Chapter 23: The Milky Way Galaxy

A Spiral in Space

Outline

Summary

Over the course of the past 22 chapters, we have been increasing scale in both time and distance. We first worked within our own solar system and even then, the scale seemed large. Next we reached for the stars and watched the distance scales increase by several orders of magnitude. We continue in this chapter to expand the scale along with the imaginations of the students as we soon will venture into dimensions incomprehensible in comparison.

There is a tendency to dissect the Galaxy's structure and the processes at work within it. Try to avoid doing this; keep the "grand design" always present. It is a kiloparsec view, not an A.U. or parsec view. It is a view of galactic years (= 225 million years), billions of stars, spiral arms wrapping around the Galaxy tens of kiloparsecs in length, dark matter on the scale of the Galaxy's mass, and an uncertainty of the true enormity of the Galaxy overall. It is the beginning of a new cosmic perspective that will quickly lead to the universe itself.

Chapter 23 describes the major characteristics of our Galaxy as well as the techniques used to determine them. Cepheid variables and RR Lyrae stars are added as the next rung on the cosmic distance ladder. The formation of the Milky Way is discussed. Galactic rotation curves and their role in the discovery of dark matter are explained. The chapter ends with the Galactic center and the current theory that a massive black hole resides there.

Major Concepts

- Characteristics of the Milky Way
  - Size and shape
  - Numbers and types of stars
  - Bulge, disk, and halo
  - Orbital motion and differential rotation
  - Structure and spiral arms
- Distance determinations by variable stars
  - Cepheid variable and the period-luminosity relation
  - RR Lyrae stars
- Mass of the Milky Way
  - Rotation curves
  - Dark matter
- Stellar populations I and II

- The formation of the Milky Way
- The center of the Milky Way

Teaching Suggestions and Demonstrations

This point in the course provides another excellent excuse to take your students out for nighttime observing, or to suggest they go themselves. It does not require a telescope to be impressed by the sight of the Milky Way; in fact, a telescope makes the view less dramatic. Choose a dark area and make sure students' eyes are dark-adapted before you begin. Binoculars are nice to have; they will give students a sense of what it was like for Galileo when he first pointed his telescope to the Milky Way and found that it was composed of stars. Viewing the Milky Way is another good exercise in changing point of view.

For beginning astronomy students, connecting the band of light in the sky with a picture or diagram of a spiral galaxy is nontrivial. Ask students to imagine being embedded in a (diffuse) pancake. If they look up or down, away from the plane of the pancake, they are looking through a small thickness of material. But, if they look *along* the plane, they are looking through a great thickness of material. Of course, the "up" and "down" do not correspond to "up" and "down" with respect to standing on Earth. If you are outside with your students, sweep your arm along the Milky Way in the sky; this is the "plane of the pancake" view. Ask them to point to a direction perpendicular to the plane; this view is "out of the pancake." If you are not outside with your students at night, you can still use the pancake analogy and show images, such as Figures 23.1, 23.2 and 23.3. Figure 23.1b is a view of our galaxy from within our galaxy. Figures 23.2 and 23.3 are views of other galaxies (from outside) and not very different from what an extragalactic observer might see when looking at the Milky Way from the outside.

Section 23.1

To truly understand and appreciate the magnificence of the Milky Way, it must be viewed on a dark, clear, moonless night. In the northern hemisphere, summer is best, but the winter Milky Way, with the great constellation of Orion and its nebulae, is still very impressive. If a suitable observing location is not immediately available to you and your students, encourage them all to seek one out at a later time. The Milky Way and the night sky is part of their environment, their heritage, and they should not be denied it by lights, pollution, and man-made obstructions.

Once you have either held an observing session or shown images of the Milky Way, give some **basic data**, including size, shape, dimensions, and number of stars. Point out the **galactic disk**, the **galactic bulge**, and the **halo** in a diagram of our Galaxy as well as in photos of external galaxies. Studying external galaxies, such as those shown in Figure 23.2 and 23.3 can help us learn about our own. Just as we cannot study the whole evolution of a single star, we cannot view a single galaxy from many different vantage points. So, we study multiple stars to view the different stages of evolution and, in a similar manner, we study multiple galaxies to help construct our view of what a galaxy is really like. Figures 23.2 and 23.3 show three spiral galaxies, one face-on, one edge-on, and one tilted. Ask students what pieces of information come from each view, and then combine all the pieces into a coherent picture of a spiral galaxy.

