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Steps towards atmospheric and MHD modelling of habitable exoplanets

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Abstract. One of the primary objectives of nowadays astrobiology is to seek potentially habitable worlds and biosignatures. In 2020, as a response to this quest, the Italian Space Agency held its first workshop to outline a national roadmap aimed at supporting new findings in astrobiology. Here, we briefly introduce some of the scientific topics currently investigated by the astrobiological research group working at INAF - Trieste Astronomical Observatory. In particular, we highlight the following four lines of research: 1) modelling multi-parametric planetary habitability with ESTM (*Earth-like Surface Temperature Model*), including the potential role of galactic chemical composition scenarios; 2) vegetation feedbacks in the ESTM climate simulations; 3) characteristics of the observed exoplanets required as an input of habitable planet models and 4) star-exoplanet interaction for constraining atmospheric escape scenarios.

Key words. Astrobiology – Extrasolar planets – Climate models – ESTM – Numerical methods

1. Introduction

The climate of a planet is of paramount importance to establish the possible presence of liquid water at its surface, and thus, in a wide sense generally accepted by the scientific community, to assess its habitability. Climate simulations require a high number of input parameters, both astrophysical (e.g., luminosity of the host stars, distance of the planet from the star, orbital eccentricity) and planetary (inclination of the rotation axis, duration of the day, atmospheric composition and pressure, presence and fraction of oceans, presence and type of soil, orography, topography, etc.). In the case of exoplanets, only a small number of such parameters can be constrained by observations. Therefore flexible, although approximate, climate models lend themselves to better serving at parameter space exploration than complex Global Circulation Models (GCM, see e.g. Flato & Marotzke 2013). In reason of their much lower computational cost, models of lower complexity allow running thousands of experiments at the same computational time of a single GCM's run. A representative example of such a streamlined model is ESTM (Vladilo *et al.* 2015). ESTM is based on the numerical solution of a modified diffusion equation for the meridional heat transfer, coupled with a radiative-convective column atmospheric model to account for the vertical transport of radiation (downward and upward).

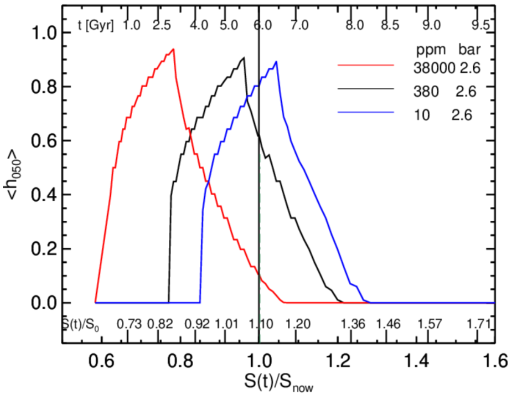

Fig. 1. Evolution of the habitability index h_{050} for Kepler-452b, at p= 2.6 bar and variable CO2 content (Silva et al. 2017b).

It has been used for studying individual exoplanets (Silva et al. 2017b) and performimg statistical analysis of planetary climates (see e.g. Murante *et al.* 2020). Here, we briefly review the perspectives for future application of ESTM and we present a study of star-planet interaction aimed at modelling the process of atmospheric escape in habitable exoplanets.

2. Climates of exoplanets and habitability

The Galaxy is teeming with planets, with small planets outnumbering Jupiter-like ones, and an estimated occurrence rate of Earth-size planets in the Habitable Zone (HZ) of Sun-like stars of about 22%. The quest for life outside the Solar System is focused on the spectral detection of atmospheric biosignatures in rocky exoplanets. The observational challenge will be paired by the interpretation of the spectral signatures in terms of biological or geological activity, if any. Most planetary quantities affecting surface temperature T and atmospheric conditions are not currently measurable, and must therefore be treated as free model parameters. The surface T distribution allows to explore different definitions of habitability criteria, besides the commonly adopted liquid water criterion. We have introduced a new habitability index, h_{050}, based on the thermal limits of life with active metabolism, i.e. able to generate atmospheric chemical imprints, suited for multicellular poikilotherms and O_2 producers (Silva et al. 2017a). The flexibility of ESTM also allows us to track the evolution of habitability as a function of the luminosity evolution of the star. We have applied the model to investigate the onset of life-sustaining conditions in Kepler-452b, as given by the time evolution of h_{050} at different values of the atmospheric composition (Silva et al. 2017b, Fig. 1).

