Chapter 24: Normal and Active Galaxies

Building Blocks of the Universe

Outline

Summary

Chapter 24 explores the wide variety of galaxies found in the universe. "Normal" galaxies are treated first; topics include Hubble's classification scheme, the characteristics of spiral, barred-spiral, elliptical, and irregular galaxies, and the organization of galaxies into clusters and superclusters. The chapter continues with a discussion of active galaxies, quasars, radio galaxies, and the supermassive black holes in galactic nuclei.

Major Concepts

- Classification of galaxies
  - Spirals
  - Barred spirals
  - Ellipticals
  - Irregulars
  - Hubble's "tuning fork" diagram
- Distances to galaxies—additional methods
  - Tully–Fisher relation
  - Supernovae as standard candles
- Clusters of galaxies
  - Rich and poor clusters
  - Superclusters, or clusters of clusters
  - The Local Group
  - The Virgo Supercluster
- Hubble's law
  - Expansion of the universe
  - Redshifts and recessional velocities of galaxies
  - Relationship between recessional velocity and distance
  - Value of Hubble's constant
  - Using Hubble's law to determine distances
- Active galaxies and quasars
  - Seyferts
  - Radio galaxies
  - Quasars
  - Characteristics of active galaxies
  - Energy source

Teaching Suggestions and Demonstrations

The Andromeda Galaxy is a good place to begin the discussion of galaxies in general. It is shown in Figure 23.2 from the previous chapter. Using a star chart, point out to students how to locate Andromeda in the night sky. It is easily visible with binoculars and even visible with the naked eye from a reasonably dark site. Also, spend a little time on the Shapley–Curtis debates regarding the nature of the "spiral nebulae." We take for granted now that galaxies are at great distances from us, but when they were first discovered their distances were unknown, and many astronomers believed galaxies were nebulae inside our own Milky Way Galaxy.

Section 24.1

You may want to begin this section with a slide show of lots of different **galaxies**. Show individual images as well as clusters of galaxies and deep-field images. Darken the room and ask students to concentrate on similarities and differences, and specifically on characteristics that could be used to categorize galaxies into different types. List their suggestions for characteristics and discuss. For instance, characteristics like size can be problematic because sizes are not known unless distances are. Your students will likely come up with the same major three groups that Hubble did: spirals, ellipticals, and irregulars, although they may not come up with the same names. If you are able, project a transparency of Table 24.1 on a separate screen while you show pictures of the various types of galaxies. It contains a useful summary of the properties of the different types of galaxies. These can be pointed out as you progress through the types of galaxies. Students can classify each galaxy shown and justify their classification based on the properties in the table.

Next, focus on the **spiral galaxies** and **barred-spiral galaxies**. After showing images of a variety of spirals, ask students to describe any relationships they see between different galaxy characteristics. They will probably notice that the galaxies with the most tightly wound arms tend to have the largest nuclei. Discuss the criteria for classification and give students more examples to classify. The line dividing the different subclasses is vague, since, for instance, the nuclear bulges come in a continuous range of sizes, not just small, medium, and large.

Far less attractive, but no less important, are the **elliptical galaxies**. Show a variety that indicate the range in ellipticity. Contrast their shapes and colors with those of the spirals. Be certain to show images of dwarf ellipticals and giant ellipticals as well. The dwarf ellipticals contain so few stars, they appear transparent. Their absolute magnitude is about -10, about as bright as one massive supergiant star or one million stars like the Sun! Obviously, they do not contain very many stars. For giant ellipticals, M87 is a must to show. Most photographs of M87 will show large numbers (several thousand are known) of globular clusters surrounding it. Note other galaxies in the field that may be similar to the size of the Milky Way. Giant ellipticals in the centers of other clusters of galaxies are truly enormous when compared to the other galaxies in their clusters.

Irregular galaxies are particularly interesting because they tend to have lots of star formation. The best examples of this class of galaxy are the Large and Small Magellanic Clouds (LMC and SMC) and NGC 6822, all in the Local Group. As a group they might be characterized as being like small spirals without having ever developed their organized structure. There is some observational evidence suggesting irregular galaxies may be younger than most galaxies and that they go through epochs of star formation. They are rich in emission nebulae and also help provide the calibration for their use in the distance scale. The LMC contains one of the largest known nebulae.

