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The Habitable Zone

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Contents

1 Abstract

Continuing advances in the field of radial velocity and planetary transit obervations allow for the accurate detection of exoplanets, and the determination as to whether or not said planets have the possibility of hosting life.

We explore some of requirements necessary for the origin and flourishment of life on these planets and how suitable the exoplanetary conditions are from the NASA exoplanet archive.

The Circumstellar Habitable Zone was plotted for Earth-like planets orbiting the sun, followed by the investigation of planets of various cloud cover. The effect of cloud cover on planets' Habitable Zone was significant, whereby a planet with 0% cloud cover is of the "thinnest" HZ boundary. With the closest point being at 0.86AU for said planets, and the furthest being 1.67AU, it is clear that the opportunity for life is substantially reduced. Cloud cover is essential for closer orbits to prevent complete evaporation (The runaway Greenhouse effect) or the freezing of liquid water (in the runaway Albedo Effect).

Exoplanet host star masses were plotted atop the Habitable Zone plots and it was found that higher mass planets most occupy within the boundaries of said zone. This is due to the possibility of a magnetic field being present and the greater likelihood of retention of a protecting atmosphere.

Kepler's Third Law was then investigated and the exoplanetary obedience of this law was proved.The result was a logarithmic plot showing a straight line trend, aside from a small spread (reasons for which are hypothesised later).

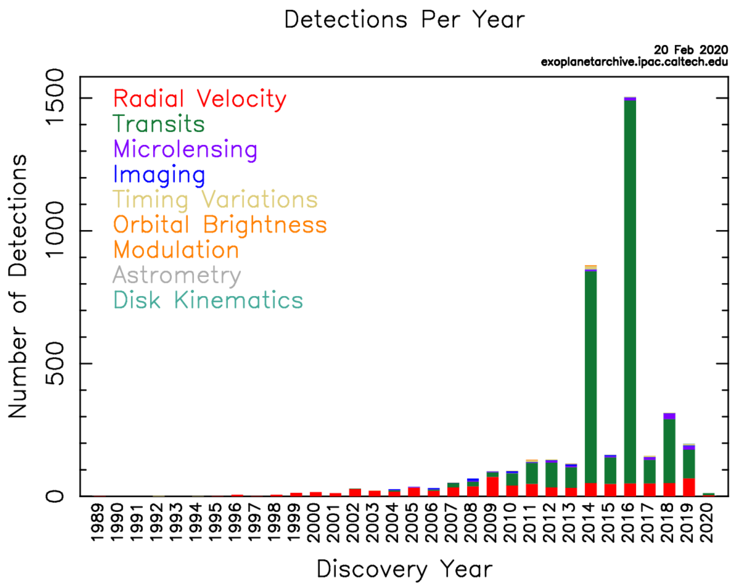
The densities of the exoplanets were then explored and it was found that the majority were greater than that of Earth. This is a promising find in terms of the possibility of life as, to reiterate, a denser and more stable planet, means a greater possibility of living development.

2 Brief Introduction

[7] As of the 13th of February 2020, NASA has discovered 4,126 exoplanets in our Universe. [1] Advances in radial velocity surveys mean potentially life-inhabiting planets can be detected. Simply put, such studies detect planets by using the [8] "Transit Method" and the "Wobble Method". The latter measures the changes in a star's radial velocity, and through observations of Doppler shifts, the wavelengths of the star's light vary in accordance with its varying distance from the point of observation. The gyrations of a star about its centre axis are suitable evidence for the presence of orbiting planets. The launch of the spacecraft Kepler in 2009 utilised the "Transit method" whereby a planet passing "in front" of its host star with respect to the point of observation will lead to the star's brightness being diminished. Said method allows for accurate measurement of a the orbiting planet's size.

Furthermore, measurement of the time between successive transits allows for the determination of the planet's distance from its host star, and hence its temperature. The TESS (Transiting Exoplanet Survey Satellite) mission also launched by NASA has played an imperative role in the detection of exoplanets in orbit of the nearer and brighter stars. Figure 1 shows a comparison of the number of discoveries via various methods of exoplanet detection. The two main methods discussed here are the main contributors to exoplanet discovery by NASA: the Radial and Transit methods.

