The sample includes 101 Cepheids with radial velocities, 99 Cepheids with proper motions (mostly from Hipparcos and Tycho-2) and 91 Cepheids with space velocities. Their heliocentric distances, calculated with Berdnikov et al. (1996) multi-colour 'period–luminosity' relation (PL relation), do not exceed 6 kpc. Two approaches have been used: (1) The comparison of first derivatives of angular velocity law for the Galactic disc, calculated separately from radial velocities and proper motions; (2) The maximum likelihood estimation of all kinematical parameters (including the distance scale parameter) for three-dimensional velocity field. The first (robust) version of the statistical parallax method requires small (approximately 5%) reduction of distances, whereas the second version requires small (about the same 5%) expansion of all distances, both with large errors (15% and 10% respectively). We can conclude, that pre-Hipparcos Cepheids distances do not require an appreciable revision and are in general agreement with the short distance scale, with LMC distance modulus $\mathrm{DM}_{LMC} < 18.4$. The kinematical parameters, calculated from space velocities of 91 Cepheids, are: $[U_0, V_0, W_0] = (-8, -12, -6) \pm 1$ km s^{-1}, $[\sigma V_R, \sigma V_\theta, \sigma V_Z] = (15{,}10{,}11) \pm 0.8$ km s^{-1}, angular velocity $\Omega_0 = (26.5 \pm 1.2)$ km s^{-1} kpc^{-1} and its first derivative $\Omega_0' = (-4.45 \pm 0.3)$ km s^{-1} kpc^{-2}.

The thick-disc and halo local populations of Galactic field RR Lyrae stars are analyzed by applying a bimodal version of the statistical parallax (maximum-likelihood) technique to a sample of 361 RR Lyraes with known periods, radial-velocities, metallicities, 2MASS K-band photometry, and absolute proper motions on the ICRS system. We inferred the following parameters: the thick-disc star fraction $f_{\rm disc} = 0.31 \pm 0.03$, the velocity-distribution parameters $[U_0, V_0, W_0]_{\rm halo} = (-14 \pm 5; -239 \pm 8; -16 \pm 4)$ km s^{-1}, $[\sigma V_R, \sigma V_\theta, \sigma V_Z]_{\rm halo} = (172 \pm 9; 82 \pm 5; 87 \pm 5)$ km s^{-1} and $[U_0, V_0, W_0]_{\rm disc} = (-14 \pm 5; -52 \pm 5; -16 \pm 4)$ km s^{-1}, $[\sigma V_R, \sigma V_\theta, \sigma V_Z]_{\rm disc} = (56 \pm 5; 44 \pm 4; 35 \pm 4)$ km s^{-1} and the infrared PL relation $< M_K >= -2.33 \times \log P_F - 0.94$ ($\pm$ 0.06). A bimodal version of the 2D maximum-likelihood technique (without radial velocities) applied to a sample of 1204 *bona fide* type ab and c RR Lyraes with known periods, 2MASS K-band photometry, UCAC2 absolute proper motions, and heliocentric distances inferred using the above PL relation yielded the following results: $f_{\rm disc} = 0.42 \pm 0.02$; $[U_0, V_0, W_0]_{\rm halo} = (-24 \pm 5; -255 \pm 7; -12 \pm 3)$ km s^{-1}, $[\sigma V_R, \sigma V_\theta, \sigma V_Z]_{\rm halo} = (189 \pm 8; 76 \pm 6; 114 \pm 8)$ km s^{-1} and $[U_0, V_0, W_0]_{\rm disc} = (-24 \pm 5; -52 \pm 6; -12 \pm 4)$ km s^{-1}, $[\sigma V_R, \sigma V_\theta, \sigma V_Z]_{\rm disc} = (48 \pm 6; 48 \pm 5; 22 \pm 4)$ km s^{-1}. Our zero point for the infrared PL relation for RR Lyrae variables implies a solar Galactocentric distance of $R_0 = 8.0 \pm 0.4$ kpc and an LMC distance modulus of $\mathrm{DM}_{LMC} = 18.32 \pm 0.08$.

Key words: Cepheids; RR Lyrae stars; Distance scale.

