24.E: Black Holes and Curved Spacetime (Exercises)

Articles

Black Holes

Charles, P. & Wagner, R. “Black Holes in Binary Stars: Weighing the Evidence.” *Sky & Telescope* (May 1996): 38. Excellent review of how we find stellar-mass black holes.

Gezari, S. “Star-Shredding Black Holes.” *Sky & Telescope* (June 2013): 16. When black holes and stars collide.

Jayawardhana, R. “Beyond Black.” *Astronomy* (June 2002): 28. On finding evidence of the existence of event horizons and thus black holes.

Nadis, S. “Black Holes: Seeing the Unseeable.” *Astronomy* (April 2007): 26. A brief history of the black hole idea and an introduction to potential new ways to observe them.

Psallis, D. & Sheperd, D. “The Black Hole Test.” *Scientific American* (September 2015): 74–79. The Event Horizon Telescope (a network of radio telescopes) will test some of the stranger predictions of general relativity for the regions near black holes. The September 2015 issue of *Scientific American* was devoted to a celebration of the 100th anniversary of the general theory of relativity.

Rees, M. “To the Edge of Space and Time.” *Astronomy* (July 1998): 48. Good, quick overview.

Talcott, R. “Black Holes in our Backyard.” *Astronomy* (September 2012): 44. Discussion of different kinds of black holes in the Milky Way and the 19 objects known to be black holes.

Gravitational Waves

Bartusiak, M. “Catch a Gravity Wave.” *Astronomy* (October 2000): 54.

Gibbs, W. “Ripples in Spacetime.” *Scientific American* (April 2002): 62.

Haynes, K., & Betz, E. “A Wrinkle in Spacetime Confirms Einstein’s Gravitation.” *Astronomy* (May 2016): 22. On the direct detection of gravity waves.

Sanders, G., and Beckett, D. “LIGO: An Antenna Tuned to the Songs of Gravity.” *Sky & Telescope* (October 2000): 41.

Websites

Black Holes

Black Hole Encyclopedia: http://blackholes.stardate.org. From StarDate at the University of Texas McDonald Observatory.

Black Holes: http://science.nasa.gov/astrophysics/focus-areas/black-holes. NASA overview of black holes, along with links to the most recent news and discoveries.

Black Holes FAQ: cfpa.berkeley.edu/Education/BHfaq.html. Frequently asked questions about black holes, answered by Ted Bunn of UC–Berkeley’s Center for Particle Astrophysics.

Black Holes: Gravity’s Relentless Pull: http://hubblesite.org/explore_astronomy/black_holes/home.html. The Hubble Space Telescope’s Journey to a Black Hole and Black Hole Encyclopedia (a good introduction for beginners).

Introduction to Black Holes: www.damtp.cam.ac.uk/research/gr/public/bh_intro.html. The Cambridge University Relativity Group’s pages on black holes and related calculations.

March 1918: Testing Einstein: http://www.nature.com/nature/podcast/index-pastcast-2014-03-20.html. Nature Podcast about the 1919 eclipse expedition that proved Einstein’s General Theory of Relativity.

Movies from the Edge of Spacetime: archive.ncsa.illinois.edu/Cyberia/NumRel/MoviesEdge.html. Physicists simulate the behavior of various black holes.

Virtual Trips into Black Holes and Neutron Stars: http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html. By Robert Nemiroff at Michigan Technological University.

Gravitational Waves

Advanced LIGO: www.advancedligo.mit.edu. The full story on this gravitational wave observatory.

eLISA: https://www.elisascience.org.

Gravitational Waves Detected, Confirming Einstein's Theory: http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html. *New York Times* article and videos on the discovery of gravitational waves.

Gravitational Waves Discovered from Colliding Black Holes: http://www.scientificamerican.com/article/gravitational-waves-discovered-from-colliding-black-holes1. *Scientific American* coverage of the discovery of gravitational waves (note the additional materials available in the menu at the right).

LIGO Caltech: https://www.ligo.caltech.edu.

Videos

Black Holes

Black Holes: The End of Time or a New Beginning?: https://www.youtube.com/watch?v=mgtJRsdKe6Q. 2012 Silicon Valley Astronomy Lecture by Roger Blandford (1:29:52).

