Draft version September 11, 2022
Typeset using LaTeX **twocolumn** style in AASTeX63

On the Habitability of Exomoons

ABSTRACT

Characterization of habitability in planetary systems is a challenging investigation due to absence of empirical evidence for extraterrestrial life. We present a framework that models the habitability of exomoons in planetary systems in the universe. By analysing the effects of various energy sources on an exomoon such as tidal heating from the host planet, stellar irradiation and the build up of greenhouse gases, we develop a model that is able to combine all of these factors and predict using physical and orbital parameters of the moon, whether it is habitable or not. We relate the equilibrium temperature along with the energy budget to deduce whether a planet can sustain liquid water and thus life. We model the percentage of energy that is absorbed and emitted back out by the moon over geological time scales. Being able to estimate whether a natural satellite is habitable or not will allow us to rank known bodies with respect to their potential for supporting life. Once exomoons are discovered, we will be able to use this ranking to target satellites like the JWST at these moons to advance our voyage for discovering life outside our Earth.

1. INTRODUCTION

Despite the tentative evidence for their existence, we do not yet have compelling evidence for the existence of exomoons, i.e., satellites of ple (). re have not been discovered yet whereas many exoplanets have already been identified (Heller & Barnes 2013a). This makes the concept of an exomoon, which is a natural satellite orbiting an exoplanet located outside our solar system, theoretical (Kipping et al. 2022). However, there have been many candidates for exomoons that are being discovered. With the help of new technology and space telescopes like the James Webb Space Telescope (JWST), infrared spectroscopy can be used to identify these exomoons as well as the compositions and biosignatures that they have. (Peters & Turner 2013)

There are several factors that influence the habitability of exomoons which we analyze in this work: the runaway greenhouse effect, eclipses of the star by the planet on the moon, stellar illumination, planetary illumination, thermal radiation from the planet, tidal heating, primordial heat, radiogenic decay, the parent planet's magnetosphere and orbital resonance (Tjoa et al. 2020).

The main source of heating on a moon is tidal heating which arises due to a moon's elliptical orbit. (Heller & Barnes 2013b) The difference in the strength of gravity from the host planet on one side of the moon from the other causes a stretching effect which is otherwise known as a tidal bulge. (MacDonald 1964)

Another source of heat that a moon receives is that from the star and host planet. Stellar illumination is extremely important even though it might seem like it does not contribute to much due to the distance of the moon from the star. (Heller & Barnes 2013b) TSI (Total Solar Irradiance) is the accumulation of all the energy arriving from the host start to the moon. The surface temperature of the moon is highly dependent on this TSI (Cubasch & Voss 2000).

The runaway greenhouse effect is important when calculating the habitable zone around a planet for moons and it depends highly on the composition of a moon (Kodama et al. 2018). Greenhouse gases along with TSI are extremely important in determining the temperature of a moon accurately. Certain greenhouse gases and elements such as carbon dioxide and methane absorb a lot of heat and they are the gases that cause global warming on the Earth. They cause heat to remain on an astronomical body rather than allowing it to be reflected into outer space thus increasing the equilibrium temperature of a moon. If temperatures great too high, liquid water will not be able to form which is not ideal for a body to be classified as habitable. As a result, it is important to assess the bio signatures and elements that are present in the atmosphere. (Kodama et al. 2018) Infrared spectroscopy is a method that is trying to be implemented to achieve this feat with JWST being one of the most prominent telescopes which is going to make use of it. Spectroscopy analyzes the bands given off from a moon or planet and matches that with known elements which gives an indication of the composition of the targeted object (Peters & Turner 2013).

Along with these sources of energy, there are also other facts such as moon-moon tidal heating, thermal radiation given off by the host planet, primordial heating and many more. (Hay et al. 2020a)Relative to other sources of energies, some of these factors can be assumed to be negligible as they will not contribute to that much energy being absorbed by the moon and therefore they will not contribute to that habitability of the moon.

By exploring and delving deeper into the effects that these factors have on the energy being received by the moon, we will be able to come up with a general algorithm that will be able to determine the area of habitability around a planet for which a natural satellite would be able to sustain water and therefore life.

