

OpenStax Astronomy, Ch.25: WS Solutions (Apr-2021)

Solutions

1. Explain why we see the Milky Way as a faint band of light stretching across the sky.

The Milky Way in the sky is our particular view of the inward part of the Milky Way Galaxy as seen from our location within the Galaxy's disk. Since we are part of the disk, we see a band of diffuse light that completely encircles us.

2. Explain where in a spiral galaxy you would expect to find globular clusters, molecular clouds, and atomic hydrogen.

Globular clusters consist of older population II stars and are typically found in the spherical haloes of spiral galaxies. Clouds of molecular gas and atomic hydrogen are the sites of current or future star formation and are typically found in the disk; they are especially concentrated along the spiral arms.

3. Describe several characteristics that distinguish population I stars from population II stars.

In our Galaxy, population I stars are restricted to the disk. As such, they have circular co-planar orbits of relatively high velocity. Compared to population II stars, they are richer in elements heavier than hydrogen and helium—although population I stars in the outer disk are significantly depleted in these elements. They have a range of ages—from the most recently born to more than 10 billion years. Population II stars occupy the spheroidal component of the Galaxy—and the spheroids of other spiral galaxies. They have orbits that are highly elliptical and with little sense of a common plane. Their overall rotational velocity is very low. Their abundances of elements heavier than hydrogen and helium are much lower than in population I stars—with the exception of the population II stars occupying the galactic bulge. Almost all population II stars are ancient, with ages of 10 to 13 billion years.

4. Briefly describe the main parts of our Galaxy.

Our Milky Way Galaxy contains a barred bulge; a thin disk of stars, gas, and dust with concentrations in spiral arms; a much less substantial thick disk of stars; and a spheroidal halo of ancient stars and globular star clusters. Deep within the central bulge dwells a supermassive black hole. In addition, there appear to be considerable amounts of unknown dark matter surrounding the Galaxy.

5. Describe the evidence indicating that a black hole may be at the center of our Galaxy.

The most compelling evidence consists of recorded stellar tracks within 1 arcsecond (0.13 light-years) of the galactic center, whose orbital periods and radii indicate the presence of a central source of gravity having a mass equivalent to more than 4 million Suns, yet being concentrated within a radius less than 17 light-hours. Other evidence includes unique radio and X-ray emissions from the galactic center.

6. Explain why the abundances of heavy elements in stars correlate with their positions in the Galaxy.

The lowest abundances of elements heavier than hydrogen and helium are found in stars belonging to the galactic halo. These stars are also known to be very ancient—formed before a lot of supernovae had a chance to explode and enrich the interstellar medium with heavier elements. Much higher abundances are found in the younger disc component of the Galaxy, which is explained by the disk having been formed after the halo. There prior generations of stars have had time to seed the disk's



interstellar medium with heavy elements. Stars and gas and dust were most concentrated in the inner bulge of the Galaxy. There more star formation occurred and enriched the interstellar medium there to a greater extent.



7. What will be the long-term future of our Galaxy?

In a few billion years, the Milky Way Galaxy and Andromeda galaxy (M31) will merge. During the merger process, great tidal streams of stars will be drawn out of both galaxies. Ultimately, the two spiral galaxies will blend into a single elliptical galaxy surrounded by tidal streams. Students might also mention that as time goes on, and more cycles of star birth and death occur in the Galaxy, there will be a greater and greater enrichment of the heavier elements.

8. Suppose the Milky Way was a band of light extending only halfway around the sky (that is, in a semicircle). What, then, would you conclude about the Sun's location in the Galaxy? Give your reasoning.

If the Milky Way appeared to extend only halfway around the sky, then we would be at its outer edge. Try sketching a picture to show that if we were located in such a position, the band of light produced by stars in the disk of the Milky Way would stretch over only 180°.

9. The globular clusters revolve around the Galaxy in highly elliptical orbits. Where would you expect the clusters to spend most of their time? (Think of Kepler's laws.) At any given time, would you expect most globular clusters to be moving at high or low speeds with respect to the center of the Galaxy? Why?

Most globular clusters would spend their time at great distances from the nucleus. Kepler's second law relating to equal areas indicates that the globulars are moving most slowly when they are at the greatest distance from the nucleus of the Galaxy. Therefore, the globulars will spend most of their time moving at slow speeds in the part of their orbit that is farthest from the galactic center.

10. Shapley used the positions of globular clusters to determine the location of the galactic center. Could he have used open clusters? Why or why not?

Shapley could not have used open clusters because they lie in the plane of the Galaxy. Dust in the plane absorbs starlight so efficiently that open clusters cannot be seen at distances of more than a few thousand light-years. Therefore, they cannot be used to map the extent of the Galaxy, which is about 100,000 light-years in diameter, nor can they be seen at the distance of the galactic center, which is about 25,000 light-years distant.

11. Consider the following five kinds of objects: open cluster, giant molecular cloud, globular cluster, group of O and B stars, and planetary nebulae.

- A. Which occur only in spiral arms?
- B. Which occur only in the parts of the Galaxy other than the spiral arms?
- C. Which are thought to be very young?
- D. Which are thought to be very old?
- E. Which have the hottest stars?

(Students may need reminding that planetary nebulae are produced by low-mass stars that are on the way to becoming white dwarfs.) A. open cluster, giant molecular cloud, group of O and B stars; B. globular cluster, many (but not all) planetary nebulae; C. some open clusters, giant molecular cloud, group of O and B stars; D. globular cluster, some planetary nebulae; E. planetary nebula central stars are the hottest stars known; the youngest open clusters, group of O and B stars, some molecular clouds contain fairly hot stars.