2.1. Multi-parametric planetary habitability with ESTM

We used ESTM to calculate the surface temperature of a large number of simulated exoplanets. We fixed the atmospheric chemical composition and the radiation spectrum of the central star (identical to our Sun's) and varied atmospheric surface pressure, orbit eccentricity, semi-major axis of the orbit and inclination of the planet rotation axis. We also varied the fraction of ocean to continents and the partial pressure of CO_2. We produced a publicly-available database ARTECS (`https://wwwuser.oats.inaf.it/exobio/climates/`) and used it to study the possible *bistability* of planetary climates: i.e. the existence of two stable states corresponding to the same set of parameters, one cold and frozen - *snowball*, and one warm. Interestingly, we found that the set of planets parameters allowing for bistability largely overlaps with the set of "habitable" planets, defined as those for which the surface temperature is between the freezing and the evaporation temperature of water, for a given atmospheric pressure. The database will be extended by using different atmospheric chemical compositions and different spectral types of the host star.

2.2. Vegetation feedback in ESTM simulations

Vegetation can modify the planetary surface albedo, being usually darker than the bare surface of the continents (Charney mechanism: Charney et al. (1975); and e.g. Baudena *et al.* (2008), and references therein). Other possible

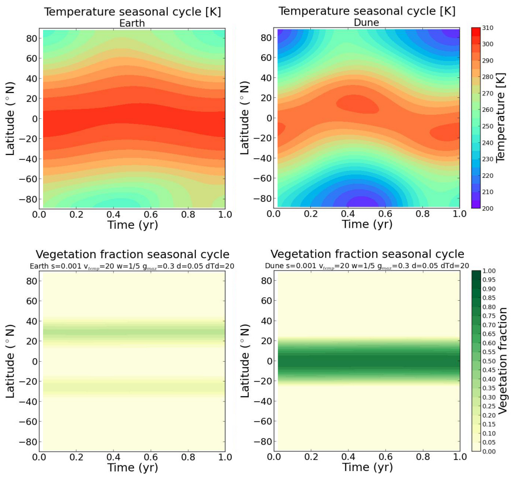

Fig. 2. *Top:* temperature as a function of time and latitude. *Bottom:* vegetation fraction as a function of time and latitude. *Left:* Earth. *Right:* Dune (Bisesi 2019, internal report to CNR/IGG).

vegetation-climate interactions include "slow" and "fast" carbon cycles – concerning the way in which plants, or more generally biospheres (or even geospheres), can hold back and re-emit carbon into the atmosphere causing the global greenhouse effect. Focusing on the first effect, ESTM can be exploited to investigate the impact of the Charney mechanism on an exoplanet's habitability. ESTM has been recently updated to take into account the evolution of one or more vegetation types (Nastasi 2020). Fig. 2 reports two examples of simulations of planetary temperature (top panels) and vegetation (bottom panels) as a function of time and latitude, for Earth (left panels) and for a cold, ocean-free planet, named *Dune* (right) as in Baudena *et al.* 2008. We found: *(i)* both planets exhibit high temperature gradients between the Equator and the poles; *(ii)* latitudinal temperature variation, as well as seasonal variation, is more prominent for Dune than for the Earth; *(iii)* in general, Dune is much colder than the Earth. As for the vegetation fraction, main differences between Dune and Earth, for the same parametric set, are: *(i)* substantial rise in the vegetation amount (for the same combination of parameters) and *(ii)* shrinkage of the vegetated belt closer to the Equator.

A newly calibrated vegetation-switched-on version of ESTM is used to study the circumstellar habitable zone and exoplanets' habitability. As different equilibrium states correspond to different planetary surface albedo, one can expect that vegetation will extend the planet's circumstellar habitable zone beyond its present external border as a consequence of a decrease in surface albedo. In special cases known as "waterbelt" – e.g., planets almost completely covered by ice, except for a narrow band near the Equator – plants could also heat up the planet, thus enlarging the liquid water band and extending the overall habitability fraction.

2.3. Connection with observables

Climate simulations allow one to recover a number of indexes (e.g. planetary habitability) as a function of model parameters. Often the control parameters of those models are not physical quantities directly derivable from the observables. For example, Silva et al. (2017a) used ESTM to provide various indexes of planetary habitability H as a function of I, $p_{\mathrm{CO_2}}$ and p_{dry}/g, where I is the level of averaged yearly insulation, $p_{\mathrm{CO_2}}$ is the partial pressure of CO_2 in the atmosphere and p_{dry}/g is the ratio of surface pressure to surface gravitational acceleration. While I and $p_{\mathrm{CO_2}}$ can be derived from transits, this is not obvious for p_{dry}/g.

