HIPPARCOS PROPER-MOTION SYSTEM WITH RESPECT TO FK5 AND SPM 2.0 SYSTEMS

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ABSTRACT. Carrying out a kinematical analysis of the Galaxy for proper-motion systems of the FK5 and Hipparcos, a large difference in proper motions between two systems is found, even if the precessional correction to the FK5 system has been considered. Comparing the PPM and ACRS proper motions, which are constructed on the FK5 system, with those of the Hipparcos, an interiorly nonrigid rotation existing in the FK5 proper-motion system is detected. Proper-motion differences between the FK5 and Hipparcos systems cannot be explained by the constant of the FK5 precessional correction, which is given by the VLBI and LLR observations. Analyzing proper motions of the Hipparcos and SPM 2.0 systems, the component ω_y of the rotational vector of the SPM 2.0 proper-motion system related to the Hipparcos is obtained, that is almost as large as twice 0.25 mas yr^{-1} for the uncertainty of the Hipparcos inertiality.

1. INTRODUCTION

More than 100,000 stars were measured by the Hipparcos astrometric satellite. The capability of accurate wide-angle measurements over the whole sky of the Hipparcos mission has ensured that the system of stellar positions, proper motions, and parallaxes is characterized by a high degree of internal consistency. The positions and proper motions in the Hipparcos Catalogue define a reference frame which is likely to be accurate, on a global scale, to about 0.1 mas at the epoch J1991.25 and 0.1 mas yr^{-1}. It is not doubtful that the system can be considered to be free of regional errors, when we compare it with any existing global catalogue. Considering its observations were made in space and its high internal precision of about 1 mas for positions and 1 mas yr^{-1} for proper motions, there is no evidence to suspect the color- and magnitude-dependent systematics in the Hipparcos system to a significant level. Because of the favorable internal systematics, the Hipparcos Catalogue provides us the best optical materialization to analyze internal systematic errors of other catalogues.

The Hipparcos data were preliminarily adjusted to the FK5 system, which was formally based on the mean equator and dynamical equinox of J2000.0. The final catalogue was subsequently linked to the International Celestial Reference System (ICRS), which was defined and realized by a set of radio sources observed by the VLBI technique. The estimated uncertainty of the Hipparcos link corresponds to a standard error of 0.6 mas in the alignment of the axes at the catalogue epoch J1991.25 and 0.25 mas yr^{-1} in the rate of rotation of the system with respect to distant extragalactic objects (Kovalevsky et al. 1997).

On the other hand, the FK5 has been constructed by applying dynamical as well as kinematical concepts. In order to tie the FK5 system to an inertial coordinate system, a constant of the lunisolar precessional correction and a correction of the fictitious motion of the equinox should be applied to the FK5 proper-motion system. Several years observations by the VLBI and LLR have given a coincident value of the precessional correction $\Delta p = -3.0 \pm 0.2$ mas yr^{-1}(Charlot et al. 1995, Chapront et al. 1999, Fukushima 2000). If one considers the FK5 system, in the global sense, as a rigid frame ignoring its regional errors, the proper-motion system should differ from the ICRS only by the lunisolar precessional correction to Newcomb's value and by the fictitious motion of the equinox.

Properties of the proper-motion system play a critical role in the evaluation of the galactic kinematics via the proper-motion data of stars, as well as in the characterization of the inertiality of the coordinate system itself. In order to understand the overall properties of proper motions of the Hipparcos system and examine the systematic errors in proper motions of other catalogues, we concentrate our present work on proper-motion analysis.

