Revisiting Seager's 2013 Habitability Diagram with 2025 Data

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Keywords: Exoplanet, Habitability

Abstract

In a 2013 review, S. Seager presented a summary of known exoplanets and discussed habitability within the classic habitable zone framework. We extend Seager's work by incorporating a much larger and more current dataset of 5,834 confirmed exoplanets from the NASA Exoplanet Archive. We further highlight exoplanet types (Terrestrial, Super-Earth, Neptune-Like, Gas-Giant), scale data points by planet size, and calculate 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 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 [1] 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 revisit the star–exoplanet orbital relationship that Seager illustrated in her 2013 Figure 2, but with a greatly expanded dataset. In addition, we introduce (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 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 (accessed 15 February 2025) [2]. To attach exoplanet type (Terrestrial, Super-Earth, Neptune-Like, and Gas-Giant), we joined these records with NASA's Exoplanet Catalog (accessed 4 January 2025) [3]. Because the catalog does not offer a direct download, we wrote a Python script to parse exoplanet names and types from the web pages.

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. The final dataset includes exoplanet radius, exoplanet orbital semi-major axis, exoplanet type, host star mass, host star effective temperature, and host star radius for each system.

2.2 Habitable Zone Boundaries

We adopt a simplified greenhouse-based formula (similar to the approach in [4]) to estimate inner and outer HZ boundaries for each host star. The average surface temperature of a planet, $T_{surf,ave}$, depends on:

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

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. Defining the HZ where $273.15\text{ K} \leq T_{surf,ave} \leq 373.15\text{ K}\,(0-100°\text{C})$, we invert the above equation to solve for the orbital distances that correspond to these boundaries. We then record the inner (100°C) and outer (0°C) HZ distances for each star in our dataset.

3. Results

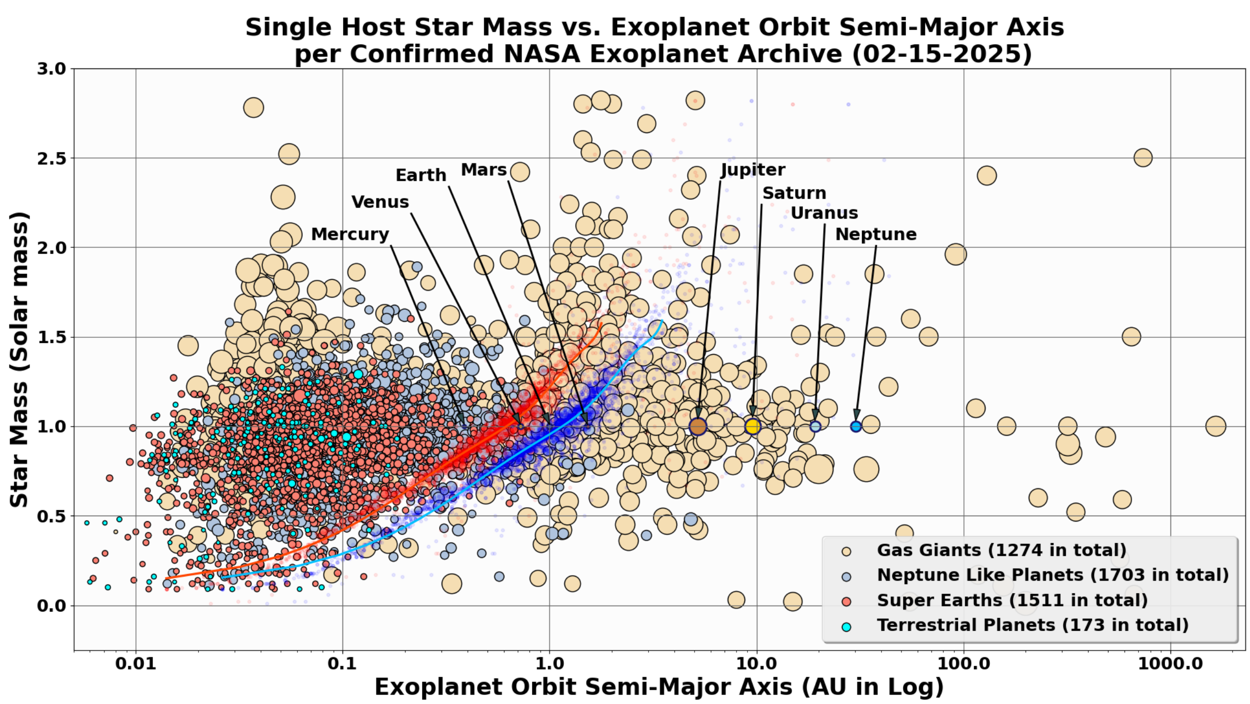

Figure 1. Single- host star mass vs. exoplanet orbital semi-major axis. Exoplanets are colored by type and scaled by planet radius. Red and blue markers show the computed inner and outer HZ boundaries, respectively, for each star, with 5th-degree polynomial fits indicated by solid curves.

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

This updated figure reinforces Seager's central conclusion 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 2013 review 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.

References

[1] Seager, S. 2013, *Science*, 340, 577.

[2] NASA Exoplanet Archive. NASA Exoplanet Archive: Planetary Systems Composite Data. 2024. Available online: https://exoplanetarchive.ipac.caltech.edu/ (accessed on 15 February 2025).

[3] NASA Exoplanet Catalog. 2025. Available online: https://science.nasa.gov/exoplanets/exoplanet-catalog/ (accessed on 4 January 2025).

[4] Jiang, J.H., P.E. Rosen, C.X. Liu, Q. Wen, and Y. Chen, Analysis of Habitability and Stellar Habitable Zones from Observed Exoplanets, *Galaxies* 12, no. 6: 86, 2024.