What is Tidal Heating?

When we think of tides on Earth, images of changing sea levels at a beach or lake may come to mind. A different but certainly related definition of a tides is presented by Morrison and Owen (1996):

"A tide is a distortion in the shape of one body induced by the gravitational pull of another nearby object."

In the case of the Earth, the moon and (to a lesser extent) the sun both raise tides on the planet. What results on the Earth due to the gravitational field of the moon—or more specifically, the *variation* of this field over the volume of the Earth—are two distinct **tidal bulges**. One bulge is on the side of the Earth closer to the moon, and the other is opposite of this. Together, these are responsible for the two high tides observed daily on Earth. The variations are due to the sensitive dependence (inverse square) of the Newton's Universal Law of Gravitation; they are known as **tidal forces** (Fig 1).

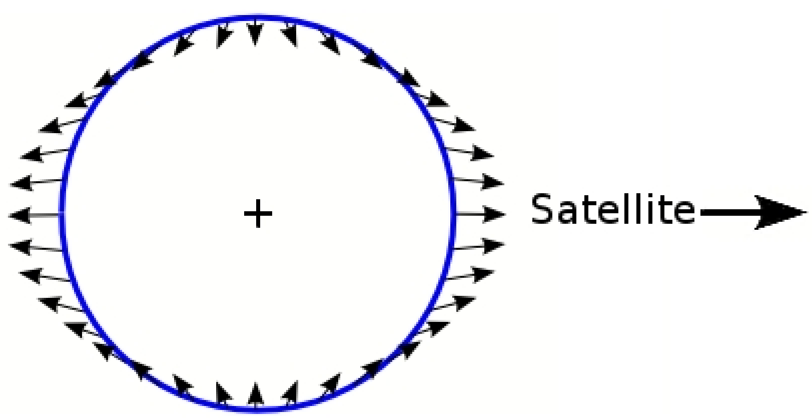

Figure 1: Tidal forces due to the Earth on the Moon assuming an inertial reference frame. Only the tidal forces (exaggerated) at the surface are shown here.

Similarly, the much more massive Earth deforms the moon such that the side of the moon "nearer" to the Earth experiences a gravitational "tug," and two bulges separated by 180 degrees in lunar longitude are formed (not unlike a "football" shape) (Fig 2).

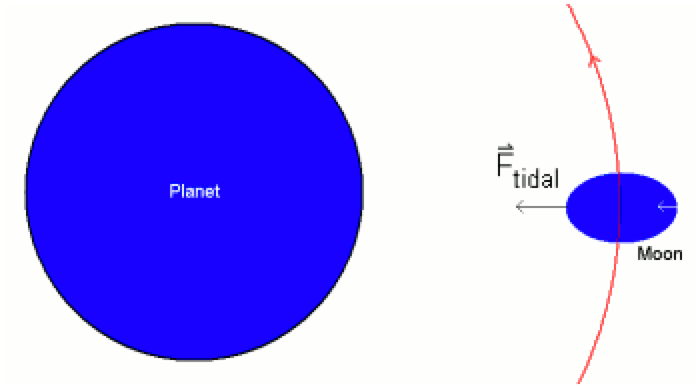

Figure 2: Deformation of the moon due to tidal forces

Our moon is in **synchronous** orbit with the Earth to reduce the amount of energy that is removed from its rotation. In this configuration, the moon's period of revolution is equal to its period of rotation; the same side of the moon is always distorted (and therefore always faces the Earth). Another way to say this is that the moon is **tidally locked** to the Earth. This is common of all major satellites in the solar system, including those of the planet **Jupiter.**

Jupiter is much more massive than the Earth, so it deforms its moons much more dramatically. Where things become interesting for this purpose is the fact that Jupiter's moons, Io; Europa; and Ganymede, are in what is called **orbital resonance.** Io and Europa are in what is called 2:1 resonance. This means that for every complete orbit that Europa makes around Jupiter, Io completes exactly two (Fig 3).

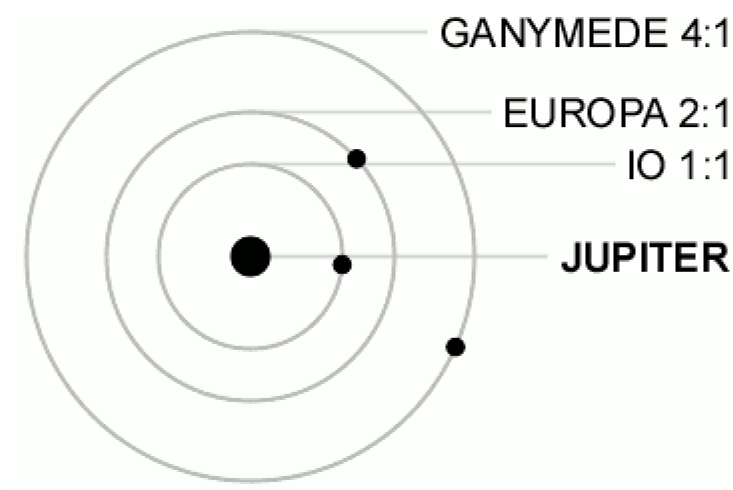

Figure 3: Orbital resonances of three Galilean satellites of Jupiter. Orbital paths, distances, and sizes are not to scale.

Taking just the case of Io and Europa into consideration, a consequence of these configurations is that when two satellites "line up" (also called *conjunction)*, the gravitational pull of Europa on Io is enough to alter its orbit from what would be to a perfectly circular, synchronous orbit into that of an **ellipse** (Fig. 4)

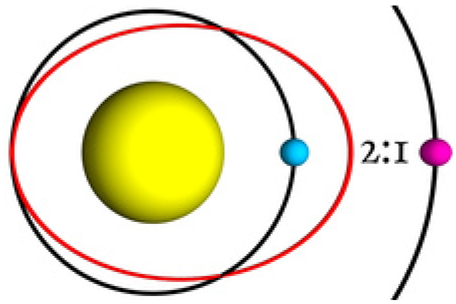

Figure 4: Io (inner) and Europa (outer) in conjunction around Jupiter (yellow). Eccentricity is exaggerated for effect.

A geometric consequence of this new orbit for Io is that its distance from Jupiter is *constantly changing* (compared to a constant radius in a circle), and therefore the tidal forces on it (inversely proportional to the cube of distance) are constantly deforming the satellite. Given the short period of orbit for Io (less than 2 Earth days) and the considerable mass of Jupiter, what results is a tremendous amount of internal friction in the moon's structure. This friction generates the heat that is responsible for making Io the most active volcanic place in the solar system! The process by which this occurs is known as **tidal heating.**

Because of Europa's location between Io and the more massive Ganymede, it also undergoes this same mechanism (but to a lesser extent due to its mean orbital distance). This heats the subsurface of Europa; to date, it is at the center of much research regarding a possible subsurface ocean layer beneath the moon's icy surface.

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