23.E: The Death of Stars (Exercises)

For Further Explanation

Articles

Death of Stars

Hillebrandt, W., et al. "How To Blow Up a Star." *Scientific American* (October 2006): 42. On supernova mechanisms.

Irion, R. "Pursuing the Most Extreme Stars." *Astronomy* (January 1999): 48. On pulsars.

Kalirai, J. "New Light on Our Sun's Fate." *Astronomy* (February 2014): 44. What will happen to stars like our Sun between the main sequence and the white dwarf stages.

Kirshner, R. "Supernova 1987A: The First Ten Years." *Sky & Telescope* (February 1997): 35.

Maurer, S. "Taking the Pulse of Neutron Stars." *Sky & Telescope* (August 2001): 32. Review of recent ideas and observations of pulsars.

Zimmerman, R. "Into the Maelstrom." *Astronomy* (November 1998): 44. About the Crab Nebula.

Gamma-Ray Bursts

Fox, D. & Racusin, J. "The Brightest Burst." *Sky & Telescope* (January 2009): 34. Nice summary of the brightest burst observed so far, and what we have learned from it.

Nadis, S. "Do Cosmic Flashes Reveal Secrets of the Infant Universe?" *Astronomy* (June 2008): 34. On different types of gamma-ray bursts and what we can learn from them.

Naeye, R. "Dissecting the Bursts of Doom." *Sky & Telescope* (August 2006): 30. Excellent review of gamma-ray bursts—how we discovered them, what they might be, and what they can be used for in probing the universe.

Zimmerman, R. "Speed Matters." *Astronomy* (May 2000): 36. On the quick-alert networks for finding afterglows.

Zimmerman, R. "Witness to Cosmic Collisions." *Astronomy* (July 2006): 44. On the Swift mission and what it is teaching astronomers about gamma-ray bursts.

Websites

Death of Stars

Crab Nebula: http://chandra.harvard.edu/xray_sources/crab/crab.html. A short, colorfully written introduction to the history and science involving the best-known supernova remant.

Introduction to Neutron Stars: https://www.astro.umd.edu/~miller/nstar.html. Coleman Miller of the University of Maryland maintains this site, which goes from easy to hard as you get into it, but it has lots of good information about corpses of massive stars.

Introduction to Pulsars (by Maryam Hobbs at the Australia National Telescope Facility): http://www.atnf.csiro.au/outreach/education/everyone/pulsars/index.html.

Magnetars, Soft Gamma Repeaters, and Very Strong Magnetic Fields: http://solomon.as.utexas.edu/magnetar.html. Robert Duncan, one of the originators of the idea of magnetars, assembled this site some years ago.

Gamma-Ray Bursts

Brief Intro to Gamma-Ray Bursts (from PBS' *Seeing in the Dark*): http://www.pbs.org/seeinginthedark/astronomy-topics/gamma-ray-bursts.html.

Discovery of Gamma-ray Bursts: http://science.nasa.gov/science-news/science-at-nasa/1997/ast19sep97_2/.

Gamma-Ray Bursts: Introduction to a Mystery (at NASA's Imagine the Universe site): http://imagine.gsfc.nasa.gov/docs/science/know_l1/bursts.html.

Introduction from the *Swift* Satellite Site: swift.sonoma.edu/about_swift/grbs.html.

Missions to Detect and Learn More about Gamma-ray Bursts:

- Fermi Space Telescope: http://fermi.gsfc.nasa.gov/public/.
- *INTEGRAL* Spacecraft: www.esa.int/science/integral.
- *SWIFT* Spacecraft: swift.sonoma.edu/.

Videos

Death of Stars

BBC interview with Antony Hewish: http://www.bbc.co.uk/archive/scientists/10608.shtml. (40:54).

Black Widow Pulsars: The Vengeful Corpses of Stars: https://www.youtube.com/watch?v=Fn-3G_N0hy4. A public talk in the Silicon Valley Astronomy Lecture Series by Dr. Roger Romani (Stanford University) (1:01:47).

Hubblecast 64: It all ends with a bang!: http://www.spacetelescope.org/videos/hubblecast64a/. HubbleCast Program introducing Supernovae with Dr. Joe Liske (9:48).

