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Gravity and the stop watch

Measuring the effect of gravity on perception of time has got one better, says S.Ananthanarayanan.

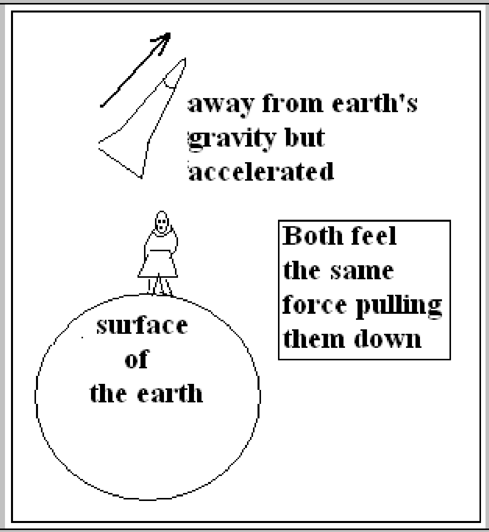
An important consequence of Einstein's General Theory of Relativity is that a clock would run slower if it was in a gravitational field. How far this is true has much importance for resolving quantum theory, which works perfectly with atoms and nuclei, with Einstein's theory of gravity, which works in the cosmos. ***Holger Müller*** and colleagues at Berkley, USA have used existing data about the Caesium atom to arrive at the most accurate estimate yet of the clock slowing effect of gravity.

Theory of Relativity

The startling discovery, in experiment, that light moved with the same speed even when emitted from a moving source, led Einstein to reinterpret the meaning of space and time. Einstein worked it out that lengths and time intervals were different when measured by observers in relative motion, but the differences becoming significant only when the relative speed was comparable to the speed of light.

How Einstein came to this was by reworking the laws of motion to be the same for observers in uniform relative motion and yet to provide for the speed of light to be the same for both observers. The same theory also interpreted energy and relativity of mass, in different frames of reference and arrived at the relation, $E=mc^2$, between energy and mass itself.

Another aspect, related to gravity, was that we experience a force of being pulled downwards, just like increased gravity, when we are in a lift that moves rapidly upwards. This is the equivalence of gravity and acceleration. A person inside a spaceship, far away from the earth's gravity, should then feel the same force as on the earth if the spaceship was accelerated upwards at the same pace as a stone falling, back on earth.



Einstein's formulation, to include gravity as a manifestation of mass, with the coordinates of space and time, led to the concept of mass reducing to a curvature in the structure of a four dimensional space, which included the usual three dimensions we all know and also a dimension for time. A simplistic way of expressing this is to imagine space as a vast, stretched trampoline, with cannon balls placed on it to represent masses. The cannon balls would cause depressions in the stretched fabric and smaller masses would roll towards them, as if ‘attracted’.

But a consequence of the theory is gravity not only bends space, it also stretches time itself - so that clocks in a gravitational field (which is also the same as an accelerated clock) would run slower than clocks in free space. The Special Theory of Relativity had shown that clocks in relative motion run slower than clocks at rest. But what the Theory of Relativity said was that even when relatively at rest, the clock in higher gravity would run slower!

Gravity and quantum physics

While the General Theory of Relativity has brought great order in our understanding of the motion of planets, stars and galaxies, the quantum theory, that energy, at the very fine level, consists not of a continuous stream, but of tiny, separate parts, called ***quanta***, has met unprecedented success in explaining matter at the atomic level. While gravity is a force that acts even at great distances, like between the sun and the earth, it is a very weak force and is quite negligible between the tiny particles that make up atoms and nuclei. But at these tiny distances, the electric force, and other forces which act only at short distances, are very strong, and they enable the existence of atoms, matter, planets and stars!

We have thus 2 theories, each highly successful in its home ground, but irrelevant in that of the other. Hence the interest in correlating the 2 theories, to develop a ***quantum theory of gravity***, which, hopefully, would enable scientists to find a way out of other impasses that the existing theories, for all their success, now find blocking their way!

Closer look at gravity.

The refinements in astronomical calculations that the General Theory of Relativity imposes have been amply verified and are now routinely used in cosmology. The ***bending of space*** has also been dramatically verified, by the stars that should be hidden behind the sun springing into view when the sun is blocked in a solar eclipse. But the slowing down of a clock in a gravity field, this has not been verified with equal accuracy.

The way it has been done been with the ***Pound-Rebka experiment***, of 1959, where it was shown that the colour of light got shifted to the red (longer wavelength) side when in a stronger gravitational field. The waves of light, which have a frequency, are in effect a time-keeper and when the frequency reduces, this is nothing but shifting the colour to a longer wavelength.

A variety of the iron atom, called Fe^{57}, which readily, but very selectively, emits and absorbs short wavelength gamma rays, were used at the bottom and the top of the Jefferson tower in Harvard University. When Fe^{57} atoms are placed in the way of the gamma rays emitted by other Fe^{57} atoms, the gamma ray photons get absorbed. But if the photons are not of exactly the same wavelength, then, Fe^{57} just allows them to pass undisturbed.

Solid samples of Fe^{57} were placed at the top and bottom of the tower (22.5 metres apart), with a detector placed behind the sample that was to block gamma rays by absorption. Now, because of the difference in the force of gravity at the top and bottom of the tower, the gamma rays emitted from the top would be 'blue shifted', when they reached the stronger gravity at the bottom. They would then not be absorbed and would be detected. But if the source atoms were accelerated, just to compensate the slight frequency change, the gamma rays would be absorbed.

The source Fe^{57} was therefore mounted on a loudspeaker diaphragm, which vibrated. There was then a mix of frequencies emitted and correlating the tone in the loudspeaker with the signal in the detector was able to estimate the extent of gravitational red shift.

The result, accurate to 10%, was in agreement with theory. Related experiments, comparing atomic clocks that stayed on the ground with another that aboard an aircraft and again aboard a spacecraft, have led to verification of around 10 parts in a million. But verification of red shift is still considered to be a weak link in confirming the theory.

The current computation

The work of ***Müller*** and others at Harvard uses the results of an experiment some ten years ago for measuring gravity itself. The method used was of splitting a beam of high energy atoms, with the help of a laser pulse, into equal numbers that absorb a photon and which do not. The beam then splits into two paths, one which goes higher, to lesser gravity and one which stays lower, with higher gravity. A second laser pulse then causes brings the two beams back again and then the strength of the beam is measured.

As the atoms display wave nature, like all high energy particles, they have a shared, characteristic frequency when they are together. When they are split into beams that traverse different paths, the higher beam, which feels less gravity, is at a higher frequency than the lower beam, because of the ***red shift***. Hence, when the beams come together, the two may not be in step, and if they are largely out of step, they may annul each other, in the manner that waves returning from the sea shore sometimes depress the next incoming wave.

Varying the laser pulses and carrying out detection under different conditions leads to data that enables sensitive assessment of the phase difference of the two beams and hence the red shift. The data that ***Müller*** and Co. used was originally collected for measuring how much atoms were accelerated in free fall. But the same data permits assessment of red shift and the results obtained, which soundly agree with theory, are correct to about 7 parts in a billion.

Being sure of gravity being a manifestation of space curvature is important in the quest for a theory of quantum gravity.