# Chapter 25: Galaxies and Dark Matter

*The Large-Scale Structure of the Cosmos*

## Outline



## Summary

In our discussion of stars, we first introduced our own star, the Sun, and then examined the different types of stars, how they are classified and how they evolve. Our discussion of galaxies, as you may have already noticed, is taking the same path. We introduced our own particular galaxy, the Milky Way, and then overviewed the different types of galaxies as well as the "Tuning Fork" classification scheme. This chapter brings together many of the concepts discussed in Chapters 23 and 24 and begins to explore theories of galactic formation and evolution. It introduces dark matter, which plays an important role in the evolution of galaxies. We learn that the varied types of galaxies can be thought of, possibly, as the results of commonly occurring galactic interactions.

Galactic engines, supermassive black holes, are further investigated in this chapter and then we begin to move on to the ultimate scale of the Universe by discussing large scale features within the visible universe thus preparing us for the following two chapters on cosmology.

## Major Concepts

- Matter in galaxies
  - Rotation curves
  - Dark matter
  - Determining masses
  - Halos
  - Intracluster gas
- Galaxy Collisions
- Galaxy formation and evolution
- Galactic Nuclei
- Large-scale structure
  - Redshift surveys
  - Voids and filaments
  - The Great Wall
  - Quasar absorption lines
  - Gravitational lensing

# Teaching Suggestions and Demonstrations

## Section 25.1

By now, students should be able to make a pretty good guess regarding some of the methods of determination of **galaxy masses**. Using rotation curves (see Figure 25.1) and applying Kepler's third law to binary galaxies are two of the familiar methods that students will come up with. Discuss analysis of motions of galaxies within clusters as well. As with the measurement of mass of the Milky Way, there is a large discrepancy between what we see and how much mass these dynamical measurements tell us there should be. This unseen matter is called **dark matter** and represents more than 90% of the mass in the known universe. It is almost as if the further out we look, the less we see!

## Section 25.2

Start this section out by mentioning that our galaxy is currently experiencing close interaction with two other galaxies, the Sagittarius Dwarf galaxy and the Canis Major dwarf. Also, we are currently on a collision course with our largest neighbor M31, the Andromeda galaxy.

As mentioned in the text, when galaxies collide, their stars "slide past one another" because stars are very small compared to the distances between them. ➲ **DEMO** For scale, use two softballs, holding one in each hand. Tell the students that the distance between galaxies is relatively small compared to their size. Two softballs held a less than meter or so apart will serve as an adequate demonstration of the relative proximity of neighboring galaxies. If the softballs were stars, however, then they would have to be separated by kilometers.

It is helpful to point out that velocities between galaxies are typically a few hundred km/s (possibly higher inside of galaxy clusters). Large galaxies around the Milky Way are separated by roughly 1 Mpc. At a velocity of 500 km/s, a distance of 1 Mpc will be traveled in 2 billion years. Although this is a long time, it is much shorter than the age of the universe. Galaxies, which are separated by 1 Mpc or less, will likely have encountered other galaxies rather often over the past 15 billion years. (Note: there are many smaller galaxies at much closer distances than 1 Mpc. Collisions and encounters with these may occur very frequently.)

## Sections 25.3 and 25.4

Figure 25.19 shows a possible **evolutionary sequence for galaxies**. Emphasize to students that the details are yet far from certain in this active and exciting area of astronomy. Also point out the difference between galaxy evolution as described, which hinges on chance encounters, mergers, and collisions, and stellar evolution, which relies on the intrinsic properties of the stars. Remind students again of the typical sizes of galaxies compared to the distances between them to justify the assumption that galaxy interactions, mergers, and collisions are not uncommon events.

The roles of quasars and active galaxies in the sequence is consistent with our observations as we look out in space and back in time. Compare Figure 25.14, a computer simulation in which spiral arms are formed, with the photo of the Whirlpool galaxy, Figure 24.2b. Also show Figures 25.15 and 25.17 while discussing the results of galaxy mergers where the central black holes are, themselves, merging or have merged to form **supermassive black holes**.

### Section 25.5

We have now reached examination of the **large-scale structure** of the universe. Try to find several slices of the **redshift survey** to give your students a better feel for the voids, filaments, and bubble-like patterns. Some 3-D pictures that can be rotated on a computer screen are available (an internet search, keyword "redshift survey" will provide many sites where these can be downloaded). Remind students of the scale; it is truly remarkable that we can make such plots!

