# Are there astronomers on the moon?

Lucas C. Monteiro - fc52849@alunos.fc.ul.pt

***Abstract*** - *We explored the elements for the emergence of complex life on the surface of a natural satellite. What physical constraints of the moon and its system need to be met to facilitate life as we know it. How the primary influences moon formation, evolution, and consequently the arisal of biological processes. Our incentive is to find where in the universe we should look for moon astronomers and imagine how they'll differ from us.*

## Elementals

Since ancient times the Moon influences life on Earth. Be it by the tidal forces, animal migration patterns, or even poetry. So this leads to the question *Are there astronomers on the moon?* No, we aren't seeking astronomers on our moon. Well, hopefully in the next decades we'll see hoards of curious scientists on our satellite's surface, debating about the mysteries of the cosmos. But we want to explore the possibility of complex life in the natural satellites of exoplanetary bodies.

Much of recent research on the field of astrobiology states that moon life is a possibility, even in our cosmic backyard, be it in Jupiter's Europa [1] or Saturn's Enceladus [2], the big contenders of the solar system for moon life. However these lifeforms would probably be confined to subsurface habitats, dwelling deep in subsurface oceans maintained by geologic activity, tidal heating, and irradiation [3]. The most probable is that these creatures will never see starlight as we do, so even if they develop fully-fledged underwater civilizations, will astronomers be among their social classes? In this essay, we'll explore the necessary elements for moon *surface* life. Not just that, but we'll try to create the *best* conditions needed for astronomy, our oldest science, to arise. We have to note, that our quest will be made through the thin scope of the only sample case that we have on biological processes - Earth life. Also here is where we find the only astronomer specimens.

Would these strange moon astronomers exist, they'd probably try to explain their lucky existence through complex reasoning. Their protosciences would discuss how the elemental deities - *Ether, Air, Earth, Fire* and *Water* - came to existence and how its perfect balance blessed their home with life.

## Ether

So in our quest for this Gaia moon, we have to know where to find moons first. In our Solar system, we observe several paths of natural satellite formation. Most are thought to have been formed out of the same collapsing region of the protoplanetary disk that created its primary [4]. Gas giants' relatively large mass indicates they formed in mass-rich portions of the early protoplanetary disk of our solar system. Such material abundance would lead to the formation of many bodies around these planets.

Another possibility is the capture of rogue bodies. In my short essay, we discussed planetary migration and how the disturbance of orbital eccentricities could have completely scattered a thick planetesimal disk leading to the capture of these bodies by the giants. Triton is thought to have been a dwarf planet from the Kuiper belt, later being captured by Neptune. Due to their physical size and great mass, giants will also have the upper hand in capturing migrating bodies, concerning their smaller rocky siblings.

The last moon formation path that we'll be discussing is the catastrophic one. Cirugical collisions between large proto-planetary objects, that create the right conditions that lead to the formation of large natural satellites from the ejected debris. This is believed to be the genesis of our Moon and possibly Charon [6].

Also, the remote environment of distant giants may be conducive to maintaining moons since the proximity to the star can destabilize small orbiting bodies via tidal interaction and photon pressure. This might be the cause of moonless Mercury and Venus [7]. All leads to the belief that most moons in the universe will be orbiting massive planets, most probably gas giants. This is the case in the solar system where we observe hundreds of moons around the gas and icy giants and one abnormally large Earth moon and two small Martian moons. We hope that our astronomer friends won't be too distracted by their primary but in the next chapter, we'll see how its neighbor can be their blessing or curse.

## Air

The fact that moons orbit another body provides an additional set of constraints on their potential habitability. Moons are likely to be tidally locked to their planet, having rotation periods of days or months. This could lead to large diurnal temperature fluctuations. Also, if their primaries have highly eccentric orbits, they might experience large seasonal temperature fluctuations. These are some possible constraints on the arisal of life however the fluctuations can be mild enough to not disturb biological processes. We want to explore more fundamental natural satellite-only constraints.

The presence of an atmosphere is of utter importance for a life-bearing world. On Earth, primary producers rely on its carbon dioxide for growth while consumers use its oxygen as a source of energy. It protects from harmful ultraviolet radiation in the upper atmosphere due to the presence of ozone, and other celestial visitors like meteorites. The atmosphere's pressure means that water doesn't evaporate away into space. Atmosphere presence also means good insulation and creates rich heat transfer mechanisms across the surface, mechanisms that might be very important in mitigating the supra cited temperature fluctuations.

