Second Thoughts on General Relativity?

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FOR a long time since it was propounded in 1915, Einstein's general theory of relativity remained somewhat aloof from the realm of experimental physics. The reason, which applies equally to most modern gravitation theories, is this: gravitation is a very weak force compared to other interactions of interest to the laboratory physicist, and it is very difficult to think of any test to distinguish between the predictions of the simple Newtonian theory of gravitation and of the other, more sophisticated, theories like general relativity. One such test involved the motion of the perihelion (the point of closest approach to the Sun) of the orbit of the planet Mercury. Newtonian theory could not account for all of the observed angular motion of the perihelion — some 575 seconds of arc per century. The theoretical estimate was 532 seconds of arc per century. Forty-three seconds per century thus remained unexplained, and was almost entirely accounted for by general relativity. The small difference is an indication of the problem of distinguishing between the two theories of gravitation.

With advancements in techniques of observation in astronomy, however, the chances of verifying the correctness of general relativity have improved. One example is provided by cosmology. The simplest models of general relativity describe the universe as expanding from a primeval explosion, the big bang. Such an expansion is indeed observed, if one examines the spectrum of light from a distant galaxy. The spectrum shows familiar lines of the type seen in our galaxy, the Milky Way, or some nearby galaxies like the Andromeda, but with one difference. The wavelengths of these lines are all increased by a fraction, and the lines tend to shift towards the red end of the spectrum. This is called the *redshift*. A redshift, that is, an increase in the wavelength or a decrease in the frequency of light, may be naively interpreted as arising from the recession, or moving away, of the source of light from the observer. This is the familiar Doppler Effect. (A similar effect for sound waves implies that sound from a receding source has reduced pitch, or that it appears flatter to the listener.)

It was Edwin Hubble, an American astronomer, who, in the late 1920s, first discovered this effect and found a simple relation: that the farther the galaxy, the larger is the redshift. Hubble found a linear relation between the redshift and the distance. In the Doppler Effect interpretation, this means that the velocity of recession increases in proportion to the distance of the source of light, or the farther the source, the faster it moves away. In practice, the observer does not measure the distance of the galaxy directly, but estimates it from its relative brightness compared to a nearby galaxy. The fainter the galaxy, the farther it is inferred to be, assuming, of course, that the intrinsic brightness of the galaxy does not vary.

WITH increasingly improved astronomical techniques, astronomers have extended Hubble's relation to more and more remote galaxies. At the same time, they have tried to see whether this relation tells us about how fast the universe was expanding in the remote past compared to now. The orthodox models of general relativity tell us that the expansion should slow down as the universe becomes older. This is because, the particles of matter in the universe tend to attract each other and, hence, have a tendency to draw closer. If the matter density is higher than a critical value, then Einstein's theory predicts two results: (*i*) The universe is closed, that is, it is finite in extent but unbounded. (The surface of a sphere has a finite area, but no boundary or edges; a person moving on the surface of the Earth does not encounter an edge or a barrier. The same idea can be extended to higher dimensions and applied to the universe.); (*ii*) The universal expansion comes to a halt eventually and the universe begins to contract.

If the recent finding that the gravity in the universe is weakening is confirmed, it will not only mean a set-back to Einstein's general theory of relativity but will have several other implications

The observations of Allan Sandage and his collaborators at the Hale Observatory in Southern California, USA, seemed to bear out these predictions — until about a year ago. The expansion of the universe appeared to be slowing down fast enough to imply that its density exceeded the critical value.

Towards the end of 1974, however, the observational situation changed dramatically. Astronomers like Jim Gunn and J. B. Oke, both of California Institute of Technology, USA, Beatrice Tinsley of the University of Texas, USA, and even Sandage recognised that there were several uncertainties in the interpretation of the data. First, there is a strong possibility that the intrinsic brightness of a galaxy changes with its age; theories of evolution of stars suggest that galaxies (which are made of stars) may become fainter as they get older. Second, there is the likelihood of the existence of an intergalactic medium as yet undetected, and such a medium would absorb light from distant galaxies. And to make matters worse, there is a great deal of variation in the intrinsic brightness of galaxies. As mentioned earlier, the astronomer estimates the 'distance' of a galaxy by measuring its faintness — the fainter the galaxy looks from the Earth, the farther away it is assumed to be. But any of the factors mentioned above could distort the interpretation of the distance of a galaxy. For instance, a galaxy appearing faint may actually be nearby, but intrinsically less bright than the neighbouring galaxies. Consequently, a realistic assessment of the various uncertainties has resulted in widening the range of possible answers. Thus the data permit not only a decelerating universe but also an *accelerating universe.*

IN the early days of general relativity, Einstein had been tempted to introduce a new force of cosmic dimensions — the so-called λ-term — in his equations to balance the force of gravitational attraction. It was a force of repulsion which increased in proportion with the distance between the interacting particles. Thus it was negligible on the scale of the Earth or the Solar system, but became significant on the scale of the universe (over 10,000 million light years). With the help of this new force, Einstein constructed a static model of the universe in which the gravitational attraction was exactly balanced by the λ-repulsion.

Eventually, however, Einstein abandoned this term. This was partly because it was shown that the Einstein universe was unstable; it would either collapse or expand on a slight disturbance. Also, Hubble's observations seemed to support an expanding rather than a static universe. Since models of such a universe could be obtained without the λ-term, most cosmologists felt that it was unnecessary to bring in this new force. Orthodox general relativity, therefore, does not incorporate the λ-term.