## Student Writing Questions

1. You live in a spiral galaxy much like the Milky Way and, being an observant student of astronomy, you know that the huge nearby galaxy you see in your night sky will soon collide with your galaxy. Describe what it will be like to be in a galaxy as such a collision takes place. What will you see occurring? How long will it all take? What will be the fate of your star and planetary system? You may need to extend your lifetime a bit in order to witness the entire event. You can choose the type of galaxy that collides with you and whether there is a direct collision or a near-miss. Both types produce interesting effects.

2. How "necessary" is dark matter to understanding various problems in astronomy? Is it something that has definitely been discovered or is it a panacea for a number of possibly related problems?

3. Describe what the night sky might look like for you if you lived on a planet orbiting a star very near the core of our galaxy. Describe what the evening sky might look like if you orbited a star that is part of one of the "streams" of halo stars.

4. Describe what the universe must have been like during the age of quasars. If you were a life form back then, what kind of universe was it? What did it look like and how was it different from today's universe? Would life even have been possible back then?

## Answers to End of Chapter Exercises

### Review and Discussion

1. The mass of a galaxy can be determined in several different ways. The rotation curve is the most accurate method. By measuring the velocity of rotation, Kepler's third law can be applied to calculate the mass. If the galaxy is part of a binary galaxy system, Kepler's third law can be applied again, but now to the orbit of the galaxies around each other. There are some uncertainties in this method and it is best applied to a large number of binaries in order for a statistical result to be obtained.

2. The motion of galaxies within a cluster must be balanced by the total gravitational field produced by all the mass in the cluster. When traditional methods are applied to determining the total mass of the galaxies in a cluster, it always results in total masses that are 10 to 100 times too little compared to the mass necessary to hold the cluster together. But because the cluster is a cluster, it must be held together by its own gravity. The question arises: where is the extra mass?

3. The clouds of gas that went into early galaxy formation were small to begin with. Most galaxies formed as a result of collisions and mergers among many smaller galaxies. Distant galaxies are seen when they are still young and not fully formed.

   These young galaxies appear bluer than nearby galaxies because of the large number of bright, young stars in them. These stars are very hot and bluish in color. Large numbers of stars form when galaxies collide; a process that is common among young galaxies.

4. Galaxies are actually seen being tidally distorted by another nearby galaxy. In other cases, we see the aftermath of such a collision or near-miss. Direct collisions result in starburst galaxies, where clouds of interstellar matter have collided and quickly formed many new stars. The velocity of motion of galaxies and their relative nearness to each other also strongly suggests that collisions must occur.

5. It now appears that large galaxies grow through repeated mergers or collisions with smaller galaxies. This process is not at all like star formation but in many ways is more similar to planetary formation. We do not know how this process affects the type of galaxy that results. Certainly this process continues today; interacting galaxies are relatively common.

6. The merger of a large spiral with another galaxy can strip the disk away and form an elliptical galaxy. Most of the gas is quickly processed into stars. Supernovae blow away the remaining gas.

7. Collisions between galaxies can be partly evolutionary. The large central galaxies found in clusters certainly share an evolutionary history; they have cannibalized many smaller galaxies in their cluster. But collisions and close encounters are random processes, each case being a little or a lot different from the next. The result is that each galaxy may have, to some degree, a uniqueness to it—a structure unlike any other—that disallows any discussion of evolution. The evolution of a one-solar-mass star will be just like any other star of the same mass and composition; this cannot be said for any Sb, E3, or any other type of galaxy.

8. The tidal streams in the halo, as discussed in Chapter 23, are believed to be remnant occupants of galaxies that have collided with our own Milky Way. They are maintaining the orbits of their original host galaxy.

9. Starburst galaxies are observed to have undergone huge amounts of recent star formation. They are likely the result of recent mergers, collisions, or tidal interactions between galaxies.

10. A head-tail radio galaxy is formed by a galaxy moving through the intergalactic gas of the cluster of which it is a part. In doing so, the gas forming the lobes is being pushed by the intergalactic gas and a tail is formed as the galaxy continues to move.

11. In addition to the very large quantities of energy emitted from a very small region in the nucleus of a galaxy, the very rapid motions of gas around that nucleus have been measured. The results give masses that are often in the billions of solar masses. The only object that massive and that small is a supermassive black hole.

