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Earth Similarity Index (ESI)

Introduction

The Earth Similarity Index (ESI), or the "easy scale," is an open multiparameter measure of Earth-likeness for solar or extrasolar planets as a number between zero (no similarity) and one (identical to Earth) (Schulze-Makuch *et al.*, 2011). Similarity measures are used in many fields to solve many pattern recognition problems such as classification, clustering, and retrieval problems (Cha, 2007). The ESI can be used to simplify planet comparisons, identify planets of interest from large databases, prioritize follow-up observations, and perform statistical analyses on the occurrence of Earth-like planets.

The ESI is not a direct measure of habitability but formally a fuzzy comparison, using a distance metric, between a selected set of planetary properties of a planet and Earth. The more properties that are used in the ESI calculation the better the comparison with Earth (i.e. identify the 'Earth' cluster in a large database). The search for Earth-like planets is synonymous with the search for planets with ESI values closer to one. There are many ways that an ESI can be mathematically constructed depending on the needs and available data. Once constructed the more important thing is how to interpret its values.

ESI for Exoplanets

A simple ESI expression, as a function of a planet's stellar flux and radius, is used for exoplanets since there is little information about them. The ESI(S,R) is given by:

$$\mathrm{ESI}(S,R) = 1 - \sqrt{\frac{1}{2}\left[\left(\frac{S-S_\oplus}{S+S_\oplus}\right)^2 + \left(\frac{R-R_\oplus}{R+R_\oplus}\right)^2\right]}$$

where S is stellar flux, R is radius, $S_\oplus$ is Earth's solar flux, and $R_\oplus$ is Earth's radius. This ESI expression uses the quadratic mean as the distance metric, which is very convenient to interpret statistically (e.g. as a chi-squared distribution). This expression can be used for those planets detected by the transit method (e.g. Kepler, TESS, Plato, etc.) where only the planet's radius is known. It is also extendable to planets detected by the radial velocity method (i.e. HARPS) where only the mass is known by assuming that $R = M^{1/3}$, where M is the planet's mass (or minimum mass). A mass-radius relationship can also be used for this conversion but it is not necessary since it gives similar results within the interest values (i.e. close to ESI = 1.0). The ESI(S,R) is used by the Habitable Exoplanets Catalog to sort its objects of interest (Figure 1).

