Revisiting Seager's 2013 Habitability Diagram with 2025 Data

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Abstract

In a 2013 review, S. Seager presented a summary of known exoplanets and discussed habitability within the classic habitable zone framework. We extended Seager's work by incorporating a much larger and more current dataset of 5,834 confirmed exoplanets from the NASA Exoplanet Archive. We then further highlighted exoplanet types (Terrestrial, Super-Earth, Neptune-Like, Gas-Giant), scaled data points by planet size, and calculated inner and outer habitable zone (HZ) boundaries with a simplified greenhouse-based temperature model. Our updated figure illustrates the distribution of exoplanets relative to stellar mass and exoplanet orbits, underscoring the complex interplay of planetary and stellar properties that drive the potential for habitability.

1. Introduction

Exoplanet habitability is a core theme in modern astronomy and astrobiology. In a 2013 review, Seager (2013) emphasized the wide diversity of exoplanets—spanning masses, sizes, and orbital configurations—and discussed the challenges in defining habitability solely by distance from the host star. At that time, roughly one thousand exoplanets were known, and the community had only begun mapping out how exoplanets cluster around different stellar types.

Since then, exoplanet discoveries have grown dramatically, with thousands of additional confirmed planets and vastly improved measurements of planetary and stellar parameters. Here, we revisited the star mass–exoplanet orbital relationship that Seager illustrated in her Figure 2 (2013), but with a greatly expanded dataset. We also introduced (1) exoplanet types (Terrestrial, Super-Earth, Neptune-Like, Gas-Giant), (2) planet-size scaling of data points, and (3) explicit habitable zone (HZ) boundary curves derived from a simple greenhouse-based surface temperature model. While Seager's original figure (2013) established the overall diversity of exoplanets, our updated visualization shows how that diversity has evolved over the past decade and provides a modern snapshot of potential habitability.

2. Data and Methods

2.1 Data Sources

We obtained stellar and planetary parameters for 5,834 confirmed exoplanets from the Planetary Systems Composite Data of the NASA Exoplanet Archive[1] (accessed 15 February 2025). Following Seager's emphasis on physically robust detections, we excluded exoplanets flagged as controversial ("pl_controv_flag=1") and restricted the sample to single-star systems to reduce complications from stellar multiplicity.

[1] https://exoplanetarchive.ipac.caltech.edu/

The NASA Exoplanet Catalog[2] (accessed 4 January 2025) classifies exoplanets into four types: Terrestrial (smaller than Earth), Super-Earth (size between Earth and Neptune), Neptune-Like (Neptune sized and smaller than Saturn), and Gas-Giant (similar size as Saturn or larger). We adopted this radius-based classification in our analysis.

2.2 Habitable Zone Boundaries

We adopted a simplified greenhouse-based formula similar to the approach by J. H. Jiang et al. (2024) to estimate inner and outer HZ boundaries for each host star. The average surface temperature of an exoplanet, $T_{surf,avg}$, depends on:

$$T_{surf,avg} = kT_*(1-A)^{0.25}\left(\frac{R_*}{2d}\right)^{0.5} \qquad (1)$$

where T_* and R_* are the host star's effective temperature and radius, d is the exoplanet's orbital distance, A is albedo, and k accounts for atmospheric greenhouse effects. We set $A = 0.306$ (Earth's value) and $k = 1.13$ to approximate an Earth-like atmosphere. To estimate the HZ inner and outer boundaries for each host star, we rearranged the above equation (1) into equation (2) to calculate the corresponding exoplanet orbital distances where $T_{surf,avg} = 373.15$ K (100°C) and $T_{surf,avg} = 273.15$ K (0°C):

$$d = \frac{k^2 T_*^2 (1-A)^{0.5} R_*}{2T_{surf,avg}^2} \qquad (2)$$

We then fitted the host stars' HZ inner boundary data points and outer boundary data points to the corresponding 5^{th}-degree polynomials through least squares regression.

3. Results

Figure 1 updates Seager's diagram (2013)—originally ~1,000 exoplanets—by plotting 5,834 confirmed exoplanets as of early 2025. We set host star mass as the y-axis and exoplanet orbital semi-major axis (logarithmic scale) as the x-axis, color-coding by planetary type and scaling the points by exoplanet radius. The Earth and the other Solar System planets are included for reference. We also computed each star's HZ boundaries and marked them in red (inner edge) and blue (outer edge), with the 5^{th}-degree polynomial fits shown as solid curves.

The updated figure shows several Terrestrial exoplanets within HZs which are particularly worthy of further analysis. They are rocky and Earth-like in size, making them promising candidates for supporting life. Gliese 12 b (M. Kuzuhara et al. 2024), TOI-700 e (E. A. Gilbert et al. 2023), and TRAPPIST-1d (J. de Wit et al. 2018) are among these exoplanets. Super-Earth exoplanets, larger than Earth and potentially rocky, could also be promising candidates if located within HZs—HD 20794 d (N. Nari et al. 2025), Kepler-452 b (J. M. Jenkins et al. 2015), and TOI-715 b (G. Dransfield et al. 2024) are several such examples. The figure also indicates that a number of Gas-Giant exoplanets fall within the HZs of their host stars. While Gas-Giant exoplanets themselves cannot harbor life due to their composition, the moons orbiting them might be potentially habitable.

[2] https://science.nasa.gov/exoplanets/exoplanet-catalog/

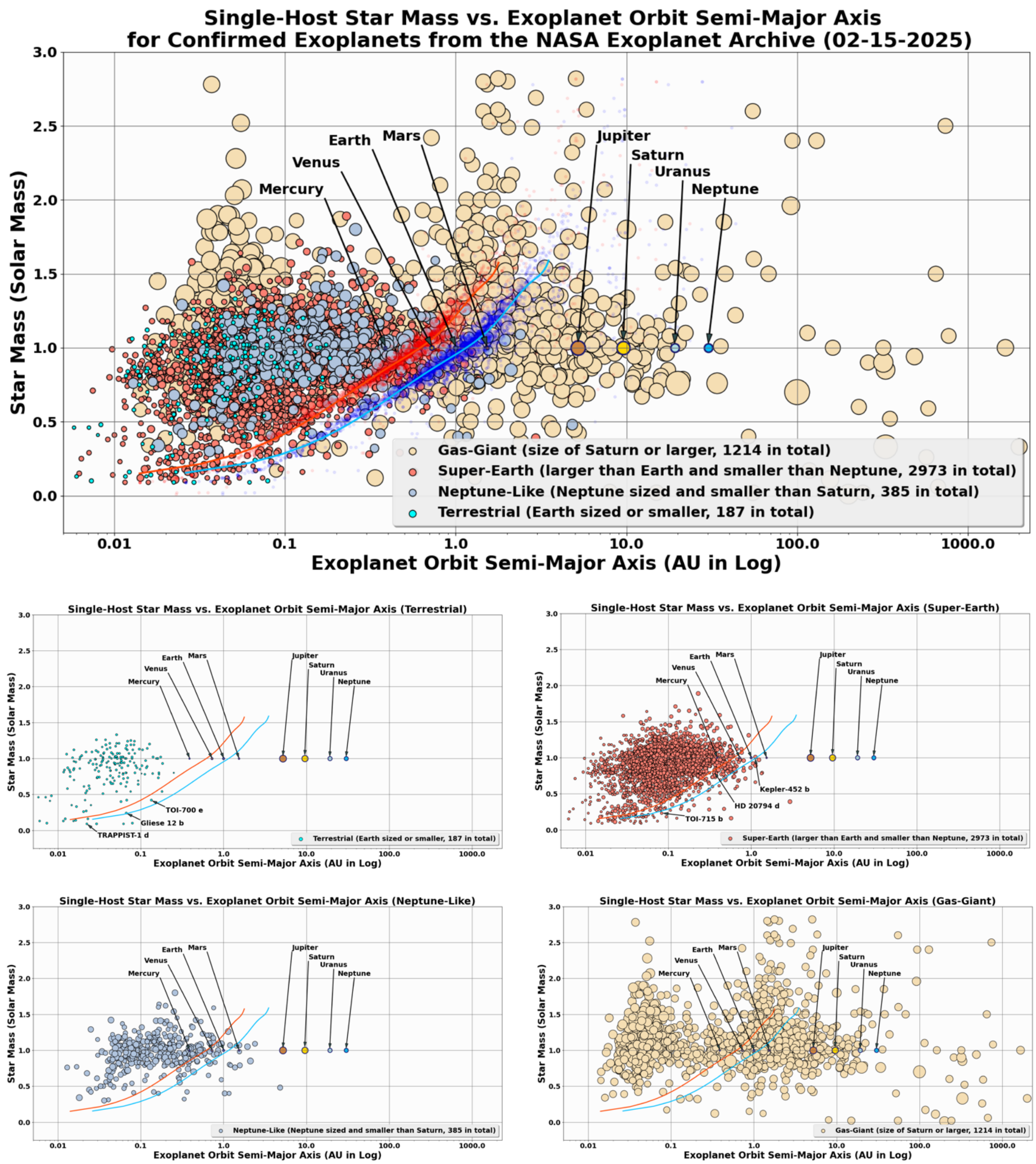

Figure 1. Top: single-host star mass vs. exoplanet orbital semi-major axis diagram. Exoplanets are colored by type and scaled by radius. Each pair of red and blue markers show the computed inner and outer HZ boundaries respectively for each host star, with the 5$^{\text{th}}$-degree polynomial fits (from the least squares regression) indicated by the red and blue solid curves. Graphs on the mid-left, mid-right, bottom-left, and bottom-right are the breakdown diagrams for Terrestrial, Super-Earth, Neptune-Like, and Gas-Giant exoplanets respectively.

Venus, known to be too hot for life, appears within the HZ in the figure. This discrepancy is due to using Earth-like values for A (albedo) and k (constant accounting for atmospheric greenhouse effects) in equation (2) when estimating the HZ inner and outer boundaries. In reality, Venus has a dense, CO_2-rich atmosphere that traps heat and thus has a much higher k value compared to Earth, resulting in a much higher surface temperature. This highlights the importance of including atmospheric characteristics—such as greenhouse gas composition and cloud cover—when evaluating planetary habitability.

Overall, this updated figure reinforces Seager's central conclusion (2013) that "anything is possible within the laws of physics and chemistry," as the known exoplanet population continues to exhibit remarkable diversity. The newer, larger sample confirms that exoplanet orbital distributions remain wide-ranging. Future work on atmospheric characterization—particularly for smaller exoplanets in or near the HZ—will be essential to refine habitability assessments.

4. Summary

We have expanded upon Seager's review (2013) by updating the star-mass vs. exoplanet-orbit diagram with a far more extensive exoplanet catalog, incorporating exoplanet types, radii, and HZ boundary estimates. This single figure reveals both the profound diversity in exoplanetary systems and the importance of an Earth-like atmospheric model in estimating habitable zones. As we move toward an era of more detailed atmospheric observations, especially for smaller worlds, these data will guide deeper investigations into whether any truly habitable—and possibly inhabited—exoplanets lie among the thousands now known.

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