See if students can come up with a reason for a relationship between an irregular shape and vigorous star formation. Remind them of the necessity to trigger star formation in interstellar clouds. What could possibly be the trigger in the case of these galaxies? The LMC and SMC provide a rich source of young, massive stars by which astronomers study stellar evolution in a way not possible in the Milky Way. All the stars either in the LMC or SMC can be assumed to be at the same distance from us, a distance which we know fairly well. Therefore, all objects in the LMC and SMC have known absolute magnitudes or luminosities. The Cepheids of the LMC and SMC provide the details of the period-luminosity relationship that then allows Cepheids to be used for determining distance to other galaxies. There are literally thousands of Cepheids and RR Lyrae variables in the two Magellanic Clouds.

Peculiar galaxies are often thought of as a fourth type of galaxy, although most astronomers agree that each of these galaxies was previously one of the other types. For the most part, they are the result of galaxy-galaxy collisions and close encounters. Colliding galaxies and close encounters are covered in the next chapter but this is a good time to mention several basic facts about this type of galaxy.

After showing Figure 24.1, the question invariably comes up: "Do any of those galaxies ever collide?" The answer is a resounding "yes." Collisions are not uncommon and a section in the following chapter will be devoted solely to that discussion. As will be pointed out then, the results of some of these collisions are the starburst galaxies mentioned at the very end of this chapter. Bursts of star formation may be induced by tidal interaction between galaxies in a close encounter. Even a collision of a spiral with an elliptical may produce significant and sudden star formation through tidal effects on the gas and collisions with very low density gas remaining in the elliptical.

Finally, use Figure 24.9 to illustrate **Hubble's "tuning fork" scheme**. Emphasize that it does *not* represent an evolutionary sequence. In discussion of elliptical classifications be sure to point out that our classifications scheme operates within the limits of our observations. We see these galaxies from only our location relative to them, from our point of view. It is entirely probable that the various ellipticals categorized from E0 to E7, might be categorized completely differently from another point of view. ➲ **DEMO** To show this, use a football as a possible (prolate) model. Show how, when viewed from different positions, the ball may look like anything from an E0 to an E7 galaxy. Use the double paper plate (oblate) model in the same way. Face on, it gives the appearance of an E0; tilted, it can have almost any ellipticity up to E7. It is very easy to confuse the terms prolate and oblate. Make sure your students understand the differences in the shapes.

Section 24.2

Not long ago we were discussing Earth's place in the Solar System, then the Sun's place in the Milky Way Galaxy. Well, we are now ready to discuss our galaxy's place among galaxies. Tell the students that galaxies tend to be "pack animals" traveling in groups rather than alone. The Milky Way is a member of the pack called **Local Group**, which in turn is a member of the **Virgo Supercluster**. Discuss clusters and superclusters of galaxies while showing Figures 24.13 and 24.14. Contrast the Local Group, a "poor" cluster, with a rich cluster of galaxies like that shown in Figure 24.15 or 24.1.

This section also provides the next two rungs for the cosmic distance ladder, the **Tully–Fisher relation** and **standard candles**, in particular, supernovae. (See Figure 24.12.) Discuss both of these methods and compare them to the earlier methods. Point out again how important distance determinations are to astronomy.

Throughout this manual, we have suggested visualizations to help students with the concepts of size and distance. The same is true here, but fortunately it will not be necessary to model the entire local group. The Milky Way and the Andromeda galaxy (an image of which is shown in Figure 23.2) are the major players here. ➲ **DEMO** The model of the Milky Way, which was suggested in the previous chapter, would fit into a room 15 m × 15 m. This time, the same sized room will contain the Local Group of galaxies. Use a scale of 1 m = 50,000 pc. The Milky Way and Andromeda galaxy are separated by 14 m. Notice that this scale is 25 times the scale used for the Milky Way. Just as we tried to see the solar system when viewing the Milky Way, can we view the Milky Way or Andromeda galaxy at the current scale? These two galaxies are about the same size, 30,000 pc in diameter. At the current scale they would each be 60 cm in diameter. There is no trouble seeing them at all!

Section 24.3

As we peer deep into space on the scale of superclusters, in no matter what direction we look we see galaxies receding from us. Furthermore, the *farther* these galaxies are from us, the *faster* they are receding. This relationship between recessional velocity and distance is called the **Hubble Law**. The Hubble Law is so fundamental to understanding that it is well worth the effort to spend some additional time covering it. While discussing Figure 24.17, there are several points that need emphasis. First, the Hubble Law is an empirical relationship, and therein lies much of its importance. Various theories and cosmological interpretations will come and go but the Hubble Law will always remain because it is an observational fact. The Hubble Law is *not* theory, although its interpretation is.

It is also important to understand the nature of the Hubble constant. Its units can be confusing; they are a mixture of distance divided by time divided by a different unit of distance. Make sure you point out that its units are really those of velocity per distance. Objects at 1 Mpc are moving, on average, at 65 km/s. At 2 Mpc they are moving at 130 km/s, and so on. But if some of your more knowledgeable students point out that the distance units should cancel out, if they are put into similar units, agree with them. This will be important in the study of cosmology and the age of the universe.

