Testing Einstein's Universe

From the moment that Einstein published his General Theory of Relativity in early 1916, scientists around the world have been trying to verify its propositions through observation and experiment. Einstein's theory basically consists of a set of mathematical equations that theoretically describe the motion of matter and energy and the shape of spacetime throughout the universe. While these equations adhere to the logic of mathematics, the true test of Einstein's theory is in the real world. Does Einstein's theory of curved spacetime match the reality of observable phenomena?

Einstein's Predictions

Einstein was well aware that scientists would want empirical proof if they were to accept his theory of curved spacetime. He offered three specific phenomena that curved spacetime could explain—starlight deflection, the error in Newton's description of Mercury's orbital precession, and the gravitational redshift. Over the past century, scientists have closely observed these phenomena, in addition to examining a fourth phenomenon known as the Shapiro time-delay.

Just past the 100th anniversary of Einstein's publication of the Special Theory of Relativity (1905), three experiments are underway to further test the validity of curved spacetime. Two missions, LIGO and LISA, are attempting to detect "gravity waves"—ripples in spacetime caused by orbiting bodies such as pulsars.

The third mission, called Gravity Probe B, launched an Earth-orbiting satellite experiment in 2004 to detect and measure the shape and motion of curved spacetime around the Earth. Using the world's roundest and ultra-precise gyroscopes, Gravity Probe B (GP-B) will provide the most sophisticated test of Einstein's Theory of General Relativity ever attempted.

1. Starlight Deflection

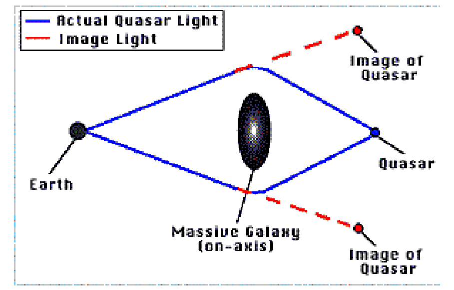
The central premise of Einstein's general relativity is that all matter and energy moving through the universe are affected by curved spacetime. This includes the path of light rays as they emerge from distant stars and make their way across the universe to our Earth-based telescopes and eyes. When the light passes near a massive body, such as a galaxy or our Sun, its path deflects slightly to follow the curve of spacetime around the massive body.

Following this logic, this means that when a star is obscured from our view on Earth by an intervening mass (e.g., the Sun, a galaxy), it may still be possible to see the star because its light would bend around the mass and reach Earth.

In 1919, merely three years after Einstein published his theory, a British astronomer took on the challenge of observing and measuring this phenomenon. Sir Arthur Eddington, with the help of Astronomer Royal Frank Dyson, organized concurrent expeditions to South America and West Africa to observe and photograph a solar eclipse. The solar eclipse gave Eddington the opportunity to see stars that appeared very close to the edge of the Sun by blocking out the Sun's intense light.

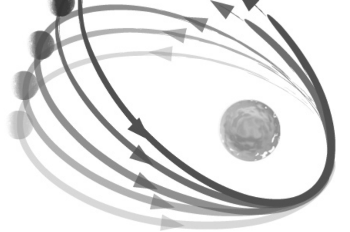
The stars that Eddington observed were actually closer to the Sun than they appeared. Eddington proved this by photographing the same area of sky later in the year and comparing the locations of the stars. When the Sun intervened between the Earth and the distant stars, it curved spacetime and bent the path of starlight around it. From our perspective on Earth, the starlight appeared to come from a point farther off the edge of the Sun.

In the decades following Eddington's observations, his results have been reproduced to a higher and higher precision as the technology for observing stars has improved. Between 1969 and 1975, twelve measurements were made using radio telescopes to measure the deflection of radio waves from a distant quasar around a galaxy. These measurements matched general relativity's predictions to within 1%.



2. Mercury's Perihelion Precession

As Mercury orbits the Sun, it does not follow the exact same elliptical path each year. As it goes around, Mercury's orbit slowly turns, or precesses, in the direction of its revolution around the Sun. Its perihelion point (the point of orbit closest to the Sun) shifts slightly each time around. Astronomers have observed that over every one hundred years Mercury's orbit has precessed another 574 arcseconds around (0.16 degrees).



Newton's theory of gravity partially accounted for this phenomenon and explained that it is caused by the gravitational perturbations of the other planets. But it did not account for it exactly right. Each century, Mercury's orbit has precessed a little farther than Newton's equations predicted – 43 arcseconds more, to be precise.

