Probing the Extrasolar Systems

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Astronomy, being the oldest science has always intrigued the human mind since ages. For centuries, fictional depictions of planets orbiting other stars have fired our imagination. We humans have always been fascinated with the idea of exotic, far-off worlds. We now know that worlds beyond our solar system — known as exoplanets — do exist. In fact, there are a whole lot of them. We have found over 5,000 exoplanets, and we believe that most stars have their own solar systems. In this project, we intend to study the extrasolar planetary systems' data and compare it with our own solar system to investigate whether some correlation between them exists.

Keywords: Exoplanets, solar system, mass distribution, eccentricity distribution, habitable zone

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I. INTRODUCTION:

Our universe is estimated to have over 100 billion galaxies, each with hundreds of billions of stars. If most stars have one or more planet around them, there may be *billions of trillions* of planets in the universe. Any planetary body that is outside the solar system and that usually orbits a star other than the Sun is called an *extrasolar planet* or an ***exoplanet***. Extrasolar planets were first discovered in 1992. Planets are much fainter than the stars they orbit. Hence, extrasolar planets are extremely difficult to detect directly. There are lots of reasons to learn about exoplanets, but perhaps the most compelling is that we could find another world that hosts living organisms. If we discover life beyond Earth, it could change the course of human history.

II. RADIAL VELOCITY METHOD:

The radial-velocity method for detecting exoplanets relies on the fact that a star does not remain completely stationary when it is orbited by a planet. The star moves, ever so slightly, in a small circle or ellipse, responding to the gravitational tug of its smaller companion. When viewed from a distance, these slight movements affect the star's normal light spectrum, or color signature. The spectrum of a star that is moving towards the observer appears slightly shifted toward bluer (shorter) wavelengths. If the star is moving away, then its spectrum will be shifted toward redder (longer) wavelengths.

By far the most successful technique for finding and studying extrasolar planets has been the radial velocity method, which measures the motion of host stars in response to gravitational tugs by their planets. Swiss astronomers Michel Mayor and Didier Queloz discovered the first planet using this technique, 51 Pegasi b, in 1995, for which they won the 2019 Nobel Prize in Physics for their discovery. Radial velocity measurements determine the sizes and shapes of the orbits of extrasolar planets as well as the lower limits of the masses of these planets. They provide only lower limits on planetary mass because they measure just the portion of the star's motion toward and away from Earth.

Using highly sensitive spectrographs attached to ground-based telescopes, planet hunters can track a star's spectrum, searching for periodic shifts spectral wobbles. The spectrum appears first slightly blue-shifted, and then slightly red-shifted. If the shifts are regular, repeating themselves at fixed intervals of days, months, or even years, it is almost certainly caused by a body orbiting the star, tugging it back and forth over the course of its orbit. If the body has a mass lower than about 10 times that of Jupiter (about 3,000 times the mass of Earth), then it is probably a planet. (Larger-mass objects are probably stars.)

The source of this trouble with radial velocity is that the method can only detect the movement of a star towards or away from the Earth. This is not a problem if the orbital plane of the distant planetary system appears edge-on when observed from the Earth. In that case, the entire movement of the star will be towards or away from Earth, and can be detected with a sensitive spectrograph. The mass of the planet, derived from this movement, will in this case be fully accurate.

If, however, the orbital plane of a planet is face-on when observed from the Earth, the entire wobble of the star will be perpendicular to an observer's line of vision. While the star may move significantly within the orbital plane, no part of its movement will be towards or away from the Earth. No spectrum shift will be detected, and the Earth-bound observer will remain ignorant of the presence of a planet orbiting the star.

In most cases a distant planet's orbital plane is neither edge-on nor face-on when observed from Earth. Most commonly the orbital plane is tilted at some unknown angle to the line of sight. This means that a spectrograph would not detect the full movement of the star, but only that component of its wobble that moves it toward Earth or away from it. The mass of the suspected planet is directly proportional to the star's actual wobble. If only a portion of this wobble is detected, then the measured mass will be lower than the true one and provide only a minimum figure for the planet's mass.