The Hubble Law can only be used for determining distances over cosmological distances. It is rather useless for even nearby galaxies. Students sometimes mistakenly believe that it can be used for determining distances to stars and clusters. Use Figure 24.18 not only as a way of reminding them of how the distance scale is built up with various methods; this diagram, as implied by the right-most scale, also tells us the distance over which the methods are useful. Note that the Hubble Law is useful *beyond* 100 million pc.

"Since the recession from us is in all directions, doesn't that imply that *we* are at the center of the Universe?" Students typically have a difficult time visualizing the omni-directional expansion without placing us at the center. ➲ **DEMO** A balloon can provide a very effective demonstration showing how we can see distant objects receding from us in all directions if they are being carried on an expanding manifold. Bring an uninflated, spherical balloon to class and draw small, evenly distributed galaxies on the balloon. Show the balloon to the class and then tell them to watch what happens as the balloon inflates. Blow up the balloon and then show the students. They will see that the galaxies have separated by some distance. You can point out that the separation distance grew faster for galaxies that were farther apart to begin with simply by measuring the distance between two nearby galaxies and two distant galaxies before and after the expansion ensued. The same amount of time elapsed during the expansion, but the distant galaxies separated by a larger distance than the nearby galaxies. Since velocity is distance over time, the larger distance implies higher velocity.

Show the spectra in Figure 24.16 and explain how the **recessional velocities** are obtained. Revisit the Doppler shift here, but point out that there is a fundamental difference between the cosmological redshift and the Doppler redshift. ➲ **DEMO** The cosmological redshift can be demonstrated using the balloon as described above. Simply draw a few cycles of a short wavelength wave on the balloon prior to inflating it. As the balloon inflates, the wavelength of the wave very clearly increases to longer wavelengths. Point out that a wave will first be emitted from within a galaxy and as it traverses space, which is expanding, it expands as well. Between the time it left a distant galaxy and arrived at the Earthbound detector, it has had time to expand. The further it traveled, the more time it had in which to expand.

Show your students how Hubble's law provides a straightforward method of obtaining **distances** to very faraway objects, since recessional velocities can be found from spectra, and distance is just the recessional velocity divided by Hubble's constant. The catch is that enough objects with already *known* (and agreed upon!) distances must be used to determine the value of **Hubble's constant, H_0**. The **units** of Hubble's constant, k/s/Mpc, can be confusing for students. Distance divided by time divided by distance actually leaves you with the inverse of time, a point that will subsequently come up in connection with the age of the universe. In the meantime, remind students that the units represent a speed-per-unit distance. So, a galaxy 1 Mpc away will be receding from us with a velocity of 70 km/s, whereas a galaxy 2 Mpc away will be receding at 140 km/s.

Several methods for determining distances to galaxies are discussed throughout the chapter. The primary purpose behind these significant efforts is to provide a reliable Hubble Law. Since it saw first-light in 1948, the 200-inch Hale telescope at Mt. Palomar has had much of it use dedicated to various aspects of this one problem. The Hubble Space telescope is also spending part of its time working on this problem, too. With a reliable Hubble Law, distances to galaxies and quasars in the universe become almost trivial to determine and Hubble's law can be used itself as a **standard candle**. But a reliable Hubble Law can only be had through careful measurements of distance to most nearby and some distant galaxies. The distances to nearby galaxies are most often used to calibrate other methods of distance determination to more remote galaxies. There are several other standard candles to note, such as spectroscopic parallax, novae and supernovae

Spectroscopic parallax can be used to nearby galaxies. The brightest stars have absolute magnitudes between -5 and -10 and can be used out to 10 to 100 Mpc. Although elliptical galaxies may lack such bright stars (because they are massive stars and have already evolved), they are readily available in spirals, irregulars, and peculiars.

Novae have peak absolute magnitudes in about the same range as the brightest stars. Although difficult to discover because they occur unpredictably, when a galaxy is caught with a nova it may provide useful information on the distance.

Supernovae may provide one of the best methods for determining the Hubble Law. Since supernovae brighten to almost the luminosity of the entire galaxy they are in, they allow us to determine distances to virtually any galaxy we can see. There are two problems in using them, however. First, a supernova has to be "caught" prior to its maximum because it is the maximum light that provides the best calibration for distance. Second, supernovae occur very infrequently in any one galaxy. To address both of these problems, astronomers have established automated surveys that examine hundreds of galaxies per night. An image of a galaxy is taken using a CCD and compared with a standard image of that galaxy. If anything has changed, like the sudden brightening of a supernovae, astronomers are notified immediately in order to conduct further observations. If these surveys are allowed to run for enough years they have the potential for providing excellent information on extragalactic supernovae.

