Rotational Velocity in the Milky Way

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Abstract

In this report we present a model for the rotation of stars in the Milky Way around its center. In a fisrt simpler model, we assume that the stars in the GC (Galactic Center) frame move in circular orbits around its origin with a constant velocity V_{rot}, as well as the LSR (Local Standard of Rest), and that the Sun frame is moving with a velocity $U_\odot$ in the x-direction and $V_\odot$ in the y-direction in the GC frame with respect to the LSR. Then, we present a second, more complex model, in which we add, for each star, a random component $v'_{\mathrm{rand}} \sim N(0, \sigma^2)$ to its radial velocity.

In this report, we used the data provided by GAIA DR2 [1], considering, for each star on the galactic plane, its longitude, parallax, and radial velocity, along with the respective uncertainties.

These data are used to make Bayesian inference on the parameters of the two models, namely $\theta_{\mathbf{1}} = (V_{rot}, U_\odot, V_\odot)$ and $\theta_{\mathbf{2}} = (V_{rot}, U_\odot, V_\odot, \sigma)$, using MCMC (Monte Carlo Markov Chain) to estimate the non-normalized posterior of the two models.

1 Datas

In this work we will use data taken from GAIA DR2 [1]. From the vast dataset of stars analyzed by GAIA, we first select only those for which radial velocities, v_{rad}, were measured relative to the Sun using the Doppler effect. To manage the dataset size efficiently, we then apply a random selection to significantly reduce the quantity of data, imposing the random index of data to be less than 100000000.

For each selected star, we extract key parameters from GAIA DR2, including parallax p and its associated error σ_{p}, radial velocity v_{rad} with its measurement uncertainty σ_{v}, and galactic coordinates, i.e. latitude b and longitude l.

To focus our analysis on stars located within the galactic plane, we impose a selection criterion of $|b| < 5°$. Additionally, to ensure the reliability of the data, we retain only stars with a relative parallax error smaller than 20% and a radial velocity error below 5 $\mathrm{km\,s^{-1}}$.

2 Model

2.1 Physical Model

In our model, the Sun's frame moves around the Galactic Center GC with a drift velocity (that of the Local Standard of Rest LSR) plus a random vector. The drift velocity of the LSR in this model is considered in module equal to the drift velocities of each star in our galaxy and analyzed by GAIA DR2. In the following, primate vectors are in the frame of reference of the Sun, whereas unprimed ones are in the frame of reference of the center of the galaxy. Angles are supposed to be expressed as radians.

Calling $\boldsymbol{v}_\odot$ the total velocity of the Sun relative to the center of the galaxy, we have the following relation:

$$\boldsymbol{v}_\odot = \boldsymbol{v}_{\mathrm{LSR}} + \boldsymbol{v}_{\mathrm{rand}} \tag{1}$$

We can fix the frames of reference in the center of the Galaxy and on the Sun as in fig.1. In the picture, all the velocities are represented in the frame of reference fixed at the center of the galaxy. In our model, in this frame, all the stars (and the LSR frame) move around the center with velocity V_{rot}, therefore, the velocity for a star s at angle φ from the x-axis is:

$$\begin{aligned} \boldsymbol{v}_s &= V_{rot}(-\hat{e}_\varphi) \\ \hat{e}_\varphi &= \begin{pmatrix} -\sin(\varphi) \\ \cos(\varphi) \end{pmatrix} \end{aligned} \tag{2}$$

In particular, the Sun in this frame of reference has $\varphi = \pi$ and we add for it also $\boldsymbol{v}_{\mathrm{rand}}$, as in equation 1, which is composed by two component, $U_\odot$ along the x-axis, and $V_\odot$ along the y one. In this way its velocity is given by the equation:

$$\boldsymbol{v}_\odot = \begin{pmatrix} 0 \\ V_{rot} \end{pmatrix} + \begin{pmatrix} U_\odot \\ V_\odot \end{pmatrix} \tag{3}$$

The frame of reference of the sun is moving with velocity $\boldsymbol{v}_\odot$ given by eq.1, and its axis are rotating with an angular velocity $\boldsymbol{w}_\odot = -w_\odot \hat{e}_z$. Therefore, the velocity $\boldsymbol{v'_s}$ of a star s at distance d from the Sun is given by the equation

$$\boldsymbol{v'_s} = \boldsymbol{v_s} - \boldsymbol{v}_\odot - \boldsymbol{w}_\odot \times \hat{e}'_r d = \boldsymbol{v_s} - \boldsymbol{v}_\odot + w_\odot \hat{e}'_l d \tag{4}$$