But some fresh, recent data, which imply that the universe may be accelerating, has revived the λ-term. Gunn and Tinsley (*Nature,* **257,** 454, 1975) have examined other cosmological checks available at present. These include considerations like the age of the universe, the abundance of deuterium produced soon after the big bang, the formation of galaxies, etc. The universe as a whole must be older than the oldest known object! The estimates of galactic ages, therefore, tell us something about the age of the universe, which in turn tells us how fast it has been expanding in the past. The very early expansion rates and the density of matter also play an important role in the synthesis of nuclei like deuterium and helium from the elementary particles, protons and neutrons, in the primordial material. These factors, at a somewhat later stage, control the formation of galaxies. On the basis of various considerations, Gunn and Tinsley conclude that the model 'best' fitting the data involves the reintroduction of the λ-term. For, none of the models of orthodox general relativity (without the λ-term) fits the data.

A **SECOND** possible threat to the structure of orthodox relativity has emerged from the recent and rapidly improving technology of atomic clocks. With the help of very accurate time-keeping devices it should be possible to measure the rate of change of the gravitational constant *G*. General relativity predicts that *G* must be strictly a constant.

In 1937, the English physicist, P. A. M. Dirac, suggested a cosmological theory in which the gravitational constant slowly decreased with

the epochs. How slowly? In modern framework, Dirac's prediction would suggest a current rate of decrease of G per year of $1\frac{1}{2}$ parts in 10,000 million (that is, $G/G \sim 1{\cdot}5 \times 10^{-10}\,\mathrm{yr}^{-1}$)! A gravitational theory proposed by Brans and Dicke in 1961 predicts a rate of decrease of G slower than this by over a factor 10 to 100. In 1972, Fred Hoyle and I concluded on the basis of our gravitation theory that a rate of decrease of G at one-third the rate predicted by Dirac should result from the expansion of the universe.

Recently, K. P. Sinha and C. Sivaram, of the Indian Institute of Science, Bangalore, have suggested another theoretical framework which talks of *two* gravities — one, a strong gravity measured by a coupling constant G_f and the other, the weak gravity, measured by the Newtonian gravitational constant G. The strong gravity is a characteristic of the atomic properties of matter and is unaffected by the universal expansion. The weak gravity, on the other hand, changes as suggested by Dirac. According to Sinha and Sivaram, G and G_f were equal in the early hadron era, when the age of the universe was of the order of 10^{-33} seconds, the characteristic time of strong interaction of heavy elementary particles, the hadrons. Subsequently G_f stayed constant but G decreased with time

In all these cases, the present rate of decrease is so low that at first sight it would appear to be unmeasurable. Thanks to the progress in making highly stable time-keeping devices, the prospect of checking the constancy of G is not so remote now. Indeed, preliminary results indicating a decreasing G have already been separately reported by Van Flandern of the US Naval Observatory and P. M. Muller of the Jet Propulsion Laboratory, California, USA.

These studies make use of the discrepancies which would result in the three-body system of the Sun, the Earth and the Moon, if G were changing slowly; decreasing gravity would imply that the Moon's orbit about the Earth will steadily get larger and its period of rotation about the Earth will get longer. Consequently, this will affect the frequency of occurrence of eclipses. All these results would give us the answer to the question whether G has changed over the past few centuries, provided we know the accurate positions of the Moon. The calculations are again fraught with uncertainties such as the extent to which the lunar and solar tidal forces would affect the result. Hence, although values in the neighbourhood of about 5 parts in 100,000 million per year are quoted for the rate of change of G, these must be viewed with caution until further experimental checks are made.

At present, clocks which are stable to 10^{-15} seconds have been built. An improvement in accuracy by 2 to 3 orders of magnitude (feasible theoretically) will make a purely laboratory experiment to detect weakening gravity a distinct possibility.

EINSTEIN'S general theory of relativity assumes G to be a constant, and if it is found to vary, the entire structure of the theory will collapse. If experiments do indeed show such a trend, it may be necessary to abandon Einstein's theory in favour of theories with changing G. The general theory of relativity could then be used only as an approximate theory, mainly in discussing phenomena involving short timescales, for instance, the motion of planets around the Sun over periods of a few hundred centuries. For cosmic timescales, extending up to billions of years, Einstein's theory may not hold good.

Besides, a steadily decreasing gravitational force has several significant implications for the structure of, and life on, the Earth itself. For instance, the equilibrium of the Earth in its orbit is maintained by certain internal forces and the gravitational force acting on it. A decrease in the gravitational force will affect this equilibrium, and the Earth will tend to expand. One could possibly argue that an expansion like his in the past produced internal pressures which led to continental drifts. And possibly, the Earth was also closer to the Sun in the past than it is now, and, therefore, it may have received a larger amount of energy from the Sun. This has much effect on the evolution of life on the Earth. The changes will, of course, occur over a long period and any significant difference will not show up over a million years.

The evolution of stars and galaxies will also be affected if the gravitational constant G steadily decreases with time. In that case, the Sun itself could have been brighter in the past than it is now. Many of these effects have still to be worked out by astrophysicists, and may considerably alter some of the current ideas on the evolution of stars and galaxies. Before undertaking such investigations, the astrophysicists would, however, like to be convinced that gravity is indeed getting weaker.

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