Assessing the Habitability of Exoplanets*

Bilal Haq

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Abstract

In this paper, we examine detailed descriptions of planets and perform an assessment of their habitability. The analysis will be based on the methods taught and practiced in class, as well as independent research. Thus we demonstrate how to use the properties given; star/planet information, atmospheric composition, and other known values, to determine if that planet is capable of sustaining at least single celled life. We will look at planets 1 and 2 of the given three, corresponding to text files p1 and p2. The analysis was conducted using R (R Core Team (2020)). The data was obtained from http://astro.utoronto.ca/~ast251/AST251_2022_Project2/.

*Code and data are available at: https://github.com/haqbilal/Assessing-Hability-of-Exoplanets

1 Introduction

Firstly, a slightly looser definition of habitable from Kasting et al. (2014), is an Earth-like planet around different types of main-sequence stars having liquid water on its surface over an extended period of time. Moreover, the habitable zone is the range of orbital distances for which a planet described above may exist. For each case, we are given properties of the star, the planet, and other useful values to help determine the habitability of each planet.

1.1 Properties of the Star

From Raghavan et al. (2010), stars supporting habitable planets will have spectral class within the range of late F mid K. And according to Greicius (2015), stars must be at least a hundred million years old (and we assume the planets formed around the same time). Single-star systems will have more stable orbits, so they are more habitable. A luminosity that doesn't vary too much is ideal for habitability, keeping the energy output of the star similar at all times. Also, the luminosity is directly proportional to the star's habitable zone, while the radius is inversely proportional (Morris (2010)). Lastly, from Waltham (2017), stars smaller than 0.65 solar masses are statistically unlikely to host habitable planets.

1.2 Properties of the Planet

The orbital period of a planet has no percieved effect on it's habitability (Shields et al. (2016)), but we may use the semi-major axis to determine if the planet is in the habitable zone (Morris (2010)). Further, using the habitable planets catalog ((n.d.)), we see that habitable planets often have a radius of between 0.5 and 1.5 Earth radii. From Bolmont et al. (2016), planets with eccentricity close to Earth's (0.01671) may be suitable for life, but the effect of high luminosity combined with high eccentricity is not known, so other methods may be used. Finally, planets containing one of CH4, H20, N2, O2, CO2 as the dominant compound in their atmospheres are likely candidates for habitability according to Konatham, Martin-Torres, and Zorzano (2020). Alongside, most candidate habitable exoplanets also contained H/He. Thus planets with this composition or an Earth-like composition are likely to be habitable.

1.3 Other Useful Properties

Primarily, locations with high star population density can be problematic to the formation of life on a planet, because of excess radiation from stellar evolution of all local stars (Skibba (n.d.)). Thus the optimal location for stars and their planets in terms of habitability is the disk of the Milky Way galaxy, where stars are more spaced apart, meaning their influence on other stars' planets is lessened. As atmospheric pressure increases, so does the habitability of a planet because it allows for water to exist in liquid form for a wider range of temperatures (Vladilo et al. (2013)). Thus planets with higher atmospheric pressures than Earth, and all other attributes similar, are more likely to be habitable as a result. By Del Genio et al. (2019), a bond albedo of ~0.3 (close to Earth) or 0 is often assumed when assessing the habitability of planets, but Earth's albedo of 0.3 is usually only the minimum required for a planet with an F-K type star. Thus planet's albedo can vary, and still result in a habitable world. From McKay (2014), water can exist in liquid form in the range -15 to 122 degrees Celsius, which is 258 to 395 degrees kelvin. Thus a planet with surface temperature in this range is required for life to grow and reproduce. In addition, the axial tilt of a planet causes different parts of a planet to be in direct radiation from it's star. This causes seasonal change on Earth, which has an axial tilt of 23.5 degrees. For example, if a planet's tilt is such that it's glaciers come into the star's radiance, then they would melt and allow for liquid water, even among other non-habitable conditions (Garner (2015)). In combination with a high albedo, a slowly rotating planet is a candidate for habitability because of long daytime illumination. A fast rotating planet (like Earth) with low albedo allows for more illumination during a smaller time period, to accomplish habitabiltiy as well (Yang et al. (2014)). Also, Lammer et al. (2009) indicates that a strong magnetic field is required for habitability, as it protects a planet from stellar wind eroding away the atmosphere necessary for life to exist.

