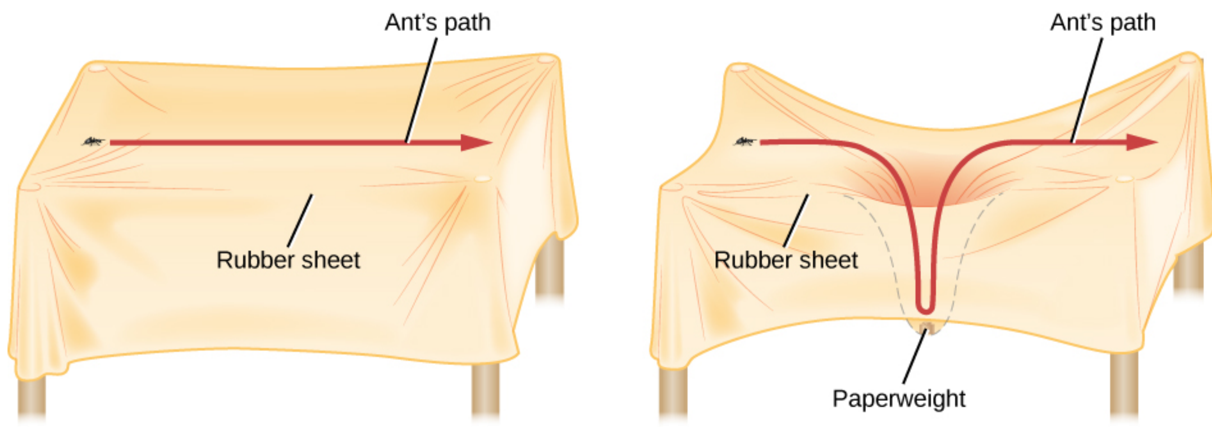

Figure 24.8 Three-Dimensional Analogy for Spacetime. On a flat rubber sheet, a trained ant has no trouble walking in a straight line. When a massive object creates a big depression in the sheet, the ant, which must walk where the sheet takes it, finds its path changed (warped) dramatically.

Now let's again send the ant on a journey that takes it close to, but not on top of, the paperweight. Far away from the paperweight, the ant has no trouble doing its walk, which looks straight to us. As it nears the paperweight, however, the ant is forced down into the sag. It must then climb up the other side before it can return to walking on an undistorted part of the sheet. All this while, the ant is following the shortest path it can, but through no fault of its own (after all, ants can't fly, so it has to stay on the sheet) this path is curved by the distortion of the sheet itself.

In the same way, according to Einstein's theory, light always follows the shortest path through spacetime. But the mass associated with large concentrations of matter distorts spacetime, and the shortest, most direct paths are no longer straight lines, but curves.

How large does a mass have to be before we can measure a change in the path followed by light? In 1916, when Einstein first proposed his theory, no distortion had been detected at the surface of Earth (so Earth might have played the role of the grain of sand in our analogy). Something with a mass like our Sun's was necessary to detect the effect Einstein was describing (we will discuss how this effect was measured using the Sun in the next section).

The paperweight in our analogy might be a white dwarf or a neutron star. The distortion of spacetime is greater near the surfaces of these compact, massive objects than near the surface of the Sun. And when, to return to the situation described at the beginning of the chapter, a star core with more than three times the mass of the Sun collapses forever, the distortions of spacetime very close to it can become truly mind-boggling.

24.3 TESTS OF GENERAL RELATIVITY

Learning Objectives

By the end of this section, you will be able to:

- Describe unusual motion of Mercury around the Sun and explain how general relativity explains the observed behavior
- Provide examples of evidence for light rays being bent by massive objects, as predicted by general relativity's theory about the warping of spacetime

What Einstein proposed was nothing less than a major revolution in our understanding of space and time. It was a new theory of gravity, in which mass determines the curvature of spacetime and that curvature, in turn, controls how objects move. Like all new ideas in science, no matter who advances them, Einstein's theory had to be tested by comparing its predictions against the experimental evidence. This was quite a challenge because the effects of the new theory were apparent only when the mass was quite large. (For smaller masses, it required measuring techniques that would not become available until decades later.)

When the distorting mass is small, the predictions of general relativity must agree with those resulting from Newton's law of universal gravitation, which, after all, has served us admirably in our technology and in guiding space probes to the other planets. In familiar territory, therefore, the differences between the predictions of the two models are subtle and difficult to detect. Nevertheless, Einstein was able to demonstrate one proof of his theory that could be found in existing data and to suggest another one that would be tested just a few years later.

The Motion of Mercury

Of the planets in our solar system, Mercury orbits closest to the Sun and is thus most affected by the distortion of spacetime produced by the Sun's mass. Einstein wondered if the distortion might produce a noticeable difference in the motion of Mercury that was not predicted by Newton's law. It turned out that the difference was subtle, but it was definitely there. Most importantly, it had already been measured.