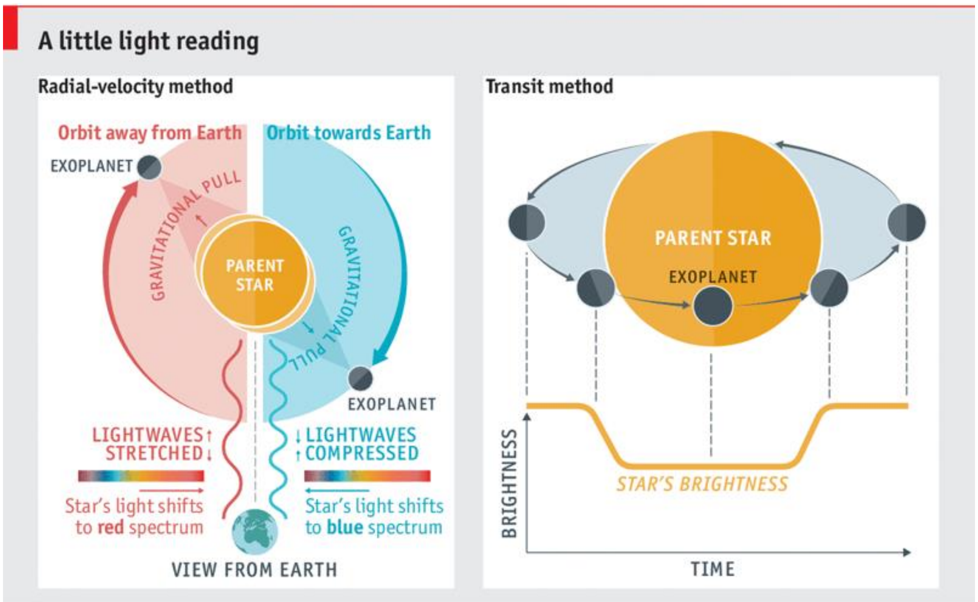
III. TRANSIT METHOD:

A complementary technique is *transit photometry*, which measures drops in starlight caused by those planets whose orbits are oriented in space such that they periodically pass between their stars and the telescope; transit observations reveal the sizes of planets as well as their orbital periods. Radial velocity data can be combined with transit measurements to yield precise planetary masses as well as densities of transiting planets and thereby limit the possible materials of which the planets are composed. Spectroscopic studies that rely on variations in the depth of the transit with wavelength have been used to identify gases such as hydrogen, sodium, and methane in the upper atmospheres of some close-in giant planets. The first detected transiting planet was HD 209458b in 1999. Both radial velocity and transit techniques are most sensitive to large planets orbiting close to their stars.

A transit occurs when a planet passes between a star and its observer. Transits within our solar system can be observed from Earth when Venus or Mercury travel between us and the Sun.

Transits reveal an exoplanet not because we directly see it from many light-years away, but because the planet passing in front of its star ever so slightly dims its light. This dimming can be seen in light curves – graphs showing light received over a period of time. When the exoplanet passes in front of the star, the light curve will show a dip in brightness.

This data is part of why transits are so useful: Transits can help determine a variety of different exoplanet characteristics. The size of the exoplanet's orbit can be calculated from how long it takes to orbit once (the period), and the size of the planet itself can be calculated based on how much the star's brightness lowered.
We can also learn about an exoplanet's atmosphere during a transit. As it transits, some light will go through its atmosphere and that light can be analyzed to determine what different atmospheric elements influenced its particular dispersion. Atmospheric composition is important to determining habitability. Habitability can be further shown through orbital size and star temperature. These help determine the temperature of the planet itself, thus telling us whether its surface is a comfortable temperature or unsuitable for life.