12. Although the lifetime of quasars is unknown, we know it can neither be very short nor very long. If quasars existed for just a few years, we probably would not see any. Records indicate quasars on old photographs dating back many decades. If quasars last billions of years then there are two problems. First, where would they get all the mass to feed their energy needs? Some quasars are using between 10 and 100 solar masses a year. Over 10 billion years would require between $10^{11}$ and $10^{12}$ solar masses; in other words, the mass of

entire large galaxy. Second, if quasars lasted this long, we should see many more of them near to us, which we do not. It is reasonable to expect that quasars lasted just a few tens of millions of years; it is consistent with the numbers and distances of quasars.

13. The rate at which a supermassive black hole must consume matter suggests that if quasars were not short-lived, they would consume the entire mass of the galaxy. In addition, counts of quasars at various distances strongly suggest the quasar process turns on suddenly when the universe was young but does not continue for a long time; the process dies out as the universe ages.

14. The massive black hole used up most of the available matter in the central portion of the galaxy. With less material entering it, the energy source surrounding the black hole dies down.

15. Normal galaxies are generally thought to be the results of mergers of active galaxies, each of which must have contained a black hole at their center. Merging galaxies result in the black holes of each falling together, merging in their own right, to form larger, supermassive black holes. These, in fact, are being detected at the centers of normal galaxies like NGC 4258

16. Redshift surveys are exercises in mapping the large scale structure of the Universe. The redshifts of galaxies are measured and used, in the context of the Hubble Law standard candle, to determine the distances to galaxies within chosen data wedges or slices of the sky. The direction and distance for each galaxy is plotted in the appropriate position along any given survey slice. The overall distribution in a volume of space can then be mapped simply by combining the survey slices volumetrically.

17. Voids are large, roughly spherical regions that do not contain any galaxies.

18. Two discoveries led astronomers to the "soap bubble" distribution of galaxies. First, voids were discovered. Second, galaxies seemed to group in sheets of galaxies, as if they were the surface of giant bubbles.

19. Clouds of gas between quasars and us will produce absorption lines in the spectrum of the quasar. These can be distinguished from the quasar absorption lines (if any exist) by their different redshifts, corresponding to their respective distances. The quasar can also be gravitationally lensed by a galaxy or cluster of galaxies lying between it and us. Study of the lensing pattern can provide information regarding the mass and mass distribution of the galaxy or cluster.

20. On the now relatively small scale of individual galaxies, we use rotation curves combined with Kepler's laws to deduce the presence of dark matter. On larger scales, we can deduce the presence of unseen mass by examining the orbital properties of binary galaxies and galaxy clusters. Also, by observing such things as head-tail radio galaxies and the shapes of their "swept-back" lobes, we can deduce that the galaxies must be moving through clouds of dark matter which are providing a sort of "drag" effect.

## Conceptual Self-Test

1. T
2. F
3. F
4. T
5. F

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

## Problems

1. Distance divided by velocity gives time. Convert 800 kpc to kilometers. Also convert final answer in seconds to years.

$$800{,}000 \text{ pc} \times 3.1\times10^{13} \text{ km/pc} = 2.5\times10^{19} \text{ km.}$$

$$2.5\times10^{19} \text{ km} / 120 \text{ km/s} = 2.1\times10^{17} \text{ s.}$$

$$2.1\times10^{17} \text{ s} / 3.2\times10^{7} \text{ s/yr} = 6.6 \text{ billion years.}$$

(The Sun will likely have evolved to a red giant by this time!)

2. Assume a velocity of 350 km/s at 20 kpc. Another way of looking at the velocity equation from *More Precisely 2–3* is $v = 30$ km/s$\sqrt{M/R}$ where $M$ and $R$ are in solar units and A.U. respectively. $350 = 30\sqrt{M/}$ (20,000pc × 206,000 A.U./pc), $M = 5.6\times10^{11}$ solar masses.

3. The rotational speed is 350 km/s but towards or away from us. Using the Doppler formula $\Delta\lambda = \lambda\frac{v}{c}$, $\Delta\lambda = 0.76$ nm. But the line broadening will be twice this because of the motion towards and away; $\Delta\lambda = 1.53$ nm.

