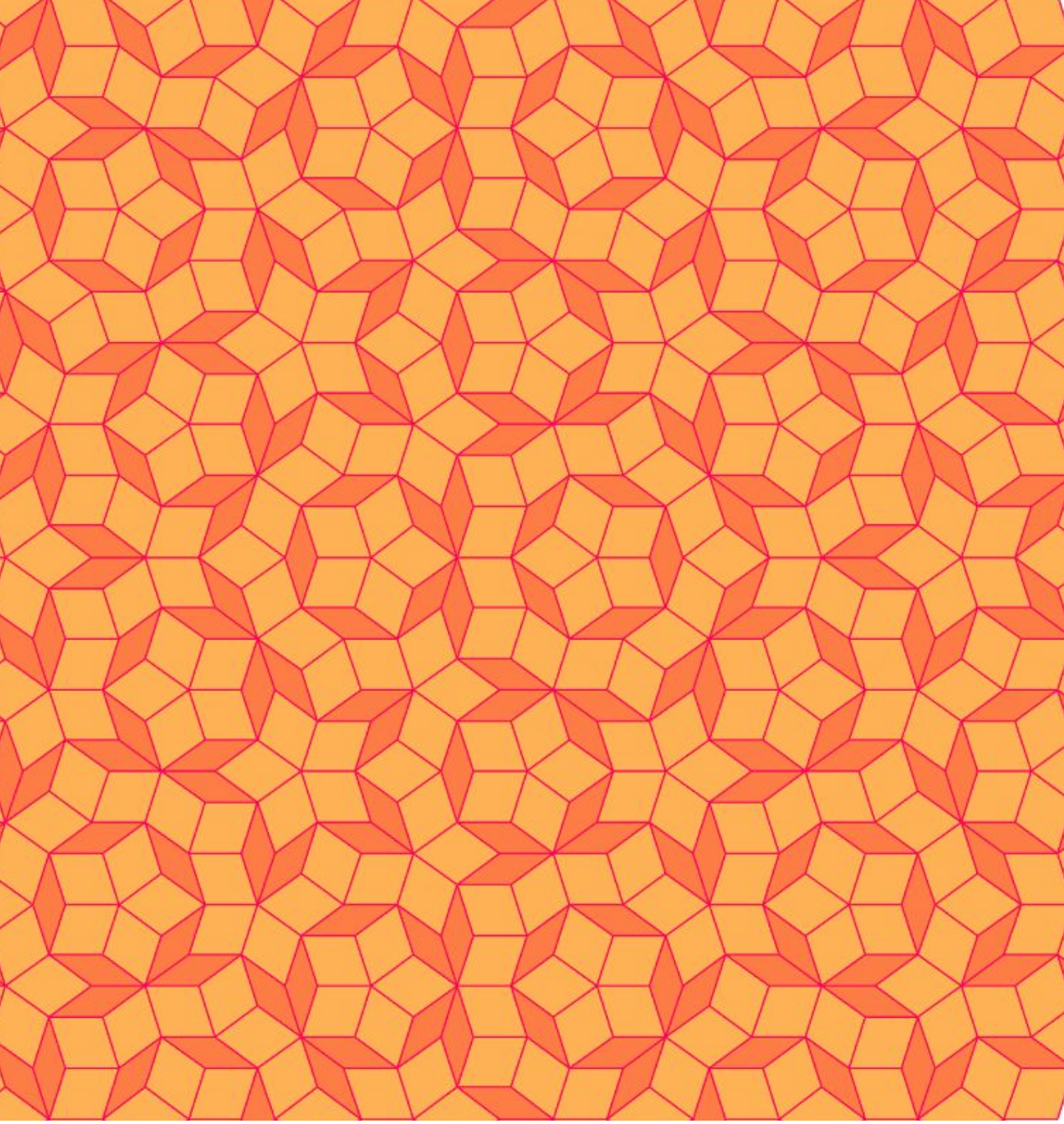

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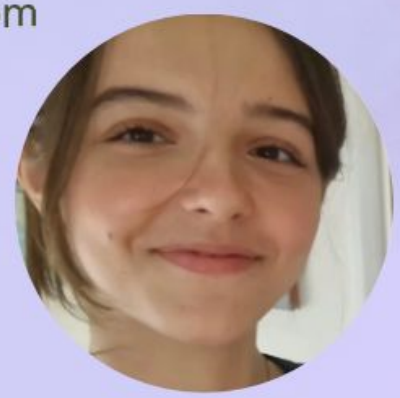

