Estimating the Mass of the Milky Way Galaxy

Celeste Artiga, Yilun Ma, Ayla Weitz, Alex Ye (Mentor)
University of California, Berkeley - Department of Astronomy - Undergraduate Lab at Berkeley

Abstract

Estimating the mass of the Milky Way puts into perspective how a galaxy's mass can contribute to its evolution. To carry out such a process could be challenging as we are observing from within; however, with the Gaia satellite, we now can estimate mass of the Milky Way using escape velocities. Previous studies on mass estimation have been conducted using this method, yet we are using a different group of stars in the disk to test the consistency of the model and the estimation.

For the purpose of this project, we took advantage of the precision of Gaia Data Release 2's astrometric measurements. Velocity distributions for stars constrained in rings of width 1 kpc, deemed r-bins, were then obtained. Using `emcee`, Markov Chain Monte-Carlo (MCMC) simulations were implemented on the distribution in each r-bin to fit an escape velocity curve. In the end, we used the escape velocity derived for each r-bin and Newtonian mechanics to make a rough estimation of the Milky Way's mass. Our findings of a relatively constant escape velocity at different radii hints at the presence of dark matter.

Method for Determining Escape Velocity

Data were selected from Gaia DR2. So we only obtained data from stars within the galactic disk, we required that the stars have a galactic latitude value between -20 and 20 degrees. Also our query excluded stars with any null astrometric measurement, and we used the constraints set forth by Monari G. et al. (2018).

After acquiring the data of 1,134,770 stars, distances were calculated by inverting parallax values. Having compared the calculated distance values with values provided in `external.gaiadr2_geometric_distance` and upon plotting the residuals, we found the Bailer-Jones distance values for that catalogue were significantly more accurate at great distances. Thus, we decided to use the Bailer-Jones values in our further calculations.

Coordinate transformations were carried out on both the position and velocity of the stars into galactocentric coordinates using `SkyCoord`. Stars were divided into r-bins of 1 kpc; we assumed that the escape velocity would be similar within each r-bin. Based off Monari G. et al. (2018), we cut velocities below 250 km/s (assumed lower possible escape velocity) and above 800 km/s. Additionally, we assumed 10% error for each bin.

A speed distribution was then created for each r-bin using the following power law model detailed by Monari G. et al. (2018):

$$f(v|v_e,k) = \begin{cases} (k+1)(v_e - v)^k/(v_e - v_{cut}), & v \le v_e, \\ 0, & v > v_e, \end{cases}$$

The value of k is chosen to be 3 according to Monari G. et al. (2018).

Using this model and an initial guess for our best fit where the distribution first reaches $\left|\frac{\Delta N}{\Delta v}\right| < 5$, MCMC simulations were carried out with 500 iterations for each r-bin. Our error values were also calculated based upon the statistical method given in Monari G. et al. (2018).

Method for Determining Mass

Once escape velocities are determined, we are able to calculate the mass enclosed by each r-bin, using the following relationship:

$$v_e = \sqrt{\frac{2GM}{r}}$$

As long as the enclosed mass is obtained for each r-bin, it is able to approximately extrapolate the total mass of the Milky Way Galaxy.

Mass errors were calculated using typical error propagation.