2. KINEMATICAL ANALYSIS FOR PROPER-MOTION SYSTEMS

The kinematical parameters of the Galaxy can be statistically derived from the stellar proper motions in an inertial coordinate system. Analyzing proper-motion data from the ACRS Part1 catalogue that is in the FK5 system, Miyamoto & Sôma (1993) have studied the local kinematics from the galactic K-M giants. They have derived the kinematic parameters of the conventional Oort constants A and B, yielded the precessional correction $\Delta p = -2.67 \pm 0.28$ mas yr^{-1} and the correction of the fictitious motion of the equinox $\Delta e + \Delta\lambda = -1.16 \pm 0.26$ mas yr^{-1} to the FK5 system. Using the proper motions from the ACRS catalogue, Miyamoto, Sôma, and Yoshizawa (1993) have investigated further the kinematics for the young O-B stars.

Based on the Hipparcos proper motions of stars, we have analyzed the galactic kinematics for the late type K-M giants and the young O-B5 stars (Miyamoto & Zhu 1998, Zhu & Yang 1999, Zhu 2000a). The Oort constants A and B, derived from the ACRS and Hipparcos proper motions, are listed in Table 1, where the rotational velocities of the Galaxy V_0 are given at the galactic distance of the Sun $R_0 = 8.5$ kpc. It is obviously shown that the rotational velocities derived from the Hipparcos proper motions are more large than those derived from the conventional FK5 proper motions. For the K-M giants, the difference of the rotational speeds ΔV_0 is as large as 70 km s^{-1}, while the velocity difference for the O-B stars reaches to 50 km s^{-1}.

To inspect the systematic difference between the two proper-motion systems, we have further analyzed the proper-motion differences between the ACRS Part 1 and the Hipparcos Catalogue for about 24,000 K-M giants. Prior to making the proper- motion differences $\Delta\mu_\ell^* = (\mu_\ell^*)_{ACRS} - (\mu_\ell^*)_{HIP}$, the precessional correction and the equinoctial motion correction are applied to the ACRS proper motions. According to the classical Oort-Lindblad model for the galactic differential rotation, we have the following equation

$$\kappa\Delta\mu_\ell^* = r^{-1}(\Delta S_1 \sin\ell - \Delta S_2 \cos\ell) + (\Delta A \cos 2\ell + \Delta B)\cos b, \qquad (1)$$

where $\kappa = 4.74047$ is the conversion factor of units and r is the heliocentric distance of the star; S_1 and S_2 are the components of the local solar motion toward the galactic center and in the direction of the galactic rotation.

Applying the least squares to the equation, we found

$$\Delta S_1 = -0.12 \pm 0.20 \ \ \text{km s}^{-1} \ \ , \quad \Delta S_2 = -0.13 \pm 0.21 \ \ \text{km s}^{-1},$$
$$\Delta A = -0.61 \pm 0.15 \ \ \text{mas yr}^{-1}, \quad \Delta B = 1.03 \pm 0.10 \ \ \text{mas yr}^{-1}.$$

Table 1: Parameters of the galactic kinematics derived from the ACRS and Hipparcos proper motions. The rotational velocities V_0 are given at the galactic distance of the Sun $R_0 = 8.5$ kpc.

Proper motions	A (mas yr^{-1})	B (mas yr^{-1})	V_0 (km s^{-1})
ACRS gK-gM	2.63±0.12	−1.76±0.10	177.1±6.2
ACRS O-B	2.85±0.19	−2.60±0.15	219.9±9.8
Hipparcos gK-gM	3.27±0.14	−2.93±0.10	249.6±7.0
Hipparcos O-B	3.39±0.24	−3.28±0.18	268.7±11.9

The difference in the galactic rotation is thus obtained as $\Delta V_0 = -\ 66.1 \pm 7.2$ km s^{-1}. The present solution coincides well with the large difference in the galactic rotation individually derived from the ACRS proper motions and from the Hipparcos proper motions.

3. REGIONAL ERRORS IN THE PPM AND ACRS PROPER MOTIONS

As the star density in the FK5 is so low, we selected stars from the PPM Star Catalogue and the Astrographic Catalog Reference Stars (ACRS) Part 1 in the present analysis, and compared their proper motions with the Hipparcos system. The PPM and ACRS are all sky catalogues constructed on the FK5 system. The PPM catalogue contains 93,772 Hipparcos stars, while the ACRS Part1 includes 83,188 stars common to the Hipparcos Catalogue. For a general description of the PPM and ACRS catalogues, see Röser (1994).

