

Part I: Motions of Planets

An object's orbit depends on the "mass inside" its orbit (also known as the *interior mass*). For a planet in our solar system, you can find the interior mass by adding the Sun's mass to the mass of each object between the Sun and the planet's orbit. For example, the interior mass to Earth's orbit would be the Sun's mass plus the mass of Mercury plus the mass of Venus.

Here is a table that lists each planet, the mass inside each planet's orbit, and the speed at which the planets orbit the Sun.

Planet	Interior Mass (solar masses)	Orbital Speed (km/s)
Mercury	1.00	47.9
Venus	1.00000017	35.0
Earth	1.0000026	29.8
Mars	1.0000056	24.1
Jupiter	1.0000059	13.1
Saturn	1.00096	9.66
Uranus	1.0012	6.81
Neptune	1.0013	5.43

- 1) Where is the vast majority of mass in the solar system located? What object or objects account for most of this mass?

- 2) Two students are discussing their answers to Question 1:

Student 1: *I think the majority of the mass in the solar system must include both the Sun and the planets. As you get farther away from the Sun, the interior mass gets bigger and bigger because you include more planets.*

Student 2: *I disagree. The majority of the mass in the solar system is from just the Sun by itself. Sure the mass gets a little bigger as you include more planets, but the additional mass from planets is really small.*

Do you agree or disagree with either or both of the students? Explain your reasoning.

- 3) How do the orbital speeds of planets farther from the Sun compare to the orbital speeds of planets closer to the Sun?

A planet's orbital speed depends on the gravitational force it feels. The strength of the gravitational force depends on the amount of mass that is inside of the planet's orbit as well as how far away the planet is from this interior mass.

- 4) How does the gravitational force on a planet far from the Sun compare to the gravitational force on a planet close to the Sun? Explain your reasoning.

- 5) Complete the blanks in the sentences of the following paragraph by either writing in the necessary information or circling the correct response in the parentheses (). It may be helpful to base your responses on the information provided in the table above and your answers to the previous questions.

There are ____ planets inside Neptune's orbit and ____ planets inside Mercury's orbit. However, the interior mass for Neptune is ____ (much greater than/approximately the same as/much less than) the interior mass of Mercury. Neptune is ____ (much closer to/much farther from/about the same distance from) the Sun as/than Mercury. Therefore the gravitational force exerted on Neptune is ____ (stronger/weaker/about the same strength) as/than the force exerted on Mercury. As a result, Neptune has an orbital speed that is ____ (much slower/much faster/about the same speed) as/than the orbital speed of Mercury.

Imagine you were able to add a very, very large amount of mass distributed evenly *between* the orbits of Jupiter and Saturn.

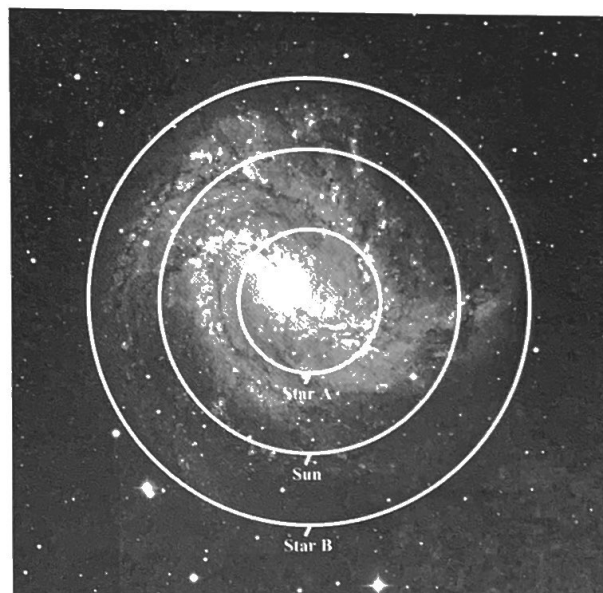
- 6) Which planet(s) will experience an increase in gravitational force and an increase in orbital speed from this added mass? Explain your reasoning.

Part II: Motions of Stars

One way to estimate the amount of mass in a spiral galaxy is by looking at how much light the galaxy emits. Where there is more light, there must be more stars and hence more mass. When astronomers measure the amount of light emitted by different regions of a galaxy, they often find that more light is emitted from the center of the galaxy and less light is emitted from the outer regions.

