MAIN WAYS IN WHICH STARS INFLUENCE THE CLIMATE AND SURFACE HABITABILITY OF THEIR PLANETS

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Abstract. We present a brief overview of the main effects by which a star will have an impact (positive or negative) on the surface habitability of planets in orbit around it. Specifically, we review how spectral, spatial and temporal variations in the incident flux on a planet can alter the atmosphere and climate of a planet and thus its habitability. For illustrative purposes, we emphasize the differences between planets orbiting solar-type stars and late M-stars. The latter are of particular interest as they constitute the first sample of potentially habitable exoplanets accessible for surface and atmospheric characterization in the coming years.

1 Introduction

From birth to death, the evolution of the nature of a planet (i.e. of its interior, surface and atmosphere) is intrinsically linked to that of its host star. Over time, as the nature of a planet evolves, its ability to offer all the necessary conditions for the emergence and development of life will thus evolve.

Based on our experience on Earth, we can identify some necessary (and certainly not sufficient) conditions for life to emerge and develop such as the availability of elements to make complex organic molecules (the famous "CHNOPS": carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur). Liquid water is considered an irreplaceable solvent for habitability (see Forget (2013) and references therein) but while it is known to exist in the interior of a large variety of planetary bodies (Europa, Ganymede, Callisto, Titan, Pluto, Triton, etc.; see Lunine (2017) and references therein), planets that have liquid water on their surface have additional qualities. In fact, a source of low-entropy energy to initiate the irreversible chemical reactions necessary to initiate proto-metabolisms may require

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the exposition of liquid water to stellar radiations (Boiteau and Pascal (2011); Pascal (2016)). In the case of exoplanets, which will remain for a long time out of reach for in-situ exploration, identifying signs of life from interstellar distances (if possible) is likely to require photosynthetic processes and therefore surface liquid water. Lithoautotrophic life able to thrive without stellar light may indeed be unable to modify a whole planetary environment in an observable way (Rossing (2005); Kasting et al. (2014)). In summary, the remote search for habitable planets outside the solar system boils down to the search for planets capable of maintaining liquid water on their surfaces (Kasting et al. (1993); Kopparapu et al. (2013)). This is why we focus in this manuscript on the main effects by which a star will have an impact on the ability of its planets to maintain surface liquid water.

A first naive thing that comes to mind when thinking of the effects that a star may have on the habitability of its planets is the following thought experiment: what would happen to a planet without a star? Science fiction provides ideas of the situations in which this could happen. Although a planet around a black hole seems like an attractive configuration (see e.g., the Interstellar movie), black holes may lead to several warming mechanisms (e.g., by the blueshifting and beaming of incident radiation of the background stars on the planet; see Schnittman (2019)) so that the system is not equivalent to a planet with no star. Better analogues are more likely rogue or free-floating planets, which are wandering planets without star. We now have direct evidence that such planets do exist by collecting the light directly emitted by the youngest, hottest and thus brightest of these objects (Zapatero Osorio et al. (2000); Luhman et al. (2005); Bihain et al. (2009); Delorme et al. (2012); Liu et al. (2013); Dupuy and Kraus (2013)). Although these direct detections are limited so far to massive planets (several times the mass of Jupiter), we know these rogue planets exist in the terrestrial-mass regime too thanks to micro-lensing surveys (Sumi et al. (2011); Mróz et al. (2017)). The most likely formation scenario for these low-mass planets is that they have been ejected from their initial planetary system (see Laskar (1994); Kroupa and Bouvier (2003); Ma et al. (2016) and references therein). Rogue planets can maintain a subsurface ocean by the insulation of their internal heat flux by a thick layer of, for example, ice (Abbot and Switzer (2011)). They can even keep a surface temperature above 273 K under a dense enough H$_2$ atmosphere (Stevenson (1999); Seager (2013)) thanks to the opacity induced by H$_2$-H$_2$ collisions (Borysow (2002); Pierrehumbert and Gaidos (2011); Ramirez and Kaltenegger (2017)). However, in the absence of stellar irradiation and given the challenge of sounding their atmosphere, the habitability of these objects is likely to remain an academic case for some time, unless there is a close encounter with the solar system (Abbot and Switzer (2011)). In short, having a star seems to be a necessary ingredient for a planet to be potentially habitable in a detectable way.

Therefore, we present below a brief overview of the dominant effects by which a star will have an impact on the habitability of planets in orbit around it. A more general list of all the effects that can affect the habitability of planets is provided
in Segura (2018) and Meadows and Barnes (2018) but the main influence comes from the type of the host star, which strongly impacts both the possible lifespan of habitable conditions and our ability to remotely probe planetary environments. Stars more massive than 2.5 M⊙ live less than 1 Gyr and during this short life their luminosity increases dramatically offering conditions compatible for life on their planets for a fraction of this lifetime only. In addition, these massive stars are rare (less than 1 % of the galactic stellar population) and therefore distant while the detection and characterization of exoplanets around these bright stars is very challenging with our current observation techniques. At the other end of the stellar population, M stars represent ~ 75 % of the all stars, live tens to hundreds of Gy with a very stable luminosity (except for their earliest stage, which we will discuss below). Temperate terrestrial planets are frequent around these red-dwarfs and their characterization works far better with today’s instruments. Therefore, along with Sun-like stars, they constitute a potential key population for habitable planets host-stars. To illustrate the ways in which a star may influence the habitability of its planets, we compare throughout the manuscript how the habitability of a planet varies – everything else being kept fixed – depending on whether it is orbiting a sun-like star or a late M-star. For the latter, we chose to use our closest neighbour, the star Proxima Centauri, as the archetype of a late M star (M5.5V, Teff = 3090K) ; firstly because the star has been extremely well documented (see Ribas et al. (2017) and references therein) ; secondly because with the detection of a terrestrial-mass planet in temperate orbit (Anglada-Escudé et al. (2016); Damasso et al. (2020); Suárez Mascareño et al. (2020); Kervella et al. (2020)), it presents one of the most promising systems for our quest to find a habitable planet outside the solar system (Turbet et al. (2016); Lovis et al. (2017); Boutle et al. (2017); Leung et al. (2020)).

