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COMPARATIVE HABITABILITY OF TRANSITING EXOPLANETS

Rory Barnes, Victoria S. Meadows, Nicole Evans (2015)

Paper Review (https://iopscience.iop.org/article/10.1088/0004-637X/814/2/91)

I. Introduction

A lot of attention for the past few years has been focused on exoplanet searches in pursuit of finding a habitable planet. Learning more about exoplanets would help us understand the formation mechanism of our own solar system. Studies on exoplanets would often fall under four categories according to Schneider (2017): (a) planet properties (interior and exterior features), (b) planet interactions with stars, (c) global statistics (e.g. number of planets per star), and (d) biology. Interestingly, these studies led to the development of techniques and technologies on high-resolution spectroscopy, search algorithms, and imaging.

This *review* tackles an ApJ paper by Barnes et al on the habitability of exoplanets based on a comparison between a planet's semimajor axis to the habitable zone of its parent star. Their analysis uses data from the *NASA* exoplanet archive to constrain searches for habitable exoplanets based on the emitted flux by a candidate planet. For a planet to be considered habitable, it must emit fluxes within the allowed values in the habitable zone and must be terrestrial. The emitted flux of a planet is directly related to its absorbed flux. This could tell us if the surface temperature is suitable for life, i.e. whether there could be liquid water on the planet's surface or not. The existence of life in the cloud tops of gas giants like Jupiter is not yet out of the picture. However, these exoplanets are not prioritized in habitability searches since life, as we know it, could not probably thrive there. To account for these conditions in searches, an index called HITE or "habitability index for transiting exoplanets" was used. Together with these conditions, parent stars of Kepler objects of interest (KOIs) should be detectable by other telescope missions to be given priority in this habitability search. The bulk of this review is allocated to a discussion of the HITE and its implications in searches. Like the structure of the paper, we shall go through its application to confirmed *Kepler* objects of interest and conclude with a summary of this paper.

II. Methodology

The main parameter used in the search algorithm proposed is the "habitability index for transiting exoplanets" or HITE. It mainly depends on the host star's luminosity L_*, the planet orbit's semi-major axis a, radius R_p and eccentricity e, and its albedo A[1]. These quantities are related to the emitted flux by an exoplanet candidate. We start the discussion by immediately defining the habitability index. After which, we can look at its parameter dependence.
The value of the outgoing flux F from a planet is given by,

$$F = \frac{L_*(1-A)}{16\pi a^2\sqrt{1-e^2}}$$

where both A and e could range from 0 to 1. Increasing the albedo would lead to a decrease in F ; while an increase in e would lead to an increase. It implies that there could be distinct pairs of (A, e) that correspond to the same flux value. This is what they call the "eccentricity-albedo

[1] measured from a scale of 0 to 1 depending on how an object reflects incident radiation

degeneracy." In order to address this, the fluxes were calculated for all possible eccentricity-albedo pairs that would result in values within the habitable limits. The habitability index H is given by,

$$H(R_p) = \frac{\sum_j h_j(A,e)p_j(e)}{\sum_j p_j(e)} p_{rocky}(R_p)$$

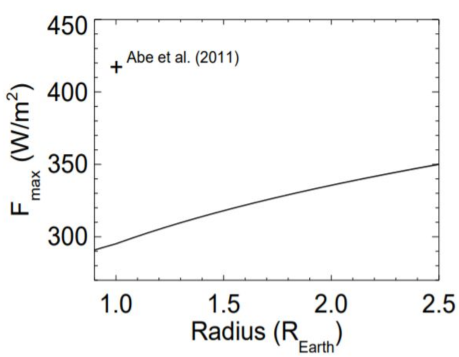
where the albedo runs from 0.05 to 0.8, and the eccentricity falls within limits that will be discussed later on. Each j index represents a unique eccentricity-albedo pair. Hence, H is defined as the fraction of (A, e) space over all combinations that are considered habitable, multiplied to the probability p_{rocky} that a planet is terrestrial. The h function is given by,

$$h(A,e) = \Theta(F(A,e) - F_{min}) \times \Theta(F_{max} - F(A,e))$$

where the extremal fluxes are limited by runaway greenhouse effect [2]. In the next subsections, we dissect the H index into parameters that factor into its value. We note that a higher HITE would imply that a candidate is more likely to be habitable.

