Module 6: Rotation Curves and Dark Matter

Objectives/Key Points

0. Pre-Lesson: Generalize Motions Find Mass to refer to “enclosed” mass rather than central object mass.
1. Define rotation curve as a plot of rotation velocity versus distance from the center of rotation.
2. Identify and predict different types of rotation curves (solid-body, planet-like, etc.) distinguishing between linear velocity plots and angular velocity plots.
3. Apply knowledge of rotation curves to qualitatively explain the evidence for dark matter in galaxies, recognizing these as systems of stars and gas like our Milky Way.
4. Synthesize knowledge of rotation curves and Motions Find Mass equation to quantify amount of dark matter in a galaxy.

Enrichment: Discuss possible make up of dark matter, the history of its discovery, and why the amount of it is uncertain.

Unit Home

After Waves and Newton’s Laws.

Prerequisites

Teacher should have covered modules 1, 3, 4, and 5 or equivalent material on basic astronomical nomenclature and scientific notation, angular measurements and motion, the Motions Find Mass equation ($M=v^2R/G$), and Doppler Shifts.

Time: 60 min (+ 5-10 min enrichment discussion time)

Materials

1 – 2 meter sticks
worksheet with graphs (appended)
to prepare for the Enrichment discussion, the teacher may wish to review the material at
http://www.eclipse.net/~cmmiller/DM/

Sticking Points

1. This lesson relies on the assumption that when computing gravitational force, the enclosed mass within a given radius behaves like a point mass at the center. The teacher may wish to point out that while this is formally provable for a spherical mass distribution (beyond the scope of this lesson), it is just an approximation for non-spherical galaxies.

2. As in Module 4 (Motions Find Mass), students may slip into imprecise understanding of V, R, and M – the teacher should emphasize precision of language.

3. Having enough space for the demos may be tricky in some classrooms; if you rearrange the desks into a U-shape with an open space in the middle that can work well.

Pre-Lesson (Students follow along and fill in worksheet.)

0. Have students remember the Motions Find Mass equation and state what object (orbiting vs. orbited) the M, V, and R refer to. Now explain the fact that it doesn't matter for this law whether the mass is literally at the center, so long as it is roughly spherically symmetric – for example, the Space Station orbiting the Earth obeys the Motions Find Mass equation where the "central" mass is the entire enclosed mass of the Earth.

Main Lesson (Students follow along and fill in worksheet.)

1. Define rotation curve as a plot of rotation velocity versus distance from the center of rotation, using the familiar example of planets around the Sun shown on the worksheet. Remind students that the velocities of the planets must meet the condition that the centripetal force (mv^2/r) required for a *stable circular orbit* equals the gravitational force. Remind students that under this condition we derived the Motions Find Mass equation that will be used today.

2. Teacher will model solid body rotation with a meter stick (preferably two taped together to make it two meters long) held out horizontally and volunteer students holding on to the meter stick (at least three students). Teacher will begin to rotate to demonstrate that the student on the outside has to walk faster to keep up, but that the angular speed of all students along the stick is constant. Students graph the shape of the linear and angular rotation curves on their worksheet without numbers. Teacher will sketch correct answers on the blackboard (linear v graph is a rising straight line; angular velocity ω graph is a flat straight line).

3. Teacher will repeat demo for non-uniform rotation. The volunteer students and the teacher will lock arms in a line. With the teacher at the center of rotation, teacher will begin to rotate and students will try to keep up. The outer student will lag behind the others. Students graph these examples of non-uniform rotation and teacher will sketch the correct answers on the board (linear v graph is a rising but not straight line, becoming flatter with increasing radius as the velocity lags; angular velocity ω graph is falling, indicating the lag with increasing radius).

4. Students classify examples of rotation curves on the worksheet by choosing the appropriate rotation curve. *(Answers: C, A, B, D.)*

5. Teacher reminds students (using diagrams in worksheet) that galaxies are giant systems of stars and gas and illustrates how Doppler shifts can be used to obtain their rotation curves. To understand galaxy rotation curves, students must use the facts that (i) the gravity from the enclosed mass behaves like it is at the center (exactly true for a spherical mass distribution, approximately true for a galaxy) and (ii) the gravity from the mass outside a given radius cancels to give no net force (exactly true for a spherical mass distribution, approximately true for a galaxy). The proofs would be an appropriate enrichment for a calculus-based class, but this activity simply assumes these facts.