The manuscript is organized as follows. Firstly, we review in Section 2 how the spatial and spectral distribution of the incident bolometric (mostly visible and near-infrared) flux affects the habitability of planets. Secondly, we discuss in Section 3 the influence of the far and mid-UV incident flux on the photochemistry, which can further affect the atmospheric composition and thus the habitability of planets. Thirdly, we present in Section 4 how the X and EUV incident radiation can affect atmospheric escape, which can not only affect atmospheric composition but also endanger the very existence of an atmosphere around planets, which has severe consequences for their habitability. Fourthly, we show in Section 5 how the temporal evolution of the bolometric emission of a star (as well as its most energetic part, e.g. the XUV emission) impacts the habitability of planets around it.

2 Influence of the bolometric emission distribution on the climate

In this section, we briefly review how the climate and thus the habitability of a planet can be directly affected by the spectral type of its host star. The first naive effect is that the spectral type of the star changes its luminosity (for example, the luminosity of Proxima Cen is 0.15% that of the Sun) and thus the incident
bolometric flux received by a planet at a fixed distance from the star. However, for a fixed amount of incident bolometric radiation received by the planet, the way in which stellar bolometric emission is distributed spectrally and spatially directly affects the way in which the surface, atmosphere and clouds absorb and reflect incident light, which changes the planet’s surface temperature and thus the conditions of habitability.

The main factor in the spectral distribution of the incident bolometric flux on a planet is the effective temperature of the host star. According to Wien’s law, the cooler the star, the more the bolometric emission is shifted to long wavelengths. As a matter of fact, while the peak of the Sun’s emission ($T_{\text{eff}} = 5780\,\text{K}$) is $\sim 0.47\,\mu\text{m}$, that of Proxima Centauri ($T_{\text{eff}} = 3090\,\text{K}$) is $\sim 1.1\,\mu\text{m}$ (see Fig 1a). Note that due to the spectral shape of the Planck’s law, the median of the stellar emission is shifted to higher wavelengths (compared to the peak). Median of solar emission is $\sim 0.73\,\mu\text{m}$ while that of Proxima Centauri is $\sim 1.4\,\mu\text{m}$ (see Fig 1b).

This has important consequences on a planet, because the surface, the atmosphere and the clouds absorb and/or scatter light differently at different wavelengths. Firstly, spectral variations of the surface albedo can have severe consequences on the stability of liquid water at a planetary surface. Ice and snow albedo are high at short wavelengths, and low at long wavelengths (see Fig 1c). As a result, ice and snow are much more reflective around a sun-like star than around a low-mass star, indicating that planets orbiting solar-type stars are more prone to glaciation (e.g., to be trapped in a snowball state) than planets orbiting low-mass stars (Joshi and Haberle (2012); Shields et al. (2013); von Paris et al. (2013)). More generally, spectral variations in surface albedo, which have now been documented for many types of surface (Hu et al. (2012)), can have a significant effect on a planet’s climate (Madden and Kaltenegger (2020)).

Secondly, Rayleigh scattering by the atmospheric gases can efficiently back-scatter (i.e. reflect back to space) incident stellar light, as illustrated by Keles et al. (2018) for N$_2$-dominated atmospheres, or by Kopparapu et al. (2013) for CO$_2$-dominated atmospheres. Given that the Rayleigh scattering efficiency is $\propto \lambda^{-4}$ (see Fig 1d), the reflection of incoming stellar light by this process is much more efficient around a solar-type star than a low-mass star. Thirdly, direct absorption of incident stellar radiation by gases can vary greatly depending on the type of star. Most common gases lack strong absorption features in the optical wavelengths (Gordon et al. (2017)). This is illustrated in Fig 1e for H$_2$O absorption bands that absorb preferentially in the Proxima Cen emission wavelengths than those of the Sun. By combining the three ingredients mentioned above, we can conclude that – for a given incident flux – low-mass stars warm habitable planets more efficiently than sun-like stars do. This explains why the boundaries of the Habitable Zone are shifted towards lower incident stellar fluxes for low-mass stars (see e.g., Fig 8 in Kopparapu et al. (2013)).

Clouds may also have different properties whether they are exposed to a solar-like or a low-mass star incident radiation. This is illustrated in Figs. 2c, d and e which show the spectra of the key microphysical properties (extinction efficiency, single scattering albedo and asymmetry factor) of water ice clouds for several
Fig. 1. First panel: Incident flux spectra (at the top of the atmosphere) on a planet receiving a total of 1362 W m\(^{-2}\) (i.e. the solar constant on Earth; note that the average flux received on the planet is four times lower, i.e. 340.5 W m\(^{-2}\)). The black curve is based on solar spectra reconstructed from Meftah et al. (2018) for \(\lambda < 3\mu m\) and from Kurucz et al. (1984) for \(\lambda \geq 3\mu m\). The red curve is based on Proxima Centauri spectra reconstructed from Ribas et al. (2017). Second panel: Cumulative incident flux spectra. Third panel: Albedo spectra for snow and water ice from Joshi and Haberle (2012). Fourth panel: Rayleigh scattering cross-section spectrum (in arbitrary units). Fifth panel: Water vapor absorption spectrum, calculated at 200 K, 1 bar, and 0.1% of water vapor.

Whether the presence of a particular type of ice particle or liquid water droplet serves to increase or decrease planetary albedo depends on
Fig. 2. First panel: Incident flux spectra as in Fig. 1, panel 1. Second panel: Cumulative incident flux spectra as in Fig. 1, panel 2. Third panel: Water ice cloud extinction efficiencies for 4 spherical particle sizes (radius of 0.1, 1, 10 and 100µm). Fourth panel: Water ice clouds single scattering albedos (i.e., the ratio of scattering efficiency to total extinction efficiency; single-scattering albedo is equal to 1 if all is due to scattering, and equal to 0 if all particle extinction is due to absorption). Fifth panel: Water ice clouds asymmetry factors (i.e., the mean cosine of the scattering angle; the asymmetry factor is 0 for isotropic radiation and ranges from -1 [negative values mean backward scattering is predominant] to 1 [positive values mean forward scattering is predominant].)

the interplay among extinction efficiency, single scattering albedo and asymmetry factor (Fu (2006)). Clouds made of small particles (e.g., 0.1 µm) are very reflective (asymmetry factor close to 0, single scattering albedo close to 1) for a wide range
of stellar types. While clouds made of larger particles (e.g., $1 \mu m$ and larger) are still highly reflective, they can absorb an appreciable fraction of the incident flux near $1.5$, $2$ and $2.9 \mu m$, which favors warming for planets around low-mass stars. However, overall, it has been shown that the differences between the different types of stars should be relatively small (Kitzmann et al. (2010)).

