OpenStax Astronomy, Ch.28: WS Solutions (Apr-2021)

Solutions

1. How are distant (young) galaxies different from the galaxies that we see in the universe today?

Distant galaxies look very different from nearby galaxies such as the Milky Way or Andromeda. Young galaxies do not fit in Hubble's galaxy classification scheme. These distant systems lack identifiable bulges or spiral arms. In addition to being visually different, the distant galaxies are also smaller, fainter, and gas-rich when compared to galaxies in the nearby universe.

2. What is the evidence that star formation began when the universe was only a few hundred million years old?

Using powerful telescopes, we observe galaxies of stars so far away that they must have formed more than 13 billion years ago. Even these early galaxies show evidence of heavier elements in their spectra, indicating that massive stars must have gone through their lives and exploded as supernovae. We also directly observe stars today, such as in the Milky Way's globular clusters, that apparently have ages of more than 13 billion years.

3. Describe the evolution of an elliptical galaxy. How does the evolution of a spiral galaxy differ from that of an elliptical?

Some giant ellipticals probably formed in a dramatic gravitational collapse of huge isolated clouds of gas and dark matter. But most ellipticals seem to have formed from the "bottom up": the assembly by gravity of small pieces of galaxies that had already formed their stars. Star formation in most ellipticals essentially stopped when the universe was less than half its current age. The bulges of spirals may have formed very similarly, but the disks formed over a more protracted period, and their growth included fresh gas from small galaxies and streams of gas flowing under the influence of gravity. The gas was able to lose energy and settle into a disk and also to fuel star formation that continues today in spiral galaxies.

4. Explain what we mean when we call the universe homogeneous and isotropic. Would you say that the distribution of elephants on Earth is homogeneous and isotropic? Why?

Homogeneous means uniform, and isotropic means it looks the same in all directions. On the largest scales (larger than galaxy superclusters) the universe does appear that way: we see the same sort of pattern no matter where we look. Since elephants are strongly clustered in a few parts of Africa and Asia but mostly absent elsewhere, their distribution on Earth is neither homogeneous nor isotropic.

5. Describe the organization of galaxies into groupings, from the Local Group to superclusters.

The Milky Way is one of three spiral galaxies (with the Andromeda galaxy and M33) in the Local Group. The Local Group is part of the Virgo supercluster, which is centered on the massive Virgo cluster of galaxies. On even larger scales, clusters and superclusters of galaxies are distributed on sheets and filaments like beads on a string spanning hundreds of millions of light-years.

6. What is the evidence that a large fraction of the matter in the universe is invisible?

The existence of dark matter is supported by three main pieces of evidence. (1) Stars and clusters orbit the centers of their host galaxies faster than they would if only visible matter (stars, gas, dust, planets) made up most of the mass. (2) Galaxies in clusters likewise move much faster than can be explained by the gravity of only luminous matter. (3) Galaxy clusters emit copious X-rays best explained by fast motion of gas particles under the influence of gravity much stronger than just the luminous matter can supply.

7. When astronomers make maps of the structure of the universe on the largest scales, how do they find the superclusters of galaxies to be arranged?

> To the surprise of astronomers, they found the superclusters to be arranged in filaments and sheets surrounding emptier regions that are now called voids. The layout reminds them of good Swiss cheese, where the walls of cheese surround large empty regions.

8. Describe how you might use the color of a galaxy to determine something about what kinds of stars it contains.

> Massive, hot blue stars have lifetimes on the main sequence of only a few million years. If we see a galaxy that is blue, it must have a significant population of stars in it that are very hot and therefore young. (Note that while white dwarfs and the central stars of planetary nebulae are also very blue and very hot, they are intrinsically so faint that they do not contribute significantly to the total luminosity emitted by a galaxy.) A red galaxy must contain mostly old stars.

9. Given the ideas presented here about how galaxies form, would you expect to find a giant elliptical galaxy in the Local Group? Why or why not? Is there in fact a giant elliptical in the Local Group?

> Giant elliptical galaxies are usually found in the dense regions in the centers of rich clusters of galaxies, probably because many giant ellipticals are formed by the merger of smaller galaxies. The Local Group is a sparsely populated cluster of not very high density. It would be surprising to find a giant elliptical in such a region, and indeed none is a member of the Local Group. The Local Group does contain dwarf ellipticals.

10. Can an elliptical galaxy evolve into a spiral? Explain your answer. Can a spiral turn into an elliptical? How?

> No, an elliptical cannot turn into a spiral because an elliptical contains too little dust and gas to form the disks and young stars found in spiral galaxies. While a single spiral galaxy cannot turn into an elliptical galaxy, some smaller spiral galaxies may have been involved in collisions that eventually built up a giant elliptical in a rich cluster.

11. Suppose you are standing in the center of a large, densely populated city that is exactly circular, surrounded by a ring of suburbs with lower-density population, surrounded in turn by a ring of farmland. From this specific location, would you say the population distribution is isotropic? Homogeneous?

> The distribution of population in this example is isotropic (the same in all directions) but it is not homogeneous. The density is higher near the center of the city and drops as you move away from the city center.

12. Astronomers have been making maps by observing a slice of the universe and seeing where the galaxies lie within that slice. If the universe is isotropic and homogeneous, why do they need more than one slice? Suppose they now want to make each slice extend farther into the universe. What do they need to do?

