Astronomy and Astrophysics in the Gaia sky
Proceedings IAU Symposium No. 330, 2017
A. Recio-Blanco, P. de Laverny, A.G.A. Brown & T. Prusti, eds.

doi:10.1017/S1743921317006068

Kinematics of our Galaxy from the PMA and TGAS catalogues.

Anna B. Velichko, Volodymyr S. Akhmetov and Peter N. Fedorov

Institute of Astronomy, V. N. Karazin Kharkiv National University,
61022, 35 Sumska str., Kharkiv, Ukraine
email: Velichko.Anna.B@gmail.com, akhmetovvs@gmail.com, pnfedorov@gmail.com

Abstract. We derive and compare kinematic parameters of the Galaxy using the PMA and *Gaia* TGAS data. Two methods are used in calculations: evaluation of the Ogorodnikov-Milne model (OMM) parameters by the least square method (LSM) and a decomposition on a set of vector spherical harmonics (VSH). We trace dependencies on the distance of the derived parameters including the Oort constants A and B and the rotational velocity of the Galaxy V_{rot} at the Solar distance for the common sample of stars of mixed spectral composition of the PMA and TGAS catalogues. The distances were obtained from the TGAS parallaxes or from reduced proper motions for fainter stars.

The A, B and V_{rot} parameters derived from proper motions of both catalogues used show identical behaviour but the values are systematically shifted by about 0.5 mas/yr.

The Oort B parameter derived from the PMA sample of red giants shows gradual decrease with increasing the distance while the Oort A has a minimum at about 2 kpc and then gradually increases.

As for models chosen for calculations, first, we confirm conclusions of other authors about the existence of extra-model harmonics in the stellar velocity field. Secondly, not all parameters of the OMM are statistically significant, and the set of parameters depends on the stellar sample used.

Keywords. astrometry, stellar kinematics, Galactic structure

1. Introduction

The quality of kinematic investigations is mainly determined by accuracy and amount of the used catalogue data. The *Gaia* DR1 catalogue (Gaia collaboration *et al.* (2016a)) provides a huge number of astrometric data that open new opportunities in different domains of astrometry and stellar astronomy. It allowed to build a new catalogue of absolute proper motions called PMA (Akhmetov *et al.*(2017)). The PMA was derived from a combination of the *Gaia* DR1 and 2MASS (Skrutskie *et al.* (2006)) catalogues. It contains more than 420 million stars with positions, proper motions as well as photometry in G, J, H and K bands taken from both catalogues used.

Also the *Gaia* mission has produced a sub-set of about 2 million stars to be common with the Tycho-2 catalogue, *Tycho-Gaia astrometric solution* (TGAS, Michalik *et al.*(2015), Gaia collaboration *et al.* (2016), Lindegren *et al.* (2016)), containing stellar positions, proper motions and parallaxes. This data is a qualitatively new material for kinematic investigations of our Galaxy.

We use two different ways for deriving kinematic parameters. The first one involves some physical model containing a set of parameters with the known physical meaning. The values of this parameters are derived after applying the LSM to the set of the model equations. Several conventional models of various degrees of complexity are described in literature. To select the most suitable one is the hard challenge, because it is unknown a priori which of constituents are present in the observed stellar velocity field. Instead, there is an opportunity to peak out all statistical significant harmonics in the stellar velocity field and then choose the adequate model using decomposition on a set of orthonormal functions on the sphere. We use 2-dimensional (in the tangential plane) VSH first applied by Mignard & Morando (1990) to analyze systematic differences between the *Hipparcos* (Perryman *et al.* (1997)) and FK5 catalogues. Later this method was expanded by Vityazev & Shuksto (2005) to investigation of stellar kinematics. It was applied to analysis of stellar proper motions of the *Hipparcos* catalogue.

The goal of this work is to compare kinematic parameters derived from the PMA and TGAS catalogues as well as verify the completeness of the OMM.

2. Working equations

Within framework of the OMM (du Mont, 1977, Rybka, 2004) the stellar velocity field can be represented as follows:

$$\mathbf{V} = \mathbf{V}_0 + \mathbf{\Omega} \times \mathbf{r} + \mathbf{M}^+ \times \mathbf{r} \tag{2.1}$$

It is assumed that the systematic constituent of stellar spatial motions $\mathbf{V}$ consists of translational motion of the Sun $\mathbf{V}_0 = (U, V, W)$ relative to the centroid used, the angular velocity of the rigid-body rotation $\mathbf{\Omega} = (\omega_x, \omega_y, \omega_z)$ of the stellar sample as well as the symmetric deformation tensor $\mathbf{M}^+ = (M^+_{12}, M^+_{13}, M^+_{23}, M^+_{11}, M^+_{22}, M^+_{33})$. The first three parameters of the deformation tensor correspond to deformations of the stellar velocity field in $(x, y), (x, z)$ and (y, z) Galactic planes while the others - to its contraction - expansion along three principal Galactic axes.