The main effect by which clouds may affect the climates of habitable planets differently depending on the type of host star is actually related to their spatial distribution. It has indeed been shown that planets orbiting in temperate orbits around low mass stars are prone to be locked in a state of synchronous rotation (Dole (1964); Kasting et al. (1993); Barnes (2017)), for which one planet hemisphere is permanently facing its host star. This has severe consequences for the distribution of the insolation at the TOA (top of atmosphere) or surface of a planet, as illustrated in Fig. 3. While the solar flux is on average relatively evenly distributed on a fast-rotating planet (in particular at large obliquities; see Fig. 3a), the stellar flux received on a synchronously-rotating planet is highly concentrated on one side of the planet (see Fig. 3b). It has been shown that on a planet covered with liquid water, this concentration of stellar flux leads to strong moist convection concentrated in the substellar region, which leads to the formation of a thick layer of reflecting clouds (Yang et al. (2013); Kopparapu et al. (2016); Yang et al. (2019); Fauchez et al. (2020)). These clouds, because of their stabilizing effect (higher temperature means stronger convection, which means more clouds are formed, which means incoming stellar radiation is reflected more efficiently, which cools the planet), have a first-order effect on the climate and habitability of synchronously-rotating planets (Yang et al. (2013); Kopparapu et al. (2016)), and thus on a significant fraction of planets orbiting low mass stars (Leconte et al. (2015)).

3 Influence of the UV emission on the photochemistry

The stellar Hydrogen Lyman-$\alpha$ (at 121.6 nm), far-ultraviolet ($\sim 122-200$ nm) and mid-ultraviolet ($\sim 200-300$ nm) spectral emissions are the main drivers of planetary photochemistry. UV ($\sim 100-300$ nm) photons can in fact photolize (i.e. break) atmospheric molecules, forming radicals capable of generating multiple, complex chemical reactions. These photochemical reactions can deeply affect the atmospheric composition of a planet in a way that depends on initial composition and the total amount and spectral distribution of the UV stellar emission (Yung and Demore (1999)). Eventually, the photochemically-driven destruction or buildup of greenhouse gases in the atmosphere will affect planetary surface temperature and thus the surface habitability of the planet.

Each molecule has an UV absorption cross-section (see Fig. 4c) that, combined with the quantum yield (i.e. the probability that an absorbed photon actually breaks the molecule) and the UV incident spectral flux (Fig. 4a), gives the photolysis rate of the molecule. Depending on the spectral type of the host star, the photolysis rate of atmospheric molecules may – everything else being kept fixed – significantly vary. For illustration, the flux received by a planet (given a fixed
bolometric incident flux) around a low-mass star is 2-3 orders of magnitude lower than that of a planet around a solar-type star in the main spectral region for ozone photodissociation (Hartley band: near ~250 nm), a clue that oxygen and ozone chemistry must operate in a very different way around these two stars. More generally, the flux dichotomy near ~150 nm (relative to its total bolometric luminosity, a M-star emit more photons below 150nm, and much less photons above 150nm) should have strong impact on the photochemistry of planetary atmospheres (Arney et al. (2017); Meadows et al. (2018)).

Although in most atmospheres the impact of photochemistry is primarily to modify the relative abundances of minor species (Rugheimer et al. (2015); Arney et al. (2017); Meadows et al. (2018)), there are some situations where photochemistry can entirely change the composition of an atmosphere (Lorenz et al. (1997); Gao et al. (2015); Luger and Barnes (2015); Hu et al. (2020)).

Finally, photochemistry can also lead to the formation of long carbonated chains suspended in the atmosphere, namely hazes. These radiatively active pho-

Fig. 3. First panel: Zonal annual mean average of the incident flux on an asynchronously-rotating planet receiving a total of 1362 W m$^{-2}$ (i.e. the solar constant on Earth), for four distinct obliquities (0, 23.5, 50, 90°). Second panel: Incident flux on a synchronously-rotating planet (also receiving a total of 1362 W m$^{-2}$) versus substellar longitude. The zonal fluxes were calculated using equation 1 of Nadeau and McGehee (2017).
Fig. 4. First panel: Incident flux spectra (at the top of the atmosphere) on a planet receiving a total of 1362 W m$^{-2}$ (i.e. the solar constant on Earth). The black curve is based on solar spectra reconstructed from Meftah et al. (2018) for $\lambda < 3\mu$m and from Kurucz et al. (1984) for $\lambda \geq 3\mu$m. The red curve is based on Proxima Centauri spectra reconstructed from Ribas et al. (2017). Second panel: Cumulative incident flux spectra. Third panel: UV cross-sections for common atmospheric species ($\text{H}_2\text{O}$, $\text{N}_2$, $\text{CO}_2$, $\text{O}_2$, $\text{O}_3$, $\text{CH}_4$) in terrestrial planetary atmospheres. The cross-sections were taken from Keller-Rudek et al. (2013).

tochemical hazes can deeply affect the climate, either directly by absorbing and reflecting incoming stellar radiation in particular through Mie scattering, often resulting in surface cooling, or either indirectly through feedbacks on photochemistry e.g. by shielding molecules from incident UV radiation (Arney et al. (2017)).

