Solutions

1. Describe some differences between quasars and normal galaxies.

> Normal galaxies host anywhere from thousands of stars in the smallest galaxies to trillions of stars in the largest ones. Quasars appear to be single, solitary energy sources. Normal galaxies are observed throughout the universe, while quasars are generally found only at very large distances with very high redshifts. Luminous quasars are typically 100 times brighter than a large galaxy. Large galaxies can be hundreds of thousands of light-years in diameter, while quasars are typically much less than 1 light-year in diameter. Normal galaxies do not emit much energy at radio frequencies, while many quasars are extremely luminous at radio frequencies.

2. Describe the arguments supporting the idea that quasars are at the distances indicated by their redshifts.

> Quasars have extremely large redshifts, indicating that they are receding from us at large fractions of the speed of light. Any objects moving this rapidly from a nearby galaxy would easily achieve escape speeds from even the largest host galaxies. Hubble Space Telescope observations have shown that quasars sit in the middle of host galaxies, and the host galaxies have the same redshifts as their quasars, confirming that quasars obey Hubble's law and their high redshifts are due to their distance.

3. In what ways are active galaxies like quasars but different from normal galaxies?

> Like quasars, active galaxies have very luminous central regions that emit prodigious amounts of energy, particularly in the radio region of the spectrum. Both quasars and active galaxies are powered by infalling material that forms an accretion disk around a central supermassive black hole. Both quasars and active galaxies emit jets of mass and energy perpendicular to the plane of the host galaxy's disk.

4. Why could the concentration of matter at the center of an active galaxy like M87 not be made of stars?

> To explain the large masses in the centers of galaxies that we observe, there would have to be at least a million stars in a region about the size of the solar system. This requires that they would have be only two star-diameters apart, meaning there would be constant collisions between stars. Those stars would then merge, and soon, the resulting giant star or stars would collapse into a black hole.

5. Describe the process by which the action of a black hole can explain the energy radiated by quasars.

> Quasars are galaxies that contain a supermassive black hole, surrounded by an accretion disk in which material is heated to extreme temperatures. Because the gravity of the black hole is very strong near its event horizon, material in the accretion disk is falling in and releasing a huge amount of gravitational energy as it falls. It is this energy that powers the glowing accretion disk and explains the luminosity of quasars. Quasars represent an early stage in the development of galaxies, when vastly more material, mostly interstellar gas and dust, fell into the central supermassive black hole during the galaxy's accretion stage. Quasars can also be "reborn" when another galaxy collides with the quasar host, and its material provides new fuel for the quasar accretion disk.

6. Describe the observations that convinced astronomers that M87 is an active galaxy.

M87 possesses jets that stream from a very luminous and compact center perpendicular to the plane of the galactic disk. In addition, Hubble Space Telescope observations show a disk of hot material circling the central black holes in M87, and Doppler shift measurements indicate that this black hole is 3.5 billion solar masses, about 1000 times more massive than the Milky Way’s central supermassive black hole, and more than sufficient to produce the tremendous energy we observe radiating from the galaxy in its radio jets.

7. Why do astronomers believe that quasars represent an early stage in the evolution of galaxies?

Quasars and their host galaxies all have very large redshifts, indicating that they are at least 1 billion light-years away, and often much farther. When we recall that light travels at a finite speed, we see that looking out in space is the same thing as looking back in time. Because all the quasars we see are so far away, the light we see from them today must have left the quasar billions of years ago, back when the universe was much younger than it is today. Thus, we are seeing galaxies in an early stage of their formation. The number of quasars increases as we look further back in time and was greatest when the universe was about 20% of its current age.

8. What is the typical structure we observe in a quasar at radio frequencies?

At radio frequencies, quasars have a very small but extremely luminous center that coincides with the center of its host galaxy. There are often two very narrow but bright jets that extend in opposite directions from the center of the host galaxy and which terminate by spreading out into two large amorphous bright radio lobes.

9. What evidence do we have that the luminous central region of a quasar is small and compact?

Fluctuations in the energy output of a quasar can change over relatively short time periods (a few months to a few years at most). This means that the region from which the changing energy is coming cannot be larger than the distance that light can travel over a few month or a few years. In other words, the region that is fluctuating must be no more than a few light months to a few light years wide. Typical galaxies are tens of thousands to hundreds of thousands of light-years across. The short timescale energy fluctuations suggest that the region of greatest luminosity in a quasar must be much smaller than the size of the host galaxy.

