New Test of Variable Gravitational Constant

Two groups using same data put new limits on how much G can vary with time, making Dirac's Large Numbers Hypothesis less likely

The gravitational constant G appears both in Einstein's field theory of gravity, general relativity, and in Newton's classical law. Its value determines the strength of the gravitational force between two bodies. Scientists consider G to be one of the fundamental constants of nature with a value that is assumed to be independent of when and where in the universe measurements are made.

This assumption is subject to experimental verification. Until recently, the best evidence restricted changes in the value of G to less than 100 parts per 1 trillion per year. However, given the age of the universe, about 20 billion years, even smaller changes could add up over time to have detectable consequences. Now two recent reports place far more stringent limits on how much G can vary with time.

One report, published in *Physical Review Letters* on 31 October by a collaboration comprising researchers from the Jet Propulsion Laboratory (JPL) in Pasadena and the NASA Goddard Institute for Space Studies in New York City, set a limit of either 6 or 18 parts per 1 trillion per year for the maximum possible change in G, depending on which of two theories they used. Both numbers are much smaller than the 50 parts per trillion per year predicted by the Large Numbers Hypothesis of British physicist Paul Dirac (now at Florida State University). Dirac's 1937 proposal is what started physicists thinking that G might be variable.

The second report, presented last May at a meeting of the Royal Society in London by researchers at the Harvard-Smithsonian Center for Astrophysics and the Massachusetts Institute of Technology (MIT), was based on the same sets of data. But it quotes a less restrictive limit on the time variability of G of 30 parts in 1 trillion per year.

Clocks are the key concept. Nature provides at least two types of clocks. The first is the kind that people have used since timekeeping began, typified by the orbital period of the earth around the sun. Time defined in this way is fixed entirely by gravitational physics. More recently, atomic timekeeping has become the standard method. Rather than the orbital period of an electron around the nucleus of an atom, actual atomic clocks depend on the frequency of radiation emitted when an electron jumps from one orbit to another. In either case, time is entirely an atomic physics affair.

Dirac's Large Numbers Hypothesis traces to his observation of certain numerical relations between gravitational and atomic physics quantities. For example, the age of the universe in atomic time units is about 10^{40}. Similarly, the relative strengths of the electromagnetic and gravitational forces between an electron and a proton is about 10^{40}. Dirac conjectured that this is not just a coincidence and that the fundamental constants of gravitational and atomic physics may be related in a manner that depends on the age of the universe.

In order to maintain any such relationship between the constants, one or more of them would have to be time-dependent. As a consequence, gravitational and atomic clocks would run at different rates with respect to one another. Although there is no a priori reason to specify which clock is "actually" changing, it has been customary to look at changes of the gravitational clock. In Dirac's first model, for example, G varied inversely with time; that is, gravity is much weaker now than in the past. No one has ever proposed a more specific cause for a time-varying G than the vague words "cosmic effects."

> Dirac observed certain numerical relations between gravitational and atomic physics quantities.

Dirac never worked out a full field theory of gravity that incorporated his idea. But in 1961, Carl Brans (now at Loyola University in New Orleans) and Robert Dicke of Princeton University devised what has become the best known alternative to Einstein's general relativity. It explicitly allowed for a variable G. There have been several variations of this prototype theory.

The evidence for a time-varying G has been mixed. In 1948, for example, Edward Teller (now at the Lawrence Livermore National Laboratory) calculated that if gravity was decreasing at the rate Dirac suggested, then in the past the earth would have been much warmer since the sun would have been burning more intensely in the past. If so, the oceans would have been boiling, thereby precluding the evolution of life as presently conceived. Not all physicists accept Teller's calculations, however.

And, in the last decade, a series of tests of theories of gravity have consistently verified general relativity and virtually ruled out the Brans-Dicke and related theories. Most of these tests depend on measuring precisely the time delay (or the deflection) of electromagnetic radiation as it passes by the sun, which has a gravitational field large enough to generate an observable effect. "At present, there are no fully worked out field theories of gravity that allow for a time variation in G and that satisfy the other tests," says Ronald Hellings of JPL.