If one assumes that extrasolar giants form in similar ways to ours, then we'll probably find volatile-rich atmosphere-capable moons. These moons might even be *too* much volatile-rich, as we see in the examples of Ganymede and Callisto that if the ice melted we'd have oceanic worlds. This wouldn't preclude habitability but we're focusing on land-based life. So better contenders for this would be inner moons with more rocky and less icy compositions, like Io and Europa [9]. Cometary bombardment could also enrich the natural satellites with volatiles has been proposed as the case for the source of the dense atmosphere of Saturn's moon Titan [10].

**Earth**

But a habitable moon will have to retain this volatiles for billions of years. Its effectiveness in doing so will depend on its mass, the flux of ionizing it receives from its star, and, a satellite exclusive, the charged particle flux it receives from within its primary's magnetosphere. This would pose a great threat to moons' atmospheres around giant planets since they could be reaped apart, by charged particles trapped in the planet's magnetosphere, by a phenomenon called sputtering. A non-magnetized moon's atmosphere could be sputtered away in mere millions of years. Take the example of Jupiter's inner magnetosphere electron flux of $\sim 4 \times 10^8 cm^{-2}\, s^{-1}$ and the solar-wind particle flux at Mars's orbit, that is thought to sputter away its $CO_2$ and O, of $\sim 4.8 \times 10^5 cm^{-2}\, s^{-1}$. [9]

A magnetic field would not only be imperative to eliminate atmospheric sputtering but to protect its host from the intensity of stellar extreme ultraviolet radiation. So, the question comes down to mass. Increasing the mass of a moon eases atmospheric retention but its importance doesn't stop there. Smaller planets have smaller diameters and thus higher surface-to-volume ratios, losing internal energy rapidly and rendering them geologically dead. On Earth, volcanoes and tectonic activity supply the surface with life-sustaining material and the atmosphere with temperature moderators like carbon dioxide.

This is the planetary scale mechanism that recycles important chemicals and minerals, it also fosters biodiversity through continent creation and increased environmental complexity and helps create the convective cells necessary to generate Earth's magnetic field [11]. Plate tectonics in conjunction with the carbonate-silicate cycle and its effect on the concentration of $CO_2$ are crucial for long-term climate regulation for example in situations of unstable stellar brightness. This mechanism would be important in land-based life-bearing worlds since the presence of significant dry land, i.e where silicate weathering occurs, is important in this feedback process [9].

So massive moons, and planets overall, have prolonged geological activity and plate tectonics through time. If the moon is too massive though, the high pressures in the moon's interior could increase the mantle viscosity and depress heat transfer throughout the mantle as well as in the core, suppressing the dynamo that becomes too weak to generate a magnetic field or sustain plate tectonics. So this goldilocks range of moon masses starts at $\sim 0.1\, M_{\oplus}$, the minimum mass that an exomoon is required to drive a magnetic shield on a billion-year timescale [12], and a maximum mass can be placed around $2\, M_{\oplus}$ [13].

**Fire**

So inner, massive moons provide good conditions for life to arise. These moons are likely to be tidally locked to their planet and hence experience days much shorter than their orbital period around the star and have seasons, all of which works in favor of habitability. However, these satellites can receive more illumination per area than their host planets, as the planet reflects stellar light and emits thermal photons. Life needs energy, but an oversupply of it can push a planet or an exomoon into a runaway greenhouse effect and thereby make it uninhabitable. Four major energy reservoirs exist in a moon system: stellar illumination, stellar reflected light from the planet, thermal radiation from the planet, and tidal heating. [14]

To be habitable, moons must orbit their planets outside of a **habitable edge**, analogous to the circumstellar *habitable zone*. It is defined as the innermost circumplanetary orbit in which an exomoon will not undergo a runaway greenhouse effect by a not-insubstantial amount of energy intake from its primary *planetshine*. However, given the right conditions, moons orbiting gas giants experience regularly a phenomenon that can potentially offset some of the extra energy input from planetshine - *eclipses*. [14]

For eclipses, lost stellar illumination for an exomoon in a close orbit is up to 6.4%. Also, these would only darken and lighten one hemisphere. Asymmetric illumination on the moon could induce wind and temperature patterns, both in terms of geography and in time, which are unknown from planetary climates.

