36 General Relativity

The chapter opens with the now familiar GPS device, and a photo of the NGC 6744 galaxy, which is an intermediate between a barred and unbarred spiral galaxy. This is what our galaxy may look like from afar. And between these photos is Richard Crowe, the late professor and astronomer at the University of Hawaii at Hilo—where "telescope heaven" sits atop Mauna Kea. The bottom photo is my niece Stephanie Hewitt.

The personality profile continues with Albert Einstein.

The three most important theories of physics in the 20th century are the special theory of relativity (1905), the general theory of relativity (1915), and the theory of quantum mechanics (1926). The first and third theories have been focal points of interest and research since their inceptions, yet the second, general relativity, has been largely ignored by physicists—until recently. New interest stems from many of the new astronomical phenomena discovered in recent years—pulsars, quasars, compact X-ray sources, black holes, all of which have indicated the existence of very strong gravitational fields that could be described only by general relativity. The move is now on to a quantum theory of gravitation that will agree with general relativity for macroscopic objects.

One important point to make is that relativity doesn't mean that everything is relative, but rather that no matter how you view a situation, the physical outcome is the same. There is a general misconception about this. Point out that in special and general relativity that fundamental truths of nature look the *same* from every point of view—not different from different points of view!

We measure velocities with rods and clocks; rods for space, and clocks for time. In our local environment, rods and clocks are no different when in different locations. In a larger environment in accord with general relativity, however, we find that space and time are "warped." Rods and clocks at appreciably different distances from the center of the Earth are affected differently. Accordingly, gravitation can be seen as the effects of a curved space-time such that the motion of objects subject to what we call the gravitational force is simply the result of objects moving freely through curved space-time.

So the theories of special and general relativity, quantum mechanics, nuclear power, and the theory of the Big Bang, computers, and DNA are products of the Twentieth Century. In the later part of this 21st century, what will power automobiles? How will electricity be produced? What will the climate be? How will wars be fought? What changes will occur in national borders? We don't have the answers to these questions. What we can do is to educate our students to better orient, anticipate, think, decide, and to act. What they most need to learn most is the process of learning itself.

In my student days we had to think when using slide rules. The decimal point was not given as it is with calculators. Do today's students learn to solve problems, or search for solutions on the internet? Tablets are a mixed blessing at best.

Getting back to the chapter, gravitational lensing is a consequence of general relativity. The gravity of massive objects distorts the fabric of space-time and thereby the pathways of light rays passing the objects. The amount of this bending depends on the mass of the object. By measuring the bending and having a measure of how much visible matter the object possesses, investigators can infer how much dark matter must also be present in the object.

I presented Figure 36.8 as a Figuring Physics in the May 2005 issue of *The Physics Teacher* magazine, where it gained attention. The question arose as to whether the light would fall twice the distance the hypothetically same-speed ball would fall in the same time. The essence of the equivalence principle, after all, is that what happens in a uniform gravitational field duplicates what happens in an accelerated frame of reference in field-free space. So dropped balls and light move the same in a uniform gravitational field as in an accelerated frame of reference. The Earth’s field, however, over a small region, is only approximately uniform—not exactly so for it is an inverse-square field. For nonrelativistic objects like dropped balls, the difference is inconsequential. Does it matter for light? Does light near the Earth, even in a tiny region, “sense” that it is moving in a central inverse-square gravitational field? And in accordance with Einstein’s theory, does it “fall” twice as far as in an accelerated frame? So in the hypothetical experiment of Figure 36.8, light would fall 4.9 m in 1 s in a frame accelerating with acceleration g in empty space. But from a rest frame of reference in Earth’s gravitational field, would it instead fall 9.8 m in 1 second? Me thinks not.

Einstein applied his thinking to the universe. More recently, Carl Sagan did the same. As Richard Dawkins asks: "Was Carl Sagan a religious man? He was so much more. He left behind the petty, parochial, medieval world of the conventionally religious; left the theologians, priests and mullahs wallowing in their small-minded spiritual poverty. He left them behind, because he had so much more to be religious about. They have their Bronze Age myths, medieval superstitions and childish wishful thinking. He had the universe."

I do not have a suggested lecture presentation for this chapter, and welcome ideas from you that I can incorporate into future printings of this manual.