4 Influence of the X-EUV emission on atmospheric loss

X ($< 10$ nm) and Extreme-UV ($\sim 10$-100 nm) stellar emissions, also referred together as XUV, should play a fundamental role in atmospheric escape (Lammer et al. (2003); Tian (2015); Catling and Kasting (2017)). XUV radiation heats the planetary thermosphere up to the exobase, which corresponds to the boundary where the atmosphere transitions from a collisional to a collisionless region. Hydrogen atoms are light enough to be lost to space when reaching the exobase even for a low XUV heating, like that of the Earth. The erosion of the water reservoir through this process is thus not controlled by the XUV flux but by the upward transport and photolysis of $\text{H}_2\text{O}$. Thanks to the cold trap of the tropopause that results in a $\text{H}_2\text{O}$-poor stratosphere, the erosion of Earth’s water reservoir is neg-
ligible. When the XUV flux is sufficiently high, models predict that the heating powers an hydrodynamic expansion of the atmosphere, which is lost through a planetary wind (Johnstone et al. (2019)). Even if hydrogen is the only species likely to be lost hydrodynamically with realistic XUV fluxes, other heavier species (e.g., oxygen) can also be accelerated through collisions and then be lost to space (Johnstone (2020)). In this hydrodynamical regime, the loss rate is controlled by the intensity of the XUV flux (as well as the availability of hydrogen atoms).

XUV incident flux on a planet can strongly vary depending on the type of host star, e.g. between 2-5 orders of magnitude depending on the exact wavelength between solar-type and low-mass stars (see Fig. 4a; for a fixed bolometric incident flux), and depending also on the level of activity of the low-mass star. The total XUV flux of Proxima Cen is $\sim 200$ times higher than that of the Sun (see Fig. 4b), relatively to their total bolometric emission. This means that the atmospheric escape rate can be significantly higher for planets around late M-stars than for Sun-like stars.

Most of stellar-driven atmospheric escape processes including XUV-driven escape (but also driven by the stellar wind drag or the photochemical escape) are also expected to be stronger around low-mass stars than solar-type stars (again, for a given total bolometric flux).

This is important information, given atmospheric escape can change the chemical composition or remove most of all of a planetary atmosphere. In the future, this threat against habitability around active late stars will have to be assessed with both observations/statistics of planetary atmospheres in various XUV/particle irradiation contexts and with robust modeling of the escape processes. The latter will require significant progress in order to treat in 3-D the transition between the fluid expanding atmosphere and the diluted particle regime where kinetic and electromagnetic interactions occurs far from LTE.

5 Influence of the temporal evolution of the stellar emissions

From birth to death, stars evolve in luminosity. They start their life with a super-luminous pre-main sequence phase during which they cool by radiating their initial accretion energy, then evolve on the main sequence during which their luminosity gradually increases as they fuse hydrogen into helium (Chabrier and Baraffe (1997); Baraffe et al. (1998, 2015)) and until they finally die. The duration of each of these two phases (pre-main sequence and main sequence), as well as the evolution of luminosity across them, has major consequences on the climate and habitability of the planets.

Firstly, the duration of the main sequence phase, which is all the longer the smaller the star, plays a key role in the stability of habitability conditions over time. While the duration of the main sequence of the Sun is a few billion years (but can be much shorter for higher mass stars), that of very low mass stars is expected to be much longer than the age of the Universe.

Secondly, while the pre-main sequence phase duration of solar-type stars is very short ($\sim 10$ million years), that of very low mass stars can last for several
hundreds of million years. During this phase, planets are exposed to a much larger incident flux, up to 10 x higher for planets around Proxima Cen (Fig. 5a). Planets that receive today the right incident flux to maintain surface liquid water were likely so hot (in the pre-main sequence phase of their host star) that they experienced a runaway greenhouse (Ramirez and Kaltenegger (2014)), with a thick steam atmosphere (assuming they formed with significant amounts of water) but no surface liquid water.

This is particularly critical for the habitability of planets around such stars, because water in the form of vapor is exposed to strong loss to space (Luger and Barnes (2015); Bolmont et al. (2017); Bourrier et al. (2017); Wordsworth et al. (2018); Bourrier et al. (2017); Johnstone (2020)). Pre-main sequence phase can in fact potentially lead to complete water loss on a planet, depending on the initial reservoir. This is even more critical knowing that XUV heating, i.e. the main process by which the planet is likely to lose its atmosphere and its water, is also much more efficient during the pre-main sequence phase. This stems from the fact that the XUV radiation decreases even more rapidly than bolometric radiation during the pre-main-sequence phase (see Fig. 5b). Note that while the XUV flux emitted by a solar-like star may also have been very high in the past (at least for the fast rotator population; see Tu et al. (2015)), the cumulative XUV radiation (see Fig. 5c) is in general significantly larger around low-mass stars than sun-like stars. Combined with the long pre-main-sequence phase during which the planets are more irradiated than the runaway greenhouse threshold, and therefore during which water is exposed to atmospheric escape, this indicates that water loss is potentially much stronger on planets around late M-stars than around sun-like stars, which can have serious consequences for their habitability.

6 Conclusions

We briefly reviewed the main effects by which a star can have an impact on the habitability of planets in orbit around it. Firstly, spectral and spatial variations of the bolometric (i.e. visible and near-infrared) stellar emission can affect the way a planet’s surface, atmosphere and clouds will absorb or reflect incident light. These changes can affect the climate of a planet (especially the surface temperature) which can thus impact its habitability. Secondly, variations in UV (far and mid-UV) incident fluxes on a planet can drive different photochemistry. This can potentially cause significant changes in the atmospheric composition, and thus the radiation balance of a planet, which can again strongly impact its habitability. Thirdly, cumulative variations in XUV (X and extreme-UV) incident fluxes on a planet can lead to various degrees of atmospheric erosion, potentially leading to dramatic effects (e.g. through the partial or complete loss of the atmosphere and the water) on the habitability.