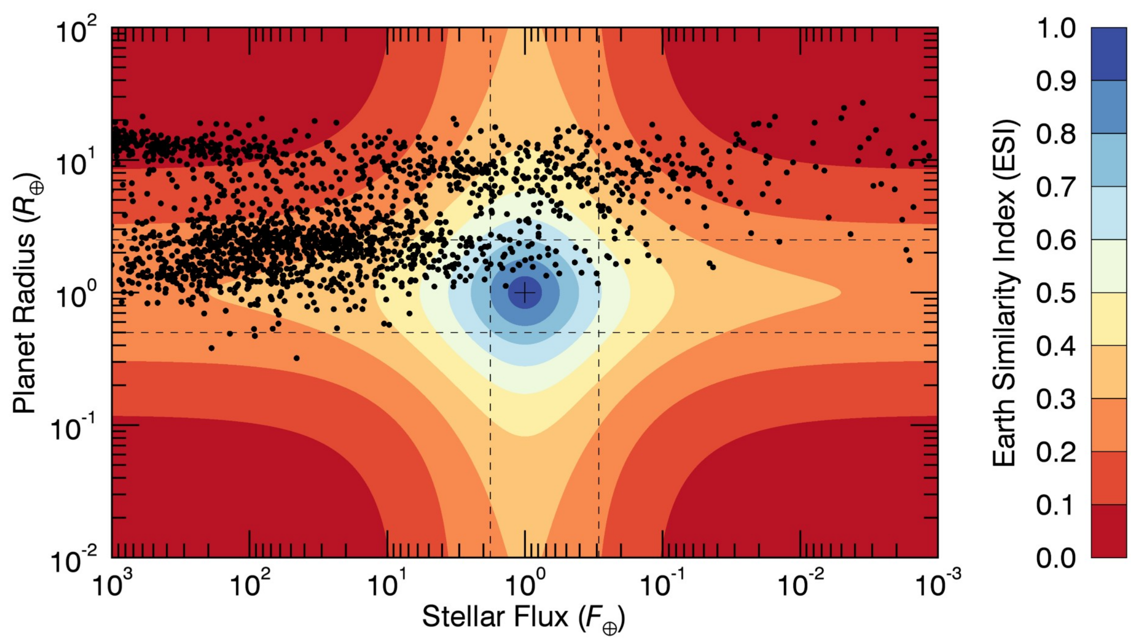

Figure 1. Space of an Earth Similarity Index (ESI) as a function of stellar flux and radius. Black dots represent known planets. Vertical dashed lines enclose the HZ for Sun-like stars. Horizontal dashed line enclose 0.5 to 2.5 Earth radii.

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ESI from Radius, Density, Escape Velocity, and Surface Temperature.

An ESI formulation given a planet's radius, density, escape velocity, and surface temperature provides the simplest and best combination of parameters to compare planets with Earth (Schulze-Makuch *et al.*, 2011). Using this ESI formulation, any planetary body with an ESI value over 0.8 can be considered an Earth-like planet. This means that the planet is likely rocky and support a temperate atmosphere. Planets with ESI values in the 0.6 to 0.8 range (e.g. Mars) might still be habitable since habitability depends on many other factors. The ESI is given by:

$$\mathrm{ESI} = \prod_{i=1}^{n} \left(1 - \left|\frac{x_i - x_{io}}{x_i + x_{io}}\right|\right)^{\frac{w_i}{n}}$$

where xi is a planetary property (e.g. surface temperature), xio is the corresponding terrestrial reference value (e.g. 288 K), wi is a weight exponent, n is the number of planetary properties, and ESI is the similarity measure. The weighting exponents are used to adjust the sensitivity of the scale and equalize its meaning between different properties. In practice, a simpler and more limited form of the ESI formulation is used for exoplanets (using only stellar flux, mass or radius) since this is the only data available of them.

The parameters for the ESI equation for mean radius, bulk density, escape velocity, and surface temperature are shown in Table 1. Sample calculations for solar and extrasolar planets (assuming different mass, radius, and surface temperatures) are shown in Figure 1. They are also divided for convenience into an Interior ESI, based on the mean radius and bulk density, and a Surface ESI, based on the escape velocity and surface temperature. Both the interior and surface ESI are combined into a global ESI. The ESI is more a surface than a subsurface indirect indicator of habitability due to its Earth-centric definition (Table 1).

A similarity formulation can be constructed for other planetary bodies using different reference values (e.g. jovian-like planets). One of the most practical applications of the ESI is in studies about the distribution and diversity of Earth-like planets (Figure 2). Sample ESI values of the Kepler planets candidates are shown in Figure 3. Complete data table for the solar, extrasolar and Kepler planets ESI values and IDL code is available in the resources section below.

Table 1. Reference values and weight exponents for the four planetary properties used to define the ESI. The scale is much more sensitive to surface temperature than to the other planetary properties.

Planetary Property	Reference Value	Weight Exponent
Mean Radius	1.0 Eu	0.57
Bulk Density	1.0 Eu	1.07
Escape velocity	1.0 Eu	0.70
Surface Temperature	288 K	5.58

Note: Eu = Earth's units

Results (These plots are outdated)

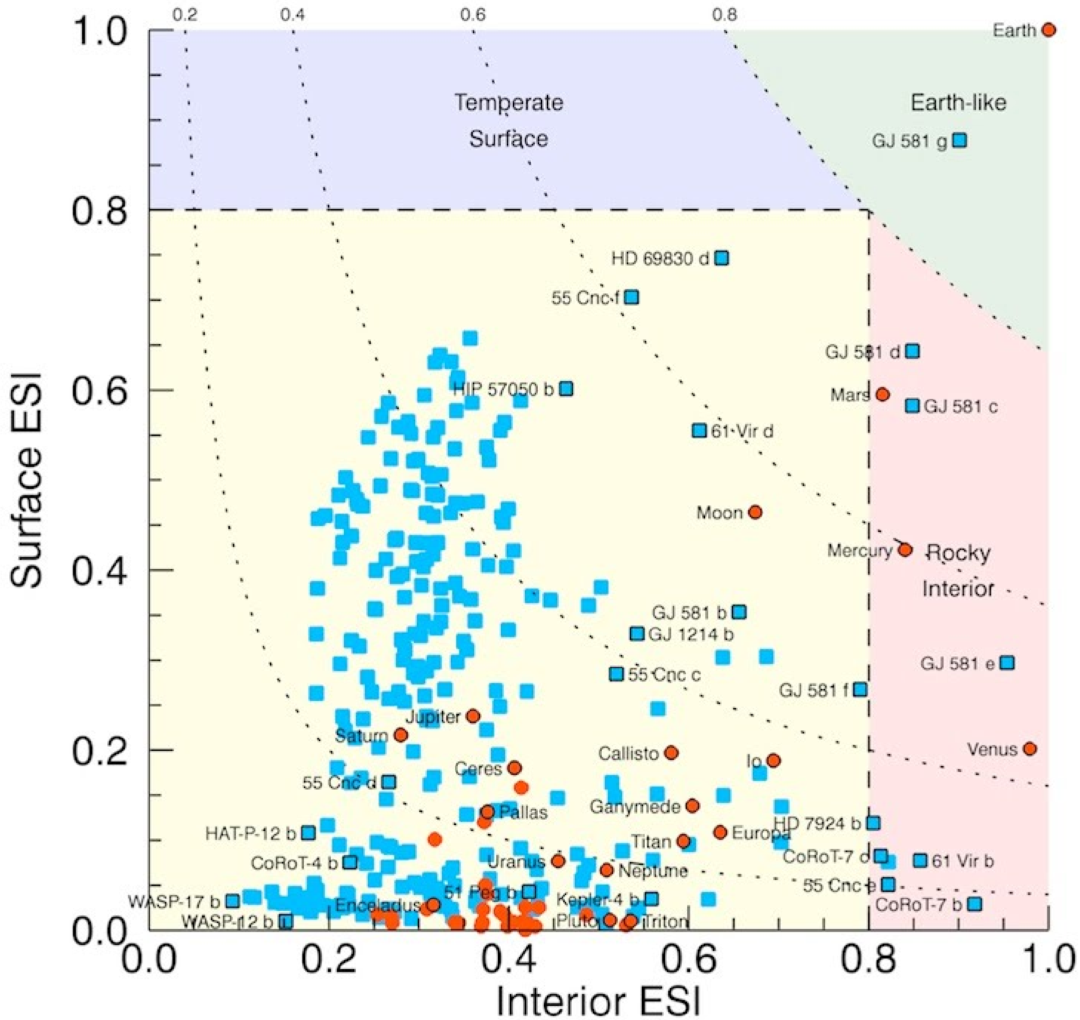

Figure 2. ESI for 47 Solar System bodies with radius greater than 100 km (orange) and 258 known extrasolar planets (blue). Only some of the most notable bodies are labeled. The ESI scale makes a distinction between those rocky interior (light red area) and temperate surface (light blue area) planets. Only planets within these two categories can be considered Earth-like planets (light green area). The dotted lines represent constant ESI values. If confirmed, only Gliese 581 g is in the Earth-like category together with Earth.

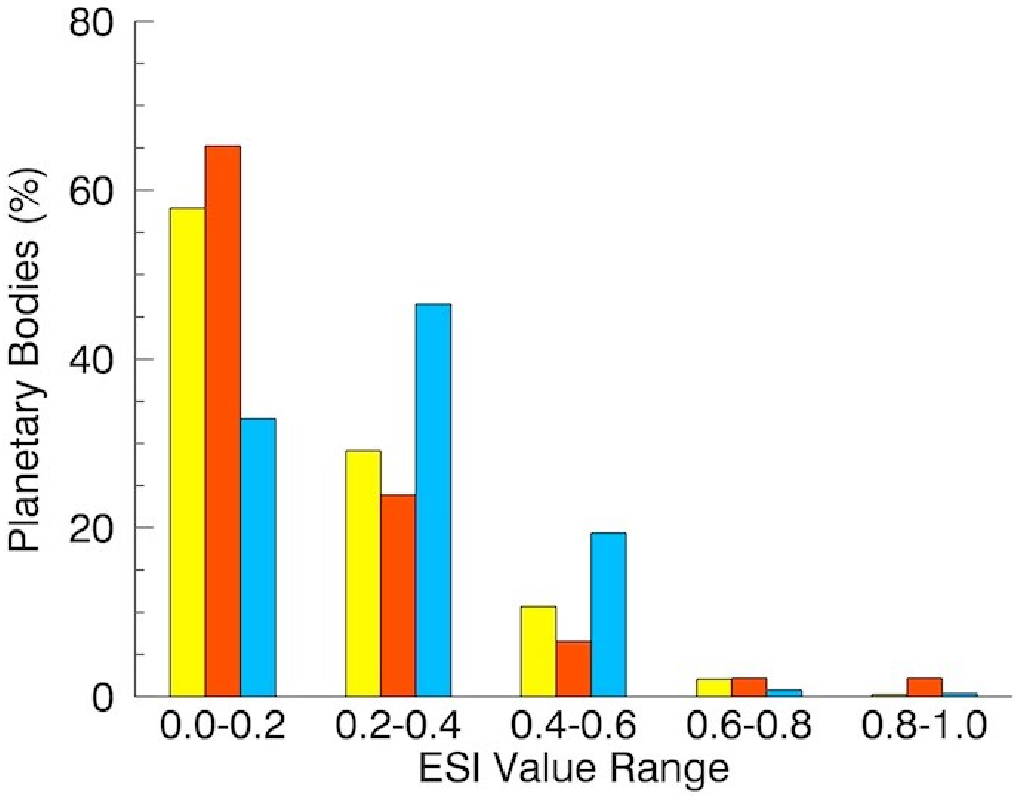

Figure 3. Distribution of ESI values based on a theoretical statistical prediction (yellow), for 47 Solar System bodies with radius greater than 100 km (orange), and 258 known extrasolar planets (blue). Our Solar System match the prediction but the bars for the known extrasolar planets show the bias of current observational techniques toward large planetary bodies (ESI values between 0.2 and 0.4). This type of analysis with the ESI can be used to predict the number of expected Earth-like planets within a sample of stars.

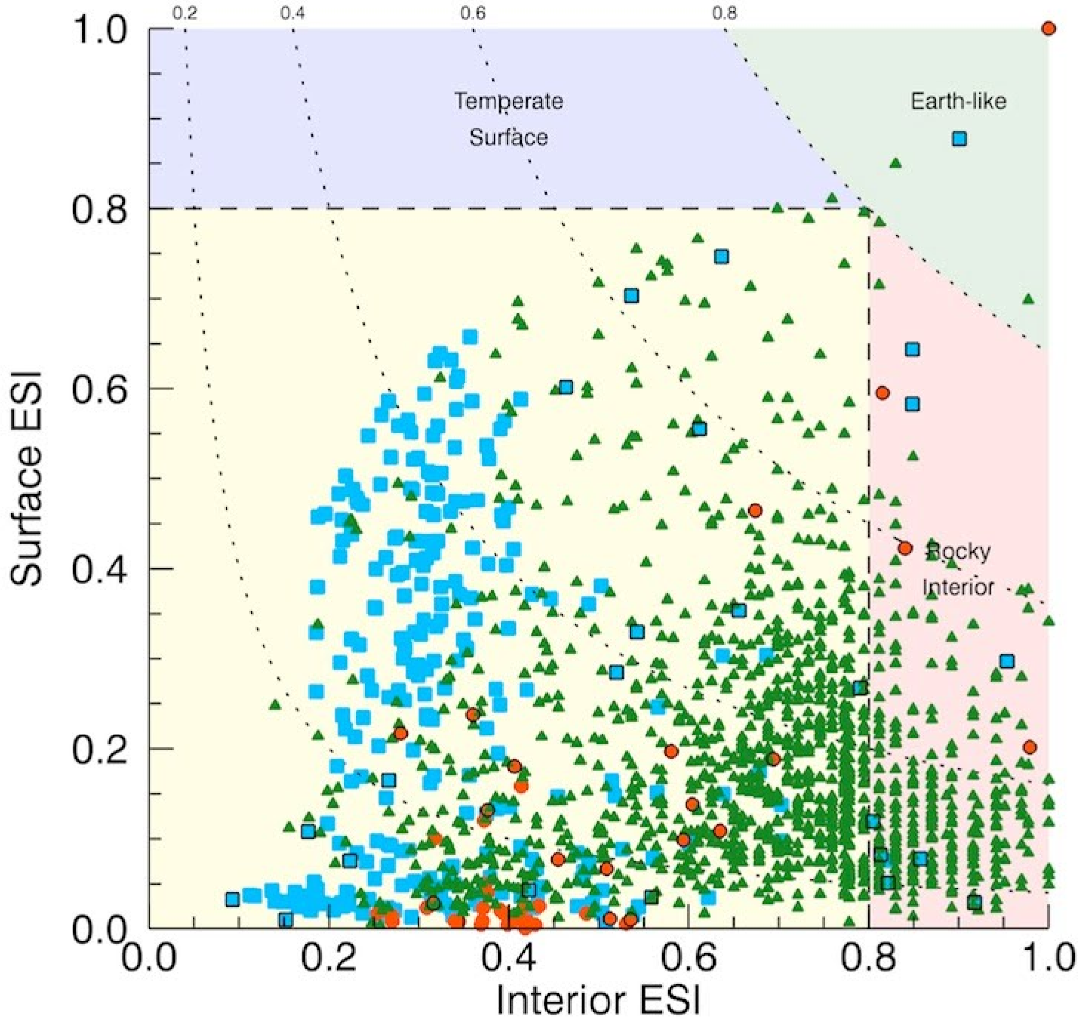

Figure 4. ESI for 47 Solar System bodies with radius greater than 100 km (orange), 258 known extrasolar planets (blue) and Kepler's 1235 planet candidates (green). The mass for the ESI calculations was estimated using generic mass-radius relationships for gas, ocean, and rocky planets (there was no mass in the dataset). The surprising result in the Kepler data is the potential abundance of rocky bodies and the presence of two Earth-like planets candidates, plus a few more close to this category. The information on this planetary candidates is very limited and further observations will be necessary to confirm them.

Resources (This data is outdated)

- ESI Data Table for solar planets.
- ESI Data Table for extrasolar planets.
- ESI Data Table for Kepler's planetary candidates.
- ESI Code in IDL (works with the free GDL too).

References

- Schulze-Makuch, D., Méndez, A., Fairén, A. G., von Paris, P., Turse, C., Boyer, G., Davila, A. F., Resendes de Sousa António, M., Irwin, L. N., and Catling, D. (2011) A Two-Tiered Approach to Assess the Habitability of Exoplanets. Astrobiology 11(10): 1041-1052. [paper link]

- Cha, S.-H. (2007). Comprehensive Survey on Distance/Similarity Measures between Probability Density Functions. International Journal of Mathematical Models and Methods in Applied Sciences. 1(4). [Paper Link]

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