The regional errors of proper motions were derived in such a way: first, we divided the whole celestial sphere into 36°×18° cells which run from 0° to 360° in galactic longitude and from −90° to +90° in galactic latitude. Each cell is 10°×10° in size, containing from several tens to hundreds of stars depending on the galactic latitude zonal.Then, in the galactic coordinate system, the mean differences of proper motions of stars in each cell were calculated for the two coordinates ($\Delta\mu_\ell^*$, $\Delta\mu_b$), in sense of considered catalogue minus Hipparcos. Note that stars with large residuals of proper motions were removed from the calculation (>2.6 σ). The vector diagram in Figure 1 shows distributions of the proper-motion differences in the galactic coordinate system, where the top panel gives relative errors in proper motions between the PPM and Hipparcos catalogues, and the bottom panel demonstrates those between the ACRS and Hipparcos.

Regional differences of the PPM and ACRS related to Hipparcos exhibit a similar distribution over the whole sky and appear to have alike systematics. But quantitatively, they are obviously inconsistent for the same individual region, even if both catalogues were aligned to the same FK5 system. This is probably due both to their own localized errors of proper motions existing in the PPM and ACRS catalogues and to different accuracies of the alignments to the FK5 system. Therefore, these regional errors of the PPM and ACRS cannot be fully recognized as the representation of local errors of the FK5 itself. Figure 1 shows remarkably large residual velocities from both the PPM and ACRS catalogues, which are mainly around the axis from the south celestial pole (SCP) to the north celestial pole (NCP).This rotation of residual velocities in the southern hemisphere is more pronounced than the northern part. From the kinematic point of view, such a structure of the velocity distribution will lead to decreasing the determined absolute values of Oort constants A and B of the galactic kinematics. That is one of the reason why we have found a remarkably larger galactic rotation from the Hipparcos proper motions than that from the ACRS proper motions.