On the positive side, since 1970, Thomas Van Flandern of the U.S. Naval Observatory in Washington, D.C., has published a number of analyses of measurements of the moon's period about the earth which indicate a nonzero effect. The most recent 1981 report suggests that G is decreasing at the rate of 64 parts per trillion per year. One difficulty with this finding is that the earth-moon system is complicated by poorly understood tidal effects that have to be taken into account. Another is that systematic errors in the measurements of the moon's period cannot be excluded.

Meanwhile, Vittorio Canuto and his colleagues at the Goddard Institute began a reanalysis of the whole question. They reemphasized that Dirac's Large Numbers Hypothesis requires only that the relative rates of gravitational and atomic clocks change with time. A variable gravitational constant would be one way to accomplish this but not the only way.

In 1982, Canuto and Itzhak Goldman of the Goddard Institute devised a theoretical framework (although not a full field theory of gravity) that explicitly allowed for changes in certain nongravitational quantities, such as the masses in atomic units of macroscopic bodies, and thereby for gravitational and atomic clocks to run at different rates. They also calculated that the fractional change in the gravitational constant in their theory was twice the fractional change in the relative clock rates.

This year, Canuto and Goldman analyzed with their model several types of astrophysical and geophysical data ranging from the abundance of helium and deuterium that was synthesized in the early minutes of the universe to paleomagnetic data on the size of the earth a few hundred million years ago. In particular, they showed that, even if gravitational and atomic clocks ran at rates as different as required by the Large Numbers Hypothesis, the past earth would not have been plagued by boiling oceans. However, their most recent conclusion is that the overall fractional change in the clock rates cannot have exceeded 10 parts per trillion per year.

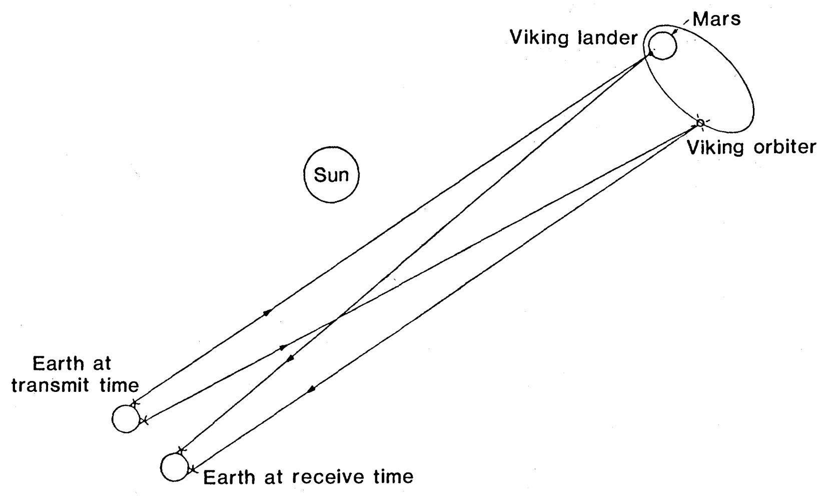
While these findings relate to the question of whether clocks were changing in the past, the two new experiments examine the present behavior of gravitational and atomic clocks.

The idea of the experiments begins with a calculated orbit of a planet in the solar system relative to the earth. The calculation assumes a standard model of the solar system with, for the case of a variable gravitational clock, the fractional change in G as one of several parameters to be determined. Measurements taken over a period of several years of the actual distances between the earth and the planets are fitted to the model solar system by a curve-fitting procedure to yield any time changes in G during the observing period.

For the method to work, the measurements have to be referenced to atomic time in some way. A changing G would affect all gravitational clocks the same way, so no time variation would show up if only gravitational clocks were used. In 1964, Irwin Shapiro of MIT (now at the Center for Astrophysics) proposed radar ranging with atomic clocks as a means of testing for a changing G.