Figure 1: *Plot of the Number of exoplanet discoveries by NASA through various detection methods [7]*



For the purposes of this investigation, the data obtained from the NASA exoplanet archive as of October 5th 2017 was utilised. This contains all the detected exoplanets until this date [7] since its launch in 2011. Said exoplanets are those whose host stars are less than 2 solar masses. [3] Stars in this size range can be identified as F, G, K or M type stars. Where F-type stars are the most massive and hottest of these types (at $1.7\mathrm{M}_{\odot}$ and around $7,000K$ in surface temperature. G, K and M type stars are around $1.1, 0.8$ and 0.3 in solar masses respectively. These types of stars are considered to be most suitable for accommodating life as we know it. [2] Stars in such a range have greater planetary habitability for several reasons: Firstly, these stars are longer-lived than the hotter O, B and A type stars, lasting at least 2 billion years. This would provide life with the opportunity to evolve. Secondly, the likelihood of orbiting planets hosting liquid water on the surface is increased, combined with the radiation emitted being of wavelengths conducive for photosynthetic processes. These host stars also emit sufficient levels of near UV radiation to allow for the formation of ozone.

The Circumstellar Habitable Zone [9] is known as the region around a star which supports a range of planetary orbits for the presence of liquid water, given appropriate atmospheric pressure. It forms a shell-like region in which the existence of life is more possible than for planets orbiting outside of this limit.

The boundaries of this zone will be elaborated upon in the "Discussion section".[2] With larger stars, drastic increases in the luminosity means the orbiting bodies may only have a brief window where they are in the Habitable zone, and hence a reduced chance of life developing (such fluctuations in temperature and high exposure to gamma and X-ray radiation may be too great for life to adapt). It is therefore appropriate to investigate only those low mass stars, as discussed.

The presence of planets within the Habitable Zone is not the sole condition for the presence of life.

The host star's type being suitable has been expressed here, but many other geophysical factors contribute. For instance, [4] the formation of planets via the protoplanetary disk is much less likely should this disk be relatively less abundant in metals. Planets which do form under low-metal conditions are subsequently lower in mass and therefore, as will be explained, less suitable for life. Thus, it is more constructive to investigate planets orbiting younger stars in the interest of habitability, since these stars are more metal-rich.

Low-metallicty and hence low-mass planets are unsuitable candidates as they have a smaller gravitational influence and hence a lesser likelihood of retaining an atmosphere. [5] This results in poor heat transfer and lack of protection from impact and radiation. Furthermore, atmospheric pressure is insufficient for the existence of liquid water.

Earth is large enough in density to sustain geological diversity, namely: tectonic movement. This is essential for maintaining atmospheric temperature moderators such as Carbon Dioxide in, for instance, the carbonate-silicate cycle (shown in 2). Tectonic activity is also integral in the recycling of the chemicals utilised in biological cycles.

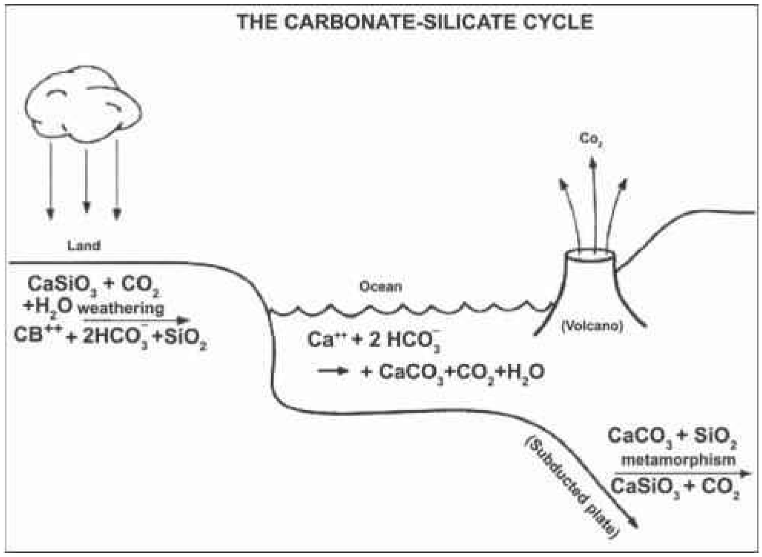


Figure 2: [10] *Crude depiction of the Carbonate-Silicate cycle- an essential factor in contributing to a life-sustaining atmosphere.*