As noted in the text, there is little doubt that the Milky Way has a halo and corona that contain substantial amounts of matter. The form the matter is in remains a question. However, the halo contains substantially more volume than the disk, so the matter filling it may be very sparsely distributed. For the disk with a radius of 15 kpc and an average thickness of 500 pc, the volume is 3.5×10^{11} pc^3; for the spherical halo of the same radius, the volume is 1.4×10^{13} pc^3 or 40 times the volume of the disk. For a corona with a radius of 50 kpc, the volume is 1500 times the volume of the disk! That is a very large volume in which matter might hide.

Many slides and diagrams of the Milky Way distort the actual dimension, often exaggerating the thickness of the disk and nuclear bulge. Show Figure 23.11, which is a COBE image of the Milky Way; it is an actual cross-sectional view of our Milky Way. You can construct a **model of the galaxy** to help students visualize its dimensions and the Sun's place within it. ➲ **DEMO** For a typical classroom, the following scale model works nicely: For a diameter of 30,000 pc, the scale will be 1 m = 2,000 pc. The center of the Milky Way will be in the center of the room; the nuclear bulge will be 2 m high, top to bottom, and 3 m in diameter, in the plane of the disk. The disk is only 15 cm thick at the location of the Sun, which is about halfway (4 m) out from the center, but thickens towards the center. On this scale, the solar system is so small (2×10^{-7} m or 0.2 microns) you would need a high-powered microscope just to see its diameter of about 100 A.U.! Note that standard models do a good job with sizes and/or distances, but do not give any impression at all of motions. Emphasize to students all the motions that Earth undergoes within your model. It rotates on its axis, revolves around the Sun, and follows the Sun on its orbit around the center of the galaxy.

Continue the discussion of your model. When you look up at the stars at night, the stars you see with your naked eye will extend away from the Sun about 25 cm on this scale. Vega, the bright summer star, is only 4 mm from the Sun. In winter, the great Orion nebula is 21 cm from the Sun and located in a direction about opposite the direction to the center of the Milky Way. One of the largest globular clusters, Omega Centauri, lies to the right of the center, 1 m above the disk, and 2.5 m distant. It's the size of a quarter (coin). Stand at the position of the Sun, in your model. With your arm extended in the plane of the disk, sweep your arm and hand around 360°. The section of the disk that you just swept contains about 4 billion stars, i.e., the observable stars available to all but the largest telescopes. Dust is so thick beyond this distance that you would have trouble seeing your fingers (assuming they were luminous like stars!). And yet, you have only swept a few percent of the total number of stars in the Milky Way.

Briefly discuss historical changes of the **view of our place in the universe**. The belief that Earth was the center of the universe prevailed until Copernicus moved it into orbit around the Sun. Then, bolstered by Hershel's star counts, people believed for many years that the solar system was the center of the Milky Way Galaxy. Discuss the observational evidence for these views and why observation can be misleading. In the case of the galaxy, astronomers were unaware of the effect of interstellar dust. To investigate the effect that interstellar dust has/had on observations you can ask students to imagine being in a large parking lot, say, at a mall. On a clear day, the view from your spot shows you cars in every direction, but, unless you are in the center, you will see more cars in some directions than in others and be able to determine where you are with respect to the center. If a dense fog rolls in, however, and you are neither at the center nor all the way at an edge, you will probably look around and see about the same number of cars in all directions, concluding, falsely, that you are indeed at the center.

Section 20.2

Harlow Shapley's "brilliant intellectual leap," as described in the text, was to connect the **globular cluster distribution** he observed to the actual extent of the galaxy. You can extend the parking lot analogy (though it is a bit of a stretch!) to illustrate. You need to imagine that the dense fog is a layer extending from the ground to just over your head and the tops of the cars. So, when you look up, you can see the lightposts extending up above the fog in all directions. If you are not at the center, more lightposts will be visible in some directions than in others. Shapley's interpretation is an excellent example of how "thinking outside the box" can result in tremendous advances in scientific understanding.

To determine the distances to the globular clusters, Shapley needed to use **RR Lyrae variable stars**, which, along with **Cepheid variables**, form the next rung on the distance ladder, as shown in Figure 23.8. As an activity, find data on Cepheid variables and have students plot their own period-luminosity graphs to discover the relationship. Then show a graph of another Cepheid's apparent brightness and have students determine its distance. This exercise will clarify the procedure for them.

