Stellar Kinematics from Hipparcos Proper Motions

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Abstract. From Hipparcos proper motions, we have analyzed the local kinematics of the Milky Way from the young O-B5 stars, classical Cepheids, and the late-type K-M giants. Comparing the derived results, the kinematical discrepancies between each subset of stars have been analyzed, and the possible reasons for the kinematical differences have been discussed.

1. Introduction

In the early part of this century, the kinematics of stars near the Sun have been known to provide crucial information regarding both the structure and the evolution of the Galaxy. Lindblad (1927) and Oort (1927) developed an axisymmetric model of the rotation. In the 1950s, the stellar kinematics were found to vary systematically with stellar type. Thereafter, analyses of the Galactic structure and kinematics have been carried out via various observational data. Considering the results obtained before, IAU has recommended a set of Galactic constants in 1985 (Kerr & Lynden-Bell, 1986). Thanks to the improvements of the observational techniques, many important results for Galactic astronomy have been achieved in recent years.

The present work will concentrate on investigating the kinematical features characterized by different samples and discussing the possible reasons for kinematical discrepancies derived from the different stellar samples.

2. Basic Data and Analyses

The basic materials for our kinematical analyses of the Galaxy include astrometric parameters of stars incorporated with astrophysical measurements. The Hipparcos Catalogue provides observations of stars with precision in position, parallax, and proper motion of 1 mas and 1 mas yr^{-1}.

In order to obtain astrophysical quantities (MK classification, luminosity class, spectroscopic parallax, *etc.*), the SKYMAP catalog containing 248,558 stars is used. Carrying out cross-identification between the Hipparcos and SKYMAP catalogs, excluding all binaries, multiples, and suspected non-single systems, we have found 1,801 O-B5 stars and 23,181 K-M giants common to both catalogs. According to Westin's study, the Gould belt stars are embedded in the solar vicinity (Westin, 1985). We have individually removed 278 Gould belt stars from our O-B5 sample. Hence, the sample of O-B5 stars to be analyzed is 1,523 in total.

The Hipparcos Catalogue provides observations of 223 classical Cepheids. Based on the spectroscopic observations (Metzger *et al.*, 1998; Pont *et al.*, 1994), we have obtained 198 Hipparcos Cepheids with radial velocities. In the present work, we adopted the PL (period-luminosity) relation recently proposed by Feast & Catchpole (1997) to calibrate the heliocentric distances of Cepheids.

The first-order Taylor expansion at the Sun of the velocity field of stars gives a three-dimensional kinematical model (Clube, 1972). The equations of condition for the transverse velocity components of stars contain 9 kinematical parameters to be solved: three components of solar motion (u_0, v_0, w_0), three components of vorticity $(D_{32}^-, D_{13}^-, D_{21}^-)$, and three components of strain velocity $(D_{12}^+, D_{13}^+, D_{32}^+)$. The relevant equations were given by Miyamoto & Sôma (1993).

Combining the transverse and radial velocities, we have the equations of condition with 12 parameters to be determined, including three additional components of Galactic expansion and/or contraction $(D_{11}^+, D_{22}^+, D_{33}^+)$. The detailed description is given by Zhu (2000). Note that in the circular stream model of Oort-Lindblad, the coefficients D_{12}^+ and D_{21}^- are identical to the familiar Oort constants A and B.

In a galactocentric cylindrical coordinate system (R, θ, z), we define that R is measured from the Galactic center. The azimuthal angle θ is reckoned from the $x-$axis counterclockwise around the axis z. Then, we have

$$A = D_{12}^+ = \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} - \frac{V_\theta}{R}\right)_{R=R_0}, \tag{1}$$

$$B = D_{21}^- = \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} + \frac{V_\theta}{R}\right)_{R=R_0}, \tag{2}$$

where R_0 (=8.5 kpc) denotes the galactocentric distance of the Sun. V_θ is the rotational velocity of the local standard of rest (LSR) about the Galactic center.

The kinematical parameters will be solved using the generalized least-squares method. Prior to applying least-squares to the equations of condition to derive the parameters, a few concerns about the sampling domain of stars should be raised.

