KINEMATICS OF THE LOCAL STELLAR SYSTEM

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Abstract. The hypothesis of the rotation of the Local stellar system (LSS) is used to explain the components in the proper motions of stars that the standard kinematic model does not describe. The LSS rotational parameters are derived from the proper motions of the GC reduced onto fundamental systems of the catalogues N30, FK4 and FK5. A weak dependence of the parameters on choice of the fundamental system is found. Some preliminary results are obtained from the radial velocities of the FK5 and the proper motions of the PPM.

1. Introduction

It is a tradition to interpret proper motions by a kinematic model based on considering the residual precessional motion of the Earth axis, the Solar motion and the Galactic rotation.

It was noticed long ago that the use of this model does not give a full description of the kinematics contained in the observational material. For example, it does not describe the North-South asymmetry of Galactic proper motions and the terms proportional to $\sin 3l$ and $\cos 3l$ (these terms are called Dyson's terms, 1929). The existence of the systematic parts that cannot be interpreted within the limits of the standard model was found by Brosche and Schwan (1981) and by Vityazev and Tsvetkov (1989,1990).

All these things force supplementing of the standard model with new terms describing the kinematics beyond the standard model. What is the physical nature of these effects?

One of the possible explanations of Dyson's terms and of the North-South asymmetry is the hypothesis of the Local Stellar System (henceforth the LSS) and its rotation. In 1879, a condensation of bright stars along a large circle inclined to the Milky Way was discovered. This star formation is known as the Gould's Belt by the name of its pioneer.

In 1950 Shatsova obtained equations which describe the influence of the LSS rotation on proper motions. In this fundamental work, she developed a method to study the LSS kinematics from proper motions of the GC and found the parameters of the axis orientation and angular velocity. However, because of computational limitations of that time, she used a specific method that allowed to solve only one of the equations for all stars together without any division of them by spectral types. Besides, the GC has large systematic errors both in positions and in proper motions of stars (Vityazev and Vityazeva, 1985).

At present, when new fundamental systems and new extensive catalogues are available, it is expedient to pursue a more detail study of the LSS kinematics. The purpose of the present work is to give a review of our results obtained from the proper motions and radial velocities of the stars listed in various catalogues.

2. The Equations of the LSS Rotation

Let us fix a coordinate system with its origin placed at the center of the Sun and the Z-axis directed to the North Galactic pole . We arrange the X-axis in such a way that the LSS rotation vector ω be parallel to XZ-plain and the Y-axis be normal to both others. The longitude of the X-axis coincides with the longitude of the rotational pole L_0; we denote its polar distance as P_0. Draw the perpendicular from point S to ω; the point of their intersection M_0 we call the center of rotation of the LSS. Extend the vectors $\mathbf{r}$ from point S to point M (an arbitrary star) and $\mathbf{r}_1$ from M_0 to M. The longitudes of these points are $l - L_0$ and $l_0 - L_0$; the latitudes are b and b_0 (*Fig. 1*).

For the velocity of the point M we can write

$$\mathbf{v} = \mathbf{\Omega} \times \mathbf{R} + \omega \times \mathbf{r_1}, \tag{1}$$

where Ω is the angular velocity of the Galaxy, $\mathbf{R}$ is the distance from the Galactic center.

From observational data we can determine only a differential effect, if we assume that the Sun takes part in the rotation of the LSS:

$$\mathbf{\Delta v} = \mathbf{v} - \mathbf{v_0}. \tag{2}$$

Using the relations $\mathbf{r_1} = \mathbf{r_0} + \mathbf{r}$ and $\mathbf{R} = \mathbf{R_0} + \mathbf{r}$, from Eqs. (1) and (2) we finally get

$$\mathbf{\Delta v} = (\mathbf{\Omega} - \mathbf{\Omega_0}) \times \mathbf{R_0} + \mathbf{\Omega} \times \mathbf{r} + (\omega - \omega_\mathbf{0}) \times \mathbf{r_0} + \omega \times \mathbf{r}, \tag{3}$$

Figure 1. The rotation of the Local Stellar system

where subscript $_0$ refers to the Sun.

From Eq. (3) one can see that the Galactic rotation and that of the LSS are separated. Under supposition that the Galactic rotation is known the terms $(\omega - \omega_{\mathbf{0}}) \times \mathbf{r_0} + \omega \times \mathbf{r}$ yield the contribution of the LSS rotation to the proper motions and radial velocities. Thus, at least theoretically, from equations of the LSS rotation it is possible to determine the following eight parameters of the LSS:

L_0, P_0 - the latitude and the polar distance of the rotational pole;
l_0, b_0, r_0 - the coordinates of the rotational center;
$\omega_0, \omega_0', \omega_0''$ - the angular velocity and its derivatives in the Sun neighbourhood.

