Exploring Exoplanet Climates and Habitability

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Mathematics of Climate, MATH (MARS) 4730.

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Project Rubric

MATH(MARS) 4730/6730, Fall 2022

Your project written report is expected to complete the following tasks:

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1. Does the narrative flow smoothly? Are there abrupt changes from one topic to another? Are sections clearly labeled? (5 points)
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_______ - 15 Introduction

1. Does the introduction give a clear explanation of the subject of the project? (4 points)
2. Does the introduction discuss the importance of the subject? (5 points)
3. Does the introduction include a **complete** description of the subject suitable for someone not familiar with the situation? (6 points)

_______ - 10 Notation and Mathematical Style

1. Are the figures labeled? Are the axes labeled? Do figures include a caption? (2 points)
2. Are the equations numbered and properly punctuated? They should be part of a sentence. (See bullets above.) (2 points)
3. Are the equations properly formatted? (3 points)
4. Are all symbols (variables) used in the equations explained in the text? (3 points).

_______ - 25 Content

1. Is the report mathematically and scientifically correct? (5 points)
2. Are important concepts clearly explained? (5 points)
3. Are connections to climate and climate modeling stated clearly? (3 points)
4. Are models from the literature discussed? (3 points)
5. Is at least one model explored in detail (including numerically) or is a new model developed? (5 points)
6. Are all results and/or conclusions clearly explained? (4 points)

_______ - 5 Conclusion

1. Is an overview of the problem provided? (2 points)
2. Are the results stated again? (2 points)
3. Are any ideas offered as to any potential questions raised by the results? (1 points)

Abstract

This report aims to perform exploratory data analysis on the Kepler database, containing 571 exoplanets, and use energy balance equations to determine whether liquid water can exist on confirmed exoplanets. The database is extracted and relevant features, and data are visualized to find any underlying trends. The model created includes the calculated surface temperature from the energy balance model, habitable zone considerations, and planetary characteristics such as radius, mass, and eccentricity. Once the planets have been screened, the most promising candidates are ones that exhibit the most Earth-like conditions. The findings suggest that from the 571 screened exoplanets, roughly .005% contain liquid water on their surface (3 exoplanets).

1 Introduction

Studying exoplanets, especially exoplanets similar to Earth, can help us analyze how planetary systems are developed and deepen our understanding of how Earth and our solar systems were formed. Another reason is to find life outside of Earth. Trying to find extraterrestrial life can be difficult but there are ways we can attempt to find life forms. Searching for extraterrestrial life can be done by examining exoplanets' characteristics. Checking if exoplanets fall inside the habitable zone and factors including star size, age, temperature, planet distance, albedo, atmospheric composition, orbital eccentricity and several more. This way we can determine if the planet is capable of containing liquid water, which is a major indicator for life or habitability of a planet.

Going forward there are some concepts to define and understand. First is the habitable zone, this is the orbital region around a star where a planet can possibly have liquid water. This region is determined by multiple factors, some of the major factors include X-Ray irradiance from star, their relative abundance, star longevity, and distance from the star. There are three distinct zones defined by their sun's dwarf size (per NASA): They are the M, K, and G dwarfs habitable zones. M dwarfs (red stars) are the smallest stars with the smallest habitability zones due to high radiation and low temperatures. K dwarfs (orange stars) are sort of the sweet spot for finding planets in the habitable zone due to intermediate star mass, lower stellar activity, and long life spans. G dwarfs (yellow stars) are like our sun where they have the broadest habitable zone but are shorter lived.

2 Methodology

This paper bases most of the analysis from the Kepler database. This is an extensive dataset that has recorded exoplanet features and data ranging from 2009-2018. It's currently one of the largest exoplanet discovery projects. Over 2600 confirmed exoplanets and 530,506 stars discovered. Some key dataset features:

Star temperature, mass, luminosity, spectral classification, stellar age.
Planet orbit periods, radius, semi-major axis, eccentricity, planetary mass,
and estimated surface temperature.

Once the confirmed exoplanets dataset was downloaded, the following data pre-processing and analysis steps were taken. Cleaned the data/removed missing entries, defined features and variables. Then visualized the features through a correlation matrix to find any relevant data to include when screening the planets.

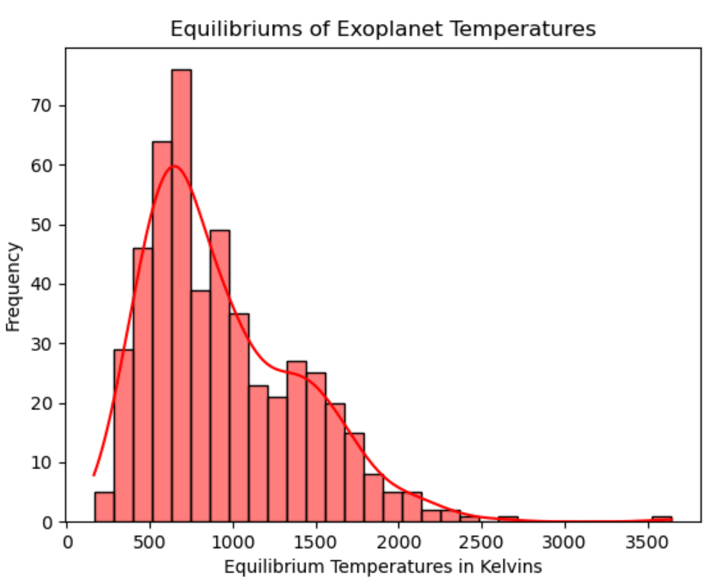
Once exoplanet data has been read, iterate the data over applying the energy balance model (using exoplanets incoming solar radiation, albedo, emissivity, and stefan-boltzmann constant). This will give insight to the exoplanets surface temperature, telling us if there are conditions for liquid water to be present. Then for the habitable zone, we can check their surface temperature, orbital conditions, and radiation intensity from the respective sun.

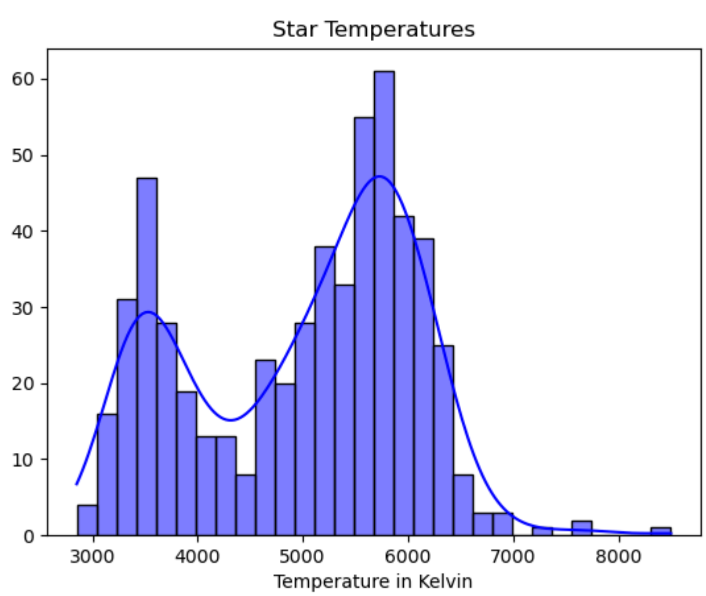
3 Implementation and Initial Analysis

To start, I made several visualizations of the dataset to get an idea of what I am working on, and the range of the data. They are shown below with the correlation matrix.

```
# Visualizing the distribution of key parameters related to habitability
sns.histplot(data['st_teff'], kde=True, bins=30, color='blue')
plt.title('Star Temperatures')
plt.xlabel('Temperature in Kelvin')
plt.ylabel('Frequency')
plt.show()

sns.histplot(data['pl_eqt'], kde=True, bins=30, color='red')
plt.title('Equilibriums of Exoplanet Temperatures')
plt.xlabel('Equilibrium Temperatures in Kelvins')
plt.ylabel('Frequency')
plt.show()
```





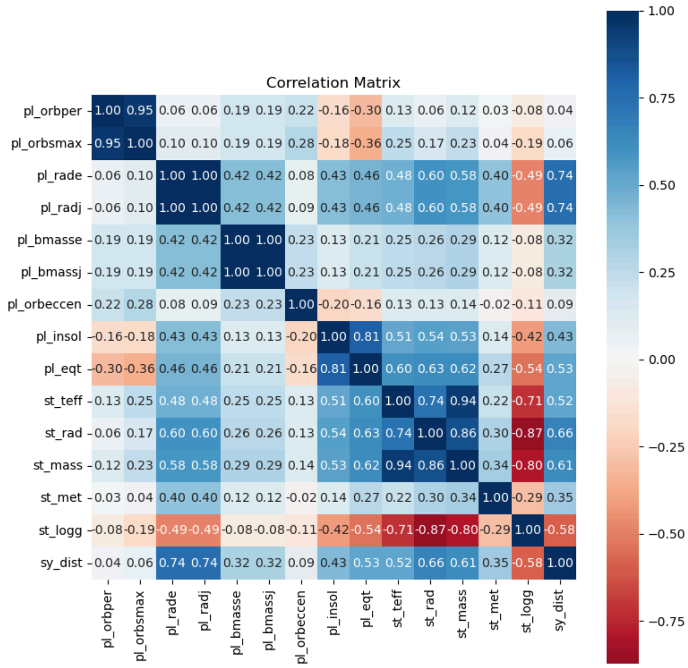


Figure depicting the correlation heatmap matrix.

From the plots shown above we can see that the average equilibrium temperature of the planets in the dataset is roughly 500 kelvin. The star temperatures have two significant peaks, around 6000 Kelvin (the most significant) and around 3500 Kelvin which is the second most significant peak. This implies that most of the planets in the dataset have type G and M stars (G stars are hotter, yellow, and most similar to our Earths sun, while M stars are cooler, older, and more X-ray radiation. This would mean that M type stars gives off radiation that is not conditions that are not conducive for life. From the correlation matrix there are several features to observe. The most correlated features were mass correlations (earth and jupiter masses as they are measured in the same unit, but different measurements) and orbital/stellar features (orbital period and semi-major axis high correlation from kepler's third law [$P^2 \propto a^3$]), and star mass was highly correlated with temperature (as larger stars are generally hotter).

Additional Plots.

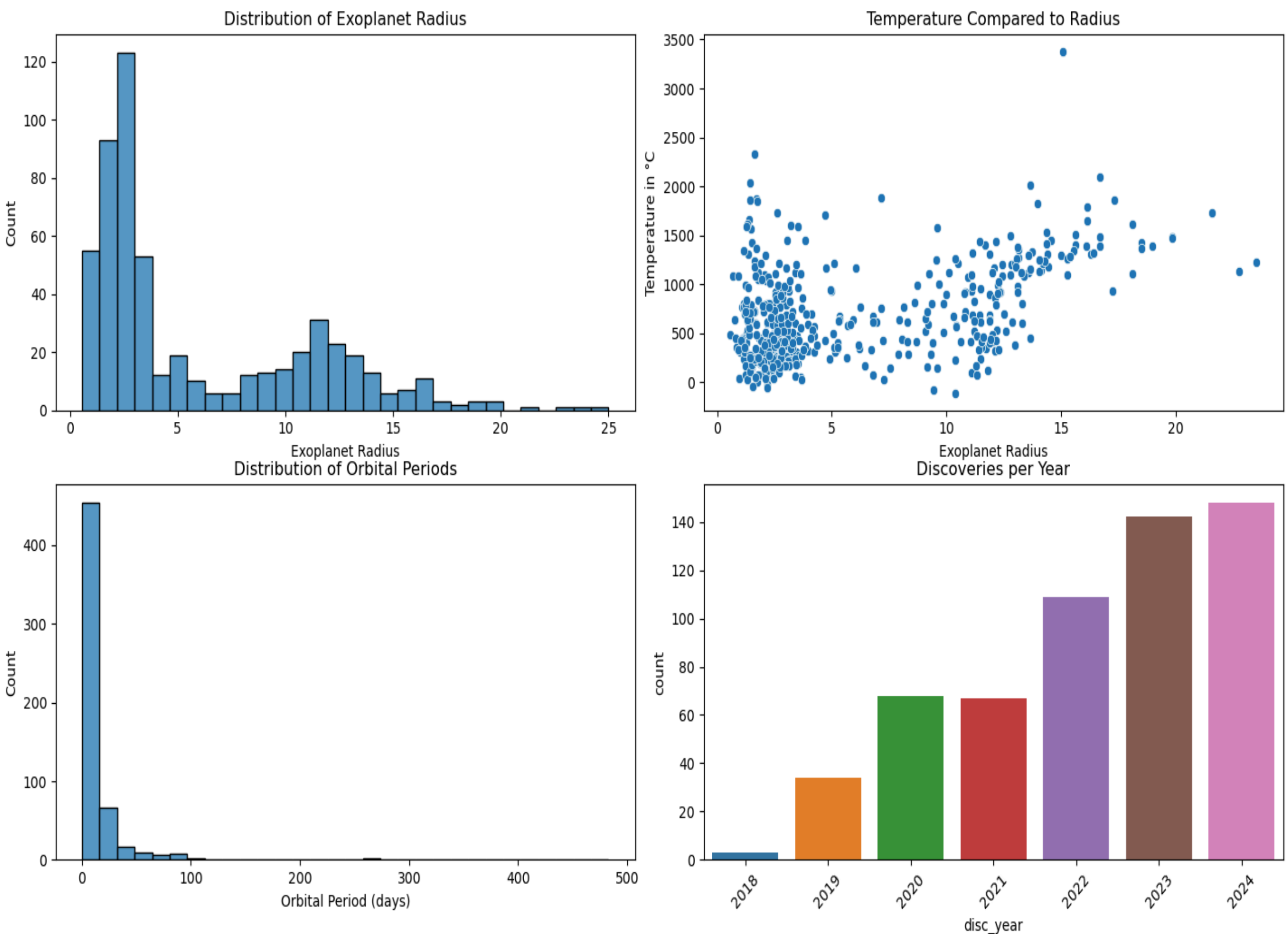


Figure with multiple plots depicting various exoplanet characteristics. From top-left, reading left to right, bottom to top, the fist plot shows the distribution of the exoplanets' radii, in multiples of Earth's radius. Most of the exoplanets were between 0.5 - 3.5 times Earth's radius. Similarly, for exoplanet temperatures, the largest cluster ranges from 0 Kelvin to 1500 Kelvin, this seems to be consistent across all the planets, even those much larger in radius to Earth. Next, in the bottom left, we see that most of the exoplanets' orbital period around their host stars tends to from 300 - 450 days.

4 Results

Now that the dataset has been cleaned and pre-processed, we can use a simple energy balance model to compute the solar constant and surface temperature for each planet. The solar constant is computed by $SolarConstant\ = (Luminosity)/\ (4\ *\ pi\ *\ distance^2)$. Then we can use this to calculate surface temperature by using a simple energy balance model, similar to in-class, $surfaceTemp\ = \ ((solarConstant\ *\ (1 - albedo))/(4 * sigma))^{1/4}$.

```python
# Define constants
#assume similar albedo and emissivity as that of Earth
sigma = 5.67e-8  #(W/m^2/K^4)
albedo = 0.3
emissivity = 1.0
#function to compute surface temperature for exoplanet
def getSurfaceTemp(row):
    if pd.notnull(row['st_teff']) and pd.notnull(row['pl_orbsmax']):

        #exoplanet host star properties
        starTemp = row['st_teff']
        starRadius = row['st_rad'] * 6.957e8  #in meters

        #get distance to start
        distance = row['pl_orbsmax'] * 1.496e11 #in meters

        #calculate solar constant and luminosity
        #using formula SolarConstant = (Luminosity / 4* pi * distance^2)
        Luminosity = 4 * np.pi * (starRadius**2) * sigma * (starTemp**4)

        #check for empty cells and apply formula
        if not np.isnan(distance):
            #get solar constatn
            sConstant = Luminosity / (4 * np.pi * distance**2)
        else:
            sConstant = np.nan

        #compute suface temperature by [(sConstant*(1-albedo))/(4*sigma)]^(1/4)
        if not np.isnan(sConstant):
            #get surfacetemp
            surfaceTemp = ((sConstant * (1 - albedo)) / (4 * sigma))**0.25
        else:
            surfaceTemp = np.nan

        return surfaceTemp

#apply surface temperature computation to data
data['T_surface'] = data.apply(getSurfaceTemp, axis=1)

#screen for planets that have a temperature from 273 Kelvin to 373 Kelvin, as this assumeed habitable temp.
habitable_planets = data[(data['T_surface'] >= 273) & (data['T_surface'] <= 373)]

#compare to earth by making similar assumptions
#comparing radius, mass, and orbital eccentricity to that of earths
habitable_planets = habitable_planets[
    (habitable_planets['pl_rade'] >= 0.5) & (habitable_planets['pl_rade'] <= 2) &
    (habitable_planets['pl_bmasse'] >= 0.1) & (habitable_planets['pl_bmasse'] <= 10) &
    (habitable_planets['pl_orbeccen'] <= 0.2)
]

#after planets screened for ones most similar to Earth,
#print list of planets
print(habitable_planets[['pl_name', 'hostname', 'st_teff', 'pl_orbsmax', 'pl_rade', 'pl_bmasse', 'pl_orbeccen', 'T_surface']])
```

Code snippet covering the calculation of exoplanet surface temperature, and screening for habitability.

Initially, I only calculated for the surface temperature and screened for planets between 273 and 373 Kelvin. This generated a list of 20+ exoplanets, but not all the planets were suitable to have water. To further refine my search, I checked for planets that would have similar characteristics to Earth. This was done by comparing the exoplanets radius, mass, and orbital eccentricity to Earth; this significantly reduced the list of exoplanets down to just 3. These are the exoplanets TOI-1452 b, TOI-2095 b, and c. Further information is found in the figure below. (Additionally, the assumptions made on the values for albedo and emissivity of the exoplanets were made by using similar values as Earth.).

	pl_name	pl_eqt	temp_celsius	pl_insol	temp_viable	size_viable
202	TOI-1452 b	326.0	52.85	1.80	False	True
294	TOI-2095 b	347.0	73.85	3.43	False	True
295	TOI-2095 c	297.0	23.85	1.84	True	True

Picture indicating output results for screened exoplanets, along with their temperature in Celcius.

Here we can see the three planets screened to have liquid water. Further information about their characteristics is attached in the submission as habitable_planets.csv. Exoplanets TOI-1452 b and TOI-2095 b and c are similar to Earth in radius, shape, orbit, and eccentricity. They all, however, have several times more mass than Earth, and TOI-1452 b and TOI-2095 b are hotter. The exoplanet I feel most likely to contain liquid water is TOI-2095 c, as this planet has the most Earth-like conditions, a surface temperature of 23.85 Celsius (or 75 degrees Fahrenheit). Though all of these exoplanets exhibit Earth-like conditions (or as similar as possible), the largest point of concern is the host star. For all three of the exoplanets, the host stars are type M, meaning they give off a lot of X-ray radiation and aren't conducive to life.

5 Conclusion

Finding exoplanets that can contain liquid water or possibly be habitable is a complex task with many variables. By using Earth's planetary characteristics as a benchmark, we can proceed to apply these known features and try to screen habitable exoplanets. Using the Kepler database, we have found 3 distinct exoplanets that share similar features to Earth and can possibly contain water. The exoplanet most likely to have water was TOI-2095 c.

Going forward, there are several improvements that can be made to find more suitable planets. First, a more advanced energy balance model can be implemented (instead of assuming the planet just radiates as a blackbody). A two-layer energy balance model can definitely lead to improvement. Another approach for the implementation is to make a machine learning model for identifying planets with water. Using a classification model trained on the most relevant features conducive to liquid water, we can get better insight and a more thorough list of exoplanets. Thus, there is much work and expansion for future implementations.

6 Resources

Works Cited

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