Determining the Habitability of Exoplanets

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Abstract

Given the many possible variables in the detection of life and the habitability of planets, there must be a method implemented to efficiently process the data collected from the Kepler telescope and other imaging systems. The general process of identifying a habitable exoplanet first includes collecting spectroscopy data, among other information regarding a particular exoplanet. Finally, these planets are determined to be habitable in accordance with the analysis, which should produce information such as the location of an exoplanet with respect to its star's habitable zone, and the planet's possible composition. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

Approximating Habitable Zones

In general, the habitable zone (HZ) refers to the area around a particular star where liquid water could exist on the surface of a planet in orbit, given the parameters of the host star and the planet being observed. An approximation of the inner and outer boundaries of the HZ is given by the equations $r_i = \sqrt{\frac{L}{1.1}}$ and $r_o = \sqrt{\frac{L}{.53}}$, where r_i and r_o are the values of the inner and outer radius, L is the absolute luminosity of the host star, and the values 1.1 and 0.53 are constants describing stellar flux at the inner and outer radius respectively. This estimate is based on the concentration and form of CO_2 in the atmosphere of a planet which relates to a stable atmosphere and the presence of liquid water on the surface.

Fig. 1 depicts the relationship between star luminosity and the position of the HZ (increasing distance at a square root rate), while Fig. 2 displays the position of each viable planet in their respective zones ((pl_dist - lower_zone_dist) / zone_width). Most are clustered around the inner limit of the HZ. Overall, in the dataset, 39 planets are located in a favorable HZ.

Figure 1

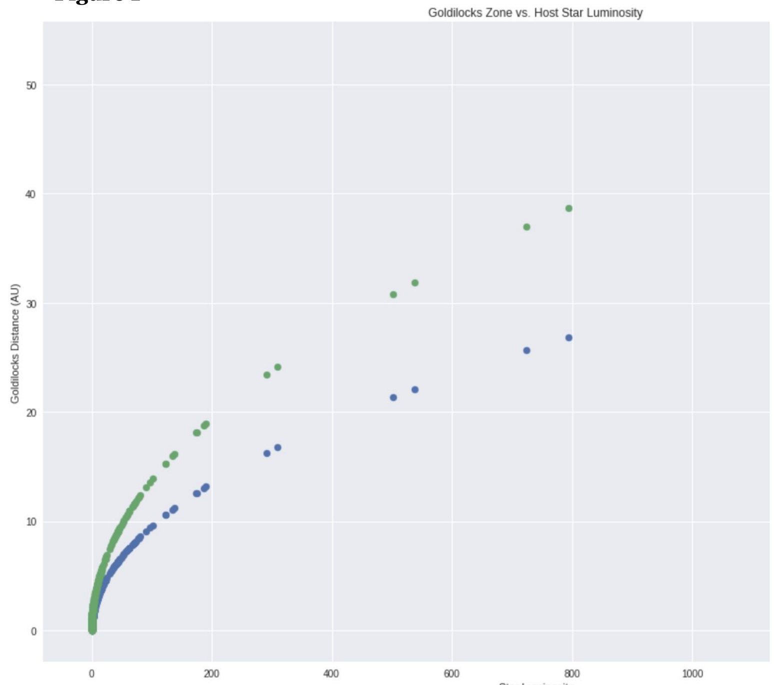
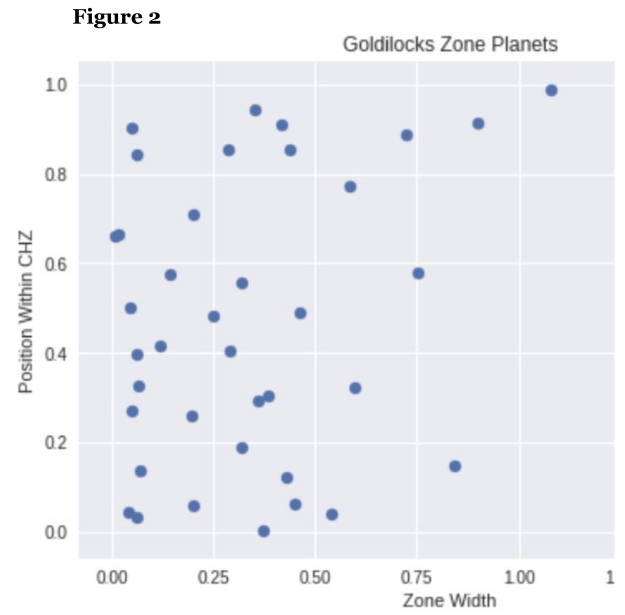


