

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 first 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 $v'_{\text{rand}} \sim N(0, \sigma^2)$ 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 $\theta_1 = (V_{\text{rot}}, U_{\odot}, V_{\odot})$ and $\theta_2 = (V_{\text{rot}}, U_{\odot}, V_{\odot}, \sigma)$, using MCMC (Monte Carlo Markov Chain) to estimate the non-normalized posterior of the two models.

With the first model, we estimated the parameters and their 95% confidence interval to be: $V_{\text{rot}} = 211.45$, 95% CI = [211.42, 211.50] km s^{-1} ; $u_{\odot} = 11.638$, 95% CI = [11.633, 11.644] km s^{-1} ; $v_{\odot} = 21.604$, 95% CI = [21.599, 21.609] km s^{-1} . With the second one instead, we got: $V_{\text{rot}} = 204$, 95% CI = [202, 206] km s^{-1} ; $u_{\odot} = 11.7$, 95% CI = [11.4, 12.0] km s^{-1} ; $v_{\odot} = 21.7$, 95% CI = [21.4, 22.1] km s^{-1} ; $\sigma = 30.6$, 95% CI = [30.5, 30.8] km s^{-1} .

1 Datas

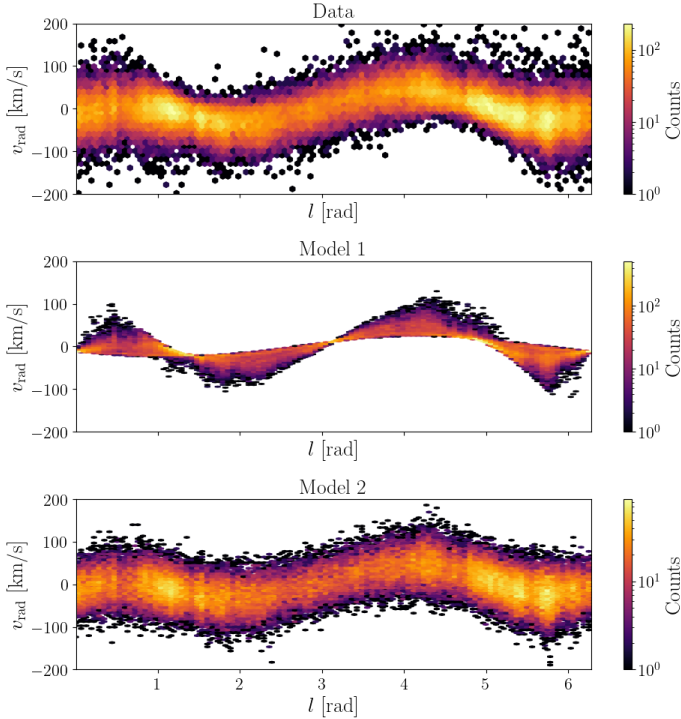


Figure 1: Upper: radial velocities in the interval $[-200, 200]$ km s^{-1} of the used data. Middle: predictions of the radial velocities with the first model. Lower: simulation of the distribution of the radial velocities with the second model.

In this work we 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 $|b| < 5^\circ$. 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 km s^{-1} . Following these criteria, 75659 stars were selected. The distribution of their radial velocity with respect to the Sun is plotted in the upper panel of figure 1 as a function of their longitude. Only values in the interval $[-200 \text{ km s}^{-1}, 200 \text{ km s}^{-1}]$ were reported for better visualisation. However, values up to 500 km s^{-1} were observed. These are likely outliers, and a more sophisticated data selection procedure may improve the quality of the following analysis.

2 Model

In this section we present the physical and the statistical models we developed for the study of the Galactic kinematics of the Milky Way. Our physical assumptions, presented in the paragraph 2.1, lead to a prediction for the radial motion of stars with respect to the Sun as a function of their longitude l and parallax p . The prediction, for each star, can then be compared to the direct measurement. In the paragraph 2.2 we formally present our statistical assumptions on the data and the parameters of the two models with their priors and likelihoods.

2.1 Physical Model

In our model, we only consider the motion on the galactic plane ($b \approx 0$). We assume that each star moves with a circular orbit around the Galactic Center GC with the same speed, V_{rot} . Fixing the frame of reference as in figure 2, a generic star s has a velocity \mathbf{v}_s given by:

$$\mathbf{v}_s = V_{\text{rot}} \begin{pmatrix} \sin(\varphi) \\ -\cos(\varphi) \end{pmatrix} \quad (1)$$

where φ is the angle from the x -axis of the star with respect to the GC. In the following, primed vectors are in the frame of reference of the Sun, whereas unprimed ones are in the frame of reference of the GC. Angles are supposed to be expressed as radians.