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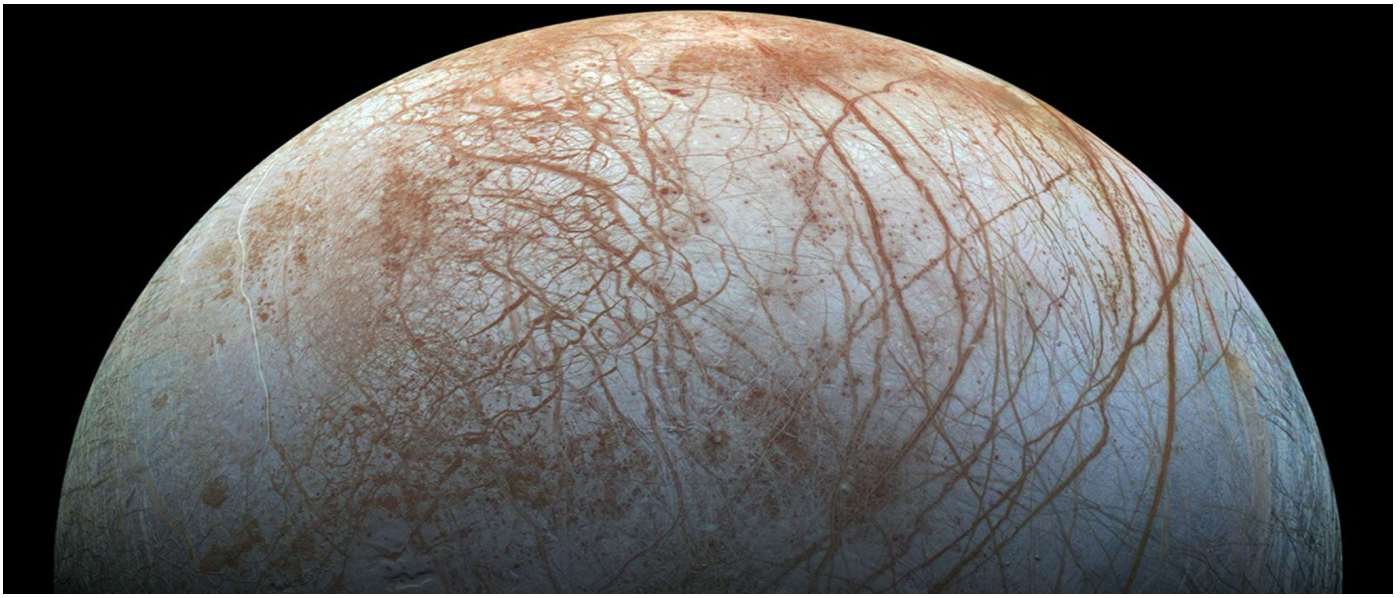


Tidal Heating in Icy Moons: A New Order

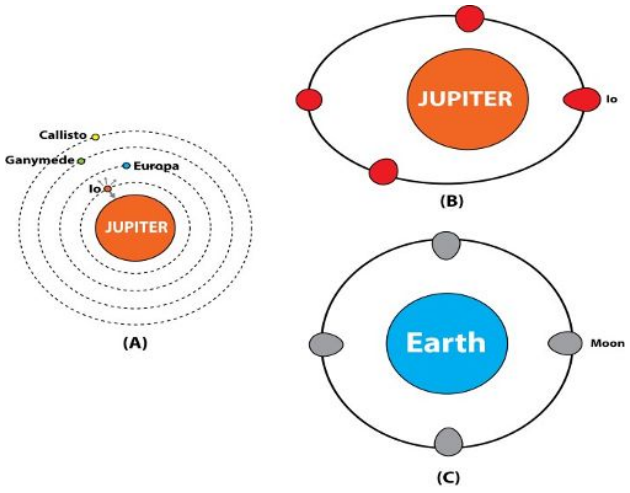
We inhabit an era that fosters an unpredictable age where the possibility of life and inhabitants elsewhere verges on the horizon. Though our eyes rest upon the prospect of Mars to be the answer to all our queries, my own belief is that we look to the moons of giant planets to represent an alternative to the classical portrait of habitable worlds. As they rely on a marvel coined Tidal Heating. If we observe Jupiter's largest moon Io, which possesses the most volcanically active site in our solar system, possesses a surface that is constantly reshaped by tidal forces. And Europa, Jupiter's icy moon, not yet frozen over, due to the same process.

