Gravity – Aristotle to Einstein

6/23/2016
Rick Dower

Aristotle (d. 322 BCE) assumed that Earth was the center of the universe and things tended to move toward their natural places in the universe.
"How can we account for the motion of light things and heavy things to their proper stations? The reason for it is that they have a natural tendency respectively towards a certain position." (Aristotle, *Physics*, trans. R. P. Hardie and R. K. Gaye in *Great Books of the Western World*, Encyclopedia Britannica, 1952, Vol. 8, p. 340.)

"We see with our eyes…that earthly things sink to the bottom of all things and move toward the centre….and we observe fire to move upward even in the air itself….Fire then has no weight [gravity]. Neither has earth any lightness [levity] ." (Aristotle, *On the Heavens*, trans. J. J. Stocks, in *Great Books of the Western World*, Encyclopedia Britannica, 1952, Vol. 8, p. 403.)

"[A]ir and water each have both lightness and weight, and water sinks to the bottom of all things except earth, while air rises to the surface of all things except firs." (Aristotle, *On the Heavens*, trans. J. J. Stocks, in *Great Books of the Western World*, Encyclopedia Britannica, 1952, Vol. 8, p. 404.)

Nicolaus Copernicus in 1543 put the Sun in the center of the universe and speculated

> "that gravity is merely a certain natural inclination with which parts are imbued by the architect of all things for gathering … into the form of a globe. It is easy to believe that the Sun, Moon, and other luminaries among the wandering stars [planets] have this tendency also, so that by its agency they retain the rounded shape." (N. Copernicus, *On the Revolution of the Heavenly Spheres*, A. Duncan, trans., David & Charles, London, 1976, p. 46.)

Isaac Newton argued in Book 3, "The System of the World", of his *Mathematical Principles of Natural Philosophy* (1st ed. 1687) that planets orbit the Sun in response to a $1/r^2$ force, the Galilean satellites orbit Jupiter in response to a $1/r^2$ force, multiple moons orbit Saturn in response to a $1/r^2$ force, and the Moon orbits Earth in response to the $1/r^2$ force of Earth's gravity. Using his Rules for Reasoning in Philosophy, especially Rule IV,

> In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they [the inductions] may either be made more accurate, or liable to exceptions. (I. Newton, *Mathematical Principles of Natural Philosophy*, trans. by A. Motte, rev. and ed. By F. Cajori, University of California Press, Berkeley, 1962, p. 400.)

Newton argued that gravity was a universal force between any two masses (m_1 and m_2) separated by distance r with the form

$F_g = G\frac{m_1 m_2}{r^2}$, where G is a proportionality constant.

However, in a letter to Richard Bentley in 1693, Newton wrote

> That Gravity should be innate and essential to Matter, so that one Body may act upon another at a Distance thro' a Vacuum without Mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity, that I believe no Man who has in philosophical matters a competent Faculty of thinking, can fall into it. Gravity must be caused by an Agent acting constantly according to certain Laws; but whether this Agent be material or immaterial, I have left to the Consideration of my Readers. (quoted in I. B. Cohen, *Isaac Newton's Papers and Letters on Natural Philosophy*, 2nd ed.,, Harvard University Press, Cambridge, 1978, p. 302.)

Newton assumed the existence of absolute space and absolute time in which objects moved. There is no provision for time of transmission of the gravitational force in his force law. So, presumably, the force acts instantaneously. Since time is absolute, events that happen simultaneously in one reference frame, also happen simultaneously in all reference frames. The metrics connecting the measurements of events are $\Delta t = \Delta t'$ for time coordinates and for simultaneous events $\Delta r^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 = \Delta x'^2 + \Delta y'^2 + \Delta z'^2 = \Delta r'^2$ for spatial coordinates. This is the Euclidian metric. So the time interval between events is invariant (the same in all reference frames), and the distance between simultaneous events is invariant.

Albert Einstein in his 1905 paper on special relativity proposed that the speed of light (currently defined as c = 299792458 m/s in vacuum) was invariant in different reference frames. The space and time coordinates of events are connected in different reference frames. The invariant interval between events in different inertial reference frames is given by $\Delta\tau^2 = \Delta t^2 - \Delta r^2 = \Delta t'^2 - \Delta r'^2 = \Delta\tau'^2$, where $\Delta\tau = \Delta\tau'$ is referred to as the spacetime interval between events. In this expression the coordinates are measured in the same unites (light-meters of time and meters of distance or in seconds of time and light-seconds of distance). This relationship between space and time coordinates of events is called the Lorentz metric. A region of spacetime with very weak gravity fields in which the Lorentz metric applies is called a region of flat spacetime.

In 1915 Einstein proposed his theory of general relativity that provides a mechanism to explain gravitational interaction. Einstein argued that the presence of a mass at a location alters the local structure of spacetime around the mass, and other masses move along that distorted local spacetime structure. Late in 1915 Karl Schwarzschild provided a solution to Einstein's field equations for a spherically symmetric, non-spinning, non-charged mass. The Schwarzschild metric in a plane through the center of the mass is

$\Delta\tau^2 = \left(1 - \frac{r_s}{r}\right)\Delta t^2 - \left(1 - \frac{r_s}{r}\right)^{-1}\Delta r^2 - r^2\Delta\phi^2$, where $r_s = \frac{2Gm}{c^2}$ is the Schwarzschild radius.

For Earth and Sun, the Schwarzschild radii are

r_{sEarth} = 9 mm (r_{Earth} = 6.4 x 10^6 m) and r_{sSun} = 3 km (r_{Sun} = 7.0 x 10^8 m).

The Schwarzschild metric indicates how the presence of a mass alters the relation between space and time in the vicinity of the mass.

With General Relativity, Einstein accounted for the previously unexplained residual (43 seconds of arc per century) in the advance of the perihelion of Mercury. (Of the total observed motion of 574 seconds of arc per century, 531 seconds of arc per century could be explained by Newtonian gravitational interactions between Mercury and the other planets.) Einstein also predicted the magnitude of the deflection of starlight as it passed near the Sun during a solar eclipse. His prediction was verified by the Eddington expedition to observe the 29 May 1919 solar eclipse. General relativity also predicts the gravitational red shift of light observed by Pound and Rebka in their 1960 experiment. More recently, energy loss due to gravitational wave radiation matches the observations by Hulse and Taylor of the gradual inspiral of the two orbiting neutron stars in the binary pulsar (PRS b1913+16). Finally, gravity waves produced during the final orbits of coalescing black holes have been observed by the LIGO-VIRGO collaboration on 14 September 2015 and 26 December 2015.