This paper consists of the following sections. Section 2 We will explore how equilibrium temperature varies for different semi-major axes for moons specifically in the solar system. In section 2, we will move onto other orbital parameters such as eccentricity and their affect on equilibrium temperature. We will then look into tidal heating and its effect on equilibrium temperature. We will dissect this section further into subsections by looking at the different sources of tidal heating from the host planet and neighbouring moons. We will analyse whether there is significant effect of tidal heating from other exomoons in close proximity potentially orbiting the same host planet and whether this is a factor that should be factored into the final equation that determines of a moon is habitable or not. Then we will find out more about the runaway greenhouse effect.

2. METHODS

The most important factor for whether life could thrive on any planetary body is signs of water. (Sargen 2019) This fact is mainly due to the properties of water. Due to the lone pairs of electrons which forms when hydrogen bonds to oxygen, water is polar. This means that the charges in water are attracted more towards oxygen than the hydrogen atoms. This allows water to dissolve other polar substances and has been deemed as a 'universal solvent'. (Sargen 2019)Biological processes depend on the movement of molecules which is provided with water. However, in conditions that are too warm or too cold, water will change to gas and solid state respectively which would stop allowing it to dissolve substances. Therefore, we will attempt to pin-point certain moons that will have certain equilibrium temperatures which would allow them to host liquid water. (Pohorille & Pratt 2012)

2.1. *Stellar Illumination*

2.1.1. *Equilibrium temperature against semi-major axis for satellites in the solar system*

One of the main energy sources that a moon receives is from the star it is orbiting. Moons of rogue planets are excluded from the analysis of this paper as the mechanics for these moons that are not gravitationally bound are very complex. (Schulze-Makuch & Fairén 2021)

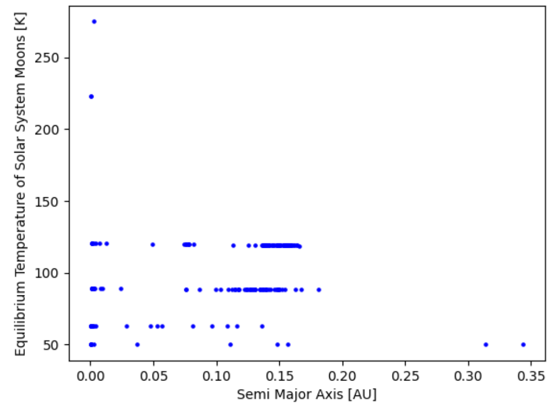

Figure 1. In the above plot, the predicted equilibrium temperature of exomoons in our solar system have been plotted against their semi major axis. We used the above equations to predict the equilibrium temperature due to stellar irradiance.

Thus, we sought to initially plot how the semi-major axis (a key orbital property of a moon for the amount of energy it receives) relates to the predicted equilibrium temperature of a moon. We have decided to do this for all moons in the solar system first. The equation for the temperature of the surface of the moon from solar flux is

$$T = \left(\frac{S_0(1-A)}{4\sigma} \right)^{\frac{1}{4}} \tag{1}$$

In the equation, S_0 is the solar constant or total solar irradiance (TSI). This is calculated using another equation given below. A is the geometric albedo of the moon (ratio of its actual brightness as seen from the light source (i.e. at zero phase angle) to that of an idealized flat, fully reflecting, diffusively scattering (Lambertian) disk with the same cross-section) (Wikipedia contributors 2022) and σ is the Boltzmann constant which is $5.67 * 10^-8JK^-1$

The equation for total solar irradiance (TSI) is

$$TSI = \frac{L_{sol}}{4\pi R^2} \tag{2}$$

L_{sol} is the luminosity of the host star. In the calculations, this is the luminosity of the sun which is $3.828 * 10^26W$. R is the radius.

In the graph below, we have plotted predicted equilibrium temperature of the surface of moons in the solar system as a function of semi-major axis.

We used the JPL Horizons database mainly for the albedos and distances from the star for each of the moons in the solar system. Unfortunately, a few of the ephemerides did not contain values for the albedos likely because they have not been measured yet. In these instances, we assumed the albedo for the moons to be 0.4

As seen from the graph of equilibrium temperature against semi-major axis for various moons in the solar system, as semi-major axis increases, the temperature of the moon decreases. Intuitively, this makes sense. The intensity of the sun's energy from the TSI equation shows us that the power decreases as distance from star to moon increases. Due to this decreased intensity, the energy provided by the sun which is one of the main sources of energy, is smaller.