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IV. OTHER METHODS:

Three other techniques that have detected extrasolar planets are *pulsation timing*, *microlensing*, and *direct imaging*. Pulsation timing measures the change in distance between the signal source and the telescope by using the arrival times of signals that are emitted periodically by the source. When the source is a pulsar, current technology can detect motions in response to a planet whose mass is as small as that of Earth's Moon, whereas only giant planets can be detected around pulsating normal stars. The first extrasolar planets to be discovered were found in 1992 around the pulsar PSR 1257+12 by using this method. Microlensing relies upon measurements of the gravitational bending of light (predicted by Albert Einstein's general theory of relativity) from a more distant source by an intervening star and its planets. This technique is most sensitive to massive planets orbiting hundreds of millions of kilometres from their star and has also been used to discover a population of free-floating giant planets that do not orbit any star. Direct imaging can be done by using starlight reflected off the planet or thermal infrared radiation emitted by the planet. Imaging works best for planets orbiting those stars that are nearest to the Sun, with infrared imaging being especially sensitive to young massive planets that orbit far from their star.

The most massive planets that transit their stars are made primarily of the two lightest elements, hydrogen and helium, as are the Sun and its two largest planets, Jupiter and Saturn. The term *Jupiters* is often used to describe these worlds, and the term *hot Jupiters* is applied to those massive planets orbiting very near their stars. Similarly, the terms *Neptunes* and *hot Neptunes* refer to planets less than about 10 percent of Jupiter's mass, and the term *super-Earths* refers to those planets that may well be rocky bodies only a few times as massive as Earth. The divisions between these various classes are not well defined, and these terms may well overemphasize the similarities with particular objects in the solar system. However, the lowest-mass transiting planets contain larger fractions of heavier elements than do transiting giant planets. An analogous relationship between planetary mass and composition exists within the solar system.

Nevertheless, many of the mentioned properties of extrasolar planets are in sharp contrast to those in the solar system. Jupiter, which takes nearly 12 years to travel around the Sun, has the shortest orbital period of any large planet (more massive than Earth) in the solar system. Even the closest planet to the Sun, Mercury, requires 88 days to complete an orbit. Within the solar system, the planets, especially the larger ones, travel on nearly circular paths about the Sun. Most extrasolar giant planets with orbital periods longer than two weeks have elongated orbits. Models of planetary formation suggest that giant extrasolar planets detected very near their stars formed at greater distances and migrated inward as a result of gravitational interactions with remnants of the circumstellar disks from which they accumulated. The free-floating giant planets had a different history in that they were probably formed in circumstellar disks but were ejected from their solar systems through gravitational interactions.

Stars that contain a larger fraction of heavy elements (i.e., any element aside from hydrogen and helium) are more likely to possess detectable gas giant planets. More massive stars are more likely to host planets more massive than Saturn, but this correlation may not exist for smaller planets. Many extrasolar planets orbit stars that are members of binary star systems, and it is common for stars with one detectable planet to have others. The planets detected so far around stars other than the Sun have masses from nearly twice to thousands of times that of Earth. All appear to be too massive to support life like that of Earth, but this too is the result of detection biases and does not indicate that planets like Earth are uncommon.

V. HOW ARE EXOPLANETS NAMED?

Exoplanet names can look long and complicated at first, especially in comparison to names like Venus and Mars. But they have a logic behind them that is important to scientists cataloguing thousands of planets. For example, HD 189733 b. The first part of the name is usually the telescope or survey that found it. In this case "HD" stands for the "Henry Draper Catalogue," a widely-used star catalogue. The number 189733 is the order in which the star was catalogued by position (the 1,89,733rd star added to the catalogue). The lowercase letter "b" stands for the planet, in the order in which the planet was found. The first planet found is always named b, with ensuing planets named c, d, e, f and so on. The star that the exoplanet orbits is usually the undeclared "A" of the system, which can be useful if the system contains multiple stars, which themselves may be designated B, C. (Stars are designated with capital letters; planets receive lowercase designations.) If a bunch of exoplanets around the same star are found at once, the planet closest to its star is named b with more distant planets named c, d, e and so on.

VI. MASS DISTRIBUTION:

Initially, the radial velocity technique was able to discover only very massive (Jupiter-class) planets in close-in orbits around their parent stars. One of the reasons for this selection effect is that these objects exert the greatest gravitational influence on their parent star and generate the largest reflex radial velocities. The other reason is that a star must be observed over a time interval greater than the orbital period of the planet before the existence of the planet can be confirmed. As the amount of time increases for the systems being surveyed, the longer time-line data have allowed researchers to find lower-mass planets and planets orbiting farther from the star. From the statistical studies of the systems investigated so far, it is evident that nature seems able to produce planets with a range of masses, with the lowest-mass planets being the most common.

$$\frac{dN}{dM} \propto M^{-1}$$

where dM is the range of mass of exoplanets, and
dN is the number of planets within the range dM.