If an exomoon's orbit takes it too close to its planet, tidal heating could push the energy budget too high. Io is the most volcanically active body in our solar system due to this effect, being heated up by the strong gravitational pulls of Jupiter [15]. Furthermore, if its primary is too close to its star, the moon can fall beyond the so-called *Hill radius* or the planet's sphere of gravitational dominance, becoming gravitationally unbound to its host planet, ripped away by the star's gravity. For an earth-like moon around Kepler-22b, an exoplanet orbiting within the habitable zone of the Sun-like star Kepler-22, the habitable edge would be of around 10 planet radii, similar to Europa's orbital radius in relation to Jupiter. However, the calculation would vary significantly with parameters like the albedo of both moon and primary, and stellar luminosity.

This leads to the question what stellar systems are most prone to hold the most fantastic Pandoras? Would they be abundant in our universe? To answer this question, we must explore the final pivotal element for life, the element that distinguishes Earth as the *Blue Planet*.

**Water**

As far as our current knowledge goes, life needs water. Liquid water is the common ecological requirement for Earth life due to its unique properties. It has excellent solvent properties, that help cells transport and use substances like oxygen or nutrients. It has a broad temperature range over which it remains liquid, helping animals regulate body temperature. High surface tension helps cells maintain shape and structure, critical for biochemical processes. All these properties are rooted in the ability of water molecules to form hydrogen bonds, strong bonds that help for example plants to take up water at their roots. Water also contributes to the formation of membranes surrounding cells and drives the folding of amino acid chains, as different types of compounds seek or avoid interacting with water. It is directly involved in many chemical reactions to build and break down important components of the cell and buffers cells from the dangerous effects of acids and bases. Many properties of water could be cited and how they matter to life on Earth. Still, researchers continue to establish new properties of water such as additional effects of its asymmetrical structure. No other known molecule matches water when it comes to unique properties that support life.

Besides, water plays a central role in planetary cycles. A high heat capacity and a solid phase of lower density than its liquid phase create planet scaled systems that regulate climate, e.g altering the planet's albedo. Interactions between crustal rocks and water sustain a broad range of processes that collectively meet most of the important energy and resource requirements of living systems. Such interactions ultimately determine the overall habitability of a planet, thus setting the stage for life's origin and ensuring its persistence over geologic timescales.

The previously discussed plate tectonic system is thought to be crucial for long-term biological presence on a planetary surface. Infiltration of surface water reduces the friction of deeper geological layers, easing the start of massive convection currents carrying heat from the interior to the planet's surface [16]. Volcanic outgassing regulates atmospheric composition and evolution. On Earth, water also mediates the carbonate-silicate weathering cycle, controlling atmospheric CO2 partial pressure (pCO2) in response to changes in surface temperature, which in conjunction with plate tectonics stabilizes the climate over geologic timescales [17]. On moons, the existence of substantial heat flux from its interior is necessary for maintaining plate tectonics and tidal heating might play an important role regarding this [9]. However, this is not sufficient. A water-rich environment is still necessary for these cycles to arise. So, where in the universe could we best find the most pristine moon shorelines?

Astrophysicists have defined *circumstellar habitable zone*, or **CHZ**, as the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure. This concept applies to moons too, besides the previously discussed habitable edge, since stellar irradiation still dominates the energy flux of the moon [14][18].

Low-mass stars are the most common kind of stars in the Universe, so mere probability would eventually yield a life-bearing moon. However, CHZs of low-mass stars are very tight. For a planet-moon binary in such a CHZ, the proximity of the star forces a close orbit for the moon to remain gravitationally bound to the planet, into the habitable edge. Also, stellar perturbations become important considerations for exomoon habitability. Computational investigation [18] into exomoon evolution for systems in the CHZ of low-mass stars, $\lesssim 0.6M_{\odot}$, shows that dwarf stars with masses $\lesssim 0.2M_{\odot}$ cannot host habitable exomoons within the stellar CHZ due to extreme tidal heating. Perturbations from a central star may continue to have deleterious effects in the CHZ up to $\sim 0.5M_{\odot}$. They note too that in cases with lower intensity tidal heating the stellar perturbations may have a positive influence on exomoon habitability by promoting long-term heating and possibly extending the CHZ for exomoons.

