TWO EXAMPLES OF HOW TO USE OBSERVATIONS OF TERRESTRIAL PLANETS ORBITING IN TEMPERATE ORBITS AROUND LOW MASS STARS TO TEST KEY CONCEPTS OF PLANETARY HABITABILITY

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Abstract. Terrestrial planets in temperate orbit around very low mass stars are likely to have evolved in a very different way than Solar System planets, and in particular Earth. However, because these are the first planets that are and will be accessible for in-depth atmosphere, clouds and surface characterizations with existing and forthcoming telescopes, we need to develop the best possible observational strategies to maximize the scientific return from these characterizations. Here I discuss and expand on the recent works of Bean et al. (2017) and Turbet et al. (2019) to show that terrestrial planets orbiting in temperate orbits around very low mass stars are potentially an excellent sample of planets to test how universal the processes thought to control the habitability of Solar System planets and in particular Earth are. Precise measurements of density or amospheric CO_2 concentration for planets located both inside and outside the Habitable Zone could be used to statistically test habitability concepts such as the silicate-weathering feedback, CO_2 condensation, or runaway greenhouse, which have been identified as key processes controlling the present and past habitability of Venus, Mars and Earth.

Keywords: exoplanet, habitability, statistical tests, carbonate-silicate cycle, runaway greenhouse

1 Introduction

As of August 2019, astronomers have already detected about forty exoplanets in temperate orbit (Pepe et al. 2011; Tuomi et al. 2013; Borucki et al. 2013; Anglada-Escudé et al. 2013; Quintana et al. 2014; Lissauer et al. 2014; Anglada-Escudé et al. 2014; Torres et al. 2015; Crossfield et al. 2015; Wright et al. 2016; Gillon et al. 2016; Morton et al. 2016; Anglada-Escudé et al. 2016; Crossfield et al. 2016; Gillon et al. 2017; Luger et al. 2017; Astudillo-Defru et al. 2017; Bonfils et al. 2018; Díaz et al. 2019; Tuomi et al. 2019; Zechmeister et al. 2019), with masses or radii or sometimes even both that are similar to the Earth. Most of these recently detected exoplanets are orbiting around nearby, very low mass stars. This specificity make them not only easier to detect, but also easier to characterize with respect to planets orbiting more massive, e.g. solar-type stars. In-depth characterization of these exoplanets could be achieved through:

1. combined mass and radius precise measurements. This allows to estimate the planet density, and thus to gain information on its bulk interior and possibly atmospheric composition.

2. atmospheric, clouds and/or surface measurements, through a variety of techniques such as transit spectroscopy, direct imaging, secondary eclipse or thermal phase curves.

However, planets orbiting around very low mass stars have at least two characteristics that are likely to make them evolve very differently from Solar System planets, and in particular Earth. These two characteristics are:

1. **A hot history.** Very low mass stars can stay for hundreds of millions of years in the Pre Main Sequence (PMS) phase, a phase during which their luminosity can decrease possibly by several orders of magnitude (Chabrier & Baraffe 1997; Baraffe et al. 1998, 2015). During this PMS phase, planets are exposed to strong irradiation, which make them really sensitive to atmospheric processes such as runaway greenhouse (Ramirez & Kaltenegger 2014), indicating that all the so-called volatile species (e.g. H_2O, CO_2, CH_4, NH_3) and most of their byproducts must be in gaseous form in the atmosphere. Note that the runaway greenhouse atmospheric process is discussed in more details below.

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2. **An exposition to strong atmospheric escape.** Very low mass stars emit much more high energy X/EUV photons than solar-type stars, in proportion to their total bolometric emission (Ribas et al. 2017), exposing therefore the atmosphere of close-in planets to strong atmospheric erosion mechanisms such as hydrodynamic escape (Lammer et al. 2009; Zahnle & Catling 2017; Bolmont et al. 2017).

Combining these two previous constraints lead Tian & Ida (2015) to infer that terrestrial planets in temperate orbit around very low mass stars are likely to end up in two very different states: (i) If the initial amount of volatile species present at the time of the planet's formation exceeds what can be lost through atmospheric erosion processes, then the planet should remain volatile-rich, and likely water-rich since water is the most abundant volatile species, and also the most likely to condense on the surface among all common volatile species. (ii) Otherwise, the planet would have to be completely dry by the end of the PMS phase, but could later have been replenished with some volcanic and/or volatile gases delivered by impacts. In summary, these planets are likely to be either (i) **extremely water-rich** or (ii) **water-poor**[*], i.e. planets that have low enough water to have continents present.