Section 24.4

In these sections, concentrate on the characteristics that distinguish **active galaxies** from normal galaxies. Active galaxies, including Seyferts, radio galaxies, and others, emit tremendous amounts of energy from fairly compact nuclei. The energy also usually spans the electromagnetic spectrum rather than following a blackbody curve as stellar radiation would. Show pictures of active galaxies and always point out the wavelength range in which the image was made. Remind students to consult the icons underneath the figures in the text to show what type of electromagnetic radiation is represented. In addition to illustrating important information about active galaxies, you can use these pictures as an opportunity to remind students of the importance of observing in different regions of the spectrum. A galaxy that appears quite normal in the visible may turn out to be spectacularly energetic in radio observations.

Quasars are now considered to most likely be the very bright cores of distant galaxies. The discovery of quasars and their identification as extragalactic objects is another example of the success that can come from thinking "outside the box." The spectral lines of quasars were not recognizable at first; because the objects appeared to be star-like, no one considered that the lines could be redshifted by such large amounts.

The discovery of quasars as extragalactic objects is interesting because of the series of events that led to it. Through lunar occultations, the positions of several unidentified radio sources were refined to the point that optical astronomers could look precisely at the locations in an attempt to identify these objects. What they found were objects that looked like stars! In fact, they were referred to as "radio stars." That name, as it turned out, was important and highly misleading.

When Matthews and Sandage took the first spectrum, it contained emission lines that were unrecognizable. Thinking in terms of stars, they knew that stars could not have highly shifted (blue or red) spectra because their motions in the Galaxy are relatively slow. In fact, the escape velocity from the Galaxy, in the vicinity of the Sun, is about 350 km/s. So the lines they saw in the spectrum might be shifted a little but not by much if they were stars. Of course, everyone called them radio stars and they looked like stars, so they must be stars, right? Astronomers remained baffled by these new objects for about 2 years.

Maarten Schmidt made his breakthrough when he stopped thinking of them as stars, but rather as possible extragalactic objects. Such objects could have high redshifts, so high that the visible spectrum is shifted into the near infrared, and the ultraviolet, which normally cannot be seen, is shifted into the visible. Schmidt made his discovery because he stopped thinking of these objects as "stars."

There is a lesson to be learned here, both in science and in many other areas. We sometimes think we know or understand something by the label that is attached to it. But we, or others, are the ones making the labels. We can easily fool ourselves. Because someone called these objects radio "stars," they could not think of them being anything else but stars. The label was wrong and some very bright scientists struggled for two years with the problem.

Section 24.5

Section 24.5 begins with an excellent list of the properties of active galactic nuclei. Go through this list carefully, and as you present the theory for the **energy production**, point out how the theory explains some of the properties listed. Figure 15.33 is a good place to start. Figure 15.36 will also help explain the formation of jets and the radiation observed at different viewing angles. Students may be confused by the fact that black holes are "engines" powering these nuclei. After all, nothing can escape from a black hole. Remind students that the material spiraling toward a black hole but not yet at the event horizon can emit radiation that will reach us as it is heated up to high temperatures. As mentioned in the text, 10 to 20 percent of the total mass–energy of the in-falling matter can be radiated away. Calculate with students the amount of energy that would come from the equivalent of one solar mass falling into the central black hole. Because the constant *c* is such a large number, the amount of energy is impressive!

Of fundamental importance to this entire chapter is the energy derived from matter "falling" into a black hole. The matter actually spirals into the hole and this is important in converting the energy into a form that can be radiated away. The primary questions are: "Where does this energy come from?" and "How much energy is produced?" Both of these questions can be rather easily answered using the simple physics already presented in previous chapters.

Showing students the following explanations can help them gain insight to a very important astrophysical process. If your students are not able to understand the mathematics, you may still be able to present some of the ideas to them in a general way. The entire principle is based on circular orbits and what we already know about black holes.

We know from circular orbits that the gravitational force provides the centripetal force.

$$E = \mathrm{KE} + \mathrm{PE}$$

The mass being orbited is *M*, the mass doing the orbiting is m and has a velocity *v*. *M* and *m* are separated by a distance *R*. The minus signs have been retained for the following discussion.