Taking into account at the same time all the effects by which a star interacts with its planets in the same model, to simulate in a coherent way the evolution of the atmosphere and the habitability of the planets around any type of star, is one of the great challenges of the field. This ambitious scientific objective requires,
Fig. 5. First panel: Temporal evolution of the incident flux (at the top of the atmosphere) on a planet receiving a total of 1362 W m$^{-2}$ (i.e. the solar constant on Earth). The black curve is based on the solar evolution model of Baraffe et al. (2015). The red curve is based on the Proxima Centauri evolution model of Ribas et al. (2017). Second panel: Temporal evolution of the XUV (10-120 nm) incident flux (at the top of the atmosphere) on a planet receiving a total of 1362 W m$^{-2}$ (i.e. the solar constant on Earth). The black curves are based on the XUV emission solar models of Tu et al. (2015) (based on Gallet and Bouvier (2013)) for slow (lower curve) and fast (upper curve) rotator scenarios. The red curves are based on the two evolutionary scenarios of Ribas et al. (2017): (1) Proxima Cen has spent its entire lifetime in the XUV emission saturation regime (lower curve); (2) Proxima Cen was in the saturation regime only for the first $\sim 1.6$ Gigayear of evolution (now aged of $\sim 4.8$ Gigayear). Third panel: Cumulative XUV incident flux starting 10 million years after the star formation, which is around the time the planets are expected to have formed.

among other things, a precise knowledge of the spectral properties (from infrared to XUV radiation) of the star at the time it is observed, but also of how these properties have evolved over time.

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References

Abbot, D. S. and Switzer, E. R. (2011). The Steppenwolf: A Proposal for a Habitable Planet in Interstellar Space. The Astrophysical Journal Letters, 735:L27.

Anglada-Escudé, G., Amado, P. J., Barnes, J., Berdiñas, Z. M., Butler, R. P., Coleman, G. A. L., de La Cueva, I., Dreizler, S., Endl, M., Giesers, B., Jeffers, S. V., Jenkins, J. S., Jones, H. R. A., Kiraga, M., Küster, M., López-González, M. J., Marvin, C. J., Morales, N., Morin, J., Nelson, R. P., Ortiz, J. L., Ofir, A., Paardekooper, S.-J., Reiners, A., Rodríguez, E., Rodríguez-López, C., Sarmiento, L. F., Strachan, J. P., Tsapras, Y., Tuomi, M., and Zechmeister, M. (2016). A terrestrial planet candidate in a temperate orbit around Proxima Centauri. Nature, 536:437–440.

Arney, G. N., Meadows, V. S., Domagal-Goldman, S. D., Deming, D., Robinson, T. D., Tovar, G., Wolf, E. T., and Schwieterman, E. (2017). Pale Orange Dots: The Impact of Organic Haze on the Habitability and Detectability of Earthlike Exoplanets. The Astrophysical Journal, 836:49.

Baraffe, I., Chabrier, G., Allard, F., and Hauschildt, P. H. (1998). Evolutionary models for solar metallicity low-mass stars: mass-magnitude relationships and color-magnitude diagrams. Astronomy & Astrophysics, 337:403–412.

Baraffe, I., Homeier, D., Allard, F., and Chabrier, G. (2015). New evolutionary models for pre-main sequence and main sequence low-mass stars down to the hydrogen-burning limit. Astronomy & Astrophysics, 577:A42.

Barnes, R. (2017). Tidal locking of habitable exoplanets. Celestial Mechanics and Dynamical Astronomy, 129(4):509–536.

Bihain, G., Rebolo, R., Zapatero Osorio, M. R., Béjar, V. J. S., Villó-Pérez, I., Díaz-Sánchez, A., Pérez-Garrido, A., Caballero, J. A., Bailer-Jones, C. A. L., Barrado y Navascués, D., Eislöffel, J., Forveille, T., Goldman, B., Henning, T., Martín, E. L., and Mundt, R. (2009). Candidate free-floating super-Jupiters in the young σ Orionis open cluster. Astronomy & Astrophysics, 506(3):1169–1182.

Boiteau, L. and Pascal, R. (2011). Energy Sources, Self-organization, and the Origin of Life. Origins of Life and Evolution of the Biosphere, 41(1):23–33.

Bois, E., Selsis, F., Owen, J. E., Ribas, I., Raymond, S. N., Leconte, J., and Gillon, M. (2017). Water loss from terrestrial planets orbiting ultracool dwarfs: implications for the planets of TRAPPIST-1. Monthly Notices of the Royal Astronomical Society, 464:3728–3741.

Borysow, A. (2002). Collision-induced absorption coefficients of H₂ pairs at temperatures from 60 K to 1000 K. Astronomy & Astrophysics, 390:779–782.
Bourrier, V., de Wit, J., Bolmont, E., Stamenković, V., Wheatley, P. J., Burgasser, A. J., Delrez, L., Demory, B.-O., Ehrenreich, D., Gillon, M., Jehin, E., Leconte, J., Lederer, S. M., Lewis, N., Triaud, A. H. M. J., and Van Grootel, V. (2017). Temporal Evolution of the High-energy Irradiation and Water Content of TRAPPIST-1 Exoplanets. *The Astronomical Journal, 154*:121.

Boutle, I. A., Mayne, N. J., Drummond, B., Manners, J., Goyal, J., Hugo Lambert, F., Acreman, D. M., and Earnshaw, P. D. (2017). Exploring the climate of Proxima B with the Met Office Unified Model. *Astronomy & Astrophysics, 601*:A120.

Catling, D. C. and Kasting, J. F. (2017). *Atmospheric Evolution on Inhabited and Lifeless Worlds*.

Chabrier, G. and Baraffe, I. (1997). Structure and evolution of low-mass stars. *Astronomy & Astrophysics, 327*:1039–1053.

Damasso, M., Del Sordo, F., Anglada-Escudé, G., Giacobbe, P., Sozzetti, A., Morbidelli, A., Pojmanski, G., Barbato, D., Butler, R. P., Jones, H. R. A., Hambsch, F.-J., Jenkins, J. S., López-González, M. J., Morales, N., Peña Rojas, P. A., Rodríguez-López, C., Rodríguez, E., Amado, P. J., Anglada, G., Feng, F., and Gómez, J. F. (2020). A low-mass planet candidate orbiting Proxima Centauri at a distance of 1.5 AU. *Science Advances, 6*(3):eaax7467.

Delorme, P., Gagné, J., Malo, L., Reylé, C., Artigau, E., Albert, L., Forveille, T., Delfosse, X., Allard, F., and Homeier, D. (2012). CFBDSIR2149-0403: a 4-7 Jupiter-mass free-floating planet in the young moving group AB Doradus? *Astronomy & Astrophysics, 548*:A26.

