AN OVAL STREAM MODEL OF K–M GIANTS IN THE GALACTIC DISK

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ABSTRACT

We have analyzed proper motions of about 23000 K–M giants chosen from the astrometric catalogue ACRS Part 1 on the FK5 system, using the Maximum Likelihood Method, and determined a consistent set of the generalized Oort constants, the solar motion, and velocity dispersion together with a rational set of the corrections δp and $\delta e + \delta\lambda$ to the FK5 proper motion system. Comparing the present result with the previous one for O–B stars, we have found a large difference (~44 km/s) in the galactic rotations for K–M giants (176 km/s) and O–B stars (220 km/s). The difference cannot be explained by the difference (~4 km/s) in the solar motions with reference to the centroids defined by K–M giants and O–B stars, respectively. We show that the present contradictory kinematics for K–M giants and O–B stars can be reconciled, if an oval stellar-stream model with the axis ratio 0.9 is introduced, instead of the classical galactic rotation model(the circular galactic rotation). We hope that the investigation of present kind on the deviation from the circular symmetry of the galactic disk will be further extended on the basis of accurate proper motions supplied by Hipparcos and post-Hipparcos projects, such as GAIA.

Key words: Galactic rotation, Oort constants, solar motion, velocity dispersion, K–M giants, O–B stars, oval disk, GAIA

1. Introduction

The *direct* determination of the galactic rotation at the sun has been so far made only for the young population objects, including the interstellar gases. This is because, the determination of the circular velocity equivalent to LSR (Local Standard of Rest) at the sun has been fundamental in the galactic dynamics, and moreover the kinematical data of stars have not been sufficient to yield meaningful statistics for individual stellar populations. Recently, the large astrometric catalogue ACRS (Corbin & Urban 1991) has been available for examining the kinematics of the different populations, individually. Based on ACRS proper motions, Miyamoto & Sôma (1993) and Miyamoto et al. (1993) have found the different rotational velocities 177 km/s and 220 km/s for K–M giants and O–B stars, respectively. However, such a large difference in the galactic rotation can be explained neither by the difference in the solar motion nor by that in the asymmetric drift.

The solar motion with respect to the centroid defined by each sample of stars can be determined more easily than the centroid velocity with respect to the galactic center. Therefore, the difference in the galactic rotation among the different populations has been derived so far *indirectly* from the difference in the solar motion defined by the different populations (cf. Gilmore 1989), assuming that the difference in the solar motion should be equal to that in the galactic rotation (the centroid velocity with respect to the galactic center). Thus, we have never met the chance to compare *directly* the galactic rotations inherent in respective stellar populations.

In the present work, re-examining proper motions of K–M giants chosen from ACRS Part 1 (Corbin & Urban 1991) in a fully consistent fashion, we have determined a consistent set of the generalized Oort constants A and B, the solar motion, and the velocity dispersion, and found once again the low galactic rotation 176 km/s for K–M giants. In order to reconcile the low galactic rotation for K–M giants to that for O–B stars, we propose an oval stellar stream model which permits inevitably a velocity gradient with respect to the galactocentric azimuth.

2. Results

We have analyzed proper motions of ~ 2000 O–B stars (Miyamoto et al. 1993) as well as ~ 23000 K–M giants chosen from the astrometric catalogue ACRS Part 1 (Corbin & Urban 1991). The present analysis for K–M giants is carried out on the basis of the Maximum Likelihood Method (see Murray 1983), so as to derive fully consistently the remaining rotation of the reference frame, the solar motion, the systematic velocity fileld, the velocity dispersions, and the estimate of random proper motion errors of stars in the catalogue considered.

Hereafter, we use the galactocentric cylindrical coordinates (R, θ, z). As shown in Table 1, we have found the solar motion components in the direction of the galactic rotation $S_\theta \sim 16$ km/s and ~20 km/s for O–B stars and K–M giants, respectively. We have also obtained the galactic rotational velocities at the sun, assuming axisymmetry of the Galaxy. In other words, in the generalized Oort constants A and B

$$\begin{aligned} A &= \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} - \frac{V_\theta}{R} + \frac{1}{R}\frac{\partial V_R}{\partial \theta}\right) \\ B &= \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} + \frac{V_\theta}{R} - \frac{1}{R}\frac{\partial V_R}{\partial \theta}\right) \end{aligned} \quad (1)$$

we neglect the third term in the right hand side of Eq. (1).