Despite exotic characteristics, here I arguee that planets orbiting very low mass stars are still potentially an excellent sample of planets to test processes thought to control the past and present habitability of Solar System planets, and therefore an excellent way to test how universal these processes are. In particular, I discuss and expand on two processes that are thought to be key of the Earth's habitability, and which have led to proposals of observational tests (Bean et al. 2017; Turbet et al. 2019) in extrasolar planet populations, namely (i) **the carbonate-silicate cycle**, that could be tested for the **water-poor** category of planets, and (ii) **the runaway greenhouse**, that could be tested for the **extremely water-rich** category of planets.

2   First example: Testing the carbonate-silicate cycle and more broadly the CO_2 cycle

The CO_2 cycle is thought to be a key element for the stabilization of Earth's climate on geologically long timescale, through the carbonate-silicate cycle (Walker et al. 1981) which acts as a geophysical thermostat. This stabilizing cycle is thought to regulate the atmospheric CO_2 level in order to maintain surface temperatures that allow surface liquid water, based on two distinct processes: CO_2 degassing by volcanoes and silicate weathering, which strongly depends on temperature. If a planet – on which the carbonate-silicate feedback operates – gets too warm, then the silicate weathering rate increases, which decreases the amount of CO_2 in the atmosphere, which further decreases the surface temperature of the planet. If a planet gets too cold, the silicate weathering rate decreases, and CO_2 accumulates through volcanic outgassing, which leads to surface warming through CO_2 greenhouse effect.

Assuming the carbonate-silicate cycle is a universal geochemical process, Bean et al. (2017) proposed that it could be detected if we observe – with statistical significance – that Habitable Zone planets have a CO_2 content (or mixing ratio, for the observational point of view) that decreases with incident irradiation, as illustrated in Figure 1 (solid blue line). This is in fact what would be expected for planets that are sufficiently water-poor (first category) that they have both liquid water oceans or lakes, and continents. For planets very rich in water (second category), the CO_2 mixing ratio versus irradiation might look very different, because the CO_2 content is governed by other processes such as seafloor weathering or CO_2 oceanic dissolution (Kitzmann et al. 2015; Nakayama et al. 2019). We encourage future studies to better estimate how the CO_2 versus irradiation curve is expected to look like in the population of water-rich terrestrial planets.

In the water-poor limit planet population (i.e. planets that have oceans or lakes, and continents), I expand here the work of Bean et al. (2017) on how the CO_2 content should vary as a function of irradiation for planets located outside the limits of the Habitable Zone:

1. For planets receiving more irradiation than the inner edge of the Habitable Zone, water is expected to have completely evaporated into the atmosphere and thus to be exposed to photodissociation and subsequent atmospheric escape processes. This is likely what happened to Venus (see the introduction section of Way et al. 2016 for a recent review). Not only could the O_2 remaining in the atmosphere have oxidized the surface, thus producing CO_2; but also the absence of a hydrological cycle should have shut-down the silicate-weathering feedback, thus leading to the accumulation of CO_2 by volcanic degassing. Therefore,

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[*]The Earth and other Solar System terrestrial planets fit in this second category.
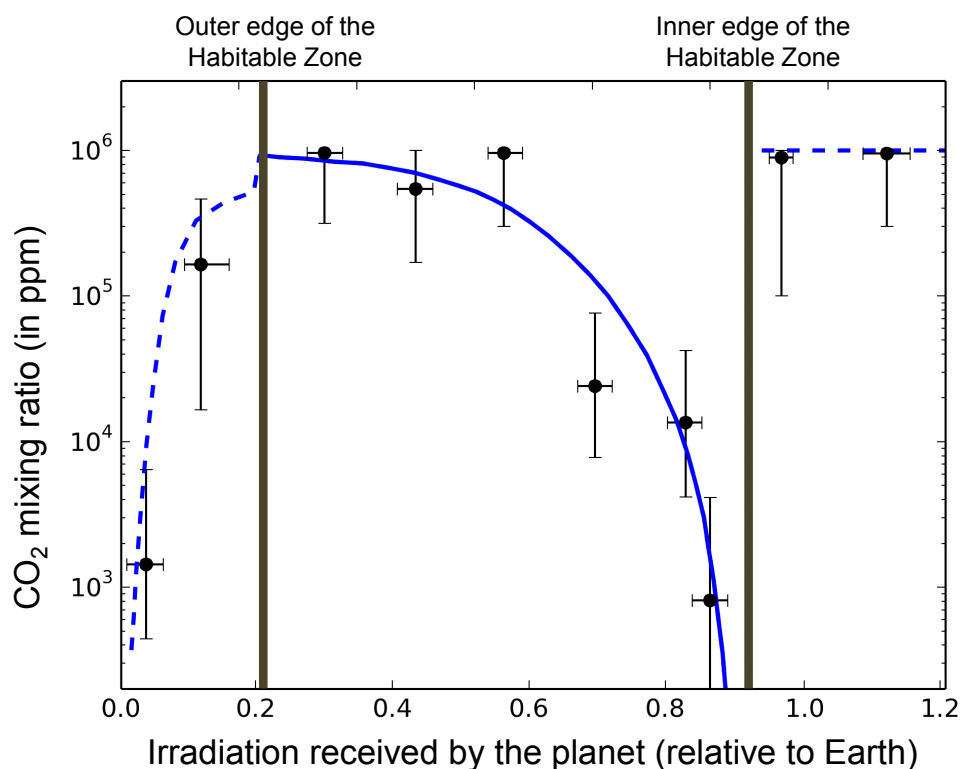
Fig. 1. This plot shows how measurements of CO_2 atmospheric mixing ratio for a sample of terrestrial-size planets spanning a wide range of irradiations could be used to statistically infer the existence of a CO_2 cycle, and even possibly the existence of a carbonate-silicate cycle. Between the inner and outer edges of the Habitable Zone (Kopparapu et al. 2013), the blue solid curve (adapted from Bean et al. 2017) shows the predicted CO_2 needed to maintain a surface temperature of 290 K. While planets located beyond the inner edge of the Habitable Zone are expected to accumulate large amount of CO_2, planets located below the outer edge of the Habitable Zone are expected to be depleted in CO_2 because of CO_2 condensation. The black points are binned data for hypothetical planets.