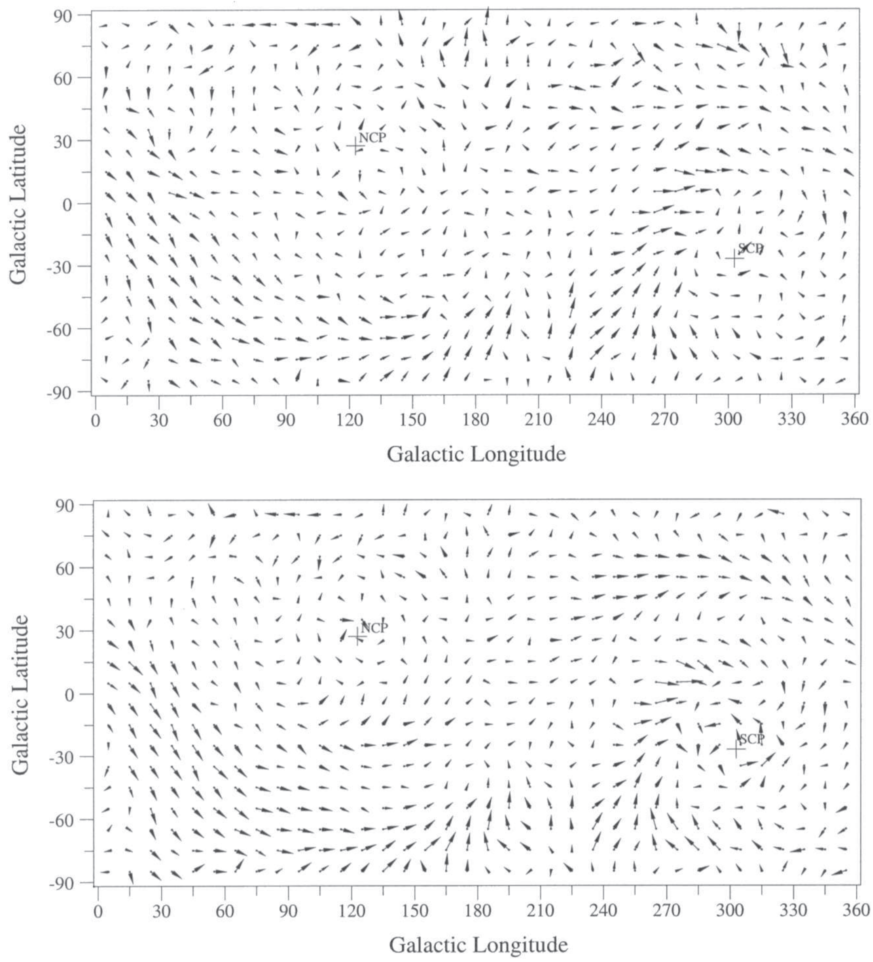

Figure 1: Regional differences of proper motions between the PPM and Hipparcos in sense PPM−Hipparcos (*top panel*), and between the ACRS and Hipparcos in sense ACRS−Hipparcos (*bottom panel*), in the galactic coordinate system .

4. MAGNITUDE AND COLOR EQUATIONS IN PROPER MOTIONS

In our previous work, we have analyzed the magnitude- and color-dependent differences in proper motions between the PPM and Hipparcos, and between the ACRS and Hipparcos (Zhu 2000b). A strong magnitude-dependent systematics were found both in the PPM and ACRS proper-motion system. Especially for the component in $\Delta\mu_{\alpha}^{*}$, it increases rapidly at the fainter magnitude and behaves more strongly for the ACRS proper motions (see Figure 6 in Zhu 2000b). The color-dependent systematics shows a similar variation in proper-motion differences for both PPM−Hipparcos and ACRS−Hipparcos (see Figure 7 in Zhu 2000b). Stars with the lowest color index exhibit more large systematics in their proper-motion differences.

From the proper-motion comparison between the PPM and Hipparcos, and between the ACRS and Hipparcos, we found clear systematic differences of proper motions depended both on magnitudes and colors. The PPM and ACRS catalogues suffer a quite similar fashion in their color and magnitude equations with respect to the Hipparcos proper-motion system.

The Southern Proper Motion (SPM) Program is the southern-sky complement to the Northern Proper Motion (NPM) Program (Platais et al. 1998a). The SPM 2.0 Catalog contains 321,608 stars (9,386 single stars common to Hipparcos) between declinations of $-22°$ and $-43°$ observed in 156 fields. The absolute proper motions were measured on an inertial reference system defined by faint galaxies. Analyzing the proper-motion differences related to the Hipparcos,

Table 2: Global rotation derived from FK5, PPM, ACRS, and SPM 2.0, relative to the Hipparcos proper-motion system. The units are in mas yr^{-1}.

Component	FK5−HIP	PPM−HIP	ACRS−HIP	SPM−HIP
ω_x	−0.30±0.10	−0.67±0.03	−0.42±0.10	−0.05±0.18
ω_y	+0.60±0.10	+0.84±0.03	+0.56±0.10	−0.49±0.15
ω_z	+0.70±0.10	+0.18±0.03	−0.08±0.10	+0.15±0.16

we found that there are neither strong systematics nor large regional errors existing in the SPM 2.0 Catalog (Zhu 2001), except a common shift $< \Delta\mu_\delta > = 0.46$ mas yr^{-1} between the two systems.

