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Defining the Circumstellar Habitable Zone

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ABSTRACT The study of habitable exoplanets is a rapidly expanding field in astronomy. Exoplanets are planets that orbit stars other than the sun. One of the keys to knowing whether or not an exoplanet is habitable is by studying the circumstellar habitable zone, or CHZ. Over the past several years, the defined limits of the CHZ have become susceptible to change as new parameters and factors are found to affect a planet's habitability. There are many factors that affect its habitability, including the composition of the star, the mass of the planet, the planet's atmosphere, etc. The focus here is divided into two parts. The first is to study how recent discoveries of physical parameters affect a planet's habitability. The second is a radically new direction: to explore life that results from different biological processes than those found on Earth. By reviewing and summarizing ongoing developments and discoveries in the field, the conclusion is that many new factors that were previously unconsidered have major implications for an exoplanet's habitability.

1. INTRODUCTION

Since Mayor and Queloz discovered the first exoplanet in 1995 (Mayor and Queloz, 1995), hundreds more have been discovered in recent years, with even more potential exoplanets awaiting confirmation. The question is no longer whether these planets exist, but instead, are they habitable?

The primary way of defining the circumstellar habitable zone, or CHZ, is based on the separation between a star and its planet and whether this separation can allow for the presence of liquid water. A one-dimensional climate model developed in 1993 by Jim Kasting first characterized these limits (Kasting 1993). The inner edge of the habitable zone is the closest that a planet can be to its sun without its liquid water evaporating away. The outer edge of the zone is the farthest a planet can be from its sun before its liquid water solidifies and freezes. In 1993, even before the discovery of the first extrasolar planet, these limits were set at 0.95 AU and 1.15 AU respectively (an AU being defined as an 'astronomical unit'; the distance from the Earth to the sun).

These values remained unchanged until 2013 when Ravi Kopparapu and his team reevaluated these limits based on an increase in knowledge of these planets from more advanced modeling. These reevaluations have resulted in wider and narrower limits of the CHZ, depending on the myriad of changing parameters.

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One of the key parameters used to determine whether or not an extrasolar planet is habitable comes from the notion of 'transiting' (Howard 2013). Spectrographic data can be obtained from distant stars by observing and analyzing their light. Using this data, it is possible to determine what elements the star is composed of. In some extrasolar systems, the exoplanets will 'transit,' which means that they pass between their parent star and the Earth. When the planet passes in front of the star, some of the star's light will be absorbed by the planet and some of it will pass through the planet's atmosphere before reaching the Earth. As a result, there will be a change in the spectrographic data that is observed. By comparing the spectrographic data of the transiting period to the star's unblocked spectrographic data, the elements residing in the planet's atmosphere can be determined. Atmospheres more similar to the Earth's are better candidates for finding Earth-like life. But even atmospheres that are different than the Earth's could also foster life. The implication is that this life could be fundamentally different than terrestrial life (other types of life are discussed in Section 4).

While the atmosphere of an exoplanet is the most telling feature of a planet's habitability, current spectrographs are just short of the required sensitivity to confirm the composition of exoplanet atmospheres. In addition to studying exoplanet atmospheres, other parameters have been considered in recent models, such as the stellar composition, stellar evolution, stellar flux/separation between star and exoplanet, exoplanet composition, cloud cover, atmospheric pressure, tectonic activity, and exoplanet rotation. Consequently, considering many of these new parameters results in changes to the previous estimates of the CHZ and necessitates much more complex models than previously used.

2. CHZ LIMITS - PARAMETERS

Many new parameters that were previously unconsidered have had an effect on the definition of the CHZ. Recently, the notion of an 'optimistic' habitable zone has taken hold, which allows planets to exist outside of the previous CHZ boundaries and yet still be habitable. For instance, the composition of a star can affect a planet's habitability. Every star is composed of varying levels of elements, and depending on these compositions, different stars will output different types and levels of radiation (Richardson and Smith 2003). For example, stars with high levels of oxygen will output more ultraviolet radiation. The importance of this fact is that ultraviolet radiation will make terrestrial (Earth-like) life impossible unless that planet, like the Earth, has a magnetosphere to protect its surface. So although a planet may be the correct distance from the star to have liquid water, its surface could be uninhabitable if it cannot protect itself from ultraviolet radiation.