Death by Black Hole: www.openculture.com/2009/02/death_by_black_hole_and_its_kind_of_funny.htm. Neil deGrasse Tyson explains spaghettification with only his hands (5:34).

Hearts of Darkness: Black Holes in Space: https://www.youtube.com/watch?v=4tiAOldypLk. 2010 Silicon Valley Astronomy Lecture by Alex Filippenko (1:56:11).

Gravitational Waves

Journey of a Gravitational Wave: https://www.youtube.com/watch?v=FlDtXIBrAYE. Introduction from LIGO Caltech (2:55).

LIGO's First Detection of Gravitational Waves: https://www.youtube.com/watch?v=gw-i_VKd6Wo. Explanation and animations from PBS Digital Studio (9:31).

Two Black Holes Merge into One: https://www.youtube.com/watch?v=I_88S8DWbcU. Simulation from LIGO Caltech (0:35).

What the Discovery of Gravitational Waves Means: https://www.youtube.com/watch?v=jMVAgCPYYHY. TED Talk by Allan Adams (10:58).

Collaborative Group Activities

A. A computer science major takes an astronomy course like the one you are taking and becomes fascinated with black holes. Later in life, he founds his own internet company and becomes very wealthy when it goes public. He sets up a foundation to support the search for black holes in our Galaxy. Your group is the allocation committee of this foundation. How would you distribute money each year to increase the chances that more black holes will be found?

B. Suppose for a minute that stars evolve *without* losing any mass at any stage of their lives. Your group is given a list of binary star systems. Each binary contains one main-sequence star and one invisible companion. The spectral types of the main-sequence stars range from spectral type O to M. Your job is to determine whether any of the invisible companions might be black holes. Which ones are worth observing? Why? (Hint: Remember that in a binary star system, the two stars form at the same time, but the pace of their evolution depends on the mass of each star.)

C. You live in the far future, and the members of your group have been convicted (falsely) of high treason. The method of execution is to send everyone into a black hole, but you get to pick which one. Since you are doomed to die, you would at least like to see what the inside of a black hole is like—even if you can't tell anyone outside about it. Would you choose a black hole with a mass equal to that of Jupiter or one with a mass equal to that of an entire galaxy? Why? What would happen to you as you approached the event horizon in each case? (Hint: Consider the difference in force on your feet and your head as you cross over the event horizon.)

D. General relativity is one of the areas of modern astrophysics where we can clearly see the frontiers of human knowledge. We have begun to learn about black holes and warped spacetime recently and are humbled by how much we still don't know. Research in this field is supported mostly by grants from government agencies. Have your group discuss what reasons there are for our tax dollars to support such "far out" (seemingly impractical) work. Can you make a list of "far out" areas of research in past centuries that later led to practical applications? What if general relativity does not have many practical applications? Do you think a small part of society's funds should still go to exploring theories about the nature of space and time?

E. Once you all have read this chapter, work with your group to come up with a plot for a science fiction story that uses the properties of black holes.
F. Black holes seem to be fascinating not just to astronomers but to the public, and they have become part of popular culture. Searching online, have group members research examples of black holes in music, advertising, cartoons, and the movies, and then make a presentation to share the examples you found with the whole class.
G. As mentioned in the Gravity and Time Machines feature box in Section 24.5, the film *Interstellar* has a lot of black hole science in its plot and scenery. That's because astrophysicist Kip Thorne at Caltech had a big hand in writing the initial treatment for the movie, and later producing it. Get your group members together (be sure you have popcorn) for a viewing of the movie and then try to use your knowledge of black holes from this chapter to explain the plot. (Note that the film also uses the concept of a *wormhole*, which we don't discuss in this chapter. A wormhole is a theoretically possible way to use a large, spinning black hole to find a way to travel from one place in the universe to another without having to go through regular spacetime to get there.)

