

Chapter 14

SETI in Rocky Exoplanets: Narrowing the Search with Climate Models



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Abstract The quest for inhabited worlds beyond the Solar System is focussed on rocky exoplanets, many of which are being discovered via transit and radial-velocity surveys. The detection of life in such planets via atmospheric biosignatures is challenging and ambient conditions that maximize the production and detectability of atmospheric biosignatures should be preferred in the selection of targets for spectroscopic observations. In this presentation we discuss how climate models that predict the temperature distribution on the planetary surface and the absorption properties of the planetary atmosphere can be used to narrow the search for exoplanets able to sustain multicellular organisms and hence, potentially, intelligent life.

14.1 Introduction

The study of the potential distribution of life in the Galaxy is one of the main goals of astrobiology and may provide effective strategies for the search of extraterrestrial intelligence (SETI). Rocky exoplanets are natural candidates in the quest for astronomical environments potentially able to host life. Based on the example of terrestrial life, the emergence of complex, multicellular life is a pre-condition for the development of neural connections, brains and, eventually, intelligent life. For this reason, in the first part of this presentation we discuss the physical conditions that are required to sustain multicellular life of terrestrial type on a planetary surface. We focus, in particular, on the ambient temperature, which plays a key role in the regulation of life processes [1]. Since the detection of life in exoplanets relies on the spectroscopic observation of atmospheric biosignatures [2], we also discuss the temperature limits that may maximize the generation of chemical constituents of

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biological origin. Searching for atmospheric biosignatures is one of the top priorities of exoplanetary observations that will be carried out with the next generation astronomical facilities in space (e.g. JWST) and on ground (e.g. E-ELT). The detection of atmospheric bio-signatures in rocky planets is extremely challenging and requires a careful pre-selection of suitable targets. In turn, this requires a modelization of the surface and atmospheric properties of the planet, starting from the modest amount of experimental data that can be obtained from the observational methods of exoplanets [3]. Modelling the surface conditions is essential to characterize the habitability of the planet and to understand if surface life, if present, can generate atmospheric signatures. Modelling the atmosphere is necessary not only to estimate the impact of atmospheric feedbacks on the climate and habitability, but also to calculate the optical depth of atmospheric biosignatures that could be detected with spectroscopic methods. The modelization of surface and atmospheric properties of exoplanets can be accomplished with the aid of dedicated climate models that we briefly discuss in the second part of this presentation.

14.2 Thermal Limits of Multicellular Life

Life has several requirements that may be used to define criteria of habitability. These requirements include, among others, the existence of suitable energy sources, physical conditions, protection from ionizing radiation, and an appropriate set of chemical constituents. The thermodynamical conditions that allow water to be present in liquid phase on the planetary surface are commonly used to define the liquid-water criterion which, with the aid of climate models, is applied to estimate the extension of the habitable zone (HZ) around planet-hosting stars [4, 5]. The liquid-water criterion provides temperature limits that can be parametrized as a function of surface atmospheric pressure to define a pressure-dependent HZ [6].

Beside its importance for the potential existence of liquid water, the ambient temperature can be used to set thermal limits of habitability based on the temperature dependence of biological processes [7]. Terrestrial life is characterized by thermal limits of survival, metabolism, and reproduction that are specific for different types of organisms [8]. Here we consider the thermal limits of multicellular organisms with active metabolism. We focus on multicellular organisms because they represent a necessary step along the evolutionary pathways that lead to the emergence of life with neural connections and brains, i.e. the type of life which is of interest for SETI. We focus on organisms with active metabolism because this is the only type of life that can generate a detectable chemical imprint in the exoplanetary atmosphere.

Among terrestrial organisms, poikilotherms are of special interest for setting thermal limits of habitability because their internal temperature depends directly on and varies with ambient temperature [1, 7]. Conversely, homeotherms do not provide straightforward limits of ambient temperature because they are able to stabilize their internal conditions over a broad range of external temperatures [9]. Homeotherms are interesting in the context of SETI, because a tight control of the internal body

temperature seems to be essential for the functioning of brains. Since homeotherms emerged from Darwinian evolution of multicellular poikilotherms, we may say that the thermal limits of multicellular poikilotherms are relevant for all multicellular life, including homeotherms.

The approximate thermal limits of multicellular poikilotherms (plants, invertebrates and ectothermic vertebrates) with active metabolism are $0 \leq T(^{\circ}\text{C}) \leq 50$ [8]. Quite interestingly, the same limits are also relevant for the biological production of atmospheric O_2 because the metabolism of the main O_2 producers (cyanobacteria and plants) drops outside this temperature interval [7]. It is hard to overemphasize the role of oxygen in this context, since the aerobic metabolism is much more efficient than anaerobic metabolism and the presence of significant amounts of atmospheric O_2 might be a necessary condition for the emergence of multicellular life in any planet [10].

The thermal limits $0 \leq T(^{\circ}\text{C}) \leq 50$ are more stringent than the liquid-water temperature range commonly adopted in studies of habitability. These stringent limits can be used to narrow the search of optimal targets for the SETI program.

14.2.1 How Universal Are the Thermal Limits of Terrestrial Life?

A comprehensive mechanistic understanding of the effects of temperature on biological processes is still lacking. In spite of this, the physical nature of the main mechanisms of thermal response at work in terrestrial life suggest that the same mechanisms would also be at work in other forms of chemical life.

At the molecular level, there are strong indications that life processes based on genetic and catalytic molecules require the existence of a network of hydrogen-bond interactions [11]. Among cosmically abundant elements and molecules, CNO elements and water have unique capabilities to form molecular groups that can interact via hydrogen bonds. Therefore, the basic aspects of terrestrial biochemistry (CHON elements and water) are likely to be universal for any type of life based on genetic and catalytic molecules.

For water-based life, the water freezing point $T = 0^{\circ}\text{C}$, which is almost independent of the ambient pressure, is likely to be a universal lower bound, because frozen water would hamper the mobility of biomolecules and, in addition, would make impossible for molecular motors [12] to harvest the kinetic energy of Brownian motion [7]. A universal upper bound is set by the temperature at which thermal energy denatures the molecular structures most sensitive to heat. Since intramolecular hydrogen bonds are essential for shaping molecular structures, the low binding energy of hydrogen bonds can be used, in principle, to set universal upper limits to the temperature of life processes [11].

At the supramolecular level, the thermal tolerance must narrow as complexity increases, because the number of molecular structures potentially limiting the

thermal tolerance increases with increasing complexity of the organism. The study of metabolic processes casts light on the supramolecular mechanisms of thermal response, suggesting that aerobic metabolism sets tighter thermal limits than other high-level functions typical of multicellular organisms [13].

The above considerations suggest that any form of multicellular, aerobic life will be characterized by stringent thermal limits due to the combined constraints that originate at the molecular level and at higher levels of structural and functional complexity. A better understanding of these mechanisms may eventually lead to the definition of universal thermal limits for specific forms of life. For the moment, in lack of better indications, we adopt the thermal limits $0 \leq T(^{\circ}\text{C}) \leq 50$, representative of terrestrial multicellular poikilotherms, as a criterion of long-term habitability of complex life outside Earth. The fact that such limits are shared by multicellular poikilotherms emerged from independent evolutionary pathways on Earth is consistent with this assumption.

14.3 Modelling the Surface Temperature of Rocky Exoplanets

Based on the above discussion we use the ambient temperature as a tool for assessing the capability of a planet to host complex life. The surface temperature of exoplanets can be calculated by inserting observational data in dedicated climate models. Unfortunately, only a small amount of data can be measured for individual exoplanets [3]. The data obtained from the transit and radial velocity surveys may include planetary structural parameters (radius, mass), orbital parameters (semi-major axis, eccentricity), and properties of the host star (luminosity, spectral type, chemical composition, and age). Other planetary quantities that impact the climate, but are currently not measurable (e.g. rotation period, axis tilt, geography, surface pressure, atmospheric composition) must be treated as free model parameters.

Climate models for exoplanets must deal with the intrinsic complexity of the climate system, characterized by different components, processes, feedbacks and time scales [14]. In addition, exoplanet climate models must be adapted to simulate conditions which are not treated in Earth climate models. Given these difficulties, a hierarchy of climate models should be employed in exoplanet studies. Models of higher complexity, tested with well-known climates of rocky planets (present Earth, Mars, Venus, paleo-Earth), should be used to validate models of lower complexity. Once properly validated, models of low complexity can be used to explore the huge parameter space that characterizes the stellar, orbital and planetary properties of rocky exoplanets.

Classic studies of the HZ have used single atmospheric column calculations, with a simplified, radiative-convective treatment of the vertical transport and an albedo representative of the mean planetary albedo [4, 5]. With an idealized treatment of the latitudinal energy transport, Energy Balance Models (EBMs) can simulate latitu-

dinal and seasonal variations of the surface temperature [15] and have been applied to studies of planetary habitability [16]. By incorporating single column, radiative-convective calculations and a schematic treatment of the clouds in classic EBMs, one obtains 2D (vertical and latitudinal) models with seasonal dependence of the surface temperature [6, 17]. A refinement of this last type of model is the Earth-like planet surface temperature model (ESTM), which incorporates a physically-based description of the meridional transport validated with models of higher complexity [18]. The ESTM provides fast estimates of the zonal surface temperature, $T_s = T_s(\varphi, t)$, as a function of latitude, φ , and time, t . The temperature distribution predicted in this way can be used to characterize the habitability of exoplanets.

14.3.1 A Temperature-Dependent Index of Complex-Life Habitability

To introduce a quantitative index of habitability we define a temperature interval, (T_1, T_2) , which we consider optimal for the maintenance of multicellular life and the production of atmospheric biosignatures. From a modelization of the zonal surface temperature, $T_s = T_s(\varphi, t)$, such as that provided by the ESTM, we then calculate a habitability function

$$H(\varphi, t) = \begin{cases} 1 & \text{if } T_1 \leq T_s(\varphi, t) \leq T_2 \\ 0 & \text{otherwise} \end{cases} . \quad (14.1)$$

By averaging $H(\varphi, t)$ in φ (weighting latitude zones according to their area) and t (over one orbital period), we obtain the index of mean planetary habitability

$$h = \frac{\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\varphi \int_0^P dt [H(\varphi, t) \cos \varphi]}{2P} . \quad (14.2)$$

The choice of the temperature limits (T_1, T_2) is a critical point of this operational definition of habitability. Based on the thermal limits for complex life discussed above, we adopt $T_1 = 0^\circ\text{C}$ and $T_2 = 50^\circ\text{C}$ in Eq. (14.1) and we call h_{050} the index calculated from Eq. (14.2) with these limits. The index h_{050} , normalized between 0 and 1 by construction, provides a quantitative estimate of the mean planetary habitability for multicellular life. Moreover, the temperature range that maximizes h_{050} is the same range in which terrestrial cyanobacteria and plants produce oxygen [7]. This is important because oxygen is a potential atmospheric biosignature and is probably necessary for the emergence of complex life [10].

In addition to the above considerations, driven by biological arguments, the index h_{050} presents an important advantage in terms of climate calculations: the low value of the upper thermal limit, $T_2 = 50^\circ\text{C}$, avoids the necessity to perform climate calculations in a regime of high temperatures that may lead to the onset of runaway

greenhouse instability [4]. This regime, characterized by high water vapour content, is extremely hard to model even with state-of-the-art, 3D climate models [19].

14.3.2 *Applications to Studies of Habitability for Complex Life*

By using the methodology described above we can estimate the index h_{050} for a broad range of factors that affect the planetary climate. Studies performed with the ESTM show that the parameters that most heavily impact $T_s(\varphi, t)$ and h_{050} are the insolation, the atmospheric properties (pressure and composition) and the albedo (surface and clouds) [18]. The index h_{050} can be applied to individual exoplanets or to perform statistical studies of exoplanetary habitability.

Kepler-452b is an example of an Earth-size planet ($R = 1.63 R_{\oplus}$) in the HZ of a sun-like star [20] that has been studied with the ESTM [21]. Under the assumption of a rocky-dominated nature, $T_s(\varphi, t)$ and h_{050} were computed for a broad range of climate factors. Even if the insolation of Kepler-452b is only 10% larger than that received by Earth, the constraints of habitability for complex life are very stringent. For most choices of parameters, habitable solutions with $h_{050} > 0.2$ are only found if the CO_2 partial pressure is $p\text{CO}_2 < 0.04$ bar. At this limiting value of $p\text{CO}_2$, the planet is habitable only if the total pressure is $p < 2$ bar. In all cases, the habitability index h_{050} drops to zero if the orbital eccentricity is $e > 0.3$. Changes of rotation period and axis tilt affect h_{050} due to their impact on the equator–pole temperature difference, which affects the possible existence of polar caps. Variations of h_{050} resulting from the luminosity evolution of the host star were estimated with the aid of stellar evolutionary tracks [22]. Only a small combination of parameters yields habitability-weighted lifetimes > 2 Gyr, sufficiently long to develop atmospheric biosignatures still detectable at the present time [21]. This study illustrates the importance of exploring the parameter space of climate factors in order to assess the potential of individual planets to host complex life.

Thanks to the flexibility of the ESTM, it is possible to run a large number of climate simulations and perform statistical studies of habitability. An example of this statistical approach is the study of the bistability of the planetary climate as a function of the initial conditions of the simulations. An intriguing result of this type of study is that the planetary conditions that support climate bistability are remarkably similar to those required for the sustenance of multicellular life on the planetary surface [23]. The statistical approach can also be used to build up multi-parameter HZs by calculating h_{050} as a function of the planet insolation, S , and other climate-impacting parameters [7, 24, 25]. At variance with the classic HZ, thanks to the low value of the upper thermal limit ($T_2 = 50^\circ\text{C}$), the inner edge of the complex-life HZ can be calculated without simulating the conditions that drive the runaway greenhouse instability.

A parameter of special interest for building up the HZ for complex life is the atmospheric columnar mass, $N_{\text{atm}} = p/g$, where p and g are the surface pressure and gravitational acceleration, respectively. The atmospheric columnar mass has a strong impact on the climate because it affects the energy transport both along the surface (horizontal transport) and between the surface and the top of the atmosphere (vertical transport). The atmospheric columnar mass also acts as a protective shield for life potentially present on the planetary surface, by absorbing and degrading cosmic rays of stellar or Galactic origin. For a planet with Earth-like characteristics (including the magnetic field), the surface dose of secondary particles of cosmic rays exceeds 100 mSv/year when $N_{\text{atm}} < 300 \text{ g/cm}^2$ [26]. By displaying h_{050} as a function of S and N_{atm} , it is possible to build up an atmospheric mass habitable zone (AMHZ) for complex life [7]. The calculations of the AMHZ can be repeated for different atmospheric compositions, showing the impact of greenhouse gases, such as CO_2 , on the location of the HZ. The AMHZ calculated with the index h_{050} is generally narrower than the classic HZ, providing tight constraints for the search of exoplanets capable of hosting multicellular life. By decreasing N_{atm} , the inner edge of the HZ gets closer to the star due to the decrease of the greenhouse heating of the surface. However, this effect becomes negligible at low values of N_{atm} and below 300 g/cm^2 the only net result is a significant rise of the surface dose of radiation [7, 26].

14.4 Conclusions

By investigating the thermal limits of multicellular life it is possible to introduce an operational definition of complex-life habitability that can be applied to SETI-oriented studies of exoplanets. Based on experimental data of terrestrial life, the temperature interval $0 \leq T(^{\circ}\text{C}) \leq 50$ is suitable for the emergence of complex life and for the biological generation of atmospheric O_2 , a biosignature potentially detectable with spectroscopic observations of exoplanetary atmospheres. With the aid of dedicated climate models, it is possible to predict the surface temperature distribution of rocky exoplanets by combining observational data with a parameterization of the climate factors that are currently unconstrained by observations. By modelling the surface temperature we can assess which range of parameter space is suitable for the sustenance of complex life and the detection of atmospheric biomarkers.

For future applications of this methodology it is desirable to upgrade climate models to be able to simulate a broad range of stellar, orbital and planetary conditions, including the climate impact of biological feedbacks. By adopting a multi-parameter approach to the study of planetary habitability it will be possible to broaden the concept of habitable zone [24, 25, 27]. To assess the universal validity of the temperature limits deduced from the properties of terrestrial life, we need to improve our understanding of the physical mechanisms that govern the thermal response of life processes. Statistical studies of exoplanets with properties suitable to sustain complex life can be applied to study the potential distribution of intelligent life in the Galactic Habitable Zone [28].

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