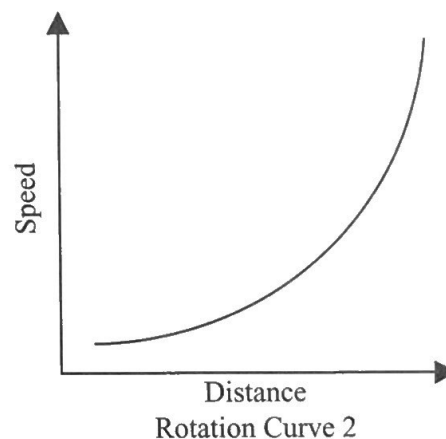
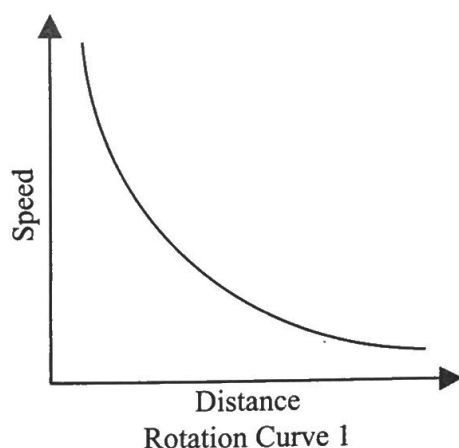
- 7) Based on the information provided above, where do you expect most of the mass of a galaxy to be located?

At right is picture of a spiral galaxy similar to the Milky Way. The orbits of three stars are labeled. Star A is a star on the edge of the Milky Way's bulge. The Sun's orbit is shown at approximately the correct position. Star B is a star located farther out in the disk than the Sun.



- 8) Based on your answer to Question 7 and the location of each star from the center of the galaxy, rank how you think the orbital speeds of Star A, Star B, and the Sun would compare from fastest to slowest. Explain your reasoning.

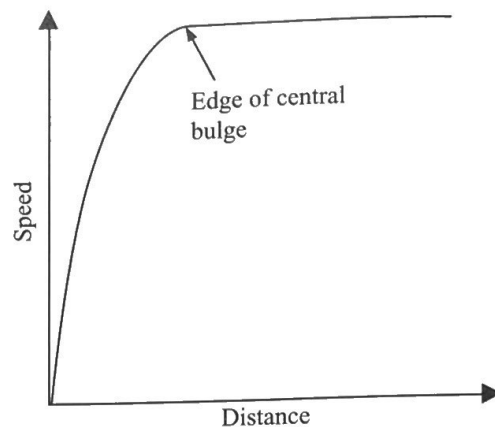
A graph of the orbital speed of stars versus their distance from the galaxy's center is called a *rotation curve*. Here are two possible rotation curves.



- 9) Which of the above rotation curves best represents the relationship you described in Question 8? Explain your reasoning.

Astronomers were surprised when they saw the real rotation curve for the Milky Way Galaxy (MWG). The rotation curve at the right is more like the MWG's real rotation curve.

- 10) Based on their orbital distance from the center of the galaxy, make three dots on the above rotation curve to represent Star A, Star B, and the Sun. Be sure to label which mark belongs to each star.



- 11) Describe how the stars' orbital speeds shown in the real rotation curve for the MWG are different from the orbital speeds shown in the rotation curve you chose in Question 9.
- 12) Using the real rotation curve for the MWG, provide a new ranking for the orbital speeds of Star A, Star B, and the Sun, from fastest to slowest. Describe any differences between this ranking and the one you provided in Question 8.
- 13) Based on your answers to Question 12, would you say that most of the mass of the Milky Way Galaxy is located at its center (as is the case with our solar system)? Explain your reasoning.
- 14) Based on the MWG's real rotation curve and your answers to Questions 11–13, is the gravitational force felt by the MWG's stars greater than, less than, or about the same as what you expected from Questions 8 and 9? Explain your reasoning.

15) Two students are debating their answers to the previous questions:

Student 1: *Stars far from the center of the Milky Way are all moving at about the same speed. If most of the Milky Way's mass is located in its center, then stars far away from the center would orbit slower than stars closer to the center. Since this is not what we see, this must mean there is more mass throughout the outer regions of the galaxy than we can see. This also means that the Milky Way's stars feel a greater gravitational force than we originally expected.*

Student 2: *I disagree. There are fewer stars in the outskirts of the Milky Way than in the center, so there's less mass out there than at the center. Most of the Milky Way's mass must be at its center. So, since the stars are all going about the same speed, where the mass is located must not affect their speed. The gravitational force these stars feel probably gets weaker just like we would expect.*

Do you agree or disagree with either or both of the students? Explain your reasoning.

16) Astronomers initially thought there was more mass in the center of the galaxy than in the rest of the galaxy because there's more light coming from the center. Describe how astronomers' observations show these initial ideas are wrong.

