Solutions

1. How does the equivalence principle lead us to suspect that spacetime might be curved?

As shown in Figure 24.6 Curved Light Path, a light beam emitted in an orbiting spacecraft must strike the wall at the same height at which it was emitted. This can happen only if the light curves down along with the ship’s motion. This suggests that the light, traveling in spacetime, follows a curved path.

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)?

Newton’s equations are simpler to use than the equations of general relativity and are accurate enough for most daily activities, such as building a bridge on Earth. That’s because the gravity on our planet is sufficiently weak that the predictions of Newtonian theory don’t differ very significantly for everyday activities from the predictions of general relativity.

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.

There are a number of possible answers. Observations of the eclipse of 1919 verified the bending of light by the Sun’s mass (or gravity). Experiments in 1959 with twin atomic clocks operating at different heights in a physics building verified the slowing of time in a stronger gravitational field. In 1976 radio signals from the Viking landers on Mars passing near the Sun were used to show the slowing of time in a gravitational field. In the mid-1970s, a hydrogen maser, carried by a rocket to an altitude of 10,000 km was compare to the frequency of the signal emitted from a similar maser on Earth, again to show that the pace of time depends on the strength of gravity. And you could say that the accuracy of GPS devices demonstrates that general relativity works, since corrections for the effects of general relativity are included in the software of all such devices, and the devices help us pinpoint our location on Earth with remarkable accuracy.

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?

The theory behind black holes, Einstein’s general theory of relativity, has been tested with a wide range of experiments, which all confirm the predictions the theory makes. Focusing on black holes themselves, while we cannot see phenomena inside the event horizon, we do observe things outside this limit. Black holes in binary star systems leave signs of their presence on neighbor stars that have been detected. These signs include X-ray emissions, accretion disks, and large orbit perturbations.

5. What is an event horizon? Does our Sun have an event horizon around it?

The event horizon of a black hole can be thought of either as the place around the black hole where the speed you need to escape becomes greater than the speed of light or as the place where the warping of spacetime around a collapsed star becomes so great that all straight lines pointing outward actually become curved paths bringing you back in. Only black holes have event horizons, so our Sun, which is a star in happy main-sequence equilibrium, cannot have one.

6. What is a gravitational wave and why was it so hard to detect?

A gravitational wave is a disturbance in spacetime caused by a rearrangement of matter. It was hard to detect because even from rearrangements of really large masses it is very weak compared to electromagnetic radiation.

7. What are some strong sources of gravitational waves that astronomers hope to detect in the future?

Astronomers hope to detect gravitational waves in the coalescence of two neutron stars in a binary system that spiral together until they merge, the swallowing of a neutron star by a black hole, the coalescence (merger) of two black holes, the implosion of a massive star to form a neutron star or a black hole, or the first “shudder” when space and time came into existence and the universe began.

8. Which is likely to be more common in our Galaxy: white dwarfs or black holes? Why?

White dwarfs are likely to be much more common. The number of stars decreases with increasing mass, and only the most massive stars are likely to complete their lives as black holes. There are many more stars of the masses appropriate for evolution to a white dwarf.

9. 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?

The period would not change at all. Far from the event horizon, a black hole’s gravitational field is indistinguishable from that of any spherically symmetric object of the same mass.

10. 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.)

Using consistent units, we have

$$R = \frac{2GM}{c^2} = \frac{2\left(6.67 \times 10^{-11}\ \text{N} \times \text{m}^2/\text{kg}^2\right)\left(2 \times 10^{30}\ \text{kg}\right)}{\left(3 \times 10^{8}\ \text{m/s}\right)^2} = 2960\ \text{m} = 2.96\ \text{km}$$

.