The radial component $v_{\mathrm{rad}'}$ of the velocity of a star with longitude l in the sun frame of reference is finally given by:

$$\begin{aligned} \hat{e}'_r &= \begin{pmatrix} \cos(l) \\ \sin(l) \end{pmatrix} \\ v_{\mathrm{rad}'} &= \boldsymbol{v'_s} \cdot \hat{e}'_r = \\ &= V_{\mathrm{rot}} \Big[\sin\varphi \cos l - (1 + \cos\varphi) \sin l \Big] - U_\odot \cos l - V_\odot \sin l \end{aligned} \tag{5}$$

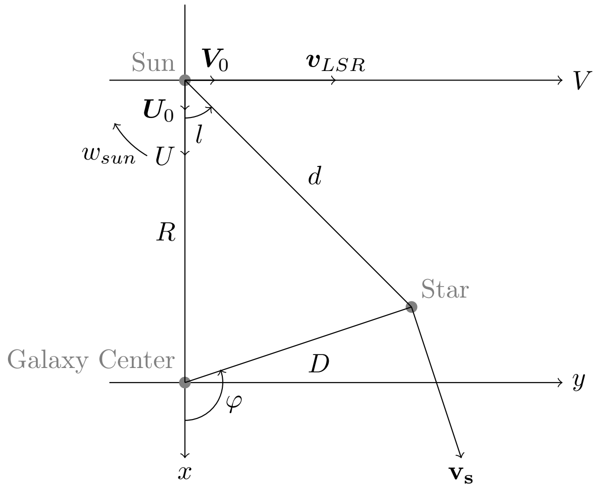

Figure 1: Frames of reference.

Eq.5 must be adapted to the actual data provided by GAIA, which means expressing $sin\varphi$ and $cos\varphi$ in terms of l and the parallax p, expressed in milliarcoseconds (mas). First of all, the distance in parsec can be computed as:

$$d[\text{pc}] = \frac{1000}{p[\text{mas}]} \tag{6}$$

Then, by applying the cosine theorem two times for R, d, D, l, φ (fig.1), we get:

$$D = \sqrt{d^2 + R^2 - 2dR\cos l} \tag{7}$$

$$\cos\varphi = \frac{d\cos l - R}{D} \tag{8}$$

and, therefore,

$$\sin\varphi = \pm\sqrt{1 - \cos^2\varphi} = \frac{d\sin l}{D} \tag{9}$$

By substituting eq.6-9 into eq.5, we get an expression for the prediction of the model for the radial component of the velocity of star i $v^{mod}_{rad,i}(l_i, p_i)$ as a function of the measurements of its longitude and parallax l_i, p_i:

$\mathrm{v}^{mod}_{rad,i}(l_i, p_i) \quad = \quad \mathrm{V_{rot}}\sin l_i(\frac{R}{\sqrt{(\frac{1000}{p_i})^2 + R^2 - 2(\frac{1000}{p_i})R\cos l_i}} \; - \; 1) \; - \; U_\odot\cos l_i - V_\odot\sin l_i(10)$

2.2 Statistical Model

2.3 Uncertainties

GAIA measurements are affected by statistical uncertainties on the evaluations of the parallax and the radial velocity. We assume the measurements to be random variables sampled from a gaussian distributrion centered at the true value of the respective quantity, with standard deviation given by the error reported by GAIA ($v_{rad} \sim N(\tilde{v}_{rad})$). Assuming the pysical model to be exact, and the measurements to be independant, the difference between the direct measure of the radial velocity, and the corresponding value given by the model by eq.5 is a random variable with variance that can be computed through propagation of errors as described in the following.

3 DataAnalysis

4 Conclusions

References

[1] A. G. A. Brown et al. "Gaia Data Release 2: Summary of the contents and survey properties". In: *Astronomy amp; Astrophysics* 616 (Aug. 2018), A1. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201833051. URL: http://dx.doi.org/10.1051/0004-6361/201833051.