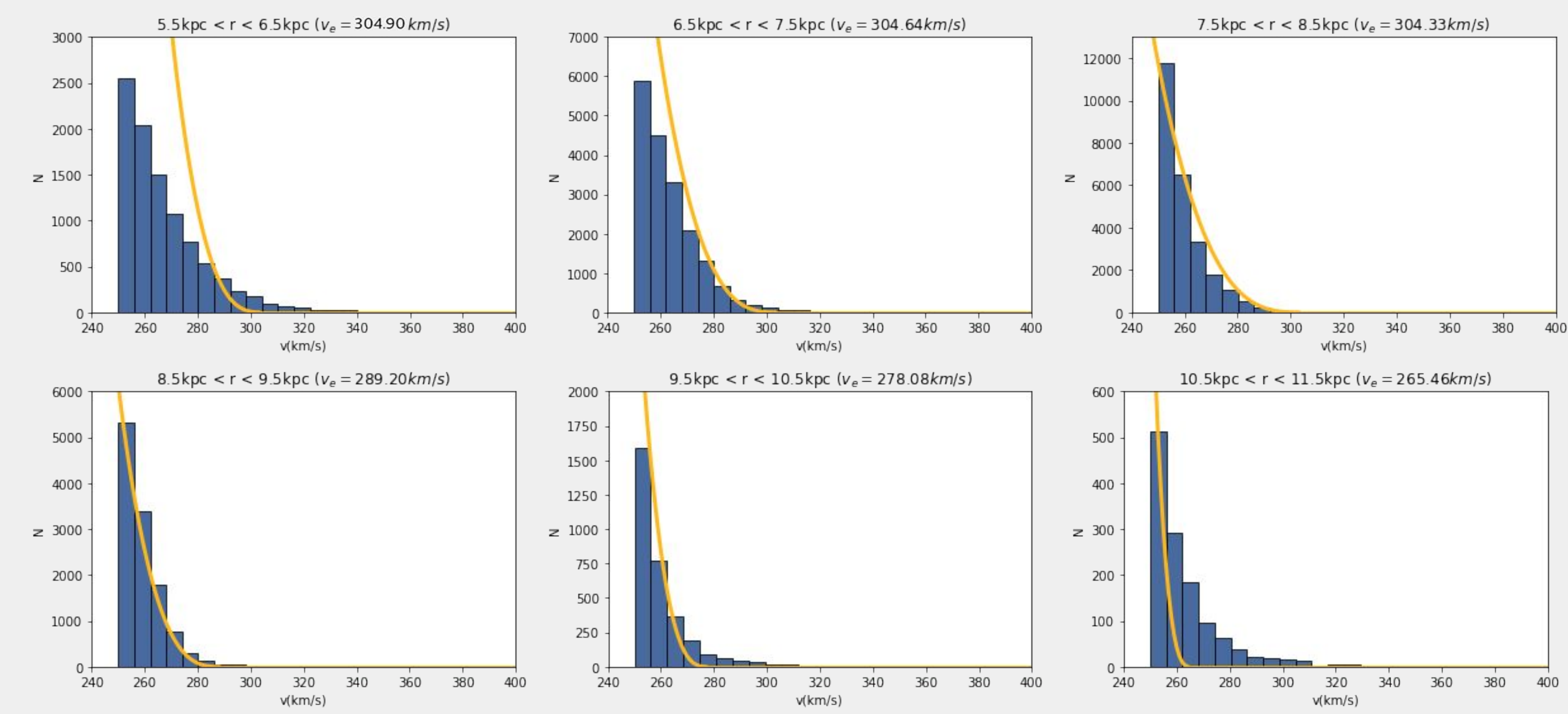

Fig. 1. Histograms of different *r*-bins, compared with $f(v|v_e,k)$ (yellow line), where v_e is derived for that specific bin and $k = 3$.

From Escape Velocity to Dark Matter

We only implemented MCMC on 6 bins ranging from 5.5 to 11.5 kpc and the results are shown in Fig. 1 where the distribution is used to fit the plot. R-bins outside of this range are unable to generate sample size large enough to provide reasonable results. This trend is already shown in Fig. 1 – the curve fits the best on 6.5 to 9.5 kpc where the maximum N value is greater than 5000. Such observation is consistent with Monari G. et al. (2018) as they only sampled stars ranging from 5.34 to 10.74 kpc for similar reasoning.

The difference in escape velocity values between Fig. 1 and 2 is due to `SkyCoord`'s coordinate transformation into a rotating frame. Fig. 2 is generated with the correction of Sun's orbital motion. As we could notice in Fig. 2, the error bars in each bin are extremely small; however, this would not guarantee accurate results as we were unable to incorporate uncertainties in certain astrometric measurements.

To check the validity of our result, we compared the escape velocity in Solar neighbourhood (r ~ 8 kpc) acquired by our simulations with the result in Monari G. et al. (2018), 580 ± 63 km/s. After the correction, we obtained 536.94 ± 0.71 km/s, which is within the error bars of the literature value, suggesting that our result is reasonable.