There are other kinematic phenomena, which interfere with the LSS rotation. Since the Galactic rotation and the Solar motion are symmetric with respect to the Galactic equator we can exclude them by considering the differences $\mu_l \cos b$ and v_r "North-South":

$$\delta\mu_l \cos b = (\mu_l \cos b)_N - (\mu_l \cos b)_S, \tag{4}$$

$$\delta v_r = (v_r)_N - (v_r)_S, \tag{5}$$

and the sums μ_b "North+South":

$$\delta\mu_b = (\mu_b)_N + (\mu_b)_S, \tag{6}$$

taken at symmetric points on the sky. Unfortunately, because of a strong correlation we refused to obtain L_0 and P_0 from proper motions. Assuming that the position of the LSS is indicated by the Gould's Belt, we adopted the coordinates of the LSS rotational pole to be those of the Gould's Belt:

$$L_0 = 343^\circ, \qquad P_0 = 17^\circ\,. \tag{7}$$

Poor knowledge of the distances results in evaluating of the next parameters

$$n_0 = \frac{r_0}{\langle r \rangle}, \quad \omega_0' \langle r \rangle\,, \quad \omega_0'' \left\langle r^2 \right\rangle. \tag{8}$$

instead of $r_0, \omega_0', \omega_0''$. Here the angle brackets denote averaging.

So, we have the following six parameters to be determined from analysis of proper motions:

$$l_0, \quad b_0, \quad n_0, \quad \omega_0, \quad \omega_0' \langle r \rangle\,, \quad \omega_0'' \left\langle r^2 \right\rangle. \tag{9}$$

Due to strong correlations between the terms in the δv_r- equation we were able to obtain only the geometrical characteristics of the LSS: $l_0, \quad b_0, \quad n_0$.

The explicit forms of our equations may be found in works by Shatsova (1950, 1952) and Tsvetkov (1995). In general, they may be represented as

$$y = f(\mathbf{x}, \mathbf{t}), \tag{10}$$

where y is either $\delta\mu_l \cos b$, $\delta\mu_b$ or δv_r;
$\mathbf{x}$ is the vector of unknown variables $l_0, b_0, n_0, \omega_0, \omega_0' \langle r \rangle, \omega_0'' \langle r^2 \rangle$;
$\mathbf{t}$ is the vector of coordinates of the northern trapezium center;
f is a nonlinear function of as $\mathbf{x}$ as $\mathbf{t}$.

To apply conventional LSM technique for solving these equations, they are to be linearized. This method was tested on artificial data and showed stability to random component.

3. Data preparation

To find the LSS parameters we must have an extensive catalogue of proper motions. In past, it was the General Catalogue (GC) of Boss that had been used for the purpose. It is well known that positions and proper motions of the GC are polluted by large systematic errors (Vityazev and Vityazeva, 1985). More exact catalogues of the FK-series contain less stars and hardly fit our aim. A way out is a compromise: we should reduce the GC to the FK5 system (Vityazev and Tsvetkov, 1991). Also, we can investigate the dependence of solutions on the fundamental system by reducing the GC on the systems of various catalogues.

The new mass photographic catalogue of position and proper motions (PPM) became available in 1993. It lists more than 300 000 stars of various spectral types up to magnitudes $14 - 15^m$. This catalogue is also suitable for our task though the structure of the PPM is heterogeneous. The GC contains basically close stars which could form the LSS. We cannot say the same about the PPM. To process the PPM data correctly, one must reject the distant stars, which are hardly participate in the LSS rotation. The study of the LSS with the PPM is not completed now, and only some preliminary results are shown here.

A catalogue with parallaxes is strongly desired. When the HIPPARCOS catalogue becomes available this work will be continued.

We do not solve the LSS equations directly for each star because of the three reasons: (**a**) we are to know the differences of $\mu_l \cos b$ and sums μ_b for opposite points of the sky and this leads us to troubles to find a suitable couple for each star; (**b**) we are to reduce the random component before solving equations by averaging the data over certain areas on a sphere; (**c**) it is not easy to solve a system of more than ten thousand nonlinear equations even with modern computers.

For this reasons we divided the celestial sphere into some zones symmetric about the Galactic equator and subdivided them by trapezia of equal size in longitude. So, we have a set of trapezia to average the data from the catalogues.

4. Results of Solution

We carried out separate and combined solutions of the LSS equations for proper motions derived from the GC after reducing them to the fundamental systems FK5, FK4, N30 in the way described above. The parameters were determined for three spectral groups of stars: O-B9, A0-G5 and G6-M9, and for all stars together. To illustrate the dependence of the parameters on catalogue we plotted the functions (4) in one latitude zone (Fig. 2). Here one can see that the values of the parameters in all the fundamental systems are similar to those in the FK5 system. For this reason, we show the results of solutions only in the FK5 system (Table 1). Also, we got some preliminary results from the PPM catalogue that may be seen in Table 2. The geometric characteristics of the LSS obtained from the radial velocities

Figure 2. The contribution of the LSS rotation into $\mu_l \cos b$ calculated in various fundamental systems for one latitude zone

of the 2537 FK5 and FK5 Ext turned out to be:

$$l_0 = 223^\circ \pm 27^\circ; \quad b_0 = 16^\circ \pm 18^\circ; \quad n_0 = 5.5 \pm 3.8.$$

Results of our investigations can be summarised as follows:

1. Proper motions of early and middle spectral type stars in the GC do not contradict the assumption that the LSS rotates.
2. Systematic errors of proper motions in fundamental catalogues have only a weak influence on LSS parameters.