So we must look at one peculiar type of star - K-type main-sequence star or *orange dwarf*. These stars are three to four times as abundant as G-type main-sequence stars and due to their greater heat, the habitable zones of K-type stars are much wider than those of M-type stars. These also emit less ultraviolet radiation than our Sun, radiation that can damage sensitive biological mechanisms. K-type stars with masses of $0.5 - 0.8M_{\odot}$ are stable on the main sequence for a very long time, twice or thrice as long as Sun-like stars! Stability over time is crucial for the development of complex life forms. A crucial missing element is then needed to consider - *Time*.

**Time**

All systems evolve through time, especially highly complex ones as biological. But let's not forget that planetary systems evolve through time as well! Even a moon that formed with no atmosphere or lost it for being inside the habitable edge, has chances of bringing forth life. Gravitational perturbations can make it migrate beyond the habitable edge, bombarding it with volatile-rich comets, building a new atmosphere.

And analyzing galactic timescales, we see that moon life is practically assured. Billions of galaxies have been formed and will still be, each one containing billions of stars. And observations tell us that there are at least as many planets as stars. At this early point in our hunt for exoplanets, most of the worlds we have found in the habitable zone are giants, not Earths. So it safe to say that many moons are ought to be found in this universe. Which ones will be teeming with life? And especially land life.

To explore these alien worlds, humanity needs to lay its eyes on one, however, we haven't confirmed the discovery of a single exomoon, mainly because our detection methods favor larger planets closer to their stars, i.e planets less likely to host moons in stable orbits as mentioned before. Astronomers are now investing in next-generation instruments, such as NASA's James Webb Space Telescope and various 30-meter-class ground telescopes. These observatories, coming online in the next decade, could be able to characterize exomoon atmospheres and offer tantalizing evidence of life.

Our search could still take many years but very recently a strong exomoon candidate was announced [19]. *Kepler-1708 b-i* orbits Kepler-1708 b, a Jupiter-sized planet orbiting a Sun-like quiescent star at 1.6 au, i.e possibly inside the CHZ of its star [20], at about 12 planetary radii. At the end of the *Fire* chapter, we noted a similar planetary system example noting a habitable edge of 10 planetary radii. This means that Kepler-1708 b-i could be outside this edge. Also, it has about 2.6 Earth radii indicating a large mass and that massive moons can form, or at least exist, around giant planets. Good news for life as long as the defined interval of $0.1 - 2M_{\oplus}$ is respected. A lot of *ifs* for life on Kepler-1708 b-i, however, it shows that the conditions for moon life discussed throughout this essay *can* be met and there's a possibility that there are bizarre astronomers out there describing how the surrounding elements forged the way for their existence, by perfectly balancing all the variables with a touch of the divine.

Life on a moon would be very different from Earth. Seasonal illumination phenomena could create unprecedented biogeochemical cycles, influenced by seasons created by the shadow of its primary. Land-dwelling species emersed in regular, frequent eclipses would surely evolve extraordinary sleep-wake and hunt-hide rhythms as well, but only those creatures on the planet-facing hemisphere. How would plants on this hemisphere diverge from their other hemisphere cousins?

How would moon cultures form and evolve? Would the presence of other moons influence their calendars, agricultural yields, or even spark their exploratory behavior, leading to the creation of space-traveling technologies. Could they develop geocentric models from their celestial perspective? And how would that change their view of the universe? Surely cosmic epics and religious systems of belief inspired by their heavenly neighbors would fill these societies' literature. We can only try to imagine how this intelligent life would thrive on its Mother-Moon. Maybe someday, a foreign human will participate in the ancient processions, where the tribes of the occult hemisphere walk for days to have a glimpse of its primary's beautiful swirling cloud-tops.

**References**


[1] Greenberg R. Exploration and protection of Europa's biosphere: implications of permeable ice. Astrobiology. 2011 Mar;11(2):183-91. doi: 10.1089/ast.2011.0608. Epub 2011 Mar 9. PMID: 21417946.

