Astro 1221 Written Report #1:

Calculating the Rotation Curve of the Milky Way

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Motivations: The base equation we use to solve for the rotation curve of galaxies is $V = \sqrt{\frac{GM}{R}}$. The V equals the orbital rotation curve, the G equals the gravitational constant, the M equals the mass of the central object, and the R equals the distance/radius of where the object is located. Normally, based on this equation, we would predict that stars that are further away from the galaxy's central super massive black hole will rotate slower than the stars that are closer to the super massive black hole. However, in actual observations the outer stars rotate at about the same rate as the inner stars. This means that there must be some kind of dark mass out there that's affecting the orbital velocity at these farther positions. Scientists who've made the same discoveries have begun to call this mass that can't be seen, "dark matter". Since dark matter hasn't properly been accounted for in most models, we have tried to make our own model that shows the true orbital velocity at these different radii. Models that take dark matter into account are able to more accurately model real world observations. In order to model the total rotation curve of the Milky Way, we have to model all the different parts of the Milky Way. The parts are the super massive black hole, the disk, the bulge, and the dark matter halo. When you combine the rotation curve of all the components, you get a model that more accurately represents the real world rotation curve.

Methods:

To build our model, a python program can be made based off of the above equation. To ease the process, the Python packages "astropy.constants", "astropy.units", "numpy", and "matplotlib.pyplot" are imported. These tools allow us to use Astrophysical constants, units, numerical operations, and build plots, respectively.

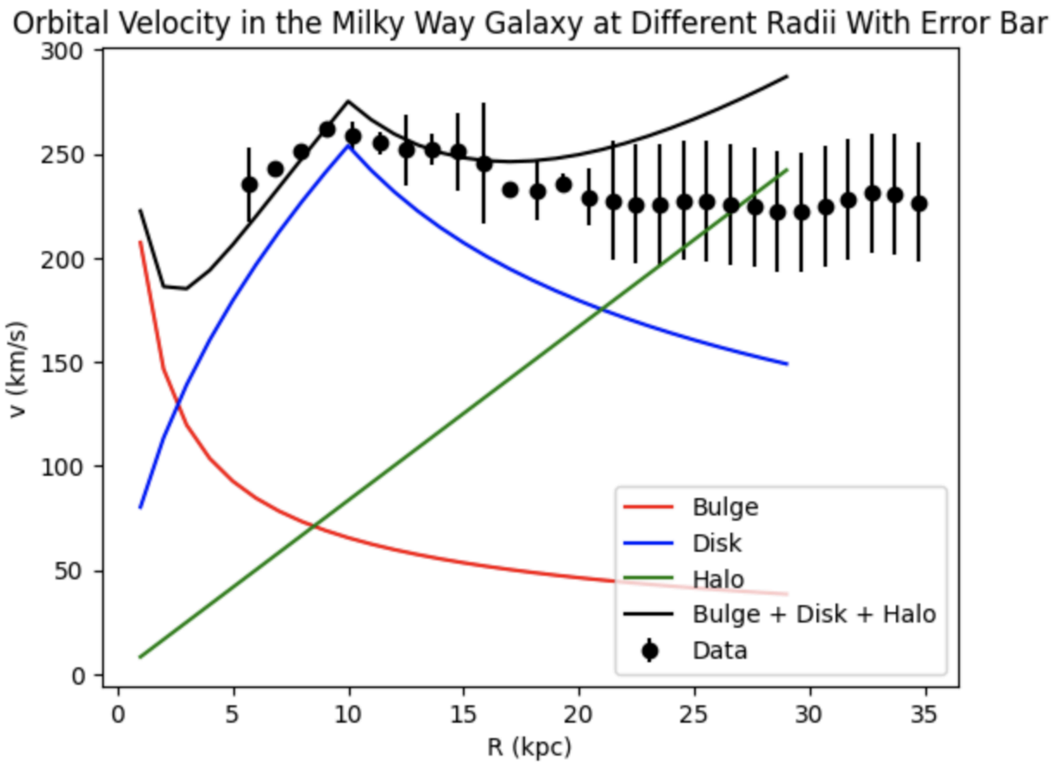
To begin building the model, we will first define a general orbital velocity function and then plot the rotation curve of the bulge component of the Milky Way. The orbital velocity function is made by defining a function with inputs of Mass and radius, in which the equation for orbital velocity defined above is used. This function yields an output of v for velocity, in units of kilometers per second. We can use this function to solve for the orbital velocity of the Milky Way's bulge, since it has a constant known mass of 1 x 10^{10} Solar Masses. This value is used in combination with a defined array of Radii (from 1 to 30 kiloparsecs) to create an array of Orbital Velocities. This array defines an orbital velocity at each radii from 1 to 30 kpc in the bulge. Finally using the plotting tools imported from before, the rotation curve of the bulge can be plotted.