Mercury has a highly elliptical orbit, so that it is only about two-thirds as far from the Sun at perihelion as it is at aphelion. (These terms were defined in the chapter on **Orbits and Gravity**.) The gravitational effects (perturbations) of the other planets on Mercury produce a calculable advance of Mercury's perihelion. What this means is that each successive perihelion occurs in a slightly different direction as seen from the Sun (**Figure 24.9**).

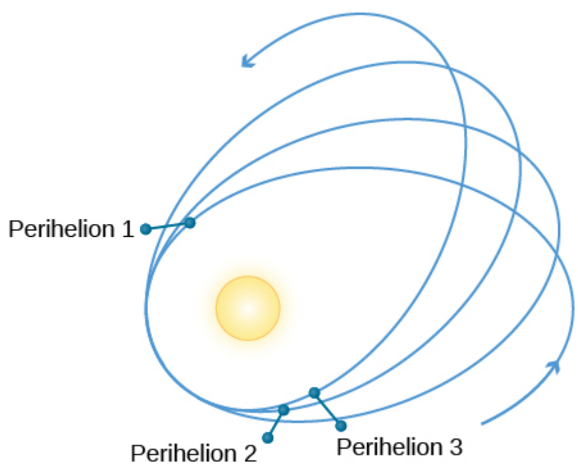

Figure 24.9 Mercury's Wobble. The major axis of the orbit of a planet, such as Mercury, rotates in space slightly because of various perturbations. In Mercury's case, the amount of rotation (or orbital precession) is a bit larger than can be accounted for by the gravitational forces exerted by other planets; this difference is precisely explained by the general theory of relativity. Mercury, being the planet closest to the Sun, has its orbit most affected by the warping of spacetime near the Sun. The change from orbit to orbit has been significantly exaggerated on this diagram.

According to Newtonian gravitation, the gravitational forces exerted by the planets will cause Mercury's perihelion to advance by about 531 seconds of arc (arcsec) per century. In the nineteenth century, however, it was observed that the actual advance is 574 arcsec per century. The discrepancy was first pointed out in 1859 by Urbain Le Verrier, the codiscoverer of Neptune. Just as discrepancies in the motion of Uranus allowed astronomers to discover the presence of Neptune, so it was thought that the discrepancy in the motion of Mercury could mean the presence of an undiscovered inner planet. Astronomers searched for this planet near the Sun, even giving it a name: Vulcan, after the Roman god of fire. (The name would later be used for the home planet of a famous character on a popular television show about future space travel.)

But no planet has ever been found nearer to the Sun than Mercury, and the discrepancy was still bothering astronomers when Einstein was doing his calculations. General relativity, however, predicts that due to the curvature of spacetime around the Sun, the perihelion of Mercury should advance slightly more than is predicted by Newtonian gravity. The result is to make the major axis of Mercury's orbit rotate slowly in space because of the Sun's gravity alone. The prediction of general relativity is that the direction of perihelion should change by an additional 43 arcsec per century. This is remarkably close to the observed discrepancy, and it gave Einstein a lot of confidence as he advanced his theory. The relativistic advance of perihelion was later also observed in the orbits of several asteroids that come close to the Sun.

Deflection of Starlight

Einstein's second test was something that had not been observed before and would thus provide an excellent confirmation of his theory. Since spacetime is more curved in regions where the gravitational field is strong, we would expect light passing very near the Sun to appear to follow a curved path (**Figure 24.10**), just like that of the ant in our analogy. Einstein calculated from general relativity theory that starlight just grazing the Sun's surface should be deflected by an angle of 1.75 arcsec. Could such a deflection be observed?

