Velocities-distance optimization of the rotation model for a Galactic ensemble of massive young stars with masers: effects of parallax reduction

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Abstract. The previously developed 4D method for modeling the kinematics of the homogeneous subsystem of the Galaxy is used to study in detail the effect of accounting for the uncertainty of the measured heliocentric distances (here, trigonometric parallaxes) on the results of this modeling. The study is based on an updated database of 213 HMSFR masers. It is shown that neglecting random errors in parallaxes (3D method) leads to an overestimation of the distance from the Sun to the center of the Galaxy, R_0, by 0.2–0.5 kpc, which is significant compared to the statistical error $\pm\sim 0.1$ kpc. Also, the 3D method overestimates the velocity dispersion of masers in the Galactic plane by about 2 times, exaggerates the azimuthal and underestimates the radial residual velocities of the Sun, and also shows a tendency to underestimate the Oort constant A. Accounting for parallax errors leads to a decrease of the level of the rotation curve in the outer region of the Galaxy. It is demonstrated that these biases do not occur due to a change in the average distance scale, but rather as a result of the elimination of a fictitious expansion of the nominal distribution of objects in the Galactic plane relative to the Sun due to the measurement variance of distance estimates. Final estimates of universal (independent of the type of objects) Galactic characteristics are obtained from the updated data: $R_0 = 7.82 \pm 0.11\,\mathrm{kpc}$; angular and linear velocities of the Sun rotation around the center of the Galaxy $\omega_\odot = 30.44 \pm 0.18\,\mathrm{km/s/kpc}$, $\theta_\odot = 238.0 \pm 3.8\,\mathrm{km/s}$; the circular velocity of the Galaxy is $\theta_\mathrm{c} = 233.24 \pm 3.8\,\mathrm{km/s}$.

Introduction

Previously, a 4D method was proposed for constructing a spatially-kinematic model of a homogeneous flat subsystem of the Galaxy, which optimizes the deviations of objects from the model according to three velocity characteristics (the usual 3D approach) and according to parallaxes, thereby taking into account the statistical uncertainty of the latter [3, 4]. Since the more accurate 4D method is much more time-consuming and requires much longer calculations than the 3D method, this paper aims to show the advantages of the 4D method in terms of its impact on the results, and the systematic errors that can occur when using the simpler 3D approach.

1. Data

New measurements have been added to the database described in [4] for 7 masers in the high-mass star-forming regions (HMSFRs), including 3 new objects [1, 2]. The final catalog of HMSFRs used here contains 213 objects. These masers represent the most homogeneous subsystem of masers with trigonometric parallaxes.

2. Method

The 4D method is based on minimizing the likelihood function

$$L(\mathbf{a}) = \sum_{j=1}^{N} \Big[\ln(\sigma_{V_r})_j + \ln(\sigma_{\mu_l'})_j + \ln(\sigma_{\mu_b})_j \Big] + \frac{1}{2} \sum_{j=1}^{N} \min_{\varpi_{0,j}} \left\{ \frac{[V_{r,j} - V_{r,\mathrm{mod}}(\varpi_{0,j})]^2}{(\sigma_{V_r})_j^2} + \right.$$
$$\left. + \frac{[\mu'_{l,j} - \mu'_{l,\mathrm{mod}}(\varpi_{0,j})]^2}{(\sigma_{\mu_l'})_j^2} + \frac{[\mu_{b,j} - \mu_{b,\mathrm{mod}}(\varpi_{0,j})]^2}{(\sigma_{\mu_b})_j^2} + \frac{(\varpi_j - \varpi_{0,j})^2}{\sigma_{\varpi,j}^2} \right\}. \tag{1}$$

Here $\mathbf{a}$ is the vector of parameters; $V_{r,j}$, $\mu'_{l,j}$, $\mu_{b,j}$, and ϖ_j are catalog (measured) values of heliocentric radial velocity V_r, longitude ($\mu'_l \equiv \mu_l \cos b$) and latitude ($\mu_b$) proper motions, and parallax ϖ for the j-th object; $\varpi_{0,j}$ — the reduced parallax value of the j-th object; N is the sample size. The total variances of the velocity characteristics for the j-th object are the the sums of two components: the measuring variance and contributions of natural dispersion $\sigma_j^{*2} = \sigma_j^{*2}(l_j, b_j, \varpi_{0,j}; \sigma_R, \sigma_\theta, \sigma_Z, R_0)$, i.e., the velocity ellipsoid $(\sigma_R, \sigma_\theta, \sigma_Z)$. Here l_j and b_j are the longitude and latitude of j-th object, correspondingly.

The complete iterative procedure of the 4D method includes simultaneous optimization of all parameters and the order of the rotation model, a flexible algorithm for eliminating outliers in the data to determine velocity variances (algorithm parameter $L' = 3$) and to evaluate the remaining parameters ($L' = 1$); for details, see [4]. In this work, objects that were spatially and kinematically isolated from the main data set were additionally excluded in order to reduce the influence of edge approximation effects. The 3D method used here for comparison includes the same procedure as the 4D method, except for the uncertainty in parallaxes—in expression (1), the last term in curly brackets is omitted, and $\varpi_{0,j}$ is replaced with ϖ_j everywhere.