Students often confuse variable stars with pulsars; the cause of the confusion is obvious. These stars are "radially pulsating" which means they are simply growing larger and smaller, larger and smaller, etc., with time. Use a balloon demonstration, but vary the size by only about 10%. The luminosity-radius-temperature relation, $L = R^2T^4$ (all in solar units), reminds us that it takes only a small change in the temperature to produce a large change in the luminosity. A typical Cepheid might change from 6000 K to 7500 K. This is sufficient to produce a one magnitude change in brightness (about 2.5 in luminosity).

In the magnitude nomenclature of Chapter 17, the absolute magnitude of a Cepheid is directly related to its period of pulsation. A 10-day period Cepheid would have an absolute magnitude of about -5. The period-luminosity relation has been determined by observing Cepheids in nearby clusters of stars whose distances have been determined using main sequence fitting. Knowing the distance to a Cepheid allows us to calculate its absolute magnitude. Once the relationship is established, it can be used in reverse, i.e., to determine the distance to the Cepheid from its period and apparent magnitude.

How far away can Cepheids be used for determining distances? For the above example of a Cepheid, and knowing that modern telescopes can observe down to at least magnitude 25, we can calculate the distance.

$25 - (-5) = 5 \text{ Log}(d) - 5$
$d = 10^7$ pc

Certainly 10 million parsecs is very far away and sufficient to determine distances to a number of the nearest galaxies. Cepheids are among the brightest stars to be seen in a galaxy, they change their brightness by a lot and so can be easily discovered, and they provide reliable distances. They provide one of the best methods for determining distances to nearby galaxies.
RR Lyrae variables have an absolute magnitude of about 0. They could be used out to about one million parsecs, a little farther than the Andromeda galaxy. However, they are most useful for determining distances to globular clusters in our own galaxy. It is the distribution of these clusters that helps determine the distance to the center of the galaxy.

One of the sources of debate concerning the location of galactic nebulae was the unimaginable sizes and distances involved. On a very clear, dark night you can see a fuzzy, elongated patch in the constellation of Andromeda. This is M31, the Andromeda Galaxy, the most distant object visible with the naked eye. How big is M31 and how distant? On photographs, its elliptical shape extends for 3°, which is 6 times the diameter of the Moon! Now 3° is 0.05 radians and the angle in radians times the distance equals the size of an object. Here is where the problem was. Assuming any distance, the corresponding size did not fit the possible objects. Here are some examples.

Distance	Size
10 pc	0.5 pc
100 pc	5 pc
1,000 pc	50 pc
10,000 pc	500 pc
100,000 pc	5,000 pc

At 10 pc its size was much too large to be a solar system or even one in formation. At 100 and 1,000 pc the size was about right for an emission nebula, but spectroscopy indicated a spectrum more like a star. At 10,000 pc it would be outside the Milky Way, larger than any known object, and comparable to a sizable portion of the (then known) Milky Way. At the (then) ridiculous distance of 100,000 pc it would be as large as the known size of the Milky Way, which was supposedly the entire universe. At any greater distance the size would grow unimaginably large and so no distance seemed right for this object. Worse yet, there were other examples of these spiral nebulae that appeared smaller but were equally inexplicable.

If astronomers in the early part of this century were told the correct answer, they simply would not have believed it; at its true distance of 700,000 pc, its size is 35,000 pc! Both the distance and the size would have been considered unacceptably large. This is a good example for the students because it is simple and illustrates how, when data does not fit anything in the status quo, the unimaginable just might be the solution. The gamma ray bursters are a good modern-day version of this same problem; theories range from them being very local objects to extremely extragalactic. At least we know the distance to the bursters *must* be in this range!

Sections 23.3 and 23.4

Before discussing information about the two **stellar populations** or the theory of the **formation of the Milky Way**, present observational comparisons of the disk, the halo, and the bulge. (See Table 23.1.) Then see if students can come up with possible explanations for the observed characteristics. Use Figure 23.10 to distinguish among the various areas. One very common misconception among students regards the relationship between the metallicities and the ages of stars. Students often assume that older stars will have more elements heavier than hydrogen and helium, because such stars are further along in their evolution. However, the opposite is true. Very old stars were formed at an earlier time in the universe when the interstellar matter was less enriched; therefore, their envelopes will be made primarily of hydrogen and helium. Younger stars were formed more recently, after earlier generations of stars spewed forth elements manufactured during their lifetimes. Consequently, their envelopes will show more evidence of heavier elements.

Also, be sure your students understand how the fact that the globular clusters are mostly reddish stars indicates that they are old. Refer back to the main-sequence turnoff points discussed earlier and to the relationship between lifetime and original main-sequence mass. Finally, show how the theory of the formation of the Milky Way Galaxy accounts for the observed differences in the disk and halo, from the compositions of stars to their orbits. You can mention conservation of angular momentum yet again; students should be quite comfortable with this concept by now!