When distance from the Galactic center increases, the escape velocity is expected to drop due to the uneven distribution of baryonic matter along the radial direction – the farther away from the center, the slower the enclosed baryonic mass increases. Yet, as our distance from the Galactic center increases, the values of escape velocity obtained from MCMC simulations show no significant difference (Fig. 2), suggesting the presence of more enclosed mass within each radius than expected. Such relatively constant escape velocity could possibly be explained by contribution from the supposing presence of non-baryonic matter, in other words, dark matter, in our Milky Way Galaxy.

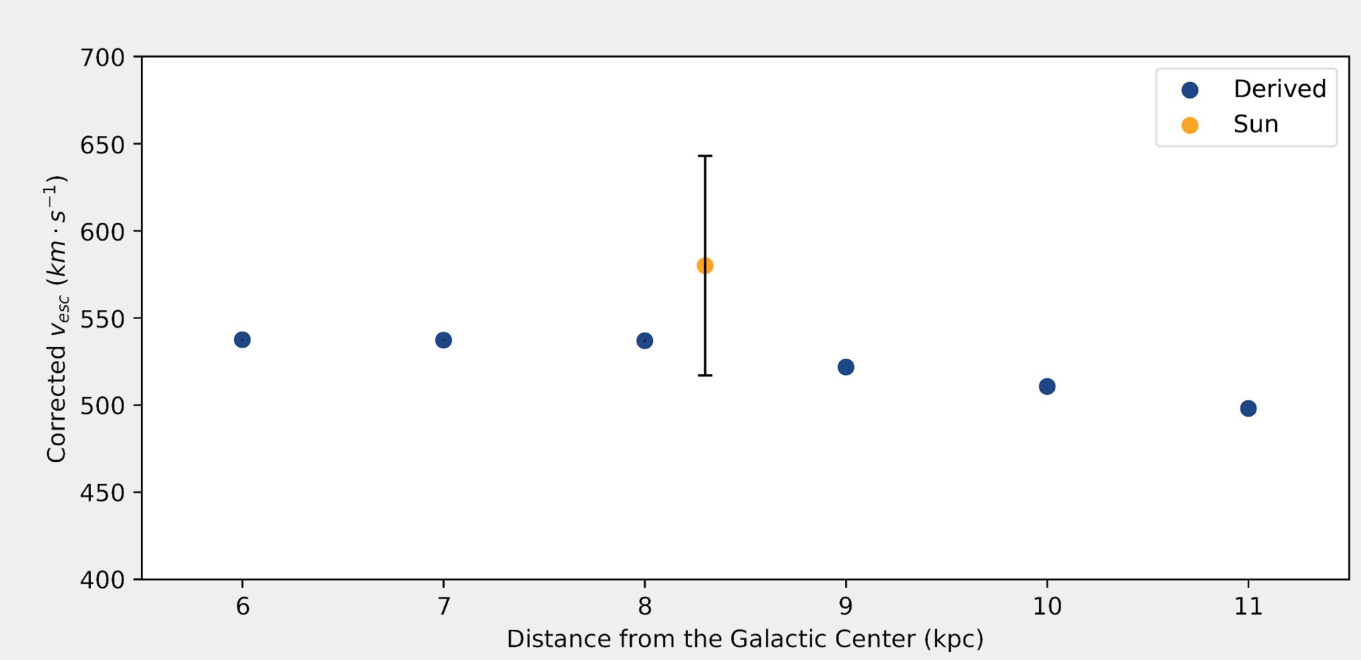

Fig. 2. Derived escape velocities at different radii (blue dots), and for reference we have included the estimated escape velocity at the Sun from Monari G. et al. (2018) (yellow dot).

