6.4 Physics JOURNAL

General Relativity

SKILLS HANDBOOK A3

ABSTRACT

According to Newtonian physics, gravity is an attractive force between two objects. This conception of gravity is powerful and effective: it accurately describes and predicts physical effects and applies not only to objects on Earth, but also to the Moon, the motions of the planets, and more.

General relativity explains falling bodies and orbiting masses, too, but through a very different perspective. The theory of general relativity explains gravity in terms of the geometry of space and time. This way of seeing the universe has led to breakthrough ideas such as black holes, gravitational lenses, and other mysterious phenomena.

Einstein's Mental Laboratory

Albert Einstein (1879–1955), a theoretical physicist often regarded as the father of modern physics, developed the general theory of relativity. The general theory of relativity explains gravitational effects through an advanced form of geometry. In 1905, while working as a patent clerk in Switzerland, Einstein completed his doctoral degree and published four highly influential research papers. Einstein's laboratory was mostly in his mind. He developed and shaped his theories through "what-if" style mental exercises called thought experiments. One of Einstein's most-quoted lines is, "Imagination is more important than knowledge." Due to the success of Einstein's methods, thought experiments are considered valid scientific studies today.

From Newtonian Gravitation to General Relativity

Einstein's breakthrough idea that led to the theory of general relativity was that there is no experiment that observers can perform to distinguish whether acceleration occurs because of a gravitational force or because their reference frame is accelerating, as shown in **Figure 1**.

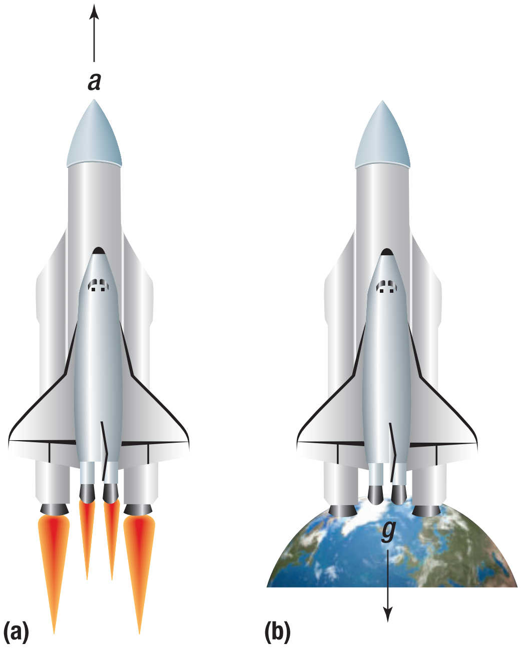

Figure 1 Einstein's theory states that there is no physical difference between (a) an accelerating frame of reference and (b) a frame of reference in a gravitational field.

For example, there would be no way to test (by, say, dropping or tossing balls or any other experiment that involves applications of Newton's laws) whether an observer is standing on Earth and therefore under the influence of Earth's gravitational field or whether the observer is standing on a spaceship accelerating at 9.8 m/s^2. In both cases, the observer experiences the same effects. Einstein called this relation the "principle of equivalence."

Einstein created brilliant thought experiments to study the principle of equivalence. His results led him to create a theory of gravity based on an advanced version of geometry. This theory, now called general relativity, deals with the curvature of space-time in the universe (**Figure 2**). It has several differences from Newton's theory of gravity.

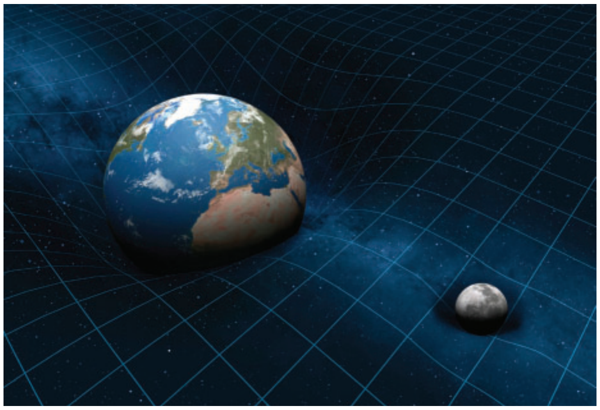

Figure 2 Albert Einstein's theory of general relativity deals with the curvature and other geometric features of space-time.

