Estimating the Kinematic Parameters and the Distance-Scale Zero Point for the Thin-Disk, Thick-Disk, and Halo Population Tracers via 3D Velocity Data

A. K. Dambis
Sternberg Astronomical Institute, Universitetskii pr. 13, Moscow, 119992 Russia

Abstract. We use the method of statistical parallaxes to constrain the distance-scale zero points and analyze the kinematics of extensive samples of Galactic classical Cepheids, RR Lyrae type variables, and blue horizontal branch stars, which serve as standard candles/kinematic tracers of various Galactic populations. We obtain three consistent estimates for the local circular velocity based on the mean velocities of halo RR Lyrae variables, BHB stars, and Galactic rotation curve inferred from Cepheid data with an average value of $210 \pm 6$ km s$^{-1}$, which is close to the average circular velocity in the 5–40 kpc interval of Galactocentric distances inferred from BHB star data ($195 \pm 5$ km s$^{-1}$), thereby providing further supporting evidence for the practically flat shape of the Galactic rotation curve beyond $\sim$ 5 kpc from the center. The inferred distance-scale corrections imply a solar Galactocentric distance of $7.7 \pm 0.4$ kpc, an LMC distance modulus of $18.42 \pm 0.06$, and a Hubble constant of 73–85 km s$^{-1}$ Mpc$^{-1}$.

1. Introduction
Establishing the kinematics of the major Galactic subsystems — the halo and the thin and thick disk — is a task of fundamental importance, bringing us closer to understanding the origin, evolution, and mass distribution in the Galaxy. In this work, we choose Cepheids as our kinematic tracers for the young (thin) Galactic disk and RR Lyrae variables as the kinematic tracers for the thick disk and halo. We further expand our halo kinematic-tracer base by including an extensive sample of blue horizontal-branch stars (BHB) spanning heliocentric (and Galactocentric) distances from $\sim$ 5 to several tens of kpc.

Here we use the method of statistical parallaxes in its rigorous maximum-likelihood version suggested by Murray (1983) (pp. 297–302) to estimate the kinematical parameters of the sample of Galactic Cepheids, RR Lyrae type variables, and BHB stars and to calibrate the underlying photometric distance scales (based on the period-K-band luminosity relations for Cepheids and RR Lyraes and on the BHB star distance scale proposed by Sirko et al. (2004), which is based on SDSS colors and the appropriate model atmospheres).

2. Cepheids
Our sample consists of 215 Cepheids with bona-fide proper motions from the new reduction of Hipparcos data [van Leeuwen 2007], accurate $\gamma$-velocities from Gorynya et al. (1992, 1996, 1998) and photometry from Berdnikov (1995, 1998)
and Berdnikov et al. (2000). The distances are based on the Cepheid $K$-band PL relation derived by Berdnikov et al. (1996) and the procedure proposed in the latter paper. The results are listed in Table 1. Here $U_0$, $V_0$, and $W_0$ are the components of the local mean solar velocity toward the Galactic center, in the direction of Galactic rotation, and toward the North Galactic Pole, respectively, relative to the sample considered, $\sigma V_R$, $\sigma V_\phi$, and $\sigma V_Z$ are the diagonal components of the velocity dispersion tensor in the directions of projected Galactocentric radius, Galactic rotation, and toward the North Galactic Pole, respectively. The parameters $\Omega_0$, $A$, and $\Omega''$ are equal to the local angular circular rotation velocity, Oort’s constant $A$, and the second derivative of the local angular circular rotation velocity with respect to projected Galactocentric distance, respectively, and $k$ is the distance-scale correction factor (to be multiplied by the initial distances to obtain the corrected distances).

Table 1. Kinematical and distance-scale solution for Cepheids ($N=215$ stars). Here $U_0$, $V_0$, $W_0$, $\sigma V_R$, $\sigma V_\phi$, and $\sigma V_Z$ are in km s$^{-1}$, $\Omega_0$ and $A$ are in km s$^{-1}$ kpc$^{-1}$, and $\Omega''$ is in km s$^{-1}$ kpc$^{-3}$.

| $U_0$ | $V_0$ | $W_0$ | $\sigma V_R$ | $\sigma V_\phi$ | $\sigma V_Z$ | $\Omega_0$ | $A$ | $\Omega''$ | $k$ |
|-------|-------|-------|---------------|---------------|---------------|------------|----|------------|----|
| -8.5  | -12.2 | -7.1  | 13.0          | 9.3           | 8.9           | 27.5       | 15.7| 0.80       | 1.18|
| ±1.0  | ±0.9  | ±0.9  | ±0.8          | ±0.6          | ±0.9          | ±0.8       | ±0.7| ±0.13      | ±0.06|

3. **RR Lyrae type variables**

Our sample consists of 364 RR Lyrae type variables with bona-fide proper motions, radial velocities, and phase-corrected 2MASS $K$-band magnitudes. The distances are based on the $K$-band PL relation derived by Jones et al. (1992). See Dambis (2009) for a complete description of the data set, which is available from the CDS. We applied to it a bimodal version of the statistical-parallax method (Dambis 2009) and obtained the results that we list in Table 2.