Next-Time Questions:
- Gravitational Lens
- General Relativity Test
- General Relativity

Hewitt-Drew-It Screencasts: •*General Relativity* •*Principle of Equivalence*

Answers for Chapter 36

Reading Check Questions

1. The principle difference is acceleration in the general theory.
2. Motion of the dropped ball will be the same in both situations.
3. What is equivalent is observations made in an accelerated frame of reference are indistinguishable from observations made in a Newtonian gravitational field.
4. Both bend downward by the same amount in the same time.
5. Only during an eclipse can the stars somewhat behind the Sun be viewed.
6. Strong gravitation slows time.
7. The slower clock is the one on the shore of Lake Michigan.
8. A lower frequency is seen in a spectral line of light from the Sun.
9. We see time slowing.
10. Mercury is in the strongest part of Sun's gravitational field because it's closest.
11. Newton's law of gravity is valid where the gravitational field is relatively weak.
12. Along a radius the stick is not moving parallel to its length, so the meterstick undergoes no length contraction.
13. When rotating, the circumference undergoes length contraction, whereas the diameter does not.
14. Mass produces warps in the geometry of spacetime.
15. A change in motion produces gravitational waves.
16. Gravitational waves, like light, take 10 years to travel a distance of 10 light years.
17. Gravitational waves are difficult to detect because of their weakness.
18. Einstein's gravitation does not invalidate Newton's gravitation for nominal gravitational fields. For huge fields, like near a black hole, Einstein's gravity better describes the physics.
19. Newtonian physics indeed was paramount in getting humans to the Moon.
20. Newtonian physics links with quantum theory where the domain is massive and large, and with relativity theory where speeds are low compared with the speed of light and the gravitational fields aren't relatively strong.

Think and Explain

21. The reference frames of special relativity are of uniform motion—constant velocity. The reference frames of general relativity include accelerated frames.

22. In accord with the principle of equivalence, she cannot discern between accelerated motion and gravitation. The effects of each are identical. So unless she has other clues, she will not be able to tell the difference.

23. When in orbit, an astronaut, although in the grip of Earth gravity is weightless because of no support force (as explained back in Chapter 9). Both the astronaut and the spaceship are in free fall together.

24. You would feel as on Earth if the spaceship accelerates at Earth *g*, or your spaceship rotates at a rate that causes a centripetal acceleration of *g*.

25. The separation distance of two people walking north from the Earth's equator decreases, and if they continue to the North Pole their separation distance will be zero. At the North Pole, a step in any direction is a step south!

26. Bending due to gravity isn't noticed only because it is negligible for short distances.

27. We don't notice the bending of light by gravity in our everyday environment because the gravity we experience is too weak for a noticeable effect. For distances used by surveyors, a beam of light is the best approximation of a straight line known.

28. Practically speaking, and for short distances, we say that a laser beam of light *defines* a straight line.
29. Agree. Starlight bends whether or not the Moon obstructs our view of it. The role of the eclipse is simply to better see the bending effect by comparing displacement of stars on the other side of the Sun.

30. Mercury's mass is much too small for observation of this effect.

31. Distortion of the Sun at sunset is due to atmospheric refraction, which doesn't occur on the Moon due to its absence of an atmosphere. Gravitational deflection of light is too slight to be seen grazing the Moon or the Earth.

32. A beam of light traveling horizontally for one second in a uniform gravitational field of strength 1 *g* will fall a vertical distance of 4.9 meters, just as a baseball would. This is providing it remains in a 1-*g* field for one second, for it would travel 300,000 kilometers during this second, nearly 25 Earth diameters away, and well away from the 1-*g* field strength of the Earth's surface (unless it were confined to the 1-*g* region as shown in Figure 36.8, with mirrors). If light were to travel in a 1-*g* region for two seconds, then like a baseball, it would fall $1/2gt^2$ = 19.6 meters.

33. The change in energy for light is evidenced by a change frequency. If the energy of light is lowered, as in traveling against a strong gravitational field, its frequency is lowered, and the light is said to be gravitationally red shifted. If the energy of the light is increased, as when falling in a gravitational field, then the frequency is increased and the light is blue shifted.

34. The clock will run slower at the bottom of a deep well than at the surface because in going down the well, we are moving in the direction that the gravitational force acts, and this results in a slowing of clocks. More correctly we say that the clock is moving toward a lower gravitational potential. (Actually, decrease in gravitational potential, only hinted at in this chapter, results in slowing of the clock.)

35. Events on the Moon, as monitored from the Earth, run a bit faster and are slightly blue shifted. Even though signals escaping the Moon are red shifted in ascending the Moon's gravitational field, they are blue shifted even more in descending through Earth's stronger *g* field, resulting in a net blue shift.

36. The gravitational field intensity will increase on the surface of a shrinking star because the matter that produces the field is becoming more compact and more localized. This is easiest to see by considering the force on a body of mass *m* at the surface of the star of mass *M* via Newton's equation, $F = GmM/d^2$, where the only term that changes is *d*, which diminishes and therefore results in an increasing *F*.