In this frame of reference, the Sun has $\varphi = \pi$, and we assume it to be at a fixed distance $R = 8300$ pc with respect to the GC. In this model, the drift velocity of the LSR (Local Standard of Rest) is also given by equation 1. In addition, the Sun has its own peculiar motion with respect to the LSR, with components, U_{\odot} along the x -axis, and V_{\odot} along the y one. Therefore, the total velocity \mathbf{v}_{\odot} of the Sun is:

$$\mathbf{v}_{\odot} = \begin{pmatrix} 0 \\ V_{\text{rot}} \end{pmatrix} + \begin{pmatrix} U_{\odot} \\ V_{\odot} \end{pmatrix} \quad (2)$$

The velocity \mathbf{v}'_s of a star s , in the frame of reference of the Sun, at distance d from the Sun is given by the equation:

$$\mathbf{v}'_s = \mathbf{v}_s - \mathbf{v}_{\odot} \quad (3)$$

We can now project the velocity \mathbf{v}'_s onto radial direction with respect to the Sun \hat{e}'_r ,

obtaining the radial component $v_{\text{rad}'}$ of the velocity of a star with longitude l in the Sun's frame of reference:

$$\begin{aligned} v_{\text{rad}'} &= \mathbf{v}'_s \cdot \hat{e}'_r = \\ &= V_{\text{rot}} \left[\sin \varphi \cos l - (1 + \cos \varphi) \sin l \right] - U_{\odot} \cos l - V_{\odot} \sin l \end{aligned} \quad (4)$$

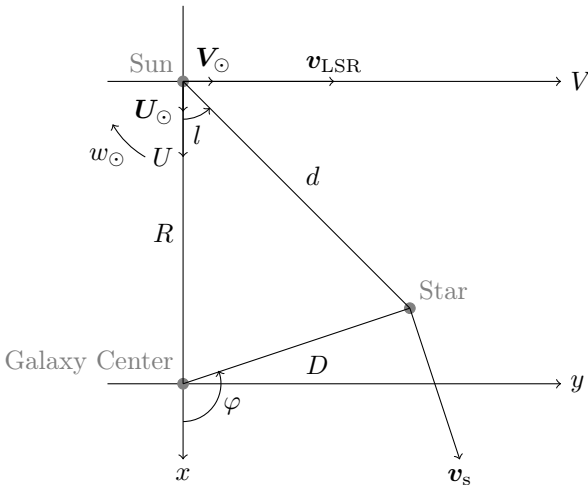


Figure 2: Frames of reference. The angular frequency w_{\odot} only contributes to the tangential component of the velocities of the stars with in the Sun's frame of reference, and is therefore omitted in equation 3.

Eq.4 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 milliarcseconds (mas). First of all, the distance in parsec can be computed as:

$$d[\text{pc}] = \frac{1000}{p[\text{mas}]} \quad (5)$$

Then, by geometric considerations we can evaluate D , $\sin \varphi$ and $\cos \varphi$ as a function of R , d and l (see figure 2), obtaining:

$$D = \sqrt{d^2 + R^2 - 2dR \cos l} \quad (6)$$

$$\sin \varphi = \pm \sqrt{1 - \cos^2 \varphi} = \frac{d \sin l}{D} \quad (7)$$

$$\cos \varphi = \frac{d \cos l - R}{D} \quad (8)$$

By substituting eq.5-8 into eq.4, we get an expression for the prediction of the model for the radial component of the velocity of star i $\hat{v}_{\text{rad},i}^{(1)}(l_i, p_i)$ as a function of the measurements of its longitude and parallax l_i, p_i :

$$\begin{aligned} \hat{v}_{\text{rad},i}^{(1)}(l_i, p_i) &= V_{\text{rot}} \sin l_i \left(\frac{R}{\sqrt{\left(\frac{1000}{p_i}\right)^2 + R^2 - 2\left(\frac{1000}{p_i}\right)R \cos l_i}} - 1 \right) - \\ &- U_{\odot} \cos l_i - V_{\odot} \sin l_i \end{aligned} \quad (9)$$

In a second, more sophisticated model, we also consider the random motion of all stars, adding to the right-hand-side of equation 9 a random variable $v_{\text{rand},i} \sim N(0, \sigma)$, obtaining:

$$\begin{aligned} \hat{v}_{\text{rad},i}^{(2)}(l_i, p_i) &= V_{\text{rot}} \sin l_i \left(\frac{R}{\sqrt{\left(\frac{1000}{p_i}\right)^2 + R^2 - 2\left(\frac{1000}{p_i}\right)R \cos l_i}} - 1 \right) - \\ &- U_{\odot} \cos l_i - V_{\odot} \sin l_i + v_{\text{rand},i} \end{aligned} \quad (10)$$