Multiplying both sides by *R* gives

$$-\frac{GMm}{R} = -mv^2$$

The term on the left side is just the gravitational potential energy, PE. On the right side is twice the kinetic energy, KE, with a negative sign in front.

$$\mathrm{PE} = -2\mathrm{KE}$$

$$\mathrm{KE} = -\frac{1}{2}\mathrm{PE}$$

The total energy, *E*, of an orbiting body is just the sum of the kinetic and potential energies. Substituting for the kinetic energy, we can get the total energy in terms of the potential energy.

$$E = \mathrm{KE} + \mathrm{PE}$$

$$E = -\frac{1}{2}\mathrm{PE} + \mathrm{PE}$$

$$E = \frac{1}{2}\mathrm{PE}$$

$$E = -\frac{1}{2}\frac{GMm}{R}$$

Now consider a mass, *m*, very far away from a black hole moving into an orbit very near to it. At a great distance, the potential energy is about zero because *R* is very large and so the total energy is also zero. Very near the black hole, the total energy is what is shown above, where *M* is the mass of the black hole and *R* is the distance between the black hole and *m*. If we look at the *change* in energy, ΔE, going from very far away to very close, this will be 0 - *E* or

$$\Delta E = \frac{1}{2}\frac{GMm}{R}$$

If the mass gets very close to the black hole, then *R* is just the Schwarzschild radius $R = 2GM/c^2$ (from Chapter 22). Substituting in this value for *R* gives

$$\Delta E = \frac{mc^2}{4}$$

Einstein told us that the energy equivalent of an object's rest mass, *m*, is $E = mc^2$. So, an object spiraling into a black hole could potentially give up as much as one quarter of its rest mass energy before entering the black hole. Through collisions with other material in the disc surrounding the black hole, it will give up a substantial fraction of this but not all of it. But 25% of its rest mass energy is available. For a one solar mass object this is equivalent to 5×10^{46} J or enough to power an average quasar for about a year. Keep in mind that the fusion of hydrogen into helium converts only 0.7% of the rest mass of hydrogen into energy. Allowing matter (and it could be hydrogen or old cars) to spiral into a black hole is much more energy productive.

Although the above discussion uses only classical physics and is therefore very approximate, as in the case of deriving the Schwarzchild radius from a simple expression for escape velocity, the result is conceptually correct and surprisingly close to what detailed calculations will show.

Our two initial questions have been answered. The energy comes just from gravitational potential energy and the amount of energy that is available is up to one quarter of the rest mass energy. Notice, too, that the result does not depend on the mass of the black hole! Indirectly, the result does depend on the mass of the black hole. If the black hole has low mass, then *r* is very small. The mass m will experience a small gravitational potential energy and will have to fall farther to reach the Schwarzchild radius *r*. For a supermassive black hole, *r* will be much larger but so is the gravitational potential energy. So mass *m* will not have to fall as far. Either way, the same amount of energy is given up whether the black hole has a high or low mass.

Student Writing Questions

1. Much of the material of this chapter is at the cutting edge of astronomical research. Discuss all the topics you have encountered here that are still not understood or about which there are some significant uncertainties. Some of this may also pertain to recent chapters; that would be good to include, too.

2. Elliptical galaxies are mostly made up of lower-mass old stars. For this reason they do not look very interesting. But sometime in the past they must have had lots of gas, bright young

stars, and so forth. Describe what a young elliptical galaxy might have looked like back then.

3. Most civilizations on Earth have some type of mythology based on the stars and planets. But imagine if we were in the center of our galaxy or some other galaxy that has an extremely rich sky, filled with hundreds of times the stars we see in our sky. How do you think the mythologies of these civilizations would be affected? Would they develop an awareness of astronomy sooner than we did? Or would the "heavens" play an even greater role in their daily lives, their religions, and their culture?

4. What would it be like to live in an active galaxy? Assume you lived on a planet orbiting a star about halfway out from the center of the galaxy. The galaxy has an active nucleus and ejects plasma jets every few hundred million years. What impact would there be on life or its development? Would life be wiped out by these events? What do you think you would experience during one of these episodes?

5. Quasars were originally named "radio stars" because they looked optically like stars but emitted radio waves. But stars implied they were local, in our Galaxy. Maarten Schmidt, while looking at the unidentifiable lines in a radio star's optical spectrum, considered for a moment a possibility "outside of the box." In so doing he discovered the cosmological distance to quasars. Find examples where the label or name we give to something biases our thinking to the point that we completely miss what it is we are experiencing. Examples outside of science are appropriate.

Answers to End of Chapter Exercises

Review and Discussion

1. The size of the central bulge distinguishes type a, b, and c. Type a has the largest.

2. Elliptical galaxies have a stellar content remindful of the halo of our galaxy. The stars are generally low mass and old. Their distribution more resembles our halo too; ellipticals probably have a prolate shape and some may even be spherical. There is no observed cold gas or dust in either the elliptical galaxies or in our halo. However, x-ray emissions from elliptical galaxies indicate the presence of large amounts of very hot gas throughout the galaxy and even beyond; the halo has no x-ray emissions.

