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Article · October 2009

Source: DOAJ

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(Dated: September 1, 2009)

Abstract

This article analyses the nature of classical Newtonian gravity beginning with Galileo's experiments and the paradox that ensues from Aristotle's law of falling bodies, delving on the notions of inertial and gravitational masses. Arguing that Newton's gravity law is inconsistent with relativity, it briefly describes Einstein's relativistic theory of gravity, pointing out the importance of weak equivalence principle in the formulation of general theory of relativity. It also provides a short discussion on an important prediction of general relativity, namely, the existence of gravitational waves and the attempts to detect them. Finally, the article touches on the current challenges facing the gravity researchers.

It was Galileo who through his experiments with falling bodies established that every dropped object accelerates towards Earth with the same acceleration, provided other forces like friction due to air, buoyancy etc. acting on the object is negligible. This result clearly rejected the Aristotelian view which stated that heavier objects fall faster. Galileo's observations illustrate one of the basic tenets of science that only through careful experiments can one arrive at a fundamental principle. Aristotle's incorrect law was based on the apparent every day phenomena that heavy objects like stones, metal spheres etc. fall faster than lighter materials like feathers, papers, dried up leaves etc. without the realization that it is air friction and buoyancy that cause the lighter objects to accelerate downwards at a slower rate.

Aristotelian postulate that 'heavier bodies when dropped accelerate downwards faster than the lighter ones' was also logically flawed, giving rise to a paradox. Suppose you tie a lighter body A by a thin steel wire to a heavier object B, and then let both fall freely. Then, if Aristotle is right, B will tend to pull A down while A falling at a slower rate will try to put brakes on B's fall, so that both will together descend at a rate which is lower than the rate at which B would have fallen if it was not attached to A. But A and B together constitute a heavier mass than B by itself, so that according to Aristotle's law A+B ought to descend faster than B falling alone. There is clearly a contradiction here. It gets resolved by Galileo's principle that all bodies acted upon by Earth's pull alone, accelerate downwards with the same acceleration.

The next leap in the understanding of gravity took place when Isaac Newton while trying to make sense of Kepler's laws of planetary motions stumbled on the idea that all bodies attract each other by a force. The French philosopher Voltaire, who was a contemporary of Newton and who was under exile in England during the time of the discovery of law of gravity, reported that the falling of an apple inspired the latter to propose gravity to be a universal force [1]. As an aside, it is interesting to observe that Aryabhatta, the famous astronomer and mathematician who lived in the fifth century AD in Kusumapura, had already proposed that Earth rotates around its axis and because of this revolution we see Sun rising and setting everyday. When he was challenged by his rivals that if Earth indeed spins then why are not terrestrial objects thrown out (as it would happen if people in a rotating merry-go-round are not held to their seats by other external forces), he was supposed to have speculated that there must be some force directed towards the centre of our planet that prevents us from being hurled out [2].

It was the sheer genius of Newton to have realized that the Moon's rotation around Earth is nothing but its falling towards the Earth (After all, when an object moves in a circle, its acceleration is directed towards the centre of the circle, and since Moon goes around the Earth in a near circular orbit, its centripetal acceleration points at the Earth and the centripetal force necessary to keep it rotating around is provided by our planet's gravity.). From a simple calculation, Newton immediately established that the ratio of Moon's centripetal acceleration to a falling apple's acceleration is just square of the ratio of Earth's radius to Moon's distance from our planet. That is how he arrived at the inverse square law. Only a superb mind can deduce such a profound law of nature from simple observations.

The magnitude of the gravitational force between two point masses are proportional to the product of their masses and inversely proportional to the square of the distance between them, while the direction of gravity is along the line joining the two point particles (See Eq.(1) below.). Newton's law of gravitation successfully explained why the planetary orbits are elliptical in nature with Sun as the focus and why the square of the orbital time period is proportional to the cube of the planet's distance from the Sun. It is Newton's law which governs the motion of artificial satellites around Earth, trajectories of space-crafts, motions of stars in the galaxy, dynamics of interacting galaxies, and so on.