VII. THE HABITABLE ZONE:

The standard definition is that the habitable zone is the range of distances from a star in which liquid water could exist.

From the references obtained on the internet,

The Minimum and Maximum distance (in terms of A.U) from a star where a planet exists and which can be called as the habitable zone can be calculated as such:

$$r_i = \sqrt{\frac{L_{ab}}{1.1}}, \qquad r_o = \sqrt{\frac{L_{ab}}{0.53}}$$

r_i = the inner boundary of the habitable zone in astronomical units (AU)

r_o = the outer boundary of the habitable zone in astronomical units (AU)

$L_{ab} = \frac{L_{star}}{L_{sun}}$ is the absolute luminosity of the star. Luminosity is the amount of energy received at distance (r), per unit time and per unit area and this decides the temperature at that distance (r).

(1.1) is a constant value representing stellar flux at the inner radius.

(0.53) is a constant value representing stellar flux at the outer radius.

VIII. WHAT IS THIS PROJECT ABOUT?

This Projects aims at the study of the exoplanetary data and compare it with the data of solar system and to see if there is any correlation or not. The comparison is done of the basis of parameters like eccentricities and masses distribution of planets with respect to the average distance of planet from the host star.

IX. METHODOLOGY:

1. The data of the solar system and exoplanetary systems are fetched in the CSV file format from credible sources. (Sources and their links are provided in the end.)
2. A python code has been developed to select out the data which is required for analysis in the project.
3. For Solar system, eight planets are sorted out from the CSV file of solar system along with other information such as their semi major axis in A.U (average distance from the sun) eccentricities of their orbits and also their value of masses (Jupiter mass).
4. The Eccentricity vs Average distance (A.U) of planet from the sun & Mass vs Average distance (A.U) of planet from the sun plots are obtained.
5. For the further analysis, data of mass and average distance is normalized to the mass of sun and radius of the sun and plots are obtained again for Eccentricity vs

average distance of planet from sun and mass vs average distance of planet from sun.

6. For Exoplanetary data analysis, similar procedure is followed like it has been followed for solar system analysis.
7. There is around information of about more than 4000 exoplanets in the exoplanet data set. So, to compare other systems with the solar system, few conditions are imposed on the data and three exostellar systems are extracted.
8. The planetary systems are selected by imposing conditions such as:
   a. The stellar system must have only 1 star.
   b. The planets in the extrasolar system have to be at least 4.
9. There are number of stars are obtained, only three stars are selected on the basis of the position they lie in the spectral classification.
10. Only relevant data for three stars systems is sorted out for further analysis like eccentricities of orbits of planets, their masses and their average distance in A.U from their host star.
11. The Eccentricity vs Average distance (A.U) of planet from the host star & Mass (Jupiter mass) vs Average distance (A.U) of planet from the host star plots are obtained.
12. For the further analysis, data of mass and average distance is normalized to the mass of host star and radius of the sun and plots are obtained again for Eccentricity vs average distance of planet from host star and mass vs average distance of planet from sun.
13. Also, in this project, a count of how many planets lie in the Habitable zone of their host star is obtained, by checking if their average distance from the host star lies inside the boundary defined by Habitable zone or not.
14. In the CSV data of exoplanetary data base, the star's Luminosity in given in the terms of the logarithm of Absolute Luminosity.
    Log (Absolute luminosity) = x (given in the data)
    For calculation of habitable zone, Absolute Luminosity is required, thus