Section 23.5

We see **spiral arms** in external galaxies, but how do we know that *our* Galaxy has them? Discuss the "tracers," including molecular clouds, young star associations, and 21-cm observations. The traffic jam explanation for the density wave theory explained in *Discovery 23-2* is excellent and will help students understand why the arms of galaxies are not wrapping up tighter and tighter.

Viewing other spiral galaxies from a distance, due to the dominance of the luminous blue stars, we see structure and color in the spiral arms. Are the stars that make up the disk that much different than the stars in the rest of the Galaxy? The primary difference is that star formation produces a few hot, bright main sequence stars. If such a star has an absolute magnitude of -5 and a typical star is a faint, low-mass main sequence star of absolute magnitude 10, then the bright star is one million times brighter than the typical faint star. It will actually take one million of those typical faint stars to equal the brightness of one bright main sequence star. The ratio of their numbers is not far from a million-to-one, but the combined light will still appear bluer than the disk stars without any bright main sequence stars present.

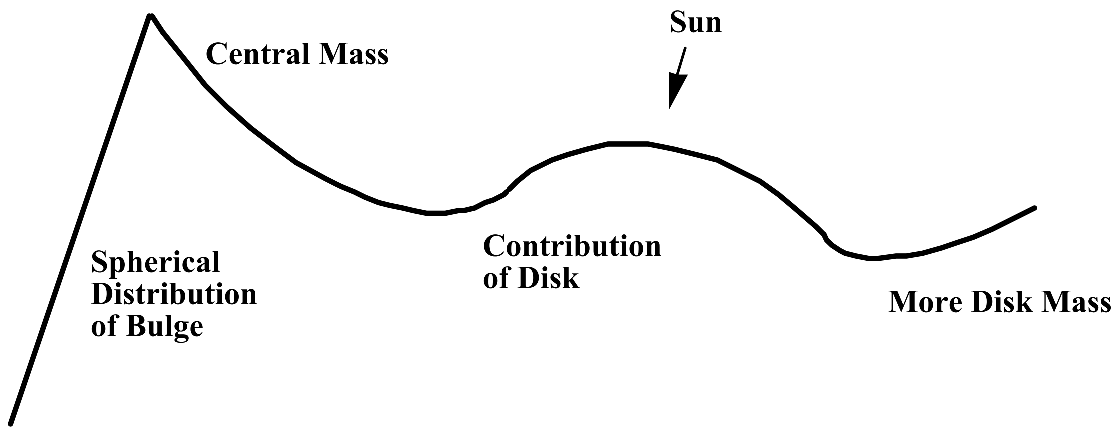
The point is, the disk stars are rather similar to the halo stars and the stars of the nuclear bulge, but a few bright main sequence stars changes the overall appearance. It should be noted, too, that the dust clouds in the disk preferentially reflect blue light. This can enhance the blueness of the disk.

Section 23.6

A quick review of Kepler's third law is warranted at the beginning of this section, because it is significant in the determination that much of our Galaxy must be made of **dark matter**. Students may have heard the term "missing mass" used in this context; the problem with this term is that the *mass* is not missing; we have too much mass and cannot account for it all. Also point out that "dark" does not mean just a lack of visible light. The galaxy has been probed in all wavelengths of the electromagnetic spectrum and still we cannot explain the rotation curve. Have students look up some information about Vera Rubin, an astronomer who was very influential in the initial study of galactic rotation curves and the determination of dark matter.

Refer to Figure 23.21 and the figure below. A typical **galactic rotation curve** (velocity versus distance) for a spiral galaxy or the Milky Way can be described as follows: From the center the velocity increases rapidly, starts to drop off slowly, then rises slowly or becomes constant. Some may show a final slow drop. Examine the reasons behind these shapes with students. Let us assume that the stars and gas clouds are all moving in circular orbits around the center of the galaxy. This is not a bad assumption. Then we already know that gravity from inside the orbit must balance the centripetal force: $GM/R^2 = v/R$. So the velocity simply equals $v = (GM/R)^{1/2}$. But the mass, M, increases with radius R unless there is negligible mass outside of R. Mass (M) can be thought of as varying three different ways with respect to R. For a spherical distribution of mass, $M \propto R^3$; for a disk, $M \propto R^2$; with little or no mass outside of R, M is a constant.