But what mass was Newton referring to - gravitational or the inertial mass? Inertial mass is a fundamental attribute of matter. More the inertial mass of an object, larger is its linear momentum, and therefore larger is the force required to deflect the object. From special theory of relativity (STR), we also know that energy and inertial mass are equivalent (recollect the celebrated expression $E = mc^2$!). Every elementary particle is associated with its trademark inertial rest mass. To create an elementary particle in an experiment, the minimum energy required is its rest mass times square of the speed of light. On the other hand, gravitational mass is that which acts as a source of gravity. For electrostatic forces, the Coulomb's law states that the electric force between two charge particles is proportional to the product of their electric charges and inversely proportional to the square of the distance between them. Coulomb's law is so much like Newton's gravity law - just replace the electric charges by the gravitational masses! In the case of gravity, gravitational mass is analogous to gravitational charge.

According to Newton's laws of motion the trajectory of a point mass A is obtained by solving the Newton's equation which states that its inertial mass $m_{\rm A}$ times its acceleration $\vec{a}_{\rm A}$ equals the total force acting on the point particle. If this force is due to the gravity of another bigger body B placed at a distance d from A, then this equation reads as follows:

$$m_{\rm A}\vec{a}_{\rm A} = -\frac{GM_{\rm B}M_{\rm A}}{d^2}\hat{e}_r, \tag{1}$$

where $M_{\rm A}$ and $M_{\rm B}$ are the gravitational masses of A and B, respectively, and $\hat{e}_r$ is the unit vector pointing towards A from B.

But according to Galileo's discovery, A's acceleration $\vec{a}_{\rm A}$ should be independent of the mass $m_{\rm A}$. This can happen, as can be verified from Eq.(1), only if the ratio of $M_{\rm A}$ to $m_{\rm A}$ is a universal constant for all objects. One can then always choose the unit of measuring the gravitational mass such that this universal constant is 1 (unity). The equality of gravitational mass and inertial mass for all objects is called Weak Equivalence Principle (WEP) according to which acceleration of a body falling in a gravitational field is independent of its mass. This has been experimentally tested by several groups since the times of Eötvos [3]. Recent measurements of accelerations of Earth and Moon falling in the gravitational field of the Sun, indicate that the agreement between the two values is better than 2×10^{-13} [4], demonstrating a high degree of validity of the WEP. The Gravity Group of Tata Institute of Fundamental Research, Mumbai, is also carrying out measurements pertaining to WEP.

Interestingly enough if WEP is correct then there cannot be any repulsive gravity between point particles since gravitational mass cannot be negative (as inertial mass is always positive). A legitimate question is, what if there are some exotic particles in nature with negative inertial mass? Such particles will really exhibit then bizarre behaviour. For instance, since kinetic energy of any object is $\frac{1}{2}mv^2$ where m and v are the inertial mass and speed, respectively, if one extracts energy from such a negative mass particle, its energy will further decrease (i.e. become more negative) and hence it will move faster. While if one supplies energy to it, it will slow down. No such particle has ever been found in nature. Because there are no negative mass objects around, gravitational forces cannot be screened, unlike electric forces. Athough the gravitational force between two protons is negligible (about 10^{-40} times the mutual electrostatic repulsion), as the physical scale increases like in the case of Earth or stars or galaxies, gravity starts dominating over all other forces since masses are additive.

When Einstein put forward STR in 1905, one of its consequences was that nothing can travel faster than speed of light in vacuum. If one looks at Eq.(1), one immediately realizes that it is inconsistent with STR since according to Eq.(1) the gravitational force acting on A due to B depends on the instantaneous separation d. That is, if we change the distance slightly to $d + \Delta d$ in a very short time interval Δt, then according to Eq.(1), the new force on A immediately after the time interval Δt is given by,

$$\vec{F}_{\mathrm{A}} = -\frac{GM_{\mathrm{B}}M_{\mathrm{A}}}{(d+\Delta d)^2}\hat{e}_r, \tag{2}$$

But this would mean that the information that B's position has been changed reaches A in a short interval Δt even though the distance d can be as large as few light-years! This contradicts STR's claim that nothing moves faster than 3×10^{10} cm/s. From such considerations, Einstein knew that Newton's law of gravitation had to be modified.