3. Systematic effects caused by ignoring errors in parallaxes

The results obtained by 4D and 3D methods were compared for the same stages of the algorithms application, for the same samples (to check the effect of the sample), for popular restrictions on the sample (on the Galactoaxial distance R, on the relative error of the parallax), and for the variant of the spherical ellipsoid of velocities with fixed components ($\sigma_R = \sigma_\theta = \sigma_Z = 5\,\text{km/s}$; see [6]).

Systematic biases due to the neglect of errors in parallaxes in the 3D method, are most pronounced for the following pairs of correlated parameters: for R_0 the bias is $+(0.2 \div 0.5) \pm 0.1\,\text{kpc}$ ($+3 \div 6\%$), for the Oort parameter A is $(-0.8 \div 0.0) \pm (0.2 \div 0.4)\,\text{km/s/kpc}$ (Fig. 1); the dispersions σ_R and σ_θ are overestimated by $\sim$2 times; the azimuthal residual velocity of the Sun is overestimated, and the radial velocity is underestimated by about one statistical uncertainty. The 4D method reduces (by decreasing the value of R_0) the level of the rotation curve by $\sim 15\,\text{km/s}$ in the outer region of the Galaxy ($R > 5\,\text{kpc}$), which leads to a decrease in the mass of the halo, disk, and entire Galaxy, as well as to a decrease in the radial scale of the disk.

These systematic effects do not occur because of a change in the average distance scale (the 4D method leaves it unchanged), but as a result of the elimination of the nominal expansion relative to the Sun of the distribution of objects in the Galactic plane due to the dispersion of distance estimates: due to the geometric features of the contribution of rotation to the radial velocity, the reduction in the average distances to nominally distant objects reduces the value of R_0 to a greater extent than it increases due to the elongation of close distances.

Final estimates of universal characteristics: $R_0 = 7.817^{+0.109}_{-0.105}$ kpc; the angular and linear velocities of the Sun's rotation around the Galactic center $\omega_\odot = 30.44 \pm 0.18\,\text{km/s/kpc}$, $\theta_\odot = 238.0 \pm 3.8\,\text{km/s}$; the circular rotation speed of the Galaxy $\theta_c = 233.24 \pm 3.8\,\text{km/s}$ (at azimuth peculiar velocity $v_\odot^{\text{LSR}} = 4.76 \pm 0.49\,\text{km/s}$ [5]).

Conclusion

Ignoring parallax errors can lead to significant biases in the results of kinematic modeling of the Galaxy. The complexity of the 4D method is compensated by its systematic accuracy.

References

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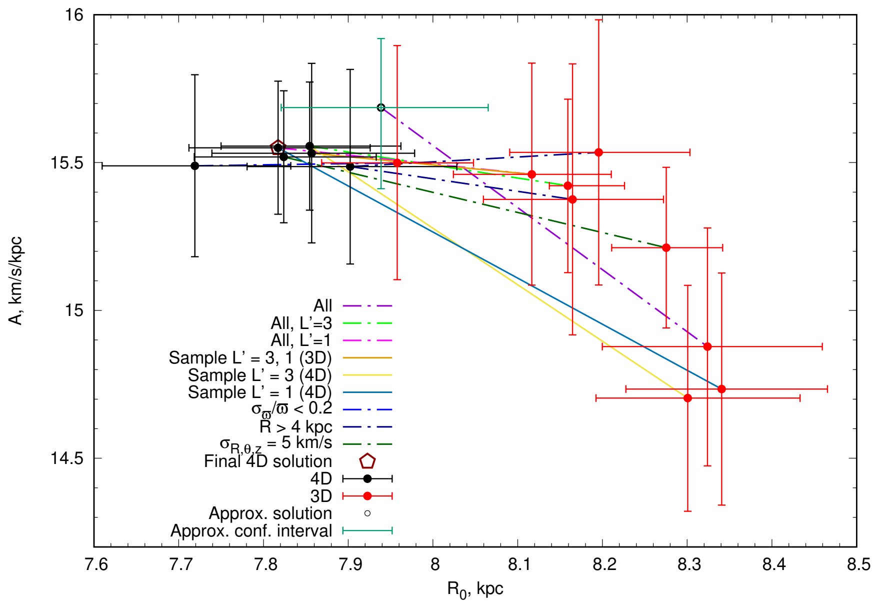

FIGURE 1. Effect of parallaxes' reduction (accounting for their statistical uncertainty) on estimates of the distance to the center of the Galaxy R_0 and the Oort constant A for different samples of HMSFR masers and fixed values of the velocity dispersion components ($\sigma_R = \sigma_\theta = \sigma_Z = 5\,\mathrm{km/s}$). Comparable estimates by the 4D method (black dots) and by the 3D method (red dots) are connected by straight lines: obtained independently by the full 4D- and 3D-algorithms under the same other conditions by dash-dotted lines, obtained by the same samples by solid lines.

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