In these three cases, the velocity v will vary with R as either $\propto R$, $\propto R^{1/2}$, or $\propto R^{-1/2}$. Coming out from the center, the nuclear bulge is like a spherical distribution of mass, and so the velocity varies linearly with R. As R increases and the disk is entered into, the velocity varies as $R^{-1/2}$ because it "sees" the bulge as one large mass and does not yet see much mass in the disk. As more disk is encountered, the velocity varies as $R^{1/2}$ and therefore increases slowly with distance. Sooner or later, at some large value of R, the velocity should return to a $R^{-1/2}$ dependence and slowly drop off. This is not always seen, and often the velocity remains constant. This implies $M \propto R$, which is somewhere between a disk and a central distribution of mass, the additional mass coming presumably from the outer halo or corona. There is more mass there than meets the eye (or detector). Show Figure 23.21 and interpret the ups and downs of the curve using the previous explanations. Ask your students how they would interpret the relatively constant velocity at large distances.



Section 23.7

Finally, end the chapter with a "trip" to the **center of the galaxy** and a discussion of the Sgr A* source. Draw on knowledge students now have of black holes as you describe the observations and interpretations. Emphasize that this area of astronomy still has a lot of unanswered questions and exciting puzzles associated with it.

Student Writing Questions

1. It is not uncommon for science fiction stories to talk about "galactic empires." Considering the size of the Galaxy, number of stars, and motions within the Galaxy, discuss some of the difficulties in having an empire such as those suggested in these stories. Do you think it would be ultimately possible to have such an empire? What would be needed for such an empire to remain as a cohesive unit?

2. It takes the Sun about 225 million years to go once around the Galaxy. This means that the Sun and the solar system have gone over 20 times around the Galaxy. Look up information on the development of life on Earth, such as when it first existed, developed nucleated cells, multicellular life, etc. Give this history and when these events occurred, not in millions or billions of years, but in revolutions around the Galaxy, i.e., Galactic Years. For example, it took two Galactic Years before life arose on Earth.

3. Describe the Milky Way from the vantage point of a planet located around a star in the halo.

4. What will the conditions in the solar system be like when the Sun becomes a RR Lyrae star? What would it be like in the inner solar system? The outer solar system? What would the Sun look like?

5. We often think of the Earth as providing the conditions necessary for life. But are there places in the Galaxy that provide good or bad environments for life? Where in the Galaxy is it safest for life to exist on a planet? Where is it the least satisfactory? Evaluate the Galaxy with regard to the question of providing an environment supportive for life on a planet.

Answers to End of Chapter Exercises

Review and Discussion

1. A wide band of light completely surrounds us and is known as the Milky Way. Perpendicular to this band are relatively few stars. Our perspective is from within a large disk of stars.

2. Because we are inside the disk of the Galaxy, it is hard to determine what it looks like. Dust clouds obscure most features that are distant. In many directions, the disk looks pretty much the same.

3. Spiral nebulae were observed by astronomers of the last century as cloudy patches of light that had a spiral shape, in some cases. With the advent of photography, this description was only better defined but not understood. At one time early this century they were thought to be swirling regions of star formation. When finally resolved into stars, these nebulae were discovered to be galaxies like our own.

4. The globular clusters are found in the halo of the Galaxy. But because the clusters' motions take them close to the galactic center and then back out into the halo, many clusters are found within the galactic bulge.

5. Cepheids have the unique property of a relationship between their period of pulsation and their luminosity. By observing the Cepheid and determining its period of variation, its true luminosity is known. Comparing the true luminosity with the apparent luminosity allows the distance to be determined.

6. Because of their intrinsically high luminosity, Cepheids can be seen, and therefore used, out to a few million parsecs. They are used to determine distances to the nearest galaxies.

7. RR Lyrae variables are very useful for determining distances to globular clusters. By knowing how the globular clusters are distributed in the Galaxy, the halo is mapped out. But most importantly, the distribution of globular clusters gives the distance to the center of the Galaxy from the Sun. This also helped tell astronomers how large the Milky Way actually is.

8. In the radio part of the spectrum, atomic hydrogen gas emits 21-cm radiation. Because its long wavelength allows it to travel throughout the Galaxy, astronomers can use it to map the structure of gas clouds in the Galaxy. Molecular hydrogen is very difficult to observe, but other molecules, such as carbon monoxide, are used to map molecular clouds.