We believe that the most probable values of LSS parameters follow from a combined solution for stars of A0-G5 spectral types in the FK5 fundamental system:

TABLE 1. The LSS parameters derived in the FK5 fundamental system.
Units: l_0, b_0 *– degree;* n_0 *– dimensionless;* ω_0, $\omega_0' \langle r \rangle$, $\omega_0'' \langle r^2 \rangle$ *– arcsec/cy.*

Equation	Parameter	All Sp	O-B9	A0-G5	G5-N9
$\delta\mu_l \cos b$	l_0	$285. \pm 10.$	$298. \pm 27.$	$287. \pm 12.$	
	b_0	$-8. \pm 6.$	$-25. \pm 55.$	$-10. \pm 8.$	
	n_0	0.89 ± 0.35	1.06 ± 0.39	0.73 ± 0.23	
	ω_0	1.23 ± 0.54	2.34 ± 2.70	1.74 ± 0.65	
	$\omega_0' \langle r \rangle$	-1.35 ± 0.56	-3.04 ± 4.43	-2.20 ± 0.77	
	$\omega_0'' \langle r^2 \rangle$	4.33 ± 3.20	4.45 ± 6.30	5.62 ± 3.40	
$\delta\mu_b$	l_0	$269. \pm 4.$		$258. \pm 7.$	$275. \pm 7.$
	b_0	$7. \pm 3.$		$7. \pm 5.$	$8. \pm 6.$
	n_0	1.12 ± 0.15		0.78 ± 0.21	2.50 ± 1.17
	ω_0	0.35 ± 0.33		0.54 ± 0.50	0.51 ± 0.37
	$\omega_0' \langle r \rangle$	-1.36 ± 0.35		-2.44 ± 0.53	-0.47 ± 0.46
	$\omega_0'' \langle r^2 \rangle$	3.75 ± 0.89		4.07 ± 1.42	2.08 ± 1.43
Combined solution	l_0	$280. \pm 5.$	$291. \pm 13.$	$278. \pm 6.$	$270. \pm 2.$
	b_0	$-4. \pm 2.$	$-6. \pm 4.$	$-7. \pm 3.$	$-4. \pm 1.$
	n_0	1.29 ± 0.16	1.83 ± 0.82	0.94 ± 0.14	0.10 ± 0.06
	ω_0	0.69 ± 0.25	1.09 ± 0.99	1.05 ± 0.35	0.34 ± 0.41
	$\omega_0' \langle r \rangle$	-1.26 ± 0.30	-1.75 ± 1.29	-2.20 ± 0.44	1.26 ± 0.23
	$\omega_0'' \langle r^2 \rangle$	3.46 ± 0.80	5.93 ± 3.80	3.75 ± 1.22	-0.29 ± 1.22

TABLE 2. The LSS parameters derived from $\mu_l \cos b$ of the PPM catalogue
Units: l_0, b_0 *– degree;* n_0 *– dimensionless;* ω_0, $\omega_0' \langle r \rangle$, $\omega_0'' \langle r^2 \rangle$ *– arcsec/cy.*

Parameter	All Sp	F	G
l_0	236.7 ± 5.18	264.2 ± 14.58	245.1 ± 9.12
b_0	-5.4 ± 1.03	-20.2 ± 17.53	-4.3 ± 1.57
n_0	0.09 ± 0.06	0.30 ± 0.14	0.20 ± 0.15
ω_0	0.20 ± 0.15	0.73 ± 0.22	-0.22 ± 0.22
$\omega_0' \langle r \rangle$	0.00 ± 0.04	-0.23 ± 0.17	0.03 ± 0.08
$\omega_0'' \langle r^2 \rangle$	5.92 ± 0.99	1.16 ± 0.78	6.48 ± 1.83

coordinates of rotation center: $l_0 = 278° \pm 2°$,
$b_0 = -7° \pm 3°$;
the relative distance to the rotation center: $n_0 = 0.94 \pm 0.14$;
with the adopted value of the average distance of all stars in the GC to be 200 pc this yields: $r_0 = 190 \pm 28\,pc$;
the angular velocity and its derivatives: $\omega_0 = 1.05 \pm 0.35\,''/cy$;
$\omega_0' \langle r \rangle = -2.20 \pm 0.44\,''/cy$;
$\omega_0'' \langle r^2 \rangle = 3.75 \pm 0.44\,''/cy$;
the coordinates of the rotation pole: $L_0 = 343°$;
$B_0 = 17°$.

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