17) Is there more or less mass in the Milky Way's disk and halo than we can see? Explain your reasoning.

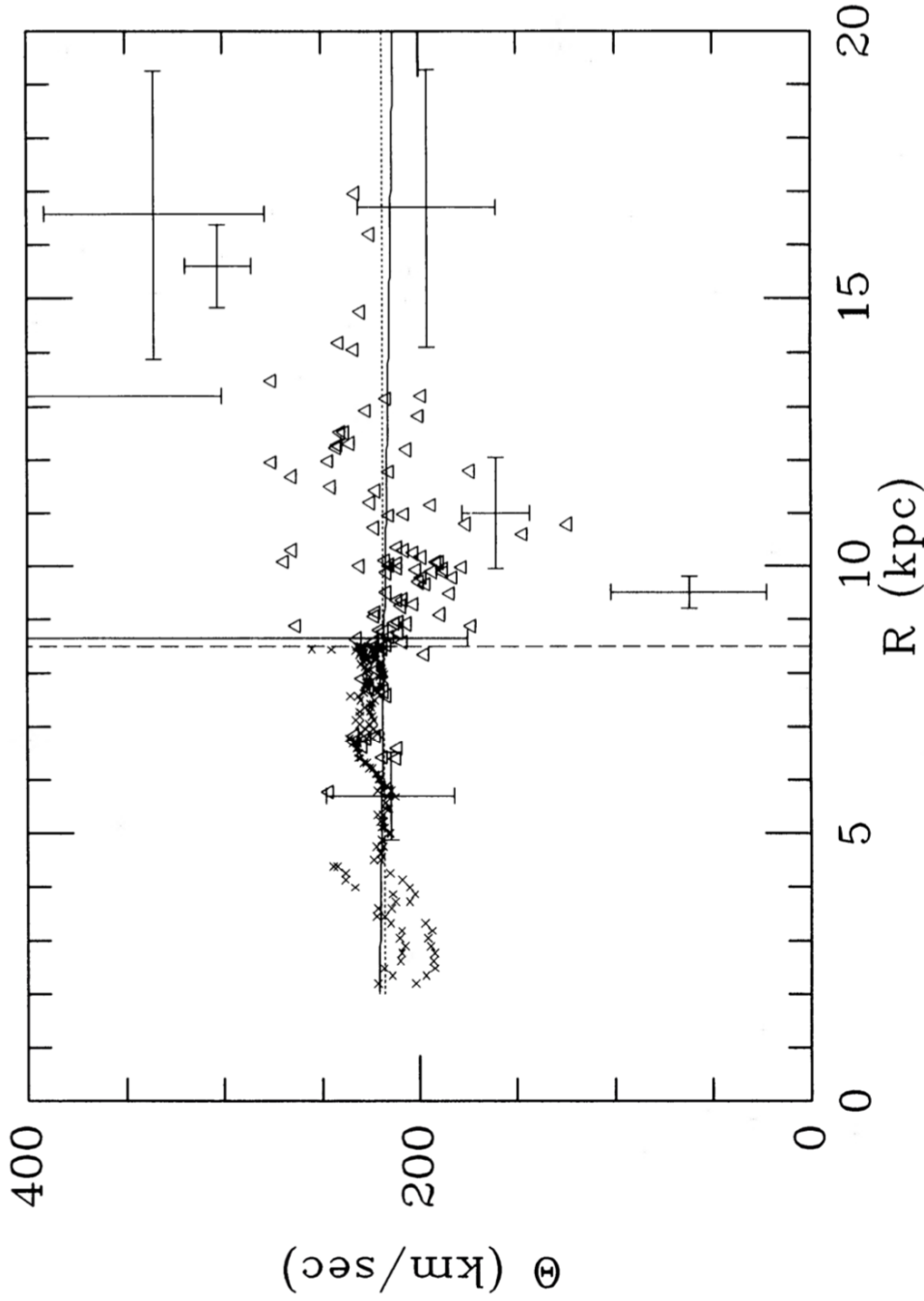


FIG. 2b

FIG. 2.—The data points used for the rotation curve determinations (crosses from H I regions, triangles from CO data). Error bars are shown for a few outlying H I regions. Error bars for H I regions near the center of the distribution and for the H I points are in general smaller than the symbols used to plot the positions. (a) ω vs. R plot. (b) Θ vs. R plot. We show error bars for a few of the most uncertain CO data points. The “best-fit” linear (dashed line) rotation curves for the IAU standard values of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s⁻¹ are shown.