Space Movie Reveals Shocking Secrets of the Crab Pulsar: http://hubblesite.org/newscenter/archive/releases/2002/24/video/c/. A sequence of Hubble and Chandra Space Telescope images of the central regions of the Crab Nebula have been assembled into a very brief movie accompanied by animation showing how the pulsar affects its environment; it comes with some useful background material (40:06).

Gamma-Ray Bursts

Gamma-Ray Bursts: The Biggest Explosions Since the Big Bang!: https://www.youtube.com/watch?v=ePo_EdgV764. Edo Berge in a popular-level lecture at Harvard (58:50).

Gamma-Ray Bursts: Flashes in the Sky: https://www.youtube.com/watch?v=23EhcAP3O8Q. American Museum of Natural History Science Bulletin on the *Swift* satellite (5:59).

Overview Animation of Gamma-Ray Burst: http://news.psu.edu/video/296729/2013/11/27/overview-animation-gamma-ray-burst. Brief Animation of what causes a long-duration gamma-ray burst (0:55).

Collaborative Group Activities

1. Someone in your group uses a large telescope to observe an expanding shell of gas. Discuss what measurements you could make to determine whether you have discovered a planetary nebula or the remnant of a supernova explosion.
2. The star Sirius (the brightest star in our northern skies) has a white-dwarf companion. Sirius has a mass of about 2 M_{Sun} and is still on the main sequence, while its companion is already a star corpse. Remember that a white dwarf can't have a mass greater than 1.4 \(M_{\text{Sun}}|). Assuming that the two stars formed at the same time, your group should discuss how Sirius could have a white-dwarf companion. Hint: Was the initial mass of the white-dwarf star larger or smaller than that of Sirius?
3. Discuss with your group what people today would do if a brilliant star suddenly became visible during the daytime? What kind of fear and superstition might result from a supernova that was really bright in our skies? Have your group invent some headlines that the tabloid newspapers and the less responsible web news outlets would feature.
4. Suppose a supernova exploded only 40 light-years from Earth. Have your group discuss what effects there may be on Earth when the radiation reaches us and later when the particles reach us. Would there be any way to protect people from the supernova effects?
5. When pulsars were discovered, the astronomers involved with the discovery talked about finding "little green men." If you had been in their shoes, what tests would you have performed to see whether such a pulsating source of radio waves was natural or the result of an alien intelligence? Today, several groups around the world are actively searching for possible radio signals from intelligent civilizations. How might you expect such signals to differ from pulsar signals?
6. Your little brother, who has not had the benefit of an astronomy course, reads about white dwarfs and neutron stars in a magazine and decides it would be fun to go near them or even try to land on them. Is this a good idea for future tourism? Have your group make a list of reasons it would not be safe for children (or adults) to go near a white dwarf and a neutron star.
7. A lot of astronomers' time and many instruments have been devoted to figuring out the nature of gamma-ray bursts. Does your group share the excitement that astronomers feel about these mysterious high-energy events? What are some reasons that people outside of astronomy might care about learning about gamma-ray bursts?

Review Questions

1. How does a white dwarf differ from a neutron star? How does each form? What keeps each from collapsing under its own weight?
2. Describe the evolution of a star with a mass like that of the Sun, from the main-sequence phase of its evolution until it becomes a white dwarf.
3. Describe the evolution of a massive star (say, 20 times the mass of the Sun) up to the point at which it becomes a supernova. How does the evolution of a massive star differ from that of the Sun? Why?
4. How do the two types of supernovae discussed in this chapter differ? What kind of star gives rise to each type?
5. A star begins its life with a mass of 5 M_{Sun} but ends its life as a white dwarf with a mass of 0.8 M_{Sun}. List the stages in the star's life during which it most likely lost some of the mass it started with. How did mass loss occur in each stage?
6. If the formation of a neutron star leads to a supernova explosion, explain why only three of the hundreds of known pulsars are found in supernova remnants.
7. How can the Crab Nebula shine with the energy of something like 100,000 Suns when the star that formed the nebula exploded almost 1000 years ago? Who "pays the bills" for much of the radiation we see coming from the nebula?
8. How is a nova different from a type Ia supernova? How does it differ from a type II supernova?
9. Apart from the masses, how are binary systems with a neutron star different from binary systems with a white dwarf?
10. What observations from SN 1987A helped confirm theories about supernovae?
11. Describe the evolution of a white dwarf over time, in particular how the luminosity, temperature, and radius change.
12. Describe the evolution of a pulsar over time, in particular how the rotation and pulse signal changes over time.
13. How would a white dwarf that formed from a star that had an initial mass of 1 M_{Sun} be different from a white dwarf that formed from a star that had an initial mass of 9 M_{Sun}?
14. What do astronomers think are the causes of longer-duration gamma-ray bursts and shorter-duration gamma-ray bursts?
15. How did astronomers finally solve the mystery of what gamma-ray bursts were? What instruments were required to find the solution?