2.2 Statistical Model

In the following we describe the Bayesian inference we have made on the parameters of the two models. We used Monte Carlo Markov Chains (MCMC) provided by the emcee package in python to get an approximation of the non-normalized posteriors of our models $\mathbb{P}^*(\theta|\mathcal{D})$, considering only the numerator of Bayes' theorem (posterior):

$$\mathbb{P}^*(\theta|\mathcal{D}) = \mathcal{L}(\mathcal{D}|\theta)\mathbb{P}(\theta) \quad (11)$$

where $\mathcal{L}(\mathcal{D}|\theta)$ is the likelihood and $\mathbb{P}(\theta)$ is the prior. In practice, the logarithms of these quantities were used to achieve numerical stability.

For simplicity, in both models, we assumed each measurement and each parameter to be independent of all the others. Under this assumptions, the likelihood and the prior factorize in the product of individual terms. Then, we assume the value m of each measure to be the sum of its true value, and a random error $\epsilon \sim N(0, \sigma_m)$, extracted from a normal distribution centered at 0, with standard deviation given by the statistical uncertainty provided by GAIA database.

For the first model we have a set of three parameters $\theta_1 = (V_{\text{rot}}, U_{\odot}, V_{\odot})$. Neglecting the uncertainties associated to the parallax measurements, the difference between the measure of the radial velocity $v_{\text{rad},i}$ and its prediction $\hat{v}_{\text{rad},i}^{(1)}$ is a random variable extracted from a normal distribution centered in

0, with standard deviation only given by the statistical uncertainty on the measurements of the radial velocity. The log-likelihood of this model therefore is given by the sum of independent terms as:

$$\log \mathbb{P}^{(1)}(\mathcal{D}|\theta_1) = -\frac{1}{2} \sum_i [\log(2\pi\sigma_{v,i}^2) + \frac{(v_{rad,i} - \hat{v}_{rad,i}^{(1)})^2}{\sigma_{v,i}^2}] \quad (12)$$

Then, we chose a flat prior for $V_{rot} \in [0, 500 \text{ km s}^{-1}]$, in order to include typical values of the rotational motion of stars in spiral barred (Sb) galaxies which are found in the range $[144 \text{ km s}^{-1}, 330 \text{ km s}^{-1}]$ [2]. For U_\odot and V_\odot we chose a gaussian prior centered in 0, $\log \mathbb{P}^{(1)}(U_\odot) + \log \mathbb{P}^{(1)}(V_\odot) \sim -\frac{U_\odot^2 + V_\odot^2}{v_{gal}^2}$, assuming the peculiar motion of the sun to be analogous to a stochastic thermal motion. As a value for v_{gal} , we arbitrarily chose 200 km s^{-1} as a reference number for the random motion of stars in a Sb galaxy.

In our second model, there are four parameters: $\theta_2 = (V_{rot}, U_\odot, V_\odot, \sigma)$. Accounting for the errors on the parallax measurements, the model prediction $\hat{v}^{(2)}_{rad,i}$ (see equation 10) is a random variable extracted from a normal distribution centered in 0, and with variance σ^2 given by the sum of the variance of the random component σ^2 , and the contribution $\sigma_{p \rightarrow (2)}^2$ originating from the error on the parallax measurement, which can be computed by error propagation as:

$$\sigma_{p \rightarrow (2)}^2 = \left(\frac{\partial \hat{v}_{rad,i}^{(2)}}{\partial p_i} \right)^2 \sigma_{p_i}^2 \quad (13)$$

and for the random motion of stars, the difference between the measured value of the radial velocity $v_{rad,i}$ and the model

prediction $\hat{v}^{(2)}_{rad,i}$ is a random variable extracted from a normal distribution centered in 0, and with total variance given by the sum of the variances of the error on the radial velocity measurements, that

$$\log \mathbb{P}^{(2)}(\mathcal{D}|\theta_2) = -\frac{1}{2} \sum_i \left\{ \log[2\pi(\sigma_i^2 + \sigma^2)] + \frac{(v_{rad,i} - \hat{v}_{rad,i}^{(2)})^2}{\sigma_i^2 + \sigma^2} \right\} \quad (14)$$

where σ_i^2 is the sum of the variance for the normal distribution on the radial velocity measurements and for the one on the parallax propagated through the model (see equation 10).