Additionally, we can clearly see many moons having the same equilibrium temperature but different Semi Major Axis. This is because these moons are orbiting the same planet. Since the moons are orbiting the same planet, they are roughly the same distance form the sun and similar stellar irradiance will be incident upon the surfaces of the moons. If we were to take into account tidal heating and other energy sources, the lines would not be horizontal.

2.2. *Heat against eccentricity*

We denote the orbital averaging of a quantity q by

$$\bar{q} = \frac{1}{T}\int_0^T q dt \tag{3}$$

(Méndez & Rivera-Valentín 2017) physical average distance of planets

$$r = a(1 + \frac{e^2}{2}) \tag{4}$$

average stellar flux of elliptical orbits

$$F = \frac{L}{a^2\sqrt{1-e^2}} \tag{5}$$

The equilibrium temperature of a moon is given by

$$\bar{T}_e = T_0\left(\frac{(1-A)L}{\beta\epsilon a^2}\right)^{\frac{1}{4}}\frac{2\sqrt{1+e}}{\pi}E\left(\sqrt{\frac{2e}{1+e}}\right) \tag{6}$$

Where r is the orbital distance, F is the stellar flux, T_e is the equilibrium temperature, a is the semi-major axis, T is the full orbital period, L is the star's luminosity, e is the eccentricity and E is the complete elliptic integral of the second kind. is the thermal emmisivity which is the total energy emitted by a body.

It has been assumed that the heat-redistribution for all the moons is 1, and emissivity is 1. Additionally, all the moons have a host star of the Sun which has a luminosity of 1 in solar units so all the moons have a luminosity of 1 as well.

Name of Satellite	A	e	a(AU)
Moon	0.12	0.0549	1.00000
Deimos	0.068	0.00033	1.52366
Phobos	0.071	0.0151	1.52366
Ganymede	0.43	0.0013	5.20336
Callisto	0.22	0.0074	5.20336
Io	0.63	0.0041	5.20336
Europa	0.67	0.009	5.20336
Titan	0.22	0.00288	9.53707
Rhea	0.949	0.00126	9.53707
Enceladus	1.375	0.0047	9.53707
Phoebe	0.06	0.156	9.53707

Table 1. Table displaying the geometric albedo, eccentricity and semi-major axis in AU for chosen moons in the solar system which has been plotted in the equilibrium temperature against eccentricity graph.

It has also been assumed that the semi-major axis of the orbit of the moons from the host star is equal to that of the host planet. This is because the semi-major axis of the orbit around the planet is comparatively extremely small with that around the planet.

2.3. *Heat against tidal heating*

2.3.1. *Tidal heating from the host planet*

The equation for rate of tidal heating of the moon from the host planet is:

$$E_{tidal} = -\mathtt{Im}(k_2)\frac{21}{2}\frac{G^{\frac{3}{2}}M_h^{\frac{5}{2}}R^5e^2}{a^{\frac{15}{2}}} \tag{7}$$

k_2 is the love number, G is the gravitational constant, $M_h$is the mass of the host planet, R is the radius of the moon, e is the eccentricity and a is the semi-major axis of the orbit of the moon. The love number of an exomoon is a dimensionless measure of how elastic the surface of the planet is under a force.(Ni 2018)

When the tidal heating of the host planet is factored into the predicted temperature of the moon with only stellar irradiance, we obtain the graph:

In Figure 3, the top panel shows the predicted temperature when only stellar flux is taken into account and the bottom one is the graph with both stellar flux and tidal heating factored.

By putting the graphs side by side, we can clearly see that there are significant changes in the predicted temperature for some moons when tidal heating is taken into account. For some moons, there is a very minimal effect.

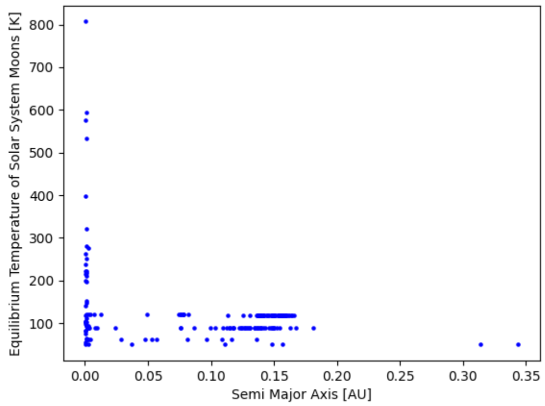

Figure 2. In the above plot, the predicted equilibrium temperature of the moons in our solar system are computed using stellar irradiation along with tidal heating from the host planet.

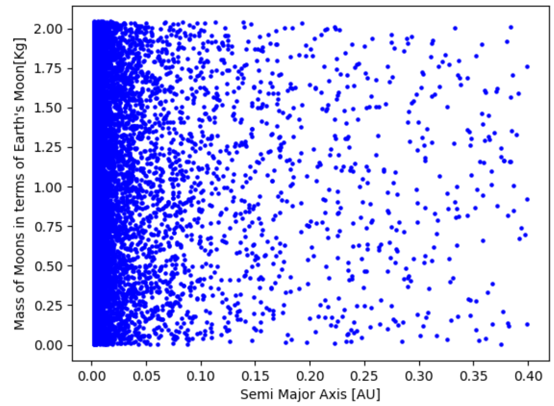

Figure 4. The input mass and semi-major axes of exomoons.

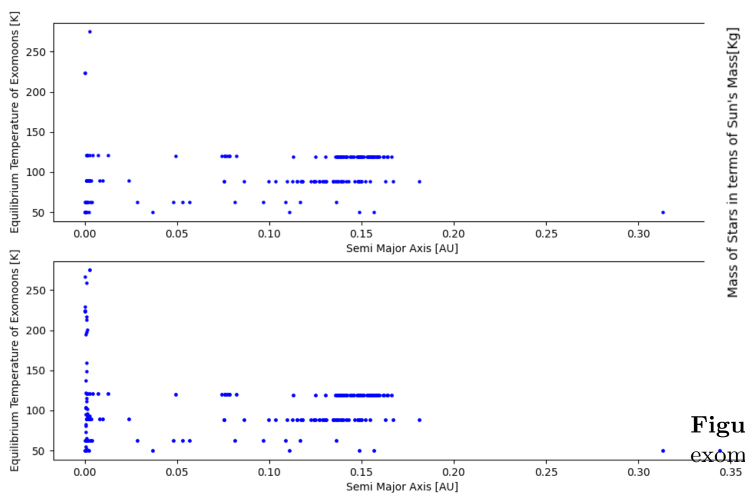

Figure 3. The above plot shows the temperature of the moons when only the solar flux is accounted for against semi major axis. The bottom graph shows the temperatures when the effects of tidal heating are taken into account.

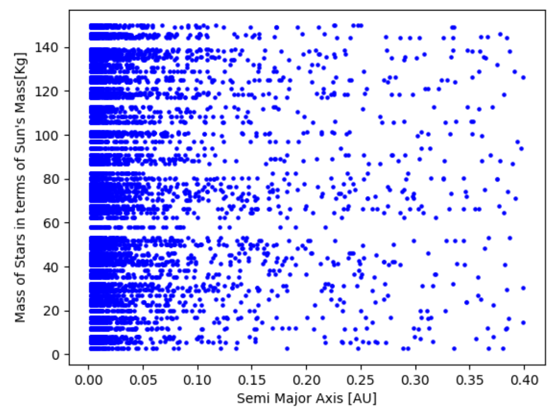

Figure 5. The input mass of stars and semi-major axes of exomoons.

RESIDUAL PLOT

2.3.2. *Tidal heating from other moons*

Apart from the tidal heating caused by the host planet of a moon, there can be tidal interactions caused by the close proximity of moons from other moons orbiting the same host star.

Although the effects of moon-moon tidal heating has largely been ignored by other researchers being put down as negligible, the effect can be substantial depending on the positioning of the moons in space. For example, it was recently discovered that Europa, Callisto, Ganymede and Io are heating up more than expected. (Hay et al. 2020b) Due to Jupiter's large gravitational force, the tidal heating between the moons was not taken into account but there is now evidence that we must account for this as it is causing significant differences between expected surface temperature and the observed value.

occurrence rate of exomoons and how are they distributed, distances from planet, mass, and star is necessary to predict the habitability of exomoons. through educated guesses.

predict through insulation, tidal heating and remnant heating.

After analyzing the heating from stellar irradiance and tidal heating for only solar system moons, we put this in the context of a distribution of exomoons.

Figure 6. The predicted equilibrium temperature and temperature anisoptropy (diurnal and yearly) distributions of exomoons in the Galaxy.

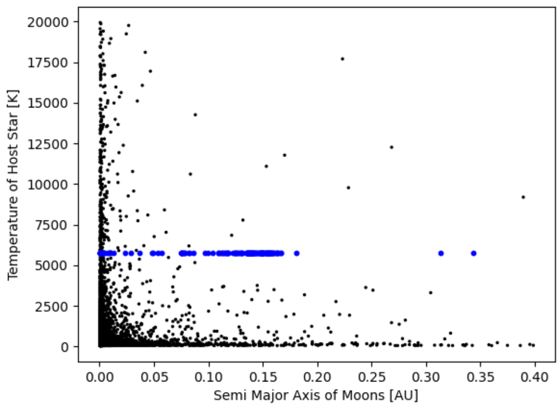

Figure 7. The graph shows the plot for the temperature of the host star against the semi-major axis of the moon's orbit. Here we have assumed a Gaussian distribution of the temperature of the stars and semi-major axes that follows a power law. The points labelled in blue are the moons in our solar system.

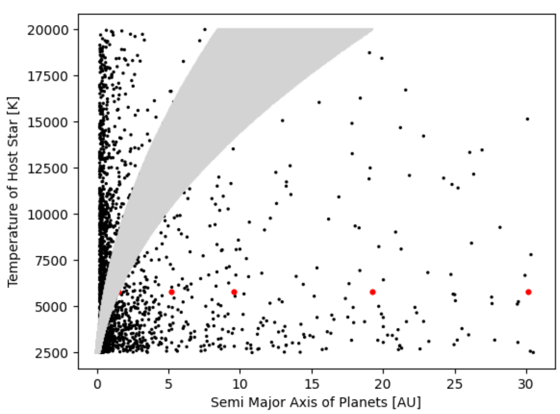

Figure 8. We have plotted the habitable zone on the graph for temperature of host star against semi major axes of planets. In this graph, the red points represent the solar system planets excluding Mercury and Venus. The Earth is in the habitable zone and Mars is on the boundary of the habitable zone.

2.3.3. *Plotting the power of a random distribution of exomoons*

It is important to note assumptions we have made in order to create these graphs.

The mass of the planet is either Earth's mass for some of the plots or Jupiter's mass.

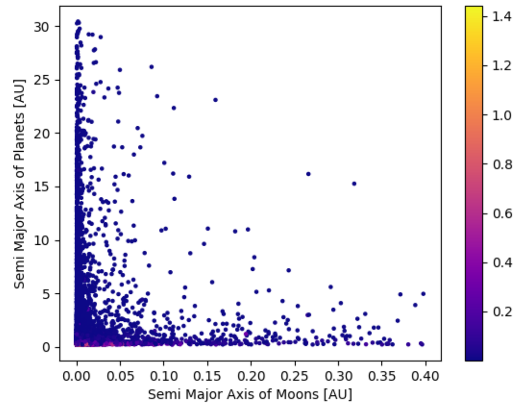

Figure 9. We plot distance of the host planet from the star against distance of the moons from the host planet. The coloring represents the power due to insolation plus power due to tidal heating. Intuitively, planets with smaller semi-major axes will mean the moons are closer to the sun which results in greater stellar irradiance. Additionally, the closer a moon is to the planet, the greater the tidal heating. Thus, the total power should be greater for data points on the left corner of the graph which is the case on the graph.

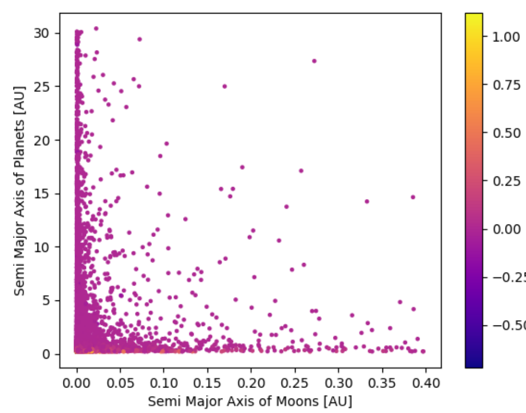

Figure 10. We plot distance of the host planet from star against distance of the moons from the host planet. The coloring represents the power due to insolation minus power due to tidal heating.

The radius of the moon has also been set to a constant to allow for easy comparison between the different data points on the graph. This value is 1800 * 1000 m.

The eccentricity is being randomly distributed between a value of 0.003 and 0.3.

The k_2 value, which is needed in the calculations of tidal heating, is also randomly distributed for various moons. The minimum value is 0.1 and the maximum is 0.5

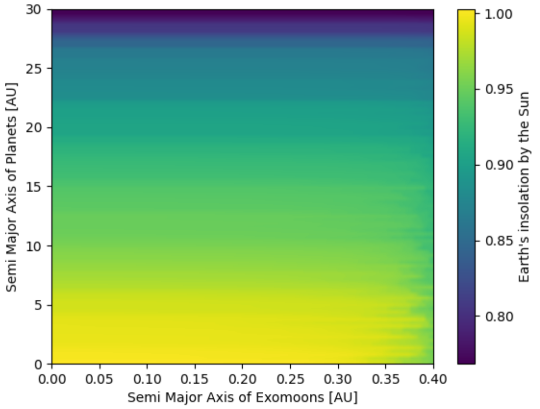

Figure 11. We plot the semi major axis of planet against the semi major axis of exomoons. The colour of each of the points indicates the total power from stellar irradiance and tidal heating that a given exomoon would have compared to the Earth's insolation by the sun. On the colour scale, a value of 1 indicates that the total power is equal to 1 times the power that the Earth receives from the Sun. The mass of the planet is assumed to be Earth's mass. This is $5.9{*}10^{24}$ kg. Additionally, the range of the semi major axes of the planets are from 0.2AU to 30.5AU. Along with these, we have kept all other factors such as radius of the moon, eccentricity, the K2 love number and the quality factor.

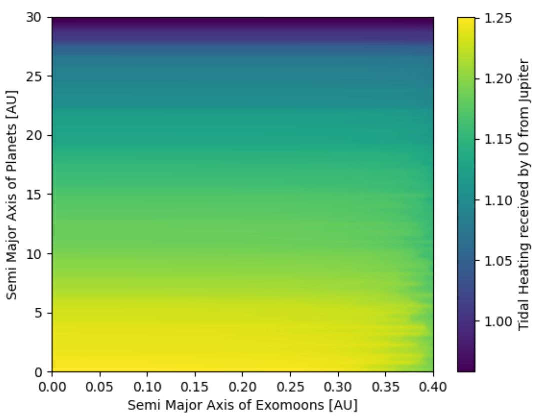

Figure 12. The graph again plots semi major axis of planet against the semi major axis of moons. Here, the colour of each of the points indicates stellar irradiance - tidal heating. The colouring is done comparing the power to the tidal heating of io from Jupiter. This plot is created assuming the parent planet of the moon is a planet with mass close to the Earth's mass

Finally, the quality factor is between 5 and 10.

2.4. *Atmosphere*

In order for an exomoon to be habitable, it is critical that it has an atmosphere. (Konatham et al. 2020)Atmospheric pressure allows for water (key for driving the processes of life) to be stable. Additionally, the presence of an atmosphere absorbs heat being reflected off the surface of a moon. Without an atmosphere, all of the heat would be reflected off into space which would leave the moon being too cold for habitable life to survive.

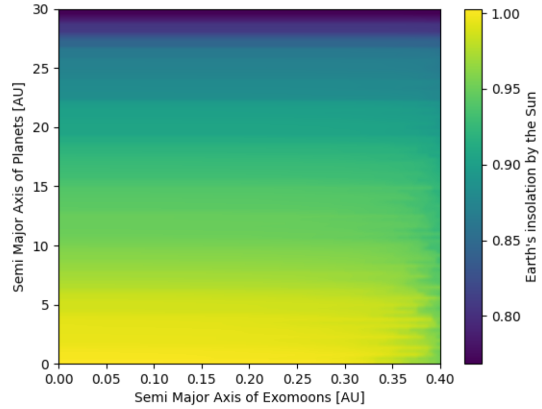

Figure 13. The plot displays the stellar irradiance of exomoons compared to Earth's insolation by the Sun. This plot is created assuming the parent planet of the moon is a planet with mass close to the Earth's mass

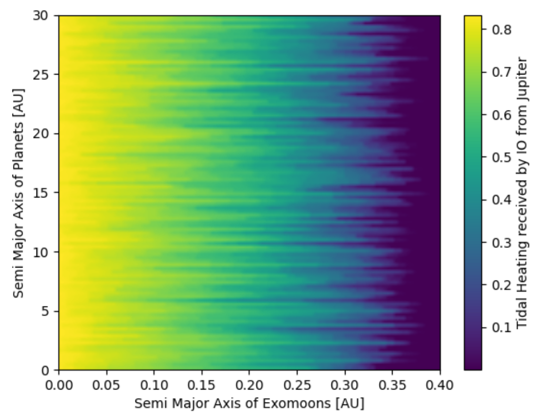

Figure 14. This plot displays the tidal heating on an exomoon compared to the tidal heating Io receives from Jupiter. Darker colours indicate lower tidal heating whereas lighter colours show a greater tidal heating. This plot is created assuming the parent planet of the moon is a planet with mass close to the Earth's mass

We have constructed a binary classifier that determines whether an exomoon with given properties such as its mass would be able to retain an atmosphere. Log g, surface gravity, of a moon is what determines whether it is able to retain an atmosphere or not. There are

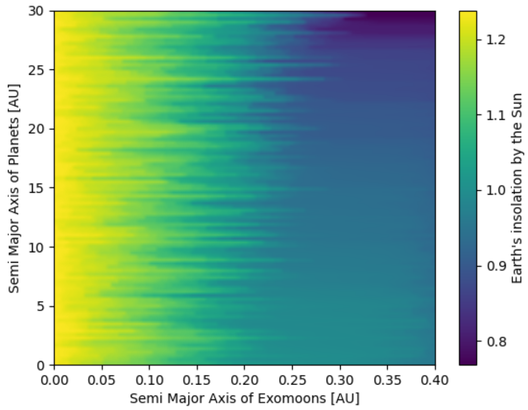

Figure 15. This plot is very similar to figure 10. It shows the total power (stellar irradiance + tidal heating) of an exomoon. However, this plot assumes the parent planet of the moon is a planet with mass approximately equal to Jupiter's mass. We use a mass of $1x10^8 kg$. The powers are compared to Earth's insolation by the sun.

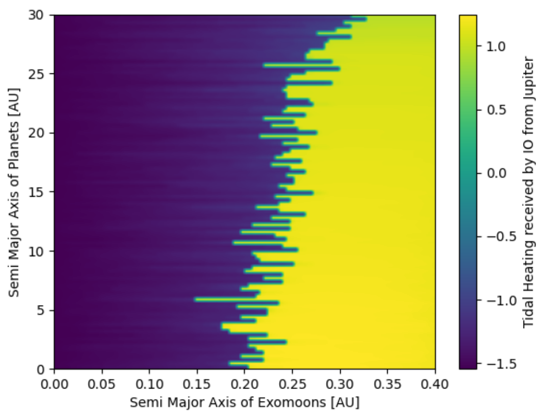

Figure 16. The colouring of the plot shows the difference between stellar irradiance incident on exomoons and the tidal heating of the exomoons. The dark blue areas on the graph indicate negative values. This is when tidal heating is greater than stellar irradiance which is significant information for us. Similar to the previous plot, the parent planet of the exomoons are assumed to be a planet close to Jupiter's mass. The large mass of the host planet allows for large tidal heating values when the semi-major axis of the exomoon is small.

two atmospheric escapes that may occur which we have taken into account in the binary classifier.

Jeans escape - when the atmosphere doesn't have a mean velocity. The mean molecular rate and surface gravity are the forces acting on gases

There is also hydro thermal escape (much more effective process) - the gas has a mean velocity.

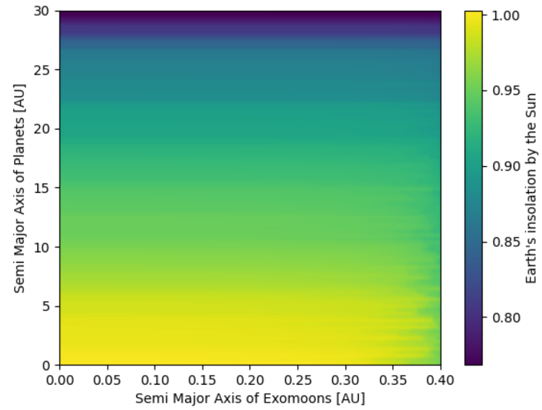

Figure 17. The colouring of the following graph only shows stellar irradiance of exomoons. The stellar irradiance is compared to Earth's insolation by the sun and the host planet of the exomoons is again assumed to be a planet with similar mass to Jupiter.

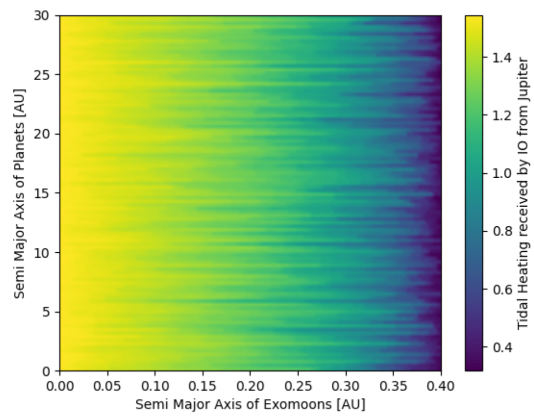

Figure 18. The colouring of the graph shows tidal heating of exomoons compared to the tidal heating of Io from Jupiter. The host planet is assumed to have a mass similar to that of Jupiter. Since the colouring is only based on tidal heating, there is a change in the colouring as the semi-major axis of the exomoons change, not when the semi-major axis of the planet changes. For larger exomoon semi-major axes, tidal heating reduces as there is a lower gravitational force from the host planet which we can see clearly in the graph.

The atmospheric loss there is per time is key in the classifier.

There is outgassing which is the production of gas through volcanism and other events on moons. Along with that there is also atmospheric escape. When these two forces acting on elements is in equilibrium and is above a certain threshold, an atmosphere is formed.

(Rovira-Navarro et al. 2021)

q- The amount of heat transported via convection

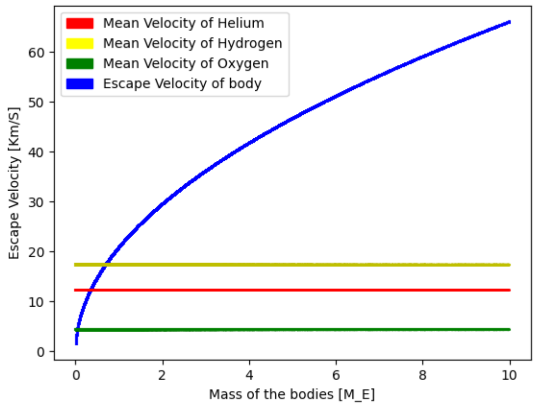

Figure 19. The graph shows mean velocities for various elements such as Helium, Hydrogen, Oxygen as well as the escape velocity of planetary body against varying masses of planetary bodies. The mass of the body is used to calculate the escape velocity. When the mean velocity of an element is greater than the escape velocity, it is lost to space.

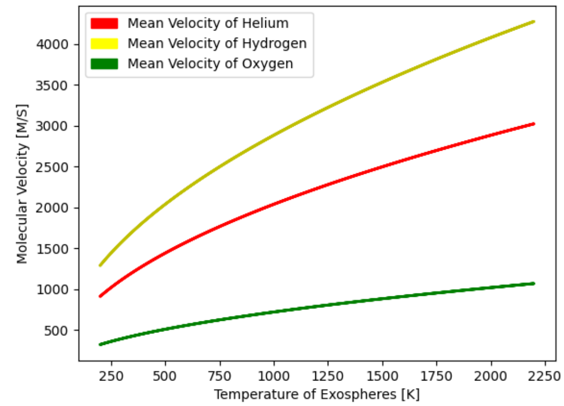

Figure 20.

3. RESULTS

4. DISCUSSION AND CONCLUSION

Software: Astropy (**??**)

ACKNOWLEDGMENTS

This work was supported by an LSSTC Catalyst Fellowship awarded by LSST Corporation to T.D. with funding from the John Templeton Foundation grant ID 62192.

APPENDIX

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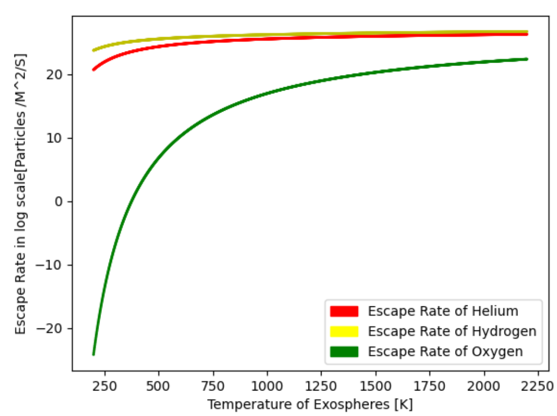

Figure 21.

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