2 Methodology

Now we apply the methods discussed above and assess the habitability of the planets provided in the dataset. Planet 1 corresponds to the dataset 'haqbila1_p1.txt' and Planet 2 corresponds to 'haqbila1_p2.txt'.

2.1 Planet 1

The properties of Star 1 (corresponding to Planet 1) are satisfactory to continue analysis. With a spectral type F, and an age of 2.55 Gyr, as well the system having no other stars, this star is capable of hosting habitable planets. The star's mass is 1.41 solar masses, greater than 0.65, meaning it isn't statistically unlikely to host habitable planets. We don't need to use the star's luminosity or radius because the planet's surface temperature is given at 310K, which is in suitable range for water to exist in liquid form. An orbital period (2.07), semi-major axis (1.82), planet mass (3.61), planet radius (1.49), are all within acceptable range to Earth's properties. The exception is for the planet's eccentricity (0.182), which combined with the relatively high stellar luminosity of 3.91 does not provide definite information.

Planet 1's atmosphere is dominantly comprised of CO2, and it also contains H2O and O2. This follows with the atmospheric compositions of discovered known habitable planets as in the study referenced above, which is another potential sign of habitability. The planet is located in the Milky Way disk, so there are no problems in the galactic neighbourhood, but nearby planets don't provide enough information about the region. The planet's atmospheric pressure is low at 0.319, which means water exists in liquid form in a lower temperature range, but a surface temperature of 310K is likely to be contained in this restricted range. The high planetary albedo of 0.46 combined with the slow rotational period of 22.1 hours is another sign that life could sustain on this planet. With an axial tilt of 4.85 and magnetic field strength of 76.6% that of Earth's, this planet is capable of undergoing seasonal change, while maintaining it's atmosphere.

2.2 Planet 2

The properties of Star 2 are enough to continue analysis as well. It has a spectral type F, an age of 1.01 Gyr, is the only star in it's system, and has a mass 1.55 > 0.65. While it's stellar radius is 1.51 > 1.5, it is close enough to warrant further study. We can use the star's luminosity, 5.74, to determine the habitable zone with the formula from Whitmire and Reynolds (1996):

$$r_0 = \sqrt{\frac{L}{1.1}} = \sqrt{\frac{5.74}{1.1}} = 2.3 \text{ AU}$$

$$r_1 = \sqrt{\frac{L}{0.53}} = \sqrt{\frac{5.74}{0.53}} = 3.3 \text{ AU}$$

Thus planets within 2.3-3.3 AU are in the habitable zone of this star. Although Planet 2, with distance 1.12AU from the star is thus not within the habitable zone, research as indicated above has discovered it is still possible for this planet to be habitable, based on other properties. Planet 2's orbital period is very close to Earth's, at 0.957, but it's mass and radius put it at smaller in size. It's orbit is also not very eccentric, with eccentricity 0.0606.

In terms of the atmosphere, with a chemical composition primarily made up of CO2, and traces of O2, N2, H2O, and SO2, this planet is similar in regard to other known habitable planets, including Earth. As it is located in the Milky Way disk, with no neighbouring planets, there are no problems with it's region in space. The very high planetary albedo of 0.745 will require a rotational period (unknown) faster than Earth in order for Planet 2 to stay a valid candidate for habitability. However, it does have a strong enough magnetic field, 95.8% of Earth's, to help maintain it's atmosphere.

3 Discussion and Next Steps

Thus, overall, for Planet 1, we have justified and provided evidence as to why each quality is in line with those of other observed habitable planets as well as Earth, which means we can reasonably conclude that Planet 1 is habitable. On the other hand, we have evidence pointing in both ways, towards and away from habitability, for Planet 2, because it is not in the habitable zone, but does have other factors in favour. So we cannot conclude anything definite on the habitability of Planet 2.

If more information on Planet 2's surface temperature, atmospheric pressure, and planetary rotational period was available, we could potentially draw more sound conclusions.

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