We keep for the first three parameters the same priors decided in the first model, while we also assume the fourth parameter σ to be uncorrelated to the others (stars peculiar motion at a first glance shouldn't depend on the Sun's one either on their average rotational motion).

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 distribution centered at the true value of the respective quantity, with standard deviation given by the error reported by GAIA ($v_{rad} \sim N(v_{rad}, \sigma_v)$). Assuming the physical model to be exact, and the measurements to be independent, the difference between the direct measure of the radial velocity, and the corresponding value given by the model by eq.4 is a random variable with variance that can be computed through propagation of errors as described in the following.

3 DataAnalysis

4 Conclusions

A Posterior distributions

References

- [1] A. G. A. Brown et al. "Gaia Data Release 2: Summary of the contents and survey properties". In: *Astronomy and Astrophysics* 616 (Aug. 2018), A1. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201833051. URL: <http://dx.doi.org/10.1051/0004-6361/201833051>.
- [2] Peter Schneider. *Extragalactic Astronomy and Cosmology: An Introduction*. 2nd. See table 3.2 for the typical rotational speed of spiral galaxies. See appendix B for the estimation of the mass from measurements of luminosity. Heidelberg, Germany: Springer-Verlag Berlin Heidelberg, 2015. ISBN: 978-3-642-54082-0. DOI: 10.1007/978-3-642-54083-7.

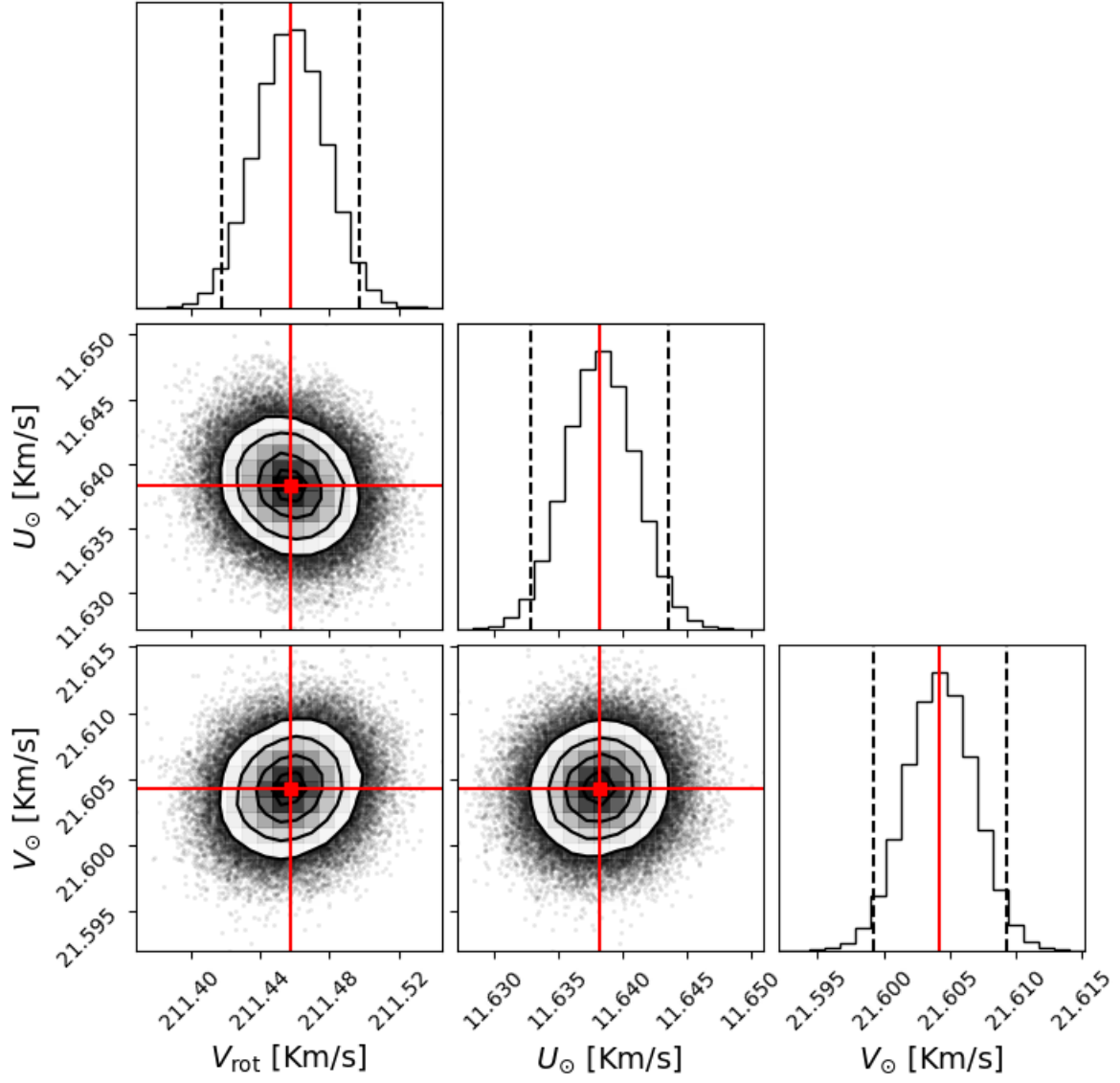


Figure 3: Posterior distribution for the parameters of the first model.