A directly observable quantity is the level of extinction induced by the atmosphere, often expressed as a change of apparent planet radius ΔR_{p}. The latter is not easily usable in climate modelling, as it depends on the wavelength, the cross section of each species, the bandpasses of the instrument, etc. Indeed, ΔR_{p} depends on N_{ext} the number of absorbers (molecules, drops and grains) seen in the atmospheric annulus overlapping the disk of the host star during the transit. For this application, it is desirable to find a relationship between N_{ext} and p_{dry}/g. However, although N_{ext} has to increase with p_{dry}/g, there is no a simple analytical formula connecting these two quantities, even for a simple exponential atmosphere, characterized only by its columnar integral and scale height. For an Earth-like atmosphere, we

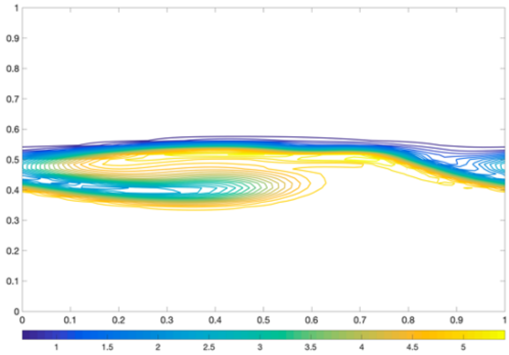

Fig. 3. Developed Kelvin-Helmholtz and tearing mode instabilities at the magnetosphere of a habitable planet. Case study: Planet A in super-Alfvenic regime (Cohen et al. 2014).

used ESTM to calculate $N_{\rm ext}$ as a function of $p_{\rm dry}/g$ for fixed I and $p_{\rm CO_2}$ (for Earth conditions $p_{\rm dry}/g = 1$, $I = 1$, $p_{\rm CO_2} = 1$). The main result is that up to $I \approx 1.24$, $\log(N_{\rm ext})$ varies linearly with $\log(p_{\rm dry}/g)$, with a slowly changing slope of I. This does not occur for higher insulations, since $\log(N_{\rm ext})$ does not change monotonically with $\log(p_{\rm dry}/g)$; in particular, the monotonicity is lost either where I is too high causing Runaway Greenhouse Effect, or $\log(p_{\rm dry}/g)$ is too low and the surface water evaporates. However, the latter case is out of the habitable range of $\log(p_{\rm dry}/g)$ and I. Therefore, $N_{\rm ext}$ could be used as a proxy of $p_{\rm dry}/g$ over all the parameter space of planetary habitability.

3. Interaction planet-star

The planetary habitability can be also addressed as a result of the interaction between the stellar wind and planetary magnetic field, if any. Rocky Earth-like planets are good candidates for such studies as they are most likely found around M-dwarf stars, which have low luminosity (so that the Habitable Zone is very close to the star) and close enough to be detected with current observational techniques. We study the energy transfer and magnetic reconnection at such planets, because the orientation of the magnetic field of the wind compared to that of the planetary one dictates the energy transfer from the wind to the planet as it drives magnetic reconnection leading to particle acceleration and particle precipitation at the top of the atmosphere (Cohen et al. 2014). In addition, assuming magnetized or unmagnetized planet scenario, developed magnetic hydrodynamics (MHD) instabilities could constrain the simulations of atmospheric escape. Intrinsic magnetic field implies that a 1-bar atmosphere of Earth-like planet can deplete for a few Gyr (Dong et al. 2020). We present a test study of MHD instabilities (Fig. 3) at the magnetospheric structure and the energy deposition into the upper atmosphere in close-in Earth-like planets orbiting an M-dwarf star. Based on the upstream stellar wind conditions, extracted along the planetary orbit from a model for the stellar wind to drive a MHD model (Cohen et al, 2014) for the global planetary magnetosphere and the ionosphere, we exploit our local MHD model (Ivanovski et al. 2011) to study the influence of the magnetic interaction/configuration to the planetary magnetosphere, and how it changes as a function of the stellar wind parameters, dynamic pressure, magnetic field topology and planetary field strength. The transition along the planetary orbit between sub- to super-Alfvenic regime affects the magnetosphere and the energy deposition onto the planet and occurs for close-in exoplanets, something that does not hold in our Solar System.

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