3. Radar ranging is used to establish distances within the solar system and gives us the size of the A.U.

   Parallax uses triangulation to measure distances to the nearest stars. The radius of the Earth's orbit, 1 A.U. is one side of the triangle. Distances are good out to about 100 pc.

   Spectroscopic parallax utilizes the properties of stars in the H–R diagram. Using parallax, the absolute luminosities of some types of stars are established. When identified in the H–R diagram, similar stars at unknown distances can have their distances determined by comparing their apparent luminosities with those that are known. Distances can be determined to at least 1,000 pc.

   Pulsating variable stars such as Cepheids have a strong relationship between the period of their pulsations and their absolute luminosities. Once established using nearby Cepheids, this method can be extended to the nearest galaxies. Distances to at least 5 Mpc are possible.

4. The Local Group of galaxies is about one million parsecs (1 Mpc) in diameter. The 20 or so galaxies making up this group fill very little of the space; only 3 of the galaxies are of full size, the others are dwarf irregulars or ellipticals.

5. A standard candle is an object with a known luminosity. As such, when seen at a distance astronomers can determine that distance by comparing the observed and known luminosities and using the inverse square law.

6. The Tully–Fisher relation is a correlation between a galaxy's luminosity and its rotational velocity. The rotational velocity is determined from the broadening of the 21-cm line width. Here is a way in which a galaxy's total luminosity can be independently determined and, when compared to its apparent luminosity, the distance can be calculated. This relation is also independent of many of the other methods in its calibration.

7. The Virgo Cluster is one of the nearest rich clusters of galaxies. It contains about 2500 galaxies and is about 20 Mpc distant.

8. Galaxies are observed to have redshifted spectra, which is interpreted as meaning that all galaxies are receding from us. Hubble discovered that the recessional velocity is proportional to the distance for all galaxies. This is known as the Hubble Law.

9. Once the Hubble Law is known, it is almost trivial to use for determining distances to galaxies. The spectrum of a galaxy will reveal its recessional or radial velocity. The Hubble Law states how this velocity is proportional to the distance; the distance is immediately determined once the velocity is known.

10. In order to establish the Hubble Law, each galaxy observed must have its velocity and distance determined. The velocity is relatively easy to determine because it comes directly from the spectrum of the galaxy. The distance, however, is much more difficult and uncertain. Hubble's constant is the constant of proportionality between the distance and the velocity of galaxies. Its value ranges between 50 and 90 km/s/Mpc. With distances uncertain, Hubble's constant remains uncertain, too.

11. Active galaxies are different from normal galaxies in at least two ways. First, they emit much more radiation than normal galaxies, up to thousands of times more. Second, the nature of the radiation is different. Normal galaxies emit most of their radiation around and near the visible part of the spectrum. This is because they are composed of stars which are all emitting light at various wavelengths of the visible spectrum. But active galaxies emit most of their radiation at infrared or radio wavelengths. The source of these emissions must be other than stars and this radiation is referred to as nonthermal radiation.

    A normal galaxy emits most of its light in and near visible wavelengths. In the radio part of the spectrum, emissions are typically a million times less. In an active galaxy, this situation can almost be reversed. Their optical radiation may be approximately the same as a normal galaxy, even a bit less, but their radio emissions can be tens of millions or more greater.

12. There are only a few active galaxies relatively nearby. Most are much more distant.

13. Seyfert galaxies emit most of their radiation from a small central region called a galactic nucleus. The radiation coming from the nucleus is nonstellar. The spectrum of the nucleus

is also nonstellar, with many strong, wide emission lines of highly ionized heavy elements. The line widths indicate high internal motions on the order of 1,000 km/s.

The primary source of energy for a Seyfert galaxy comes from its center because we observe about 10 times as much energy coming from the nucleus and it is just this radiation that is nonstellar.

14. The lobes of a radio galaxy are aligned on either side of the nucleus; a straight line joining the lobes would always pass through the nucleus. In some lobe radio galaxies a filament of radio-emitting material can be traced connecting the lobes to the nucleus.

15. The energy-emitting regions of active galaxies are highly variable over time. This becomes a constraint on how large they can be. They are generally considered to be smaller than a parsec.

16. The spectra of quasars have highly redshifted lines. The redshift is so high, lines normally found in the ultraviolet are shifted into the visible; visible lines are shifted out into the infrared. This is what caused so much confusion in understanding their spectra. Astronomers were expecting to see normal visible lines that were slightly shifted. The high redshifts also implied very large distance, much farther away than ever seen in any other type of object.