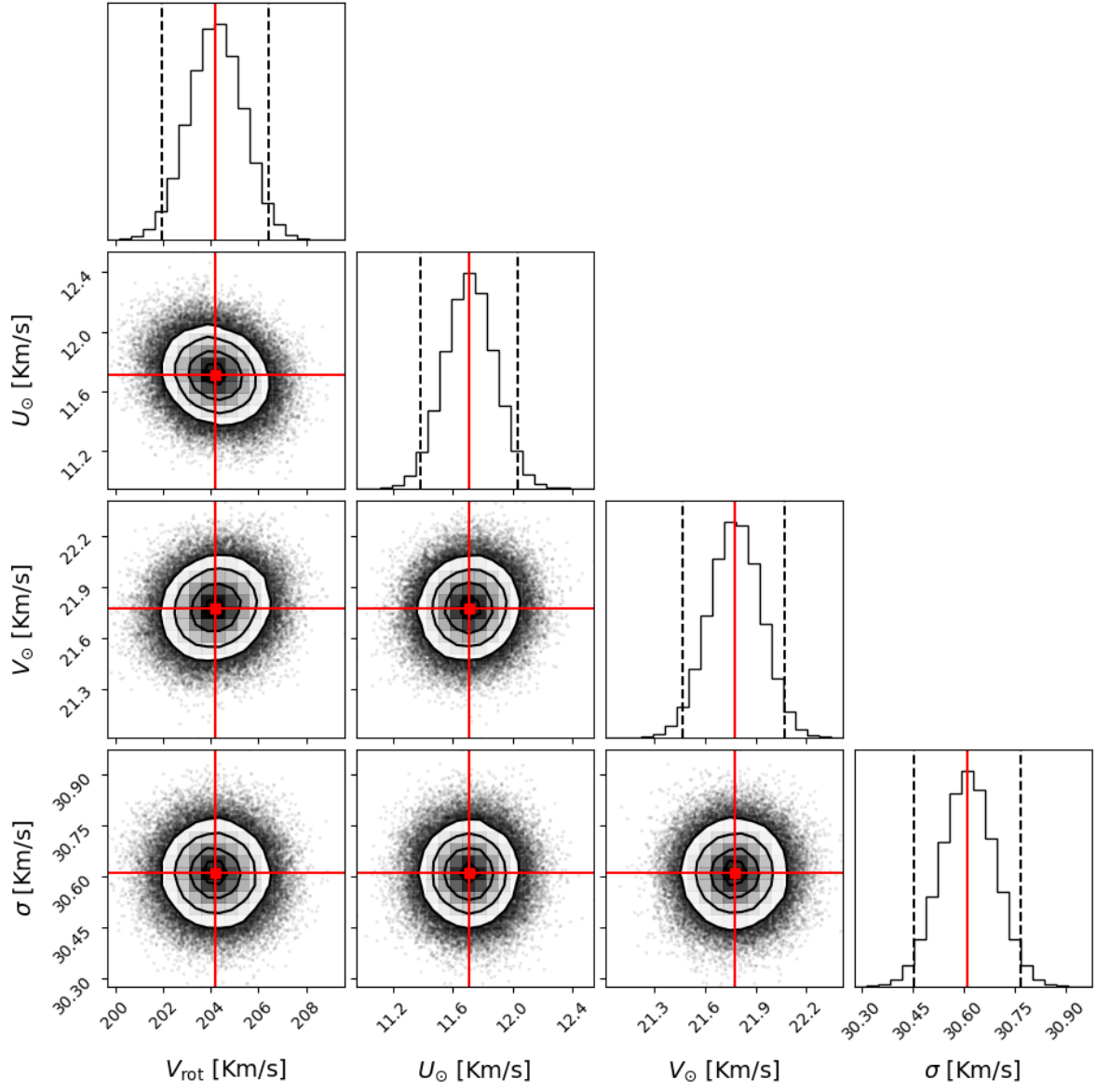


Figure 4: Posterior distribution for the parameters of the second model.