This discrepancy was troubling to 19th and early 20th century astronomers and physicists, who attempted to solve it by postulating the presence of another as-yet-undiscovered planet orbiting the Sun inside of Mercury's orbit. Supposedly, the gravitational pull from this "hidden planet" was responsible for altering Mercury's orbit.

This phenomenon was one of the key tests of Einstein's theory. Could his new description of the universe, as a place ruled by curved spacetime instead of gravity, resolve this discrepancy?

When Einstein's equations were applied to the orbit of Mercury, it was a precise success. Einstein's calculations predicted that Mercury's orbit would precess 43 arcseconds per century more than Newton's equations predicted. This matched the astronomers' observations exactly. The additional 43 arcseconds were a natural effect of Mercury's motion through the spacetime curved by the Sun.

3. Gravitational Redshift

Another phenomenon predicted by Einstein's General Theory of Relativity is that light loses energy as it emerges from a gravitational field. When light loses energy, its wavelength becomes longer and the color of the light shifts toward the red end of the spectrum (thus called the "redshift").

For example, if a blue light bulb was turned on near the surface of the Earth, light with short wavelengths and high energy (blue) would streak up into the sky, away from the Earth. As the light travels farther from the surface, it loses energy due to the gravitational pull of the Earth. When it loses energy, its wavelengths stretch out. For an astronaut looking down to Earth, the light emerging from the blue bulb would appear red, leading her to conclude that it was a red light bulb.

Two key tests of the gravitational redshift are the Pound-Rebka Experiment and Gravity Probe A. In 1960, physicists Robert Pound and Glen Rebka were able to detect the redshift of high-energy gamma rays in an elevator shaft at Harvard University. They sent gamma rays up from the bottom of the shaft to a sensor 74 feet high. As the gamma rays climbed the 74 feet out of Earth's gravitational field, they lost a miniscule amount of energy (~ 2 parts in a trillion), which Pound and Rebka were able to detect. Their measurement agreed with Einstein's predictions to within 10%.

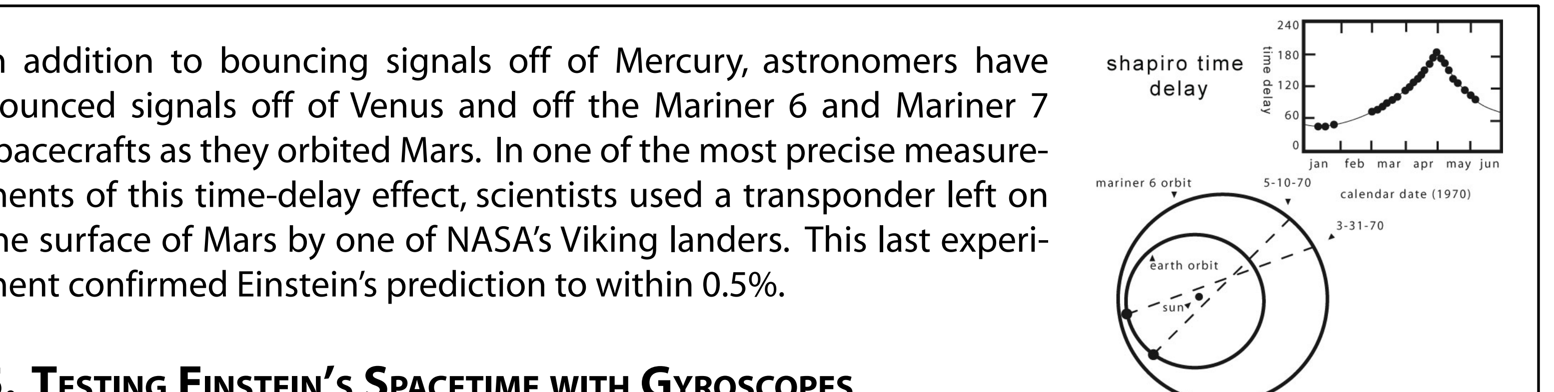
A more precise test of the redshift was conducted by Gravity Probe A in 1976, a rocket-based experiment also known as the Vessot-Levine test. In this experiment, a hydrogen-maser clock was launched to an altitude of 6,000 miles. The frequency of the clock in flight was compared to the frequency of a matching clock on the ground. The experiment revealed that the frequencies of the clocks differed slightly, matching Einstein's predictions to within 70 parts per million.