Dole, S. H. (1964). *Habitable planets for man*.

Dupuy, T. J. and Kraus, A. L. (2013). Distances, Luminosities, and Temperatures of the Coldest Known Substellar Objects. *Science, 341*(6153):1492–1495.

Fauchez, T. J., Turbet, M., Wolf, E. T., Boutle, I., Way, M. J., Del Genio, A. D., Mayne, N. J., Tsigaridis, K., Kopparapu, R. K., Yang, J., Forget, F., Mand ell, A., and Domagal Goldman, S. D. (2020). TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI): motivations and protocol version 1.0. *Geoscientific Model Development, 13*(2):707–716.

Forget, F. (2013). On the probability of habitable planets. *International Journal of Astrobiology, 12*:177–185.

Fu, W. Q. (2006). Radiative transfer. In Wallace, J. M. and Hobbs, P. V., editors, *Atmospheric Science (Second Edition)*, pages 113 – 152. Academic Press, San Diego, second edition edition.

Gallet, F. and Bouvier, J. (2013). Improved angular momentum evolution model for solar-like stars. *Astronomy & Astrophysics, 556*:A36.
Gao, P., Hu, R., Robinson, T. D., Li, C., and Yung, Y. L. (2015). Stability of CO2 Atmospheres on Desiccated M Dwarf Exoplanets. *The Astrophysical Journal*, 806(2):249.

Gordon, I. E., Rothman, L. S., Hill, C., Kochanov, R. V., Tan, Y., Bernath, P. F., Birk, M., Boudon, V., Campargue, A., Chance, K. V., Drouin, B. J., Flaud, J. M., Gamache, R. R., Hodges, J. T., Jacquemart, D., Perevalov, V. I., Perrin, A., Shine, K. P., Smith, M. A. H., Tennyson, J., Toon, G. C., Tran, H., Tyuterev, V. G., Barbe, A., Császár, A. G., Devi, V. M., Furtenbacher, T., Harrison, J. J., Hartmann, J. M., Jolly, A., Johnson, T. J., Karman, T., Kleiner, I., Kyuuberis, A. A., Loos, J., Lyulin, O. M., Massie, S. T., Mikhailenko, S. N., Moazzen-Ahmadi, N., Müller, H. S. P., Naumenko, O. V., Nikitin, A. V., Polansky, O. L., Rey, M., Rotger, M., Sharpe, S. W., Sung, K., Starikova, E., Tashkun, S. A., Auwera, J. V. e., Wagner, G., Wilzewski, J., Wcislo, P., Yu, S., and Zak, E. J. (2017). The HITRAN2016 molecular spectroscopic database. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 203:3–69.

Hu, R., Ehlmann, B. L., and Seager, S. (2012). Theoretical Spectra of Terrestrial Exoplanet Surfaces. *The Astrophysical Journal*, 752(1):7.

Hu, R., Peterson, L., and Wolf, E. T. (2020). O2- and CO-rich Atmospheres for Potentially Habitable Environments on TRAPPIST-1 Planets. *The Astrophysical Journal*, 888(2):122.

Johnstone, C. P. (2020). Hydrodynamic Escape of Water Vapor Atmospheres near Very Active Stars. *The Astrophysical Journal*, 890(1):79.

Johnstone, C. P., Khodachenko, M. L., Lüftinger, T., Kislyakova, K. G., Lammer, H., and Güdel, M. (2019). Extreme hydrodynamic losses of Earth-like atmospheres in the habitable zones of very active stars. *Astronomy & Astrophysics*, 624:L10.

Joshi, M. M. and Haberle, R. M. (2012). Suppression of the Water Ice and Snow Albedo Feedback on Planets Orbiting Red Dwarf Stars and the Subsequent Widening of the Habitable Zone. *Astrobiology*, 12:3–8.

Kasting, J. F., Kopparapu, R., Ramirez, R. M., and Harman, C. E. (2014). Remote life-detection criteria, habitable zone boundaries, and the frequency of Earth-like planets around M and late K stars. *Proceedings of the National Academy of Science*, 111(35):12641–12646.

Kasting, J. F., Whitmire, D. P., and Reynolds, R. T. (1993). Habitable Zones around Main Sequence Stars. *Icarus*, 101:108–128.

Keles, E., Grenfell, J. L., Godolt, M., Stracke, B., and Rauer, H. (2018). The Effect of Varying Atmospheric Pressure upon Habitability and Biosignatures of Earth-like Planets. *Astrobiology*, 18(2):116–132.
Keller-Rudek, H., Moortgat, G. K., Sander, R., and Sørensen, R. (2013). The MPI-
Mainz UV/VIS Spectral Atlas of Gaseous Molecules of Atmospheric Interest. 
*Earth System Science Data*, 5(2):365–373.

Kervella, P., Arenou, F., and Schneider, J. (2020). Orbital inclination and mass 
of the exoplanet candidate Proxima c. *Astronomy & Astrophysics*, 635:L14.

Kitzmann, D., Patzer, A. B. C., von Paris, P., Godolt, M., Stracke, B., Gebauer, S., 
Grenfell, J. L., and Rauer, H. (2010). Clouds in the atmospheres of extrasolar 
planets. I. Climatic effects of multi-layered clouds for Earth-like planets and 
implications for habitable zones. *Astronomy & Astrophysics*, 511:A66.

Kopparapu, R. K., Ramirez, R., Kasting, J. F., Eymet, V., Robinson, T. D., 
Mahadevan, S., Terrien, R. C., Domagal-Goldman, S., Meadows, V., and Deshpande, R. (2013). Habitable Zones around Main-sequence Stars: New Estimates. 
*The Astrophysical Journal*, 765:131.

Kopparapu, R. K., Wolf, E. T., Haqq-Misra, J., Yang, J., Kasting, J. F., Meadows, V., Terrien, R., and Mahadevan, S. (2016). The Inner Edge of the Habitable 
Zone for Synchronously Rotating Planets around Low-mass Stars Using General 
Circulation Models. *The Astrophysical Journal*, 819:84.

Kroupa, P. and Bouvier, J. (2003). On the origin of brown dwarfs and free-floating 
planetary-mass objects. *Monthly Notices of the Royal Astronomical Society*, 
346(2):369–380.