(1) To avoid problems at the solar vicinity, we exclude all the nearby stars. For the O-B5 stars and Cepheids, the sampling domain is confined within

$$|\, z \,| \leq 0.35 \text{ kpc}, \qquad 0.1 \text{ kpc} \leq r \leq 3.0 \text{ kpc}. \tag{3}$$

For the K-M giants, we confine ourselves to the sample within the domain

$$|\, z \,| \leq 0.5 \text{ kpc}, \qquad 0.3 \text{ kpc} \leq r \leq 1.0 \text{ kpc}. \tag{4}$$

(2) In order to exclude stars with extremely erroneous transverse and radial velocities as well as extremely large random motions, we introduce a numerical filter $|\, \varepsilon \,|$. Considering both the measurement errors and random velocities, we set $|\, \varepsilon \,|$=50 kpc s^{-1} for the O-B5 stars and Cepheids, and $|\, \varepsilon \,|$=90 kpc s^{-1} for the K-M giants.

3. Solutions of Solar Motion

Solutions of solar motion for each type of stars are given in Table 1. $S_0=(u_0, v_0, w_0)$ is the total velocity of the Sun relative to the type of stars with the apex towards $\ell_\odot$ and $b_\odot$.

Table 1. Solar motion derived from O-B5 stars, classical Cepheids, and K-M giants.

Type	Data	u_0(km s^{-1})	v_0(km s^{-1})	w_0(km s^{-1})	S_0(km s^{-1})	$\ell_\odot$(°)	$b_\odot$(°)
O-B5	PPMs	11.59±0.49	13.39±0.48	7.12±0.44	19.09±0.48	49.1±1.6	+21.9±1.3
Cep	PPMs	10.62±1.20	16.06±1.14	8.60±1.02	21.09±1.17	56.0±3.5	+23.8±2.8
Cep	PPMs+RVs	9.79±0.86	13.65±0.86	8.40±0.86	18.78±0.86	54.4±2.9	+26.6±2.6
gK-gM	PPMs	9.66±0.31	21.45±0.32	7.95±0.26	24.87±0.30	65.8±0.7	+18.6±0.6

The solutions of solar motion derived from each type of stars are apparently different. The radial and vertical components u_0 and w_0 of the velocity of the Sun do not vary significantly with stellar groups. The component in the direction of Galactic rotation, v_0, differs from type to type. Possible reasons for such a large variation are discussed below.

(1) The solar motion is derived from individual groups of stars. It is well-known that the solar motion with respect to the type of stars, especially the component pointing to the direction of Galactic rotation, is strongly correlated with the velocity dispersion (asymmetric drift). Analyzing nearly 12,000 Hipparcos main-sequence stars, Dehnen & Binney obtained the component v_0 varied from 9 to 25 km s^{-1} with different B-V (1998). The youngest disk population of stars, the O-B5 stars and Cepheids, yields much lower velocity dispersion than the K-M giants. Thus, the solar motion v_0 derived from K-M giants should be remarkably larger than that derived from O-B5 stars and classical Cepheids.

For the very early type O-B5 stars and Cepheids, the variation of the v_0 component cannot be explained as given in the last paragraph. The real feature could be much more complicated.

(2) For the classical Cepheids, the values of the v_0 component, derived from Hipparcos proper motions, from radial and transverse velocities, are significantly different. The causes of the large difference in solar motion from Cepheids should be carefully investigated further. One of the possibilities is due to a systematic shift between the radial velocity system and the proper motion system.

4. Galactic Rotation Solutions

The final solutions for the Galactic kinematics are given in Table 2, where the unit of $D^{\pm}_{ij}$ is km s^{-1}. The parameters D^{+}_{12} and D^{-}_{21} correspond to the familiar Oort constants A and B for the Oort-Lindblad model, given in eqs. (1) and (2). Taking R_0 = 8.5 kpc, we obtained the rotational velocity V_0, listed in Table 2.

The IAU has recommended a set of Galactic constants in 1985, in which V_0 = 220 km s^{-1} for the Galactic rotation and R_0 = 8.5 kpc. The present solution of Galactic rotation are remarkably large, compared with the IAU recommendation. Analyzing the proper motions of the Southern Proper Motion Program

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Table 2. Galactic rotation derived from O-B5 stars, classical Cepheids, and K-M giants. The unit of $D^{\pm}_{ij}$'s is km s^{-1} kpc^{-1}.