4. Shapiro Time-Delay

In 1964, Irwin Shapiro identified another phenomenon that Einstein's curved spacetime should cause: the apparent reduction of the speed of light (or electromagnetic waves) when it passes through a gravitational field. Since spacetime is curved near masses, electromagnetic waves (light, radio, gamma rays) must follow that curve in spacetime. The result is that the waves traveling through curved spacetime take longer to reach their destination than they would if the mass causing the curve in spacetime was not present.

Since 1964, a systematic program has been in place to test the presence of this phenomenon to a greater and greater precision. Scientists have used radio telescopes to perform "radar ranging" on various objects whose distance is precisely known. They began by bouncing signals off of Mercury and Venus.

When the line of sight between the Earth and Mercury was far from the Sun, the travel time of the signal was barely delayed, if at all. But as the line of sight neared the Sun, the delay increased. Scientists predicted that, according to Einstein's equations, the signal would be delayed by 200 microseconds if it traveled right next to the Sun. When performing the experiment, the result matched this prediction.



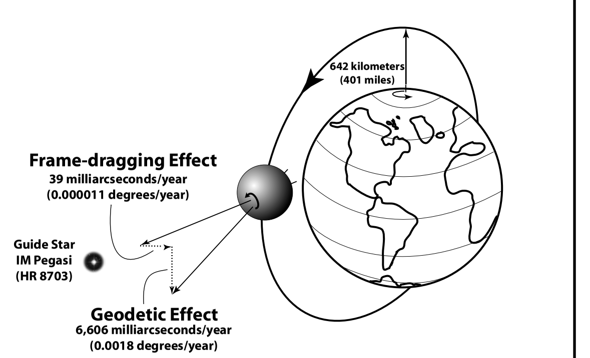
In addition to bouncing signals off of Mercury, astronomers have bounced signals off of Venus and off the Mariner 6 and Mariner 7 spacecrafts as they orbited Mars. In one of the most precise measurements of this time-delay effect, scientists used a transponder left on the surface of Mars by one of NASA's Viking landers. This last experiment confirmed Einstein's prediction to within 0.5%.

5. Testing Einstein's Spacetime with Gyroscopes

All of the tests described above show, with increasing accuracy and precision, that Einstein was on the right track. However, in most of the previous tests, the relativity signals had to be extracted from a significant level of background noise. The purpose of the Gravity Probe B (GP-B) experiment, which began in 1961 and finally launched in 2004, was to test Einstein's theory by carrying out the experiment in a pristine orbiting laboratory, thereby reducing the background noise to insignificant levels and enabling the Probe to examine general relativity in new ways.

GP-B placed four near-perfect gyroscopes in polar orbit around the Earth to measure two extraordinary, unverified predictions of Albert Einstein's General Theory of Relativity (1916):

1) ***The curved spacetime, or geodetic, effect***—Einstein's theory predicted that the presence of a mass in space, such as the Earth, would warp local spacetime, creating a dip or curve in spacetime.
2) ***The frame-dragging effect***—A few years after Einstein published his theory, physicists Joseph Lense and Hans Thirring predicted that the rotation of a mass in space would twist or drag the local spacetime frame around it.



In orbit, each gyroscope's spin axis was monitored for a year, as it traveled through local spacetime. Einstein's theory predicts that each gyroscope's spin axis will deflect 6,606 milliarcseconds in the plane of the spacecraft's orbit due to the local spacetime curvature, and a mere 39 milliarcseconds in the Earth's equatorial plane due to the frame-dragging effect. Was Einstein right or wrong?

GP-B finished collecting data in September 2005, and the science team then began analyzing the data—slow and painstaking work that is still in progress as of spring 2008. If GP-B's final results agree with Einstein's theoretical predictions, this will be the most conclusive proof of Einstein's theory of gravity ever produced; if not, general relativity may need to be amended.

For More Information:
- Gravity Probe B — *http://einstein.stanford.edu/*
- General Relativity Tests — *http://www.drphysics.com/syllabus/GRTest/GRTest.html*
- Putting Relativity To The Test — *http://archive.ncsa.uiuc.edu/Cyberia/NumRel/EinsteinTest.html*
- The Pound-Rebka Redshift Experiment — *http://hyperphysics.phy-astr.gsu.edu/hbase/relativ/gratim.html*
- Gravitational Redshift Essay — *http://www.astro.ku.dk/~cramer/RelViz/text/exhib3/exhib3.html*
- The Shapiro Time-Delay — *http://www.geocities.com/newastronomy/Shapiro.htm*
- Gravity Probe A — *http://funphysics.jpl.nasa.gov/technical/grp/grav-probea.html*
- Binary Pulses and Gravity Waves — *http://www.psc.edu/science/Taylor/Relativity.html*