4. Convert 500 kpc to A.U. as follows: 500 kpc × 1,000 pc/kpc × 206,000 A.U./pc = $1.03\times10^{11}$ A.U. Set up Kepler's third law as usual.

$$\left(3\times10^{10}\right)^2 = \frac{\left(1.03\times10^{11}\right)^3}{M}$$

$$M = 1.2\times10^{12} \text{ solar masses}$$

5. The circumference of the orbit is $2\pi \times 2$ Mpc = $1.3\times10^7$ pc. Convert this distance to kilometers, divide this distance by speed, and convert the time into years to get the period.

$$1.3\times10^{7} \text{ pc} \times 3.1\times10^{13} \text{ km/pc} = 3.9\times10^{20} \text{ km}$$

$$3.9\times10^{20} \text{ km} / 750 \text{ km/s} = 5.2\times10^{17} \text{ s}$$

$5.2 \times 10^{17}$ s / $3.2 \times 10^{7}$ s/yr = 16 billion years

Using Kepler's third law and converting the 2 Mpc to A.U. gives $M = (206{,}000 \times 2\times10^{6})^{3} / (1.6\times10^{10})^{2}$, $M = 2.7\times10^{14}$ solar masses. At best it is an approximation. The orbit is likely not circular. The 2 Mpc distance depends on the Hubble constant.

6. Use the relationship derived for Problem 2, $v = 30$ km/s$\sqrt{M/R} = 30\sqrt{10^{15}} / (3{,}000{,}000 \times 206{,}000) = 1200$ km/s. From *More Precisely 8–1*, average molecular speed = $0.157\sqrt{T/M_{molecular}}$. Setting this equal to the velocity just calculated, and with $M_{molecular} = 1$, $T = 6\times10^{7}$ K.

7. For hydrogen, the average molecular speed = $0.157\sqrt{T}$ km/s. For 20 million K this gives 700 km/s.

   Calculating the orbital speed as in Problem 8, v = 30 km/s$\sqrt{M/R} = 30\sqrt{10^{14}} / (10^{6} \times 206{,}000) =$ 660 km/s. This speed is comparable to the molecular speed.

8. Total distance covered is 200 kpc. Convert 200,000 pc to kilometers. 200,000 pc × $3.1\times10^{13}$ km/pc = $6.2\times10^{18}$ km. Dividing this distance by the velocity will give the amount of time. $6.2\times10^{18}$ km / 1500 km/s = $4.1\times10^{15}$ s. A year has $3.2\times10^{7}$ s/yr. Making the conversion to years gives $4.1\times10^{15}$ s / $3.2\times10^{7}$ s/yr = $1.3\times10^{8}$ yr or 130 million years.

9. At a recessional velocity of 6500 km/s, using the Hubble Law, the distance will be 92 Mpc. 0.1° = 360". Calculate their true separation, 360" = 206,000"($R$ / 92), $R$ = 0.16 Mpc. Converting to A.U. $R = 3.3\times10^{10}$ A.U. Use the orbital velocity relationship from Problem #2, $v = 30$ km/s$\sqrt{M/R}$. $50 = 30\sqrt{M/3.3\times10^{10}}$ $M = 9\times10^{10}$ solar masses.

10. The cluster's recessional velocity is 13,000 km/s and has a distance, from the Hubble Law, of 186 Mpc. Proceed as in the previous question, using 1650" for the angular radius and 500 km/s for the orbital velocity. 1650" = 206,000"(R / 186), $R$ = 1.5 Mpc. Converting to A.U. $R = 3.0\times10^{11}$ A.U. Use the orbital velocity relationship from Problem 4, $v = 30$ km/s$\sqrt{M/R}$. $500 = 30\sqrt{M/3.0\times10^{11}}$ $M = 9\times10^{13}$ solar masses.

11. $10^{41} = 0.10 \times M \times (3\times10^{8})^{2}$, $M = 1.1\times10^{25}$ kg/s. Over $10^{10}$ years this will be $1.1\times10^{25} \times 10^{10} \times 3.2\times10^{7} = 3.5\ 10^{42}$ kg. Converting this to solar masses gives $M$ = 1.8 trillion solar masses.

12. $10^{40} = 0.20 \times M \times (3\times10^{8})^{2}$, $M = 5.6\times10^{23}$ kg/s. $10^{8} \times 2\times10^{30} / 5.6\times10^{23}$ kg/s = $3.6\times10^{14}$ s. Converting to seconds gives 11 million years.

13. 0.15c = 45,000 km/s. $d$ = 45,000 / 70 = 643 Mpc. 0.155c = 46,500 km/s. $d$ = 46,500 / 70 = 664 Mpc. 664 - 643 = 21 Mpc.

14. Redshift of 3 is a distance of 6540 Mpc. Half this distance, to the galaxy, is 3270 Mpc. 3" = 206,000 × d / 3270, $d$ = 0.048 Mpc = 48 kpc.

15. Putting the information into an equation gives $\theta = kM/r$. To determine the constant of proportionality, $k$, put in the information for the Sun. 1.75" = $k$ (1 solar mass) / 1 solar radius, $k$ = 1.75.

