Experimental Tests of Relativity

Technological developments since World War II have led both to several astrophysical discoveries and to new methods of testing gravitational theory. Many of the astrophysical observations require explanations in gravitational terms, and the combination of this need and the possibility of new tests has produced something of a renaissance in gravitational studies. The discipline is not large, but it covers a wide range of important topics. For example, at the Third "Cambridge" Conference on Relativity held at the Goddard Institute for Space Studies in New York City on 8 June all the major experiments now in progress were discussed by only 14 speakers, but the results of these experiments will have consequences for a variety of problems including pulsars, the beginning of the present epoch of the universe, and the possibility of a quantum gravitational theory.

Gravitational effects that can be detected experimentally are tied up with various theories in rather complex ways, and it is somewhat arbitrary to speak about a specific number of gravitational tests; but for the work described here it is convenient to refer to eight effects.

The first three are the classical observational differences between Newton's and Einstein's theories: the advance in the perihelion rotation of Mercury of 43 seconds of arc per century, the deflection of starlight by the sun's gravitational field, and the effect of a gravitational field on the wavelength of electromagnetic radiation. (The wavelength can be shifted to either the red or blue end of the spectrum, but for historical reasons this effect is called gravitational red shift.)

Two more relativistic effects have been measured in the past 3 years with instruments made possible by recent technological advances. These are the possible detection of gravitational radiation by Joseph Wever of the University of Maryland and the measurement by Irwin Shapiro of Massachusetts Institute of Technology of a relativistic effect on radar signals that were reflected by Mercury and Venus as they passed on the opposite side of the sun from the earth.

Two additional effects predicted by general relativity which can probably be measured within the next few years are parallel vector translation and the Lense-Thirring effect. Vector translation is produced in a body as the result of its orbit, and is detected as the precession of the axis of the orbiting body. The Lense-Thirring effect is an axis precession produced in one object by the rotation of another object.

The general theory of relativity is a field theory in which gravity is considered a property of the geometry of space-time. It employs a tensor field and a Riemannian geometry. In addition to these mathematical underpinnings, it is based on broad philosophical principles and bears the strong stamp of Einstein's personal taste. Other relativity theories are possible. The one that now is receiving considerable attention is that proposed by Carl Brans (Loyola University in New Orleans) and Robert Dicke (Princeton University) in 1961. This theory also uses Riemannian geometry and a tensor field, but it employs an additional scalar field.

The tensor and scalar fields exert forces on matter separately, so most of the effects predicted by the general relativity tensor theory are slightly different from those predicted by a scalar-tensor theory like that of Brans and Dicke. In addition, the scalar field in the Brans-Dicke theory is associated with the expanding universe and this produces what can be considered the eighth relativistic effect—the weakening of the gravitational constant with respect to time. Of the eight gravitational effects mentioned, only gravitational red shift is the same in both theories. Much of the excitement of current relativity studies is based on the fact that, for the remaining seven effects, it is possible to think of a technically feasible experiment that is capable of detecting the small differences between the two theories. Experiments designed to measure the currently predicted differences in all seven cases are now under way, and progress reports were given at the New York meeting on 8 June.

Perihelion Advance

By the time Einstein proposed his theory of general relativity in 1916, observations showed that an advance in the perihelion of Mercury of 43 seconds of arc per century could not be explained in Newtonian terms. Einstein's theory showed that there should be a relativistic effect of 43.03 seconds of arc, and the observations of Mercury's orbit have been considered one of the main experimental supports of general relativity.

Dicke is now casting a shadow on this neat success story. According to the Brans-Dicke theory the perihelion advance should be less by a factor of $1-(4s/3)$, where s is a parameter that must be determined experimentally. Dicke has proposed that part of the 43-second advance is a Newtonian effect caused by a quadrupole moment in the sun. In 1967 Dicke and Mark Goldenberg reported a value for the oblateness of the sun that resulted in a value of 0.07 for s. Thus, the advance in the perihelion of Mercury should be 9 percent less than that predicted by Einstein.

