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Circumstellar Habitable Zone of Solar Mass Stars

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Habitable Zones of Solar Mass Stars

Abstract

The formation of life on Earth is in large part due to the intrinsic luminosity of the Sun and the radiant flux Earth receives. Earth lies within the circumstellar habitable zone (CHZ) of the solar system, a region of inner and outer radius around a star that will most likely support intelligent life. This project used computational models to estimate what range of solar masses would allow for the formation of life on Earth as we know it. The minimum and maximum radiant flux humans could possibly withstand was calculated, and then this value was used to determine a range of luminosities within the models of stars of different masses that are feasible to support life. There are only certain mass stars for which their stellar properties and resulting CHZ last long enough, a time period of about four billion years, within the required range to foster the creation of life.

Introduction

To begin the analysis of CHZs of solar mass stars, the inverse square law provides insight into the radiant flux, the amount of energy received per square meter of Earth’s surface. In other words, this energy deals with the spectral distribution of radiation, and if this energy is too dissimilar from the Sun’s, the star would produce too much UV radiation for life to occur. The equation shown how the flux decreases with the square of the distance from the star:

\[ F = \frac{L}{4\pi r^2} \]

The most recent estimate on the solar system’s CHZ is from 0.5 AU to 1.688 AU (2013). Using the MESA code (see Methods), the minimum and maximum intrinsic luminosity of the sun was recorded for the past one billion years. These values correspond to the CHZ radii, and plugging them into the equation yields an estimate of the minimum and maximum radiant flux that humans can withstand on Earth. In watts per square meter, the range is:

\[ 436 \leq F \leq 5662 \text{ W/m}^2 \]

Earth currently receives a radiant flux of 1365 W/m², so this result makes sense. The resulting range of fluxes corresponds to a factor of 0.319 \( \text{L}_\odot \) and 4.15 \( \text{L}_\odot \) for the minimum and maximum flux, respectively. Using the ratio of luminosity to solar luminosity, \( \log(L/L_\odot) \), the values of the minimum and maximum luminosity that humans can possibly withstand were obtained:

\[ -0.495646 \leq \log(L/L_\odot) \leq 0.617837 \]

These values occurred in the main sequence stage of evolution of each solar mass star, and each star maintained this desired intrinsic luminosity range for different amounts of time, thus resulting in ruling out certain solar masses that do not provide enough time in the CHZ for the evolution of life to occur.

As expected, we get a bell-curve like graph of solar mass vs. habitable time, with the smallest and greatest masses yielding a time less than four billion years, so these masses are not conducive to long-lasting evolving life. The sweet spot of over four billion years is highlighted in the graph on the left, ranging from 0.6 \( \text{M}_\odot \) to 1.2 \( \text{M}_\odot \). The graph on the right shows the lower and upper limits and their area of intersection. This is the area of habitability for the given range of solar mass stars. Again, it is shown that stars below 0.6 \( \text{M}_\odot \) and above 1.2 \( \text{M}_\odot \) are not feasible candidates for the evolution of life.

An interesting find is that the greatest habitable time range peaks between 0.8 and 0.5 \( \text{M}_\odot \) rather than at 1 \( \text{M}_\odot \), our sun. This result is not entirely unexpected—the masses are very close to that of the sun and even accounting for error within the models, this may very well be true. As stars increase in mass, their lifetimes become shorter. The area of interest for this project, the main sequence stage of stellar evolution, feels this effect. As the solar mass increases, the star spends continually less time in the main sequence.

Results and Discussion

If this result is in fact due to error, it would arise from the gap in information between models in the MESA code. Going from one model to the next may leave a gap anywhere between 0.001 and 0.1 luminosities, so analyzing their limits is not entirely precise. Either way, the maximum luminosity was recorded without going over the limit, and these small inaccuracies could have accounted for the majority of experimental error.

Pictured on the left is a zoomed in Hertzsprung-Russell diagram from the sample png in Methods. The log of the effective temperature is on the x-axis and the log of the ratio of luminosity to the luminosity of the sun is on the y-axis. This graph shows the main sequence stage of stellar evolution. The stage has the best long-lasting range of luminosities and radiant fluxes humans can withstand. The upper and lower luminosity limits are marked here with purple dots (approximately -0.4 to 0.6).

Methods

Modules for Experiments in Stellar Astrophysics (MESA) was the computing platform utilized for this project. This code contains presets that allow the user to run simulations of stars while manipulating specific parameters. Solar mass, of course, was the independent variable and the stellar luminosities and star age were read out from the resulting data once the simulation ran its course.

Conclusion

- The optimal solar mass stars for habitability, producing luminosities and radiant fluxes that support the evolution of life for at least four billion years, are 0.6 \( \text{M}_\odot \) to 1.3 \( \text{M}_\odot \).
- This range peaks at 0.8 \( \text{M}_\odot \), with an estimated habitable age range of 19.2 billion years.

Using these two pieces of information, the search for candidate planets that may support alien life can be narrowed down significantly. Instead of searching for the planets themselves, telescopes can set their sights upon the stars at the center of systems to see what their solar mass has to tell us. If the star is within the ranges specified above, then the radii of the CHZ can be calculated and the search can begin for existing planets within the CHZ. If we ever need to evacuate planet Earth or seek the help of our friendly neighborhood life forms, the answer begins here.

References

https://en.wikipedia.org/wiki/Circumstellar_habitable_zone
http://mesa.sourceforge.net