9. The stars in the Galactic disk move in roughly circular orbits around the center of the Galaxy. The orbits all lie in the plane of the disk. The halo stars have approximately the same velocities as the disk stars but are moving in various directions, relative to the disk, forming a spherical halo around the Galaxy. These stars pass in and out of the disk, towards the center of the Galaxy and back out again into the halo. When seen locally, they appear to have high velocities relative to the Sun and other disk stars and the direction of their motion is at an angle to the plane of the disk.

10. Radio observations of objects in the Galaxy reveal its spiral shape. Radio waves travel unhindered through dust clouds and so the entire Galaxy can be mapped.

11. The spiral arms of a galaxy are bright and contain very luminous stars, open star clusters, and emission nebulae. All of these objects are found in star formation regions and are all considered young objects.

12. The gas and dust enter the spiral arm from behind and become compressed as they encounter the density wave. Star formation starts from the compressed gas and dust. The stars and unused gas and dust move on through the spiral arm and continue with their normal orbital motion around the Galaxy.

13. Imagine a group of newly formed massive stars somewhere in the galactic disk. When these stars form, the H II regions, or emission nebulae, that appear around them send shock waves through the surrounding gas. These waves can trigger new star formation. Similarly, when the stars explode in supernovae, more shock waves are formed. The formation of one group of stars provides the mechanism for the formation of more stars.

14. The stars in the halo have orbits that form a spherical halo around the Galaxy. This tells us the original shape of the cloud of gas that was the galaxy before stars formed. The entire halo appears to rotate, which further tells us that this cloud was rotating. The formation of a disk is the result of the cloud having some initial rotation.

15. Different parts of the Galaxy rotate at different rates. The rotation is actually the motions of the stars and gas around the Galaxy. Because the Galaxy is not a solid body, like the Earth, different parts of it move at different rates. The orbital motions are determined strictly by the amount of mass interior to the orbit. The velocity of the orbits at differing distances gives us the rotation curve of the Galaxy. By looking at the outermost orbits, the total mass of the Galaxy can be determined.

16. The rotation curve for the Galaxy provides strong evidence for dark matter. By studying the motion of stars around the Galaxy, the mass interior to their orbits can be determined. However, more mass is found, by about a factor of 2, than can be accounted for by ordinary matter. Furthermore, the Galaxy seems to be larger than previously known. The rotation curve of the outer part of the Galaxy continues to show greater and greater amounts of matter, extending out to what is know as the galactic corona.

17. Possible explanations for dark matter makes for a long list. Some are: brown dwarfs, black dwarfs, black holes, WIMPS, MACHOS, ...

18. Gravitational lensing is the bending of light by a gravitational field. If one star passes directly in front of another, the light of the more distant star may be bent in such a way that it appears to brighten. Dark matter is searched for by looking for lensing of background stars by foreground objects that may be too dark for detection.

19. The central regions of the Galaxy are obscured by thick clouds of interstellar dust. Visible light cannot penetrate these clouds. However, infrared and especially radio waves can easily penetrate these clouds and so we can see the center of the Galaxy at these wavelengths.

20. From a disk of hot gas spanning 10 pc across the center of the Galaxy, infrared spectral lines are broadened, indicating the motion of the gas. For this motion to be possible, there must be a massive central mass. Radio observations also aid in examining the Galactic center, particularly the clouds of gas that are moving around the center.

Conceptual Self-Test

1. T
2. F
3. F
4. T
5. T
6. F
7. F
8. F
9. F
10. T
11. D
12. D
13. D
14. B
15. B
16. C
17. A
18. B
19. D
20. C

Problems

1. 1 A.U. at 1 pc subtends an angle of 1" (by definition of the parsec). 200 A.U. at 100 pc will subtend the same angle, 2". This is 10,800 times smaller than the angular size of the Andromeda galaxy.

2. This would simply be a distance 10,800 times closer than the 100 pc in the previous question, or 0.0092 pc or 1900 A.U.

   A star with a luminosity 10 times that of the Sun will have an absolute magnitude $2.512^{\Delta M} = 10$, $\Delta M = 2.5$ greater than the Sun or about $M = 2.5$. Its apparent magnitude will be $m - 2.5 = 5\text{Log}(0.0092) - 5$, $m = -12.7$ which is the brightness of the full Moon.

3. $20 - 0 = 5\text{Log}(d) - 5$, $d = 100{,}000$ pc = 100 kpc.

4. Using the inverse square law, if a Cepheid is 100 times brighter than an RR Lyrae variable, it should be visible at 10 times the distance. In other words, placing the Cepheid 10 times farther away will make it 10^2 times fainter, or 100 times fainter. Therefore it would equal the RR Lyrae star's brightness.