A request to relinquish the mind of all preconceptions of space and life in space and enter with a fresh headspace. To justify the ambition of such a statement is to define why tidal heating is an answer, a glistening star partially obscured by a sea of jet black. In a simple notion, it is the breakdown of an object, in response to an external time-varying force, like car brakes or vibrating guitar strings. This response generates frictional energy which heats up the object's interior. This is a direct effect of the friction [1]. When we consider a time-varying force we first observe that its magnitude fluctuates, whereby the strength of its force can increase or decrease over the course of time. The force is affected by speed and distance as well as the change in direction. The process of tidal heating is natural for satellites, whose driving force is the gravitational pull of the planet they are orbiting as well as other planets. If we observe the moon's gravitational force, it may be understood that it causes the earth's water to bulge out on the side, closest to the Moon, as well as on the other side, further away from it. The work done by the gravitational force is dissipated into the oceans, thus producing a prominent contribution to the Earth's heating [1].

Make no error in judgement: this is not just technical curiosity. It is the one sole idea with the ability to revolutionize humanity's homes and habitats, and everything beyond this planet, humanity inhabits. Originally, we placed ourselves into a safe sanctuary, by believing that anything habitable had to orbit near a star, within the distance from which liquid water can thrive, to exist on a planet's surface. If we go beyond this range - the water will freeze. If we shorten this distance, the water will boil. But then came forth this new age, coined Tidal Heating, where scientific boundaries were nudged and physics challenged the cosmological comfort zone that science had secluded itself in. This is demonstrated with the example of Europa and Enceladus, two moons orbiting far beyond the sun's warmth, which astoundingly display signs of liquid oceans under the moon surface – a direct result of Tidal heating. This is not powered by starlight but by the force of the gravitational pull [1]. It is without a doubt that this endeavour proves unsuccessful and science refrains from further utilising

this process as a means of colonization. Nevertheless, tidal heating poses a second possibility in the prospects of space colonisation. It provides research of the process with the key notion; that habitable zones are longer about distance but energy.

As mentioned previously, in the case of a satellite and its eccentric orbit, the distance and direction to the primary is constantly changing. This continuous deformation generates heat [2]. By eccentric orbit we refer to a value possessing no dimension, and to communicate that the orbit of the object deviates from a perfect circle.



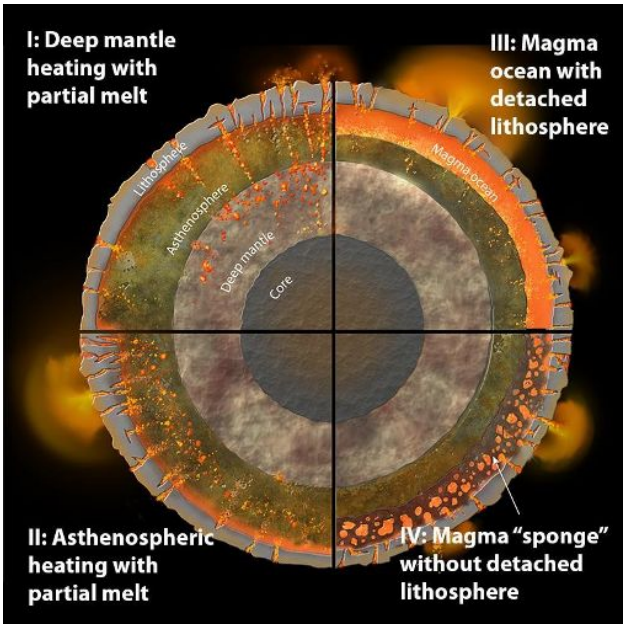
We can express this rate of heat production on the terms that the eccentricity is small, and that the satellite spin and period of orbit, are synchronized to each other, with the equation -

$$E = \frac{21}{2}\frac{n\,{}^{5}R_{s}^{\,5}}{G}e^{\,2}\frac{k_{2s}}{Q_{s}} = 15GW\frac{k_{2s}/Q_{s}}{0.01}$$