48 kpc = 48,000 × $3.1\times10^{13}$ / $7\times10^5$ = $2.1\times10^{12}$. Put this information into the above formula, 3 = $1.75M$ / $2.1\times10^{12}$, $M = 3.6\times10^{12}$ solar masses.

## Resource Information

### Student CD Media

#### Movies/Animations
Cosmic Jets
Birth of a Quasar
Supermassive Black Hole
Active Galaxy
Black Hole in Galaxy M87
Dark Matter
Gravitational Lensing

#### Interactive Student Tutorials
None

#### Physlet Illustrations
Quasar

### Transparencies

| | | | |
|---|---|---|---|
| T-234 | Figures 25.1/2 | Galaxy Rotation Curves and Galaxy Masses | p. 668/669 |
| T-235 | Figure 25.5 | Head-Tail Radio Galaxy | p. 671 |
| T-236 | Figure 25.9 | Galaxy Collision | p. 673 |
| T-237 | Figure 25.11 | Hubble Deep Field | p. 675 |
| T-238 | Figure 25.12 | Starburst Galaxies | p. 676 |
| T-239 | Figure 25.13 | Galactic Cannibalism | p. 677 |
| T-240 | Figure 25.14 | Galaxy Interaction | p. 677 |
| T-241 | Figure 25.15 | Binary Black Hole | p. 678 |
| T-242 | Figure 25.18 | Galaxy Evolution | p. 681 |
| T-243 | Figures 25.22/23 | Galaxy Redshift Survey and the Large Scale Universe | p. 683/684 |
| T-244 | Figures 25.26/28 | Gravitational Lens and Galaxy Cluster Lensing | p. 687/688 |
| T-245 | Figure 25.29 | Dark-Matter Map | p. 689 |

## Suggested Readings

Bartusiak, Marcia. “What makes galaxies change?” *Astronomy* (Jan 1997). p. 36. Discusses the mechanisms for galactic evolution.

Bechtold, Jill. “Shadows of creation: quasar absorption lines and the genesis of galaxies.” *Sky & Telescope* (Sept 1997). p. 28. Describes how absorption features in quasar spectra can be used to probe the early universe.

Bromm, V. “Cosmic Renaissance.” *Mercury* (Spetember/October 2003). p. 25. Nice discussion of galactic evolution. Nice overview of cosmology.

Djorgovski, S. George. “Fires at cosmic dawn.” *Astronomy* (Sept 1995). p. 36. Discusses the connection between quasars and galaxy formation.

Eicher, David J. "Galactic genesis." *Astronomy* (May 1999). p. 38. Describes the formation and evolution of galaxies.

Ford, Holland; Tsvetanov, Zlatan I. "Massive black holes in the hearts of galaxies." *Sky & Telescope* (June 1996). p. 28. Discusses observations of supermassive black holes in the centers of ordinary and active galaxies.

Graham, David. "Clusters in collision." *Astronomy* (May 1999). p. 58. Discusses the interaction of galaxies in clusters.

Keel, W. "Quasars Explained." *Astronomy* (February 2003). p. 35. Everything you need to know about quasars. Nice diagrams and images.

Keel, William. "Before galaxies were galaxies." *Astronomy* (July 1997). p. 58. Describes how observations of radio galaxies are used to probe galactic formation.

Parker, Samantha; Roth, Joshua. "To see the world in a grain of sand: the Hubble Deep Field." *Sky & Telescope* (May 1996). p. 48. Describes results obtained from the Hubble Deep Field.

Nadis, Steve. "Here, there, and everywhere?" *Astronomy* (Feb 2001). p. 34. Discusses supermassive blackholes and the formation of galaxies.

Shara, Michael. "Cannibals of the cosmos." *Natural History* (Feb 2000). p. 70. Describes how collisions between galaxies influence galactic evolution.

Villard, R. "Order out of Chaos." *Astronomy* (November 2003). p. 38. Outstanding discussion of the Local Group. Includes discussion of the evolution of the Milky Way and galactic collisions.

Villard, R. "Unveiling the Dark Universe." *Astronomy* (November 2002). p. 42. Discusses Current research into Dark Matter. Also includes discussion of gravitational lensing.

Voit, G. Mark. "The rise and fall of quasars." *Sky & Telescope* (May 1999). p. 40. Discusses the connection between quasars and collisions of galaxies.

## Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

*Demonstration and activity materials:*

*Notes for next time:*