6. Teacher will guide student inquiry activity on the nature and existence of dark matter using worksheet.

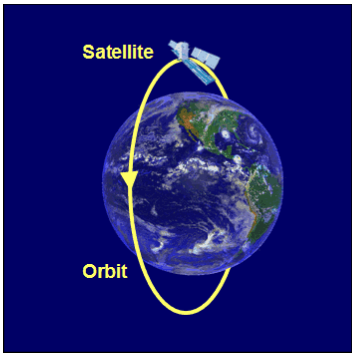
Enrichment Discussion

Discuss what dark matter could be made of: WIMPS (weakly interacting massive particles) which are tiny exotic particles postulated by particle physicists, MACHOS (massive compact halo objects) such as brown dwarfs or black holes, neutrinos. Another competing idea is that we do not have a correct theory of gravity. Proponents of this idea point to flat rotation curves as evidence that we need a new theory of gravity that would predict a 1/R dependence for gravitational forces at large distances.

Homework or In-Class Independent Practice

See end of worksheet.

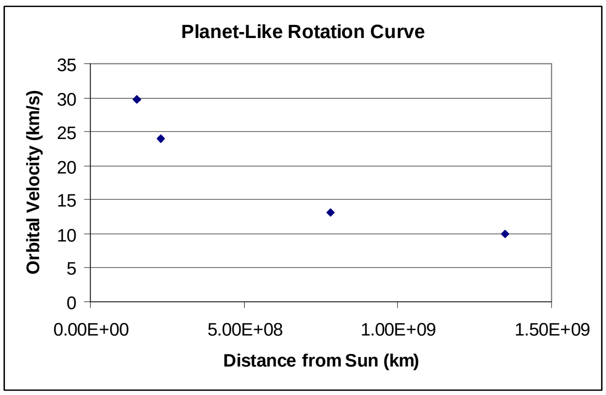
In-Class Worksheet for Rotation Curves and Dark Matter Class



Refresher: What is the Motions Find Mass equation?

What does each variable in the equation refer to in the picture?

Note that it is okay to treat any spherical enclosed mass distribution (like the Earth in this picture) as equal to a point mass at the center!!



I. Definition of a Rotation Curve -

____

____

____

____

____

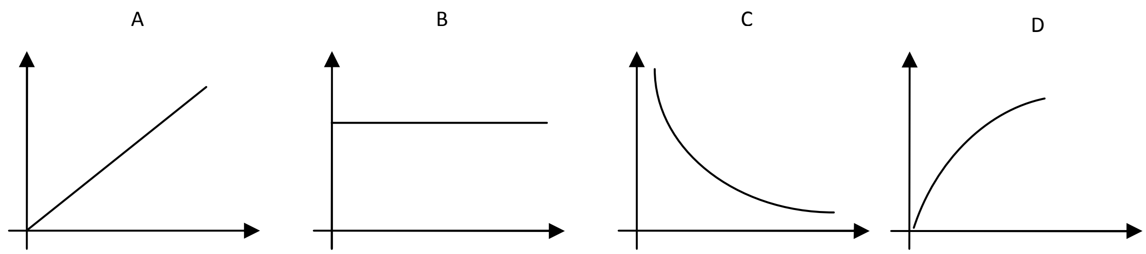
____

II. Plots for Demo: Correctly label the axes using the <u>top</u> two plots for linear motion rotation curves and the <u>bottom</u> two for angular motion rotation curves.

Rigid Solid-body Rotation

Non-rigid Fluid-like Rotation

III. Determine the appropriate rotation curve



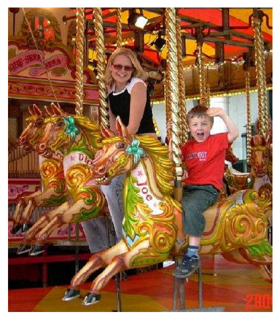
Which of the above sketches could represent each of the following? Assume “rotation curve” means linear velocity plot unless otherwise stated.