The measurements are very difficult, and complex corrections and assumptions must be made (Dicke's talk in New York was a detailed analysis of the assumptions). Hence few physicists think that the work is yet a major threat to general relativity.

Another approach to the perihelion problem is to get measurements which will make it possible to more accurately determine the effects of all the planets in the solar system on Mercury's orbit. Seven years ago Shapiro, Michael Ash, and William Smith began collecting optical and radio observations on the planets that will be combined with radar observations made during the past few years in order to get the best possible solution for solar-system dynamics. They now have over 400,000 individual observations, but these have not yet been processed sufficiently to distinguish between relativity and the Brans-Dicke theory.

Deflection and Delay

From the value of s obtained from the solar oblateness measurement, one would expect, on the basis of Brans-Dicke theory, that the bending of electromagnetic radiation in a gravitational field should be 7 percent less than the bending predicted by general relativity. But the optical measurements are only accurate to 10 percent, so they are not useful for testing the two theories. Recent measurements of the deflection of radio waves and the related problem of the slowing of electromagnetic radiation in a gravitational field have more promise.

Two quasars, 3C273 and 3C279, are about 8 degrees apart, and 3C279 is occulted by the sun each October; thus, it is possible to get its precise position with respect to 3C273 and then to measure the apparent displacement of 3C279 as its radio signals are bent toward the sun.

At the relativity conference, results were reported by two California Institute of Technology teams. Richard Sramek reported that the group making measurements at a wavelength of 3 centimeters had obtained a value for deflection of 1.77 ± 0.2 seconds of arc (Einstein's theoretical value is 1.75). Sramek's group used an interferometer consisting of two Owens Valley Radio Observatory telescopes on a 1-kilometer baseline and made measurements for about 100 hours between 10 September and 13 October.

Measurements at 13 centimeters by the second team and a calculation that combined the two sets of results were reported by Duane Muhleman. The interferometer utilized the 64-meter Goldstone antenna and a 26-meter antenna on a 21-kilometer baseline. The team made observations for 16 hours during 4 days around the occultation of 9 October. After making corrections for deflection by the solar plasma (which is not a problem at 3 cm) they arrived at a value of $1.82 + 0.24 - 0.17$ arc seconds. The combined 3-cm and 13-cm results were 1.70 ± 0.16. (The averaging technique gives the lower value.)

These measurements are still no more accurate than those from optical deflection experiments (about 10 percent), so they are not sensitive enough to detect the 7 percent reduction in deflection predicted by the Brans-Dicke theory. The experiments have the potential for refinement; and a longer baseline experiment that involved telescopes at Lincoln Laboratory, National Radio Astronomy Observatory, and Owens Valley may soon yield more precise results.

There are several measurements of the related phenomena of gravitational delay of radio waves, which are beginning to give results with uncertainties of less than 10 percent. Since 1966 Shapiro, Smith, and Gordon Pettengill have been using the Haystack antenna to make delay measurements of radar signals reflected from Mercury and Venus, and at the New York meeting Shapiro, Smith, and Gordon Pettengill for the determination of the relativistic delay was 6 percent. Plans are under way to do the experiment jointly with a Jet Propulsion Laboratory team headed by Richard Goldstein, in which the signals would be transmitted by the Haystack antenna and the Goldstone antenna would receive the echoes. Shapiro said this "Goldstack" experiment should increase the accuracy by "almost an order of magnitude."

Accuracy of the same order of magnitude is being achieved with Mariner 6 and Mariner 7 satellites. These spacecraft went into solar conjunction on 29 April and 10 May, respectively, and are equipped with transponders that can return signals sent from the Goldstone antenna. John Anderson of Jet Propulsion Laboratory reported time-delay values with a 10 percent error at the New York meeting but recently told *Science* that the error had been reduced to "the level of 5 percent or so." He also said that "our solutions are coming out the other side of Einstein." That is, there is more time delay rather than less as predicted by the Brans-Dicke theory. The results are preliminary, but there appears to be much confidence in the method—both by the research team and by outside observers. If the time delay is actually higher than predicted by Einstein it would have important consequences for relativity theory, so the value will be watched closely as it is refined.