37. It will run slightly slower. For observers on Earth, this is because moving a clock from a pole to the equator is moving it in the direction of the centrifugal force, which slows the rate at which clocks run (the same as if it were moving in the direction of a gravitational force). For observers outside in an inertial frame, the slowing of the clock at the equator is an example of time dilation, an effect of special relativity caused by the motion of the clock. (The situation is much like that shown in Figure 36.9.)

38. At the top of the mountain you age faster (see Figure 36.10).

39. Going up in a building is going in a direction opposite to the direction of the gravitational force, and this speeds up time. The person concerned about living a tiny bit longer should live on the ground floor. Strictly speaking, people who live in penthouses live faster lives.

40. Time would run slower at the edge.

41. The photons of light are climbing against the gravitational field and losing energy. Less energy means less frequency. Your friend sees the light red-shifted. The frequency she receives is less than the frequency you sent.

42. Light emitted from the star is red-shifted. This can be understood as the result of gravity slowing down time on the surface of the star, or as gravity taking energy away from the photons as they propagate away from the star.

43. The astronaut falling into the black hole would see the rest of the universe blue shifted. The astronaut's time scale is being slowed, which makes time scales elsewhere look fast to the astronaut. The blue shift can also be understood as the result of the black hole's gravity adding energy to photons that "fall" toward the black hole. The added energy means greater frequency.

44. There are various ways to "see" black holes. If it is the partner of a visible star, we can see its gravitational effect on the visible star's orbit. We could see its effect on light that passes close enough to be deflected but not close enough to be captured. We can see radiation emitted by matter as it is being sucked into a black hole (before it crosses the horizon to oblivion). In the future, perhaps, we will detect gravitational radiation emitted by black holes as they are being formed.

45. Yes. If the star is massive enough and concentrated enough, its gravity could be strong enough to make light follow a circular path. This is what light does at the “event horizon” of a black hole.

46. Mercury follows an elliptical path in its orbit about the Sun, with its perihelion in a stronger part of the Sun’s gravitational attraction than its aphelion. If Mercury followed a circular orbit, then there would be no variation of the Sun’s gravitational attraction in its orbit.

47. Agree, just as a step in any direction from the North Pole is a step south.

48. Yes. For example, place the Sun just outside one of the legs in Figure 36.14.

49. Binary stars that move about a common center of mass radiate gravitational waves, just as do all accelerating masses.

50. Gravitational waves are extremely long waves.

51. Oscillating mass (or, more generally, accelerated mass) is the mechanism for emission of gravitational waves, just as oscillating or accelerated charge is the mechanism for emission of electromagnetic waves. When it is absorbed, a gravitational wave can set mass into oscillation, just as an absorbed electromagnetic wave can set charge into oscillation. (Scientists seeking to detect gravitational waves try to detect tiny oscillations of matter caused by the absorption of the waves. See Figure 36.16.)

52. Einstein’s theory of gravitation predicts the same results as Newton’s theory of gravitation in weak gravitational fields such as those of the solar system. In weak fields, Einstein’s theory overlaps, corresponds, and gives the same results as Newton’s theory, and therefore obeys the correspondence principle.

53. The flat universe expands forever.

54. Open-ended.

55. Open-ended.

Think and Discuss

56. If the spaceship is set into rotation, it will spin of its own rotational inertia like a top, once set spinning. An astronaut in the ship experiences a centrifugal force that provides a simulated “gravity.” No fuel is consumed to sustain this effect because the centrifugal (or centripetal) force is perpendicular to rotational motion and does no work on the astronaut.

57. Ole Jules called his shot wrong on this one. Drifting in a spaceship through space, whether under the influence of Moon, Earth, or whatever gravitational field, a ship and its occupants are in a state of free fall—hence there is no sensation of up or down. Occupants of a spaceship would feel weight, or sense an up or down, only if the ship were made to accelerate—say, against their feet. Then they could stand and sense that down is toward their feet, and up away from their feet.

58. The light will be red-shifted. The accelerating car is equivalent to a stationary car standing vertically with its rear end down. The light going from the back to the front of the accelerating car behaves just like light going upward away from the surface of a planet. It is gravitationally red shifted.

59. Prudence is older. Charity’s time runs slower during the time she is at the edge of the rotating kingdom (see Figure 36.9).

60. We would need a telescope sensitive to very long wavelength radiation such as radio waves. The light from the astronauts would be red shifted to very long wavelength, eventually infinitely long wavelength.