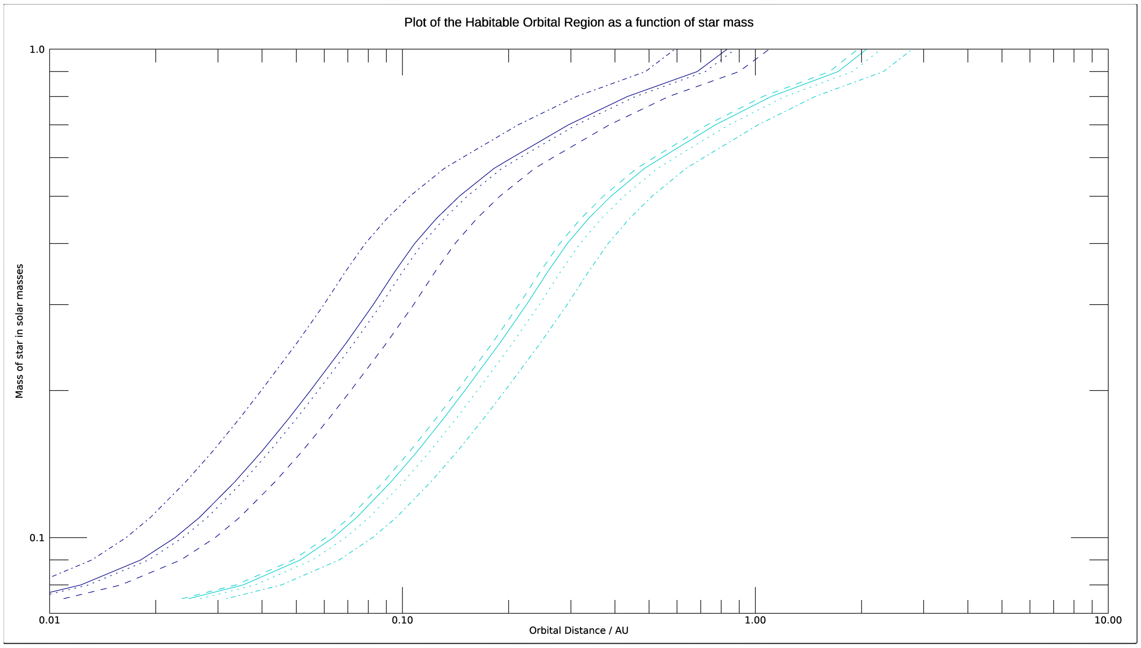
[5] Finally, a larger planet is more likely to possess an iron core. If liquid, formation of a protective magnetic field will form. Thus, the planet's susceptibility to solar winds and cosmic rays has been reduced.

Furthermore, a planet's eccentricity can result in the formation of life being inhibited entirely. Should the eccentricity be large, the temperature fluctuations of the surface of the planet will be greater, making it difficult for life to adapt. One factor which may not be so obvious is the neighbouring systems of the one in which the potential life-sustaining planet is situated.

[6] One of the many factors to consider regarding galactic neighbourhood is: if within a globular cluster, the gravitational effects and increased radiation exposure may have detrimental influences on the possibility of life. It is thus essential that the host star is neither over-crowded nor in extreme isolation.

3 Results and Discussion

Figure 3: Plot of the limits of the Habitable Zone for various Cloud Cover levels



It was briefly mentioned earlier what the Habitable Zone is: a region which, given the correct atmospheric pressures, [9] the planets orbiting in this region may have liquid water on the surface. Simply put, [2] the innermost edge of the Circumstellar HZ is the distance whereby the runaway greenhouse effect would vaporise any water reservoir which may be present. The runaway greenhouse effect is where the planet's atmosphere is such that it blocks much of the thermal radiation from leaving the surface. Thus, the planet has no mechanism for cooling and hence the presence of liquid water is highly unlikely.