Kurucz, R. L., Furenlid, I., Brault, J., and Testerman, L. (1984). *Solar flux atlas 
from 296 to 1300 nm*.

Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Bauer, S. J., and Weiss, W. W. 
(2003). Atmospheric Loss of Exoplanets Resulting from Stellar X-Ray and 
Extreme-Ultraviolet Heating. *ApJL*, 598:L121–L124.

Laskar, J. (1994). Large-scale chaos in the solar system. *Astronomy & Astro-
physics*, 287:L9–L12.

Leconte, J., Wu, H., Menou, K., and Murray, N. (2015). Asynchronous rotation of 
Earth-mass planets in the habitable zone of lower-mass stars. *Science*, 347:632– 
635.

Leung, M., Meadows, V. S., and Lustig-Yaeger, J. (2020). High-Resolution Spectral 
Discriminants of Ocean Loss for M Dwarf Terrestrial Exoplanets. *arXiv e-prints*, page arXiv:2004.13731.

Liu, M. C., Magnier, E. A., Deacon, N. R., Allers, K. N., Dupuy, T. J., Kotson, 
M. C., Aller, K. M., Burgett, W. S., Chambers, K. C., Draper, P. W., Hodapp, 
K. W., Jedicke, R., Kaiser, N., Kudritzki, R. P., Metcalfe, N., Morgan, J. S., 
Price, P. A., Tonry, J. L., and Wainscoat, R. J. (2013). The Extremely Red, 
Young L Dwarf PSO J318.5338-22.8603: A Free-floating Planetary-mass Analog
to Directly Imaged Young Gas-giant Planets. *The Astrophysical Journal Letters*, 777(2):L20.

Lorenz, R. D., McKay, C. P., and Lunine, J. I. (1997). Photochemically-induced collapse of Titan’s atmosphere. *Science*, 275:642–644.

Lovis, C., Snellen, I., Mouillet, D., Pepe, F., Wildi, F., Astudillo-Defru, N., Beuzit, J.-L., Bonfils, X., Cheetham, A., Conod, U., Delfosse, X., Ehrenreich, D., Figueira, P., Forveille, T., Martins, J. H. C., Quanz, S. P., Santos, N. C., Schmid, H.-M., Ségransan, D., and Udry, S. (2017). Atmospheric characterization of Proxima b by coupling the SPHERE high-contrast imager to the ESPRESSO spectrograph. *Astronomy & Astrophysics*, 599:A16.

Luger, R. and Barnes, R. (2015). Extreme Water Loss and Abiotic O2Buildup on Planets Throughout the Habitable Zones of M Dwarfs. *Astrobiology*, 15:119–143.

Luhman, K. L., Adame, L., D’Alessio, P., Calvet, N., Hartmann, L., Megeath, S. T., and Fazio, G. G. (2005). Discovery of a Planetary-Mass Brown Dwarf with a Circumstellar Disk. *The Astrophysical Journal Letters*, 635(1):L93–L96.

Lunine, J. I. (2017). Ocean worlds exploration. *Acta Astronautica*, 131:123–130.

Ma, S., Mao, S., Ida, S., Zhu, W., and Lin, D. N. C. (2016). Free-floating planets from core accretion theory: microlensing predictions. *Monthly Notices of the Royal Astronomical Society*, 461(1):L107–L111.

Madden, J. and Kaltenegger, L. (2020). How surfaces shape the climate of habitable exoplanets. *Monthly Notices of the Royal Astronomical Society*, 495(1):1–11.

Meadows, V. S., Arney, G. N., Schwieterman, E. W., Lustig-Yaeger, J., Lincowski, A. P., Robinson, T., Domagal-Goldman, S. D., Deitrick, R., Barnes, R. K., Fleming, D. P., Luger, R., Driscoll, P. E., Quinn, T. R., and Crisp, D. (2018). The Habitability of Proxima Centauri b: Environmental States and Observational Discriminants. *Astrobiology*, 18(2):133–189.

Meadows, V. S. and Barnes, R. K. (2018). *Factors Affecting Exoplanet Habitability*, page 57.

Meftah, M., Damé, L., Bolsée, D., Hauchecorne, A., Pereira, N., Sluse, D., Cessateur, G., Irbah, A., Bureau, J., Weber, M., Bramstedt, K., Hilbig, T., Thiéblemont, R., Marchand, M., Lefèvre, F., Sarkissian, A., and Bekki, S. (2018). SOLAR-ISS: A new reference spectrum based on SOLAR/SOLSPEC observations. *Astronomy & Astrophysics*, 611:A1.

Mróz, P., Udalski, A., Skowron, J., Poleski, R., Kozłowski, S., Szymański, M. K., Soszyński, I., Wyrzykowski, L., Pietrukowicz, P., Ulaczyk, K., Skowron, D., and Pawlak, M. (2017). No large population of unbound or wide-orbit Jupiter-mass planets. *Nature*, 548(7666):183–186.
Nadeau, A. and McGehee, R. (2017). A simple formula for a planet's mean annual insolation by latitude. *Icarus*, 291:46–50.

Pascal, R. (2016). Physicochemical Requirements Inferred for Chemical Self-Organization Hardly Support an Emergence of Life in the Deep Oceans of Icy Moons. *Astrobiology*, 16(5):328–334.

Pierrehumbert, R. and Gaidos, E. (2011). Hydrogen Greenhouse Planets Beyond the Habitable Zone. *The Astrophysical Journal Letters*, 734:L13.

Ramirez, R. M. and Kaltenegger, L. (2014). The Habitable Zones of Pre-main-sequence Stars. *The Astrophysical Journal Letters*, 797:L25.

Ramirez, R. M. and Kaltenegger, L. (2017). A Volcanic Hydrogen Habitable Zone. *The Astrophysical Journal Letters*, 837:L4.

Ribas, I., Gregg, M. D., Boyajian, T. S., and Bolmont, E. (2017). The full spectral radiative properties of Proxima Centauri. *Astronomy & Astrophysics*, 603:A58.