____ 1. four moons orbiting Jupiter

____ 2. points along the spokes of a bicycle wheel

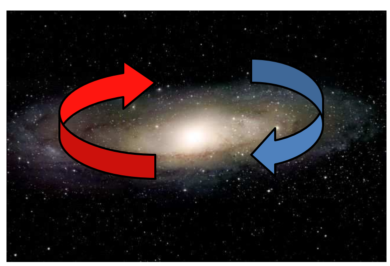
____ 3. merry-go-round (angular velocity)

____ 4. juice swirled around in a glass



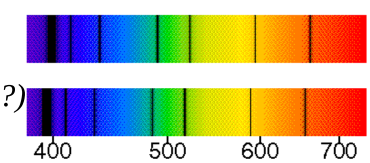
IV. Galaxy Rotation Curves

Recall that galaxies are giant systems of stars and gas. We can use Doppler shifts to measure their rotation curves.



lab spectrum

one side of galaxy *(which?)*

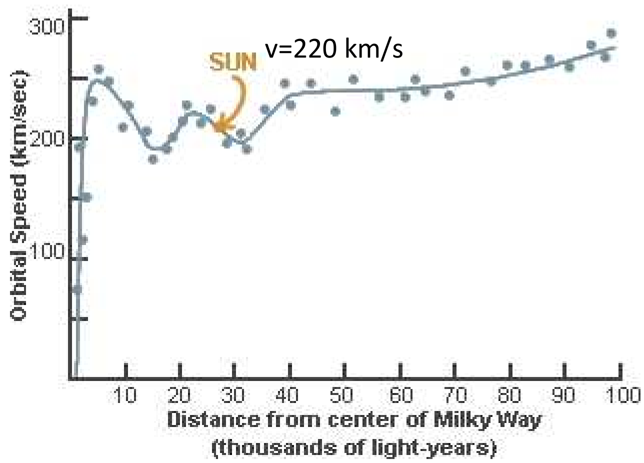


1. What would you guess a rotation curve for this galaxy would look like (linear units)? Useful Fact: if distributed spherically symmetrically, the mass *outside* a given radius has no net gravitational effect, because all forces cancel on average. This symmetry is not exactly but approximately true for a galaxy, so you may assume it.

2. From the picture we might infer that almost all of the mass is concentrated at the center. What would you predict the rotation curve to look like in this case?

Hint: Think about the solar system and rearrange the Motions Find Mass equation to find the planet rotation curve equation (v as a function of R). Your solution should look like the graph at the top of the worksheet.

3. The actual rotation curve for the Milky Way galaxy is shown below.



(a) The total observed mass within the orbital radius of the Sun is around 10^{10} solar masses. Using the Motions Find Mass equation and the value $G=1.4x10^{-5}$ kLY $(km/s)^2$ $/M_{sun}$, what would you predict for the orbital speed of the Sun? Plot that point on the graph above. What does the discrepancy imply about the amount of mass enclosed? Calculate the difference between the observed mass and the actual mass as determined from the rotation curve within the radius of the Sun.

The mass discrepancy you just found represents Dark Matter. The nature of dark matter is one of the key unsolved mysteries in astrophysics!

(b) Compared to the rotation curve you predicted in question 2, what does the shape of the actual Milky Way rotation curve tell you about how centrally concentrated the dark matter is compared to the visible mass?

(c) Strangely enough, the amount of excess mass as we go out in radius is always just enough to keep the velocity roughly constant in linear units. The fact that many rotation curves are flat like this represents another mystery astronomers do not understand. Note that this flat rotation curve is not the same as solid body rotation. Explain why not.

V. Independent Practice

1. Recently, astronomers made the news with a new measurement of the Sun’s orbital speed in the Milky Way galaxy of 250 km/s. What would this imply about the amount of dark matter? Answer quantitatively.

2. Browse the web to learn about Vera Rubin. Write one paragraph summarizing her role in history and how she knew she had discovered dark matter.

3. Suppose you find a galaxy with a solid-body rotation curve instead of a flat rotation curve. Would this galaxy have more or less dark matter in its inner parts? What about outer parts? Support your answer with a rotation curve sketch. You may assume that the visible matter is similar to other galaxies.