A Dynamic Habitable Zone and how to find Potentially Habitable Planets

Ramses Ramirez[1] [1]Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, email: rramirez@elsi.jp

Introduction: The habitable zone (HZ) is the circular region around a star(s) where standing bodies of water could exist on the surface of a rocky planet (Figure 1) [1,2]. Space missions employ the HZ to select promising targets for follow-up habitability assessment. The classical HZ definition assumes that the most important greenhouse gases for habitable planets orbiting main-sequence stars are CO_2 and H_2O [1]. Although the classical HZ is a useful navigational tool, recent HZ formulations suggest that the concept must evolve to better capture the diversity of habitable exoplanets.

With that goal in mind, I will be discussing the temporal, spatial, planetary, and stellar processes that are key to inferring planetary habitability. Supplementing the classical HZ with additional considerations improves our capability to filter out worlds that are unlikely to host life. Such improved HZ tools will be necessary for current and upcoming missions aiming to detect, rank, and characterize potentially habitable exoplanets.

In addition, as we consider next generation missions in the search for extraterrestrial life (e.g HabEX, LUVOIR, and OST), I also discuss the importance of improved observations, and what needs to be done to advance future models of the HZ from a first principles approach in the burgeoning field of "dynamic habitability [2,3]."

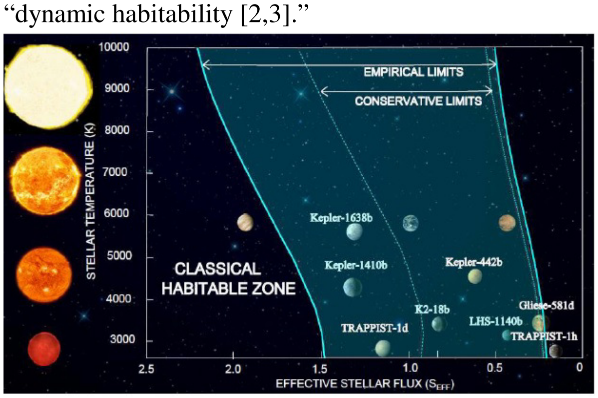

Figure 1: Extended classical habitable zone for stellar temperatures from 2,600 to 10,00 K. Reproduced from ref [2]

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Rethinking the Classical Habitable Zone

The HZ is still the best metric out there for finding life on other planets, but it needs a modern update. Here are a few example of topics I will be discussing in more detail in my talk.

Is the carbonate-silicate cycle really universal?

Several Earth-centric assumptions define the standard habitable zone. This "classical HZ" is traditionally characterized by H_2O-dominated planets near the inner edge and CO_2-dominated planets at the outer edge [1]. This variation in atmospheric composition with distance is assumed to be dictated by the carbonate-silicate cycle, which is thought to regulate CO_2 levels over million-year timescales on our planet[1]. However, there is still no direct evidence that this cycle exists on Earth, and even if it does, the details are poorly understood. Plus, its universality elsewhere is completely untested [2,4]. This is why we should test the existence of a universal carbonate-silicate cycle with upcoming missions that will measure atmospheric CO_2 levels in planets orbiting many stars. Even should such a cycle prove common throughout the cosmos, this would not necessarily preclude the existence of other planets, including ocean worlds, which might be habitable even in the absence of such a cycle [5]. Such ocean words would have lower interior densities and be easily distinguished from other terrestrial planets [5].

The untested universality of habitable planets with CO_2-H_2O atmospheres

The notion that CO_2 and H_2O are the only greenhouse gases of importance in potentially habitable planets, is another questionable (but testable) assumption of the classical HZ [1]. For instance, CO_2 levels of planets near the outer edge of the classical habitable zone are so high that they would be poisonous to Earth-like life anyway [1], raising questions about whether so-called "Earth-like" life can be expected in such planetary environments. However, the atmospheric CO_2 levels fostering habitable surface conditions can reduce dramatically if the additional warming from secondary greenhouse gases is considered. For instance, hydrogen outgassing from volcanoes, together with CO_2 and H_2O, can increase HZ width by ~50% [6] (Figure 2). The solar system HZ can extend outward to near Saturn's orbit if habitable planets can acquire primordial H_2 envelopes [7]. Moreover, hydrogen is a known food source for life, which makes these planets potentially attractive observational targets. Such planets are also considerably easier to observe via transmission spectroscopy than are CO_2-rich planets [6,8]. Other gases which are produced by life, like CH_4, may be a major greenhouse gas for worlds orbiting hotter stars [9] (Figure 2). In contrast, around M-stars, CH_4 actually acts as a cooling gas that may not be so good for life's prospects [9]. Therefore, I argue that stellar type (in part) determines what biosignatures gases we should be observing around different stars.