One important difference is that gravity has a "speed limit" in general relativity. In Newton's theory, a change in the position of a mass in one part of the universe instantly changes its gravitational field in all other parts of the universe. In general relativity, changes in the gravitational field travel at the speed of light but no faster.

These changes can travel across the universe as gravitational waves. A pair of stars locked in orbit around each other lose energy by emitting gravitational waves. The loss of energy means that the two stars fall toward each other and eventually collide or tear each other apart. A pair of stars, or a binary system, in orbit in Newton's theory would continue to circle each other with no changes. Measurements of changes in orbits of binary systems currently provide the most accurate experimental tests of general relativity.

Another important difference is that general relativity predicts that gravity affects light. Light does not have mass, so Newton's theory predicts that light experiences no force and exerts no force. In general relativity, the gravitational field can bend the path of light. For example, light travelling from a distant galaxy past a very massive object, such as a galaxy cluster, will bend and deflect around the object. This effect, called gravitational lensing (**Figure 3**), causes an observer on the other side of the massive object to see multiple, distorted images of the original light source. Gravitational lensing can create two or more images: a bright ring called an Einstein ring, partial rings, or other patterns.

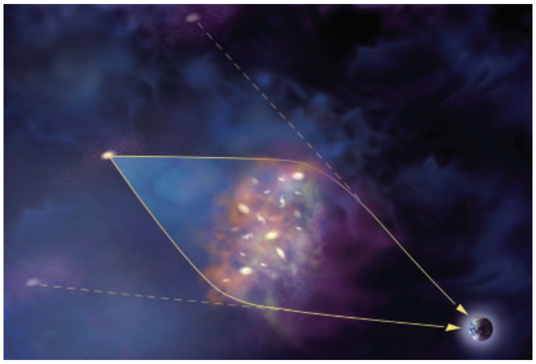

Figure 3 A massive object, such as a galaxy cluster, acts as a gravitational lens. Light from a distant star passes on both sides of the galaxy. An observer sees two separate images of the star.

One of the most mysterious predictions made by general relativity is the existence of black holes. Black holes are regions in space where the gravitational field is so strong that nothing, including light, can escape from the region after travelling into it. Black holes form as one possible product of the end of a star's life. We cannot directly see black holes, since no light can escape from one. Scientists, however, can detect black holes by studying the behaviour of objects near the suspected black hole. As material gets pulled into a black hole, the material emits X-rays and other particles that can be detected and analyzed on Earth. Black holes are so mysterious, in fact, that not even general relativity completely explains what happens to the material after it travels into the black hole.

What Is Next?

Although general relativity answers many questions about our universe, it currently faces a tough challenge. Very large objects in the universe, such as galaxies and galaxy clusters, and the universe as a whole do not behave exactly the way general relativity predicts. The orbital speed of objects at the edges of galaxies, for instance, should depend on the mass collected in the inner regions of the galaxy. Astronomers have found that the actual speeds of stars and dust in many galaxies are much faster than they would expect from the amount of mass that they can observe in the galaxies.

One solution to this challenge is that some exotic form of matter that we have never before detected exists in the universe. Physicists refer to this unknown matter as *dark matter*, since we do not directly see it. Another solution is that we have to modify the theory of general relativity so that the theory gives the correct description of the universe's behaviour. Either solution will change the way we think about gravity and the universe.

Further Reading

Guéron, E. (2009). Surprises from general relativity: "Swimming" in spacetime. *Scientific American*, August 2009, p. 34.

Einstein, A. (1952). *The principle of relativity.* New York, NY; Dover.

Schutz, B. (2004). *Gravity from the ground up.* New York, NY: Cambridge University Press.

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6.4 Questions

1. Explain what Einstein meant by his principle of equivalence. K/U C
2. Describe some of the differences between Einstein's and Newton's theories about gravity. K/U C
3. A person standing on Earth drops a ball. At the same time, a person standing at the bottom of a spaceship accelerating at $9.8\ \text{m/s}^2$, in the absence of any significant field in deep space, drops a ball. What would these people observe? T/I A
4. Explain why black holes are so difficult for scientists to study. K/U C A
5. Research general relativity and problems with the theory. Identify two possible solutions to problems with general relativity and the behaviour of galaxies. Do the solutions seem plausible to you? Why or why not? T/I C A

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