Review Questions

1. How does the equivalence principle lead us to suspect that spacetime might be curved?
2. If general relativity offers the best description of what happens in the presence of gravity, why do physicists still make use of Newton's equations in describing gravitational forces on Earth (when building a bridge, for example)?
3. Einstein's general theory of relativity made or allowed us to make predictions about the outcome of several experiments that had not yet been carried out at the time the theory was first published. Describe three experiments that verified the predictions of the theory after Einstein proposed it.
4. If a black hole itself emits no radiation, what evidence do astronomers and physicists today have that the theory of black holes is correct?
5. What characteristics must a binary star have to be a good candidate for a black hole? Why is each of these characteristics important?
6. A student becomes so excited by the whole idea of black holes that he decides to jump into one. It has a mass 10 times the mass of our Sun. What is the trip like for him? What is it like for the rest of the class, watching from afar?
7. What is an event horizon? Does our Sun have an event horizon around it?
8. What is a gravitational wave and why was it so hard to detect?
9. What are some strong sources of gravitational waves that astronomers hope to detect in the future?
10. Suppose the amount of mass in a black hole doubles. Does the event horizon change? If so, how does it change?

Thought Questions

1. Imagine that you have built a large room around the people in Figure $24.1.3$ in Section 24.1 and that this room is falling at exactly the same rate as they are. Galileo showed that if there is no air friction, light and heavy objects that are dropping due to gravity will fall at the same rate. Suppose that this were not true and that instead heavy objects fall faster. Also suppose that the man in Figure $24.1.3$ in Section 24.1 is twice as massive as the woman. What would happen? Would this violate the equivalence principle?
2. A monkey hanging from a tree branch sees a hunter aiming a rifle directly at him. The monkey then sees a flash and knows that the rifle has been fired. Reacting quickly, the monkey lets go of the branch and drops so that the bullet can pass harmlessly over his head. Does this act save the monkey's life? Why or why not? (Hint: Consider the similarities between this situation and that in the previous exercise.)
3. Why would we not expect to detect X-rays from a disk of matter about an ordinary star?
4. Look elsewhere in this book for necessary data, and indicate what the final stage of evolution—white dwarf, neutron star, or black hole—will be for each of these kinds of stars.
    1. Spectral type-O main-sequence star
    2. Spectral type-B main-sequence star
    3. Spectral type-A main-sequence star
    4. Spectral type-G main-sequence star
    5. Spectral type-M main-sequence star
5. Which is likely to be more common in our Galaxy: white dwarfs or black holes? Why?

6. If the Sun could suddenly collapse to a black hole, how would the period of Earth's revolution about it differ from what it is now?
7. Suppose the people in Figure $24.1.3$ in Section 24.1 are in an elevator moving upward with an acceleration equal to g, but in the opposite direction. The woman throws the ball to the man with a horizontal force. What happens to the ball?
8. You arrange to meet a friend at 5:00 p.m. on Valentine's Day on the observation deck of the Empire State Building in New York City. You arrive right on time, but your friend is not there. She arrives 5 minutes late and says the reason is that time runs faster at the top of a tall building, so she is on time but you were early. Is your friend right? Does time run slower or faster at the top of a building, as compared with its base? Is this a reasonable excuse for your friend arriving 5 minutes late?
9. You are standing on a scale in an elevator when the cable snaps, sending the elevator car into free fall. Before the automatic brakes stop your fall, you glance at the scale reading. Does the scale show your real weight? An apparent weight? Something else?

Figuring for Yourself

1. Look up G, c, and the mass of the Sun in Appendix E and calculate the radius of a black hole that has the same mass as the Sun. (Note that this is only a theoretical calculation. The Sun does not have enough mass to become a black hole.)
2. Suppose you wanted to know the size of black holes with masses that are larger or smaller than the Sun. You could go through all the steps in the previous exercise, wrestling with a lot of large numbers with large exponents. You could be clever, however, and evaluate all the constants in the equation once and then simply vary the mass. You could even express the mass in terms of the Sun's mass and make future calculations really easy. Show that the event horizon equation is equivalent to saying that the radius of the event horizon is equal to 3 km times the mass of the black hole in units of the Sun's mass.
3. Use the result from the previous exercise to calculate the radius of a black hole with a mass equal to: the Earth, a B0-type main-sequence star, a globular cluster, and the Milky Way Galaxy. Look elsewhere in this text and the appendixes for tables that provide data on the mass of these four objects.
4. Since the force of gravity a significant distance away from the event horizon of a black hole is the same as that of an ordinary object of the same mass, Kepler's third law is valid. Suppose that Earth collapsed to the size of a golf ball. What would be the period of revolution of the Moon, orbiting at its current distance of 400,000 km? Use Kepler's third law to calculate the period of revolution of a spacecraft orbiting at a distance of 6000 km.
