GRESHAM COLLEGE

29 JANUARY 2020

Cosmic Concepts: Shapes of free fall

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What is meant by free fall? When physicists use the term "free fall" they are specifically referring to motion that is undergoing acceleration due to gravity, and not any other kind of acceleration. More generally, the term "free fall" is used when the dominant (rather than the only) source of acceleration is gravity, for example when a parachutist first jumps out of a plane before deploying a parachute. There will be drag from air resistance that tends to offset the downward pull of gravity.

What does our Solar System consist of? At the heart of our solar system is the Sun. In orbit around the Sun are the eight planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune) and myriad dwarf planets (including Pluto and Charon). In between Mars and Jupiter is the so-called asteroid belt which contains many irregularly shaped bodies of rock. Outside of Neptune's orbit is the Kuiper belt which is like the asteroid belt though vastly more extensive. Beyond this, i.e. further still away from the Sun but centred on it, is the Oort Cloud whose outer boundary is very far from being well defined. It contains a reserve of cometary nuclei (rocky, icy bodies) whose existence is thought to date back to the origins of the Solar System itself.

How massive are the different components of the Solar System? The mass of the Sun is 2 x 10^30 kg. What is in orbit around the Sun has vastly less mass than this – indeed totalled together the orbiting mass is barely one thousandth of this, so by far the dominant mass and hence the dominant source of acceleration due to gravity, is the Sun.

How fast will something orbit around Earth? This depends on how far away from Earth the orbiting body is. For a satellite in a "low Earth orbit", the time taken to perform a complete orbit (known as the orbital period) is about an hour and a half. For a geostationary satellite, orbiting much further from the Earth, the orbital period must be an Earth day. Much further away still, our one natural satellite the moon takes one (lunar) month to orbit around us. A plot of the distances that each of these bodies is away from Earth versus their orbital periods will, on logarithmic axes, be a straight line --- an example of Kepler's Third Law.

Why does the moon have so many more craters on its surface than the Earth? Rocky debris, asteroids and meteors feel acceleration due to gravity from the mass of the Sun. Sometimes while being drawn towards the Sun, these will be deflected by a planet or satellite that they encounter en route. Jupiter, being the most massive of the bodies that are orbiting our Sun, often intercepts one of these pieces of debris from beyond Neptune. An example is that of Comet Shoemaker-Levy that collided with Jupiter in July 1994. Those bodies that travel unhindered past Jupiter towards the Sun might still encounter either Earth or the Moon which are then at risk of a collision. In the case of the Earth, such a body might be burned up by frictional heating in the atmosphere and radiate brightly as a meteor, and only in an extreme case an impact forming a crater. With the moon, the body could well land as a meteorite and cause a crater; the moon has no atmosphere to burn up what flies into it.

What was Tycho Brahe's contribution to our modern understanding of the Solar System? Tycho Brahe, from the vantage point of the Island of Hven (then part of Denmark) made myriad painstaking observations of the positions of stars and planets, with positional accuracies that were remarkable for the time. These data were the basis for Johannes Kepler to make his calculations about the orbital trajectories of the celestial bodies.

What was Johannes Kepler's contribution? Kepler was initially assistant to Brahe but was the one who pioneered calculations that led to a new (post-Copernican) paradigm for orbits in (and implicitly beyond) the Solar System.
Specifically, whereas Copernicus viewed the orbits of planets around the Sun as circles, the exquisitely detailed data of Brahe enabled Kepler to deduce that these orbits were elliptical, not merely circular, and that the Sun was not at the centre of these ellipses but at a focus of the ellipses (one of two foci that an ellipse has).

What was Robert Hooke's contribution? Robert Hooke is credited with being the person who led to our understanding that all massive celestial bodies are sources of gravitational acceleration to one another, and moreover that this acceleration followed what physicists call an "inverse-square law". Such a law means that as you halve the distance between the two bodies, the acceleration they feel increases by a factor of four.

What was Isaac Newton's contribution? Isaac Newton took the inverse-square law and demonstrated that the orbital solutions to this law for bodies that were gravitationally attracting one another were "conic sections": the geometric shapes formed by the intersection of a plane with a cone. (The equations for these geometric shapes had been worked out the best part of two millennia previously by Apollonius of Praga, but at the time these geometric studies were purely pursued because of their inherent beauty and intellectual interest.) Newton devised a new branch of mathematics in order to solve these equations, the field of differential calculus.

So, what are the shapes of free fall? The shapes of free fall, or the shapes of the orbits of massive bodies acting only under gravity due to say the Sun, are the conic sections: circles, ellipses, parabolas and hyperbolas. The Solar System planets and their moons are all on bound orbits (circles and ellipses). Comets and asteroids, on the other hand, are either ellipses or hyperbolas; the former orbits are bound and so the appearance of the comet will be periodic and the latter are unbound and these comets will never be seen again by an observer on Earth. If the central gravitational potential arises from something other than a single star, for example a double star, then the shapes of free fall (i.e. the orbits) become even more exotic and precess in and out of the plane containing the two inner stars that are orbiting one another.

Further reading and references:

"A Very Short Introduction to Gravity", Timothy Clifton, Oxford University Press, 2017

"A Very Short Introduction to the History of Astronomy", Michael Hoskin, Oxford University Press, 2003

"A Very Short Introduction to Newton", Rob Iliffe, Oxford University Press, 2007

"The Planet Factory", Elizabeth Tasker, Bloomsbury Sigma, 2017

"The Sleepwalkers: our changing vision of the Universe", Arthur Koestler, Penguin, 2014

"The Newton Papers", Sarah Dry, Oxford University Press, 2019