4. **BHB stars**

Our third sample consists of 1955 rigorously selected blue horizontal-branch halo stars from SDSS DR6 (Adelman-McCarthy et al. 2008) with photometric distances based on the calibration of Sirko et al. (2004), radial velocities determined within the framework of SEGUE project (Yanny et al. 2009). We adopted this sample from Xue et al. (2008), and supplemented it with absolute proper motions from the SDSS DR7 (Abazajian et al. 2009) database. Here we use only stars sample with $R_g \leq 40$ kpc and removed a number of evident outliers. We applied to the resulting sample a single-mode version of the statistical-parallax method parametrizing the variation of the velocity-ellipsoid parameters as a function of Galactocentric distance in terms of the model of Sommer-Larsen et al. (1997) and obtained the results that we list in Table 3.
Table 2. Kinematical solution and distance-scale correction for Galactic field RR Lyrae variables based on the bimodal solution (364 stars with $r_{hel} < 6.5$ kpc). Here $U_0$, $V_0$, and $W_0$ have the same meaning as in Table 1, and $\sigma V_R$, $\sigma V_\phi$, and $\sigma V_\theta$ are the diagonal components of the velocity dispersion tensor aligned with the spherical coordinate system centered on the Galactic center. All these quantities are in km s$^{-1}$.

| Population | Fraction | $U_0$ | $V_0$ | $W_0$ | $\sigma V_R$ | $\sigma V_\phi$ | $\sigma V_\theta$ | k  |
|------------|----------|-------|-------|-------|--------------|----------------|----------------|----|
| Halo       | 0.75     | -12   | -217  | -6    | 167          | 86             | 78             | 0.97|
|            | 0.03     | ± 10  | ± 9   | ± 6   | ± 9          | ± 6            | ± 5            |     |
| Thick disk | 0.25     | -15   | -45   | -25   | 55           | 44             | 30             | ± 0.04|
|            | 0.03     | ± 7   | ± 7   | ± 5   | ± 6          | ± 6            | ± 4            |     |

Table 3. Kinematical solution and distance-scale correction for the sample of BHB stars (1955 stars with $r_{hel} < 40$ kpc). Here $U_0$, $V_0$, and $W_0$ have the same meaning as in Table 1 and $\sigma_0$, $\sigma^+$, $l$, $r_0$, and $V_c$ are the parameters of the kinematical halo model of Sommer-Larsen et al. (1997). The parameters $U_0$, $V_0$, $W_0$, $\sigma_0$, $\sigma^+$, and $V_c$ are in km s$^{-1}$, and $l$ and $r_0$ are in kpc. Note that $V_c$ is the circular rotation velocity of the (assumed) flat rotation curve and $r_0$ is the Galactocentric distance at which the shape of the velocity ellipsoid changes from radial to tangential anisotropy.

| Population | $U_0$ | $V_0$ | $W_0$ | $\sigma_0$ | $\sigma^+$ | $l$ | $r_0$ | $V_c$ | k  |
|------------|-------|-------|-------|-------------|------------|-----|-------|-------|----|
|            | -14   | -225  | -2    | 96          | 89         | 3.7 | 19.2  | 195   | 1.06|
|            | ± 4   | ± 5   | ± 3   | ± 12        | ± 9        | ± 0.4| ± 1.6 | ± 5   | ± 0.03|

5. Distance scale

In Table 4 we list the distance-scale correction factors inferred via statistical parallax ($k$) and and the average distance-scale correction factors based on statistical and Hipparcos trigonometric parallaxes ($k_2$) for Cepheids and RR Lyrae variables, as well as the corresponding LMC distance-modulus estimates. We also give the estimate of the solar Galactocentric distance ($R_0$) based on the IR photometry of Galactic bulge RR Lyraes. The weighted average of the LMC distance modulus ($DM_{LMC}=18.42\pm0.06$) implies a Hubble constant of 73–85 km s$^{-1}$ Mpc$^{-1}$.

| Distance indicator | $k$       | $k_2$   | $DM_{LMC}$ | $R_0$, kpc |
|--------------------|-----------|---------|------------|------------|
| Cepheids           | 1.18 ± 0.06 | 1.12 ± 0.03 | 18.50 ± 0.07 |           |
| RR Lyraes           | 0.97 ± 0.04 | 0.98 ± 0.04 | 18.30 ± 0.09 | 7.7 ± 0.4     |
6. Circular velocity

Our kinematical analysis yields three independent estimates for the local velocity of circular Galactic rotation, \( V_c(\text{local}) \): 
\[ V_c(\text{local}) = |V_0(\text{halo}) - V_0(\text{Cepheids})|, \]
where \( V_0(\text{halo}) \) can be represented either by halo RR Lyraes or BHB stars (the corresponding two \( V_c(\text{local}) \) values are equal to 205 ± 9 and 205 ± 13 km s\(^{-1}\), respectively), or as 
\[ V_c(\text{local}) = |R_0 \cdot \Omega_0| = 212 \pm 13 \text{ km s}\(^{-1}\). \] They agree rather well with each other and their weighted average \( V_c(\text{local}) = 210 \pm 6 \text{ km s}\(^{-1}\) differs little from the global value of \( V_c(\text{global}) = 195 \pm 5 \text{ km s}\(^{-1}\) inferred from an analysis of the kinematics of BHB stars out to a Galactocentric distance of \( R_g \sim 40 \text{ kpc} \), thereby further reinforcing the case of the flat Galactic rotation curve beyond \( R_g \sim 5 \text{ kpc} \).

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