[2] Parkinson, C., Liang, M.-C., Yung, Y., Kirschivnk, J. (2008). Habitability of Enceladus: Planetary Conditions for Life. Origins of Life and Evolution of Biospheres, 38(4), 355-369. doi: 10.1007/s11084-008-9135-4

[3] Greenberg, R., Hoppa, G. V., Tufts, B. R., Geissler, P., Riley, J., Kadel, S. (1999). Chaos on Europa. Icarus, 141(2), 263-286. https://doi.org/10.1006/icar.1999.6187

[4] Canup, R., Ward, W.R. (2008). Origin of Europa and the Galilean Satellites. arXiv: Astrophysics.

[5] Agnor, C., Hamilton, D. Neptune's capture of its moon Triton in a binary–planet gravitational encounter. Nature 441, 192–194 (2006). https://doi.org/10.1038/nature04792

[6] Canup RM, Asphaug E. Origin of the Moon in a giant impact near the end of the Earth's formation. Nature. 2001 Aug 16;412(6848):708-12. doi: 10.1038/35089010. PMID: 11507633.

[7] Alemi, A. and Stevenson, D., "Why Venus has No Moon", vol. 38, 2006.

[8] R A Moraes, E Vieira Neto, Exploring formation scenarios for the exomoon candidate Kepler 1625b I, Monthly Notices of the Royal Astronomical Society, Volume 495, Issue 4, July 2020, Pages 3763–3776, https://doi.org/10.1093/mnras/staa1441

[9] Williams DM, Kasting JF, Wade RA. Habitable moons around extrasolar giant planets. Nature. 1997 Jan 16;385(6613):234-6. doi: 10.1038/385234a0. PMID: 9000072.

[10] Sekine, Y., Genda, H., Sugita, S. et al. Replacement and late formation of atmospheric N2 on undifferentiated Titan by impacts. Nature Geosci 4, 359–362 (2011). https://doi.org/10.1038/ngeo1147

[11] Ward, Peter; Brownlee, Donald (2000). Rare Earth: Why Complex Life is Uncommon in the Universe. Springer. ISBN 978-0-387-98701-9. pp. 191–220

[12] Tachinami, C., Senshu, H., and Ida, S., "Thermal Evolution and Lifetime of Intrinsic Magnetic Fields of Super-Earths in Habitable Zones", <i>The Astrophysical Journal</i>, vol. 726, no. 2, 2011. doi:10.1088/0004-637X/726/2/70.

[13] Stamenković, V., Noack, L., Breuer, D., and Spohn, T., "The Influence of Pressure-dependent Viscosity on the Thermal Evolution of Super-Earths", <i>The Astrophysical Journal</i>, vol. 748, no. 1, 2012. doi:10.1088/0004-637X/748/1/41.

[14] Heller, René Barnes, Rory. (2013). Exomoon Habitability Constrained by Illumination and Tidal Heating. Astrobiology. 13. 10.1089/ast.2012.0859.

[15] Peale, Stanton Cassen, P Reynolds, R. (1979). Melting of Io by Tidal Dissipation. Science (New York, N.Y.). 203. 892-4. 10.1126/science.203.4383.892.

[16] Tikoo SM, Elkins-Tanton LT. The fate of water within Earth and super-Earths and implications for plate tectonics. Philos Trans A Math Phys Eng Sci. 2017;375(2094):20150394. doi:10.1098/rsta.2015.0394

[17] Lehmer, O.R., Catling, D.C. Krissansen-Totton, J. Carbonate-silicate cycle predictions of Earth-like planetary climates and testing the habitable zone concept. Nat Commun 11, 6153 (2020). https://doi.org/10.1038/s41467-020-19896-2

[18] Zollinger, Rhett Armstrong, John Heller, René. (2017). Exomoon Habitability and Tidal Evolution in Low-Mass Star Systems. Monthly Notices of the Royal Astronomical Society. 472. 10.1093/mnras/stx1861.

[19] Kipping, D., Bryson, S., Burke, C. et al. An exomoon survey of 70 cool giant exoplanets and the new candidate Kepler-1708 b-i. Nat Astron (2022). https://doi.org/10.1038/s41550-021-01539-1

[20] Pierrehumbert, Raymond Gaidos, Eric. (2011). Hydrogen Greenhouse Planets Beyond the Habitable Zone. Astrophysical Journal - ASTROPHYS J. 734. 10.1088/2041-8205/734/1/L13.