Conversely, the outermost limit of the HZ is where any greenhouse effect present in the planet's atmosphere is insufficient to keep the planetary surface above freezing point. In figure **??**, the extension of the habitable zone was plotted, showing a graph of stellar mass versus planetary orbital distance on a logarithmic scale. The solid lines representing the inner and outer bounds of the HZ are marked by the Venus Criterion and the Early Mars criterion respectively.

The Early Mars criterion (the outer limit of the HZ) is at an orbital distance of 1.77AU from the Sun. One can see from the figure, despite the logarithmic scale, that at a stellar mass of $1M_\odot$, the orbital distance is around 1.7AU. Upon replotting the graph, finer scale labels should be used to highlight specific distance values. [1] Geophysical features of Mars indicate the presence of liquid water on the planet's surface around 4Gyr ago. At this time, the luminosity of the Sun has been accurately determined to be 28% lower than it is today. Due to its relatively larger distance from the Sun, then, atmospheric contributions to maintain a warm enough temperature to sustain life is a plausible explanation. Selsis et al. state that this is indeed the case.

More specifically: that CO_2 cloud coverage is responsible for maintaining a temperature above freezing point, where water will no longer be liquid. From these predictions, the outer boundary is thought to be somewhere between 1.77 and 2.44AU. Beyond this outer limit, there may be a point where albedo of the planetary surface is sufficient to dominate over the Infrared absorption of the atmosphere, and the planet may be subject to a runaway ice albedo effect. Thus, the Greenhouse effect is imperative in maintaining a warmer climate, setting the upper limit of 2.44AU. One can see this upper limit value is highly comparable to that of 100% cloud cover, which again have Greenhouse effects.

The empirical inner limit (The Venus Criterion) represents the recent Venus conditions: those around 1Gyr ago. For both the Mars and Venus criterion, the distance at which each planet had liquid water on the surface was found by equation 1.

$$Distance = (\frac{1}{1 - Sunluminosity(\%)})^{(1/2)} \tag{1}$$

This means the inner limit of the HZ is then 0.72AU. This limit is an indication of the water concentrations and fluctuations. In this region, the albedo will be very low at this close distance to the Sun and the IR opacity will be increased. The surface temperature of the planet is therefore substantially increased.

There are 2 values for the inner limit of the Habitable Zone. The lower of the two is the [1] runaway Greenhouse limit and the larger is the $T_s = 375K$ limit. At 0.84AU, this is the limit for a planet of zero cloud coverage, any closer and the presence of water would be regarded as impossible due to a predicted surface temperature above the critical point of water. The Runaway greenhouse effect overheats the atmosphere and vaporizes the water.

The dashed lines indicate the inner and outer limits for a planet with no cloud coverage. One can see that, therefore, the outer limit of the HZ for a solar-like star is the lowest of all the criteria. This is indicative of the lack of preservation of surface temperature, and again, the runaway ice albedo effect will occur at a lower distance of 1.67AU. A larger distance for the inner limit of the HZ is what one would expect for a planet with little albedo effect. At 50% cloud cover, the outer limit increases to a value of 1.95AU. The limits for this overage are represented by dotted lines, with the inner limit being at a comparatively lower value of 0.75AU. (For these plots, I have used the upper limit of the ranges stated by [1]. Finally, represented by dotted and dashed line, the boundaries for 100% cloud cover produce the widest range of the HZ. This is as expected as such a high coverage could prevent the complete vaporization of water reservoirs on the planetary surface. Hence, the planet can orbit more closely to the host star.

Brighter (higher mass) stars have a HZ which will characteristically be further away than that for low mass stars. This is because the location of a star's habitable zone is dependent on its luminosity. One can see in the equations given in reference [1], this luminosity dependence:

$$l_{in} = (l_{in\odot} - a_{in}T_{star} - b_{in}T^2_{star})(\frac{L}{L_\odot})^{1/2} \tag{2}$$

$$l_{out} = (l_{out\odot} - a_{out}T_{star} - b_{out}T^2_{star})(\frac{L}{L_\odot})^{1/2} \tag{3}$$

One can see that as the host star's luminosity increases, so too do the inner and outer limits of the circumstellar HZ.

Figure 4: Plot of the limits of the Habitable Zone with Exoplanet host star masses plotted

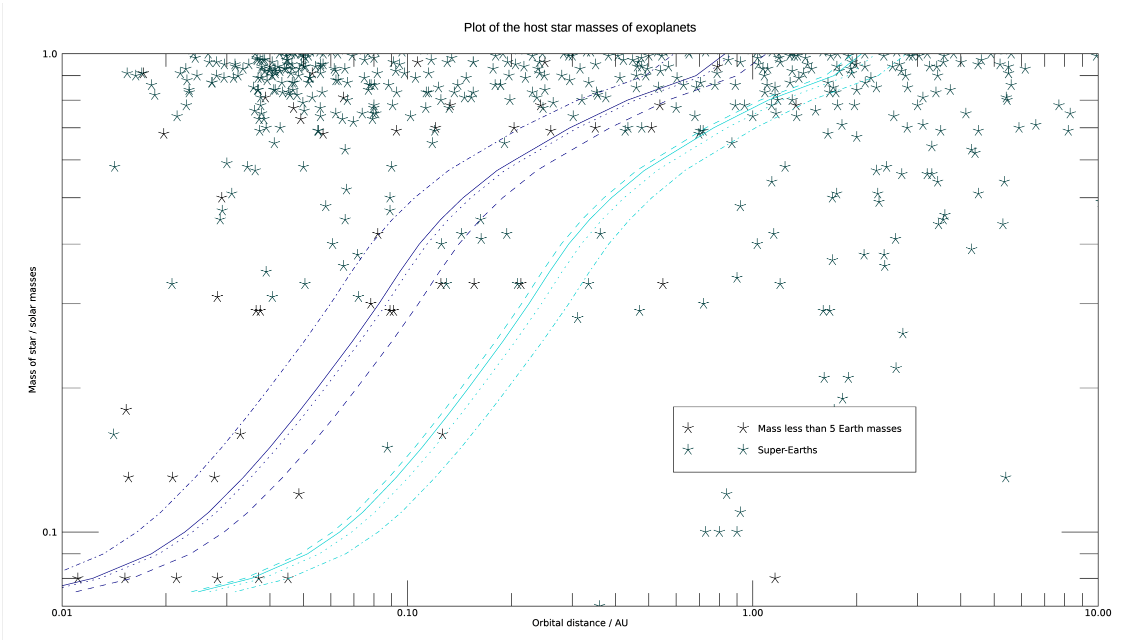


Figure 4 shows the Habitable zone boundaries for various cloud coverings, with exoplanet host stars plotted atop, retrieved from the NASA exoplanet archive. The host stars' masses were plotted both for the ease of unit consistency and to investigate whether the host stars of Earth-like planets are in the HZ. At low solar masses, the majority of orbiting planets are less than 5 Earth masses. This is as expected as low mass stars result in lower mass planets. More super-Earths appear to be present. This is not surprising as larger mass planets, as has been explained, are more likely to be able to sustain life. This is because the greater gravitational forces and high-metallicity content results in a more optimal environment for life to develop- though the retention of a protecting gaseous atmosphere and the formation of a shielding magnetic field. As previously explained, the data consisted of stars which were less than 2 solar masses, ranging from F to M types. These types of stars are suitable for life to be generated and sustained.

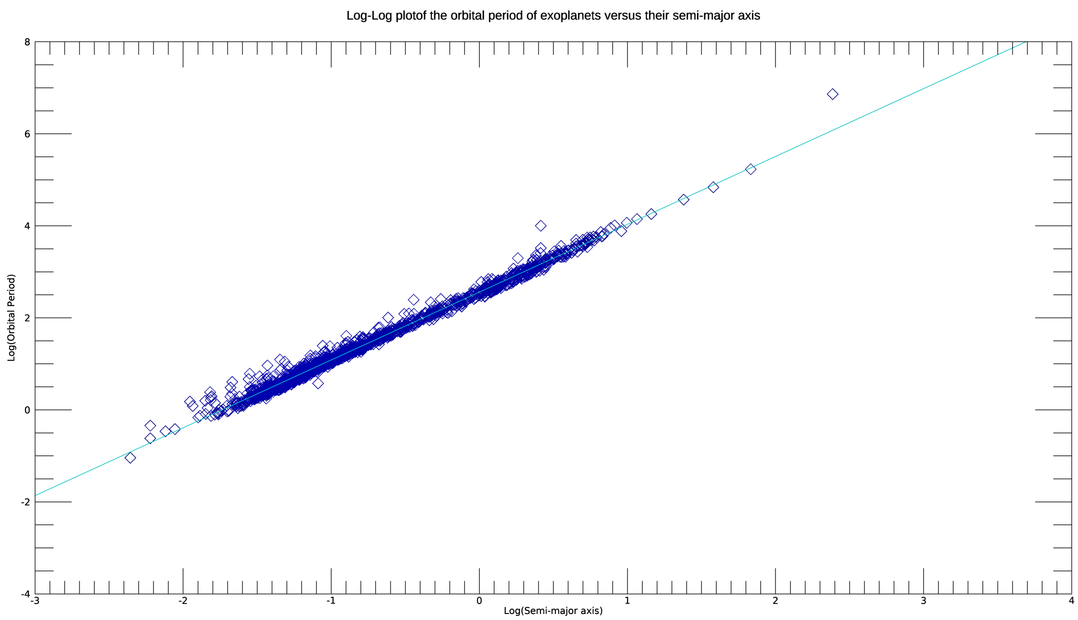
Figure 5 displays the logarithmic plot of the orbital period of the exoplanets versus their respective semi-major axes. Kepler's 3rd law is given by:

$$\frac{a^3}{T^2} = \frac{G(M+m)}{4\pi^2} \tag{4}$$

By utilising the 'linfit()' function in IDL, the straight line gradient and y intercept was determined and used to plot over the data points. The gradient was found to be approximately 1.472...±1.86% which is close to the expected value of 1.5. The intercept value was around 2.55 and takes the form:

$$c = log(\frac{4\pi^2}{G(M+m)}) \tag{5}$$

Figure 5: *Plot of the logarithmic values of the Orbital Period versus Semi-Major Axis of the exoplanets to exhibit Kepler's Third Law*



The potential physical reasons for the slight spread in the data points from the straight line could be due to background noise when measuring the data. Alternatively, it could be due to the radial offset of the object, whereby it appears to "wobble" and its relative movement to us affecting the measurement. Gravitational effects of nearby objects can also result in the distortion of an image. Thus, the value of the gradient was slightly underestimated for the exoplanets.

Figure 6 shows the logarithmic values of the radius (in cm) versus the logarithmic values of the masses of the exoplanets in grams. This gives an idea of the relative densities of the planets when lines of constant density are plotted. Here, the lines represent (from top to bottom) densities of 1, 2, 4 and $8gcm^{-3}$.

It was briefly mentioned the 2 main methods for detection of exoplanets: The Transit method and the Radial Velocity method. The radial velocity observations of stars which host planets demonstrate 'wobble'. When observing planets in transit, the radial velocities can be inferred. From determination of the orbital inclination, the minimum mass of the planet can then be inferred from the Mass-Luminosity equation. The radius of a planet is most effectively determined when observing the planet in transit across its host star. The resulting brightness drop is then proportional to the ratio of the planet's mass and host star's mass. Figure 7 displays the idea behind this concept.

Figure 6: Plot of the logarithmic scale of Exoplanet radius versus Exoplanet mass, with lines of constant density plotted for comparison

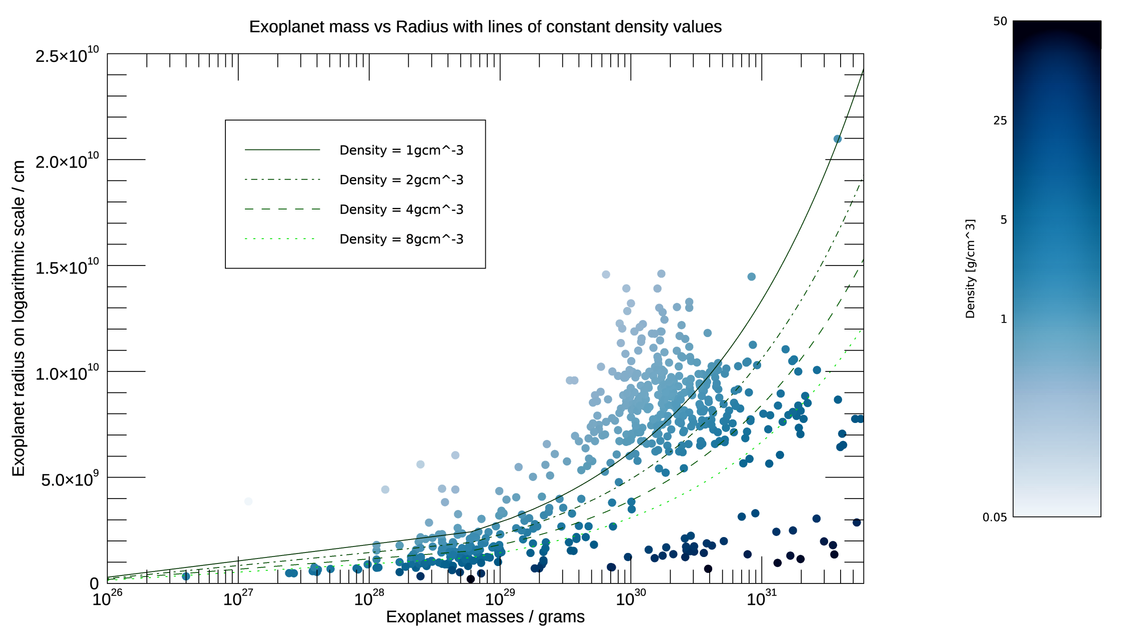
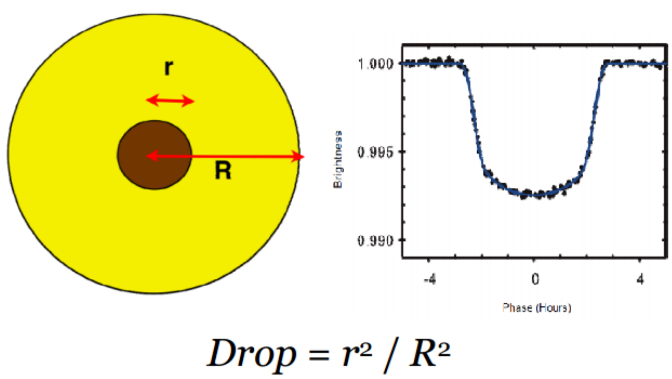


Figure 7: [11] Image displaying the idea behind determining an object's radius



4 Conclusion

To conclude, the results from the investigation were as expected. Upon plotting the Circumstellar Habitable Zone for various conditions of cloud cover, the inner and outer boundaries of said zone vary depending on atmospheric and host star masses. For sufficient amounts of cloud cover, the planets could orbit both closely (at a minimum of 0.46AU for 100% cloud cover) and farther away (maximum of 2.4AU) due to the ability to retain heat within the atmosphere to keep the surface temperature at an optimum level (without the water freezing) and to withstand a closer proximity to the host star (without complete vaporization of liquid water).

Exoplanet host star masses were then plotted atop said graph and their suitability to hosting life was analysed. The corresponding host masses to exoplanet masses was fitting, and the majority of those which fit in the HZ were of higher masses. This is due to the gravitational influence making the body capable of retaining its protective and conservative atmosphere necessary for the maintenance of life. Furthermore, denser planets mean a larger likelihood of the presence of an encompassing magnetic field: as essential component of a planet to withstand comsic rays and solar radiation.

Thirdly was to prove the obedience of the planets' orbital period ans semi-major axis values to Kepler's third law. Crudely put, one can say that Orbital period $\propto$ semi-major axis^d. In the plot, d is the value of the gradient (≈ 1.47). The expected value is 1.5 but error is certainly possible when taking transit measurements. Squaring both sides of this proportionality then leads us to Kepler's third law: Orbital period^2 $\propto$ semi-major axis$^{1.5\times2}$.

Finally, plotting the densities of the exoplanets, along with lines of constant density lead to the conclusion that the majority of the planets investigated were greater than Earth's density (of $5.51gcm^{-3}$. This may be analysed as a more promising outlook of life on said planets, as a higher density means a more optimal environmental setting for the advancement of life, through the developed by the magnetic field and retainment of a protective and sustaining atmosphere.

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