Type	Data	D^+_{12}	D^-_{21}	D^+_{13}	D^+_{32}	D^-_{32}	D^+_{22}	V_0(km s^{-1})
O-B5	PPMs	16.06±1.13	−15.56±.83		1.89±.53	1.89±.53		268.7±11.9
Cep	PPMs	16.08±1.14	−12.15±.86					240.0±12.1
Cep	PPMs+RVs	15.37±0.85	−12.92±.85				−2.60±1.07	240.5±10.2
gK-gM	PPMs	15.51±0.93	−14.14±.75	−1.42±.90		−1.52±.64		252.1±10.1

(SPM), Méndez *et al.* (1999) derived a large LSR speed of 270 km s^{-1}, which is in excellent agreement with ours derived from the O-B5 stars.

The difference of the rotational velocity from O-B5 stars and K-M giants can be explained with the velocity dispersion of the two groups of stars. The rotational velocity obtained from the classical Cepheids is obviously slower than that of K-M giants and O-B5 stars. One of the main causes is probably due to the constituent stars of moving groups, to which some Cepheids might belong.

A meaningful determination of parameters D^+_{32} and D^-_{32} ($D^+_{32} = D^-_{32} = 1.89 \pm 0.53$ km s^{-1} kpc^{-1}) has been obtained from the proper motion analysis of the O-B5 stars:

$$\left(\frac{1}{R}\frac{\partial V_z}{\partial \theta}\right)_{R_0} = -2D^-_{32} = -2D^+_{32} = -3.79 \pm 1.05 \text{ km s}^{-1}\text{ kpc}^{-1}. \qquad (5)$$

It implies a clear warping motion that is a systematic rotation of the O-B5 stars about the axis pointing to the Galactic center in the sense of increasing the inclination of the H I warp, which we have discussed in our previous work (Miyamoto & Zhu, 1998). Considering the solution of the K-M giants, a few points will be added here.

The K-M giants are considered to be well-relaxed constituents of the Galaxy, that are supposed to have already reached a steady state with some symmetry. The present solution from the Hipparcos K-M giants shows that the K-M giants seem not simply to exhibit a differential rotation along the Galactic plane as one supposed, because of a meaningful determination of the parameters D^+_{13} and D^-_{32}. At the present stage, we could not conclude that the solution of the parameters D^+_{13} and D^-_{32} reflects a new class of Galactic interior motion derived from the Hipparcos proper motions of the K-M giants. If we suppose the determination of D^+_{13} and D^-_{32} derived from the K-M giants only reflect a fictitious rotation of the Hipparcos proper motion system, the warping motion derived from the O-B5 stars will be more pronounced.

The solution from analyzing the proper motions and radial velocities of the classical Cepheids shows that Cepheids seem to exhibit a contracting motion in the solar neighborhood that is along the direction pointing to the Galactic rotation. On the assumption of the pure axisymmetric circular rotation of the Galaxy ($V_R \equiv 0$), we have

$$D^+_{22} = \left(\frac{1}{R}\frac{\partial V_\theta}{\partial \theta}\right)_{R_0} = -2.60 \pm 1.07 \text{ km s}^{-1}\text{ kpc}^{-1}. \qquad (6)$$

The present solution seems to suggest a slight contraction of the Cepheids in the solar neighborhood. However, the real feature of the contraction should be carefully investigated further, before reaching a conclusive explanation.

One of the possible reasons for the apparent contraction might be membership of stars in moving groups. For example some Cepheids in our sample may be constituents of the moving groups. Therefore, the kinematical solution should be infected by such constituent stars of moving groups, and might lead to a systematic deviation in the determination of the rotational velocity of the Galaxy.

5. Conclusion

The results of the solar motion relative to the stellar type are in good agreement with those given by Dehnen & Binney for the main sequence stars. We determined very stable solutions for the components u_0 and w_0. The component v_0 varies in a wide range depending on type of the stellar age.

The Galactic rotation derived from the O-B5 stars ($\sim$ 270 km s^{-1}) is remarkably larger than the IAU recommended value. Analyzing Hipparcos proper motions from the O-B5 stars, we have identified a clear stellar warping motion that is an asystematic rotation $\partial V_z/\partial\theta/R = -\ 3.79 \pm 1.05$ km s^{-1} kpc^{-1} of stars around the axis pointing to the Galactic center in the sense of increasing the inclination of the H I warp. The solution from the classical Cepheids seems to suggest a slight contracting motion of Cepheids along the direction of the Galactic rotation. The real feature of the contraction should be carefully investigated further.

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