Thought Questions

1. Arrange the following stars in order of their evolution:
   1. A star with no nuclear reactions going on in the core, which is made primarily of carbon and oxygen.
   2. A star of uniform composition from center to surface; it contains hydrogen but has no nuclear reactions going on in the core.
   3. A star that is fusing hydrogen to form helium in its core.
   4. A star that is fusing helium to carbon in the core and hydrogen to helium in a shell around the core.
   5. A star that has no nuclear reactions going on in the core but is fusing hydrogen to form helium in a shell around the core.
2. Would you expect to find any white dwarfs in the Orion Nebula? (See The Birth of Stars and the Discovery of Planets outside the Solar System to remind yourself of its characteristics.) Why or why not?
3. Suppose no stars more massive than about 2 \(M_{\text{Sun}}|) had ever formed. Would life as we know it have been able to develop? Why or why not?
4. Would you be more likely to observe a type II supernova (the explosion of a massive star) in a globular cluster or in an open cluster? Why?
5. Astronomers believe there are something like 100 million neutron stars in the Galaxy, yet we have only found about 2000 pulsars in the Milky Way. Give several reasons these numbers are so different. Explain each reason.
6. Would you expect to observe every supernova in our own Galaxy? Why or why not?
7. The Large Magellanic Cloud has about one-tenth the number of stars found in our own Galaxy. Suppose the mix of high- and low-mass stars is exactly the same in both galaxies. Approximately how often does a supernova occur in the Large Magellanic Cloud?
8. Look at the list of the nearest stars in Appendix I. Would you expect any of these to become supernovae? Why or why not?
9. If most stars become white dwarfs at the ends of their lives and the formation of white dwarfs is accompanied by the production of a planetary nebula, why are there more white dwarfs than planetary nebulae in the Galaxy?
10. If a 3 and 8 M_{Sun} star formed together in a binary system, which star would:
    1. Evolve off the main sequence first?
    2. Form a carbon- and oxygen-rich white dwarf?
    3. Be the location for a nova explosion?

11. You have discovered two star clusters. The first cluster contains mainly main-sequence stars, along with some red giant stars and a few white dwarfs. The second cluster also contains mainly main-sequence stars, along with some red giant stars, and a few neutron stars—but no white dwarf stars. What are the relative ages of the clusters? How did you determine your answer?
12. A supernova remnant was recently discovered and found to be approximately 150 years old. Provide possible reasons that this supernova explosion escaped detection.
13. Based upon the evolution of stars, place the following elements in order of least to most common in the Galaxy: gold, carbon, neon. What aspects of stellar evolution formed the basis for how you ordered the elements?
14. What observations or types of telescopes would you use to distinguish a binary system that includes a main-sequence star and a white dwarf star from one containing a main-sequence star and a neutron star?
15. How would the spectra of a type II supernova be different from a type Ia supernova? Hint: Consider the characteristics of the objects that are their source.