Rosing, M. T. (2005). Thermodynamics of life on the planetary scale. *International Journal of Astrobiology*, 4(1):9–11.

Rugheimer, S., Kaltenegger, L., Segura, A., Linsky, J., and Mohanty, S. (2015). Effect of UV Radiation on the Spectral Fingerprints of Earth-like Planets Orbiting M Stars. *The Astrophysical Journal*, 809(1):57.

Schnittman, J. D. (2019). Life on Miller's Planet: The Habitable Zone Around Supermassive Black Holes. *arXiv e-prints*, page arXiv:1910.00940.

Seager, S. (2013). Exoplanet Habitability. *Science*, 340:577–581.

Segura, A. (2018). *Star-Planet Interactions and Habitability: Radiative Effects*, page 73.

Shields, A. L., Meadows, V. S., Bitz, C. M., Pierrehumbert, R. T., Joshi, M. M., and Robinson, T. D. (2013). The Effect of Host Star Spectral Energy Distribution and Ice-Albedo Feedback on the Climate of Extrasolar Planets. *Astrobiology*, 13:715–739.

Stevenson, D. J. (1999). Life-sustaining planets in interstellar space? *Nature*, 400:32.

Suárez Mascareño, A., Faria, J. P., Figueira, P., Lovis, C., Damasso, M., González Hernández, J. I., Rebolo, R., Cristiano, S., Pepe, F., Santos, N. C., Zapatero Osorio, M. R., Adibekyan, V., Hoidt, J., Sozzetti, A., Murgas, F., Abreu, M., Affolter, M., Alibert, Y., Aliverti, M., Allart, R., Allende Prieto, C., Alves, D., Amate, M., Avila, G., Baldini, V., Bandi, T., Barros, S. C. C., Bianco, A., Benz, W., Bouchy, F., Broeg, C., Cabral, A., Calderone, G., Cirami, R., Coelho, J., Conconi, P., Coretti, I., Cumani, C., Cupani, G., D’Odorico, V.,
Deiries, S., Delabre, B., Di Marcantonio, P., Dumusque, X., Ehrenreich, D., Fragoso, A., Genolet, L., Genoni, M., Génova Santos, R., Hughes, I., Iwert, O., Ferber, K., Knudstrup, J., Landoni, M., Lavie, B., Lillo-Box, J., Lizon, J., Lo Curto, G., Maire, C., Manescau, A., Martins, C. J. A. P., Mégevand, D., Mehner, A., Micela, G., Modigliani, A., Molaro, P., Monteiro, M. A., Monteiro, M. J. P. F. G., Moschetti, M., Mueller, E., Nunes, N. J., Oggioni, L., Oliveira, A., Pallé, E., Pariani, G., Pasquini, L., Poretti, E., Rasilla, J. L., Redaelli, E., Riva, M., Santana Tschudi, S., Santin, P., Santos, P., Segovia, A., Sosnoswska, D., Sousa, S., Spanò, P., Tenegi, F., Udry, S., Zanutta, A., and Zerbi, F. (2020). Revisiting Proxima with ESPRESSO. *arXiv e-prints*, page arXiv:2005.12114.

Sumi, T., Kamiya, K., Bennett, D. P., Bond, I. A., Abe, F., Botzler, C. S., Fukui, A., Furusawa, K., Hearndshaw, J. B., Itow, Y., Kilmartin, P. M., Korpela, A., Lin, W., Ling, C. H., Masuda, K., Matsubara, Y., Miyake, N., Motomura, M., Muraki, Y., Nagaya, M., Nakamura, S., Ohnishi, K., Okumura, T., Perrott, Y. C., Rattenbury, N., Saito, T., Sako, T., Sullivan, D. J., Sweatman, W. L., Tristram, P. J., Udalski, A., Szymański, M. K., Kubik, M., Pietrzyński, G., Poleski, R., Soszyński, I., Wyrzykowski, L., Ulaczyk, K., and Microlensing Observations in Astrophysics (MOA) Collaboration (2011). Unbound or distant planetary mass population detected by gravitational microlensing. *Nature*, 473(7347):349–352.

Tian, F. (2015). Atmospheric Escape from Solar System Terrestrial Planets and Exoplanets. *Annual Review of Earth and Planetary Sciences*, 43:459–476.

Tu, L., Johnstone, C. P., Güdel, M., and Lammer, H. (2015). The extreme ultraviolet and X-ray Sun in Time: High-energy evolutionary tracks of a solar-like star. *Astronomy & Astrophysics*, 577:L3.

Turbet, M., Leconte, J., Selsis, F., Bolmont, E., Forget, F., Ribas, I., Raymond, S. N., and Anglada-Escudé, G. (2016). The habitability of Proxima Centauri b. II. Possible climates and observability. *Astronomy & Astrophysics*, 596:A112.

von Paris, P., Selsis, F., Kitzmann, D., and Rauer, H. (2013). The Dependence of the Ice-Albedo Feedback on Atmospheric Properties. *Astrobiology*, 13:899–909.

Wordsworth, R. D., Schaefer, L. K., and Fischer, R. A. (2018). Redox Evolution via Gravitational Differentiation on Low-mass Planets: Implications for Abiotic Oxygen, Water Loss, and Habitability. *The Astronomical Journal*, 155:195.

Yang, J., Abbot, D. S., Koll, D. D. B., Hu, Y., and Showman, A. P. (2019). Ocean Dynamics and the Inner Edge of the Habitable Zone for Tidally Locked Terrestrial Planets. *The Astrophysical Journal*, 871(1):29.

Yang, J., Cowan, N. B., and Abbot, D. S. (2013). Stabilizing Cloud Feedback Dramatically Expands the Habitable Zone of Tidally Locked Planets. *The Astrophysical Journal Letters*, 771:L45.

Yung, Y. L. and Demore, W. B. (1999). Photochemistry of planetary atmospheres.
Zapatero Osorio, M. R., Béjar, V. J. S., Martín, E. L., Rebolo, R., Barrado y Navascués, D., Bailer-Jones, C. A. L., and Mundt, R. (2000). Discovery of Young, Isolated Planetary Mass Objects in the $\sigma$ Orionis Star Cluster. *Science*, 290(5489):103–107.