Table 1: Kinematic parameters derived from proper motions given by ACRS Part 1

Kinematic Parameters	Least Squares Method K–M Giants $\lvert z\rvert \leq 0.5$ kpc	Maximum Likelihood Method K–M Giants $\lvert z\rvert < 1.0$ kpc	Least Squares Method O–B Stars $0.5 \text{ kpc} \leq r \leq 3.0$ kpc
Δp (″/cy)	-0.267 ± 0.028	-0.214 ± 0.022	-0.27 (given)
$\Delta e + \Delta\lambda$ (″/cy)	-0.116 ± 0.026	-0.075 ± 0.037	-0.12 (given)
S_R (km/s)	$+13.6 \pm 0.3$	$+13.4 \pm 0.31$	$+8.7 \pm 0.8$
S_θ (km/s)	$+23.3 \pm 0.3$	$+20.3 \pm 0.38$	$+15.9 \pm 0.8$
S_z (km/s)	$+11.9 \pm 0.3$	$+12.2 \pm 0.22$	$+9.1 \pm 0.7$
$S_{\rm total}$ (km/s)	29.5	26.7	20.3
A (″/cy)	$+0.263 \pm 0.012$	$+0.243 \pm 0.011$	$+0.285 \pm 0.019$
B (″/cy)	-0.176 ± 0.010	-0.193 ± 0.010	-0.260 ± 0.015
V_θ (km/s)*	-177.1 ± 6.2	-175.7 ± 6.0	-219.9 ± 9.8
σ_R (km/s)	–	$+31.3 \pm 0.4$	–
σ_θ (km/s)	–	$+25.2 \pm 0.5$	–
σ_z (km/s)	–	$+21.2 \pm 0.5$	–
$\epsilon_{\mu\alpha}$ (″/cy)	–	0.56 ± 0.02	–
$\epsilon_{\mu\delta}$ (″/cy)	–	0.52 ± 0.02	–
total number adopted	20292	22629	1892

* This value is derived, assuming the axisymmetry of the Galaxy (see the text).

Then we obtain

$$R_0(B - A) = V_\theta \tag{2}$$

From this relation, we can derive the rotational velocities; $V_{\theta,{\rm OB}} \sim -220$ km/s and $V_{\theta,{\rm KM}} \sim -176$ km/s, assuming the galactocentric distance of the sun is R_0=8.5 kpc.

The remakble difference in the galactic rotation $\sim$44 km/s between O–B stars and K–M giants, which is derived directly from the Oort constants A and B, can be explained neither by the difference in the solar motion between the two populations nor the asymmetric drift deduced from the velocity dispersions.

The difference (the lag) in the galactic rotation among the different populations has been derived so far *indirectly* from the difference in the solar motion with respect to centroids defined by different populations (see e.g., Gilmore 1989). The basic logic behind is that the 'absolute' solar motion $\boldsymbol{V}+\boldsymbol{S}$ with respect to the galactic center should be uniquely determined, irrespective of the stellar population considered, where $\boldsymbol{V} = (V_R,\, V_\theta,\, V_z)$ denotes the centroid of the population considered with respect to the galactic center and $\boldsymbol{S} = (S_R,\, S_\theta,\, S_z)$ the solar motion with respect to the centroid. That is,

$$(\boldsymbol{V}+\boldsymbol{S})_{\rm OB} = (\boldsymbol{V}+\boldsymbol{S})_{\rm KM} = (\boldsymbol{V}+\boldsymbol{S})_{\text{any other population}} \tag{3}$$

Especially, $(V_\theta + S_\theta)_{\rm OB}$ should be equal to $(V_\theta + S_\theta)_{\rm KM}$ in the present case. However, it is not the case for the present findings.

The present contradictory results are caused by the classical assumption of the axisymmetric galactic velocity field. The proper motion analysis to determine the generalized Oort constants A and B given by Eq. (1) can be performed without any specific assumption on the symmetry of the Galaxy (Miyamoto & Sôma 1993, where in Eq. (30), for 'α' read '$\alpha - \alpha_{\rm GP}$'). However, at the next step for deriving the galactic rotation around the galactic center, the assumption of the circular symmetry of the Galaxy ($\partial/\partial\theta = 0$) has to be introduced in the right hand side of Eq. (1). It is noted that the present rotational velocities $\sim$ –220 km/s and $\sim$ –176 km/s for O–B stars and K–M giants have been obtained on this assumption.