Another factor in addition to separation between planet and star is the evolution of the star. A star may appear to be a certain size and outputting a specific type of stellar flux, but a problem arises in determining the star's age. Said star may be expanding, having expended most of its fuel, resulting in a star that is heading toward supernova and, consequently, a planet that is nearing the end of its habitability. Therefore, smaller stars are more ideal than large stars, as supermassive stars burn their fuel at a quicker rate and have a narrower time frame for habitable planets (Lissauer 2007). Additionally, the composition of stars continues to be important, as different compositions result in different life spans. For instance, oxygen-rich stars have longer life-spans than stars that are low in oxygen levels, meaning there is a longer span of time for life to form.

Another factor still is the size of the planet itself. Planets come in all sizes, many of which do not have analogues in the solar system. There are Jupiter-sized planets orbiting where Mercury orbits in the solar system, and Mercury-sized planets orbiting where Jupiter orbits in the solar system. But despite the seemingly erratic order and position of planets in other solar systems, the size of the planet affects the planet's habitability in various ways (Kopparapu *et al.*, 2014). For instance, a planet that is much larger will have more mass and will consequently have a denser atmosphere. This is critical, as different atmospheric pressures mean that water will condense and evaporate at different temperatures. Similar to how water boils at lower temperatures on a mountain, water will boil more easily on a smaller planet than a larger one. Although current instruments cannot measure the atmospheric pressure of exoplanets, a paper by Amit Misra proposes the use of dimers (two monomers that are bound to each other) instead of monomers (molecules that are crucial to the basic structure of macromolecules) to gauge the pressure in an atmosphere, as dimers are more sensitive and can leave a detectable pattern (Misra *et al.*, 2014). Misra extends the notion to the realm of practicality by showing that NIRSpec (Near InfraRed Spectrograph) on the upcoming James Webb Telescope can be used to detect these signatures. With atmospheric pressure considered, water may exist outside of the previously defined CHZ if the exoplanet is larger than the earth, further expanding the definition into the optimistic CHZ.

In addition to an exoplanet's atmosphere, its composition also contributes to its habitability. Even though water vapor has been reported as detected for a gas planet (Lockwood *et al.*, 2014), the interior of gas giant planets (referred to as jovians and neptunians, analogous to Jupiter and Neptune) is unknown. Instead, the focus is on terrestrial, Earth-like planets. If the exoplanet is terrestrial, it is important to consider that it may exhibit tectonic activity, which can result in a planet that can help heat itself geo-thermally from the inside, further expanding its habitable zone. An even more important consequence of geo-thermal heating is the implication of a magnetosphere. Superheated, liquid metal flowing beneath the crust gives rise to a magnetosphere and can also result in tectonic plate activity, so to find one could give reason to suspect the existence of the other. Additionally, a planet's spin around its own axis can also have an impact on its ability to retain heat from its sun. Some planets rotate more quickly than others (for instance, Jupiter has a roughly 10-hour day, despite being vastly larger than Earth), and planets that rotate more rapidly will radiate away the solar heat they've received more quickly (Leconte *et al.*, 2013) than planets that are tidally locked.

Kopparapu's team looked at many of these parameters, but not all of them. Some parameters continue yield conflicting results for different teams of researchers, such as the effects of cloud cover (Brogi *et al.*, 2012), (Yang *et al.*, 2013). As more sophisticated models continue to be created and studied, the habitable boundaries continue to vary and expand or, in some cases, even contract depending on the exoplanet and its sun. As of 2014, the updated values of the CHZ resulted in an inner radius of 0.93 AU and an outer radius of 1.69 AU (Kopparapu *et al.*, 2013).

3. CHZ LIMITS - TYPES OF LIFE

The second way to expand the search is by exploring potentials for life outside of those familiar to Earth. This is an examination of the universality of the phenomenon of life. Dimitar Sasselov discusses how, "liquid water and some clays on a planet will allow for spontaneously forming bubbles that have membranes similar to every living cell of a life form on Earth." (Sasselov 2010) He defines life as a compartmentalization of the molecules important to life isolated from the rest of the environment. With this definition, he says these membranes allow molecules like nucleic acids, DNA and RNA to stay isolated as they develop, divide etc. Note that Sasselov's comparison is specifically to biology found on Earth. When viewed from the perspective of biochemistry, that is, life as a chemical process/phenomenon, it eventually becomes prudent to ask the question of whether or not life is a universal phenomenon. The prospect of life as a strictly chemical process seems to imply that life different than that on Earth might be possible.

Carol E. Cleland has taken this question in a starkly philosophical direction. A 'natural kind' is a term referring to something whose classification is determined by nature rather than human convention. (Cleland and Chyba 2002) The question then is whether or not life is a natural kind. If so, how might it be possible to obtain a deeper understanding of life beyond the features seen on Earth? There seem to be two different options. First is the synthesis of other candidate systems (liquid ammonia, methane or other hydrocarbon-based life forms rather than water-based) in a laboratory. Second is the discovery of independent, extra-terrestrial biologies. Cleland's work is primarily theoretical but others have taken it into a more practical realm. While the discovery of extra-terrestrial biologies is obviously a long shot and something that cannot be easily systematized, the first is currently being explored - most notably at Harvard University.

