Gravitational Effects in the Solar System

Chris Williams
Student 1607421
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Introduction

In the early 17th century Johannes Kepler (1571-1630), working with his predecessor's detailed record of planetary positions, determined three basic laws that elegantly encapsulated the motion of the planets:

- Each planet orbits the Sun on an elliptical path with the Sun at one focus.
- An imaginary line connecting a planet to the Sun sweeps out equal areas in equal times.
- The time a planet takes to orbit the Sun squared is proportional to the average distance from the Sun cubed.

Later in the century, Sir Isaac Newton (1642-1727) determined a mathematical equation that captures the nature of gravity and provided a solid mathematical basis for Kepler's laws. The gravitational attraction between two massive bodies is proportional to both masses (m_1 and m_2) and inversely proportional to the square of the distance (r) between them, or: $F = Gm_1m_2/r^2$.

The laws of Kepler and Newton are sufficient to explain how the solar system stays together and many interesting phenomena that have been discovered.

Tides and Tidal Gravity

In its simplest form, Newton's law treats objects as dot sized concentrations of mass. Real objects have size. Gravitational attraction declines with distance so an object on the moon-ward side of our Earth, for example, is attracted more strongly to the Moon than the same object placed at the Earth's centre or far side (see Figure 1). This gravity differential is called tidal gravity. Looking from the point of view of the Earth's centre there is a small net force acting outward on both the moon-ward and far sides. These forces are opposed by the fairly rigid body of the Earth but, nevertheless, result in a slight elongation of the Earth along the Earth-Moon axis. The oceans are free to move in response to these forces so there is a bulge in ocean levels on the moon-ward and far sides. The ocean tide rises and falls twice daily as the Earth's rotation carries the coastal observer through these bulges.

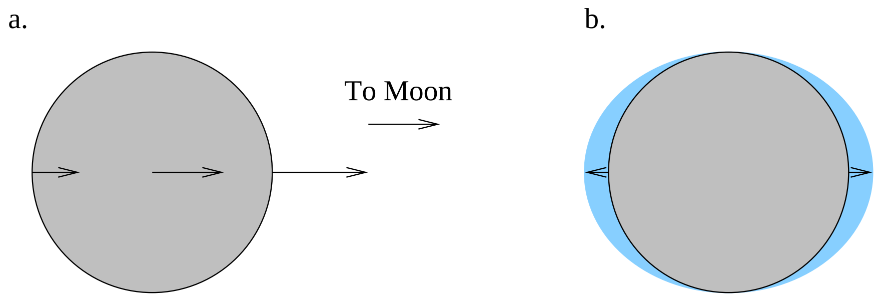

Figure 1: Tidal Gravity: a. Earth's size means that an object on the moonward side experiences a stronger gravitational force, indicated by arrows, than an object on the side furthest away. b. From the centre of Earth these forces look like small outward forces giving rise to a tidal bulge (exaggerated in blue).

The presence of tidal bulges coupled with the axial rotation of the affected bodies provides several mechanisms affecting the orbits of celestial bodies.

In cases where a body's mass is unevenly distributed, such as our Moon, tidal gravity can change the body's rotation so that the more massive side is constantly pointed at its orbital companion i.e. it spins once on its axis for every orbit. This effect is called spin-orbit resonance or coupling and is the reason we see only one side of our Moon. Mercury, with its slightly elongated shape and very elliptical orbit, displays a more complex version of spin-orbit coupling (with the Sun) in which it spins three times on its axis for every two orbits of the Sun.

Orbital Resonances

Another form of gravity related resonance in the solar system occurs between orbits. Orbital resonance occurs when the two bodies are orbiting a third in such a way that the period of the one body is a neat ratio of the period of the other, say 2:1 or 3:1. The relationship in orbital periods means that the two bodies periodically reach the same alignment. Each body attracts the other and very slightly affects its orbit. Over time these small perturbations can change the shape of the body's orbits and act to reinforce the period relationship.

Asteroids in the belt between Mars and Jupiter provide prime examples of orbital resonance. Jupiter, containing the bulk of the solar system's mass outside the Sun, has a strong gravitational field that acts to perturb the asteroids. Asteroids orbiting the Sun with a period of one half or third of Jupiter's are forced into altered orbits resulting in gaps (Kirkwood Gaps) in the asteroid belts. At distances matching Jupiter-asteroid period ratios of 2:3, 3:4, or 2:5 we find that resonances account for increased asteroid concentrations. Two other concentrations, sharing Jupiter's orbit but always 60 degrees ahead or behind Jupiter, are the Trojan asteroids. This is an orbital resonance of 1:1 around dynamically stable locations called Lagrange Points. The Saturnian moons Tethys, Callypso, and Tellisto show a similar shared orbit.

Orbital resonances can be far more complicated affairs, with interactions between multiple bodies. Among Galilean satellites of Jupiter Io is in a 2:1

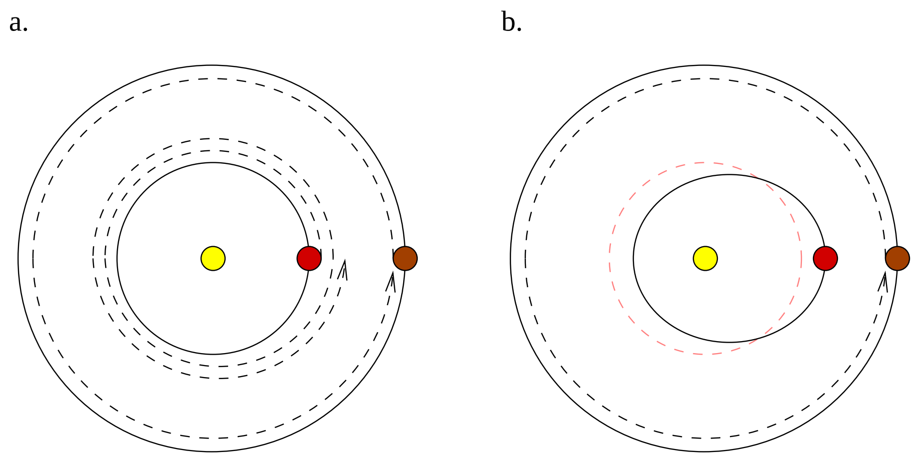

Figure 2: Resonance: a. 2:1 resonance, in which the inner body orbits twice for each outer body orbit. b. Over time the inner body's orbit becomes more elliptical whilst retaining the same period.

resonance with Europa which is, in turn, in a 2:1 relationship with Ganymede. This complex arrangement keeps Io in an elliptical orbit, maximises the tidal forces the body endures, and produces the most volcanic object known in the solar system. Around Saturn, resonance between the myriad small ring particles and Mimas is partly responsible for the most obvious gap in the ring structure.

On the whole, resonances seem far more common than chance alone would dictate. Orbits that are close to resonant can behave chaotically, which may result in close encounters with other large objects. Since gravitational forces become very large when distance becomes small close encounters can result in ejection of smaller objects from the solar system. In essence, the prevalence of resonances may be the result of evolution.

Conclusion

Gravity, with its long range and relationship to distance, explains the elliptical orbits of Kepler. As a natural result of having size, orbiting bodies experience tides that are responsible for phenomena such as spin-orbit coupling and volcanism. The asteroid belt and Saturn's rings are shaped by resonances between orbits. Overall, resonances seem the rule rather than the exception, and may actually be a requisite part of a stable system.