It took Einstein eleven years to arrive at a fully relativistic theory of gravitation. In 1916, the general theory of relativity (GTR) overturned the Newtonian concept of gravitation. According to GTR, gravity is not a force at all. Rather, the energy and momentum of matter make the geometry of the space-time curved. It is this curvature of the space-time geometry that appears as gravitation. Test particles move along straightest possible path in this curved geometry. For example, when we throw a stone, its trajectory is parabolic. This parabola is the straightest possible line in the curved space-time near the surface of Earth. It is not surprising, therefore, that WEP holds good - after all, if particles only move along the geometrically straightest possible path, why should the path depend on the tiny mass of the test particles? In other words, Einstein's relativistic theory of gravity GTR rests on the validity of WEP [3]. Einstein also applied the WEP to show that no matter how strongly curved the space-time geometry is, one can always have a sufficiently small enclosure that undergoes free fall, so that gravity in this tiny region vanishes briefly. No wonder that this phenomena is used repeatedly to simulate zero-gravity conditions for the purpose of training pilots and astronauts/cosmonauts.

As gravity is equivalent to space-time geometry, the distance between two infinitesmally separated points is completely determined by this geometry. One of the consequences of GTR is that if there is a dynamical alteration in the distribution of matter, there occurs a change in the space-time geometry and this changing geometry propagates outwards as gravitational waves with a speed of 3×10^{10} cm/s. One way to test this prediction is that if there is a powerful source of gravitational waves (GWs), measure the change in the distance between two objects as the GW passes by. Attempts to detect GWs using laser interferometric detectors analogous to Michelsion interferometers having arm-lengths of 4 km are underway. When sufficiently strong GWs impinge on the detectors, the distances between mirrors and the beam splitter change causing time dependent fringe shift.

GWs also carry energy flux, and hence if two heavy and compact objects like neutron stars rotate around the common centre of mass, they lose orbital energy by emitting GWs. This leads to inspiralling wherein the binary mass points gradually approach each other, causing steady decrease in the orbital period. This prediction has been verified from the observed changes in orbital period of Hulse-Taylor binary pulsar [4]. The other major prediction of GTR is that if in a volume of space-time consisting of matter, the matter density becomes sufficiently high, the region undergoes an unstoppable collapse, with the geometric curvature becoming very high in the central region. Such an event leads to the formation of a blackhole, a region enclosing a space-time singularity from where nothing can escape (not even light).

We have been discussing so far classical gravity, without bringing in quantum mechanics. One of the outstanding problems in physics, which many theoretical physicists today are grappling with is: how to reconcile quantum theory with GTR? Some take the approach of string theory according to which particles are nothing but excitations of a fundamental string of length $\approx 10^{-33}$ cm, while some tread the path of quantum loop gravity based on new dynamical variables first proposed by Abhay Ashtekar. An exciting outcome of semi-classical gravity is that if one treats gravity around a blackhole classically, while quantizing the fields in the blackhole background, the blackhole starts acting like a hot blackbody, spewing out thermal radiation having a temperature that is inversely proportional to the blackhole mass, a result obtained for the first time by Stephen Hawking in 1974 [5]. A solar mass blackhole has a Hawking temperature of $\approx 10^{-7}$ $^\circ$ K. Thus, according to quantum laws blackholes are thermodynamic entities.

To test quantum gravity theories experimentally one needs either to generate particles having energies of the order of 10^{19} GeV, which is beyond one's reach currently, given that even to accelerate particles to energies $\approx 10^3$ GeV is such a Herculean task or to fall back on prospective cosmological observations. What is very likely and exciting is that the final theory of quantum gravity may change the very notions of space-time, matter and even the character of laws of physics in a very fundamental manner. Therefore, gravity is no light matter!

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