12. The dwarf galaxy in Sagittarius is the one closest to the Milky Way, yet it was discovered only in 1994. Can you think of a reason it was not discovered earlier? (Hint: Think about what else is in its constellation.)

Given its name, this dwarf galaxy is located in the constellation of Sagittarius, which is also the direction toward the center of the Milky Way. This dwarf galaxy is difficult to detect for two reasons. First, obscuration by interstellar dust is strong in this direction, so the stars are dimmed by interstellar extinction. Second, this region of the sky has a high density of stars belonging to the Milky Way Galaxy's inner disk and bulge, so it is hard to pick out the members of the Sagittarius dwarf galaxy from all the foreground stars.

13. Why does star formation occur primarily in the disk of the Galaxy?

Star formation occurs in the disk because the dust and gas needed to form new stars are now found only in the disk.

14. Where in the Galaxy would you expect to find Type II supernovae, which are the explosions of massive stars that go through their lives very quickly? Where would you expect to find Type I supernovae, which involve the explosions of white dwarfs?

Supernovae of Type II (the explosions of massive stars that have short lives and were thus born relatively recently) are likely to be found in the disk, especially in the spiral arms. This is where star formation is still going on. Supernovae of Type I (involving white dwarfs in closely interacting binary systems) can be found in both the disk and the halo.

15. Assume that the Sun orbits the center of the Galaxy at a speed of 220 km/s and a distance of 26,000 light-years from the center.

A. Calculate the circumference of the Sun's orbit, assuming it to be approximately circular. (Remember that the circumference of a circle is given by $2\pi R$, where R is the radius of the circle. Be sure to use consistent units. The conversion from light-years to km/s can be found in an online calculator or appendix, or you can calculate it for yourself: the speed of light is 300,000 km/s, and you can determine the number of seconds in a year.)

B. Calculate the Sun's period, the "galactic year." Again, be careful with the units. Does it agree with the number we gave above?

A. Circumference of orbit = $2\pi \times (26,000 \text{ light-years}) = 1.6 \times 10^5 \text{ light-years}$. Since there are $9.5 \times 10^{12} \text{ km/light-years}$, the circumference = $1.5 \times 10^{18} \text{ km}$. (The size of the light-year is worked out step by step in the chapter on Science and the Universe: A

Brief Tour.); B.
$$\text{period of rotation} = \frac{\text{circumference}}{\text{orbital velocity}} = \frac{1.5 \times 10^{18}}{220} = 6.8 \times 10^{15} \text{ s} = 2.2 \times 10^8 \text{ y}$$

16. If our solar system is 4.6 billion years old, how many galactic years has planet Earth been around?

If a galactic year is 2.2×10^8 years, then in 4.6 billion (4.6×10^9) years, the Sun has been "around the block" about 21 times.



17. The best evidence for a black hole at the center of the Galaxy also comes from the application of Kepler's third law. Suppose a star at a distance of 20 light-hours from the center of the Galaxy has an orbital speed of 6200 km/s. How much mass must be located inside its orbit?

In order to use Kepler's third law, we have to express the period in years, the distance in AU, and the mass in solar masses. A distance of 20 light-hours = $(20 \times 86,400 / 24 \times 300,000) = 2.2 \times 10^{10}$ km since there are 3600 s/hour and light travels 300,000

km/sec. That means the size of the orbit is $D = \frac{2.2 \times 10^{10} \text{ km}}{1.5 \times 10^8 \text{ km/AU}} = 147 \text{ AU}$. The period

of revolution is $P = 2.2 \times 10^{10} \times \frac{2\pi}{6250} = 2.21 \times 10^7 \text{ s} = 0.7 \text{ y}$. Substituting into Kepler's third law, we have $M_{\text{BH}} \times (0.7)^2 = (147)^3$ or $M_{\text{BH}} = 6.5 \times 10^6 M_{\text{Sun}}$.

18. The next step in deciding whether the object in Question 17 is a black hole is to estimate the density of this mass. Assume that all of the mass is spread uniformly throughout a sphere with a radius of 20 light-hours. What is the density in kg/km³?

(Remember that the volume of a sphere is given by $V = \frac{4}{3}\pi R^3$.) Explain why the density might be even higher than the value you have calculated. How does this density compare with that of the Sun or other objects we have talked about in this book?

The density is given by $\rho = \frac{M_{\text{BH}}}{4/3\pi R^3} = \frac{(6.5 \times 10^6)(2 \times 10^{30} \text{ kg})}{(4/3 \times \pi) \times (2.2 \times 10^{10} \text{ km})^3} = 2.9 \times 10^5 \text{ kg/km}^3$.

If the mass is contained within a singularity as expected for a black hole, the density is higher yet. The density is much higher than the density of any ordinary object discussed in this text. What this means is that the mass around which this star is orbiting cannot be composed of ordinary stars. The calculated density is not as high as the densities calculated for white dwarfs and neutron stars in the answers to questions in the chapter on The Death of Stars. Given this limit, one might speculate whether the mass consists of a cluster of white dwarfs or neutron stars. However, if the neutron stars are packed too closely together, they will begin to merge and form a black hole. Since a star has been found that passes within 17 light-hours of the galactic center, this puts even tighter constraints on the density of the mass lying within its orbit. Thus, there appears to be no way of avoiding the conclusion that there is a black hole at the center of the Galaxy.