> Although the universe is homogenous and isotropic if we compare large volumes of space, any given small region may not be representative. We are not even sure yet how large a volume we must observe in order to have a representative sample or slice of the universe. Therefore, in order to determine the structure of the universe, it is necessary to sample many different regions in order to make sure we have sampled

the full range of conditions. To make each sample or slice extend farther into the universe, it is necessary to observe fainter galaxies at larger redshifts.

13. Galaxies are found in the "walls" of huge voids; very few galaxies are found in the voids themselves. The text says that the structure of filaments and voids has been present in the universe since shortly after the expansion began 13.8 billion years ago. In science, we always have to check to see whether some conclusion is contradicted by any other information we have. In this case, we can ask whether the voids would have filled up with galaxies in roughly 14 billion years. Observations show that in addition to the motion associated with the expansion of the universe, the galaxies in the walls of the voids are moving in random directions at typical speeds of 300 km/s. At least some of them will be moving into the voids. How far into the void will a galaxy move in 14 billion years? Is it a reasonable hypothesis that the voids have existed for 14 billion years?

In 14 billion years, an object moving at 300 km/s will move a distance d given by $d = v \times t = 300 \times 14 \times 10^9$ y $\times 3.16 \times 10^7$ s/y $= 1.3 \times 10^{20}$ km, since there are 3.16×10^7 s/yr. There are 9.46×10^{12} km/light-year, so in 14 billion years the galaxy will move

$$d = \frac{1.3 \times 10^{20}}{9.46 \times 10^{12}} = 13.7 \text{ million light-years}$$

.The text says that the typical diameter of a void is 150 million light-years, so galaxies would move only about 10% of the way into the void in the entire lifetime of the universe, and the void would still exist.

14. Assume that dark matter is uniformly distributed throughout the Milky Way, not just in the outer halo but also throughout the bulge and in the disk, where the solar system lives. How much dark matter would you expect there to be inside the solar system? Would you expect that to be easily detectable? Hint: For the radius of the Milky Way's dark matter halo, use R = 300,000 light-years; for the solar system's radius, use 100 AU; and start by calculating the ratio of the two volumes.

Remember that the formula for volume is $V = (4/3)\pi R^3$. If the dark matter is uniformly distributed, then the solar system's share of the Milky Way's dark matter should be the same as the solar system's share of the Milky Way's volume, which we can calculate:

$$\frac{\text{MDM}_{\text{SS}}}{\text{MDM}_{\text{MW}}} = \frac{V_{\text{SS}}}{V_{\text{MW}}} = \frac{(4/3)\pi\, R_{\text{SS}}^3}{(4/3)\pi\, R_{\text{MW}}^3}$$

. All the constant terms cancel, leaving us with

$$\frac{\text{MDM}_{\text{SS}}}{\text{MDM}_{\text{MW}}} = \frac{R_{\text{SS}}^3}{R_{\text{MW}}^3} = \left(\frac{R_{\text{SS}}}{R_{\text{MW}}}\right)^3$$

. Substituting the numbers for those radii, we find

$$\frac{\text{MDM}_{\text{SS}}}{\text{MDM}_{\text{MW}}} = \left(\frac{100 \text{ AU}}{300{,}000 \text{ light-years}}\right)^3$$

$$= \left(\frac{100 \text{ AU}}{300{,}000 \text{ light-years}} \times 67{,}000 \text{ AU/light-years}\right)^3 = 1.25 \times 10^{-25}.$$

If the total mass of dark matter is 10^{12} solar masses, the solar system's share of that is only $1.25 \times 10^{-25} \times 10^{12}$ solar masses $= 1.25 \times 10^{-13}$ solar masses—less than one-trillionth of the Sun's mass, or about the same mass as a small asteroid, but spread out over the entire solar system. The solar system's mass is totally dominated by the Sun, and any dark matter will be very hard to detect.

15. The first objects to collapse gravitationally after the Big Bang might have been globular cluster-size galaxy pieces, with masses around 10^6 solar masses. Suppose you merge two of those together, then merge two larger pieces together, and so on, Lego-style, until you reach a Milky Way mass, about 10^{12} solar masses. How many merger generations would that take, and how many original pieces? (Hint: Think in powers of 2.)

$$\frac{10^{12}\ M_{\text{Sun}}}{10^{6}\ M_{\text{Sun}}} = 10^{6}$$

, so we need to grow the small galaxy pieces by a factor of a million to reach a Milky Way mass. Every merger doubles the size, so we can estimate this as 2x ≈ 106, and figure out what x is. In your head or with a calculator, you can verify that 23 = 8, 26 = 64, and 212 = 4096, and finally 220 = 106. So you'd need about 20 generations of mergers to grow globular clusters into a Milky Way. The number of pieces is just the ratio of the large final size to the small original size: $\text{N} = \frac{10^{12}\ M_{\text{Sun}}}{10^{6}\ M_{\text{Sun}}}$,

$$N = \frac{10^{12}\ M_{\text{Sun}}}{10^{6}\ M_{\text{Sun}}}$$

, or N = 106. You'd need about a million globular cluster-size galaxy pieces to build the Milky Way Galaxy.