the CO_2 mixing ratio could reach unity for planets beyond the inner edge of the Habitable Zone (see dotted blue line in Figure 1, right of the Inner edge of the Habitable Zone).

2. For planets receiving less irradiation than the outer edge of the Habitable Zone, CO_2 is limited by surface condensation (Turbet et al. 2017, 2018), which should be more and more severe as the planet is further out of the host star. Therefore, it is expected that for planets receiving less irradiation than the outer edge of the Habitable Zone, the CO_2 atmospheric mixing ratio should decrease with decreasing irradiation, with possibly a gap at the exact position of the outer edge of the Habitable Zone, due to the ice albedo feedback (see dotted blue line in Figure 1, left of the Outer edge of the Habitable Zone). However, this gap is likely to be small for planets orbiting very low mass stars because the ice albedo feedback should not be very effective, due to (i) the spectral properties of water ice and snow(Joshi & Haberle 2012; Shields et al. 2013) and (ii) the fact that these planets are likely in synchronous rotation, with all ice trapped on the nightside (Menou 2013; Leconte et al. 2013b; Turbet et al. 2016).

CO_2 measurements could be attempted first through the transmission spectroscopy technique as soon as the James Webb Space Telescope (JWST) is operational, possibly through the 4.3 microns CO_2 ν_3 absorption band, which has been shown to be one of the most accessible molecular absorption band in terrestrial-type atmospheres (Morley et al. 2017; Lincowski et al. 2018; Fauchez et al. 2018; Wunderlich et al. 2019; Lustig-Yaeger et al. 2019). Not only this feature is present for a wide range of CO_2 mixing ratio, but it is also weakly affected by the presence of clouds and photochemical hazes (Fauchez et al., submitted to the Astrophysical Journal).

3   Second example: Testing the runaway-greenhouse

Planets similar to Earth but slightly more irradiated are expected to experience a runaway greenhouse transition, a state in which a net positive feedback between surface temperature, evaporation, and atmospheric opacity causes a runaway warming (Ingersoll 1969; Goldblatt & Watson 2012). This runaway greenhouse positive feedback ceases only when oceans have completely boiled away, forming an optically thick H_2O-dominated atmosphere. Venus may have experienced a runaway greenhouse transition in the past (Rasool & de Bergh 1970; Kasting et al. 1984), and we expect that Earth will in ~ 600 million years as solar luminosity increases by $\sim 6\%$ compared to its present-day value (Gough 1981). However, the exact limit at which this extreme, rapid climate transition from a temperate climate (with most water condensed on the surface) to a post-runaway greenhouse climate (with all water in the atmosphere) would occur, and whether or not a CO_2 atmospheric level increase would affect that limit, is still a highly debated topic (Leconte et al. 2013a; Goldblatt et al. 2013; Ramirez et al. 2014; Popp et al. 2016). This runaway greenhouse limit is traditionally used to define the inner edge of the habitable zone (Kasting et al. 1993; Kopparapu et al. 2013).