1. CEPHEIDS

The Cepheid distance scale still remains one of the most critical points in modern astronomy. Even Hipparcos trigonometrical parallaxes couldn't definitely terminate the wide discussion spread in the astronomical literature, because of large parallax errors for bulk Cepheids from the Hipparcos sample. However, good multi-colour photometry, precise radial velocities and reliable absolute proper motions of more than 270 classical Cepheids encouraged us to find another way to improve their distance scale. For the first time the statistical parallax technique was applied to disc stars, characterized by small peculiar velocities, in the paper of Rastorguev et al. (1999). From the analysis of statistical parallaxes of short-period Cepheids (with $P_{\rm pls} < 9$ days) they suspected that this sample may be greatly contaminated by Cepheids pulsating in the first overtone but not in fundamental tone, while their distances have been calculated by Berdnikov et al. (1996) from the 'period–luminosity' relation (PL relation) derived for fundamental tone Cepheids. It can be easily shown, that the adopted distances of these 'distinguished' Cepheids should be multiplied by a factor of 1.35. A perceptible fraction of these first-overtone pulsators could in principle explain lower values of the statistical parallaxes of the short-periodic group.

Fortunately, the long-periodic sample of classical Cepheids, as it follows from OGLE data for the LMC and SMC (Udalski et al. 1999), apparently does not include first-overtone pulsators. Our preliminary calculations, performed in 1999 for Galactic Cepheids with $P_{\rm pls} > 9$ days, generally confirmed their photometric distances.

To calculate the statistical parallaxes and, at the same time, the whole set of kinematical parameters of the sample, we have used rigorous maximum-likelihood algorithm, suggested by Murray (1983, pp. 297–302) (see also Hawley et al. 1986). This algorithm was adapted also for one-dimensional and two-dimensional velocity fields, but, obviously, without the possibility of calculating a correction factor to the distance scale. So, we have analyzed the distance scale problem in two different ways. First, by the 'robust' statistical parallax version. We compared the values of the first derivatives of the angular velocity $\Omega_0^{'}$, calculated separately from radial velocities and proper motions (1D and 2D velocity fields respectively). It is well known that their ratio, $\Omega_0^{'}$(1D) to $\Omega_0^{'}$(2D), is nearly equal to the factor of the distance scale. Second, we have calculated all kinematical parameters (including scale factor) for 3-dimensional (3D) velocity field. We have used Berdnikov et al. (1996) distances of all Cepheids as a first approximation.

Let us define the residual space velocity of a star as a difference between its observable space velocity and assumed velocity in a differentially rotating Galaxy. The three-dimensional distribution function for residual velocity column vector ν can be written as:

$$\mathrm{prob}(\nu) = (2\pi)^{-3/2}|\mathbf{M}|^{-1/2}\exp\{-\frac{1}{2}\nu^{\rm T}\mathbf{M}^{-1}\nu\} \quad (1)$$

where $\mathbf{M}$ is the covariance tensor including the effects of velocity dispersion, errors in the observed proper motions and radial velocities, and errors in stellar distances. The likelihood function, which can be calculated as a product of $prob(\nu)$ to all stars, finally depends on three components of the relative bulk motion of the objects (U_0, V_0, W_0) with respect to the Sun; three diagonal components of velocity ellipsoid $(\sigma V_R, \sigma V_\theta, \sigma V_Z)$ of the sample; angular velocity of the galactic rotation Ω_0 and its derivatives $\Omega_0^{'},\ \Omega_0^{''}$, ..., etc; the distance scale correction factor (or absolute magnitude correction ΔM_V). We thus have a total of ten or more (depending on the order of series expansion of $\Omega(R)$) unknown parameters to be determined by maximizing the likelihood function L or minimizing -$\ln L$.

For 1-dimensional and 2-dimensional velocity fields, i.e., for radial velocities and proper motions, this algorithm requires a simple and obvious modification.

We have not considered the distance to the Galactic center R_0 as a unknown parameter, because it correlates strongly with the distance scale factor; we use the value $R_0 = 8$ kpc instead.

Radial velocities of Cepheids have been measured by several authors, including our numerous observations of 106 northern Cepheids, and are very accurate. Absolute proper motions have been taken mostly from the Hipparcos and Tycho-2 (Hog et al. 2000) catalogues and are given in the ICRS reference system. Assumed distances of Cepheids were calculated with the multi-colour PL relation of Berdnikov et al. (1996) based on Cepheids – members of well studied open clusters. We included in the sample all Cepheids with $P_{\rm pls} > 9$ days and heliocentric distances less than 6 kpc. As a result, our sample consists of 101 Cepheids with radial velocities, 99 Cepheids with proper motions and 91 Cepheids with space velocities.

Calculated values of the scale factor are listed in Table 1 for various versions, differing in the order of expansion of $\Omega(R)$, interval of $r_{\rm hel}$ and subsamples used 1D, 2D and 3D velocity fields. It can be seen that all scale factors do not differ from unit value within the error interval. We can conclude that the distance scale for long-period Galactic Cepheids does not require an appreciable revision and is in general agreement with the short distance scale, where LMC distance modulus $\mathrm{DM}_{LMC} < 18.4^{\rm m}$.