Figuring for Yourself

1. The ring around SN 1987A (Figure $23.3.4$ in Section 23.3) initially became illuminated when energetic photons from the supernova interacted with the material in the ring. The radius of the ring is approximately 0.75 light-year from the supernova location. How long after the supernova did the ring become illuminated?
2. What is the acceleration of gravity (g) at the surface of the Sun? (See Appendix E for the Sun's key characteristics.) How much greater is this than g at the surface of Earth? Calculate what you would weigh on the surface of the Sun. Your weight would be your Earth weight multiplied by the ratio of the acceleration of gravity on the Sun to the acceleration of gravity on Earth. (Okay, we know that the Sun does not have a solid surface to stand on and that you would be vaporized if you were at the Sun's photosphere. Humor us for the sake of doing these calculations.)
3. What is the escape velocity from the Sun? How much greater is it than the escape velocity from Earth?
4. What is the average density of the Sun? How does it compare to the average density of Earth?
5. Say that a particular white dwarf has the mass of the Sun but the radius of Earth. What is the acceleration of gravity at the surface of the white dwarf? How much greater is this than g at the surface of Earth? What would you weigh at the surface of the white dwarf (again granting us the dubious notion that you could survive there)?
6. What is the escape velocity from the white dwarf in the previous exercise (5)? How much greater is it than the escape velocity from Earth?
7. What is the average density of the white dwarf in Exercise 5? How does it compare to the average density of Earth?
8. Now take a neutron star that has twice the mass of the Sun but a radius of 10 km. What is the acceleration of gravity at the surface of the neutron star? How much greater is this than g at the surface of Earth? What would you weigh at the surface of the neutron star (provided you could somehow not become a puddle of protoplasm)?
9. What is the escape velocity from the neutron star in the previous exercise (8)? How much greater is it than the escape velocity from Earth?
10. What is the average density of the neutron star in Exercise 8? How does it compare to the average density of Earth?
11. One way to calculate the radius of a star is to use its luminosity and temperature and assume that the star radiates approximately like a blackbody. Astronomers have measured the characteristics of central stars of planetary nebulae and have found that a typical central star is 16 times as luminous and 20 times as hot (about 110,000 K) as the Sun. Find the radius in terms of the Sun's. How does this radius compare with that of a typical white dwarf?
12. According to a model described in the text, a neutron star has a radius of about 10 km. Assume that the pulses occur once per rotation. According to Einstein's theory of relatively, nothing can move faster than the speed of light. Check to make sure that this pulsar model does not violate relativity. Calculate the rotation speed of the Crab Nebula pulsar at its equator, given its period of 0.033 s. (Remember that distance equals velocity × time and that the circumference of a circle is given by $2\pi R$).
13. Do the same calculations as in the previous exercise but for a pulsar that rotates 1000 times per second.
14. If the Sun were replaced by a white dwarf with a surface temperature of 10,000 K and a radius equal to Earth's, how would its luminosity compare to that of the Sun?
15. A supernova can eject material at a velocity of 10,000 km/s. How long would it take a supernova remnant to expand to a radius of 1 AU? How long would it take to expand to a radius of 1 light-years? Assume that the expansion velocity remains constant and use the relationship:

$$\text{expansion time } = \frac{\text{distance}}{\text{expansion velocity}}.$$

16. A supernova remnant was observed in 2007 to be expanding at a velocity of 14,000 km/s and had a radius of 6.5 light-years. Assuming a constant expansion velocity, in what year did this supernova occur?
17. The ring around SN 1987A (Figure $23.3.4$ in Section 23.3) started interacting with material propelled by the shockwave from the supernova beginning in 1997 (10 years after the explosion). The radius of the ring is approximately 0.75 light-year from the supernova location. How fast is the supernova material moving, assume a constant rate of motion in km/s?
18. Before the star that became SN 1987A exploded, it evolved from a red supergiant to a blue supergiant while remaining at the same luminosity. As a red supergiant, its surface temperature would have been approximately 4000 K, while as a blue supergiant, its surface temperature was 16,000 K. How much did the radius change as it evolved from a red to a blue supergiant?
19. What is the radius of the progenitor star that became SN 1987A? Its luminosity was 100,000 times that of the Sun, and it had a surface temperature of 16,000 K.
20. What is the acceleration of gravity at the surface of the star that became SN 1987A? How does this g compare to that at the surface of Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.
21. What was the escape velocity from the surface of the SN 1987A progenitor star? How much greater is it than the escape velocity from Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.
22. What was the average density of the star that became SN 1987A? How does it compare to the average density of Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.
23. If the pulsar shown in Figure $23.4.3$ in Section 23.3] is rotating 100 times per second, how many pulses would be detected in one minute? The two beams are located along the pulsar's equator, which is aligned with Earth.