The disk component of the Milky Way is next added to our model. This component is more complicated than the bulge, since its mass varies along its radius. Using the known quantities for mass and radius of 1 x 10^{11} Solar Masses and 11 kpc respectively, the density of the disk can be solved, since density is equivalent to mass divided by volume (pi times Radius Squared). This density is constant everywhere in the disk, so it can be used to solve for the enclosed mass at any radius. Enclosed mass is found with a new function, in which the inputs of radius and density are used to output mass. This mass is found by using any radius up to 10 kpc in the equation $M = density * \pi r^2$, or simply $M = density * \pi(10)^2$ outside of 10 kpc, the edge of the disk. One more function is then used to find a new total enclosed mass for the Milky Way, by adding the enclosed mass of the disk to our constant mass of the bulge. The rotation curve of the disk can then be plotted in our model similarly to the bulge, using Radius arrays from 1 to 30 kpc to calculate and plot different orbital velocities of the disk. The total mass function is used to solve and plot our new "total" galactic rotational curve, which only includes the disk and bulge components of the galaxy.

Our final step is to add the halo component of the galaxy, which is done in a very similar manner to the disk component. Key differences lie in how we treat the two components, since the halo is treated as a sphere instead of a flat disk. This change affects the way density of the halo and enclosed mass of the halo are calculated, but does not affect the coding methods used (I. E. the functions and plotting tools used).

To check the accuracy of our model, real data points can be imported from the class's github page and plotted onto our model. This is done by importing two packages, "files" and "astropy.io.ascii" to include our file and read its ascii text, respectively. After this is done, it is clear that our model is slightly inaccurate and should be corrected. Corrections are then made by increasing the influence of the Galactic disk and decreasing the influence of the halo to better match the data.

Results:



This graph shows a model for orbital velocities at different radii from 0 to 30 kiloparsecs in the Milky Way galaxy. In this model, the red line shows the orbital velocity of the innermost part of our galaxy, known as the bulge. The blue line shows the orbital velocity of the next component of our galaxy known as the disk. The green line shows the orbital velocity of the outermost part of the galaxy known as the halo. Finally, the black line(without the dots) shows the total orbital velocity of the galaxy at these different radii. Normally, based on what's visible to us, we would expect the total orbital velocity to decrease at farther distances, but according to our model the orbital velocities are increasing and it seems that the component that contributes the most to the orbital velocities at these farther distances is the halo component.

Conclusions:

Based on the orbital velocity equation, $V = \sqrt{\frac{GM}{R}}$, since the radius is on the denominator, we would expect that as the radius increases, the total orbital velocity would decrease as the G value is a constant. However, as we get farther from the center of the galaxy, it seems that the orbital velocity is still going up. So based on the equation, this would have to mean that there is some extra mass in the galaxy that is affecting the orbital velocities at these farther radii. The issue though, is that this mass is not visible at these different locations. Scientists refer to this extra mass as “dark matter”. Based on our model, we can very clearly see that the total orbital velocity at these farther distances is much higher than expected and that the component that seems to be contributing the most to the orbital velocity at these farther parts in the galaxy is the halo component. From this we can conclude that there is extra mass that’s not visible known as dark matter in the Milky Way galaxy and that most of it can be found in the galaxy’s outermost part known as the halo.

Contributions:

Owen Urban: Motivations
Zac Brutko: Worked on Methods
Jacob Mathew: Worked on Results and Conclusions

AI Statement:
For this project, we used Google’s Gemini in order to help us write the code to generate the graphs of the orbital velocities of the different components in the galaxy.