10. Suppose you observe a star-like object in the sky. How can you determine whether it is actually a star or a quasar?

Take a spectrum of its light. The Doppler shift of the spectral lines in a star can be no more than a few hundred km/s. The lines in even the nearest quasars are redshifted by a much larger amount.

11. Why don't any of the methods for establishing distances to galaxies, described in the chapter on Galaxies, (other than Hubble's law itself), work for quasars?

The techniques for establishing distances to galaxies all involve finding an object of known intrinsic luminosity, such as a Cepheid variable, in the galaxy. Since quasars appear as points of light, we cannot detect any "standard bulbs" in them. (We can use Hubble's Law, and estimate the distances of quasars from their radial velocities, but only after we have shown, through some other method of getting distances or by associating quasars with their host galaxies, that quasars actually obey the Hubble law.)

12. A friend of yours who has watched many *Star Trek* episodes and movies says, "I thought that black holes pulled everything into them. Why then do astronomers think that black holes can explain the great *outpouring* of energy from quasars?" How would you respond?

It is true that black holes attract matter to them, and when that matter moves inside the event horizon, it is no longer observable. However, remarkable things happen when matter is close to but still outside the event horizon. As the matter swirls toward the black hole in an accretion disk, it is accelerated to ever-higher speeds by the gravitational force of the black hole; collisions of atoms in the gas increase in frequency; the gas becomes hot. Hot gas radiates energy, and it is the radiation from the hot gas that we see as a tremendous outpouring of energy. But all this gas is still outside the event horizon of the black hole.(Students who want to read more about these processes can refer to some of the articles and websites suggested in the "For Further Exploration" section of this chapter or in the chapter on Black Holes and Curved Spacetime.)

13. Could the Milky Way ever become an active galaxy? Is it likely to ever be as luminous as a quasar?

The Milky Way could indeed become an active galaxy (at least briefly) if the central supermassive black hole was able to consume a significant amount of mass. There are clouds of dust and gas as well as several stars that orbit the central black hole extremely rapidly. If this material (or other material external to this region) were to fall into the black hole's accretion disk, the Milky Way's center would erupt into bursts of radiation. It is not likely, however, that the Milky Way could ever achieve the luminosity of a quasar. The supermassive black hole at the center of the Milky Way is several hundred times smaller than we believe those in powerful quasars are, and while some mass is almost inevitably going to fall into it, that total mass is going to be substantially less than the 10 solar masses per year that is estimated to be the fuel supply for quasars.

14. Why are quasars generally so much more luminous (why do they put out so much more energy) than active galaxies?

Quasars represent an early stage in galaxy formation when a lot of mass was being funneled toward the central black hole. This constant supply of mass to very large supermassive black holes allowed quasars to shine with the tremendous luminosities that render them visible all the way across the universe. On the other hand, active galaxies probably have either smaller supermassive black holes at their centers, or less mass to supply their accretion disks, or a combination of both. In short, while the general mechanism for generating energy is similar between quasars and active galaxies, active galaxies tend to have less voracious appetites and a smaller food supply.

15. Show that no matter how big a redshift (*z*) we measure, *v/c* will never be greater than 1. (In other words, no galaxy we observe can be moving away faster than the speed of light.)

If z becomes a truly very large number (i.e., much larger than 1), then we can ignore the 1's in the equation given in Example 27.1 Recession Speed of a Quasar, since they are insignificant relative to z. In that case, the equation reduces to a limit of

$$\frac{v}{c} = \frac{z^2}{z^2} = 1.$$

This means that v can approach c but can never exceed it.

16. If a quasar has a redshift of 3.3, at what fraction of the speed of light is it moving away from us?

$$\frac{v}{c} = \frac{(3.3\,+\,1)^2 - 1}{(3.3\,+\,1)^2 + 1} = \frac{17.49}{19.49} = 0.90,$$

If the redshift is 3.3, then the quasar is moving away from us at 90% the speed of light.

17. The quasar that appears the brightest in our sky, 3C 273, is located at a distance of 2.4 billion light-years. The Sun would have to be viewed from a distance of 1300 light-years to have the same apparent magnitude as 3C 273. Using the inverse square law for light, estimate the luminosity of 3C 273 in solar units.

$$\left(\frac{2.4 \times 10^{9}\ \text{light-years}}{1300\ \text{light-years}}\right)^{2} = 3.4 \times 10^{12}$$

The quasar must be 3.4×10^{12} times more luminous than the Sun. This is at least 30 times more luminous than the entire Milky Way!