Radar ranging means that a transmitting station on the earth broadcasts a signal to the planet in question, which reflects the signal back to the earth. Atomic clocks measure the time for the trip, which implies the distance. Shapiro and several colleagues first applied this technique to testing G in 1971. They relied mainly on radar-ranging data from the planet Mercury and obtained a bound on any fractional variation of G of less than 400 parts in 1 trillion per year.

Five years later, Robert Reasenberg of MIT (now at the Center for Astrophysics) and Shapiro combined radar-ranging data of Mercury, Venus, and Mars taken over the period from 1966 to 1974 to refine their estimate to less than 100 parts in 1 trillion per year. The largest source of error turned out to be the irregularities of the planet surfaces due to mountains and valleys.



Mars ranging

Electrically charged particles of the interplanetary plasma introduce an uncertainty in the travel time of a microwave signal sent from Earth to Mars and returned. The effect is greatest when the earth and Mars are on opposite sides of the sun, so that the signal travels near the sun. The uncertainty depends on the frequency of the signal and can be corrected by comparing the travel times of signals at two different frequencies. The Viking Mars lander did not have a two-frequency capability, but the Viking orbiters could return a signal at two frequencies, thereby permitting correction of the plasma effect for some measurements. [Source: R. D. Reasenberg, Harvard-Smithsonian Center for Astrophysics]

The newest results take advantage of the Viking Mars landers. In this case, a microwave (S-band) signal sent from Earth is received by transponders on the landers, which rebroadcast signals at the same frequency. Hellings of JPL says the accuracy of the method is good enough to fix distances to within 10 meters, thereby dramatically increasing the sensitivity of solar system tests of gravity.

Both collaborations (Hellings, Peter Adams, John Anderson, Mike Keesey, Eunice Lau, and Myles Standish of JPL and Canuto and Goldman of the Goddard Institute, and Reasenberg, Shapiro, Robert Babcock, and John Chandler of the Center for Astrophysics and Robert King of MIT) used the Viking data from the period 1976 to 1982. They also used the older ranging data of the inner planets and of the Mariner 9 Mars orbiter, as well as laser-ranging measurements of the moon and optical measurements of the sun and the planets.

Answers obtained by the two collaborations are as follows. The JPL-Goddard group reported a fractional variation in G of $(0.2 \pm 0.4) \times 10^{-11}$ per year, using the old theory. With the new model, the result is a rate of drift of atomic clocks relative to gravitational clocks of $(0.1 \pm 0.8) \times 10^{11}$ per year. The Center for Astrophysics group quoted a fractional variation of G of less than 3×10^{-11} per year, although a lower bound is likely with further analysis.

The sensitivity of the test was so great that the asteroids presented the biggest difficulty. Asteroids have a significant effect on the orbit of Mars. Moreover, asteroids are doubly devious because their effect on Mars can closely resemble that due to a variable G. The different conclusions reached by the two groups are due to their use of different models of the asteroids and to their confidence in the models. The JPL-Goddard group used many more asteroids.

How confident should one be in these findings? Leopold Halpern, an associate of Dirac's at Florida State, says that there is no doubt that the Viking Mars lander measurements are the best experimental evidence so far. But Halpern joins other observers in citing the possibility of undetected systematic errors. Investigators look for such effects by making changes in their model and in the data included and observing the effect on the output of the complicated curve-fitting procedure they use. But, in the end, says Shapiro, "the estimate of the effects of systematic errors is all very subjective. If we knew what they were, we would adjust to account for them and they wouldn't be systematic errors any more."

Ultimately, the best confirmation resides in experiments of different types that give the same result. Canuto believes that the convergence of conclusions from the astrophysical and geophysical data and from the planetary ranging provides this kind of confirmation. "It's the first time in 40 years we have a good number," he says.

—ARTHUR L. ROBINSON