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A1_8 How Habitable is the Habitable Zone?

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Abstract
We review the plausibility of the previously defined Habitable Zone of a main-sequence star, and its ability to take into account the properties of the star and conclude that it can only contain a Habitable Zone if it has a classification of F or fainter and is above a mass of $0.40M_{\odot}$.

Introduction

The Habitable Zone (HZ) is the region of space around a star under which an orbiting planet can maintain liquid water on its surface, and can be calculated using the formula for luminosity [1]:

$$L_{\odot} = 4\pi d^2 \sigma {T_{eff}}^4 , \qquad (1)$$

where $L_{\odot}$ is the solar luminosity (3.86×10^{26} W [1]), d is the distance of the habitable zone from the centre of the Sun, T_{eff} is the temperature of the surface of the planet and σ is the Stefan Boltzmann constant (5.67×10^{-8} Wm^{-2} [2]).

By choosing different values of T_{eff} and solving for d, it is possible to get a simple estimate for the position and size of the habitable zone.

Theory

Before the equation can be manipulated, it must take into account that all of the flux from the sun is not transmitted through the atmosphere. If we assume that the planet in question has an Earth-like composition, we can allow for this by adding in the transmission coefficient, $(1 - A_{\oplus})$, where $A_{\oplus}$ is the Earth's albedo and rearranging (1) we get that:

$$\left(\frac{L_{\odot}(1 - A_{\oplus})}{4\pi\sigma {T_{max}}^4}\right)^{\frac{1}{2}} \leq d \leq \left(\frac{L_{\odot}(1 - A_{\oplus})}{4\pi\sigma {T_{min}}^4}\right)^{\frac{1}{2}} . (2)$$

In this case it is assumed that no flux is absorbed by the atmosphere. If we take the average Earth albedo to be, $A_{\oplus}$ = 0.35[2], and that T_{min} and T_{max} are the freezing and boiling points of water respectively, (2) becomes:

$$0.90AU \leq d \leq 1.68AU.$$

Since the limits of d vary with $L^{0.5}$, the position and length of the habitable zone vary with the mass of the parent star as can be seen in the figure below:

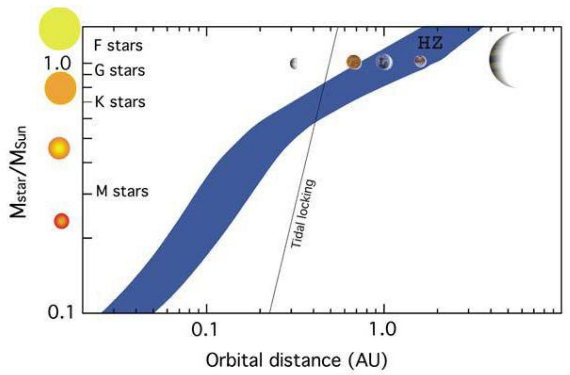

Figure 1: How the habitable zone changes with luminosity of the parent star, ranging from F stars to M stars. Image credit: [3]

However, there is an uncertainty in the range of the HZ due to the constraints applied.

For example, one can assume that liquid water can be maintained under different pressures and atmospheric composition. Then there are uncertainties in these parameters as well, leading to very optimistic estimates (0.75

AU ≤ d ≤ 1.24 AU, [4]) to very restrictive estimates (0.95 AU ≤ d ≤ 1.01 AU [5]). Therefore calculating the boundaries of the HZ is no simple task.

Other restrictions

Younger stars have higher luminosities than older stars of the same mass, and would therefore have a HZ further away from it [6].

Only some stars are able to have HZs and in the Harvard classification of stars, only F, G and K stars are able to have such a region of space around them.

Brighter stars are not able to contain HZs in which complex life can evolve as they have a lifetime that is too short [6]. Whereas, M stars would be tidally locked (the planet is unable to spin on its axis due to the proximity of the star) to planets that were in the HZ, thus only one side would be illuminated and the other would have an unsuitable climate for life, causing the planet to be un-inhabitable [6].

The maximum radius at which tidal locking will occur, r, is defined as [7]:

$$r = 0.0027\left(\frac{P_0 t}{Q}\right)^{\frac{1}{6}} M^{\frac{1}{3}} \text{ , } \dagger \qquad (3)$$

where P_0 is the orbital period of the Earth when it was formed, t is the time period after formation of the planet and Q is the reciprocal of the solid body plus ocean dissipation function. These parameters are found to be: 13.5 hours, 4.5 Gyr (1 Gyr = 1 billion years) and 100 respectively [6].

By setting r equal to the upper limit of d, remembering that:

$$L = L_{\odot}\left(\frac{M}{M_{\odot}}\right)^{3.5} . \qquad (4)$$

Is true for low-mass main sequence stars [8] and re-arranging for M, we can find the minimum mass star required to have a habitable zone:

$$M \geq \left[\left(\frac{4\pi\sigma(0.0027)^2 M_{\odot}^{3.5} T_{min}^4}{L_{\odot}(1 - \mathrm{A}_{\oplus})}\right)^3 \left(\frac{Q}{P_0 t}\right)\right]^{\frac{2}{17}} . (5)$$

Substituting the appropriate values into (5) gives $M \geq 0.40\ \mathrm{M}_{\odot}$, in order for the planet to avoid tidal locking after 4.5 Gyr.

Conclusion

We have found that the HZ is heavily influenced by the parent star of the planet. As such, only stars with classification F, G, K and M with masses greater than 0.40 $\mathrm{M}_{\odot}$ are able to host Earth-like planets. However this limit may be reduced further by taking other effects such as the atmosphere, magnetic field strength and age of the star into account.

References

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[8]http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/herrus.html#c3 Accessed (24/2/11)

† This is the SI version of equation (3) the original is calculated in CGS units [7].