Among the most difficult experiments being conducted is one by William Fairbank of Stanford University to measure both the parallel vector translation and the Lense-Thirring effect in a satellite and another by John Tyson of Bell Telephone Laboratories to detect the Lense-Thirring effect terrestrially.

Fairbank's group has been working on gyroscopes that will be made of quartz spheres coated with a superconducting metal. Changes in the orientation of the axes will produce quantum effects in the superconductors that will be read out electronically. Using more than one gyroscope they hope to separate the two relativistic effects. At the New York meeting, Fairbank said that they should have a working model this fall, but that the earliest possible date for the experiment is with the second Skylab satellite at the beginning of 1975.

The Stanford experiment should have sufficient precision to detect the difference between the magnitude of the effect predicted by the general relativity and the Brans-Dicke theories.

Tyson's experiment is another attempt to measure the Lense-Thirring effect with sufficient precision to distinguish between the two theories. Tyson is working on a system in which a metal sphere surrounded with superfluid helium is to be rotated near the limit of its tensile strength. The Lense-Thirring effect will produce a slight rotation in the helium, and this will produce a small inductance that will be picked up electronically. Tyson has a prototype built, but actual experiments with a device that is sensitive enough to measure rotations as small as 10^{-18} radian per second are several years away.

The scalar couples to all the matter in the universe; thus, according to the Brans-Dicke theory there is a slight decrease in the gravitational strength with respect to time in an expanding universe. Several relativists have considered geophysical or astrophysical phenomena that might show this weakening, and Dicke believes that there is an observational discrepancy in different ways of dating the universe that can be resolved by the Brans-Dicke theory.

At the New York meeting Shapiro reported on work that may soon test the theory's prediction of the weakening of the gravitational constant. The Haystack radar measurements give extremely accurate orbital information for Mercury and Venus. The team's measurements since 1966 indicate that, if the gravitational constant is weakening, it is doing so by less than 4 parts in 10^{10} per year. The Brans-Dicke prediction is of the order of one part in 10^{11} per year, and Shapiro said the team could get a precision of "three parts in 10^{11} per year if we get 5 more years of the same kind of radar data."

A terrestrial experiment designed to measure any change in the gravitational constant was described by David Douglass of the University of Rochester.

Since 1959 Joseph Weber has been working on gravity wave detectors that consist of large aluminum cylinders. Distortions in the cylinders stimulate piezoelectric crystals bonded to the surface and can be recorded after amplification. Weber first reported the possible detection of gravity waves in 1967. Many physicists who were skeptical of these early results were won over last winter when Weber reported that over 100 events had been detected simultaneously by detectors located at the University of Maryland and at Argonne National Laboratory near Chicago. At the New York meeting Weber presented results indicating that earlier suggestions that the "events" could be caused by cosmic rays exciting the detectors is invalid.

He also reported on a new detector that should respond only to the scalar mode of a gravitational wave. During the first 22 days of the experiment there were no scalar events that could not be accounted for as the result of random coincidences. A discussion among several theorists at the conference indicated that there is disagreement as to whether one would expect a large scalar component in the gravitational radiation produced by violent astronomical events.

For some time Weber has suspected that regular 12-hour and 6-month variations in his data are evidence that most of the gravity waves come from the galactic center, and in New York he appeared confident that this was the case. During his formal presentation, he gave no rate for radiation from the galactic center, but in response to a question he said that it could be losing energy equivalent to 1000 solar masses per year. However, he thinks this is unlikely and said that the importance of the galactic center observations is that they further discredit the suggestion that the events are random noise in the detectors.