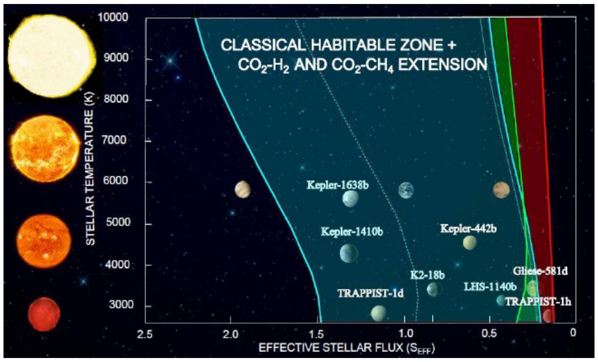

Figure 2: The classical HZ (blue) with CO_2-CH_4 (green) and CO_2-H_2 (red) extension for stars of temperatures between 2,600 and 10,000 K. Classical HZ shown as in Fig. 1. Reproduced from ref [2]

Dynamic Habitability: A First Principles Approach

Motivated by arguments such as these and others, improving our understanding of planetary habitability (and, ultimately, life) outside of our solar system will require employing first principles that focus on assessing the individual planetary system's unique traits rather than assuming that certain Earth characteristics must a priori apply elsewhere. Indeed, this very sentiment has led to the growing field of "dynamic habitability", which suggests that planetary habitability and its environment must be considered over both spatial and temporal scales [3]. I will be stressing the importance of this first principles dynamic habitability approach and how it will be necessary to maximize our chances of finding life elsewhere.

A more comprehensive habitable zone for finding life on other planets

Ramirez [2] recently published the first review paper (to the author's knowledge) of dynamic habitability, showing how the HZ concept, which is often considered to be very Earth-centric, can really become much more versatile than what has been credited in the past. Although the HZ can continue to be used to find potentially habitable planets that are similar to our own planet, it is also versatile enough to be used to search for those that may exhibit conditions somewhat different from those on our planet.

A few examples of such planets with the potential for life as *we-do-not-know-it* include: worlds with non-traditional hydrogen-rich or methane rich atmospheres, planets orbiting binary stars, worlds around white dwarfs, habitats orbiting red giants, environments around very young and luminous stars, and even ocean worlds (summarized in ref 2). All will be discussed.

The main concepts in my recent review paper provide many suggestions that current and upcoming mission concepts (e.g HabEX, LUVOIR, and OST) can employ in their search. An example of how a more "dynamic HZ" can be applied is shown in Figure 3. I will also discuss several ways an improved HZ can be used to find potentially habitable planets and rank them using metrics such as in ref.[10].

My review talk aims to incite new interdisciplinary discussion about the various possibilities, leading to new research into the prospects for life elsewhere.

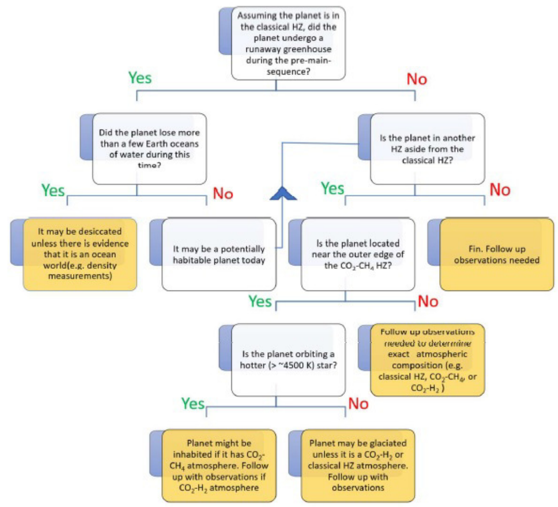

Figure 3: Sample flow chart using the classical HZ, along with CO_2-H_2, CO_2-CH_4, and pre-main-sequence HZ extensions to assess the potential habitability of planets. End states are in yellow. Reproduced from ref [2]

References:

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