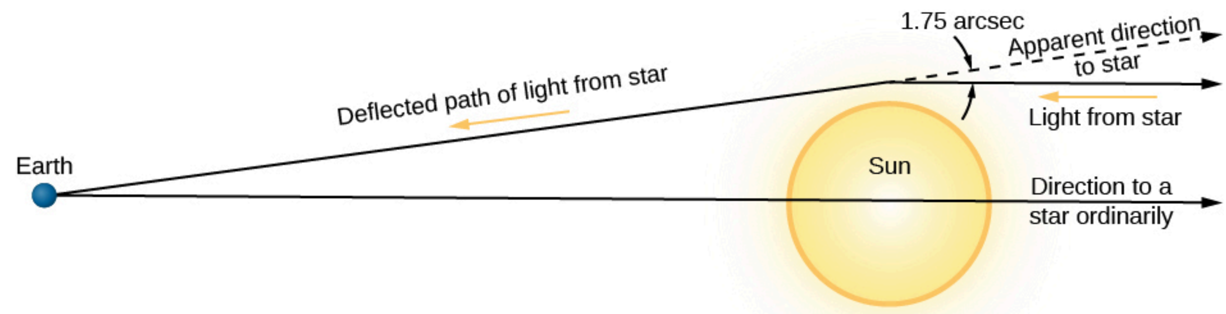

Figure 24.10 Curvature of Light Paths near the Sun. Starlight passing near the Sun is deflected slightly by the "warping" of spacetime. (This deflection of starlight is one small example of a phenomenon called gravitational lensing, which we'll discuss in more detail in **The Evolution and Distribution of Galaxies**.) Before passing by the Sun, the light from the star was traveling parallel to the bottom edge of the figure. When it passed near the Sun, the path was altered slightly. When we see the light, we assume the light beam has been traveling in a straight path throughout its journey, and so we measure the position of the star to be slightly different from its true position. If we were to observe the star at another time, when the Sun is not in the way, we would measure its true position.

We encounter a small "technical problem" when we try to photograph starlight coming very close to the Sun: the Sun is an outrageously bright source of starlight itself. But during a total solar eclipse, much of the Sun's light is blocked out, allowing the stars near the Sun to be photographed. In a paper published during World War I, Einstein (writing in a German journal) suggested that photographic observations during an eclipse could reveal the deflection of light passing near the Sun.

The technique involves taking a photograph of the stars six months prior to the eclipse and measuring the position of all the stars accurately. Then the same stars are photographed during the eclipse. This is when the starlight has to travel to us by skirting the Sun and moving through measurably warped spacetime. As seen from Earth, the stars closest to the Sun will seem to be "out of place"—slightly away from their regular positions as measured when the Sun is not nearby.

A single copy of that paper, passed through neutral Holland, reached the British astronomer Arthur S. Eddington, who noted that the next suitable eclipse was on May 29, 1919. The British organized two expeditions to observe it: one on the island of Príncipe, off the coast of West Africa, and the other in Sobral, in northern Brazil. Despite some problems with the weather, both expeditions obtained successful photographs. The stars seen near the Sun were indeed displaced, and to the accuracy of the measurements, which was about 20%, the shifts were consistent with the predictions of general relativity. More modern experiments with radio waves traveling close to the Sun have confirmed that the actual displacements are within 1% of what general relativity predicts.

The confirmation of the theory by the eclipse expeditions in 1919 was a triumph that made Einstein a world celebrity.

24.4 TIME IN GENERAL RELATIVITY

Learning Objectives

By the end of this section, you will be able to:

- Describe how Einsteinian gravity slows clocks and can decrease a light wave's frequency of oscillation
- Recognize that the gravitational decrease in a light wave's frequency is compensated by an increase in the light wave's wavelength—the so-called gravitational redshift—so that the light continues to travel at constant speed

General relativity theory makes various predictions about the behavior of space and time. One of these predictions, put in everyday terms, is that *the stronger the gravity, the slower the pace of time*. Such a statement goes very much counter to our intuitive sense of time as a flow that we all share. Time has always seemed the most democratic of concepts: all of us, regardless of wealth or status, appear to move together from the cradle to the grave in the great current of time.

But Einstein argued that it only seems this way to us because all humans so far have lived and died in the gravitational environment of Earth. We have had no chance to test the idea that the pace of time might depend on the strength of gravity, because we have not experienced radically different gravities. Moreover, the differences in the flow of time are extremely small until truly large masses are involved. Nevertheless, Einstein's prediction has now been tested, both on Earth and in space.

The Tests of Time

An ingenious experiment in 1959 used the most accurate atomic clock known to compare time measurements on the ground floor and the top floor of the physics building at Harvard University. For a clock, the experimenters used the frequency (the number of cycles per second) of gamma rays emitted by radioactive cobalt. Einstein's theory predicts that such a cobalt clock on the ground floor, being a bit closer to Earth's center of gravity, should run very slightly slower than the same clock on the top floor. This is precisely what the experiments observed. Later, atomic clocks were taken up in high-flying aircraft and even on one of the Gemini space flights. In each case, the clocks farther from Earth ran a bit faster. While in 1959 it didn't matter much if the clock at the top of the building ran faster than the clock in the basement, today that effect is highly relevant. Every smartphone or device that synchronizes with a GPS must correct for this (as we will see in the next section) since the clocks on satellites will run faster than clocks on Earth.

The effect is more pronounced if the gravity involved is the Sun's and not Earth's. If stronger gravity slows the pace of time, then it will take longer for a light or radio wave that passes very near the edge of the Sun to reach Earth than we would expect on the basis of Newton's law of gravity. (It takes longer because spacetime is curved in the vicinity of the Sun.) The smaller the distance between the ray of light and the edge of the Sun at closest approach, the longer will be the delay in the arrival time.

In November 1976, when the two Viking spacecraft were operating on the surface of Mars, the planet went behind the Sun as seen from Earth (Figure 24.11). Scientists had preprogrammed Viking to send a radio wave toward Earth that would go extremely close to the outer regions of the Sun. According to general relativity,