5. GLOBAL ROTATION

The basic relation of the global rotation between two proper-motion systems can be described by a pure rigid-body rotation:

$$\begin{aligned} \Delta\mu_\alpha^* &= -\omega_x \sin\delta\cos\alpha - \omega_y \sin\delta\sin\alpha + \omega_z \cos\delta, \\ \Delta\mu_\delta &= +\omega_x \sin\alpha - \omega_y \cos\alpha. \end{aligned} \tag{2}$$

Where the vector $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)$ represents the rotational difference between the two frames, taken in sense of considered catalogue minus Hipparcos. By means of an overall pattern comparison of the FK5 proper-motion system with Hipparcos via PPM and ACRS proper-motion data, we have determined the vectors of the global rotation between the PPM and Hipparcos, and between the ACRS and Hipparcos, proper-motion systems (Zhu & Yang 1999). A later work by Mignard & Frœschlè (2000) gave the global rotation between the FK5 and Hipparcos, and between the PPM and Hipparcos. Comparing the SPM 2.0 system with the Hipparcos, the rotational difference between the two proper-motion systems was derived (Zhu 2001). We collect all the results listed in Table 2.

The precessional correction Δp represents an additional systematic error of the FK5 proper-motion system to an inertial coordinate system, thus the FK5 proper-motion system should differ from the Hipparcos only by a precessional correction and by a correction of the fictitious motion of the equinox. Taking the precessional correction $\Delta p = -3.0 \pm 0.2$ mas yr^{-1} into account, which is independently determined by the VLBI and LLR, and accepting $\Delta e + \Delta\lambda = -1.16 \pm 0.26$ mas yr^{-1} for the correction of the fictitious motion of the equinox proposed by Miyamoto & Sôma (1993), we cannot find a consistent explanation directly from solutions in Table 2 (FK5−HIP, PPM−HIP, ACRS−HIP).

Both the SPM 2.0 and Hipparcos proper-motion systems are constructed on the ICRS. Ignoring the internal systematic errors affecting the SPM 2.0 proper-motion system and neglecting the remaining rotations of the SPM and Hipparcos systems with respect to the ICRS, then the proper-motion system of the SPM 2.0 should coincide with the Hipparcos proper-motion system. The rotational vector for the SPM 2.0 proper motions with respect to the Hipparcos shows that the two components ω_x and ω_z are apparently less than the value of 0.25 mas yr^{-1} for the uncertainty of the Hipparcos inertiality, while the component ω_y is almost as large as twice that value. It is noticed that our result is in a good agreement for all three components with the mean values of the residual spin components derived from the mean-per-field SPM-data solution using a recalibrated magnitude equation by Platais et al. (1998b).

6. CONCLUSION

On the basis of the Hipparcos data, whose system is believed to be quasi-inertial to within ± 0.25 mas yr^{-1} and to represent an internally consistent reference frame, we have performed analysis on the FK5 proper-motion system via two large astrometric catalogues, the PPM and ACRS catalogues, both constructed on the FK5 system. The regional differences of proper motions between the PPM and Hipparcos, and between the ACRS and Hipparcos, show a remarkably large residual velocity around the axis from the south celestial pole to the north celestial pole. The regional differences on the southern hemisphere are larger than those on the northern part. Considering the magnitude- and color-dependent pattern of the proper-motion difference, we have found that the PPM and ACRS catalogues suffer a quite similar fashion in their color and magnitude equations with respect to the Hipparcos proper-motion system. These reflect, at least qualitatively, the internal inconsistency of the FK5 proper-motion system. It implies that the FK5 proper-motion system is practically interiorly nonrigid, which rotates differentially from region to region, from magnitude to magnitude, and from spectral type to spectral type.

The global rotation of proper motions between the PPM and Hipparcos, and between the ACRS and Hipparcos, shows a large offset compared with the correction of the precessional constant determined by the VLBI and LLR, especially for the components of ω_x and ω_z. It could be largely due to the internal nonrigid feature of the FK5 proper-motion system and to the lower accuracy of alignment of the PPM or ACRS system to the system of the FK5.

From the proper-motion comparison between the SPM 2.0 and Hipparcos catalogues, we found that the regional differences of the SPM 2.0 proper motions exhibit neither strong systematics nor large regional errors. The global rotation related to the Hipparcos frame is slower than 0.25 mas yr^{-1} except the component along the y-axis.

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7. REFERENCES

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