A. Limiting fluxes, $F_{min} - F_{max}$

The emitted flux by a planet could tell us the amount of thermal radiation that is blocked and retained by a planet's atmosphere. Since water could only exist in liquid form for a range of temperatures, this could help us determine whether an exoplanet is habitable or not. The radiation retained at the surface due to greenhouse effect could only escape to space at surface temperatures near 1500 K. This surface condition could not harbor life according to our current convention.



Pierrehumbert (2010) proposed an analytic expression for the upper bound of the emitted flux, F_{max}. This flux limit depends on the mass and the radius, M_p & R_p, of the planet. Since M_p cannot be inferred from transit data, a compositional model by Sotin et al (2007) was used to relate the planet's radius and mass, with the Earth as reference.

Fluxes below the solid line are considered habitable conditions according to this model. A separate flux upper limit of 415 W/m^2 was calculated by Abe et al (2011) for desert planets with very limited surface water. However, they were not able to calculate for a lower bound. This condition would often represent planets located at the inner edge of the habitable zone.

A mass-dependent function for habitable zone limits was obtained by Kopparapu et al (2014) through a 1D cloud-free climate model. They considered planetary masses between $(0.1 - 5)\, M_{\oplus}$, where the lower limit corresponds to Mars-like planets; while, planets beyond the

[2] conditions where the planetary atmosphere has enough greenhouse gas content which leads to surface conditions that do not allow water to remain in liquid form, *our current condition for harboring life on a planet's surface.*

upper limit usually have a significant gas envelope. The lower bound calculated from this model is at 67 W/m^2. This value was set to be the minimum, F_{min}, for habitable planets in this study.

B. *Habitable eccentricity,* $p(e)$

Limiting a planet's eccentricity would rely on its detectability and its orbit's stability. J. Barnes (2007) showed that a lower bound on the eccentricity can be obtained from the transit data. By assuming that the objects of interest are circular, the systematic error can constrain e in terms of the transit velocity, V_{f_0},

$$e \geq \frac{(V_{f_0}/V_{circ})^2-1}{(V_{f_0}/V_{circ})^2+1}, \quad V_{f_0} > V_{circ}; \quad e \geq \frac{1-(V_{f_0}/V_{circ})^2}{1+(V_{f_0}/V_{circ})^2}, \quad V_{circ} > V_{f_o}$$

In a separate formulation by R. Barnes (2015), the minimum eccentricity was obtained by comparing the transit duration[3] of an eccentric orbit, T, and that of a circular orbit T_c in terms of the ratio $\Delta \equiv T/T_c$ (also known as the transit duration anomaly). These formulations are essentially the same since $V = D/T$.

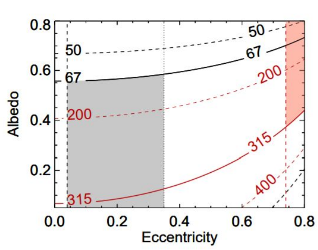
On the other hand, the maximum eccentricity was calculated by analyzing the stability of multi-planetary systems through the Hill criterion. The Hill sphere determines the maximum distance of a satellite from its parent object before it disintegrates due to tidal forces.

C. *Rocky or gaseous,* p_{rocky}

In addition to the flux emitted by an exoplanet, a candidate should also be terrestrial for it to be habitable. The criterion used in this paper is purely based on the planet's radius. This follows from Rogers' (2015) Bayesian statistical analysis of Kepler transiting sub-Neptune planets, where it was shown that there is a distinct transition from populations of rocky exoplanets and predominantly gaseous ones. In particular, exoplanets with radius 1.6 times that of the Earth have very low density for it to be terrestrial. However, a separate observation of Kepler-10c which at the time was observed to have radius of $2.35\ R_\oplus$ and mass $17\ M_\oplus$. Using the available data, a probability criterion given by,

$$p_{rocky}(R_P) = 1,\ R_p \leq 1.5\ R_\oplus;\ (2.5 - R_p),\ 2.5\ R_\oplus > R_p > 1.5 R_\oplus;\ 0,\ R_P \geq 2.5 R_\oplus$$

was used. It was argued in this paper that Kepler-10c is a rocky planet and should be taken into consideration. However, in 2017, using HARPS and HIRES datasets, Kepler-10c was found to be a gaseous exoplanet with mass $\sim 7\ M_\oplus$ and mean density 3 c/cm^3 [2]. In a separate analysis, Kepler-10c was found to be a gaseous exoplanet with mass $\sim 14\ M_\oplus$ and mean density 6 c/cm^3 [3].