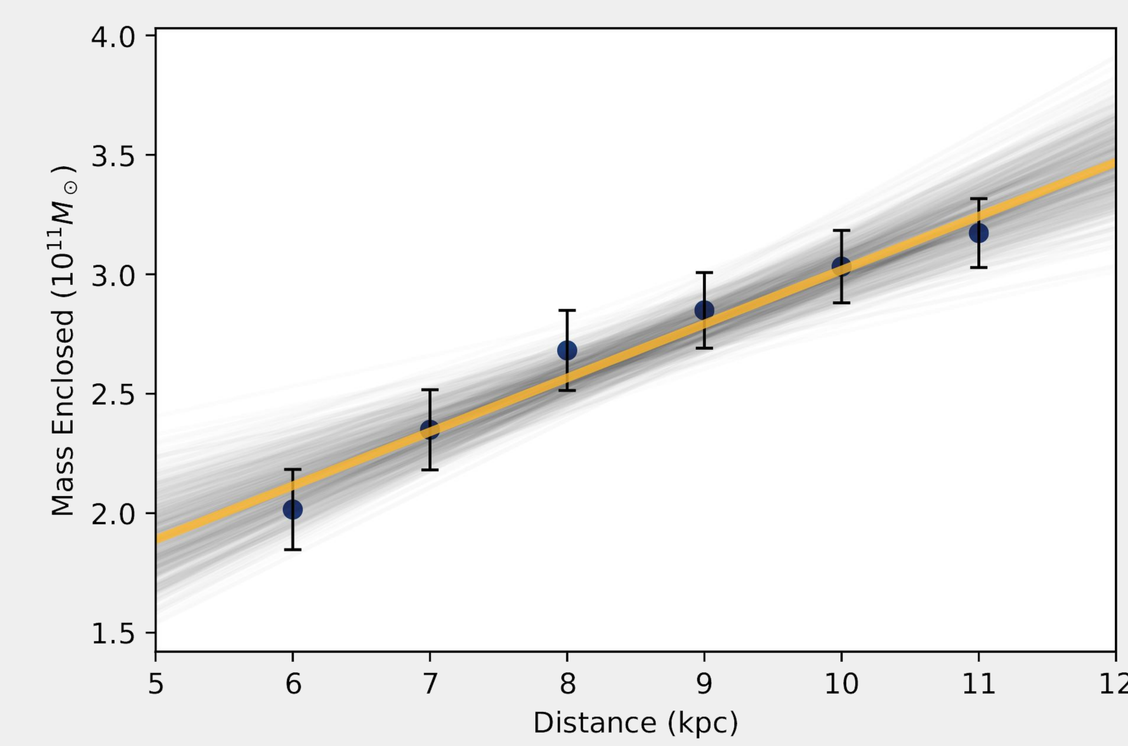

Fig. 3. Plot of the estimated enclosed masses versus radial distance. Using MCMC, we obtained a best fit line (yellow). Considering how well the linear model fits these data, it appears that the enclosed mass increases at a roughly similar rate (*m=0.23*).

Estimating the Mass of the Galaxy

Once we have an estimation on escape velocities across the Galactic radius, we are able to extrapolate the mass of our Milky Way Galaxy. We approximated the enclosed mass on different radii with a linear model. Using MCMC with 500 iterations, it is found that slope *m=0.23* and y-intersection *b=0.76* in our linear model.

We defined the radius of the Milky way to be 16 kpc, the distance at which our distance distribution becomes zero. Based on this value and our model, we obtained the total mass of our Galaxy to be $4.37 \times 10^{11} M_\odot$, smaller than the value in Monari G. et al. (2018) by two thirds. Conservatively, we would conclude that the Galaxy is larger than $\sim 10^{11} M_\odot$. However, since we only sampled stars with rather strict conditions on the galactic plane excluding the halo as well, the result might be quite biased to the disk. Moreover, our assumption of a linear relationship between distance and mass may have biased our results.

Future Work

Given our models are not perfect fits to the data, optimizing the method applied in order to obtain a line of best fit would be warranted. Error values associated with the dataset should also be considered, as opposed to omitting them for the sake of an initial approach. Furthermore, using/including samples from other regions of the Milky Way Galaxy as described in Monari G. et al. (2018), may help highlight additional parameters required to extrapolate these methods to different data queries of stars within the Milky Way. Lastly, to develop a distribution model and an algorithm only involving radial velocity would minimize the error which would give more accurate results.

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