**Impacts, symmetries and decisions: the quest for habitable worlds[[1]](#footnote-2)**

*There is a vast amount of research data from space exploration on the topics of impacts, symmetries, habitable zone, chemical compositions, atmosphere, climate and geology. The related facts, sayings and relations need to be evaluated by a theory of decision based on strategies of reflection on empirical research and cooperation. Hundreds of technological applications, appropriate inventions and innovations are being introduced for the implementation of the objective to find habitable worlds. A logic of space science and technology is being, therefore, continuously tested through focusing on efficiency, computability, polyvalence, feedback control etc. This effort needs also to be assisted by a reevaluation of conceptual and mathematical frameworks, with the adoption of new physical definitions and new units of measurement.*

*An example of the requirement for conceptual reevaluation is the increasing significance of astrobiology, on account of the quest for water, life and habitable planets. Hereby philosophy of physics meets the philosophy of biology, so far as the concepts of life and non-life could plausibly be reconsidered by space exploration, while ethical problems on the value of space medicine, health and information arise, as well.*

*An example of the requirement for reflection on mathematical frameworks is the task for an efficient motion of spacecraft to the interstellar medium, to Proxima Centauri b and other exoplanets. Such a task should require the adoption of new units of measurement, for instance, of the magnitude of ~6.000 km/s (30 times faster than the Parker Solar Probe), being thus better comparable to the speed of light (since ~6.000 km/s equals to 1/50 or 2% of the speed of light).*

*Moreover, a crucial challenge to reflection is the role of the magnetosphere, the magnetic fields and dynamos for the development and the motion of the planets of our solar system and exoplanets. A successful procedure to explaining the contribution of the magnetic field to planetary dynamics may help us answer serious scientific questions and probably may contribute to the discovery of a new unified physical theory of everything.*

***Planetesimal hypothesis and HCON***

Star formation models incorporate the physical concepts of molecular clouds, interstellar medium, protostar etc. The molecular clouds and the interstellar medium play an intermediate role throughout star formation by corresponding to differentiated layers of thermodynamic spherical and elliptical constrains, which can be represented as envelopes, tongs, claws of primordial dust and gas. Hereby, we must stress the importance of the passage from the molecular cloud and the interstellar medium, consisting of 99% volatile gas and 1% dust, to the concepts of the accretion disc, planetesimals and atmosphere.

Modern astrophysics holds that our solar system was formed from a collapsing giant molecular cloud. The collapse may have been triggered by the shock wave from a nearby supernova (e.g., Boss & Keiser 2010; Li et al., 2014). The evidence for the impact of a nearby supernova supposedly comes from the existence of short-lived radioactive nuclei in the composition of meteorites. By contrast, Young (2016) argues that we need no unusual mechanisms, such as nearby supernovae, to explain the solar system's initial composition of short-lived radionuclides. The radiochemistry of the early solar system is the normal consequence of large-scale averaging of solids from molecular clouds (Horner et al., 2020).

According to measurements of the Sun’s composition (Palme et al. 2014) and chemical thermodynamics, the most abundant species in the initial material of the solar system and probably of the molecular cloud core collectively pertain to the category “HCON”, namely, hydrogen (H2), carbon monoxide (CO), water (H2O), nitrogen (N2), together with similar ones, and the noble gas helium (He). However, HCON and noble gasses comprise a lower part of Earth’s mass.[[2]](#footnote-3) This is a first asymmetry of chemical composition, as Earth’s mass comprises iron (35%), silicon (15%), magnesium (13%), nickel (2,4%). Carbon comprises, however, only 0,025% of the mass of Earth’s crust, whereas the percentage of oxygen in the mantle and the core of Earth is nothing more than a conjecture.

The HCON species and noble gasses occur relatively rare in the terrestrial planets’ volatile abundances, because gaseous HCON host species could not be effectively captured in rocky solids during solar system formation. Condensation in rocky solids or dissolution in molten silicate or metal are entirely non-effective processes for trapping volatile elements in planetary bodies, except of carbon probably and the incorporation of oxygen into silicates and oxides (Lodders 2004). Models of the formation and evolution stages of the planetary system, nevertheless, incorporate rawer species rather than elements. Such a raw species is the planetesimal.

***Origins of the elements***

The origin of Hydrogen and Helium is regularly related to the hot, dense conditions of the early universe. [A table from NASA](https://svs.gsfc.nasa.gov/13873), for example, connects the origin of Hydrogen and Helium exclusively and directly with the so called “Big Bang”.[[3]](#footnote-4) While Oxygen corresponds now to 1% of the mass of the universe, Hydrogen comprises 73-74% of the visible universe and Helium 25%. The Sun also is mainly composed by Hydrogen (~73%) and Helium (~25%), whereas the rest elements are mostly Oxygen, Carbon, Neon and Iron. This is a second asymmetry, because of the higher abundance of Oxygen in human body (65%) and in the Earth (48,8%). A spontaneous question refers to the disproportional mass of Oxygen compared with H and He, while our solar system contains considerable amounts of water.

Another related question is “where did other elements -apart from H, He and Li- like carbon, nitrogen and oxygen come from?” Some researchers point out to the 13.7 Gyr of the alleged age of the universe, after the so called “Big Bang”. Temperature is the pivotal factor, for instance, in the fusion and fission processes of Fe and in the role of supernovae for the nucleosynthesis of elements after Fe.

***Protoplanetary disc***

A solar nebula formed by the collapse of a molecular cloud of dust and gas is called protoplanetary disc. Nowadays we can observe such discs with telescopes like ALMA, while we find samples of this primordial epoch in comets, interplanetary dust and asteroids composed of carbonaceous chondrites. A protoplanetary disk is originally heterogeneous, with large radial gradients in temperature, pressure and chemical compositions, because of the development of a central protostar, cold interstellar medium at its edges, and nearby massive, luminous stars.

After the collapse of the proto-Solar nebula, it apparently crushed out into a dynamically cold protoplanetary disk, with the larger bulk of the material moving on nearly circular, low inclination orbits. In the protoplanetary disk, the temperature was significantly variating between the very hot inner regions, near the proto-Sun, and the cold outer regions. Beyond the ice-line at ∼3 au, temperatures were sufficiently low for the formation of icy grains, which meant that significantly more solid material was available to speed the accretion of the planets, as Dodson-Robinson et al. (2009) show. Later, the solid material in the nebula started colliding, resulting to the accretion of planetary embryos. The increasing mass and density of that material accelerated the growth of the embryos. The sufficiently quick core accretion, beyond the ice-line, allowed the cores to become so massive that they could capture gas from the proto-planetary nebula, through “runaway growth” (Pollack et al. 1996). In this model, the growth of the giant planets Jupiter, Saturn, Uranus and Neptune can be divided into three key stages, as Horner et al. (2020) suggest: (a) The slow accretion of solid material from the disk accelerates by the increasing mass of the planetesimal, due to runaway growth, then decreases again, when the planet absorbs all the material in its near “feeding zone” (Lissauer 1987). A few “embryos” or “oligarchs” are created by this process; violent giant collisions take place between these embryos, until a “protoplanet” dominates in that region. (b) Thereafter, the protoplanet undergoes very slowly a long accretion, while small amounts of gas and solids are captured from the edges of the feeding zone. This stage is crucial in the evolutionary timescale of giant planet formation (Pollack et al. 1996). (c) Finally, the protoplanet reaches a critical mass, for instance, ten times the mass of the Earth (Mizuno 1980), when its gaseous and solid mass are equivalent. Runaway gas accretion takes place in this stage, until the gas in the disk is vanished by the Sun and the proto-planetary disk ceases to exist at around 2–3 Myr after the start of the formation process, rarely after ∼10 Myr (Horner et al. 2020; Li & Xiao 2016; Murphy et al. 2018; Concha-Ramírez et al. 2019).

The survey of planetary rings relates also to the research on circumstellar disks. Planetary rings can be viewed as retrievable analogies for the analysis of general disk properties such as accretion, gap formation, self-gravity wakes, spiral waves, and angular-momentum transfer with embedded masses. Cassini observations revealed that Saturn’s rings contain some exceptionally large particles reaching up to several hundred meters in diameter (Spahn et al. 2018), ranging from typical ring particles, between millimeters and a few meters in size, to moonlets with a magnitude of several kilometers. They can be regarded as analogous to growing objects in proto-planetary disks.

Nevertheless, there are many questions to be answered: Why is only Saturn surrounded by a massive dense disk? Which is the nature of the arcs in Neptune’s dense rings? Why Jupiter lacks dense rings? Which is the origin of the rings in general?[[4]](#footnote-5)

***Accretion, protoplanets, collisions and migrations***

*In 1847 Hermann von Helmholtz pointed out the connection between mechanics, temperature, light, electricity and magnetism as corresponding to different manifestations of the same energy. However, Helmholtz avoided any reference to the role of gravity. Leibniz, however, insisted that the most diverse causes are mutually dependent in his explanation of gravity, viz. simultaneously spherical radiation, magnetic attraction, the aberration of whirling matter, its internal fluid movement, the circulation of the atmosphere, all together contribute to the production of centrifugal force [centripetal force].*

In the planetary formation stage (0–20 Myr), a gaseous protoplanetary disc and the planetesimals are being developed. The disc provides the resources for the accretion of the protoplanets by dust, clumps of particles, pebbles, rocks, bolides and planetesimals.  The evolution of the planets (20 Myr–10 Gyr) requires also a temporary gaseous planetary envelope that consists of pure H and He.

A remnant of primordial planetary formation is the dwarf planet, protoplanet, or [asteroid](https://en.m.wikipedia.org/wiki/Asteroid) [Vesta.](https://en.m.wikipedia.org/wiki/4_Vesta) Rheasilvia is an [impact crater](https://en.m.wikipedia.org/wiki/Impact_crater) on the south pole basin of Vesta. It is 505 km in diameter, which corresponds to 95% of the mean diameter of Vesta. Rheasilvia is one of the [largest craters in the Solar System](https://en.m.wikipedia.org/wiki/List_of_largest_craters_in_the_Solar_System), and covers most of Vesta’s southern hemisphere. The peak in the center of the crater is 200 km in diameter and rises 20–25 km from its base, making it allegedly one of the [tallest mountains known in the Solar System](https://en.m.wikipedia.org/wiki/List_of_tallest_mountains_in_the_Solar_System). This geological formation is the result of Vesta’s battering by two giant impacts. The requirement for reevaluation of conceptual frameworks arises here again clearly: the term “mountain” does not seem suitable for Rheasilvia’s prominence or protrusion on Vesta.

***Impact craters***

The high frequency of impact craters in the solar system offers a verification of one of the more important theses of the atomist theory of physics: the dissemination of impacts and collisions. The monitoring of present-day impact flux has already made significant improvements. The upcoming missions Mars Sample Return (MSR) and Endurance-A to the Moon are going to collect samples from impact craters on Mars and the Moon respectively. According to the National Academies of Sciences (2022) repeat imaging enabled the discovery of new impact craters on the Moon and Mars. The detection of craters in the process of formation was also enabled by telescopic monitoring for impact flashes on the lunar near-side.

* Research for evidence of past life on Mars is currently underway at Jezero crater by the Perseverance rover; the mission Mars Sample Return (MSR) has the task to obtain impact-formed rocks from Jezero crater.
* The mission Endurance-A will collect samples from the South Pole Aitken (SPA) basin on the Moon, which is the largest and most ancient impact basin in the solar system.
* The most heavily cratered object in the solar system is Jupiter’s moon Callisto. In the 4.5 billion years impact history of Callisto belong simple craters as well as the enormous multi-ring impact basin Valhalla.
* Some steadily shadowed craters at the Moon's poles show indications of water ice in their interiors, such as Rozhdestvenskiy and Cabeus craters on the Moon, and Juling Crater on Ceres.

***Olympus Mons and Tharsis Montes on Mars***

Perhaps the most interesting feature of Mars’ global topology is known as the Martian Dichotomy. Aside from the vast impact basin Hellas, Mars’ southern hemisphere consists of highlands, which are heavily cratered, and considered to be ancient terrain. The northern hemisphere, by contrast, consists of smooth lowlands, with few if any scars.

There is a scarcity of water vapor in the thin atmosphere of Mars, but it tends to disintegrate, because of ultraviolet radiation bombardment. This happens, because there are no extended ozone layers in the atmosphere of Mars, since there is no atmospheric oxygen available (Conway, 2015). However, Mars Express detected ozone layers above the poles and a third one at an altitude of 30 km.

Ice collects in the [polar regions](https://marsed.asu.edu/mep/ice/polar-caps) because Mars' rotation axis tilts about 25° to its orbit around the Sun. This gives Mars four distinct seasons, like those on Earth. But polar winters on Mars are much colder (–153° Celsius or –243° Fahrenheit). Mars becomes cold enough for carbon dioxide (CO2) gas to condense directly out. When spring returns, the CO2 ice cap sublimates — it changes directly from a solid into a gas — as temperatures warm above 130° C (–202° F).

The thermal and evolved gas analyzer (TEGA) and wet chemistry laboratory (WCL) cells on the Phoenix lander confirmed the presence of water vapor, carbonates, an alkaline surface with modest salinity, and abundant perchlorates, which are strong oxidizing compounds with a bactericidal effect that complicate the detection and preservation of organics. For more information on the chemical analysis performed by the Phoenix lander, see Kounaves et al. (2010).

Because Mars is a small planet, it has lost much of its atmosphere to space over time. Mars’s small size may have also affected the chemical composition of its mantle, and hence its early atmosphere (Wade and Wood 2005; Deng et al. 2020), with important implications for climate. Mars still lies in the habitable zone.

***Valles Marineris***

Valles Marineris is Mars’ largest canyon system. The entire system extends over 4000 km (2490 mi), covering about one fifth of the circumference of Mars. Some parts of the canyon run as deep as 7 km (4 mi) and as wide as 200 km (125 mi).

Compared to Valles Marineris, the Grand Canyon on Earth seems quite small at 446 km (277 mi) long, 30 km (18 mi) wide and 1.6 km (1 mi) deep. If Valles Marineris was placed on the surface of Earth, it would stretch from Los Angeles to the Atlantic coast.

The ESA-Roscosmos ExoMars Trace Gas Orbiter has spotted significant amounts of water at the heart of Mars’ dramatic canyon system, Valles Marineris.

The ridged plains of the Hesperia Planum originate with the Hesperian period, which lasted from ~3.7 to ~3.0 billion years ago. It was characterized by catastrophic flooding that created outflow channels across the martian surface. The Noachis Terra in the southern highlands comes from the Noachian period, which lasted from ~4.1 to ~3.7 billion years ago. It was characterized by widespread cratering and by the resulting formation of impact basins. This period also shows evidence of major volcanic episodes (National Academies, 2019).

***BepiColombo from Venus to Mercury***

In the inner solar system, the major differences in the atmospheres of Mercury, Venus, Earth and Mars arise in large part from differences in the planets’ masses, distance from the Sun, and the presence or absence of a significant magnetosphere. Mercury has a large core, a modest mantle and a magnetosphere. Venus lacks magnetosphere and plate tectonics, has a ∼92-bar atmosphere, with an abundance of 96.5% CO2 and a surface temperature of ∼735 K (462 grad Celsius). Venus rotates every 243 days, but its thick atmosphere circles the planet in just 4 days. This super-rotation is caused by thermal tides driven by solar heating.

[Mercury](https://en.wikipedia.org/wiki/Mercury_%28planet%29), the [Moon](https://en.wikipedia.org/wiki/Moon), [Ceres](https://en.wikipedia.org/wiki/Ceres_%28dwarf_planet%29), [Europa](https://en.wikipedia.org/wiki/Europa_%28moon%29), and [Ganymede](https://en.wikipedia.org/wiki/Ganymede_%28moon%29) have surface boundary exospheres, which are exospheres without a denser atmosphere underneath. In general, we distinguish:

* dense atmospheres (e.g., Venus, Earth, Titan, and early Mars),
* atmospheres dominantly controlled by vapor-pressure equilibrium (current Mars, Triton, Pluto, and some other KBOs), and
* collisionless exospheres (e.g., Mercury and the Moon).

Mercury’s neutral exosphere contains nine known species: hydrogen, helium, sodium, potassium, calcium, magnesium, aluminum, iron and manganese. The proposed Mercury Lander mission would deliver a lander with a suite of instruments to the surface of the innermost planet to gain insight into the original distribution of elements in the earliest stages of solar system development and to learn how planets and exoplanets form and evolve near their host stars. The Mercury Lander could investigate the chemistry and mineralogy of Mercury’s volatile-rich surface, Mercury’s interior structure and magnetic field, the active processes that produce Mercury’s exosphere and and the geologic processes that have shaped its evolution. However, the Mercury Lander was ranked lower in priority because of the narrower scientific scope of the mission compared to the proposed ice giant system mission Orbilander, regarding the high priority placed on the astrobiology of Enceladus.[[5]](#footnote-6)

“The relevance of Mercury to exoplanetary science lies in both its chemical make-up and its interior structure: how can a rocky world with high volatile abundance and an outsize core form so close to its star? It may be that such compositions are possible in the inner portions of the protoplanetary disk. Or, perhaps, giant impacts are not all that unusual” (Kane et al., 2021).

***Asteroids***

The interplay between impacts and atmospheres lets us approach a very interesting set of data of current research: ALMA (Atacama Large Millimeter / Sub-millimeter Array) provides evidence of atmospheric protection from meteorites. Venus, Earth and Titan possess sufficiently dense atmospheres to prevent meteorites and comets reaching their surface. Giant planet atmospheres play the same role, e.g. the impact of the fragments of the comet Shoemaker-Levy 9 with Jupiter in 1994.

* The prevention of impacts with near Earth objects (NEO) is the objective of the planetary Defense Coordination Office of the Planetary Science Division (PSD) of NASA.
* See The Double Asteroid Redirection Test (DART).

***Gas giants and icy giants***

Giant planets play a decisive role in the formation and the development of planetary systems. The giant planets comprise 99.5 percent of the mass of the solar system, apart from the Sun, and 96 percent of the solar system’s total angular momentum. In 1964, [Gary Flandro](https://en.wikipedia.org/wiki/Gary_Flandro) of the [Jet Propulsion Laboratory](https://en.wikipedia.org/wiki/Jet_Propulsion_Laboratory) (JPL) noted that an alignment of [Jupiter](https://en.wikipedia.org/wiki/Jupiter), [Saturn](https://en.wikipedia.org/wiki/Saturn), [Uranus](https://en.wikipedia.org/wiki/Uranus), and [Neptune](https://en.wikipedia.org/wiki/Neptune) that would occur in the late 1970s would enable a single spacecraft to visit all the outer planets by using [gravity assists](https://en.wikipedia.org/wiki/Gravity_assist). Such a Grand Tour Window occurs every 175 years. The twin Voyager 1 and 2 spacecraft explored Jupiter and Saturn, active volcanoes on Jupiter's moon Io and Saturn's rings. Moreover, Voyager 2 is still the only spacecraft to have visited the ice giants.

Juno[[6]](#footnote-7) arrived at Jupiter on July 4, 2016, with the task to investigate Jupiter's [radiation belt](https://astronomy.com/magazine/ask-astro/2020/02/what-is-the-source-of-jupiters-radiation).[[7]](#footnote-8) The extended mission should involve close passages near Jupiter’s north polar [cyclones](https://www.missionjuno.swri.edu/junocam/think-tank?tag=cyclones); flybys of Ganymede, Europa, and Io; as well as the exploration of the faint rings encircling the planet.

Apart from Uranus, all giant planets emit more heat than they receive from the Sun.[[8]](#footnote-9) This could produce convection and mixing. However, recent analyses suggest that the abundances of major chemical species exhibit significant variability, indicating processes such as precipitation during storms. There are also vortices and waves that prohibit convection. Juno and Cassini data reveal that Jupiter’s winds reach a depth of about 3000 km, while Saturn’s extend to depths of about 8000 km.

It is plausible that oxygen from water-ice forms a significant fraction of the mass of Jupiter’s core, since water-ice is likely to be the most abundant condensate in the Jupiter-forming region. For example, Ganymede and Callisto are roughly half water-ice, half rock by mass. Yet Jupiter’s envelope is depleted of water; Helium is also depleted in Jupiter’s atmosphere. Another observation refers to isentropy: adiabatic and reversible.

***Europa:  Jupiter’s Icy Moon***

(Distance: 628,300,000 km from Earth)

One of the Galilean moons (Europa, Io, Ganymede and Callisto), Europa, possesses mysterious "bands and ridges", freckles and cracks, lines (Lineae). Galileo mission arrived at Jupiter in 1995 and made 12 close flybys of the icy moon. The surface of Europa is very smooth and young. It lacks many impact craters, but it is spotted with 10-kilometers-across-lenticulae, freckles caused by warmer ice rising through the colder ice of the outer crust of Europa. The cracks may also be caused by the influence of the Jovian gravitational tides generating heat into the subsurface ocean of Europa.

These gravitational tides around Jupiter may also produce the huge volcanoes on Io and the melting of ice on Ganymede. Any orbital changes for one icy moon should affect its interior stress, deformation and heat budget as well as those of other neighboring moons. Dynamical excitation of one moon by other moons, causes intense internal tidal heating for all the satellites involved. Such changes in dissipative heating can then change the interior structures and heat transport efficiency, which, in turn, affect the moons’ orbits.

Ganymede has also a tenuous oxygen exosphere. The oxygen exospheres of Europa and Ganymede are likely produced by sputtering of surface ice, but our understanding of this process has yet to be validated. ESA’s Jupiter Icy Moons Explorer, Juice, will make detailed observations of the giant gas planet and its three large ocean-bearing moons – Ganymede, Callisto and Europa.

***Chemical compositions***

The deep interiors of the giant planets consist of mixtures of common materials (hydrogen, helium, water, methane, ammonia, and silicates) under a wide range of pressures and temperatures. Jupiter and Saturn are gas giants, with ~85% of their mass made up of hydrogen and helium. Uranus and Neptune are ice giants, with about 65% of their mass thought to be water, 25% rock, and only 10% H2 and He gas.

The two currently proposed models for giant planets formation are the Core Accretion model and the Disc Instability model. A significant prediction of the Core Accretion model is that the giant planets have a relatively dense core of solid material, several to ten times more massive that of the Earth (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Inaba et al. 2003; Hubickyj et al. 2005). The spacecraft Juno found strong evidence for a massive core deep within Jupiter, with a mass between 7 and 25 times that of the Earth (Wahl et al. 2017). According to these results also, Jupiterʼs core is larger, less dense, or more “dilute”, than previous estimations (Wahl et al. 2017; Debras & Chabrier 2019). Liu et al. (2019) recently proposed that Jupiter's diluted core may be the result of a giant collision with a massive planetary embryo. Such an impact could have dispersed the massive compact core of proto-Jupiter, resulting in the dilution observed by Juno.

Recent measurements of Jupiter’s and Saturn’s gravitational fields, as well as observations of waves in Saturn’s rings, have revealed that both planets have dilute cores. Instead of a discrete core, both planets exhibit a smooth change in composition and density with depth. The rings of Saturn are made mainly of ice-water particles and dust. Hydrocarbons seem to be descending from the rings to Saturn's atmosphere.

The atmospheres of the giant planets are composed primarily of hydrogen and helium, like the Sun itself and the protosolar disk.[[9]](#footnote-10) Jupiter[[10]](#footnote-11) and Saturn’s interiors have a deep metallic hydrogen region and a phase separation of helium in hydrogen leading to helium rain. Their central dense cores are diluted into the metallic hydrogen envelope. Helium is the second most abundant species after hydrogen in the gaseous envelopes of Jupiter, Saturn, Uranus and Neptune. The bluish color is produced by methane on the upper layers of the atmospheres of Uranus and Neptune.

The Cassini mission tried among others to answer the question about the existence of a core in Saturn. A possible answer is that Saturn has a core of metallic hydrogen. The Radio and Plasma Instrument [[Radio and Plasma Wave Science (RPWS)](https://solarsystem.nasa.gov/missions/cassini/mission/spacecraft/cassini-orbiter/radio-and-plasma-wave-science/)] of Cassini was listening to dust particles hitting the spacecraft (see Cassini Integrated Test Lab).

Uranus and Neptune have masses of about 14.5 and 17 M⊕, and are located at 19.2 and 30 AU, respectively. “Why the name “Ice Giants”? This name has come from the average densities of Uranus and Neptune, which “weigh” in at 1.27 and 1.65 g cm−3 respectively. This early observation led to the conclusion that these planets were markedly enriched with the “heavier” elements of oxygen, carbon, sulfur and nitrogen compared to the composition of Jupiter and Saturn, whose overall makeup reflects more closely that of our Sun (as discussed above). The widely accepted view is that these elements will be in the form of ices; with H2O, CH4, H2S and NH3 combined making up ∼70% of the mass of both Uranus and Neptune, hence, the physical properties of these materials determine the interactions on these planets. In general, giant planets may contribute greatly to the supply of water to telluric planets (O’Brien et al., 2014).

***Astrobiological potentials***

Among the indispensable parts of the dynamics of astrobiology we must focus on liquid water, source(s) of energy, like tides and radiolysis, and biologically important chemical elements (C, H, N, O, P, and S or CHNOPS).[[11]](#footnote-12) The principal habitability criteria are “the presence of liquid water, conditions favorable for the assembly of complex organic molecules at some time during the planet’s history, and energy sources to sustain metabolism” (National Academies, 2019). Life is most definitely not self-sustained, just the opposite: it is an open system that exchanges matter and energy with its environment to maintain non-equilibrium state. In Peter Mitchell’s (1959) own words: life and its environment “may be regarded as equivalent phases between which dynamic contact is maintained by the membranes that separate and link them”. After all these years, one of the best definitions of life may have been formulated already in 1937 by Noble Prize winner Albert Szent-Gyorgyi: “Life is nothing but an electron looking for a place to rest”, thereby referring to metabolism and the electron transport chain.

Three key ingredients required to support life on Earth are liquid water, source(s) of energy (oxidants and reductants) and core biological elements (C, H, N, O, P, and S or CHNOPS). The Jovian satellites Europa, Ganymede and Callisto and the Saturnian satellites Enceladus and Titan may contain subsurface oceans of water.

Oxygen is generally considered as a sign of life and biosignature of habitable exoplanets. There is scarcity of oxygen on Mercury, with high abundances of sulfur and low abundances of iron; Venus Express mission found that Venus loses more oxygen to space than had been hypothesized; however, small quantities of abiotic oxygen are generated on Venus through atmospheric chemical processes (the details remain hidden).

Nitrogen is also essential for life. On Enceladus plume, Cassini detected a diversity of organic molecules containing carbon, hydrogen, oxygen and nitrogen; molecular hydrogen has been also found on Enceladus, because of hydrothermal activity that presupposes water, chemistry and energy.

There is a significant relationship between life, energy, and chemical, thermodynamic disequilibrium. The current chief astrobiological targets within the solar system are Mars, Europa, Enceladus, and Titan.

***Levels of generality***

As a summary of our research, we may point out, firstly, the importance of certain facts: impacts, collisions; chemistry; atmospheres; climate; geology (plumes, volcanism, magmatism). On the other side, we distinguish between i) sayings and hypotheses: habitable zone; life;[[12]](#footnote-13) subsurface oceans, ii) relations: symmetries; dynamics; laws of conservation, iii) intentions, influences, recommendations: regarding, for instance, energy resources.

Some hypotheses refer to hydrothermal deposits in large Martian or Cerean craters, which in the past may have been habitable zones. The whole account of habitability belongs to the domain of hypotheses, as well. Interesting hypotheses arise from the celestial dynamics of the dynamo and from the differences between exosphere and atmosphere. While early Mars possessed a dense atmosphere, other atmospheres are dominantly controlled by vapor-pressure equilibrium (current Mars, Triton, Pluto, and some other KBOs), and other correspond to collisionless exospheres (e.g., Mercury and the Moon).

There are also mysteries, such as the thick organic haze on Saturn’s moon Titan and the liquid methane cycle between Titan’s lower atmosphere and surface and near subsurface. In fact, Titan provokes speculation about the possibility of life in a hydrocarbon solvent (McKay and Smith 2005; Schulze-Makuch and Grinspoon 2005; McKay 2016; Cable et. al 2018; Malaska et al. 2018). Although Titan’s surface lacks water due to its low temperature (94 K), liquid hydrocarbons (primarily methane and ethane), condensed from the atmosphere, make up the vast lakes and seas observed by the Cassini-Huygens mission (Hayes 2016). Titan’s thick (1.5 bar) nitrogen and methane atmosphere contains several key volatiles, including hydrogen, ethane, acetylene, propane, benzene, polyacetylene, polycyclic aromatic hydrocarbons, and nitriles such as hydrogen cyanide and acrylonitrile (Wilson and Atreya 2004). Many of these deposit on the surface (National Academies, 2019).

Thus, some relevant research questions are the following: in what manner volatiles migrate on bodies with atmospheres dominated by condensation-sublimation flows (Triton and Pluto); how volatiles migrate within exospheres, such as on Mercury and the Moon; which are the causes of atmospheric superrotation on bodies like Venus and Titan, or dust storms on Mars and Titan.

Moreover, other fields of generalization correspond to the dynamics and the interactions: between tilt and climate; between impacts and atmosphere; between oceans and stellar irradiation.

There are also intentions, namely, the interplay between habitability and decision theory: we are searching either earth-like planets or are we ready to consider re-evaluating out concepts of life and organic domain.

In a similar manner, are we going to prefer the development of fusion, warp propulsion, breakthrough starshot and with what priority? Do we think to publish any other recommendations regarding fusion,[[13]](#footnote-14) nucleosynthesis, the Sun?[[14]](#footnote-15)

“Reassuringly, the Borexino experiment detected the neutrinos from the first step in the pp chain (2.1), producing the confirmation long-sought by solar astronomers. The expected count rate is much less sensitive to temperature and the experimental rates agree with the (new) neutrino theory. The measurement of ppI neutrinos thus confirms, in quantitative detail, our theoretical understanding of the interior of the Sun. More broadly, detection of solar neutrinos confirms that the Sun is powered by nuclear fusion. Element transformation illuminates the cosmos!”[[15]](#footnote-16)

***Evidence of water-ice plumes***

It is worth mentioning that observational and experimental evidence directs current research plans. Quite remarkable, there were findings of liquid and hot water in Enceladus, namely eruptions of a plume that casts gases and frozen sea spray into space. Enceladus plumes are feeding the E ring of Saturn. On the other hand, Cassini radar observations supported the idea that the E‐ring (fed by Enceladus's geysers) acts as a snow cannon, depositing freshwater ice particles onto Enceladus[[16]](#footnote-17) and its neighbors.

Orbiting deep within Saturn's magnetosphere, Enceladus is continuously overtaken by a plasma whose bulk flow almost corotates with Saturn itself. The moon's trailing hemisphere is therefore continually bombarded by ions and low-energy electrons, whilst its leading hemisphere is exposed to energetic (>1MeV) electrons that flow in the opposite direction around Saturn (e.g. Krupp et al. 2018). The moon's absorption of many energetic trapped particles largely evacuates the radiation belt region intersecting its orbit. Such interactions are seen at the other inner icy moons, as well. The presence of Enceladus's plume however makes several aspects of its interaction with its surroundings of particular interest.

 Researchers point out that six worlds, namely, Ganymede, Callisto, Europa, Enceladus, Titan, and Pluto, lie in the intersection of water and the elements needed for life. Three worlds, Europa, Enceladus, and Titan, lie in the intersection of liquid water, elements, and the energy needed for life.

Moreover, Triton is a priority candidate ocean world to target in the near term. Europa and Enceladus stand out as ocean worlds with evidence for communication between the ocean and the surface, as well as the potential for interactions between the oceans and a rocky seafloor, which is important for habitability considerations. The subsurface oceans of Titan, Ganymede, and Callisto are expected to be covered by relatively thick ice shells, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans.

Because of such pieces of evidence, the strategy “[follow the water](https://www.hq.nasa.gov/mars/presentations/FTW/slide02.html)“ is currently under re-evaluation, on account of the significance of the combination of water-rock environments, oxygen and our intentions to search the traces of a celestial big bounce.

***Axis symmetry or asymmetry***

Venus spins backwards,[[17]](#footnote-18) while Uranus‘ tilt has probably occurred by the ancient impact of a collision. Due to its extreme obliquity, Uranus is subject to extreme seasons, and during a given hemisphere's winter most of it will not see the Sun for 20 yr. Uranus is a slow and cold planet, reaching temperatures of 49 K (corresponding to 49°C over the absolute zero). Uranus' large icy moons are geologically active, and they are probably ocean worlds. Uranus Orbiter and Probe mission (2023-32) may uncover precious information.

The Uranus Orbiter and Probe Mission (2023-32) concept was selected as the highest priority Flagship-class mission by the 2023–2032 Planetary Science Decadal Survey, ahead of the Enceladus Orbilander.

A Neptunian orbit around the Sun lasts 164.8 years. Its atmosphere spins at the equator every 18 hours, whereas its magnetic axis spins every 16 hours. Unlike Uranus, Neptune radiates big amounts of heat and energy. Neptune is not deeply hazy as Uranus and is featured by storms, such as the great dark spot (anticyclone), of 1300 m/h.

The magnitude and the differentiation of a planet may give birth to an intrinsically generated dynamo, a magnetic field that could protect the surface and atmosphere from stellar activity and atmospheric stripping or could alternately contribute to atmospheric loss.

Solar dynamo is another, powerful example. Currently, the geometry and width of the tachocline are hypothesized to play an important role in models of the solar dynamo by winding up the weaker poloidal field to create a much stronger toroidal field. However, recent radio observations of cooler stars and brown dwarfs, which do not have a radiative core and only have a convection zone, have demonstrated that they maintain large-scale, solar-strength magnetic fields and display solar-like activity despite the absence of tachoclines. This suggests that the convection zone alone may be responsible for the function of the solar dynamo.

***More (a)symmetries***

Regarding symmetries National Academies (2022) have also found out the following information:

- Mercury's magnetic field is mainly axisymmetric and dipolar; however, the magnetic equator is offset along the spin axis to the north by ~20 percent of the planetary radius.

- Large impact basins on Mercury are present more in western hemisphere than the eastern, because of volcanism or/and spin-orbit evolution.

- Average crustal thickness of the Moon is ~55km on the far-side and ~30 km on the nearside. Such asymmetry is also found in porosity, heat producing elements and volcanism.

- Saturn has a weak and extreme spin-axisymmetric magnetic field. However, the magnetic equator shifted northward from the planetary equator.

- The Moon, Mars and Pluto exhibit ancient hemispheric asymmetries, which influence magmatic and tectonic activity.

- The Moon and Mars have massive crustal asymmetries.

- Venus presents polar asymmetric ion flow.

- Saturn's gravitational field is time-variable and asymmetric almost as the surface winds.

- The highly tilted and off-centered dipole moments of Uranus and Neptune generate asymmetric magnetospheres and twisted magnetotails which were only fleetingly explored by Voyager 2 flybys.

A research question proposed by the National Academies is the following: What Causes the Global-Scale Asymmetries Observed on Moons in Circumplanetary Systems? On tidally locked satellites, the surface can be geographically divided between the nearside (i.e., the planet-facing hemisphere) and the farside, or alternatively, the leading hemisphere (the hemisphere facing the direction of travel along the orbit) and trailing hemisphere. Leading/trailing hemispherical albedo and color asymmetries are evident on most tidally locked satellites in the outer solar system. Examples include dark trailing hemispheres on Io and Europa, reddened trailing hemispheres on several Saturnian satellites, and the archetype of this feature, Iapetus, with a dark leading and bright trailing hemisphere.

Not all global-scale asymmetries are well-understood, and many may arise from endogenic processes. The Moon’s nearside-farside asymmetry—the nearside has a thinner crust and more extrusive volcanism—has remained unexplained since its discovery at the dawn of the space age. Hypotheses range from asymmetric thermal evolution due to Earth-shine, to asymmetric convection of the mantle, asymmetric crystallization of the magma ocean, tidal processes, and giant impacts including South Pole Aitken or even larger. Enceladus also exhibits a pronounced global asymmetry: the majority of the present-day activity is concentrated at the south pole (Hemingway et al. 2018). Io also exhibits an unusual leading-trailing asymmetry in volcanic output—there are more, smaller volcanoes on the leading hemisphere, and fewer, larger volcanoes on the trailing hemisphere (although the total volcanic output is comparable; de Kleer and de Pater 2016). The cause of these asymmetries (endogenic or exogenic), their relationship to the circumplanetary environment, and how deep into the body they extend, remains unclear.

***Magnetosphere***

Without layers, our Earth couldn’t have a magnetic field. Without this magnetic field, our Earth could never have [atmosphere](https://science4fun.info/atmosphere/), oceans, and life. A global dipole magnetic field like the Earth’s causes the solar wind to stand off at a greater distance than it would in the absence of a field. This can protect the atmosphere from stripping by the solar wind. Mercury possesses a conductive liquid core of iron; its elliptical orbit produces friction to it, resulting to a magnetic field hundred times weaker than that of Earth. Venus has no strong magnetosphere; Pioneer Venus found that any internally generated magnetic field is at least one hundred thousand times weaker than that of Earth today. Jupiter’s magnetic field, 20 thousand times stronger than Earth’s, is produced by liquid metallic hydrogen, whereas Earth’s by molten iron and nickel. A special type of magnetic field produced by Europa, disrupts Jupiter's magnetic field, according to Galileo mission findings. More importantly, Io's volcanic ejecta also produce a large plasma torus around Jupiter.[[18]](#footnote-19)

Saturn's magnetic field is nearly aligned to her rotation axis. The magnetic fields of Uranus and Neptune may be generated by an enigmatic form of water called “super ionic”. Some researchers suggest that Uranus and Neptune carry vast amounts of water in their deep interiors. Both Uranus and Neptune have multipolar magnetic fields and inclined magnetic tilt in comparison to their rotation axis. Why the Jovian magnetosphere is the largest, extremely dense (with >106 ton of plasma) and hot, while the magnetospheres of Uranus and Neptune are near vacuum, is not well understood. The active moons Io and Enceladus dominate the magnetospheres of Jupiter and Saturn, filling their large magnetospheres with plasma disks that co-rotate with the planet.

***From Kuiper belt to Oort cloud***

New Horizons: Pluto's "encounter hemisphere" viewed by New Horizons on July 13, 2015. Neptune‘s gravity is dominating in the Kuiper belt, at about 30-50 AU, where the dwarf planets Orcus, Pluto, Haumea, Quaoar and Makemake reside. At inner heliosheath, at a distance of 122 AU, that is to say, 18 billion km away from the sun, Voyager 1 mission observed the termination shock boundary, where sun particles are pushed backwards, because of the interaction between heliopause and interstellar medium. The Oort cloud is a hypothetical spherical cloud extending from the distance of 50.000 AU (approximately 1 ly) to the 100.000 AU far from the sun.

***X-ray, ultraviolet, optical, infrared and radio spectral windows of the galaxy M81 (distance 3.7 Mpc)***

Habitability depends partly on the large thermal inertia of the oceans and liquid water reservoirs, which mitigate stellar irradiance (Wolf et al., 2020). Furthermore, habitability depends on the presence of a magnetic field, atmosphere and plate tectonics (outgassing and recycling of the atmosphere driven by plate tectonics).

Dynamic habitability, as defined in recommendations from Astrobiology Strategy (NASEM 2019), recognizes the combined effects of multiple parameters (e.g., T, P, salinity, pH etc.). This parametric approach becomes obvious in research on moons of the giant planets. One of the three big tasks of the Voyage 2050 mission (moons of the giant Solar System planets, temperate exoplanets of the galactic ecosystem, and new physical probes of the early Universe) was detecting biosignatures. This task applies also to our understanding and approach towards exoplanets.[[19]](#footnote-20) The Transiting Exoplanet Survey Satellite (TESS) is discovering exoplanets nearby bright stars, focusing on new Earths and super Earths[[20]](#footnote-21) in the solar neighborhood.

“The current exoplanet inventory contains planets of types vastly different to those in the Solar System, such as super-Earths (Bonfils et al., 2013; Howard et al., 2010; Léger et al., 2009; Valencia, Sasselov, et al., 2007), mini-Neptunes (R. Barnes et al., 2009; Lopez & Fortney, 2014; L. D. Nielsen et al., 2020), and hot Jupiters (Fortney et al., 2008; Mayor & Queloz, 1995; Wright et al., 2012)” (Kane et al., 2021).

Finally, the next steps of these projects should involve building the infrastructure to evaluate resources such as the post 2015 discovery of Earth-sized planets orbiting M-dwarf stars in their habitable zones. In general, the axis of our demands for habitability may reach a minimum in the case of ISS and a maximum in Earth, while the axis of our quest for energy resources may reach a minimum at self-sufficiency, yet a maximum, if we achieve interstellar travel.

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1. Presentation at the 86th Annual Meeting of the *German Physical Society* in Dresden, Germany (20.3.-24.3.2023). AGPhil 11: Quantum Mechanics, Philosophy and Information. [↑](#footnote-ref-2)
2. Around 90% of the mass of the Earth is composed of the [iron–nickel alloy (95% iron)](https://en.wikipedia.org/wiki/Iron%E2%80%93nickel_alloy) in the core (30%), and the [silicon dioxides](https://en.wikipedia.org/wiki/Silicon_dioxide) (c. 33%) and [magnesium oxide](https://en.wikipedia.org/wiki/Magnesium_oxide) (c. 27%) in the mantle and crust. Lower contributions are from [iron(II) oxide](https://en.wikipedia.org/wiki/Iron%28II%29_oxide) (5%), [aluminium oxide](https://en.wikipedia.org/wiki/Aluminium_oxide) (3%) and [calcium oxide](https://en.wikipedia.org/wiki/Calcium_oxide) (2%), besides numerous trace elements ([iron](https://en.wikipedia.org/wiki/Iron) and [oxygen](https://en.wikipedia.org/wiki/Oxygen) c. 32% each, [magnesium](https://en.wikipedia.org/wiki/Magnesium) and [silicon](https://en.wikipedia.org/wiki/Silicon) c. 15% each, [calcium](https://en.wikipedia.org/wiki/Calcium), [aluminium](https://en.wikipedia.org/wiki/Aluminium) and [nickel](https://en.wikipedia.org/wiki/Nickel) c. 1.5% each). [Carbon](https://en.wikipedia.org/wiki/Carbon) accounts for 0.03%, [water](https://en.wikipedia.org/wiki/Hydrosphere) for 0.02%, and the [atmosphere](https://en.wikipedia.org/wiki/Earth%27s_atmosphere) for about one [part per million](https://en.wikipedia.org/wiki/Part_per_million). [↑](#footnote-ref-3)
3. From Thales and his successors Presocratic philosophers, space was considered as infinite and eternal. On the contrary, Plato introduced the concept of the creator, Aristotle disputed the actual reality of the infinite, Christian authors emphasized the role of the creator, recently Hawking doubted about the reality of time, etc. The interpretation of the Big Bang as an absolute starting point of the Universe, whereas supposedly nothing existed before, is logically inconsistent. For this reason, the author of this article adheres more readily to the alternative conception of the Big Bounce. [↑](#footnote-ref-4)
4. According to recent discoveries, Chariklo, the largest Centaur, has two rings and rings were also found around the dwarf planet, Haumea. [↑](#footnote-ref-5)
5. National Academies of Sciences, Engineering, and Medicine (2022). *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*. [↑](#footnote-ref-6)
6. Giant planets are significant parts of planetary formation and evolution. They are rich in the primary cosmic elements hydrogen and helium and form in the first few million years, when the protoplanetary disk is in its gaseous, solar nebula stage. Because of their large gravitational fields, Jupiter and Saturn played primary roles in the scattering of solid material, dynamically exciting the solids and ejecting a large fraction from the solar system. “They therefore accelerated terrestrial planet growth and brought it to a quick end after roughly 108 years (Chambers and Wetherill 1998). Juno will provide information on Jupiter’s formation via three key measurements. First, the measurements of Jupiter’s global water abundance from microwave radiometry up to pressures of 100 bars will provide constraints on the water total abundance (Janssen et al. 2017, this issue). Second, the measurements of high-order gravitational coefficients will provide constraints on the distribution of mass within Jupiter, and the possibility of a central core of heavy elements (Asmar et al. 2017, this issue) and finally, measurements of Jupiter’s magnetic field may also provide information on the state of the interior (transition from molecular to metallic hydrogen) and possibly differential rotation when related to dynamo theories (Connerney et al. 2017, this issue). A determination of the core mass is important because a very large (>10 M⊕) or very small (i.e., undetected) core will set constraints on the sequence of accretion of solids and gas, and possibly on the size of the solid bodies that were swept up by Jupiter” (Bolton, S.J., Lunine, J., Stevenson, D. et al. 2017, pp. 15-16). [↑](#footnote-ref-7)
7. “[Jupiter's internal magnetic field](https://en.wikipedia.org/wiki/Magnetosphere_of_Jupiter) is generated by electrical currents in the planet's outer core, which is composed of liquid [metallic hydrogen](https://en.wikipedia.org/wiki/Metallic_hydrogen). Volcanic eruptions on Jupiter's moon [Io](https://en.wikipedia.org/wiki/Io_%28moon%29) eject large amounts of [sulfur dioxide](https://en.wikipedia.org/wiki/Sulfur_dioxide) gas into space, forming a large [torus](https://en.wikipedia.org/wiki/Gas_torus) around the planet. Jupiter's magnetic field forces the torus to rotate with the same [angular velocity](https://en.wikipedia.org/wiki/Angular_velocity) and direction as the planet. The torus in turn loads the magnetic field with [plasma](https://en.wikipedia.org/wiki/Plasma_%28physics%29), in the process stretching it into a pancake-like structure called a magnetodisk. In effect, Jupiter's magnetosphere is internally driven, shaped primarily by Io's plasma and its own rotation, rather than by the [solar wind](https://en.wikipedia.org/wiki/Solar_wind) as at Earth's magnetosphere.” [↑](#footnote-ref-8)
8. Radiation to space is the ultimate heat loss mechanism, modulated by the ability of the interior and atmosphere to transport heat out to the radiative zone, and by secondary internal heating processes (e.g. radiogenic, helium rain). Uranus system exerts essentially no detectable heat flow, while the Neptune system exerts the largest internal heat flow relative to absorbed sunlight of any giant planet in our Solar System. [↑](#footnote-ref-9)
9. The best information on Jupiter’s atmospheric composition comes from the Galileo probe. The helium to hydrogen ratio was found to be 0.238±0.05, smaller than the protosolar value of 0.275±0.01, inferred from solar models. [↑](#footnote-ref-10)
10. The measurement of the water abundance of Jupiter is pivotal in understanding giant planet formation and the delivery of volatiles throughout the solar system. This follows from the fact that oxygen is the third most abundant element in the universe and icy planetesimals were the dominant carriers of heavy elements in the solar nebula. The deep oxygen abundance in Jupiter was not known prior to Juno because the abundance of water—the primary carrier of oxygen in the jovian atmosphere—is in principle strongly affected by condensation and rainout associated with meteorological processes (Lunine and Hunten 1987), by advection (Showman and Dowling 2000), or both. [↑](#footnote-ref-11)
11. The commonly cited set of general criteria are (in decreasing order of certainty) as follows (National Research Council, 2007b): a means to sustain thermodynamic disequilibrium; an environment capable of maintaining covalent bonds, especially between carbon, hydrogen, and other atoms; a liquid environment; and a self-replicating molecular system that can support Darwinian evolution. [↑](#footnote-ref-12)
12. “One of the most compelling questions in comparative planetology of our solar system is the origin and evolution of life (astrobiology): When, where, how, and under what conditions did life arise, and what environments encourage its evolution or cause its extinction” (Kane et al., 2019). [↑](#footnote-ref-13)
13. A century ago, Eddington suggested that the Sun’s power arises in the nuclear fusion of hydrogen into helium, based on two facts. First, four protons have more mass than a 4He nucleus, so helium production liberates the lost rest mass energy mc2. Second, the temperature in the centre of the Sun must be enormous to provide thermal pressure to keep the Sun from collapsing under its own weight [Eddington, 1920; 1926]. The violent collisions of atomic nuclei at these temperatures and densities are sufficient to sustain nuclear reactions. No other source of energy was known that could produce the total amount of energy the Sun has emitted over the past 5 billion years. In 1925, Payne showed that the Sun has a large fraction of hydrogen, unlike the Earth, thereby demonstrating that the necessary fuel for hydrogen fusion to power the Sun was there in abundance [Payne, 1925]. [↑](#footnote-ref-14)
14. Nuclear fusion in the Sun happens in the hot, dense solar core. At a temperature of 16 × 106 K, this ionized plasma is completely opaque because of the abundant free electrons that interact easily with photons. Photons produced in nuclear reactions do not directly fly to outside observers. Instead the energy diffuses out, taking about 200000 years to make its way to the surface. The composition at the surface of the Sun is also uninformative. Most of the Sun’s interior is unmixed. The helium produced in the Sun’s core will not be visible on its surface until the end of the Sun’s life, when large convective cells will dredge up material from the interior and bring it to the surface. Thus, until the end of the Sun’s life, the action in its interior remains hidden. [↑](#footnote-ref-15)
15. BOREXINO Collaboration, Bellini, G. et al. (2014). [↑](#footnote-ref-16)
16. Enceladus’s activity indicated that its interior is differentiated into an inner rock core surrounded by a hydrosphere (e.g. Schubert et al. 2007, Hemingway et al. 2018). […]… several studies have estimated the core size between 180 and 195 km for a core density between 2450 and 2550 kg.m-3 (Cadek et al. 2016, 2019, Beuthe et al. 2016, Hemingway et al. 2018). Such a low core density requires significant porosity. Assuming chondrite-like iron-bearing hydrated minerals, Choblet et al. (2017) estimated the core porosity between 20 and 30%. The pores are likely filled with water but may also contain a significant fraction of low-density organics or small particles of clay and silt (e.g. Bland and Travis 2017). [↑](#footnote-ref-17)
17. “With respect to the background stars (the sidereal day), Venus takes some 243 days to spin once on its axis (a period longer than that of the planetʼs orbit, 225 days). However, because it spins in the opposite direction, the Solar day (the time between successive sunrises or sunsets) is around 117 days.” [↑](#footnote-ref-18)
18. “Of the terrestrial objects in our solar system only Earth, Mercury, and Jupiter’s moon Ganymede have significant internal magnetic dynamos – providing magnetic shielding to at least some latitudes on the surface. But the magnetospheres of giant planets shield the solar wind from satellites that are embedded inside (while exposing them to weathering by magnetospheric plasma – which might be more extreme).” Magnetospheres within magnetospheres, “such as Ganymede at Jupiter, might provide particularly safe havens for life in otherwise radiation heavy environments. All of this makes the magnetospheric systems of the giant outer planets an excellent place to test whether having a magnetic field is required in order to have environments that can support life.” [↑](#footnote-ref-19)
19. Terrestrial exoplanets are extremely common (Winn & Fabrycky, 2015) and will form the basis for a large-scale effort toward measurements of planetary atmospheric characteristics (Kempton et al., 2018; Lustig-Yaeger et al., 2019b), which will, in turn, be applied to understanding Solar System atmospheric abundances (Bean et al., 2017; Martin & Livio, 2015). [↑](#footnote-ref-20)
20. “… “super-Earths” (planets of ∼1.2–1.9 Earth radii) are the most common type of planet as revealed by the Kepler mission (Howard et al. 2012; Zhu et al. 2018; Hsu et al. 2019), yet are conspicuously absent in our solar system.” [↑](#footnote-ref-21)