Assuming the runaway greenhouse feedback is a universal atmospheric physics process, Turbet et al. (2019) recently proposed that the runaway greenhouse could be identified through a radius gap at the position of the runaway greenhouse irradiation. Turbet et al. (2019) actually showed two same planets – but one being located just below and the other just above the runaway greenhouse irradiation threshold – should have a different transit radius and which should be all the more different as the planet water content get higher. This radius difference or gap is a consequence of the runaway greenhouse radius inflation effect introduced in Turbet et al. (2019), resulting from the fact that for a fixed water-to-rock mass ratio, a planet endowed with a steam H_2O-dominated atmosphere has a much larger physical size than if all the water is in condensed form (liquid or solid). For Earth, the net radius increase should be around ~ 500 km, but is expected to be significantly larger (up to thousands of km) for planets with much larger total water content (Turbet et al. 2019).
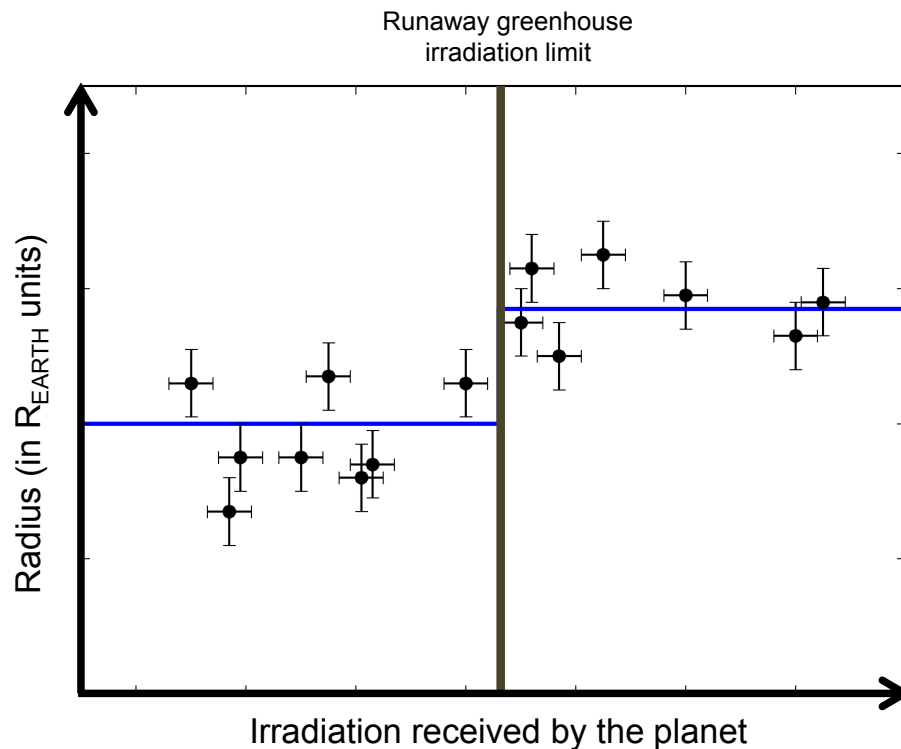

Fig. 2. This plot shows how combined measurements of masses and radii for a sample of terrestrial-size planets spanning irradiation on both sides of the runaway greenhouse irradiation limit could be used to validate the concept of runaway greenhouse. The blue solid curve (adapted from Turbet et al. 2019) shows the predicted radius gap arising from the runaway greenhouse radius inflation effect. The black points are binned data for hypothetical planets which are in a fixed terrestrial mass range.

As a result, for a sample of water-rich planets[†], the runaway greenhouse irradiation could be determined if we observe – with statistical significance – that planets located beyond the inner edge of the Habitable Zone have – for a fixed terrestrial mass range – a larger radius than planets located inside the Habitable Zone or colder, as illustrated in Figure 2 (solid blue line).

Precise density measurements for terrestrial-size planets could be attempted by combining precise transit photometry with ongoing and upcoming space missions such as HST, TESS, CHEOPS and PLATO, with precise radial velocity mass measurements with ground-based spectrographs such as ESPRESSO, CARMENES or SPIRou.

4   Conclusions

In this proceeding, I discussed and expanded on two possible observational strategies recently introduced in Bean et al. (2017) and Turbet et al. (2019) to constrain two key processes that are believed to be crucial to sustain habitability of Solar System planets: the CO_2 cycle and the runaway greenhouse. While the former could be first attempted as soon as JWST will be operational, the later could be tested with ongoing and future precise combined mass and radius measurements of terrestrial exoplanets.

Although these strategies require more work (Checlair et al. 2019) to better constrain how to carry them out (how to make these observations? with which instruments? to what precision? what is the minimum number of planets needed? what are the best planets to be selected? how to deal with confounding factors? etc.), they demonstrate at least in theory how we could use observations and characterizations of exotic planets orbiting very low mass stars to test the universality of the processes that shape the habitability of planets in the Solar System and possibly in many other exoplanetary systems.

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