17. Redshifts are observed; they have not been interpreted as anything like a velocity or distance. When the latter is done, the Hubble constant must be used and there is still uncertainty about its value.

18. Quasars appear as faint stars yet their redshifts indicate enormous distances. The luminosity of quasars could be calculated from these two facts and turned out to be extremely high.

19. In the nucleus of an active galaxy is a massive black hole surrounded by an accretion disc. Gas moving in this disc emits large quantities of radiation before entering the black hole. Up to 20% of the rest mass of the gas can be emitted before entering the black hole. This model can also account for the small size of the central engine, the rapid motions, and possibly jets coming out of the disc.

20. Radio lobes emit synchrotron radiation which is produced by fast moving electrons in a magnetic field. As the electrons spiral around the magnetic field lines, they lose energy and radiate it away in the form of radio waves. The electrons and magnetic fields are ejected out of the accretion disc surrounding the supermassive black hole at the center of active galaxies. This jet of material is ejected in opposite directions.

Conceptual Self-Test

1. F
2. F
3. T
4. F
5. T
6. T
7. F
8. F
9. T

10. T
11. A
12. C
13. A
14. C
15. C
16. B
17. B
18. B
19. A
20. B

Problems

1. Apparent luminosity is related by the inverse square law to the distance and is proportional to the true luminosity, $L_{app} \propto L / r^2$ For two objects observed by the same telescope, the apparent luminosity is the same in both cases. Set up a proportion for each case and set them equal to each other.

$$1 / 10{,}000^2 = 10^9 / r^2$$

$$r = 3.2\times10^8 \text{ pc} = 320 \text{ Mpc}$$

2. 26.3 - (-5) = 5Log (r) - 5, r = 18 million pc.

3. The Hubble Law can be expressed as follows $v_{rec} = H_0 \times D$. For a galaxy at 200 Mpc, the recessional velocity will be 70 × 200 = 14,000 km/s.

   For a galaxy whose recessional velocity is 4,000 km/s, its distance will be 4,000 / 70 = 57 Mpc.

   If the Hubble constant changes to 60 km/s/Mpc then these answers will be 12,000 km/s and 67 Mpc, respectively.

   If the Hubble constant changes to 80 km/s/Mpc then these answers will be 16,000 km/s and 50 Mpc, respectively.

4. The Virgo Cluster is about 18 Mpc distant. Its recessional velocity is 1,260 km/s. At this rate, how long will it take to move another 18 Mpc?

   Distance divided by velocity gives time. Convert 18 Mpc to kilometers. Also convert final answer in seconds to years. 18,000,000 pc × 3.1×10^{13} km/pc = 5.6×10^{20} km. 5.6×10^{20} km / 1,260 km/s = 4.4×10^{17}s. 4.4×10^{17}s / 3.2×10^{7}s/yr = 14 billion years.

5. Calculate the redshift v = $(\Delta\lambda/\lambda)c$ = (43.7 / 656.3)300,000 km/s = 20,000 km/s. From the Hubble Law, d = 286 Mpc. The angular size = 206,000"(0.040 Mpc / 286 Mpc) = 29" (radius). The diameter will be 58".

6. With a redshift of 0.25, the distance is 1080 Mpc. The absolute magnitude is 13 - M = 5Log(1.08×10^9) -5, M = -27.2 4.8 - (-27.2) = 2.5Log(L), L = 6.1×10^{12} solar luminosities. This quasar is essentially the same brightness as the Sun.

7. At redshift of 5 the distance is 7950 Mpc. 22 - M = 5Log(7.95×10^9) -5, M = -22.5. 4.8 - (-22.5) = 2.5Log(L), $L = 8.3\times10^{10}$ solar luminosities.

8. Redshift of 1 is a distance of 3460 Mpc. m - (-24) = 5Log(3.46×10^9) -5, M = -18.7

9. The mass of the central black hole is 3×10^9 solar masses. 0.5 pc is equal to 103,000 A.U. Use $v = 30$ km/s$\sqrt{M/R}$ where M and R are in solar units and A.U. respectively, taken from Problem 4 in the last chapter. $v = 30\sqrt{3\times10^9 / 103{,}000}$ = 3600 km/s

10. Using the Doppler formula, $v = 0.05c$ = 15,000 km/s. Assuming a Hubble constant of 65 km/s/Mpc, the distance d = 230 Mpc. The orbital radius is 0.1 = 206,000 d / 2.3×10^8, d = 110 pc = 2.3×10^7 A.U. 250 = $30\sqrt{M / 2.3\times10^7}$, $M = 1.6\times10^9$ solar masses.