In case of the VSH method the stellar velocity field can be represented as the sum of toroidal and spheroidal coefficients with toroidal and spheroidal harmonics:

$$\mathbf{U}(l,b) = \sum_{nkp} t_{nkp}\mathbf{T}_{nkp} + \sum_{nkp} s_{nkp}\mathbf{S}_{nkp} \tag{2.2}$$

After projection of these two equations onto the Galactic coordinate system we obtain the following sets of equations to be solved by the LSM:

$$\begin{aligned}
K\mu_l\, cos\, b = \quad & U/r\, sin\, l\, - V/r\, cos\, l\, - \omega_1\, sin\, b\, cos\, l\, - \omega_2\, sin\, b\, sin\, l\, + \omega_3\, cos\, b\, + \\
+ \quad & M^+_{12}\, cos\, b\, cos\, 2l - M^+_{13} sin\, b\, sin\, l\, + M^+_{23}\, sin\, b\, cos\, l\, - \\
- \quad & 0.5\, M^+_{11} cos\, b\, sin\, 2l + 0.5\, M^+_{22} cos\, b\, sin\, 2l \\
K\mu_b = \quad & U/r\, cos\, l\, sin\, b\, + V/r\, sin\, l\, sin\, b\, - W/r\, cos\, b\, + \omega_1\, sin\, l - \omega_2\, cos\, l\, - \\
- \quad & 0.5\, M^+_{12}\, sin\, 2b\, sin\, 2l - M^+_{13}\, cos\, 2b\, cos\, l\, + M^+_{23}\, cos\, 2b\, sin\, l\, - \\
- \quad & 0.5\, M^+_{11}\, sin\, 2b\, cos^2\, l - 0.5\, M^+_{22}\, sin\, 2b\, sin^2\, l + 0.5\, M^+_{33}\, sin\, 2b
\end{aligned} \tag{2.3}$$

and

$$\begin{aligned}
K\mu_l\, cos\, b = \quad & \sum_{nkp} t_{nkp}\mathbf{T}^l_{nkp}(l, b) + \sum_{nkp} s_{nkp}\mathbf{S}^l_{nkp}(l, b) \\
K\mu_b = \quad & \sum_{nkp} t_{nkp}\mathbf{T}^b_{nkp}(l, b) + \sum_{nkp} s_{nkp}\mathbf{S}^b_{nkp}(l, b)
\end{aligned} \tag{2.4}$$

3. Kinematic parameters based on OMM

At first, we compare the kinematic parameters derived from the PMA and TGAS proper motions within the OMM. For this, the list of 2,048,407 common stars of the PMA

https://doi.org/10.1017/S1743921317006068 Published online by Cambridge University Press

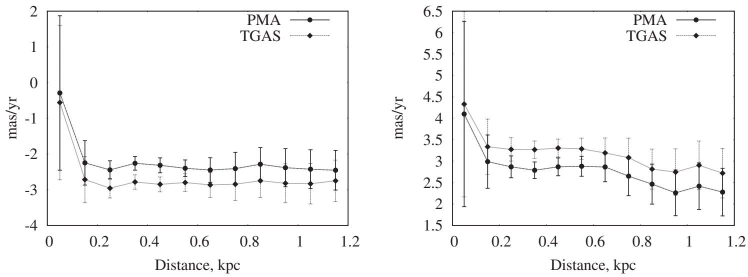

Figure 1. Kinematic parameters based on the OMM: Oort constant B (left panel), Oort constant A (right panel). The PMA data is designated by filled circles while the TGAS data - by filled diamonds.

and TGAS catalogues has been compiled. The distance to each star was determined from its parallax: $D = 1/\pi$. Stars with good parallaxes ($\sigma_\pi/\pi < 0.3$) and distances in the range from 0 kpc to 1.2 kpc were selected. The data were binned by distances with the 100 pc-sized step. The kinematic parameters were derived from the system of equations (2.3) by the standard LSM. The resulting behaviours of the Oort A and Oort B depending on the distance are shown in Fig. 1.

It can be seen from these figures that the Oort A and B constants derived from the stellar velocity field of the nearest stars with distances from 0 to 100 pc have huge root-mean-square (rms) errors. This suggests that the peculiar constituent dominates in proper motions of these stars. As the distance increases the accuracy of the parameters determination improves significantly. One more feature to be noted is the systematic differences between the PMA and TGAS data probably caused by systematic shifts between proper motions of these two catalogues in the Northern hemisphere (see Fig. 6 in Akhmetov *et al.* (2017)).

4. Applying VSH

According to the Vityazev's algorithm, applying the VSH method involves the following steps:

1) The coordinate grid regularization to make the coordinate distribution uniform throughout the sphere. For this, the Healpix (Gorsky *et al.* (2015)) pixelization scheme was used. The whole sphere was partitioned into 1200 pixels of equal area about 34.4 sq. deg. The proper motions were averaged over the pixels and referred to their centers.

2) The substraction of Solar motion effects from the stellar velocity field.

3) Detection of all statistical significant harmonics using the χ^2-test.

4) Calculation of toroidal and spheroidal decomposition coefficients t_j, s_j with all statistical significant harmonics from the system of equations (2.4).

5) Determining parameters of the OMM using the relations between the decomposition coefficients and the OMM parameters derived by Vityazev & Tsvetkov(2009).

As a result, it was found out that the stellar velocity field of the nearby stars with distances from 100 to 300 pc contains almost all constituents of the OMM. As the distance increases, only Solar motion components as well as Oort constants A and B remain in the proper motions of the TGAS. In addition to them the $M^+_{11} - M^+_{22}$ is significant for the PMA proper motions even for the farthest stars. Besides, several extra-model harmonics were detected. Among them the t_{310} and t_{211} have the greatest amplitudes. To find their physical meaning is a separate task.

https://doi.org/10.1017/S1743921317006068 Published online by Cambridge University Press

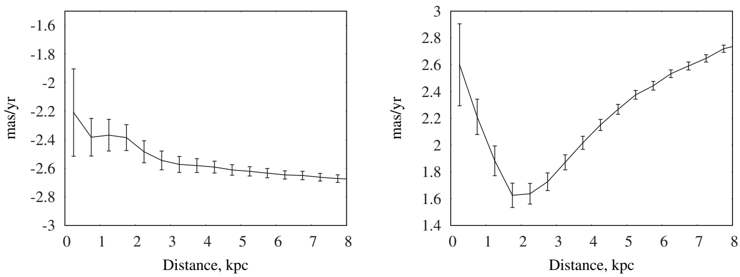

Figure 2. Kinematic parameters based on the VSH from red giants of the PMA: Oort constant B (left panel), Oort constant A (right panel).

The results just presented are related to bright range of magnitudes constituting only a small fraction of all PMA stars. To estimate distances to stars which do not have parallaxes we use reduced proper motions: $M'_{K_S} = K_S + 5 + 5lg(\mu)$. The sample of about 50 million red giants was compiled. For this sample the dependencies of the Oort constants A and B derived from the VSH method have been traced up to 8 kpc. It can be seen from Fig.2 that the Oort B gradually decreses with distance while the Oort A has a minimum at about 2 kpc and then increases. It would be interesting for theorists to explain this behaviour.

5. Acknowlegements

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. It is a pleasure to acknowlege financial support from IAU.

References

Akhmetov, V. S., Fedorov, P. N., Velichko, A. B., & Shulga, V. M. 2017, *MNRAS*, 469, 763.

Clube, S. V. M. 1972, *MNRAS*, 159, 289

Gorsky, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., Bartelmann, M. 2015 *Astrophys. J.*, 622, 759

Mignard, F. & Morando, B. 1990, *Journées 1990. Systèmes de Référence Spatio-Temporels*, 151.

du Mont, B. 1977, *A& A*, 61, 127

Perryman, M. A. C., Lindegren, L., Kovalevsky, J., Høg, E., Bastian, U., Bernacca, P. L., Crézé, M., Donati, F., Grenon, M., Grewing, M., van Leeuwen, F., van der Marel, H., Mignard, F., Murray, C. A., Le Poole, R. S., Schrijver, H., Turon, C., Arenou, F., Froeschlé, M., & Petersen, C. S., 1997, *A& A*, 323, L49

Rybka, S. P. 2004, *Kinem. i Fiz. Neb. Tel* 20, 133

Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., Huchra, J., Liebert, J., Lonsdale, C., Monet, D. G., Price, S., Seitzer, P., Jarrett, T., Kirkpatrick, J. D., Gizis, J. E., Howard, E., Evans, T., Fowler, J., Fullmer, L., Hurt, R., Light, R., Kopan, E. L., Marsh, K. A., McCallon, H. L., Tam, R., Van Dyk, S., & Wheelock, S. 2006, *ApJ*, 131, 1163

Vityazev, V. V. & Tsvetkov, A. S. 2009, *Astron. Letters*, 35, 100.

Vityazev, V. V. & Shuksto, A. K. 2005, *Vestn. Spb. Gos. Univ. Ser. 1*, 1, 116.