5. Use the same approach as in Problem 2 for determining the absolute magnitude. $2.512^{\Delta M} = 30{,}000$, $\Delta M = 11.2$ greater than the Sun or about $M = 5 - 11.2 = -6.2$. It is being assumed that the *Hubble* can see down to apparent magnitude $m - 5 = 5\text{Log}100{,}000 - 5$, $m = 25$. Therefore, $25 - (-6.2) = 5\text{Log}(d) - 5$, $d = 1.7\times10^7$ pc = 17 Mpc.

6. $25 - (-6.2) = 5\text{Log}(d) - 5 + 2.5d/1000$, $7.24 = \text{Log}(d) + d/2000$ Start an iterative solution with $d = 10^4$, $7.24 = 9$, then $d = 5{,}000$ gives $7.24 = 6.2$. Keep estimating and closing in on the solution until you reach $d = 6800$ pc.

7. From Chapter 17 of this manual use the formula for the tangential velocity, $V_t = 4.7\mu d$. Using the values given, $200 = 4.7\mu \times 3{,}000$, $\mu = 0.014''/\text{yr}$

   Yes, this is measurable, but only after 5 - 10 years. By then the angle will be large enough to observe and measure.

8. At 20 kpc, the circumference of the orbit is $2\pi \times 20{,}000$ pc = 126,000 pc. A parsec = 3.1×10^{13} km, so the circumference is 3.9×10^{18} km. At a rate of 240 km/s it will take 1.6×10^{16} s to orbit once. A year has 3.2×10^{7} s in it, so the period of the orbit is 509 million years.

   Using Kepler's third law, we have the period in years but we need the size of the orbit in A.U. There are 206,000 A.U. in 1 pc, so 20 kpc = 4.12×10^{9} A.U. Finally, we can apply Kepler's third law; the result will be in solar masses. $(5.09\times10^{8})^2 = (4.12\times10^{9})^3 / M$, M = 270 billion solar masses.

9. This question is difficult to answer accurately because the graph cannot be read accurately. It also takes a trial and error approach because the velocity is a complex function of the distance and the period is a function of both the velocity and the distance. Here's one approach that works only approximately. Assume a constant velocity for most of the rotation curve of 240 km/s. Then the first part of answer 8 becomes $P = 25400R$.

   (a) For $P = 10^8$, $R = 3900$ pc.

   (b) For $P = 5\times10^8$, $R = 19{,}700$ pc.

10. The results of this calculation will depend strongly on the assumptions made. Here is one possible solution. For the Sun's velocity around the Galaxy, the relationship derived in the previous question becomes $P = 27700R$. Using the often quoted period of 225 million years gives $R = 8100$ pc. The other star will be assumed to be at $R = 8200$ pc and with a period of 227 million years. Assuming this star is moving at the same speed as the Sun, it is 2 million years from getting back to where it and the Sun were separated by only 100 pc. This distance is 220 km/s $\times\ 2\times10^{6}$ yr $\times\ 3.2\times10^{7}$ s/yr $= 1.4\times10^{16}$ km = 450 pc. This is the distance it must travel to get back to its original position. This forms a triangle with the Sun, whose distance is $d^2 = 100^2 + 450^2$, $d = 460$ pc.

11. The time to "lap" is the same as the synodic period. At 15 kpc, stars appear to be moving at 240 km/s. $v = 2\pi r / P$, i.e., $P \propto r/v$. Since the Sun is at 8 kpc and moves at 220 km/s,

$$P = 225 \text{ million years} \times \frac{15}{8} \times \frac{220}{240} = 390 \text{ million years}$$

   Calculating the synodic period gives:

$$\frac{1}{S} = \frac{1}{390} - \frac{1}{225}$$

$$S = 530 \text{ million yrs.}$$

   At 5 kpc the velocity is about 200 km/s, so $P = 155$ million years. $S = 500$ million years.

12. Let's try an easy approach to this question. The Sun is moving at 220 km/s around the Galaxy but is approaching spiral arms at a speed of 220 - 120 = 100 km/s. This is about half its speed. We also know from the text that it takes the Sun 225 million years to go around the Galaxy once. Think about the Sun moving half as slow now. But the distance to be covered between spiral arms is also half its normal orbit because there are two spiral arms. So the Sun must cover half the distance with half the speed; it will take about as long as a normal orbit does, 225 million years. In 4.6 billion years the Sun has gone around 20.4 times, so it should have passed through a spiral arm about twenty times.