A composite equation, but when unpicked it reveals its components: *n,* the mean motion; *R*, the satellite radius; *G,* the gravitational constant; e, the orbital eccentricity and *k2,* the so-called tidal love number of the satellite [2]. The formula itself matters less than its implications. It reveals that tidal heating depends primarily on e – the orbital eccentricity - where even the tiniest eccentricities can generate mass heating, emulating the process of tidal heating [3]. A closer orbital distance amplifies this effect, and a subsequently larger planetary mass generates more heating. Yet the internal properties of the moon – expressed by *K2* and *Q* - ultimately determine how efficiently that energy is converted into heat, ensuring the accuracy and validity of the equation [3].

Tidal heating is occurring at this very moment. The most famous example of the process occurs on Io; a volcanic moon, housing hundreds of volcanoes that erupt constantly. The volcanic activity on Io is powered by tidal heating in its extreme form, which is caused by the orbital resonance from its neighboring moons – Europa and Ganymede. The surface of this moon is completely covered in sulfur, as well as the continuous flow of silicate lava [4]. Justifying the fiery sphere captured through NASA spacecraft. Experts estimate this heat flux to measure at ~100 trillion watts. This is more than enough to continuously melt the interior of this moon. Lo evidently undergoes extreme tidal heating; Ipso facto, its physical state is that of a volcanic furnace.

De facto, the heating mechanisms circulating within the moon, provide scientists with an explanation as to how the moon is geologically alive while most others are frozen [3].



Lo and the possibility of a magma ocean

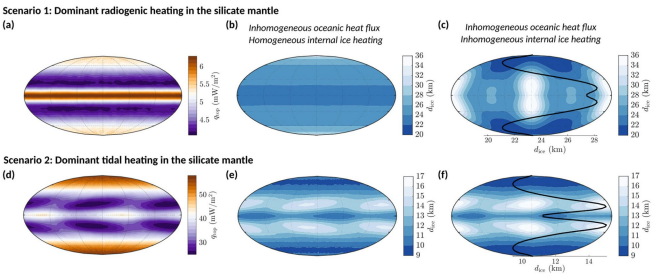
Lo is a testament to all motions, opposing the theory of tidal heating. The negative

impacts of tidal heating on Io, consist of the moon having an absence of liquid water. However, this does not aid to the argument that life can be harbored on these moons. Which explains why most research into Io paused, and shifted to center on Europa.

Europa is an icy moon with the potential to host life if the presumption is that life does not already exist there [6]. This is due to the warmth present on the icy giant due to the direct influence of tidal heating. This is primarily caused by the gravitational interactions between Jupiter and other moons like Lo and Ganymede [5]. Europa orbits Jupiter in a slightly elliptical orbit – a direct consequence of the gravitational pull from other planets. Which results in the change of distance over time between Jupiter and its fellow moon [6].

When Europa is closer to Jupiter, the strong gravity of the gas planet exerts a powerful force that causes the shape of the Europa moon to flex and deform repeatedly [5]. It is like the stretching of a rubber band, which causes tension. This constant flexing occurs on Europa and creates mechanical stress on the planet which generates this internal friction. This same friction produces heat which is known to us now as tidal heating. The heat generated in this process is not weak, in that the planet remains frozen, but powerful enough to prevent the subsurface of the liquid oceans from freezing. Observe that the heat generated is also not powerful enough to become volcanic like Io. In essence, Europa has freezing temperatures, but the warmth of the tidal heating allows the ocean to remain in a liquid state.

In simple terms, tidal heating converts GPE – Gravitational Potential Energy into thermal energy.



Europa's ocean interior with the effects of tidal heating.

It can be argued that the rocky core of Europa can also contribute energy, but it has lesser impact than tidal heating. Heat from tidal forces warrants chemical interactions between the rocky mantle and the Moon's oceans [6]. This interaction possesses the potential to cycle nutrient and energy. To demonstrate that moons such as Europa may offer another path for humanity's expansion—or, at the very least, a chance to discover life beyond our own world. Tidal heating shapes Europa's geology and is thus vital for its potential to even host life.

By Zahra Aziz '27

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