The implication of a chemical basis other than water-based is that different atmospheres could harbor different kinds of life. Titan, Saturn's moon, has methane instead of oxygen. Although methane is unsuitable for life here on Earth, it may be possible for a different kind of biology or 'life' to develop in such an environment. Consequently, the search for extra terrestrial life can be expanded to exoplanets with atmospheres differing from the Earth's (unless the search is specifically focused on finding life similar to terrestrial life).

Another group pursuing this kind of research is the Origins of Life Initiative (Szostak and Blain 2014). This group is an interdisciplinary effort from astronomers, chemists, and biologists that attempts to synthesize living cells from inanimate components. A hope is that this synthesis will illuminate the possibility of new life forms that are different from familiar, terrestrial biology. Efforts in this department are underway in Harvard University's genetics department. The idea is to build a synthetic cellular system that will undergo Darwinian evolution centered on a protocell. A protocell consists of a self-replicating genetic polymer allowing for variation and a self-replicating membrane boundary that keeps information from the genetic polymer localized. Another requirement is that nutrients must be able to enter the protocell and waste must be able to leave, but that the genetic system must remain inside. A cell's functionality is based on enzyme catalysts that are protein-based. Unfortunately, the study of life's origin hits a wall because it is commonly accepted that it takes proteins to make proteins. However, if the first organisms did not require proteins and genetic molecules like DNA or RNA could form spontaneously then this paradox would disappear. Investigation into this possibility is where current research is focused.

Lacking proteins, primitive membranes are postulated to be made of simpler materials like fatty acids. Fatty acids are a component of phospholipids, and vesicles of these materials are the most common models for the membranes of artificial cells. Without protein enzymes the protocell must necessarily copy its genetic information using components from the environment.

Most radically there have been recent studies on artificial cells based on non-membrane compartmentalization (Seager 2013). These models are based on compartmentalization via droplets rather than membranes. The most notable concern is whether the lack of a membrane barrier allows for such rapid exchange of genetic materials between droplets that the spatial partitioning of genetic materials required for Darwinian evolution is not present.

Despite efforts toward its creation, development of a self-replicating genome is still the biggest challenge. Instead, alternative processes are being researched. Both the selection of metabolic ribozymes with useful activities, such as phospholipid synthesis, and the evolution of structural RNAs that modulate cell division are possible outcomes, but the most interesting possibility may be the spontaneous emergence of a completely unexpected function (Szostak and Blain 2014). The mechanisms of life on Earth are fairly well understood, but Szostak's team continues to search for the 'unexpected functions' where life develops from mechanics that are not seen on Earth. There are many potentials for artificial cells involving biofuels and pharmaceuticals, but the relevance to the habitable zone lies more in contingencies for creation of the protocell rather than the proposed functions of the protocell. This research enlightens geochemical scenarios for the origin of life and naturally illuminates requirements for the creation of protocells capable of reproduction. If the creation of fundamentally different 'life' is successful, it will drastically change how the habitability of exoplanets is defined. Planets with atmospheres that were previously assumed to be inhospitable may in fact be breeding grounds for new biologies.

4. CONCLUSION

In conclusion, there are several ways that research in this field will continue to evolve. As new discoveries are made with artificially created cells in laboratories, these implications will continue to inform what is necessary for life to survive. As new models continue to illuminate the interactions of dozens of unknown parameters, more conclusive predictions can be made concerning the habitability of groups of planets. And as spectrographic instruments continue to improve and advance, details of specific exoplanets will allow definite confirmation the habitability of individual exoplanets. What is clear is that, until then, there are vast implications concerning how the CHZ is defined. Every parameter informs and affects other parameters, and it is vital to consider how the entire system works together. However, this research also helps narrow the search. If the search is for life similar to terrestrial life, guidelines now exist to limit the possible candidates. First, stars of longer life spans are more optimistic for finding life. Second, terrestrial planets are more likely to host life than gas giants. Third, the planet must have water on it. Various other effects such as a planet's tectonic activity, rotational speed, and size are important, but the other parameters must be satisfied first and foremost. Future computer simulations such as those done by Kopparapu's team will only help to further understand how all of these parameters interact with one another. The James Webb Space telescope will potentially be able to detect the atmospheric composition of exoplanets once it is in orbit. Only then can the habitable regions of extrasolar planets definitively be established.

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