Several other investigators have been drawn into studies of gravity waves. John Tyson said that at Bell Labs they are studying the quantum noise in a Weber antenna. David Douglass reported that in addition to his time variation experiment he has been investigating Weber antennae capable of detecting high frequency radiation, of distinguishing the scalar component of a gravity wave, and of detecting the radiation expected from the Crab Nebula pulsar. In an unscheduled talk Vladimir Braginski of Moscow State University reported that they are working on two Weber-type antennae with some significant modifications. By fall or winter they hope to have the two instruments operating along a 40-kilometer baseline.

Judah Levine from the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, spoke about the possibility of detecting gravity waves from the Crab Nebula pulsar with a device he has been building to make a new measurement of the speed of light. He has devised a strainmeter that consists of two pillars (points fixed to the earth) that are 30 meters apart. The beam from a methane laser is locked between the two points so that its wavelength is always an integral of the distance between the points. This is illuminated with a helium laser of constant wavelength. When the distance between the points changes the beat frequency produced by the two laser beams is changed. A Fourier analysis of the beat frequency provides information about the change in distance between the points.

The location and period of the Crab pulsar are known, and a prediction has been made about the frequency of the expected gravity waves. Levine thinks these features might produce a predictable pattern in his beat frequencies. (The earth has already been used as a gravity wave antenna in two experiments—by Weber and at Princeton—with null results.)

Fundamental Problems

There are several broad questions about the foundations of gravitational theory that, although somewhat philosophical, are susceptible to experimental test. One of these is the consistency of the gravitational force for different kinds of matter. Tests for the consistency of the earth's gravitational field on small objects made of different materials have been made for several centuries. In 1964 Dicke and his group at Princeton reported that the consistency holds to 1 part in 10^{11}.

At the meeting Kenneth Nordtvedt of Montana State University reported on his progress in preparing an experiment to see whether the earth and an object on the earth fall toward the sun with the same acceleration.

In principle his apparatus is simple. He will look for 24-hour variations in a system of vertical and horizontal pendulums (the horizontal pendulum is the object being tested). In practice, the experiment will take several years of painstaking preparations to get rid of or account for the thermal, seismic, and tidal disturbances that can interfere. The experiment has the potential of testing the weak equivalence principle—the statement that all bodies fall with the same acceleration. This is of special interest to Nordtvedt because in 1968 he published a theoretical paper showing that there is a small violation of this equivalence principle in the Brans-Dicke theory.

A measurement of gravitational red shift, although of no help in testing for differences in current theories, is still of considerable interest because recent technological advances introduce the possibility of improving this test by three orders of magnitude. At the conference Norman Ramsey of Harvard described an experiment designed to measure gravitational red shift by comparing times kept by earthbound and orbiting hydrogen maser clocks. Ramsey thinks the experiment is potentially capable of a precision of 1 part in 10^5. However, 2 years ago the satellite on which the maser was to ride was cut out of the space program; and of the original three investigators only Robert Vessot of the Smithsonian Institution is carrying on developmental research, and the future of the experiment is very uncertain.

Many problems involving gravitational theory await answers. These include the validity of the equivalence principle and of Mach's principle, the latter being a prerelativity statement to the effect that the inertial properties of any particle of matter should be determined by the distribution of all the matter in the universe.

Since 1966 it has been known that a singularity develops during gravitational collapse. Some physicists believe that the full understanding of this development may require the quantization of relativity theory. The singularity is already involved in one possible astronomical problem—the so-called "black holes" that may form after gravitational collapse.

Other astronomical problems include the expansion of the universe after the "big bang," which many astrophysicists believe started the present epoch, the behavior of quasars and pulsars, and—as implied in Weber's work—the gravitational radiation at the galactic center.

Some of these questions may never be answered, but the current crop of experiments holds much promise, and most relativists expect that as the results are harvested during the next decade and beyond they will find answers to some of their fundamental questions about gravity.

—Robert W. Holcomb