Figure 2



Equilibrium Temperature

According to a study done by Kaltenegger and Sasselov, for planets similar to Earth in size, the limits of the habitability zone can be can be defined by a planet's equilibrium temperature falling between 175K and 270K. This range considers the temperature needed for liquid water to exist on the surface, given atmospheric conditions, such as the greenhouse effect, that would exist on a theoretically habitable exoplanet. Of those planets with a listed equilibrium temperature, 17 fall within the range, as shown in Fig. 3. Only 4 planets satisfy the Goldilocks Zone restrictions and are in the viable temperature range -- Kepler 22b, Kepler 1653b, Kepler 1652b, and TRAPPIST 1e, giving these planets a high chance of being habitable by Earth-like life.

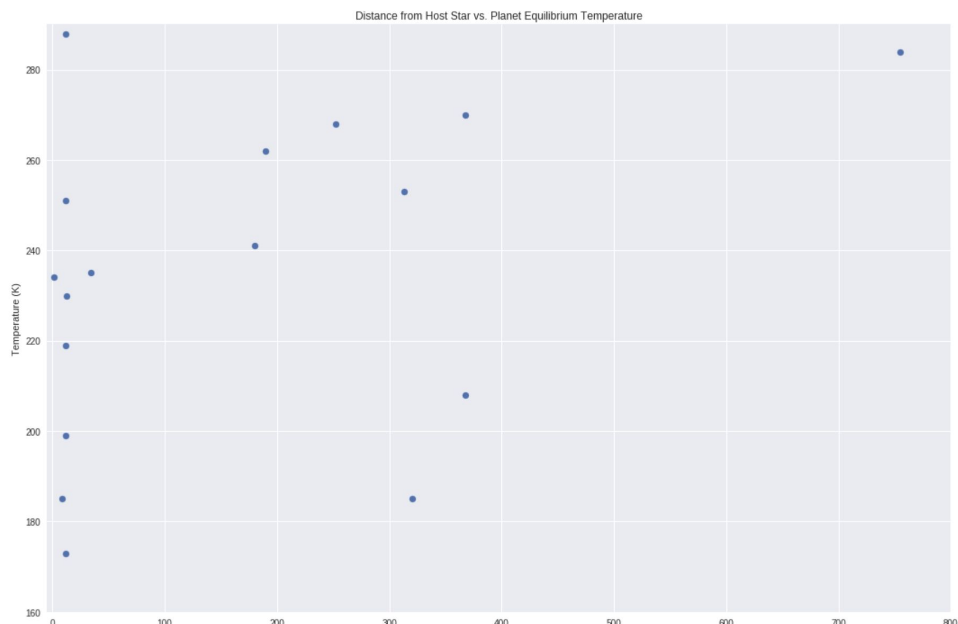


Figure 3

Figure 5

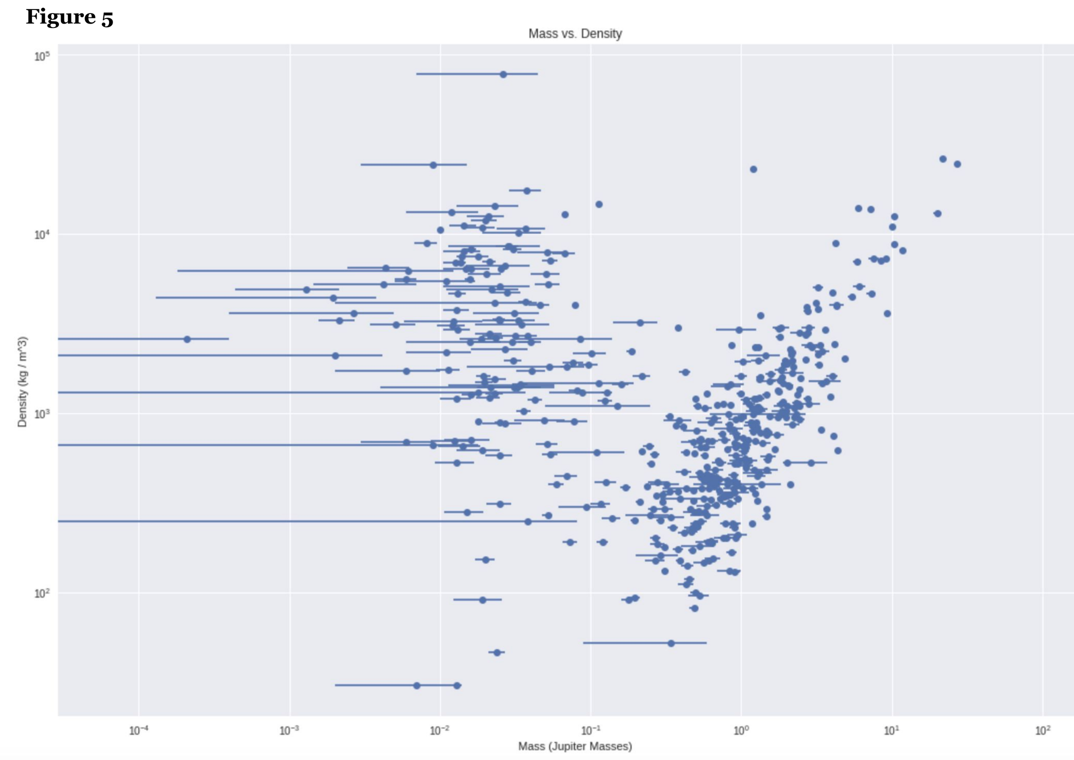


Figure 6

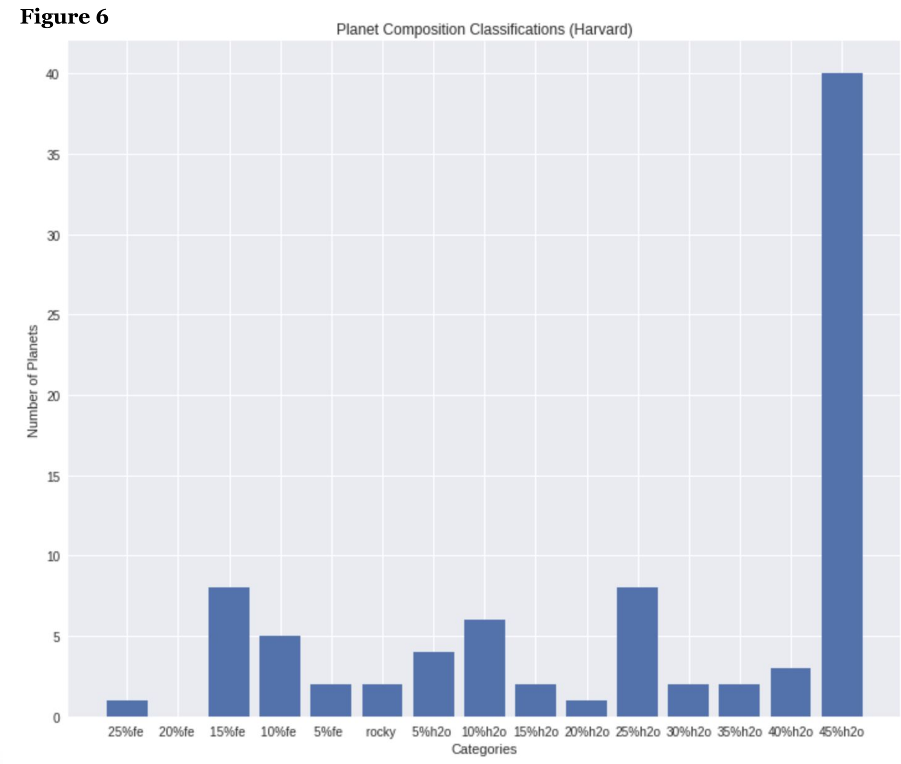


Figure 7

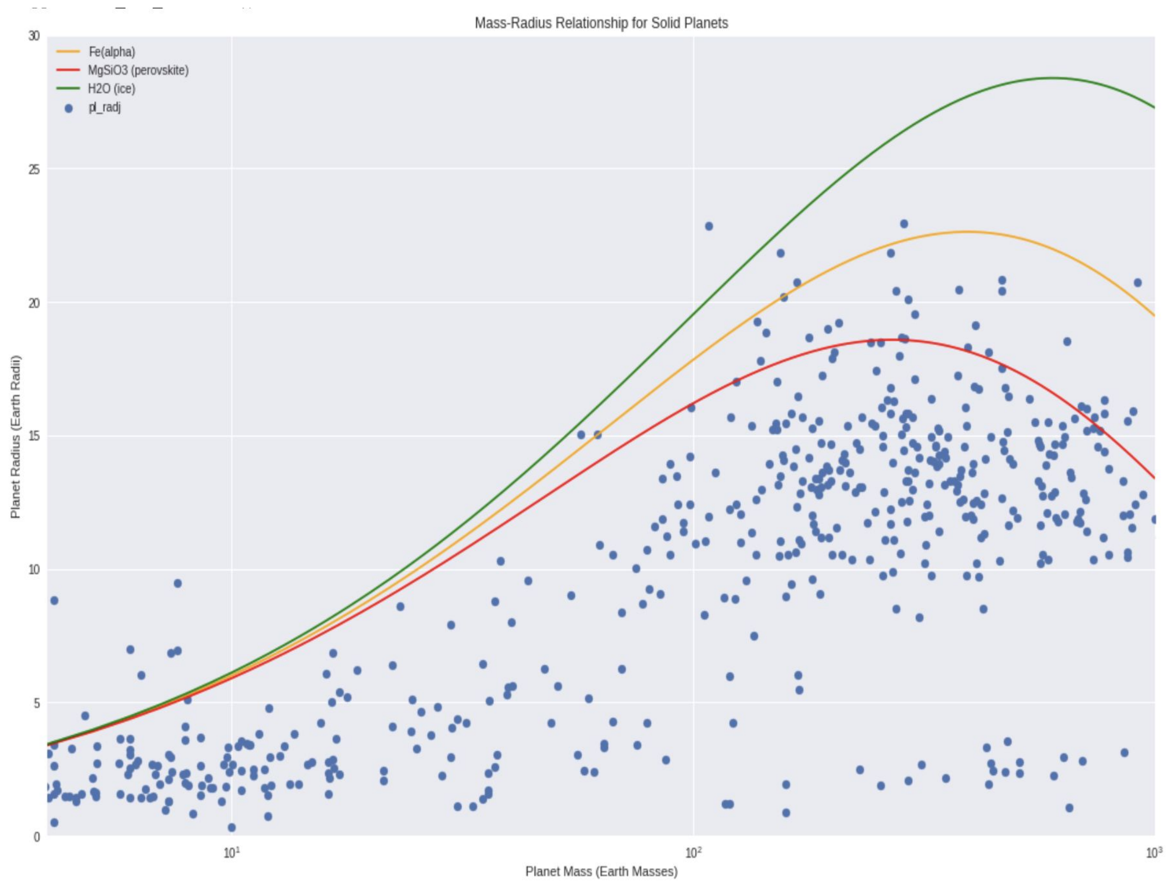


Figure 8

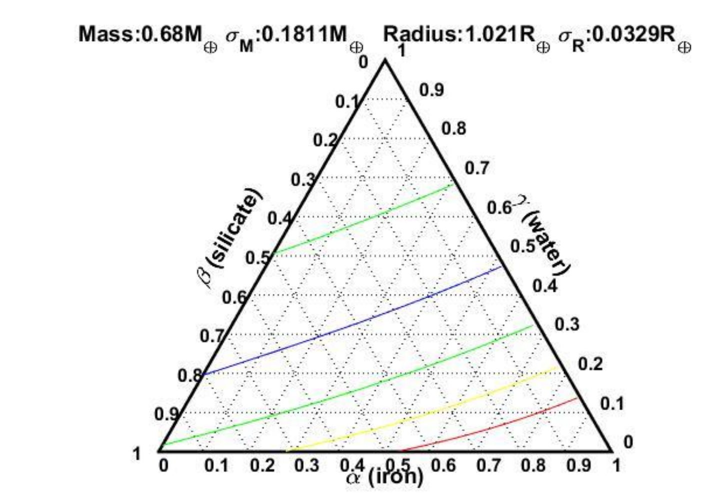
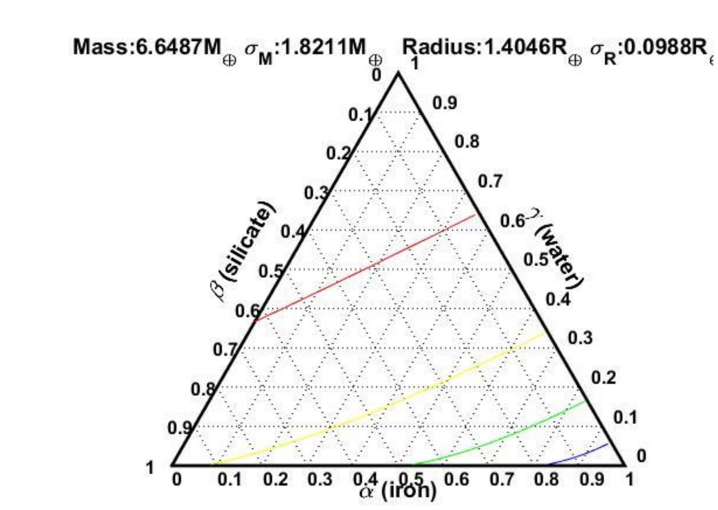


Figure 9



Planet Composition

Planetary composition is an exoplanet characteristic depending on various factors -- the gases and elements during solar system formation, distance from the sun, and even proximity to other massive / dense planets (Seager 2007). Because of these determinants, some of which may be known but have an unknown combined results, it is difficult to categorize a given planet as being likely to have a large ocean or being composed of mostly metallic compounds (Seager 2007). For instance, in order to improve prediction accuracy of the makeup of each planet, three models were used: comparing to a Harvard dataset mapping theoretical masses and radii to distinctions between 100% iron, 45% water planets, etc., the Birch-Murnagham EOS (Equation of State) which is a set of isothermal equations that relate planet volume to projected surface pressure and can therefore predict to some extent whether or not it is feasible for, CO_2, for instance, to be present in gaseous form, and ternary plots to interpret the computational ambiguities of likely solid exoplanets -- below ~$20M_E$ (Zeng 2008, Seager 2007).

As seen in Fig. 5, the transition between rocky and gaseous occurs at ~0.1 Jupiter masses, and intermediate data points are considered Super-earths, large planets that can fall into either group (Lissauer 2004). In the Kepler dataset, 2656 planets are too small and dense to maintain a thick gaseous envelope around their cores and 1055 could be classified as gas giants. Some of the results from Model 1 classification (Harvard) which involved plotting the theoretical mass v. radius data, creating logarithmic lines of best fit, and matching the test set to these equations by associating it with the equation that was minimally distant, are shown in Fig. 6. This was not applied to all planets, but only those < $35M_E$ because the data cannot be extrapolated accurately for more massive planets. Fig. 4 displays a more detailed but still incomplete summary.

Fig. 7 is a graph of the mass-radius relationship between planets such that M_S (scaled mass) < 1000 (most accurate for M_S < 40, but still a good benchmark if M_S > 4). According to the experimental EOS calculated for different substances, a study has derived an approximate power law following the format $\log_{10}R_S = k_1 + ⅓ \log_{10}(M_S) - k_2M_S^{k3}$ (Seager 2007). The constants k_1, k_2, and k_3 differ across compounds that dominate a planet's structure. Most planets lie below the expected curve values, which indicates that their radii are lower than expected and that the planets may be composed of denser materials or combinations of iron, water, and perovskite that were not focused on in the study (Seager 2008).

Fig. 8-9 are examples of interior composition ternary plots for the planets TRAPPIST-1f and LHS-1140 respectively, both of which have an equilibrium temperature within 175-270K, low eccentricity, and are of near Earth size and mass. The sides of the triangular diagram represent the theoretical mass fractions of iron, water, and silicate assuming that the planet in question has a tri-layer form. The MATLAB program used to determine this has its limitations; it can only handle mass parameters between 0-10 M_E and radii between 1-2 R_E which are near-Earth values (Seager 2008) Further work can include potentially extending this capability to gaseous or large rocky planets.

Figure 4

Category	Num. Planets
10%fe	5
10%h2o	6
100%fe	32
100%h2o	93
15%fe	8
15%h2o	2
20%fe	0
20%h2o	1
25%fe	1
25%h2o	7
30%fe	4
30%h2o	2
35%fe	3
35%h2o	2
40%fe	2
40%h2o	3
45%fe	1
45%h2o	39
5%fe	1
5%h2o	7
50%fe	1
50%h2o	3
55%fe	8
55%h2o	1
60%fe	5
60%h2o	1
65%fe	2
65%h2o	5
70%fe	4
70%h2o	0
75%fe	3
75%h2o	5
80%fe	0
80%h2o	2

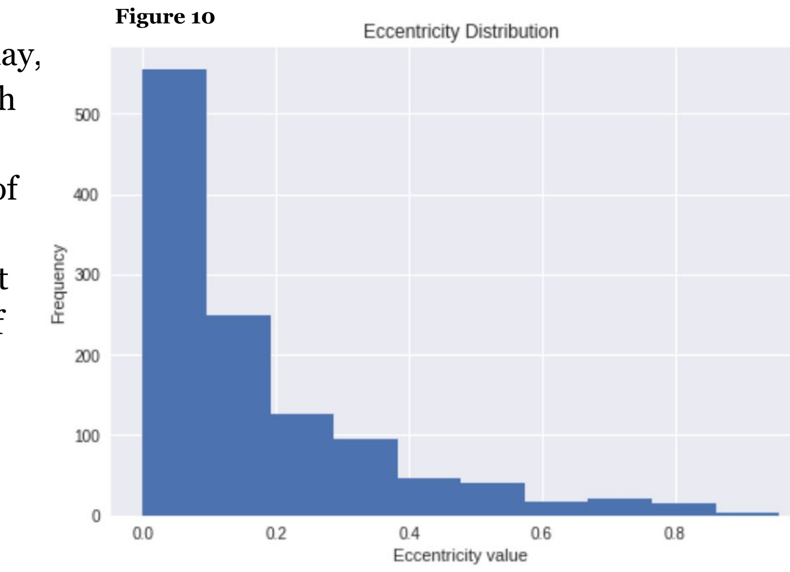
Eccentricity

The eccentricity of a planet's orbit can be crucial for determining habitability. If a planet's orbit is too eccentric it can lead to planets that cannot maintain liquid water year round as they move farther and closer to their host star.

Linsenmeier et al. (2015) studied the influence of both obliquity and eccentricity for ocean covered planets orbiting a Sun-like star on a 365 day orbit and a 24 hour day, like Earth. They found that planets with eccentricities higher than 0.2 can only sustain surface liquid water for a part of the year.

Of the planets on NASA's exoplanet archive, only 808 have eccentricities of Less than 0.2. That is 21.7% of the planets that could potentially sustain liquid surface water year round.

Figure 10



Surface Gravitational Acceleration

Gravity is an essential aspect on all planets in terms of habitability. Gravity influences the retainment of atmospheric compounds and elements as well as the ability to survive on the planet's surface.

In a research paper at the Universidad Politécnica de Madrid, it was found that there is a correlation between the gravitational acceleration and the mass of the planet. Surprisingly, those categorized as Super-earths had a similar gravitational acceleration of the earth.

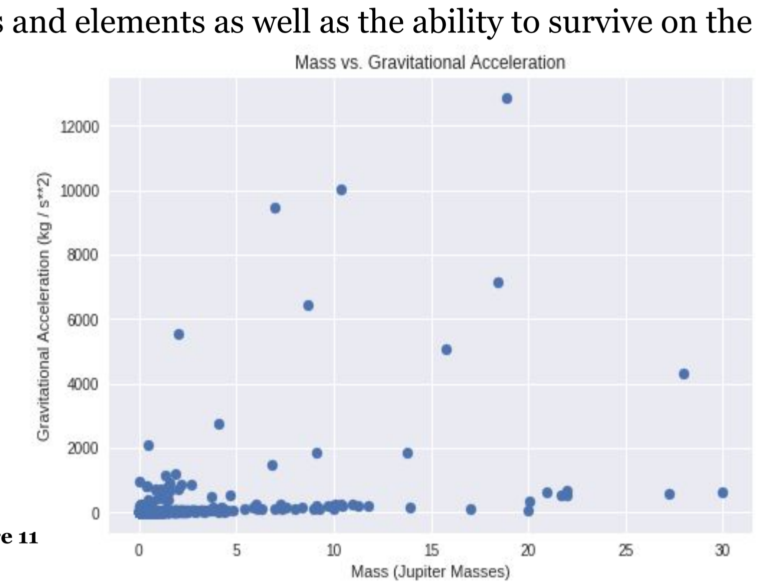


Figure 11

Future Work

Further analysis into the habitability of exoplanets should look into the atmospheric compositions of top candidates in detail, based on spectroscopy data, in order to determine if signs of water do exist on the planet. Additionally, a deeper evaluation of some of the most promising candidates, such as Trappist-1e and Kepler-22b, would be beneficial in developing the parameters that are deemed necessary to habitability an in narrowing the search for signs of life. Furthermore, we could try to incorporate tidal locking into our determination of what could be a habitable work. We could also try to get our data to be more accurate by cross referencing the NASA exoplanet database with other databases to fill in any gaps that there were.

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Acknowledgements

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