11. The distance to the Galactic center is 8,000 pc, which is 2.5×10^{20} m. The energy flux is power (watts) per square meter at this distance. 10^{37} W / $4\pi \times (2.5\times10^{20}\text{ m})^2 = 1.3\times10^{-5}$ W/m^2.

    Sirius is 23.5 times brighter than the Sun or $L = 9.2\times10^{27}$ W. At a distance of 2.7 pc = 8.4×10^{16} m, calculate its energy flux in a like manner. 9.2×10^{27} W / $4\pi \times (8.4\times10^{16}\text{ m})^2$ = 1.0×10^{-7} W/m^2

    The Seyfert nucleus would be about 100 times brighter than Sirius. But most of the light would be infrared and not affected by extinction.

12. Angular size = 57.3° × (1/4) = 14° This is about 28 times larger than the Moon, which is half a degree in diameter.

13. The lobe is 500 kpc from the nucleus, which is 1,630,000 light years. At a velocity of 0.75c it will take 1,630,000 / 0.75 = 2.2 million years to travel this distance.

14. Use $E = mc^2$, divided by the time of one day, 86,400 s; use one Earth mass, 6×10^{24} kg, and an efficiency of 0.2.

$$0.2\times\frac{6\times10^{24}\,kg\times\left(3\times10^{8}\right)^{2}}{86{,}400\ \text{sec}} = L \ \ \text{J/sec}$$

$$L = 1.3\times10^{36}\ \text{J/s}$$

15. $E = 0.15 \times 2\times10^{30} \times (3\times10^8)^2 / 3.2\times10^7 = 8.4\times10^{38}$ W = 2.2×10^{12} solar luminosities.

Resource Information

Student CD Media

Movies/Animations
Cluster Merger
Collision of Two Spiral Galaxies
Hubble Deep Field Zoom Sequence
Starburst Galaxy

Interactive Student Tutorials
None

Physlet Illustrations
Hubble's law – Doppler Shift & Distance

Transparencies

T-225	Table 24.1	Galaxy Properties by Type	p. 640
T-226	Figure 24.9	Galactic "Tuning Fork"	p. 640
T-227	Figure 24.13	Local Group	p. 644
T-228	Figure 24.15	Distant Galaxy Cluster	p. 645
T-229	Figures 24.16/17	Galaxy Spectra and Hubble's Law	p. 646/647
T-230	Figure 24.18	Cosmic Distance Ladder	p. 648
T-231	Figure 24.23	Centaurus A Radio Lobes	p. 652
T-232	Figure 24.33	Active Galactic Nucleus	p. 658
T-233	Figure 24.36	"Dusty Donut"	p. 661

Suggested Readings

Bothun, Gregory D. "Beyond the Hubble sequence." *Sky & Telescope* (May 2000). p. 36. Discusses the limitations on galaxy classification based on observed morphology, and suggests alternatives related to galactic evolution.

Christianson, Gale. "Mastering the universe: Edwin P. Hubble." *Astronomy* (Feb 1999). p. 60. Profiles the life and work of Edwin P. Hubble.

Croswell, Ken. "How far to Virgo?" *Astronomy* (Mar 1995). p. 48. Describes measurements of the distance to the Virgo cluster using Cepheid variable stars.

Disney, Michael. "A new look at quasars." *Scientific American* (June 1998). p. 52. Summarizes Hubble Space Telescope results about quasars.

Ford, Holland and 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.

Henry, J. Patrick; Briel, Ulrich G.; Bohringer, Hans. "The evolution of galaxy clusters." *Scientific American* (Dec 1998). p. 52. Describes X-ray observations of the dynamics of galaxy clusters.

Kinney, Anne L. "When galaxies were young: the Next Generation Space Telescope promises to decipher the origins of stars and galaxies." *Astronomy* (May 1998). p. 44. Profiles the plans and capabilities of the Next Generation Space Telescope.

Martin, Pierre; Friedli, Daniel. "At the hearts of barred galaxies." *Sky & Telescope* (Mar 1999). p. 32. Summarizes our knowledge of barred spiral galaxies.

Naeye, Robert. "New beast in the galaxy." *Astronomy* (Oct 2000). p. 28. A brief report on the discovery of a new microquasar in the Milky Way.

Stephens, Sally. "Hubble warrior." *Astronomy* (Mar 2000). p. 52. Profiles the life and work of Wendy Freedman, the leader of the Hubble Space Telescope Key Project.

Tyson, Neil de Grasse. "Between the galaxies." *Natural History* (June 1999). p. 34. Describes the intergalactic medium .

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: