Potential climates and habitability on Gl 514 b: a super-Earth exoplanet with high eccentricity

L. Biasiotti, P. Simonetti, G. Vladilo, S. Ivanovski, M. Damasso, A. Sozzetti, S. Monai

1 University of Trieste - Dep. of Physics, Via G. B. Tiepolo 11, 34143 Trieste, Italy
2 INAF - Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34143 Trieste, Italy
3 INAF – Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese, Italy

ABSTRACT
The recently discovered super-Earth Gl514b, orbiting a nearby M0.5-1.0 star at 7.6 pc, is one of the best benchmark exoplanets for understanding the potential climate states of eccentric planets. The elongated ($e = 0.45^{+0.15}_{-0.14}$) orbit of Gl514b, which only partially lies in the Conservative Habitable Zone, suggests a dynamically young system, where the spin-orbit tidal synchronization may not have yet occurred up to the present time. In the present work, we use a seasonal-latitudinal energy balance model, EOS-ESTM, to explore the potential impact of both constrained and unconstrained planetary, orbital and atmospheric parameters on the Gl514b habitability, mapped in terms of surface temperature. We test three distinct CO$_2$-dominated atmospheres by varying the CH$_4$ concentration values (0%, 0.1% and 1%) and the total surface pressure. As a general trend, we find that habitable conditions are favoured by high-CH$_4$ and high-pressure regimes. Habitability also increases for high axis obliquities (at least until the appearance of an icebelt), long rotation periods, and high ocean fractional coverage. If the ocean fraction is low, then also the argument of periastron becomes relevant. Our results are robust against changes of the continental distribution. Thus, we conclude that Gl514b can potentially maintain temperate surface conditions with modest seasonal temperature variations under a wide variety of planetary, orbital and atmospheric conditions. Despite no transit have been detected yet, the results found in this work should motivate the community to invest time in future observations.

Key words: astrobiology – planets and satellites: terrestrial planets – planets and satellites: individual: Gl514b – planets and satellites: atmospheres – stars: activity

1 INTRODUCTION

The search for biosignatures in exoplanetary atmospheres is one of the main drivers of present-day astronomical projects. To optimize the use of state-of-the-art, space-born instrumentation, this endeavor requires a careful selection of rocky exoplanets potentially able to host life. To this end, it is essential to supplement observational data with theoretical predictions of surface planetary conditions performed with the aid of climate models.

Traditionally, habitability studies rely on the classic definition of the Conservative Habitable Zone (CHZ, Kasting et al. 1993), and in particular on the updated calculations by Kopparapu et al. (2013). In essence, habitability is defined on the basis of the surface temperature, which must be in the liquid water range. The surface temperature is then calculated using single-column Energy Balance Models (EBMs) for a given atmospheric composition and instellation. Since this class of models deal with quantities averaged over one orbit, latitudinal and seasonal variations of temperature are neglected. More complex models, like seasonal-latitudinal EBMs or computationally intensive Global Circulation Models (GCMs) are needed to investigate a planet which is only partially habitable, either in time or space.

The recently discovered super-Earth planet Gl514b (Damasso et al. 2022), orbiting the nearby (d=7.6 pc) M-dwarf, is one of the most interesting cases to investigate potential climates of planets that radically differ from the Earth. Due to the combination of its relatively large semi-major axis (a=0.422$^{+0.014}_{-0.015}$ AU) and eccentricity ($e=0.45^{+0.15}_{-0.14}$), Gl514b lies part of the time inside the CHZ (about 34% of the orbital period) and the rest of the time beyond the outer edge of the CHZ. The fraction of time inside the optimistic HZ (Kopparapu et al. 2013) is even higher (37.7%), reinforcing the importance of Gl 514 b as a test case for a study of seasonal variations of habitability. This suggests the presence of strong seasonal variations that impact the actual habitability of the planet. Investigating the potential climates of planets that exhibit seasonal episodes of habitability can provide insights into the dynamic nature of planetary habitability and the potential for the support of life in exotic scenarios. In this sense, the study of the habitability of Gl 514 b can be generalized to all those cases in which there are strong excursions of instellation at different phases of the orbit, thus helping to define a “Seasonal Habitable Zone”.

In this work we use an enhanced seasonal-latitudinal EBM featuring a treatment of the meridional energy transport calibrated with 3D
models (Vladilo et al. 2015) and an upgraded treatment of surface planetary properties (Biasiotti et al. 2022), coupled with a physical description of the vertical atmospheric radiative transfer (Simonetti et al. 2022). Thanks to the model computational efficiency and flexibility, we can explore the climate impact of planetary properties unconstrained by observations, treating unknown quantities as free parameters, with the goal to assess how likely is Gl514b to be habitable, at least in a qualitative way, and to generalize our findings to all high-eccentricity super-Earths of astrobiological interest.

This paper is structured as follows. In the next section we discuss the observational data that are relevant for constraining the climate of Gl 514 b. In Section 3 we describe the climate models employed in our analysis. The model parameterization and predictions of climate simulations are presented in Section 4, where we explore how the surface habitability varies in different plausible scenarios of planetary and atmospheric parameters. These results are discussed in Section 5 and the conclusions and implications of this work are summarized in Section 6.

2 SUMMARY OF OBSERVATIONAL DATA

2.1 The host star Gl 514

Gl 514 has been extensively monitored since 2004 and its main properties are summarized in Table 1. Essential information on the photospheric and physical parameters have been derived in the last decade (Turnbull 2015; Stassun et al. 2019). The two most important quantities that affect the planetary energy budget and climate are the absolute luminosity, which determines the installation of the planet, and the energy distribution of stellar photons, which affects the planetary albedo. An M-dwarf star emits a substantial portion of its radiation in the near-infrared wavelengths, a factor that profoundly influences the albedo and climate. Over 90% of the radiation emitted by the M-dwarf star such as Gl 514 occurs at wavelengths longer than 0.7 μm, in contrast to nearly 53% for the Sun (Shields et al. 2013).

2.1.1 The age of Gl 514

The age of the star can be used to estimate the evolutionary state of the planet. Unfortunately, the age is the quantity most difficult to accurately measure in stars (Engle & Guinan 2023). Recently, Damasso et al. (2022) has provided a lower limit to the kinematical age of Gl 514, \( t_\star \geq 0.8 \) Gyr, considering the deviation of its space velocities from that of known young stellar moving groups.

Given the ‘spindown effect’, whereby the star’s rotation period lengthen as they age, it is possible to constrain the age of the star from a measurement of its rotation period. The rotation period of Gl 514 has been estimated adopting distinct methods. Analysis of the spectroscopic activity indices from HARPS spectra yield \( P_{\star,rot} = 28.0_{-2.9}^{+2.9} \) days (Suárez Mascareño et al. 2015). Analysis of CARMENES spectra yields \( 30.8_{-0.3}^{+0.3} \) days using the \( H_\alpha \) line and \( 30.3_{-0.2}^{+0.2} \) days using the CaII infrared triplet (Fuhrmeister et al. 2019). Combining 25 years of observations with the HIRES, HARPS, and CARMENES spectrographs, Damasso et al. (2022) found \( P_{\star,rot} = 30.6_{-0.3}^{+0.3} \) days. From this value and the age-rotation relationship described in Engle & Guinan (2023), we derive an age of \( \sim 3.0 \pm 0.9 \) Gyr. Analysis of TESS photometric data yields a signal with period of \( \sim 2.5 \) days (Damasso et al. 2022; Fetherolf et al. 2023) that could be interpreted either as a transit or as a modulation due to stellar rotation. However, the low signal detection efficiency \( \sim 3.9 \) found by Damasso et al. (2022), and the high value reduced \( \chi^2 \) \( \sim 2.8 \) reported in the TESS stellar variability catalog (Fetherolf et al. 2023) do not support any of these two interpretations.

Also the level of stellar activity is age-dependent since the stellar magnetic field responsible for the activity decreases with time as the star spins down. In this context, an important age estimator for main-sequence stars is the \( R'_{HK} \) index, which measures the chromospheric emission in the cores of the broad photospheric CaII H and K absorption lines (Mamajek & Hillenbrand 2008). Recently, Astudillo-Defru et al. (2017a) measured the \( R'_{HK} \) of 403 M-dwarfs of the HARP sample and derived \( R'_{HK} = -4.879 \) for Gl 514. A similar result was found by Marvin et al. (2023), despite using different methods to measure \( R'_{HK} \) in M dwarfs. Several attempts to establish an \( R'_{HK} \) age relation have been performed (e.g. Barry et al. 1987; Soderblom et al. 1991; Lachaume et al. 1999). Reviewing these works, Mamajek & Hillenbrand (2008) assembled \( R'_{HK} \) data from the literature for young stellar clusters and provided an updated relation (see Eq. 3 therein), which returns \( t_\star \sim 3.5 \pm 1.2 \) Gyr for Gl 514. This value is in accordance with the value derived from the age-rotation relationship.

2.2 The planet Gl 514 b

The analysis of the radial velocity data collected over 25 years indicates that Gl514b has a minimum mass \( M_p \sin i = 5.2 \pm 0.9 \) M\(_\oplus\) (Damasso et al. 2022). To date, no transits of Gl514b have been detected. A search for transit-like signals in the light curves observed by TESS (Ricker et al. 2015) has given negative results (Damasso et al. 2022). Despite the lack of radius measurement, the chance that Gl514b is a rocky super-Earth is high, with a posterior transit probability of 0.63\(^\text{1}\). Indeed, the probability that the orbital inclination \( i \) lies between 30° and 90° is \( \sim 87\% \) (Fischer et al. 2014), meaning that the mass lies within a factor of 2 of the minimum mass, posing the mass \( \geq 0.9 \) M\(_\oplus\). From this value and the gravity, \( g \), that are required for the climate calculations, by means of a mass–radius relationship derived from statistical studies of exoplanets. By inserting \( M_p = 5.2 \) M\(_\oplus\) in the relation derived by Fortney et al. (2007), we obtain \( R_p = 1.57 \) R\(_\oplus\) and \( g = 2.1 \) g\(_\oplus\). Luckily, climate models are robust against small variations in \( R_p \) and \( g \) (see §3). This fact provides confidence in the overall predictive analysis performed in this work.

2.2.1 The orbital eccentricity

Several studies have investigated the critical role of eccentricity on exoplanets’ climates and habitability (e.g., Williams & Pollard 2002; Dressing et al. 2010; Linsermeier et al. 2015; Way & Georgakarakos 2017; Wang et al. 2017; Kane et al. 2021; Damasso et al. 2022). These works generally agree on assuming such worlds habitable, despite the dramatic seasonal changes in the instellation between the periastron and the apoastron. However, they concur that planets located near the outer regions of the habitable zone may enter a globally frozen “snowball” state, posing a threat to their ability to support water-based life (Dressing et al. 2010). Detailed climate studies of highly eccentric planets provide a means for testing these predictions. In this context, Gl514b offers the best chance for such investigations. In fact, among the known exoplanets orbiting around M-dwarfs, only two super-Earths may have an eccentricity as high as Gl 514b:

\(^{1}\) This value has been calculated adopting the formulation given by Stevens & Gaudi (2013) and it is very similar to the geometrical transit probability of 0.5% (Damasso et al. 2022; Damasso & Nardiello 2022).
Wolf 1061 d (\(e = 0.55^{+0.08}_{-0.09}\), Astudillo-Defru et al. 2017b) and, possibly, TOI-1470 c (\(e <0.50\), González-Álvarez et al. 2023) (see Figure 1). GI 514 b periodically traverses the conservative HZ, residing within this zone for nearly 34% of its orbital period (see Fig. 16 in Damasso et al. 2022). The elongated orbit of GI 514 b induces an installation about 7 times stronger than the periastron (0.611 AU) than at the apoaprao (0.231 AU). Since the planet moves slower near the apoaprao than near the periastron, the winter/summer season around the apoaprao can be considerably longer than the summer/winter season around the periastron. Whether these dramatic changes in installation may cause extreme seasonal variations is discussed in Section 4.

### 2.2.2 Long term evolution of planetary properties

The luminosity of the star as well as the boundaries of its CHZ change during its lifetime. The shaded area in light blue in Fig. 2 shows the temporal variation of the boundaries of the CHZ, computed adopting the evolutionary model for a star with a mass of 0.5 Msun, similar to GI 514 (Baraffe et al. 1998). The red bar, plotted for a putative age of \(\sim 3\) Gyr, represents the present-day excursion between periastron and apoaprao, the latter lying well beyond the outer edge of the CHZ. Assuming a modest evolution of the orbital parameters, one can see that in the early stages after planetary formation the planet was predominantly in habitable conditions for a period of a few \(10^7\) yrs. This encourages us to explore to which extent the habitability may persist up to the present time.

Besides the installation, also the orbital eccentricity and planet rotation period vary with time as a result of the tidal interactions with the central star. The high orbital eccentricity of GI 514 b suggests that the system is dynamically young. However, it is hard to constrain the age from this argument, because orbital circularization around low-mass stars is predicted to take place in time scales that range from a few \(10^6\) up to a few \(10^9\) yrs, depending not only on the stellar and planetary parameters, but also on the type of model adopted (Barnes 2017). In any case, the high eccentricity suggests that the age of the system might be closer to the lower bounds of the estimates of \(t_a\).

For the purpose of the climate modelization it is important to understand whether or not GI 514 b is tidally locked as a result of the rotational spin down. To test if the planet lies within the tidal lock limit, \(r_\tau\), we adopted the formula (Peale 1977):

\[
r_\tau \propto K R_P^{1/2} M_P^{-1/6} P_{\text{rot, init}}^{1/3} M_\star^{1/6} \quad (1)
\]

where the coefficient \(K\) depends on the tidal parameters of GI 514 b, such as the dissipation function of the planet, \(Q\), and the tidal Love number, \(k_2\). Accurate determination of these parameters, taking into account the internal planetary structure, is fundamental to characterize the rotational and orbital history (Tobie et al. 2019). In the present work we adopt two values of \(k_2/Q\) that provide a sort of lower and upper limit for \(r_\tau\). One is based on the most accurate measurement derived for the Moon (Dickey et al. 1994), i.e. \(k_2/Q = 0.001136 \pm 0.000016\). For the other one we adopt the dissipation function (Tobie et al. 2019)

\[
Q = 10^{(A+B \alpha)} \times \left(\frac{\eta ref}{\eta ref \eta ref}\right)^\alpha \quad (2)
\]

where the coefficients \(A\) and \(B\) depend on the iron content, \(\delta Fe^2\), \(\eta ref\) is the reference value for the viscosity profile (\(\eta ref = 21\) day), and \(X ref = 5 \times 10^{22}\) Pa s is a reference viscosity in the high-pressure silicate mantle layer, where \(\alpha = 0.3\). For \(\eta ref\) in the range \(10^{16}\) to \(10^{18}\) Pa, typical of a rocky super-Earth, \(Q\) varies from 90 to 360, well above the Earth value (\(Q \sim 12\), Murray & Dermott 1999). These higher values of dissipation factor are appropriate for super-Earths because the rigidity increases due to self-gravitation, suppressing tidal bulges (Erofimsky 2012). Following a similar approach, we estimate \(k_2\) as a function of the planetary mass and iron content adopting the parameterization (Tobie et al. 2019)

\[
k_2(\delta Fe) = k_2^{M_\star}(\delta Fe)^{2} \frac{1 - \left(\frac{g}{g_\oplus}\right)2}{\frac{g}{g_\oplus}2} \times \Delta k_2(\delta Fe) \quad (3)
\]

where \(k_2^{M_\star}\) is the \(k_2\) value for a mass equal to that of the Earth and \(\Delta k_2\) is the correction required to obtain \(k_2\) for masses ranges from 0.1 to 10 \(M_\oplus\). These coefficients can be estimated as a function of iron content using a polynomial fit provided by Tobie et al. (2019).

In this way, adopting \(g = 2.1\ g_\oplus\) for GI 514 b, we obtain \(k_2=0.45\) which, combined with \(Q = 90\), yields \(k_2/Q=0.005\).

Fig. 2 shows how the tidal lock radius, \(r_\tau\), calculated at \(t_a = 3\) Gyr compares with the planet position (\(a = 0.42\) AU), depending on the initial rotation period, \(P_{\text{rot, init}}\), and the adopted value of \(k_2/Q\). Since GI 514 b is more massive than the Earth, it may have accumulated a larger angular momentum, \(L \propto M R^2 w\), at the stage of its accretion, starting its dynamical evolution with a fast rotation. Assuming \(P_{\text{rot, init}} = 0.1\) d, GI 514 b would become tidally locked only after 5 Gyr. We conclude that spin-orbit tidal synchronization did not take place for most of the planet’s life, and perhaps may not have yet occurred up to the present time. For this reason, and due to limitations of the validity of our code, ESTM, at very short and long rotation periods (Vладило et al. 2015; Biasiotti et al. 2022), here we consider rotation periods in the interval 0.5 - 10 days to explore the potential climates of GI 514 b (see next Section). It is worth recalling that zonally averaged models, as ESTM, cannot be applied to tidally locked planets that always expose the same face to their host stars.

Finally, it is worth mentioning that also stellar encounters may play a role in the long term dynamical evolution of the planet orbital parameters. As a matter of fact, in the case of the Solar System, chaotic

---

2 We assume an internal composition similar to that of the Earth, \(\delta Fe^2 = 25\%\).

3 Giant planets in the Solar System have a fast rotation period.
diffusion of rocky planets can be triggered by the perturbations that stellar passages impart on the orbits of giant planets (Kaib & Raymond 2024). Modelling these perturbations in the case of Gl514 b is beyond the scope of the present work.

3 METHODS

The aim of the this Paper is to derive the surface temperature \( T \) of Gl514 b in order to calculate two indexes of partial habitability, \( h \) and \( h_c \), detailed in Vladilo et al. (2015) and briefly described in Sect. 3.3. Apart from the minimum mass of the planet and some of its orbital elements (\( a \) and \( e \)), no other data is currently available about this object. Moreover, \( e \) is subject to a relatively large error, at least with respect to its potential impact on the planet’s climate. As such, studying the climate of Gl514 b is only possible by treating a variety of fundamental but completely unknown planetary (e.g. axis obliquity, rotation period) and atmospheric (e.g. surface pressure, chemical composition) features as free parameters and by performing a parameter space exploration. Below we detail the coupled radiative transfer and climate model employed in this work and the specific parameterizations concerning the surface and cloud properties adopted.

3.1 The ESTM model

The Earth-like planets Surface Temperature Model (ESTM) is a season-al latitudinal EBM with enhanced parameterizations of the horizontal heat diffusion, the cloud radiative properties and ice coverage growth. At its core, ESTM integrates the diffusion equation of energy balance (e.g. North & Coakley 1979; North et al. 1983; Williams & Kasting 1997; Spiegel et al. 2008):

\[
\frac{\partial T}{\partial t} = \frac{1}{\partial x} \left( D (1 - \kappa^2) \frac{\partial T}{\partial x} \right) + O = S (1 - \mathcal{A}) \tag{4}
\]

where \( x = \sin \varphi \). The model converges to a limit cycle after a number of orbits, giving as output a map of \( T \) as a function of the latitude

Figure 2. Shaded area in light blue: temporal evolution of conservative HZ limits (Kopparapu et al. 2013) obtained from the stellar evolutionary tracks of Baraffe et al. (1998). The horizontal arrow shows the apoastron and periapsis of Gl 514 b for a putative age of \(- 3 \) Gyr, whose errors are delimited by the vertical bar. The other shaded areas indicate the tidal lock limit assuming three distinct initial rotation periods for the planet: \( P_{\text{rot,init}} = 0.1 \) (orange), 1 (green) and 10 (pink) days (see Table 2).

### Table 1. Upper: coordinates, spectral classification, and photospheric, physical parameters of Gl 514. Lower: planetary parameters of Gl 514 b.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>M0.5-M1.0 V</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>M1.0 V</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>M0.5 V</td>
<td>4</td>
</tr>
<tr>
<td>distance, ( d ) (pc)</td>
<td>7.617780±0.003175</td>
<td>1</td>
</tr>
<tr>
<td>effective temperature, ( T_{\text{eff}} ) (K)</td>
<td>3728±68</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3707</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3697±157.0</td>
<td>3</td>
</tr>
<tr>
<td>metallic, ([Fe/H]) (dex)</td>
<td>-0.14±0.09</td>
<td>1</td>
</tr>
<tr>
<td>rotation period, ( P_{\text{rot,init}} ) (days)</td>
<td>30.6±0.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>28.0±2.9</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>30.3±0.2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>30.8±0.3</td>
<td>6</td>
</tr>
<tr>
<td>luminosity, ( L_\odot ) (log10(L_\odot))</td>
<td>-1.40±0.1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>-1.39±0.512</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>-1.37119±0.0039</td>
<td>3</td>
</tr>
<tr>
<td>mass, ( M_\odot ) (M_\odot)</td>
<td>0.510±0.051</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>2</td>
</tr>
<tr>
<td>radius, ( R_\odot ) (R_\odot)</td>
<td>0.500±0.047</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.51</td>
<td>2</td>
</tr>
<tr>
<td>age, ( t_\odot ) (Gyr)</td>
<td>&gt;0.8</td>
<td>1</td>
</tr>
<tr>
<td>chromospheric activity, ( \log (R'_H K) )</td>
<td>-4.86 ( ( T_{\text{eff}}, \text{SpT}) )</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>-4.82 ( ( T_{\text{eff}}, \text{SpT}) )</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>-4.88</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 2. Tidal lock radius, \( r_\alpha \), calculated with Eq. 1 for \( \tau_\alpha = 3 \) Gyr. First row: results obtained for \( k_2/Q = 0.0011 \), similar to that derived for the Moon (Dickey et al. 1994). Second row: results obtained for \( Q \) and \( k_2 \) values specific for a super-Earth (see Section 2.2.2).

<table>
<thead>
<tr>
<th>( k_2/Q )</th>
<th>( P_{\text{rot,init}} ) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>( r_\alpha ) (au)</td>
<td>0.0011</td>
</tr>
<tr>
<td>( r_\alpha ) (au)</td>
<td>0.0050</td>
</tr>
</tbody>
</table>
\( \varphi \) and the orbital phase \( t \). Longitudinal variability is neglected and \( T(\varphi) \) is averaged over one rotation period. We summarize each term of the equation starting from the left side:

- the term \( C \) represents the zonal heat capacity. In this work we consider three type of surfaces, namely land, ocean and ice, all of which contribute to the final thermal capacity at each latitude by their cover fraction. As far as the thermal impact of the oceans, in line with previous climate studies performed with EBMs, we account for the short-term thermal impact of oceans by considering the contribution of the mixed layer. Specifically, we adopt a mixed-layer contribution \( (C_{ml}) \) equivalent to the thermal inertia of a 50-meter wind-mixed ocean layer (Biasiotti et al. 2022).
- the diffusion term \( D \) describes the meridional heat transport, which is treated as purely diffusive:

\[
\Phi = -D \frac{\partial T}{\partial \varphi} \tag{5}
\]

where \( 2\pi R^2 \Phi \cos \varphi \) is the net rate of atmospheric heat transport across a circle of constant latitude and \( R \) is the planet radius. In ESTM, \( D \) is a function of the planetary radius and rotational period, the surface pressure and gravity, the mean molecular weight and the absolute humidity. The enhanced efficiency associated with a Hadley cell-like circulation is taken into consideration, as it is the displacement of the thermal equator in planets with non-zero obliquities. We refer the reader to (Vladilo et al. 2015) for a detailed description of the physics behind this formalism;
- the Outgoing Longwave Radiation (\( O \)) represents the thermal radiation emitted to space at each latitude as a function of \( T \). In our model, \( O \) is calculated for a specified set of atmospheric properties (chemical composition, surface pressure, vertical pressure-temperature profile) and for a grid of \( T \) values by EOS, saved in a lookup table and interpolated during calculations by ESTM;
- \( S \) is the instillation, calculated in a set of specified points of the orbit. In this work we integrate Eq. 4 on 24 points.
- The term \( A \) is the planetary albedo at the top of the atmosphere. As for \( O \), ESTM interpolates \( A \) from lookup tables, pre-calculated by EOS on a grid of \( T \), stellar zenith angles \( \varphi \) and surface albedos \( a_{\text{surf}} \). The albedo of clouds is taken into account separately via a simplified parameterization.

The ESTM code has been extensively calibrated and validated using both Earth data (Biasiotti et al. 2022) and the results of sophisticated 3D GCMs (Vladilo et al. 2015). It has already been employed to study the habitability of Kepler-452b (Silva et al. 2017), the Snowball-Temperate climate bistability (Murante et al. 2020) and the climate of the Early Mars (Simonetti et al. 2023). It is also a participant of the Functionality of Ice Line Latitudinal EBM Tenacity (FILLET) Intercomparison Project (Deitrick et al. 2023). Finally, it is worth mentioning that zonally averaged models, as ESTM, cannot be applied to tidally locked planets that always expose the same face to their host stars (Vladilo et al. 2015).

3.2 The EOS model

EOS (Simonetti et al. 2022) is a radiative transfer (RT) model derived from the GPU-accelerated codes HELIOS (Malik et al. 2019) and HELIOS-K (Grimm et al. 2021) which has been validated against other standard RT suites for a wide range of atmospheric chemical compositions. It operates in the two-stream approximation and includes prescriptions for non-isotropic scattering. RT calculations can be carried on either line-by-line or using \( k \)-distribution opacities.

EOS can be operated both "forward", i.e. by specifying \( S \) and retrieving a vertical atmospheric pressure-temperature profile and a \( T \) value, or "backward", i.e. by imposing a profile and a \( T \) and obtaining a \( O \) and a reflectance values as a result. The \( S \) needed to sustain the initially specified \( T \) can then be obtained by considering the energy balance equation for a single atmospheric column: \( O = S (1 - A) \).

In this work, we employed EOS to calculate the RT lookup tables for our seasonal-latitudeal EBM via the "backward" method (Kasting et al. 1993, as e.g. in). \( O \) has been calculated on an evenly spaced grid in \( T \) in the \([160, 360]\) K interval, with a \( 5 \) K step, for each total dry surface pressure \( p_{\text{tot}} \) in the \([1.0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.8, 16.7, 22.0]\) bar set. For \( T \) corresponding to \( p_{\text{tot}} \) higher than the condensation pressure of the main atmospheric gas, \( \text{CO}_2 \), the condensation pressure has been used instead. \( A \) has been calculated for the same \( p_{\text{tot}} \) and \( T \) interval, but using a 20 K step. As for the other two quantities (\( z \) and \( a_{\text{surf}} \)), \( A \) depends upon, we adopted the \([0.45, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95, 1.00]\) cm \(^{-3}\) grids, respectively. We used the spectral line lists available on HITRAN2020 (Gordon et al. 2022) for three gases: \( \text{CO}_2 \), \( \text{H}_2 \text{O} \) and \( \text{CH}_4 \).

The reasons for these choices are discussed in Sect. 3.3. The \( \text{CO}_2 \) absorption lines are modeled following Perrin & Hartmann (1989) and the wings are truncated at 500 cm \(^{-1}\) from the line centre, while the \( \text{H}_2 \text{O} \) and \( \text{CH}_4 \) absorption lines are considered Voigtian and truncated at 25 cm \(^{-1}\). We also included the \( \text{CO}_2 \), \( \text{CO} \) Collision-Induced Absorptions (CIAs) in the 0-750 cm \(^{-1}\) (Gryszka & Borysow 1997, 1998) and 1000-1800 cm \(^{-1}\) (Barnanos & Viganin 1999) ranges and the \( \text{CO}_2 \), \( \text{CH}_4 \) CIAs in the 0-2000 cm \(^{-1}\) range (Wordsworth et al. 2017). Self- and foreign-induced CIAs for \( \text{H}_2 \text{O} \) have instead been calculated using the MT_CKD v3.4 (Clough et al. 1989; Mlawer et al. 2012) model. All the considered species contribute to the atmospheric reflectance via Rayleigh scattering (Sleepe & Ubachs 2005; Wagner & Kretzschmar 2008). Concerning the vertical structure of the atmosphere, we adopted two saturated moist pseudo-adiabatic profiles for the lower and upper tropospheres, where \( \text{H}_2 \text{O} \) and \( \text{CO}_2 \) condensation can respectively occur, and a 15 K isothermal stratosphere. The atmosphere is divided in a number of log-spaced layers, adjusted in order to maintain a constant layer density of 10 per order of magnitude in pressure. The uppermost layer is always at 10 \(^{-5}\) bar.

3.3 The habitability indexes \( h \) and \( h_c \)

For the purpose of this investigation, we derive the fractional habitability index, \( h \), from the latitudinal and seasonal variations of surface temperature, \( T(t, \varphi) \), by adopting the liquid-water temperature thresholds, \( T_{\text{ice}} \) and \( T_{\text{boil}} \), representative of the thermal limits of a habitable environment. The former refers to the lower limit for the presence of liquid water, i.e. 273.15 K, whereas \( T_{\text{vapor}} = T_{\text{boil}}(p_{\text{tot}}) \) is the water boiling point, which depends on the surface pressure. In practice, we calculate the mean fraction of planet surface that is habitable during the orbital period using the relation (Vladilo et al. 2013; Jansen et al. 2019)

\[
h = \frac{\int_{-\pi/2}^{\pi/2} \varphi \, d\varphi \int_0^{P_{\text{rot}}} \cos \varphi \, dt \left[ H(t, \varphi) \right]}{2P_{\text{rot}}} \tag{6}
\]

where \( H(t, \varphi) \) is the habitability function, which is defined as a box-car function, such that \( H(t, \varphi) = 1 \) when \( T(t, \varphi) \in (T_{\text{ice}}, T_{\text{boil}}) \) and \( H(t, \varphi) = 0 \) when \( T(t, \varphi) \notin (T_{\text{ice}}, T_{\text{boil}}) \). In addition to \( h \), we also calculate the continuous habitability index, \( h_c \), by summing the fractional areas of the latitude zones that are continuously habitable during the whole orbital period (see Vladilo et al. 2013). By
construction, $h_c=0$ if all the latitude zones undergo a period of non-habitability during the orbital revolution.

### 3.4 Atmospheric Parameters

Since Gl 514 b receives a lower installation than Earth, we model its atmosphere as CO$_2$-dominated, following the longstanding argument that, on planets colder than Earth, CO$_2$ tends to accumulate due to inefficient removal by silicate weathering (Walker et al. 1981). CO$_2$ is one of the main components of degassed fluids on Earth (e.g., Giggenbach 1996) and likely on other planets (Gaillard & Scaillet 2014) and it is relatively stable against photolysis and non-hydrodynamic atmospheric escape due to its relatively high molecular weight. As such, it is a good candidate as the main greenhouse contributor in exoplanets near the outer edge of the CHZ (Kasting et al. 1993). We also include H$_2$O by setting a constant relative humidity ($RH$) everywhere in the troposphere of 100%. This value is higher than the average $RH$ of Earth (60%, see e.g. Fig. 2 in Brun et al. 2022) but it is usually assumed in the calculation of the outer edge of the CHZ (Kopparapu et al. 2013), thus simplifying the comparison between our results and the literature.

Methane is another important gas that might significantly contribute to the habitability of Super Earths (Ramirez & Kaltenegger 2018), although its effectiveness depends strongly on the Spectral Energy Distribution (SED) of the incoming stellar light. At variance with other reduced species that can enhance the greenhouse effect on a rocky exoplanet (Sagan & Chyba 1997), CH$_4$ is the only one that we empirically observe in high concentrations, namely in the atmosphere of Titan (Catling & Kasting 2017). CH$_4$ can be produced by the serpentinization of mafic and ultramafic rocks by water (Chasefère et al. 2013) and can potentially be maintained at the percent concentration level even if this process happens over a small fraction of the planetary surface (Ramirez & Kaltenegger 2018). There is evidence that serpentinization happens also in very dry environments, such as the present-day Mars (Etiope et al. 2013), thus it is reasonable to assume it can take place on Gl 514 b. On the other hand, at relatively high concentrations (~10%) the formation of anti-greenhouse, reflective organic hazes is expected to happen (Trainer et al. 2006) and further additions of CO$_2$ tends to accumulate due to the mean annual value of $x_cH_2$: 0%, 0.1%, and 1%.

The interval of pressures that we decided to investigate is instead dictated by the maximum greenhouse limit for a CO$_2$-dominated atmosphere. CO$_2$ is an efficient Rayleigh scatterer, which causes $\mathcal{A}$ to increase as a function of $p_{tot}$. Above a given surface pressure threshold $p_{thr}$, this becomes dominant over the greenhouse effect and further additions of CO$_2$ cool, rather than warm, the planet. For Gl 514 b and the case with $x_cH_2=0$, $p_{thr} \approx 17$ bar if $\alpha_{sf} = 0.2$, or ~23 bar if $\alpha_{sf} = 0.38$. Another issue that may arise at high enough $p_{tot}$ is the condensation of CO$_2$ at surface. At 273 K, the condensation pressure of CO$_2$ is 34.7 bar. In order to avoid the complications related to the presence of a dual liquid reservoir (i.e. water and CO$_2$), we set the model to pressures below 13 bars.

### 3.5 Surface properties

EOS-ESTM calculates the value of $\alpha_{sf}$ at each latitudinal zone by averaging the albedo of each of the four types of surfaces treated by the model (i.e. land, ocean, marine ice and land ice) in that zone, properly weighted according to their fractional coverage. Since $\alpha_{sf}$ depends on SED of the star, we cannot use the values derived in Biasiotti et al. (2022) for the Earth-Sun system. Instead, we adopt the results of Shields et al. (2013)$^1$, who calculated theoretical reflectances of several type of planetary surfaces illuminated by the M3-type star AD Leo, which has a spectral distribution similar to that of Gl 514. Specifically, we adopt a land albedo $a_l$ equal to 0.38, which refers to a bare, desert-like surface, an albedo of ice over lands $a_{il}$ equal to 0.5, which refers to a surface totally covered by snow, and an albedo of ice over ocean $a_{io}$ equal to 0.35, that corresponds to a mixture of 62% of blue marine ice and 38% of snow.

The albedo of the oceans ($a_o$) plays an especially important role due to our choice of treating the planet as having a high (0.75) fraction of the surface covered by water. While planetary habitability seems to not strictly require such a high water content, and the biosphere lifetime might even be longer on planets with a smaller surface water reservoir (e.g. Abe et al. 2011; Zsom et al. 2013), we see no particular reason against choosing an Earth-like value for Gl 514 b. Shields et al. (2013) (see Fig. 1 therein) shows that the effect of the host star SED on the albedo of oceans is negligible. Therefore, we stick to the parameterization described in Biasiotti et al. (2022), which is taken from Fujimoto (2007). All the surface albedos depend on $\zeta$.

As far as the ice fractional coverage is concerned, we stick to the prescriptions specified in Biasiotti et al. (2022). The ice cover increases when $T$ decrease following a generalized logistic function calibrated on Earth data and separately for lands and oceans.

### 3.6 Cloud properties

The significance of clouds in the thermal equilibrium of a planet poses a critical challenge for classic EBMs, since no explicit fluid dynamics calculation is carried out. As such, no microphysical properties of clouds can be actually replicated using EBMs, that are instead limited to simplified parameterizations of their spatial distribution and bulk radiative impact on the zonal energy balance. EOS-ESTM adopts a similar approach by modeling clouds in terms of fractional coverage $\alpha_c$, which in turn depends on the type of underlying surface, albedo $a_c$ and OLR forcing $CRE$.

More specifically, we assume that $a_c$ depends on (i) the mean stellar zenith distance of the latitude zone of interest and (ii) the albedo of the underlying surface. The latter dependence is captured by considering the shortwave transmittance coefficient $t$ i.e. the fraction of radiation not absorbed between the cloud top and the surface. The $t$

---

Table 3. Grid of parameters adopted for the simulations. The derived values of planetary albedo are associated to the mean annual value of $\mu = \cos Z = 0.5$, where $Z = 60^\circ$. References: 1 - Shields et al. (2013); 2 - Ding et al. (2021); 3 - Biasiotti et al. (2022).

<table>
<thead>
<tr>
<th>Albedo parameters</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>land albedo, $a_l$ (bare land)</td>
<td>0.38</td>
<td>1</td>
</tr>
<tr>
<td>ice over land albedo, $a_{il}$ (snow)</td>
<td>0.52</td>
<td>1</td>
</tr>
<tr>
<td>ice over ocean albedo, $a_{io}$</td>
<td>0.35</td>
<td>1</td>
</tr>
<tr>
<td>(mixture of 60% snow and 40% blue marine ice)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cloud albedo, $a_c$</td>
<td>0.40</td>
<td>2</td>
</tr>
</tbody>
</table>

---

$^1$ We refer to the broadband planetary albedos indicated in Table 2 and calculated without including Rayleigh scattering, atmospheric gas absorption and clouds.
and CRE parameters scale with $T$ in order to take into consideration, albeit in a simplified way, the different properties of thick intertropical and thin polar clouds.

The values and dependences of $t$, CRE and the cloud cover fractions over land, ocean and ice are kept equal to those presented in Tabs. 7 and 8 in Biasiotti et al. (2022). On the other hand, we adjusted $a_{c}$ in order to take into consideration the difference in the SEDs of the Sun and Gl 514 by means of the following procedure.

First, we convolved the SED of both the Sun and Gl 514 with the average spectral reflectance of the Earth clouds. The spectral reflectance of clouds was taken from existing literature. In particular, we consider the data published by Ding et al. (2021), who computed the overall reflectivity spectrum of Earth clouds without distinguishing between high-, mid- and low-altitude ones (as happens in EOS-ESTM). Second, we compared the two results, finding that Earth-like clouds are $\sim 10\%$ less reflective when illuminated by M-type star, with respect to the solar case. Thus, we adopt $a_{c}=0.40$.

4 RESULTS

The models described in the previous section were applied to explore how the climate and habitability of Gl 514b are affected by different sets of planetary and orbital configurations. For each set of climate simulations we calculate the surface temperature distribution, $T(\varphi, t)$, and the habitability index, $h$, for the three atmospheres described in §3.4.

For each atmospheric composition we vary the surface pressure, $p_{\text{tot}}$, to assess how the climate is affected by changes of the atmospheric column, $N_{\text{atm}} = p_{\text{tot}}/g$. This quantity represents the atmospheric mass per unit surface area and has a strong impact on the climate for two reasons. First, for a given atmospheric composition and in the investigated $p_{\text{tot}}$ interval, the greenhouse effect increases with $N_{\text{atm}}$; in our model this effect is taken into account by the EOS radiative transfer calculations. Second, the efficiency of the atmospheric transport along the planet surface increases with $N_{\text{atm}}$; in our model this effect is accounted for by the diffusion term $D_{o}$, which increases linearly with $N_{\text{atm}}$. It is worth noticing that, as long as Gl 514 b is a rocky Super-Earth, the percent uncertainty in $g$ is small, and does not affect significantly the estimates of $N_{\text{atm}} = p_{\text{tot}}/g$.

Since the atmospheres that we consider are CO_{2}-dominated, we also take into account the possibility that condensation of atmospheric CO_{2} may occur. To this end we adopt the function for the saturation vapor pressure of CO_{2} reported in Kasting (1991). The condensation of atmospheric CO_{2} would drive a collapse of the atmosphere and the formation of CO_{2} ices on the surface. The dashed areas in the figures shown in this section indicate regions of the parameter space where this effect is predicted to take place. If the atmosphere undergoes collapse, the surface habitability is compromised.

4.1 Dependence on planetary parameters

4.1.1 Surface distribution of oceans and continents

EOS-ESTM incorporates planet geography in a schematic way, assigning to each latitude zone a fractional coverage of oceans, $f_{o}$, which implies a fractional coverage of lands, $f_{l} = 1 - f_{o}$. To explore the effects of geography on habitability we first changed the global coverage of oceans, keeping $f_{o}$ constant at all latitudes, and then we fixed the global coverage of oceans, changing $f_{o}$ according to the latitude.

The results of the first test are shown in Fig. 3, where we show the variation of $h$ as a function of $f_{o}$ and $p_{\text{tot}}$. The general trend is that as the coverage of oceans increases: (i) the range of habitable conditions broadens, embracing lower and lower atmospheric pressures; (ii) the habitability tends to rise with increasing CH_{4} content. These trends can be explained as a result of the increasing thermal inertia of the climate system with increasing $f_{o}$. As the pressure increases, the efficient atmospheric diffusion combines with the high thermal inertia of the oceans, yielding year-long habitable conditions despite the relatively low instellation of Gl 514 b. For the model with higher CH_{4} content these effects can be seen in the maps of seasonal-latitude evolution of surface temperature plotted at selected values of ocean cover and surface pressure (Fig. 4). Only at the highest pressure the collapse of the CO_{2}-dominated atmospheres can be prevented in all latitude zones.

For the second test, following Vladilo et al. (2013, 2015), we fixed the global ocean coverage, $f_{o} = 0.7$, and we considered two model geographies: (1) an equatorial continent, and (2) a polar continent.In practice, the case (1) represents a continent located at latitudes within $\pm 25\degree$, whereas the case (2) represents a polar continent at latitudes below $-25\degree$. In Fig. 5 we show how these different types of model geographies introduce modest effects on the mean global annual temperature. Similarly, the mean annual habitability is almost the identical in the two continental configurations at all pressures. However, in the case of the polar continent, the fraction of habitable surface shows little seasonal oscillations, due to the formation of a larger ice cap in the presence of a polar continent. This behaviour is probably due to the combination of two factors: (i) the land has a lower thermal capacity ($C_{l}$=0.1 $10^{6}$ J m$^{-2}$ K$^{-1}$) than the water ($C_{w}$=2.10 $10^{6}$ J m$^{-2}$ K$^{-1}$) and (ii) the albedo of ice over ocean ($a_{cl}$=0.35) is much lower than that of ice over land ($a_{cl}$=0.52).

We conclude that the the global fraction of oceans coverage affects the climate more significantly than the latitudinal distribution of oceans and continents.

Aside from the mean annual values, we are also interested in studying the seasonal $T$ variability, which in our model is directly related to the seasonal habitability of the planet. Since $f_{o}$ impacts the overall thermal inertia of the planet, it plays a crucial role in shaping this value. This can be observed in Fig. 5 by comparing the cases with $f_{o}=0.0$ and $f_{o}=1.0$ at $p_{\text{tot}}$ $\sim$ 6.0 bar. In the former, $\Delta T \equiv T_{\text{max}} - T_{\text{min}}$ $\sim$ 13 K at the tropical latitudes, i.e. $\pm 23\degree$, whereas in the latter it decreases to 3 K. If the ocean fraction is high it completely dominates the planetary heat capacity and, in fact, the effect of $p_{\text{tot}}$ on $\Delta T$ becomes negligible. This is clear if we compare the cases with $p_{\text{tot}}$ $\sim$ 6.0 bar and 3.6 bar, both of which show $\Delta T \sim$ 3 K.

4.1.2 Rotation period

In a rotating planet the Coriolis forces tend to damp the atmospheric energy transport from the equator to the poles, the effect becoming stronger with increasing angular velocity of rotation, $\Omega = 2\pi/P_{\text{rot}}$. In EOS-ESTM this effect is incorporated in the diffuson term, which scales as $\Delta \sim \Omega^{-4/3}$ according to an analytic formulation of the latitudinal transport calibrated with 3D climate models (Vladilo et al. 2015). In Figs. 6, 7 and 8 we show results of climate simulations of Gl 514 b performed by varying $P_{\text{rot}}$ and total pressure, $p_{\text{tot}}$. As a general trend, two effects are visible as the rotation period increases: (i) the planet habitability tends to increase and (ii) the
surface temperature is homogenized, particularly in the high-pressure regime (see top row of Fig. 8). This effect is expected because the habitable belt can be built up at the equatorial zone for \( P_{\text{rot}} < 4.0 \) bar (in the central left panel of the figure). At the other extreme of low rotation periods \( (P_{\text{rot}} = 8 \) days) and \( P_{\text{rot}} > 4.0 \) bar the habitability index is maximized (in the top right panel of the figure). The simulations also show remarkable differences depending on the adopted atmospheric composition. In the model with higher CH\(_4\) content, the planet rotation period has a negligible impact on \( h \), with a general trend of increasing \( h \) with decreasing \( P_{\text{rot}} \) (up to \( \sim 3.5 \) bar). At low CH\(_4\) content, we find an increase in the habitability with increasing \( P_{\text{rot}} \), with a sudden transition from \( h \approx 1 \) to \( h = 0 \).

At variance with the global fraction of oceans, we find that the planetary rotation period has only a minor impact on the seasonal habitability. This effect is visible in Fig. 8 by comparing the two extreme cases tested here, \( P_{\text{rot}} = 0.5 \) and 8 days, for the same \( P_{\text{rot}} \approx 6.0 \) bar at tropical latitudes, we find that in the former \( \Delta T \approx 4 \) K, while in the latter \( \Delta T \approx 3 \) K.

Tests with even a moderate variation, for example \( \sim 30\% \) larger planetary radius (e.g. \( \sim 2.1 \) \( R_\oplus \)), provide higher habitability indices even for \( \sim 13\% \) lower surface pressure (e.g. \( \sim 2.8 \) bar), in the case of a high methane content. This evidences the robustness of the model against variations of \( R_P \). We obtain similar results also varying the other planetary and orbital parameters.

### 4.1.3 Axis obliquity

In the last two decades, several climatological studies (e.g., Williams & Pollard 2002; Dressing et al. 2010; Spiegel et al. 2010) have explored the role of obliquity on the planetary climate finding that larger values tend to increase the globally averaged temperature of a planet. In addition, Williams & Pollard (2003) found that planets with high obliquity are less prone to experience extreme events, such as the runaway greenhouse instability or transition to a snowball state. In our study of GJ 514 b we varied \( \epsilon \) from 0\(^\circ\) to 60\(^\circ\). The resulting maps of habitability, \( h \), versus obliquity and total atmospheric pressure is shown in Fig. 9 for the three atmospheric compositions considered in this work. The seasonal impact of these planetary configurations are shown in Figs. 10 and 11.

Two general trends are seen in Fig. 9: (i) the habitability increases with increasing \( \epsilon \) and (ii) the higher the concentration of methane in the atmosphere, the wider the range of habitability is. The former behaviour can be explained in the following way. The configuration at \( \epsilon = 0^\circ \) favours the formation of permanent ice caps in the polar regions, where the star is always at large \( Z \). As the obliquity starts
to increase, a larger fraction of polar regions undergo a period of higher insolation (lower \( \phi \)) and this reduces the ice caps, increasing the habitability (see Figs. 10 and 11.) However, when the obliquity is as large as 60\(^\circ\), a permanent ice belt can build up in the equatorial zones, leading to a decrease in the habitability (Fig. 10). Nonetheless, polar ice caps or equatorial ice belts tend to disappear as the pressure increases due to: (i) the stronger greenhouse effect of thick atmospheres and (ii) the higher efficiency of the horizontal transport at high \( p_{tot} \), which tends to cancel gradients of surface temperature.

Cases with very high obliquity (\( \epsilon > 60^\circ \)) are not considered here since they would require a 3D treatment of the atmospheric energy transport.

As far as the seasonal variability is concerned, we find that planetary axis obliquity do not play a significant role. This was not expected since, as \( \epsilon \) grows, both hemispheres are subject to larger and larger insolation variations during the orbit. In Fig. 11 we show that, for \( \epsilon = 20^\circ \) and \( p_{tot} \sim 3.5 \) bar, \( \Delta T \sim 3 \) K at the tropical latitudes. At high axis obliquity (\( \epsilon = 60^\circ \)), the seasonal variability is essentially identical.
Figure 7. Seasonal and latitudinal maps of surface temperature obtained by extracting the results of Fig. 6b (case with 0.1% CH₄) at constant values of planetary rotation period (from left to right: 0.5, 1, 2, 4, and 8 days) and total pressure (from top to bottom: \( p_{tot} = 5996, 4641, \) and 4 641 mbar).

Figure 8. Seasonal and latitudinal maps of surface temperature obtained by extracting the results of Fig. 6c (case with 1% CH₄) at constant values of planetary rotation period (from left to right: 0.5, 1, 2, 4, and 8 days) and total pressure (from top to bottom: \( p_{tot} = 4641, 3593, \) and 2 782 mbar).

Figure 9. Predicted values of the habitability index, \( h \), as a function of the axis obliquity and total surface pressure for three different atmospheric compositions. Left panel: CO₂-dominated; middle panel: \( \text{CO}_2 + 0.1\% \text{ CH}_4 \); right panel: \( \text{CO}_2 + 1\% \text{ CH}_4 \). For the remaining parameters we adopt \( P_{rot} = 1 \) day, \( f_0 = 0.75 \) and \( \omega_{peri} = 0 \). The dashed areas indicate the parameter space in which atmospheric CO₂ condensates.
Figure 10. Seasonal and latitudinal maps of surface temperature obtained by extracting the results of Fig. 9a (case with 0% CH₄) at constant values of axis obliquity (from left to right: $\epsilon = 20^\circ, 30^\circ, 40^\circ, 50^\circ,$ and $60^\circ$) and total pressure $p_{tot}=5,464$ mbar. Note that as the obliquity starts to increase, a larger fraction of polar regions undergo a period of higher insolation, increasing the global surface temperature. When $\epsilon = 50^\circ,$ an habitable belt can build up in the equatorial zones. Furthermore, habitable conditions are reached in the northern hemisphere during the summer solstice. At higher obliquity, polar zones reduce the ice caps and increase habitability. However, at $\epsilon = 60^\circ$ ice starts to form in the equatorial zones, decreasing $h.$ The solid line indicate the limit within which water can be maintained in liquid form.

Figure 11. Seasonal and latitudinal maps of surface temperature obtained by extracting the results of Fig. 9c (case with 1% CH₄) at constant values of axis obliquity (from left to right: $\epsilon = 20^\circ, 30^\circ, 40^\circ, 50^\circ,$ and $60^\circ$) and total pressure (from top to bottom: $p_{tot}=5,464, 3,593, 2,782, 2,154,$ and 1,668 mbar). The solid line indicate the limit within which water can be maintained in liquid form.
4.2 Dependence on orbital parameters

4.2.1 Eccentricity

The orbital eccentricity, $e$, impacts the mean annual flux, $\hat{S}$, received by a planet according to the law (e.g. Williams & Pollard 2002):

$$\hat{S} = \frac{L_*}{4\pi^2(1 - e^2)^{1/2}}$$

where $L_*$ is the luminosity of the host star and $a$ the semi-major axis. Compared to a circular orbit, the mean insolation increases by a factor $(1 - e^2)^{-1/2}$ and the maximum excursion of the insolation during the orbit grows as $(1 + e)/(1 - e)^2$, exceeding one order of magnitude when $e > 0.5$. Highly eccentric orbits generate seasons as the distance between the star and planet varies during the orbit. Neglecting the obliquity effects discussed above, both planetary hemispheres will experience the same season as the insolation varies along the orbit: summer occurs at periastron, whereas winter at apoastron. The higher the eccentricity, the stronger the seasonal temperature excursions. Our climate simulations show how the orbital eccentricity may impact the habitability of Gl 514b. In Fig. 12 we show the resulting map of the habitability index $h$ in the plane ($e$, $p$). One can see that the range of atmosphere pressure favourable to habitability becomes wider as $e$ increases. The central and right panels of Fig. 12 show that surface liquid water can persist at the highest eccentricities even for a moderate pressure ($p_{\text{tot}} \sim 1$ kbar). The above results show that, within the current uncertainty in the measurement, $e = 0.45 \pm 0.15$ (Damasso et al. 2022), the seasonal impact of the eccentricity on habitability could be quite strong.

The eccentricity as well as the global ocean coverage significantly impacts the seasonal habitability. The larger the eccentricity, the more significant is the seasonal excursion of the surface temperature. For the model with higher CH$_4$ content and $p_{\text{tot}} \sim 4$ kbar, $\Delta T$ increases by $\sim 4$ K between $e = 0.25$ and $e = 0.65$ at the tropical latitudes, bringing the total variation in the latter case to 6 K.

4.2.2 Argument of periastron

The argument of periastron, $\omega_{\text{peri}}$, is one of the six orbital elements univocally describing an orbit. In the most widely used definition, it represents the angle between the ascending node and the periastron, measured in the direction of motion. The value of $\omega_{\text{peri}}$ impacts the habitability by modulating the intensity of the seasonal temperature variations at surface, especially when both the eccentricity and obliquity are high. For cylindrically symmetric planets, such as those simulated by seasonal-latitude EBM, there are three possible distinct scenarios: (i) if $\omega_{\text{peri}} = 0^\circ$ or $180^\circ$, then the planet will be at its closest approach to the central body when it crosses the equatorial plane from South to North, i.e. at the equinox; (ii) if $\omega_{\text{peri}} = 90^\circ$, the periastron will occur at the southern hemisphere summer solstice; (iii) if $\omega_{\text{peri}} = 270^\circ$ the periastron will occur at the northern hemisphere summer solstice. If the two hemispheres are identical in terms of surface features (e.g. the ocean coverage), then the overall climatology of cases (ii) and (iii) will be essentially the same. In particular, in (ii) and (iii), seasonal temperature variations in one of the two hemispheres will be stronger than in the other, since the effect of eccentricity and obliquity are compounded. On the other hand, in case (i) both hemispheres will experience the same seasonality. A change in the magnitude of seasonal temperature variations can, for example, facilitate the condensation of the CO$_2$ atmosphere at the surface, as demonstrated for the Early Mars scenario (Simonetti et al. 2024).

5 DISCUSSION

5.1 Stellar activity and habitability

In the assessment of the habitability of Gl 514b, the strong activity of M-type stars can play a crucial role. A planet in the close-in HZ of an M-type star will be continuously bombarded with XUV radiation. As a result, the planet may lose oceans, ending up dessicated and void of surface life (Luger et al. 2015; Shields et al. 2016). Strong XUV irradiation can also enhance exospheric temperatures, making thermal escape a dominant mechanism of atmospheric loss for planets around M dwarfs at early times (Lammer et al. 2007; Sanz-Forcada et al. 2011).
According to Modi et al. (2023), photoevaporation of the planetary atmosphere is the dominant mechanism capable of partially stripping the primordial H/He envelope, for planets orbiting early-type M dwarfs at the outer edge of the HZ. The effective habitability of Gl 514 b may therefore depend on the initial volatile inventory and the degassing of volatiles from the planet’s interior, which could help replenish the atmosphere and sustain surface water, potentially compensating for the early atmospheric loss. Over the last decades, the occurrence of 2–4 R⊕ planets in the Kepler field (e.g., Howard et al. 2012) has underscored the ubiquity of inward disk-driven migration in planetary systems, suggesting that these systems likely did not form in situ (Cossou et al. 2014). In this way, Luger et al. (2015) suggested that it is possible for atmospheric escape processes to remove the thick H/He envelopes of mini-Neptunes, that reside in the HZ, effectively turning them into volatile-rich Earths and super-Earths, referring them as “habitable evaporated cores”. Finally, we note that the eccentricity of Gl 514 b may be the result of a late scattering event. In this case, changes in the planet’s orbital parameters would have heavily affected the planet’s climate equilibrium (Kaib & Raymond 2024).

During the early active phase the stellar magnetic field is strong enough to reduce the size of planetary magnetosphere, exposing more of the planet’s atmosphere to erosion (Vidotto et al. 2013; Garraffo et al. 2016; Aigrapetian et al. 2017). Atmospheric erosion can be greatly enhanced by stellar flares and associated coronal mass ejections (CMEs) resulting from stellar activity. From a biological point of view, the impact of a large amount of XUV radiation hitting the planet can be both harmful and indispensable to life. On one side, it can destruct biomolecules (Sagan 1973), and damage various species of proteins and lipids (Cockell 1998; Buccino et al. 2007). On the other side, UV radiation might have played a key role in the origin of life, as a crucial ingredient for prebiotic photochemistry.
The star may be relatively inactive (e.g., West et al. 2008), with fewer spots, less-energetic flares (Hawley et al. 2014), and lower XUV flux. In this respect, the possibility that the habitability of Gl 514 b is not compromised by stellar activity is much higher than in the case of the relatively numerous planets found in the HZ around late-M dwarfs, since these stars preserve a high level of activity for a much longer time and their HZs lie even closer to the star.

5.2 Planetary properties and habitability

In addition to the climate system, the habitability is influenced by other planetary properties, and in particular by the magnetic field (Haghighipour 2011; Vidotto et al. 2013; Driscoll & Barnes 2015; Meadows & Barnes 2018). A strong magnetic field offers protection from stellar wind erosion of the planet atmosphere (Driscoll & Bercovici 2013) and from CMEs (Kay et al. 2016). The magnetic field is also essential for the long-term persistence of surface life, protecting the orbiting planet from harmful high-energy radiation.
and cosmic rays penetrating the planetary surface (Grießmeier et al. 2005; Dartnell et al. 2011; Grießmeier et al. 2015).

Whether or not a significant magnetic field is present in Super-Earths, such as Gl 514 b, is an active topic of research (e.g., Gaidos et al. 2010; Tachinami et al. 2011; Stamenković et al. 2012). Generally, planetary magnetic fields arise from a dynamo mechanism which requires rotation, a core of liquid iron and a vigorous convection process (Stevenson 2010; Haghighipour 2011). The higher the planetary mass, the lower the efficiency of the full mantle convection, so that heat in deep interiors of Super-Earths is transferred by conduction rather than convection (Stamenković et al. 2012; Airapetian et al. 2017), reducing the magnetic dynamo. The strength of a magnetic field in Super-Earths crucially depends on as-yet unverified assumptions, such as the initial thermal profile and the viscosity law (Stamenković et al. 2012). Also planetary rotation affects the evolution of the dynamo, and slowly rotating super-Earths may exhibit weak magnetic fields, even though their dipoles may endure for more extended periods (Zuluaga & Cuartas 2012). Other studies suggest that the planetary rotation period may determine whether the generated magnetic field is dipolar or multipolar, the fraction of dipolar field possibly depending on the local Rossby number (Vidotto et al. 2013).

Since we do not know the internal structure and rotation period of Gl 514 b, it is hard to understand to which extent a protective magnetic field could be present. However, the atmospheres of super-Earths are likely to be relatively thick, reducing the risk of atmospheric escape. At the same time, a thick atmosphere shields the planetary surface from high-energy cosmic particles, the effect becoming stronger with increasing atmospheric columnar mass (Grießmeier et al. 2005). All the planetary properties that in our simulations yield habitable conditions for Gl 514 b are characterized by an atmospheric columnar mass, $m_{\text{atm}}/g$, in excess of the Earth’s value. This guarantees an effective shield from cosmic rays even for a modest value of the planetary magnetic dipole (Atri et al. 2013).

5.3 Extreme seasonal variations and habitability

The simulations presented in §4.2.1 show that at the higher end of the eccentricity interval, the habitability of Gl 514 b tend to increase despite the somewhat stronger seasonal excursions in $T_e$. A more detailed analysis of the results shows that this is possible because these seasonal excursions are not actually very large in the first place. In fact, for most combinations of parameters, $\Delta T$ at low latitudes is $\gtrsim 6$ K, which is consistent with the value derived from the ERA5 Earth observations (Hersbach et al. 2020). The quantity that causes the largest change in the strength of seasonality is $f_0$, which, when reduced to 0, drives $\Delta T$ to 13 K. This is somewhat expected due to the interplay between the relatively high thermal capacity of even a shallow slab of water and the relatively short orbital period of the planet. However, the generally modest, Earth-like temperature swings come as a surprise and supports the idea that even eccentric super-Earths can be potential targets for the search of biosignatures.

It is also worth noticing that even the presence of intense thermal cycles (including water phase changes) does not seem to preclude the existence of life, even though their impact would not be negligible (Mckay 2014). In fact, the set of space experiments called LithopanSpermia (Sancho et al. 2007) have demonstrated the resilience of lifeforms and bacteria, underlining their ability to endure harsh conditions in outer space thanks to their symbiotic nature and protection provided by the cortex (de la Torre et al. 2010). In a broader context, similar experiments have shown that several terrestrial organisms can survive to prolonged exposure to extreme temperature conditions, alongside vacuum, UVC irradiation, and cosmic rays (Kane & Gelino 2012).

A periodic increase of the sea surface temperature resulting from highly eccentric orbits may even foster a "superhabitable" environment with sustained marine biological productivity, since the transfer of particulate organic carbon from the surface to deep ocean layers would be more efficient, influencing the nutrient concentrations in the deeper and surface layers (Jernigan et al. 2023). In this scenario, the more nutrients are recycled, the greater the production/persistence of biosignatures (e.g., O$_2$ and CH$_4$), which are particularly favourable for exoplanet life detection (Lovelock 1965). When local favourable conditions exist, the transport of these gases from the marine environment to the atmosphere may lead to seasonal variations in atmospheric composition, providing an opportunity to directly quantify biological fluxes (e.g., Olson et al. 2018). Owing to the sensitivity of ocean dynamics to planetary parameters, the rotation period, axis obliquity, and atmospheric pressure too play a role in regulating the nutrient supply for the surface biosphere. As an example, the nutrients up-welling is predicted to be enhanced in planets that rotate slower and have higher $p_{\text{tot}}$, $e$ or $\Omega$ than Earth (Olson et al. 2020). However, high eccentricity exerts a more pronounced influence on marine biological productivity than high obliquity (Olson et al. 2020).

In summary, the same conditions that, according to our results (4), increase the habitability of Gl 514 b — high eccentricity, high ocean cover, high atmospheric pressure, high obliquity —, can also provide an environment able to enrich the atmosphere with biological signatures that, in principle, could be detectable with spectroscopic observations.

6 CONCLUSIONS AND FUTURE PROSPECTS

Gl 514 b is as an excellent benchmark for understanding the potential climate states and habitability of nearby super-Earths in eccentric orbits. In the present work we have applied our climate model, EOSTM, to investigate which range of planetary properties would allow this planet to have habitable conditions. To this end, we employed a habitability index dependent on the surface temperature, which was computed by complementing the measured observational quantities with a parameterization of currently unknown planetary (e.g., geography, rotation period, axis obliquity), orbital (e.g., eccentricity, argument of periastron) and atmospheric (e.g., surface pressure, chemical composition) quantities. By assuming that the planet has an internal composition similar to that of the Earth, we performed our multi-parametric exploration by adopting values of radius, $R_p = 1.6 R_E$, and gravity, $g = 2.1 g_0$. As far as the albedo properties are concerned, we estimated theoretical reflectances of several type of atmospheres and planetary surfaces illuminated by an early-type M-dwarf, such as the central star Gl 514. We tested three sets of CO$_2$-dominated atmospheres, each one with its own CH$_4$ concentration ($x_{\text{CH}_4} = 0\%$, 0.1\%, and 1\%), varying the total surface pressure in the range $p_{\text{tot}} \in (1, 13) \text{bar}$.

The main results can be summarized as follows:

- In the range of orbital eccentricity consistent with the observations ($e = 0.45_{-0.14}^{+0.15}$), the impact of the eccentricity on habitability is important. The higher $e$, the wider the range of atmospheric pressure favourable to habitability becomes, down to a moderate pressure ($p_{\text{tot}} \sim 1 \text{ bar}$). We find that the impact on habitability of Gl 514 b of eccentricity variations is higher than that induced by variations of other key planetary quantities, such as obliquity.

- When the obliquity is increased the planet experiences stronger seasonal excursions of surface temperature, i.e. a larger fraction of
polar regions undergo periods of high daily-averaged instellation, reducing the ice caps and increasing the habitability. For the model with higher CH$_4$ content, habitable conditions are reached for $p_{\text{tot}} \approx 1.6$ bar and $\varepsilon = 50^\circ$.

- The habitability index decreases when $\varepsilon$ reaches $60^\circ$ because a permanent ice belt builds up in the equatorial zones.
- The impact of higher obliquity tends to disappear as the surface pressure increases due to the high efficiency of the horizontal energy transport, that removes temperature gradients on the planet surface.
- The high thermal capacity of oceans tends to damp seasonal variations at low latitudes down to modern Earth-like values ($\sim\text{6 K}$). This is true even for modest cover fractions ($f_o \geq 0.4$). As such, oceans tend to substantially mute the relatively minor effect of $\alpha_{\text{peri}}$ variations, which are negligible in our calculations.
- A long planetary rotation period increases the meridional energy transport, damping gradients of surface temperature, particularly in the high-pressure regime. In the model with higher CH$_4$ content, $P_{\text{rot}}$ has a negligible impact on $h$, with a general trend of increasing $h$ with decreasing $p_{\text{tot}}$ (up to $\approx 3.5$ bar). At low CH$_4$ content, $h$ increases with increasing $p_{\text{tot}}$, with sudden transitions from $h \approx 1$ to $h = 0$.
- The high coverage of oceans, the more habitable the planet is. This is clearly due to the fact that oceans are darker than bare soil and the planet is, on average, cold. For the model with higher CH$_4$ content, the habitability index is nearly 1 up to $p_{\text{tot}} \approx 3.5$ bar, for $f_o = 1$. At low CH$_4$ content, the same result is obtained for $p_{\text{tot}} \approx 6.0$ bar.
- The latitudinal specific distribution of continents has a modest impact on the mean global annual temperature and generates negligible seasonal temperature oscillations. Its impact on the climate of Gl 514 b is less significant with respect to the global coverage of oceans.

As a general trend, we underline that remarkable differences exist between the low- and high-concentration of CH$_4$ as well as between the low- and high-pressure regimes. This result is expected since both the higher greenhouse effect of thick atmospheres composed of CO$_2$ and CH$_4$ and the higher efficiency of the horizontal transport at high $p_{\text{tot}}$ are well known. Damped temperature gradients both in latitude and in time favor habitability, at least in this specific case.

Future observations may help to constrain the actual range of stellar, orbital and planetary properties that affect the habitability of Gl 514 b. Asteroseismology obtained by extensive monitoring of nearby bright stars with PLATO (Rauer et al. 2014) may help to measure the age of Gl 514 and cast light on the evolutionary status of the host star. The perspectives opened by these observational developments suggest that we will be able to assess the actual habitability of planets similar to Gl 514 b as long as they transit in front of their host star.

### DATA AVAILABILITY

The data used for this article will be shared on reasonable request to the corresponding author.

### REFERENCES


Atri D., Harihan B., Griemeier J.-M., 2013, Astrobiology, 13, 910


Baranov Y. I., Vaganis A. A., 1099, Journal of Molecular Spectroscopy, 193, 319


Ben-Jaffel L., et al., 2022, Nature Astronomy, 6, 141


Brun P., Zimmermann N. E., Hali C., Pellissier L., Nikolaus Karger D., 2022, Earth System Science Data, 14, 5573


Clough S. A., Kneizys F. X., Davies R. W., 1989, Atmospheric Research, 23, 229


Damasso M., Nardiello D., 2022, Research Notes of the American Astronomical Society, 6, 184


Dicy J. O., et al., 1994, Science, 265, 482


Driscoll P. E., Barnes R., 2015, Astrobiology, 15, 739

Driscoll P., Bercovici D., 2013, Icarus, 226, 1447


Ehrenfreund P., et al., 2002, Reports on Progress in Physics, 65, 1427


Etiope G., Ehlmann B. L., Schoell M., 2013, Icarus, 224, 276


Fischer D. A., Howard A. W., Laughlin G. P., Macintosh B., Mahadevan S., Sahlmann J., Yee J. C., 2014, in Beuther H., Klessen R. S.,
p. 201
Wordsworth R., Kalugina Y., Lokshinov S., Vagasin A., Ehlmann B., Head
de la Torre R., et al., 2010, Icarus, 208, 735