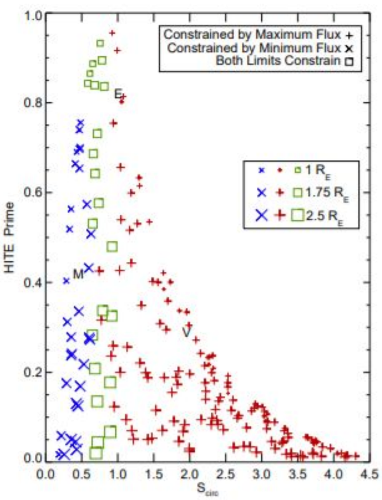


III. Results

Because of the page limitation, I will only focus on key results that pertain to the application of the HITE in analyzing *Kepler* transit data.

[3] The transit duration is the amount of time that a planet traverses the disk of a star. If the impact parameter of the transit is zero (or when the planet passes through the center of the star's disk), the transit duration is maximum. If the impact parameter is non-zero, the transit duration is shorter.

The flux constraints defined above provide us a region of the (A, e) parameter space in which climate conditions are habitable. Contour lines in the figure on the left represent slices of equal emitted flux for unique (A, e) pairs. Dashed and dotted lines represent extremal eccentricity values. An exoplanet candidate with a larger habitable region in this parameter space would receive higher priority in searches under this indexing scheme. For example, the gray area represents Kepler-62 f; while KOI 5737.01 is in red. In this illustration, one would say that Kepler-62 f is a better candidate for habitability.



Not all missions could provide a lower bound for the eccentricity of an exoplanet. Hence, an alternative index H' was used which instead goes through e values from 0 to 1. The figure on the left In Table 1 of the paper, there are H values that are equal to zero. This would indicate that eccentricity limits are not available. The importance of this limit, however, is apparent due to large gaps between H and H', as can be seen in the entry for KOI 5737.01 and KOI 5948.01. As a baseline, the H' of Earth is 0.829. In a sample 194 KOIs with $H' \geq 0.01$, nine were found to have a higher H' compared to Earth's index. However, this does not imply that these KOIs are more habitable than the Earth. It just implies that an Earth-like planetary system in the *Kepler* survey would not be as habitable as these candidates with high H' indices. Due to large statistical uncertainties in the incident stellar radiation ($\delta S_{circ} \sim 36\%$), individual H' values calculated for this *Kepler* dataset are not reliable for habitability searches.

IV. **Discussion**

Barnes et al were able to establish a new habitability index in terms of two conditions based on a candidate's eccentricity, albedo, and material composition. This method is a first approximation to an actual index as it does not take other factors like surface structure and composition into consideration. For example, other indices like SEPHI [4], consider seven planetary parameters. Timescale for life formation and evolution should also be considered in habitability ranking. Constraints on the *Kepler* survey data available for analysis makes the index unreliable for habitability searches. However, future missions could provide data with smaller statistical error, and could harness the full potential of HITE. In particular, infrared spectroscopy measurements from the *JWST* mission could provide us with data about the atmospheres of rocky exoplanets. However, there would be some limitations related to visibility time and brightness that are folded with the HITE. The *TESS* mission on the other hand would obtain transit data from stars 30-100 times brighter than observed in *Kepler* and *K2* surveys. The area covered by the *TESS* survey is also considerably larger since it covers the northern and southern ecliptic hemispheres. [5-6] *TESS* measurements could provide smaller errors for the incident radiation S mentioned above.

Careful interpretation of the data based on this metric should always be our priority. As there could be limited opportunity for us to probe the surface of high HITE candidates, these results should be taken with a grain of salt. Metrics like HITE could only provide us with priority ranking in searches. High HITE would not always translate to higher habitability [7]. This calls for better metric naming in order not to mislead the public, and the scientific community.

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