Removing now the constraint of the axisymmetry, we have the relation for respective populations:

$$R_0(B - A) = V_\theta - \frac{\partial V_R}{\partial\theta} \tag{4}$$

which means that we can no longer determine the rotational velocity V_θ in the classical way (Eq. (2)). In the present analysis we have

$$\left.\begin{aligned} \left(V_\theta - \tfrac{\partial V_R}{\partial\theta}\right)_{\rm OB} &\sim -220 \text{ km/s} \\ \left(V_\theta - \tfrac{\partial V_R}{\partial\theta}\right)_{\rm KM} &\sim -176 \text{ km/s} \end{aligned}\right\} \tag{5}$$

Thus, Eqs. (3) and (5), and the solar motion components given in Table 1 yield the differences:

$$\left.\begin{aligned} V_{\theta,{\rm OB}} - V_{\theta,{\rm KM}} &= -4 \pm 0.9 \text{ km/s} \\ V_{R,{\rm OB}} - V_{R,{\rm KM}} &= -5 \pm 0.9 \text{ km/s} \\ \left(\tfrac{\partial V_R}{\partial\theta}\right)_{\rm OB} - \left(\tfrac{\partial V_R}{\partial\theta}\right)_{\rm KM} &= +40 \pm 12 \text{ km/s} \end{aligned}\right\} \tag{6}$$

which should be explained by an oval stream model with $\partial/\partial\theta \neq 0$ of the galactic disk. In the present work, we consider only the kinematic implication of Eq. (6).

3. Oval Stream Model

Since the observables are only the differences in motion between O–B stars and K–M giants, we have to assume the motion of either of the two populations. For simplicity we assume the circular motion of O–B stars, giving $V_{\theta,\mathrm{OB}} = -220$ km/s.

The simplest oval stream with the ellipticity $\epsilon = 1 - b/a$ in the galactic plane may be described by a superposition of the simple harmonic oscillations

$$\left.\begin{aligned} X &= aR\cos[\omega(R)t + \delta(R)] \\ Y &= bR\sin[\omega(R)t + \delta(R)] \end{aligned}\right\} \tag{7}$$

with the velocity components

$$\left.\begin{aligned} V_X &= \tfrac{a}{b}\omega(R)Y \\ V_Y &= -\tfrac{b}{a}\omega(R)X \end{aligned}\right\} \tag{8}$$

where R denotes the galactocentric distance of the star considered. Eq. (8) can be rewritten as the conventional form

$$\left.\begin{aligned} V_R &= \frac{-\epsilon(2-\epsilon)}{2(1-\epsilon)}\sin 2\phi\ \omega R_\odot \\ V_\theta &= \left[(1-\epsilon)\cos^2\phi + \frac{\sin^2\phi}{1-\epsilon}\right]\omega R_\odot \end{aligned}\right\} \tag{9}$$

where ϕ is the galactocentric azimuth of the long axis of the oval stream reckoned clockwise from the sun-galactic center line. Fitting the oval stream model to the set of conditions

$$\left.\begin{aligned} V_{\theta,\mathrm{KM}} &= -216 \pm 11 \text{ km/s} \\ V_{R,\mathrm{KM}} &= 5 \pm 0.9 \text{ km/s} \\ \left(\tfrac{\partial V_R}{\partial\theta}\right)_{\mathrm{KM}} &= -40 \pm 12 \text{ km/s} \end{aligned}\right\} \tag{10}$$

we have determined the stream parameters for K–M giants as

$$\left.\begin{aligned} \omega &= -22 \pm 1 \text{ kms}^{-1}\text{kpc}^{-1} \\ \epsilon &= 0.1 \pm 0.05 \\ \phi &= 83 \pm 1.5^\circ \end{aligned}\right\} \tag{11}$$

The result implies that the stream line of K–M giants deviates slightly from the circular one of O–B stars and gives the axis ratio 0.9, and the sun lies near the short axis of the stream line. The present axis ratio is compatible with the one inferred from the axis ratio of the velocity ellipsoid (Kuijken & Tremaine 1994).

4. Discussion

Based on the proper motion analysis, we have found a large difference in the galactic rotation for K–M giants and O–B stars. Such a large difference can be explained neither by the difference in the solar motion nor the asymmetric drift.

In order to reconcile the low galactic rotation for K–M giants with the generally accepted rotation for O–B stars, we propose an oval stream model in the galactic disk. Especially, the value of $\partial V_R/\partial\theta$ constrains the ellipticity of the stellar stream. However, we encounter a puzzling problem in galactic dynamics that there co-exist the different stream lines for the different populations in the common galactic potential, though their deviation from circularity is slight.

To examine where is the cause of the contradiction, we need highly accurate proper motion data of a large variety of stars in a wide galactic region. Future space astrometry missions, and in particular GAIA, now look set to provide these data.

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