Kinematical parameters, calculated from space velocities of 91 Cepheids:

$$[U_0,\ V_0,\ W_0] = (-8,\ -12,\ -6)\ \pm\ 1\ \mathrm{km\,s^{-1}}$$
$$[\sigma V_R,\ \sigma V_\theta,\ \sigma V_Z] = (15,\ 10,\ 11)\ \pm\ 0.8\ \mathrm{km\,s^{-1}}$$
$$\Omega_0 = (26.5\ \pm\ 1.2)\ \mathrm{km\,s^{-1}\,kpc^{-1}}$$
$$\Omega_0^{'} = (-4.45\ \pm\ 0.3)\ \mathrm{km\,s^{-1}\,kpc^{-2}}$$

Table 1. Scale factors, calculated from 1D, 2D and 3D velocity fields of long-period Cepheids (101, 99 and 91 stars with $r_{\rm hel} < 6$ kpc respectively).

Model of the velocity field	Scale factor	M, expansion order of Ω(R)
1D/2D	0.95 ± 0.15	3
3D	1.04 ± 0.14	3
3D	1.05 ± 0.10	2
3D ($r_{\rm hel} < 3$ kpc)	1.06 ± 0.16	1
3D ($r_{\rm hel} < 2$ kpc)	1.01 ± 0.18	1

2. RR LYRAE VARIABLES

The population of RR Lyraes in our Galaxy kinematically breaks conspicuously into two sub-classes: halo and thick-disc stars (Layden 1995; Layden et al. 1996). The authors of the statistical-parallax analyses addressed this issue by *a priori* partitioning the RR Lyrae sample into the halo and thick-disc subsamples using criteria that were based mostly on metallicity: at first approximation, the two sub-populations can be separated by the metallicity value [Fe/H] = −1.0 with most of the more metal-deficient stars behaving as halo objects and most of more metal-rich stars, as thick-disc objects. However, Beers &

Table 2. Kinematical parameters and K-band absolute-magnitude correction of Galactic field RR Lyrae variables based on the bimodal solution (361 stars with $r_{\rm hel} < 6.5$ kpc).

Population	Fraction	U_0	V_0	W_0	σV_R	σV_θ	σW	ΔM_K
					km s^{-1}			
Halo	0.70	-8	-240	-2	172	83	86	
	± 0.03	± 10	± 8	± 6	± 9	± 5	± 5	-0.07 ± 0.07
Disc	0.30	-18	-50	-24	56	44	32	
	± 0.03	± 6	± 5	± 4	± 6	± 4	± 4	

Table 3. Kinematical parameters and K-band absolute-magnitude correction of Galactic field RR Lyrae variables based on the bimodal solution with $U_0(\rm Disc) = U_0(Halo)$ and $W_0(\rm Disc) = W_0(Halo)$ (361 stars with $r_{\rm hel} < 6.5$ kpc).

Population	Fraction	U_0	V_0	W_0	σV_R	σV_θ	σV_Z	ΔM_K
					km/s			
Halo	0.69	−14	−239	−16	172	82	87	
	± 0.03	± 5	± 8	± 4	± 9	± 5	± 5	−0.06 ± 0.06
Disc	0.31	−14	−52	−16	54	44	35	
	± 0.03	± 5	± 5	± 4	± 5	± 4	± 4	

Sommer-Larsen (1995) showed that the thick-disc population actually extends toward rather low metallicities overlapping broadly with the halo population. Here we for the first time perform a bimodal statistical-parallax analysis to obtain *simultaneously* the kinematical parameters of the two sub-populations, the fraction of thick-disc stars, and the zero point of the $\log P_F - < M_K >$ relation for RR Lyrae type stars (P_F means the fundamental-tone pulsation period). We also infer the kinematical parameters of the two populations by applying the bimodal maximum-likelihood technique to a more extensive sample of RRab and RRc type variables with known periods, UCAC2 proper motions, and 2MASS K-band magnitudes (but without radial velocities) adopting the distance-scale zero point inferred from the 3D analysis.

We generalize the above cited maximum-likelihood version of the statistical-parallax method to the case of a bimodal three-dimensional velocity distribution:

$$\mathrm{prob}(\nu) = \alpha \times \mathrm{prob}(\nu_1) + (1-\alpha) \times \mathrm{prob}(\nu_2) \quad (2)$$

where α and 1–α are the star fractions of the first and second subsamples, and indexes i = 1,2 denote two populations.