    If you want a more precise measure of this, just realize the previous calculation is correct for a speed of 110 km/s, not 100 km/s. The Sun is really moving 100/110 = 0.91 times *slower* than what we had assumed, meaning it will take *longer* to move between spiral arms and complete 0.91 *fewer* passes than we had calculated. This gives $0.91 \times 20.4 = 18.6$ passes instead of 20.

13. The difference in the speed of the star and the speed of the density wave is 100 km/s. In 10 million years this will amount to $100 \text{ km/s} \times 10\times10^6 \text{ yrs} \times 3.2\times10^7 \text{ s/yr} = 3.2\times10^{16}$ km. This is equivalent to 1,000 pc.

14. An angle of 0.2" will subtend 0.2 A.U. at 1 pc. At 8,000 pc this distance will be 1600 A.U., which is the radius of the circular orbit. The period of the orbit is $P = 2\pi r / v$. $P = 2\pi \times$ 1600 $1.5\times10^8 / 1200$, $P = 1.26\times10^9$ s = 39 yrs. Use Kepler's third law to calculate the mass. $M = 1600^3 / 39^2$ $M = 2.7\times10^6$ solar masses.

15. The eccentricity of the orbit is 0.87 and the semi-major axis is 950 AU. Therefore, the closest approach will be $a(1-e) = (950 \text{ A.U.})(1-0.87) = 124 \text{ A.U.}$.

Resource Information

Student CD Media

Movies/Animations
Cepheid Star in Distant Galaxy

Interactive Student Tutorials
Gravitational Lensing

Physlet Illustrations
Mass of Galaxy – Kepler's 3rd Law

Transparencies

T-215	Figure 23.1	Galactic Plane	p. 604
T-216	Figure 23.5/7	Variable Stars and Period-Luminosity Plot	p. 608/609
T-217	Figure 23.8	Variable Stars on Distance Ladder	p. 609
T-218	Figure 23.10	Stellar Populations in Our Galaxy	p. 611
T-219	Table 23.1	Overall Properties of the Galactic Disk, Halo and Bulge	p. 615
T-220	Figure 23.14	Milky Way Formation	p. 616
T-221	Figure 23.15/16	Gas in the Galactic Disk and the Milky Way Spiral Structure	p. 617/618
T-222	Figure 23.17	Differential Galaxy Rotation	p. 619
T-223	Figure 23.21	Galaxy Rotation Curve	p. 623

T-224 Figure 23.23 Gravitational Lensing p. 624

Materials

A four-foot long panorama poster of the Milky Way is available from the Astronomical Society of the Pacific.

Suggested Readings

Adams, Amy. "The triumph of Hipparcos." *Astronomy* (Dec 1997). p. 60. Describes Hipparcos's observations of Cepheid variable stars.

Bartusiak, Marcia. "Gravity's rainbow." *Astronomy* (Aug 1997). p. 44. Describes gravitational lenses, and how this effect is used to map dark matter.

Binney, James. "The evolution of our galaxy." *Sky & Telescope* (Mar 1995). p. 20. Describes the formation and evolution of the Milky Way.

Di Cicco, Dennis. "There's no place like home: panorama of the Milky Way." *Sky & Telescope* (Nov 1999). p. 137. Describes features seen in a stunning panorama of the Milky Way.

Eicher, David J. "Meet the Milky Way." *Astronomy* (May 1996). p. 72. A guide to observing the Milky Way with the naked eye, binoculars, and small telescope.

Mateo, Mario. "Bonuses of the microlensing business." *Sky & Telescope* (Sept 1997). p. 38. Describes gravitational microlensing and the search for dark matter.

Russell, David. "Island universes: from Wright to Hubble." *Sky & Telescope* (Jan 1999). p. 56. Traces the history of the concept of galaxies.

Schulkin, Bonnie. "Does a monster lurk close by? Massive black hole at galactic center." *Astronomy* (Sept 1997). p. 42. Discusses the evidence that the center of our galaxy contains a massive black hole.

Szpir, Michael. "Passing the bar: the Milky Way Galaxy is a barred spiral." *Astronomy* (Mar 1999). p. 46. Describes the evidence that the Milky Way is a barred spiral galaxy.

Tyson, Neil De Grasse. "The Shapley–Curtis debate." *Natural History* (May 1995). p. 66. Summarizes the key points in the historic Shapley–Curtis debate on the nature of the Milky Way.

Notes and Ideas

*Class time spent on material: Estimated:*______ *Actual:*_____________

Demonstration and activity materials:

Notes for next time: