

What Makes a Planet Habitable?

Manuel Güdel

Received 03.07.2014 - Approved 05.09.2014

Abstract / Resumen / Résumé

Before life can form and develop on a planetary surface, many conditions must be met that are of astrophysical nature. Radiation and particles from the central star, the planetary magnetic field, the accreted or outgassed atmosphere of a young planet and several further factors must act together in a balanced way before life has a chance to thrive. We will describe these crucial preconditions for habitability and discuss the latest state of knowledge.

Antes de que la vida pueda surgir y desarrollarse en una superficie planetaria, son necesarias muchas condiciones de naturaleza astrofísica. La radiación y las partículas provenientes de la estrella central, el campo magnético del planeta, la acumulación o disipación de la atmósfera en un planeta joven, y varios otros factores deben actuar conjuntamente y de manera equilibrada para dar a la vida la oportunidad de florecer. En este artículo describimos estos prerrequisitos cruciales para la habitabilidad y exponemos el estado actual de nuestro conocimiento.

Afin que la vie puisse apparaître et se développer sur la surface d'une planète, des nombreuses conditions de nature astrophysique sont nécessaires. Le rayonnement et les particules provenant de l'étoile centrale, le champ magnétique planétaire, l'accrétion ou dissipation de l'atmosphère d'une jeune planète, et plusieurs autres facteurs doivent agir ensemble et de façon équilibrée pour que la vie ait l'opportunité de prospérer. On décrit ces prérequis cruciaux pour l'habitabilité et on discute le dernier état de connaissance.

Key Words / Palabras clave / Mots-clé

Exoplanets, habitability, life

Exoplanetas, habitabilidad, vida

Exoplanètes, habitabilité, vie

1. Life and water

Why is there life on Earth, and why does it apparently not thrive on Mars? Are there other places in the solar system that may support life forms or did so in the past? And

among the countless exoplanets, which ones may be conducive to life, and what signs should we look for in our search for life in the universe?

These questions relate to at least two major challenges. We need to understand our biochemical origins in the distant past of the Earth, and in a larger context, we need to identify the main conditions required to form life on a planet in the first place. While there is hope to eventually answer the first question by a deeper understanding of the specific form of life here on Earth, the second challenge is much harder to address as it boils down to defining what life in general is. Although many attempts have been made to define “life”, for example through reproduction, metabolism, or evolutionary adaptation to changes, there is no universally valid or accepted definition, and most attempts describe minimum and general properties of the terrestrial type of life.

Until we have better constraints to what life can possibly be, it is wise to be conservative and base our assessment on what we firmly know and what we can safely extrapolate from there.

Terrestrial life had its origins in the oceans; although we could also imagine life formation on land, it seems unlikely that life started in a purely gaseous, “atmospheric” environment and evolved there. The problem of floating in an atmospheric environment without drifting into hospitable regions would have to be solved at once with the first appearance of life forms. It is therefore a safe assumption that life usually originates on rocky planets with solid or liquid surfaces, rather than on gas planets such as Jupiter or Saturn. Of course, we consider equally solid or liquid surfaces of satellites (“moons”) orbiting planets. Recent discoveries of large numbers of exoplanets and theoretical progress suggests that “rocky” planets have sizes of a

fraction of the Earth up to perhaps two Earth diameters. Larger objects would accumulate a huge mass of gas during their formation process around their host stars and grow to Jupiter-like or Neptune-like gas giants.

But then, what chemicals do we need on the surface of a rocky planet, and what liquids? All terrestrial life must have access to water for metabolism and reproduction. We believe that water does not play this dominant role by chance; water has a number of physical and chemical properties that make it ideal for a life-forming environment; first and foremost, it is a “polar” solvent that can dissolve the requisite polar molecules for life. Second, water is very abundant in the universe, is easily formed and transported. Water abounds on solar-system planets (Earth, Mars) and the many icy moons of the outer planets although mostly in frozen form. Methane, forming rivers and lakes on Saturn’s moon Titan, may be an alternative solvent, but only at extremely low temperatures where chemical reactions are very slow.

The Habitable Zone

Motivated by the importance of liquid water for probably most life forms, astronomers are focusing their search on planets orbiting their host star in the so-called habitable zone. Planets in this zone have the right distance from the host star to develop surface temperatures at which water can persist in liquid form if a suitable atmosphere is present (Kasting et al., 1993: 108).

It is relatively straightforward to calculate the surface temperature of an *atmosphere-free* rocky planet at some given distance from its star; the energy balance between incoming, mostly visible light and the outgoing infrared radiation plus the visible radiation directly reflected back to space by clouds and the surface material determine the surface temperature. Such calculation would predict a temperature of about -18 degrees C on average for the Earth’s surface, and a comfortable 27 degrees for Venus. However, planetary atmospheres can strongly influence these temperatures. Greenhouse gases such as carbon dioxide or methane, but also water vapor, may rise temperatures to acceptable levels even for planets that are relatively distant from the star and would otherwise be too cold

for liquid water; conversely, greenhouse gases can lead to a temperature runaway for planets too close to the star so that surface life becomes impossible; on Venus, for example, a dense carbon dioxide atmosphere heats the surface to 450-500 degrees C.

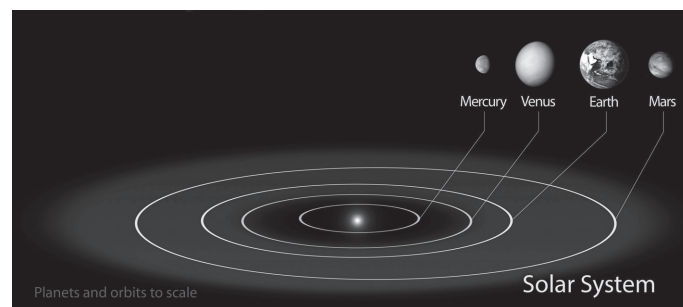


Fig. 1: The habitable zone (green ring), defining the distance from the Sun (or any host star) at which planets could potentially host liquid water on their surfaces. The Earth lies in the midst of the habitable zone, Mars just inside its outer border, while Venus is located slightly too close to the Sun. (Credit: NASA/Ames/JPL-Caltech)

The Earth’s clement climate profits greatly from the more moderate effects of greenhouse gases. The present-day Earth’s average surface temperature of 15 degrees (as opposed to -18 degrees without atmosphere) can be well explained by greenhouse gases. The appropriate habitable zone around a star is therefore difficult to determine because it depends on many poorly understood effects of greenhouse gas admixtures, but also on the presence of clouds or the water reservoir of the planet, noting that water itself acts like a greenhouse gas once in vapor form. To the best of our current knowledge, the habitable zone around our Sun ranges from a region between the orbits of Venus and Earth out to somewhat beyond Mars; therefore, indeed two solar-system planets are considered conducive to life or “habitable” even if liquid water does not exist on present-day Mars because its atmospheric pressure happens to be slightly too low.

Habitable zones can equivalently be computed for stars other than the Sun. Not surprisingly, smaller, fainter stars of lower mass than our Sun have habitable zones much closer in, while somewhat more massive, brighter stars will have them further out.

The central star

The discussion in the previous section makes it evident that we have to consider the properties of the central star to assess habitability. We will, however, find that this entails a much larger range of physical mechanisms relevant to habitability than the mere intensity of starlight. Let's first look at the evolution of a star.

After a turbulent early life as a newborn protostar, the Sun settled as an ordinary star, a so-called main-sequence star, once it started burning hydrogen in its core about 4.5 billion years ago. In this state, the Sun is guaranteed to keep a relatively stable total radiation output for about 10 billion years. The lifetime of this most important stable phase differs for stars with different masses. A star with a mass half that of the Sun lives a long 48 billion years while a star 1.6 times heavier than the Sun is stable for a mere 1.5 billion years (Lang, 1999). Such a short lifetime may set serious constraints to the formation and evolution of life: on Earth, life probably started only roughly 1 billion years after the Sun entered its main-sequence life. But even the very long lifetime of a low-mass star may have its problems, as we will see below.

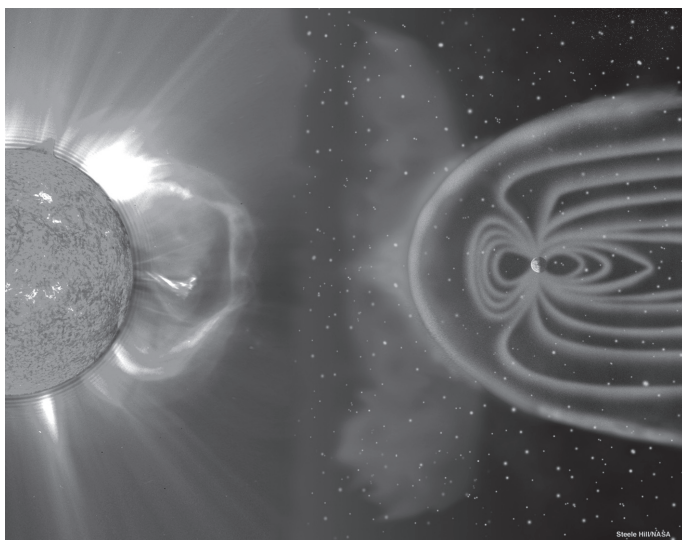


Fig. 2: Interactions between a planet and its host star are crucially important for habitability, involving stellar radiation, stellar winds, planetary magnetospheres and atmospheres. (Credit: Steele Hill/NASA)

The Faint Young Sun Paradox

More detailed calculations show that the star's central nuclear energy source becomes slightly more efficient with time so that the Sun has in fact gradually brightened during the past 4.5 billion years; at the epoch of life formation on Earth, it was some 20-30% fainter than now (Sackmann & Boothroyd, 2003: 1024). This apparently modest difference in solar energy influx in fact poses one of the major problems in current habitability research. An atmosphere of the type suspected for the young Earth, and definitely the present-day atmosphere, would not have succeeded in keeping the average Earth's surface temperature above the freezing point during the first 2.5 billion years of its life; the requisite biochemical reactions would therefore not have started forming life. Geological evidence and the simple fact of much earlier life formation suggest otherwise, however (Feulner, 2012: RG2006). The Earth was probably rather warm, and evidence for liquid water in those epochs abounds. Even more strikingly, Mars at its larger distance from the Sun shows very clear evidence for liquid water having run on its surface at those young ages.

A number of solutions have been proposed for this "Faint Young Sun Paradox". Most popular are different admixtures of efficient greenhouse gases that may have kept the atmosphere sufficiently warm. Larger amounts of carbon dioxide would be the easiest explanation, but geological evidence in minerals argues against the required amounts. Other greenhouse gases such as ammonia or methane suffer from their sensitivity to destruction by ultraviolet sunlight, or the formation of cooling haze layers. A number of further gases have been considered, without fully satisfactory conclusion so far. Alternatively, a lower reflectivity ("albedo") of the Earth's surface may have helped warming, for example owing to a lower land coverage, but effects due to clouds may then again need special consideration. Clouds can be cooling if they are low-lying, while they can trap infrared radiation when they are icy and at high altitude, thus warming the atmosphere (Rondanelli and Lindzen, 2010: D02108).

A more radical hypothesis assumes that the young Sun was slightly more massive than now. Because more massive stars are more luminous, the higher mass would balance

the smaller energy production efficiency of the young Sun; the excess mass would be gradually lost in a strong stellar wind that eventually declines to the more modest solar wind now blowing from the Sun (Sackmann & Boothroyd, 2003: 1024). Wind mass loss rates a thousand times larger than now would be required, however – but up to the present day, there is no evidence for the existence of such strong winds from solar-like stars.

The luminosity of the Sun will further increase in the next following 5 billion years, to about three times the present level. With it, the habitable zone also evolves, gradually moving to larger distances from the Sun. A planet may therefore drop out of the zone as was likely the case with young Venus, or move into it as was probably the case for Mars. The most favorable distances from the star are those that remain in the habitable zone for a maximally long time.

High-energy radiation

A very different story unfolds when we look at other wavelengths of the electromagnetic spectrum. Although the Sun and other stars radiate most of their energy in the visible and near infrared range, the shorter-wavelength ultraviolet and X-ray emissions are crucially important for photochemical reactions, ionization and heating of the upper atmospheres of planets.

Ultraviolet radiation from solar-like stars originates partly from the solar or stellar surface or “photosphere” that also emits the visible light, but partly also from gas heated by strong magnetic fields in the next higher solar atmospheric layer, the chromosphere and its adjacent transition region, where temperatures reach about ten thousand to hundred thousand degrees. Magnetic fields irregularly distributed around sunspots change on time scales of minutes to days, and so does the ultraviolet radiation. Similar things hold for the even more energetic X-rays that are radiated by the million-degree corona of the Sun and that may often burst in flares when the energy release explosively increases for minutes to hours.

From comparison samples of stars with well-measured, different ages, we know that magnetic activity is strong

in young stars that rotate rapidly and drive a strong internal magnetic dynamo. Stars lose some mass in a wind, as mentioned before already; this magnetic wind carries away angular momentum from the star and so lets it spin down. The star’s progressively slower rotation weakens the internal dynamo in turn, producing less magnetic activity, and so the ultraviolet and X-ray emissions decline with time in a rather regular and predictable way. Comparative studies show that the Sun was, when it started its main-sequence life, brighter by 100-1000 times in X-rays and perhaps a few dozen times in the ultraviolet, compared to the present time (Ribas et al., 2005: 680). This should have had profound effects on planetary atmospheres, as we will discuss below. Some lower-mass stars such as M dwarfs keep a very high level of magnetic activity for much longer than our Sun, and this may in fact delay their ability to evolve habitable environments on planets for a long time, perhaps billions of years.

The hot solar/stellar wind alluded to above, made of charged particles immersed in a weak magnetic field, also evolves with time. Indirect measurements indicate that a young star’s wind is much stronger than the Sun’s at present, by perhaps several hundred times (Wood, 2004). Such winds interact with planetary magnetospheres and atmospheres. Furthermore, very frequent “coronal mass ejections” accompanying flares would carry away considerable plasma masses from the stellar corona and thus may enhance the wind flow even further.

The magnetic properties of young stars make their environment much more violent than could be anticipated from the present-day Sun. It is indeed the high-energy radiation and the winds that severely confine habitability on planets even if they reside within their classical habitable zones, as we will discuss next.

Atmospheric chemistry

Ultraviolet radiation (UV) can both heat and chemically modify atmospheric gases. A key example is ozone (O₃), produced from oxygen (O₂) in the atmosphere at about 30 km height by solar UV radiation. This process keeps biologically dangerous UV radiation away from the Earth’s surface. For faint, low-mass, cool dwarf stars, however,

it matters whether or not they are magnetically active. Without magnetic activity, there is essentially no UV radiation because the cool photosphere does not contribute to it; but on the other hand, M dwarfs can be extremely magnetically active for a very long time, so they may drive similar ozone layers on their planets (Grenfell, 2014: 66). Stellar activity also ejects high-energy particles or “stellar cosmic rays” that break up gases like nitrogen (N_2) to form molecules NO_x that in turn destroy ozone. Other molecules are also sensitive to the visible and the ultraviolet radiation of the star, and specifically to their ratio. This is very relevant in the search of biosignatures on exoplanets, that is, molecules possibly indicating the presence of life although they may also be altered by UV radiation in the upper atmospheres

Atmospheric escape

Radiation with wavelengths shorter than about 100 nanometers, i.e., “extreme-ultraviolet” and X-ray radiation, is absorbed in the upper planetary atmospheres, namely at about 100 km height for the Earth. Absorption of photons, ionization of molecules and subsequent chemical reactions heat those atmospheric layers, additional to the ultraviolet heating mentioned above. Estimates for the fraction of the absorbed energy ending up in heat range from 15 to 60%.

Heating can eventually become strong enough that some molecules and atoms escape into space. This happens when the heat energy in a particle exceeds its binding energy due to the planet’s gravitational attraction; the particle can escape, however, only if its mean free travel distance before colliding with another particle exceeds the scale height of the atmosphere above it. If this is fulfilled, the particle is lost to space. Obviously, the higher the magnetic activity of a young star, the more atmospheric heating and the more efficient this process is. In the most energetic case, not only do some individual particles escape but the entire upper atmosphere begins to expand, flow upward and then get partly lost to space. Depending on the initial atmosphere and the strength and duration of high-level magnetic activity on the star, entire atmospheres may thus be evaporated into space. Water is among the most serious losses for the surface environment; if the atmospheric temperature is high enough to enrich the atmosphere with

water vapor, the water molecules drifting into the higher atmosphere are separated into hydrogen and oxygen atoms by UV light; hydrogen in particular will, in the EUV and X-ray heated zone, rapidly reach escape speed and therefore get lost. Oxygen may be left behind, but with the corresponding hydrogen lost, the initial water molecules are of course also permanently gone.

The youngest stages of planets

Planets form and grow in so-called protoplanetary disks, which are huge gas and dust disks orbiting the youngest stars at ages of only one to a few million years, with sizes larger than the entire solar system. Dust particles coagulate in disks to ever larger grains and accrete the smaller particles, to eventually form bodies with sizes of hundreds to thousands of kilometers. In the course of this growth, they also attract large gas masses from the surrounding disk by their increasing gravitation. Computing the mass of such an accreted atmosphere is challenging as it depends on the dust admixture, the heating of the planet by impacting smaller bodies, or on the formation history and speed of the planetary body itself. The primary atmosphere, or protoatmosphere, forming this way consists predominantly of hydrogen and should easily reach a mass of a few percent of an Earth mass, reaching out to several Earth radii where it merges with the protoplanetary disk gas. These early hydrogen atmospheres may be complemented by volatile-rich atmospheres outgassed from the planetary interiors.

When after a few million years the protoplanetary disk has disappeared as a consequence of planet formation, gas evaporation induced by stellar radiation, or due to mass infall onto the central star, the massive protoatmosphere of the growing planet is directly exposed to the strong stellar high-energy radiation; at this point, atmospheric escape sets in, but the critical question now is whether the planetary body can get rid of its extremely dense hydrogen atmosphere at all. If stellar magnetic activity and therefore X-ray radiation is too weak, the dense gas envelope may remain. Also, if the planet is too massive, escape of the atmosphere may take too long. Detailed calculations indicate that for an Earth-like planet, hydrogen of an amount up to about ten times the hydrogen bound in the Earth’s ocean water may be carried away. While this may sound impres-

sive, the initial protoatmospheres can easily be much heavier, and the loss rates for somewhat more massive planets are smaller, due to gravity.

Planets only a few times more massive than the Earth, so-called Super-Earths, may in fact be unable to get rid of the dense hydrogen envelope, ending up as “mini-Neptunes” consisting of a rocky core and a dense, very extended hydrogen envelope. Such planets stand little chance of ever becoming habitable! Recent calculations show that to get rid of the envelope, the young planet should in fact have a mass roughly in the range of 0.5-1.5 Earth masses and consequently a radius between 0.8 and 1.2 Earth radii. More massive planets remain embedded in their envelopes, and less massive planets may lose even much of their important secondary atmosphere, such as probably happened on Mars, due to lack of gravitation (Lammer et al. 2014: 3225).

Envelope-enshrouded Super-Earths may in fact have been discovered already; several exoplanets with masses only a bit higher than the Earth mass show – as judged from their measured radii – average densities that indicate the presence of a massive atmosphere (Wagner, 2011: 366).

Protecting magnetospheres

Apart from high-energy radiation, solar/stellar particles, in particular the hot plasma winds, also interact with upper planetary atmospheres. In the solar system, this interaction can be well studied for Venus and Mars. The Earth, in contrast, is surrounded by a strong magnetosphere that deflects the wind, thus protecting the atmospheric layers beneath it. However, if a planetary atmosphere is heated sufficiently strongly by highly energetic radiation, it may expand beyond the magnetosphere, in which case direct interaction with the fast particles of the wind becomes important. Among the most important processes occurring here is charge exchange between ionized, energetic solar-wind particles and neutral atmospheric atoms. In this process, the energetic solar-wind particle steals an electron from a neutral atmosphere particle. As an energetic neutral particle, it may now penetrate deeply into the planetary atmosphere, contributing to its heating. On the other hand, the atmospheric particle having lost one of its

electrons is now electrically charged and can therefore be dragged away by electric and magnetic fields in the solar/stellar wind; it thus contributes to atmospheric mass loss. New calculations indicate that this mass-loss mechanism is usually smaller than the evaporation process in young planets discussed earlier but may be important for older planets (Kislyakova et al. 2013: 1030).

Mass-loss through wind interaction may be particularly problematic for planets orbiting close to the star; it has been hypothesized that such planets rotate slowly due to tidal interaction with the nearby star, and thus they generate only weak magnetic fields from their rotation-induced dynamo, exposing their atmospheres directly to the strong wind. Because the habitable zone is closer in for lower-mass stars, wind-induced mass-loss could be particularly severe for planets in their habitable zone. On the other hand, some recent models suggest that dynamos may not require rotation but just internal convection in the planet.

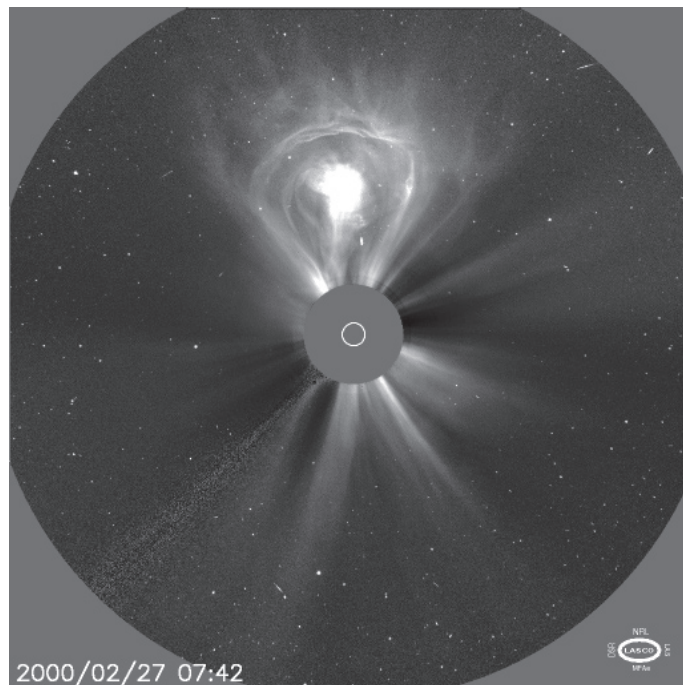


Fig. 3: A coronal mass ejection enhancing the solar particle wind that eventually interacts with the Earth's magnetosphere. (Credit: SoHO/LASCO/ESA/NASA)

Conversely, how could the magnetospheric efficiency be enhanced? Here, an intricate interaction between the

heated, expanding upper atmosphere, the magnetosphere, the stellar wind and stellar radiation comes into play. As the upper atmosphere expands, predominantly in the polar directions of the magnetic field, it is ionized by stellar radiation and stretches and drags the magnetic fields outward, like a planetary wind, while in the stronger equatorial zones, the gas remains trapped in the magnetosphere. The magnetosphere bulges out in the equatorial region, forming a very extended disk-like magnetic structure that prevents the wind from coming too close to the atmosphere (Khodachenko et al. 2012: 70).

Young Venus and Mars: Why did they fail?

Venus with a mass similar to the Earth's and only 30% closer to the Sun than our planet reveals a surface environment that can clearly not be described as habitable in any ways. Not only is the atmospheric temperature extremely high (450-500 degrees C), there is essentially no water left (about 100,000 times less than on Earth). Nevertheless, from planet formation theory, one would expect that both planets started with similar water reservoirs. The water probably came onto both planets by accretion of small bodies originating at larger distances from the Sun, and was then released by outgassing. Initial water vapor pressures could have reached 500 bar (Elkins-Tanton, 2008: 181).

Venus' proximity to the Sun was sufficient to induce a runaway greenhouse in which the atmospheric water vapor released from the warm oceans amplified the greenhouse effect, only to induce more ocean evaporation (Kasting, 1988: 472). Water was dissociated in the upper atmosphere, and hydrogen was lost to space. The escape process is so efficient that in a matter of 10-30 million years after formation of Venus, an equivalent of 2 Earth oceans worth of oxygen or hydrogen (corresponding to a steam atmosphere of 500 bars) would be lost, simply due to the extremely strong extreme-ultraviolet and X-ray radiation of the young Sun.

The Earth's larger distance from the Sun put it into a more favorable situation as the atmosphere cooled down more rapidly, forming an ocean by condensation before the escape process had eliminated all water.

Mars

Mars probably also outgassed a considerable secondary atmosphere with water and CO₂, but again the strong high-energy radiation combined with the low surface gravity efficiently removed much of the atmosphere. Because Mars formed very rapidly, in a matter of a few million years, the impact rate of smaller bodies was very high, keeping much of the protoatmosphere and therefore also water in vapor form (Lammer et al., 2013: 113). Mars also lost its magnetic field – and therefore magnetic protection. Because of its small mass, the interior rapidly cooled and the internal magnetic dynamo ceased to operate.

Astrophysical factors determining habitability

We have addressed some of the relevant astrophysical factors determining planetary habitability. Whether a planet becomes habitable or not depends on a surprisingly large number of astrophysical factors (Güdel et al., 2014). First of all, the planet must reside in a relatively narrow band of radii around the host star, to allow for temperatures under which water can remain liquid. We came across variable stellar radiation that may drag the habitable zone for liquid water past the planetary orbit; but we then also noted that even more importantly, high-energy radiation and winds from the central star induce ionization, heating and atmospheric chemistry. The interplay between these processes leads to atmospheric escape and permanent loss of water. Although a magnetosphere may help, the presence and lifetime of a magnetosphere may again depend on the location of the planet and its mass.

Most severely, we have seen that the planet formation scenario leads to the accumulation of massive protoatmospheres of hydrogen that may be so massive that the young planet resembles Uranus or Neptune, clearly not habitable in any sense familiar to us. If the forming planet is only somewhat heavier than the Earth, such protoatmospheres will never be eroded away by the stellar radiation, and no habitable secondary atmosphere can evolve, while too small planets may lose all their atmospheres easily, including any secondary atmosphere forming by outgassing.

The Earth clearly is in an advantageous situation both with respect to size and location in the solar system.

Many further factors remain to be studied. The stability of a whole planetary system is crucial for a planet to evolve towards and remain as a habitable body. Slight changes in the present-day solar-system orbits of planets, e.g., the orbit of Saturn, can induce perturbations of the Earth's orbit leading to high eccentricities taking the planet to more distant, colder regions, questioning whether the Earth's surface could remain habitable at all. Furthermore, the all-important water initially needs to be brought to Earth from a protoplanetary disk region in which water remains bound in solid bodies, which was not the case in the warm disk region where the Earth formed. Water transport may be due to changes in the early solar-system architecture, migration of bodies, scattering of small bodies and collisions, processes that require further, detailed studies.

Equally, a large array of geophysical factors not discussed here matter. Plate tectonics plays an important role on Earth, in fact in regulating the surface temperature by a cycle involving extraction of carbon dioxide from the atmosphere by rain and release of it through volcanism. A liquid interior of the Earth is required to build up its massive magnetic field protecting the underlying atmosphere from erosion by the solar wind. Also, sufficient planetary mass is required to keep a warm atmosphere bound to the planet.

All these factors have to play together to get habitability on a planet established. Much can go wrong before a planet develops an environment in which life can form or be sustained at all. Whether biological activity will ever set in is yet another question. The right chemical substances need to be present in the right, stable environment. Even then, we do not fully understand what is subsequently required to form life as we know it.

How to look for the habitable planets?

The search for habitable planets is ongoing. While only 20 years ago, the existence of planets outside the solar system was a matter of pure speculation, we now know more than 1700 extrasolar planets whose properties can be studied to

some extent. Most importantly, we know the orbital distances of these planets from their host star, and so can get a first impression on whether liquid water could possibly exist there, depending on the presence of an atmosphere. In a number of cases, we also know either the planet's mass or its radius or both. How do we find new, promising exoplanets?

A common method, and in fact the method that the group in Geneva used for the first discovery of an exoplanet around a solar-like star announced in 1995 (Mayor and Queloz, 1995: 355) uses spectroscopy. As a planet moves around its host star, it pushes and pulls on it owing to the mutual gravitational attraction. Although this imposed motion of the star is tiny, it leads to slight displacements of features in the electromagnetic spectrum of the star. By following the duration and amount of the periodic spectral motion, the orbit period of the planet around its star and an estimate of the planet's mass can be obtained. Several groups across Europe are leading this methodology.

Another technique tries to catch a planet that happens to move in front of the star in its orbit, producing a slight shadowing of the starlight for a short time. While the planet's orbit must be correctly aligned to produce such a "stellar eclipse", it readily provides a good estimate of the planet's radius. Europe's dedicated CoRoT mission took the lead in this method from space, followed by NASA's Kepler mission. Complementing radius measurements with mass estimates from the first method, one can even assess the average density of the planet, which indicates whether the planet is rocky, or gaseous, or perhaps fully liquid, or rocky with an extended atmosphere.

Direct imaging of exoplanets has succeeded in a few cases although the glaring stellar light usually makes this very challenging; imaging is typically possible only for rather distant planets but provides immediate information about the planet's brightness, from which some assessment of its temperature and radius may be made.

Very precise astrometric methods can be used to see the wobble mentioned for the first method above directly in space. Again, the motion of the host star induced by the orbiting planet is tiny and requires extreme measurement accuracy.

So-called gravitational lensing can also be exploited to detect planets. If a foreground star happens to move, as seen from our viewpoint, across a background star, its gravitational field focuses the background star's light like a lens and enhances it for typically several days during the passage. The light variation indicates the mass of the foreground star. A planet of the foreground star may produce a smaller, secondary signal that analogously provides information on the planetary mass.

What's next?

The study of exoplanets and in particular habitability on exoplanets enters a golden era especially in Europe, involving leading teams across the continent to collaborate in multinational or all-European collaborations. A number of ground-based campaigns to identify ever smaller and more Earth-like planets around stars are ongoing, and new ones are being developed; an outstanding example is the CARMENES project on the Calar Alto Observatory in Spain that will look for small planets around the smallest and coolest stars. The project is led by a consortium of German and Spanish research institutes. A breakthrough in exoplanetary research will come from the largest telescope now planned by the European Southern Observatory (ESO), the *European Extremely Large Telescope*, that will investigate exoplanets using a 39 meter diameter collecting mirror for optical and infrared light –the largest ever built– in conjunction with ultrasensitive instruments in about a decade from now.

A true revolution for exoplanetary habitability will come from space observatories, given their advantage of observing in an atmosphere-free environment. The next European mission fully dedicated to exoplanets will be the European Space Agency's (ESA) CHEOPS satellite, a mission led by Switzerland, with contributions from several European countries. CHEOPS will provide ultra-sensitive observations of "stellar eclipses" by planets and thus infer their sizes; together with their differently measured masses, the average density will be calculated and therefore the rough structure and composition of the planet be assessed. The launch of CHEOPS will take place in 2017. Around the same time, NASA's TESS mission will monitor large parts of the sky to detect new exoplanets as well.

The GAIA satellite of ESA, aimed at measuring positions, motions and other properties of millions of stars of our galaxy, will also indirectly discover a large number of exoplanets around other stars. The satellite has recently been launched and is already obtaining data.

Only one year after CHEOPS, the giant James Webb Space Telescope (JWST) with its suite of four instruments will be launched, obtaining extremely sensitive infrared spectra in which atmospheric constituents of planets crossing the stellar disk can be determined. Europe is significantly contributing to JWST through ESA, both in instrumentation and by providing the launcher, an Ariane V rocket.

Finally, in 2024, ESA plans to launch the large PLATO mission that will observe one million stars in the solar neighborhood to obtain an unprecedented inventory of planets. One of PLATO's major specific goals is to discover numerous habitable exoplanets around sun-like stars. This will be the time to find out if our solar system is special, or perhaps even unique, or if planets like the Earth abound in the universe.

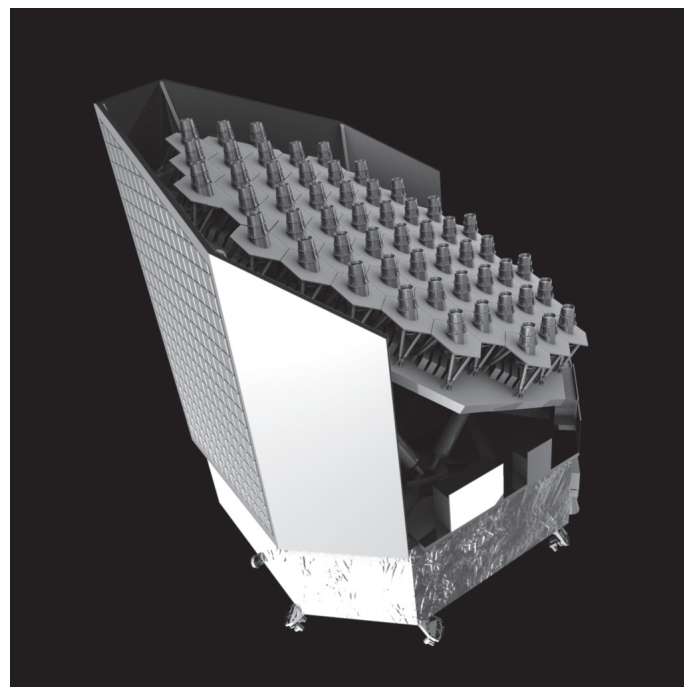


Fig. 4: Concept for the PLAnetary Transits and Oscillations of stars (PLATO) mission of ESA, to be launched in 2024; it will observe a million stars to detect new exoplanets, in particular habitable planets around solar-like stars.

References and Further Reading

- FEULNER, Georg (2012) "The faint young Sun problem", *Reviews of Geophysics*, 50, CiteID RG2006.
- ELKINS-TANTON, Linda T. (2008) "Linked magma ocean solidification and atmospheric growth for Earth and Mars", *Earth Planet. Sci. Lett.*, 271, pp. 181-191.
- GRENFELL, John L., et al. (2014) "Sensitivity of biosignatures on Earth-like planets orbiting in the habitable zone of cool M-dwarf stars to varying stellar UV radiation and surface biomass emissions", *Planet. Space Sci.*, 98, pp. 66-76.
- GÜDEL, Manuel, et al. (2014) "Astrophysical Conditions for Planetary Habitability". In *Protostars and Planets VI*, in press.
- KASTING, James F. (1988) "Runaway and moist greenhouse atmospheres and the evolution of earth and Venus", *Icarus*, 74, pp. 472-494.
- KASTING, James F.; WHITMIRE, Daniel P.; REYNOLDS, Ray T. (1993) "Habitable Zones around Main Sequence Stars", *Icarus*, 101, pp. 108-128.
- KASTING, James F.; CATLING, D. (2003) "Evolution of a Habitable Planet", *Annu. Rev. Astron. Astrophys.*, 41, pp. 429-463.
- KHODACHENKO, Maxim L., et al. (2012) "Magnetospheres of "Hot Jupiters", *Astrophys. J.*, 744, pp. 70-86.
- KISLYAKOVA, Kristina G., et al. (2013) "XUV-Exposed, Non-Hydrostatic Hydrogen-Rich Upper Atmospheres of Terrestrial Planets. Part II: Hydrogen Coronae and Ion Escape", *Astrobiol.*, 13, pp. 1030-1048.
- LAMMER, Helmut, et al. (2013) "Outgassing History and Escape of the Martian Atmosphere and Water Inventory", *Space Sci. Rev.*, 174, pp. 113-154.
- LAMMER, Helmut, et al. (2014) "Origin and loss of nebula-captured hydrogen envelopes from 'sub'- to 'super-Earths' in the habitable zone of Sun-like stars", *Mon. Not. Roy. Astron. Soc.*, 439, pp. 3225-3238.
- LANG, Kenneth (1999) *Astrophysical Formulae*, New York: Springer.
- MAYOR, Michel; QUELOZ, Didier (1995) "A Jupiter-mass companion to a solar-type star", *Nature*, 378, pp. 355-359.
- RIBAS, Ignasi; GUINAN, Edward F.; GÜDEL, Manuel; AUDARD, Marc (1995) "Evolution of the Solar Activity over Time and Effects on Planetary Atmospheres", *Astrophys. J.*, 622, pp. 680-694.
- RONDANELLI, Roberto; LINDZEN, Richard S. (2010) "Can thin cirrus clouds in the tropics provide a solution to the faint young Sun paradox?" *J. Geophys. Res.*, 115, D02108.
- SACKMANN, I.-Juliana; BOOTHROYD, Arnold I. (2003) "Our Sun. V. A Bright Young Sun Consistent with Helioseismology and Warm Temperatures on Ancient Earth and Mars", *Astrophys. J.*, 583, pp. 1024-1039.
- WAGNER, Frank W. (2011) "Interior structure models of solid exoplanets using material laws in the infinite pressure limit", *Icarus* 214, pp. 366-376.
- WOOD, Brian E. (2004) "Astrospheres and Solar-like Stellar Winds", *Liv. Rev. Solar Phys.*, 1, no 2.