In our analysis, we use two samples of RR Lyrae type variables. One is based on the list of 388 Galactic field RR Lyrae type variables, which Beers et al. (2000) included in their revised catalogue of 2106 Galactic stars selected without kinematic bias and with available radial velocities, distance estimates, and metal abundances in the range $-4.0 \leq$ [Fe/H] ≤ 0.0. We used this catalogue as the source of radial velocities, metallicities, and V-band interstellar extinction for the RR Lyrae type variables considered. We computed the K-band interstellar extinction, A_K, as

$$A_K = 0.114 \times 3.1 \times E_{B-V} = 0.353 \times E_{B-V} \quad (3)$$

in accordance with the reddening law by Cardelli et al. (1989). We adopted the periods and pulsation modes from the General Catalog of Variable Stars (Kholopov et al. 1985). We fundamentalized the periods P for first-overtone pulsators (RRc type variables) using the relation $\log P_F = \log P$+0.127 (see Frolov & Samus' 1998).

The second sample, which we used for the proper-motion based (2D) kinematical analysis, consists of 1204 *bona fide* RRab and RRc type variables cross-identified with UCAC2 astrometric catalog (Zacharias et al. 2004) located within 6 kpc of the Sun with average per component proper-motion errors not exceeding 7 mas yr^{-1}. Interstellar extinction is determined using subroutine EXTINCT by Hakkila et al. (1997). We adopted the mean K-band magnitudes from a single source – the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003).

Our primary source of proper motions was UCAC2 (Zacharias et al. 2004). Where possible, for the stars absent in the UCAC2 we used the proper motions given by the Hipparcos and Tycho-2 (Hog et al. 2000) catalogues, which are also on the ICRS frame. For the 2D kinematical analysis we used the proper motions adopted from UCAC2 astrometric catalog exclusively.

To determine adopted distances to the RR Lyrae stars of our sample, we used the infrared PL relation by Jones

Table 4. Kinematical parameters of Galactic field RR Lyrae variables based on the bimodal solution with $U_0(\mathrm{Disc}) = U_0(\mathrm{Halo})$ *and* $W_0(\mathrm{Disc}) = W_0(\mathrm{Halo})$ *(1204 stars with* $r_{hel} <$ *6.0 kpc and* $\sqrt{(\sigma(\mu_\alpha)^2 + (\mu_\delta)^2)/2} <$ *7 mas yr*$^{-1}$*).*

Population	Fraction	U_0	V_0	W_0	σV_R km s^{-1}	σV_θ	σV_Z
Halo	0.58 ± 0.02	-24 ± 5	-255 ± 7	-12 ± 3	189 ± 8	76 ± 6	114 ± 8
Disc	0.42 ± 0.02	-24 ± 5	-52 ± 6	-12 ± 4	48 ± 6	48 ± 5	22 ± 4

et al. (1992) based on the application of Baade-Wesselink method to field RR Lyrae stars:

$$< M_{K(Jones)} >= -2.33 \times \log P_F - 0.88 \quad (4)$$

We use statistical-parallax analysis to determine, among other parameters, the correction ΔM to the zero point of the above relation so that

$$< M_{K(true)} >=< M_{K(Jones)} > +\Delta M \quad (5)$$

Our *independently derived* zero point of the infrared PL relation for RR Lyr stars is 0.06^m brighter than that inferred by Jones et al. (1992). We thus upscale to R_0 = 8.0 ± 0.4 kpc the solar Galactocentric distance of R_0 = 7.8 ± 0.4 kpc estimated by Carney et al. (1995) based on the IR photometry of 58 Galactic-bulge RR Lyraes and the PL relation of Jones et al. (1992). Note that this result implies that the proper motion of the Sun as seen from the Galactic Centre – it is equal to the proper motion of the Galactic Centre as seen from the Sun – is equal to $(|V_0|/(R_0 \cdot 4.740)$ =6.30±0.34 mas yr^{-1}, which is consistent with the new determination of the proper motion of Sgr A* by Reid & Brunthaler (2004): 6.379 ± 0.024 mas yr^{-1}.

When applied to the K_s-band photometry for RR Lyrae type variables in Reticulum (Dall'Ora et al. 2004) the PL relation of Carney et al. (1995) with our zero point yields a distance modulus of 18.24 ± 0.07 for this cluster, which is purportedly associated with the LMC. The K_s-band photometry of RR Lyrae type stars in the inner regions of the LMC (Borissova et al. 2004) yields a distance modulus of 18.40 ± 0.07. The two data sets combined corroborate the short distance scale with DM_{LMC} =18.32±0.08.

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