    Absolute Luminosity = $L_{ab} = \frac{L_{star}}{L_{sun}} = 10^{x}$

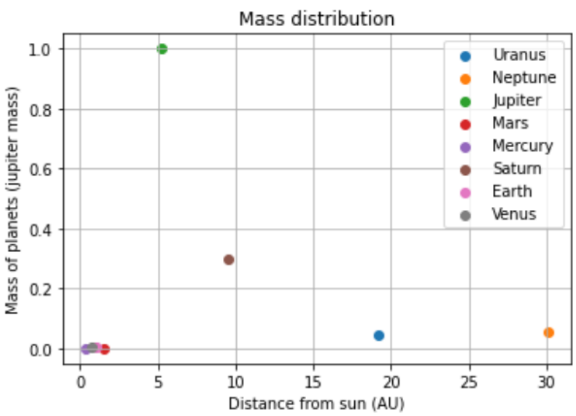
15. In this project we have also found an Earth like by sorting the data using specific conditions to match mass, radius and temperature of earth.
16. A Histogram plot of masses of plot has been generated with full range of mass values as well as narrow range of mass values.

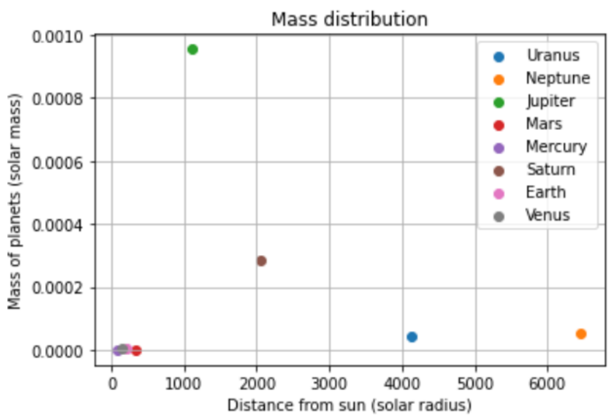
X. RESULTS

1. Solar System:

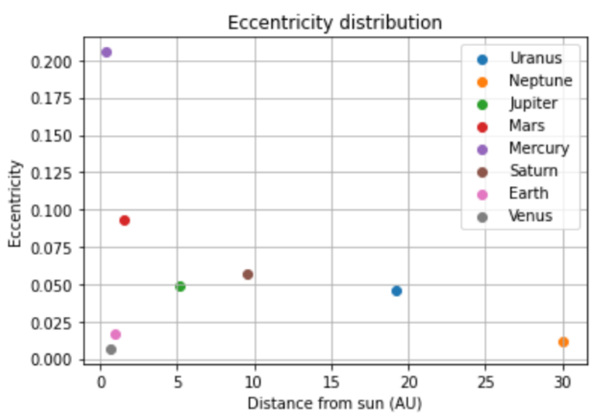
eName	eccentricity	mass(solar mass)	semi-major axis(solar radius)
Uranus	0.0457	4.360988e-05	4126.287460
Neptune	0.0113	5.124664e-05	6466.000346
Jupiter	0.0489	9.545942e-04	1118.788014
Mars	0.0935	3.225524e-07	327.646721
Mercury	0.2056	1.657979e-07	83.238791
Saturn	0.0565	2.853734e-04	2050.691997
Earth	0.0167	2.999436e-06	215.032718
Venus	0.0067	2.446776e-06	155.538990

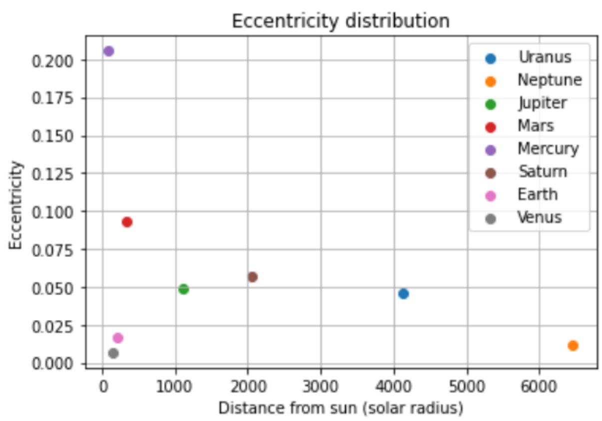
a. Mass Distribution:





b. Eccentricity Distribution:



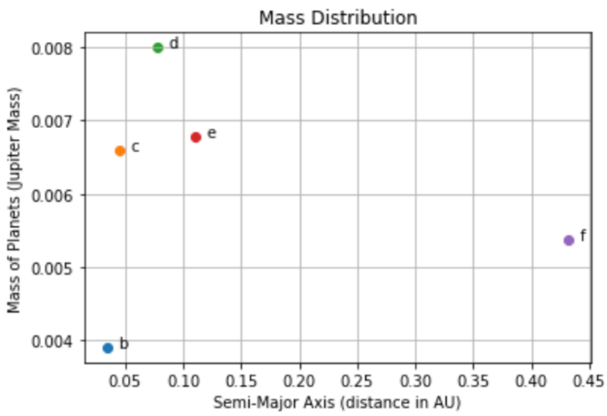


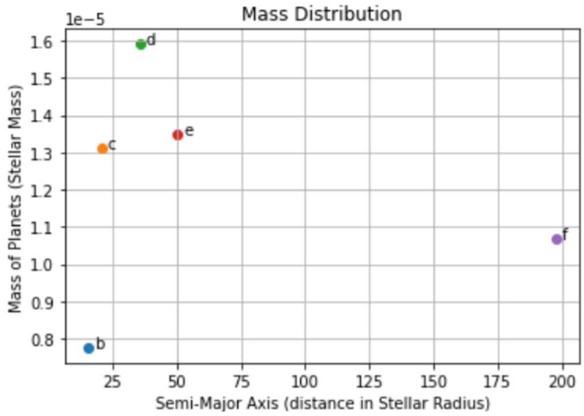
2. Kepler-186:

Star Name:	Kepler-186
Number of Planets:	05
Stellar Effective Temperature:	3788.0 K
Stellar Mass [Solar Mass]:	0.48
Stellar Radius [Solar Radius]:	0.47
Stellar Luminosity [log(Solar)]:	-1.385
Distance to star in parsec:	177.594
Spectral Type:	M1

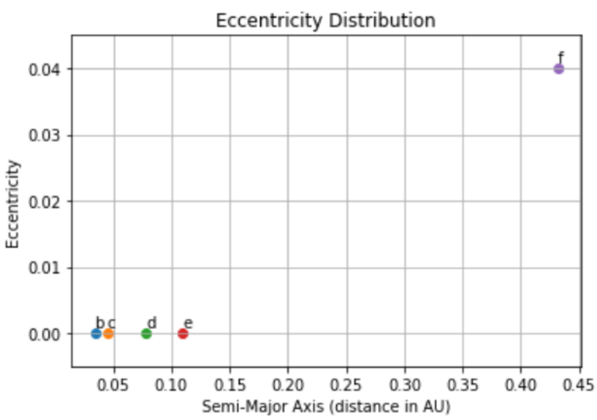
Planet Name	Planet Letter	Orbit Semi-Major Axis (Stellar radius)	Planet Mass [Stellar Mass]	Eccentricity
Kepler-186 b	b	15.692772	0.000008	0.0
Kepler-186 c	c	20.633937	0.000013	0.0
Kepler-186 d	d	35.731939	0.000016	0.0
Kepler-186 e	e	50.326675	0.000013	0.0
Kepler-186 f	f	197.646577	0.000011	0.04

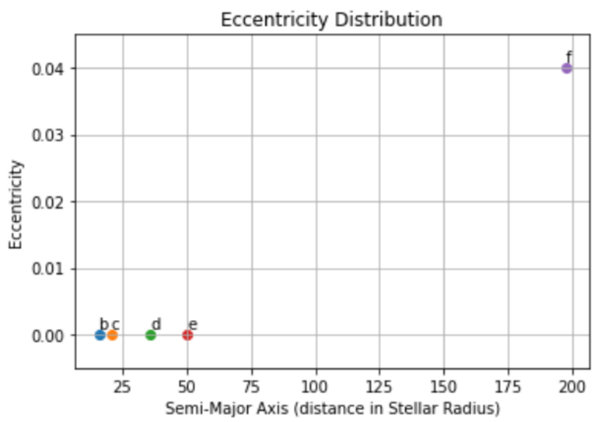
a. Mass Distribution:





b. Eccentricity Distribution:



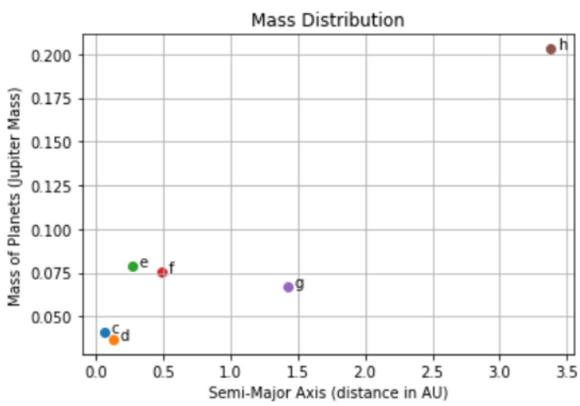


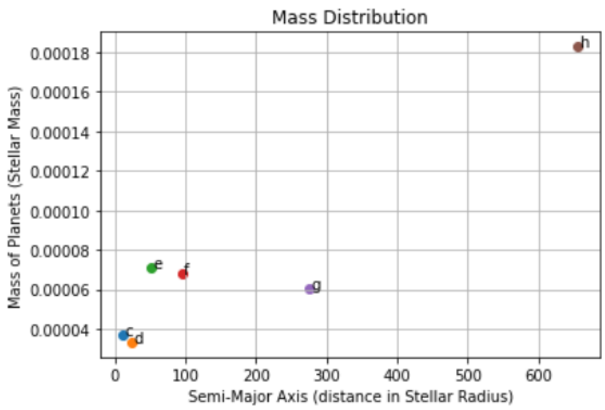
3. HD 10180:

Star Name:	HD 10180
Number of Planets:	06
Stellar Effective Temperature:	5911.0 K
Stellar Mass [Solar Mass]:	1.06
Stellar Radius [Solar Radius]:	1.11
Stellar Luminosity [log(Solar)]:	0.173
Distance to star in parsec:	38.9607
Spectral Type:	G1 V

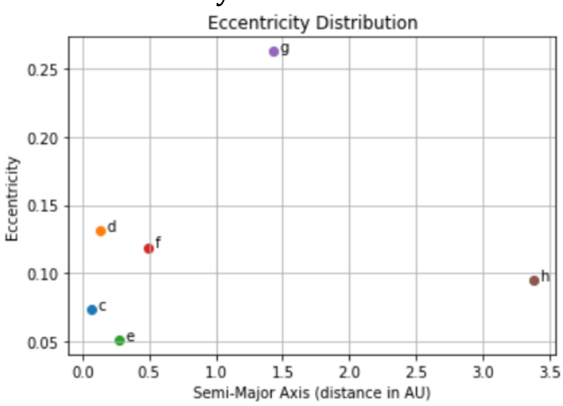
Planet Name	Planet Letter	Orbit Semi-Major Axis (Stellar radius)	Planet Mass [Stellar Mass]	Eccentricity
HD 10180 c	c	12.421497	0.000037	0.073
HD 10180 d	d	24.910797	0.000033	0.131
HD 10180 e	e	52.285747	0.000071	0.051
HD 10180 f	f	95.4859	0.000068	0.119
HD 10180 g	g	276.44224	0.000061	0.263
HD 10180 h	h	654.976323	0.000183	0.095

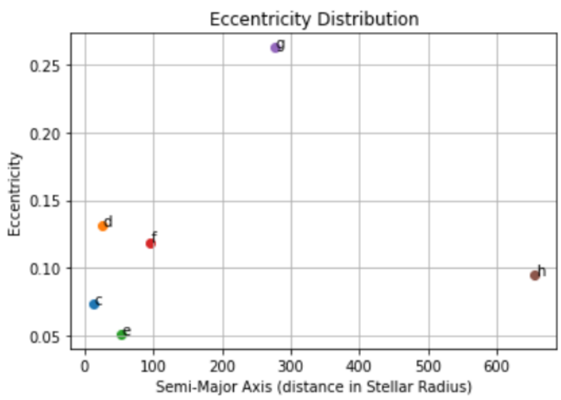
a. Mass Distribution:





b. Eccentricity Distribution:



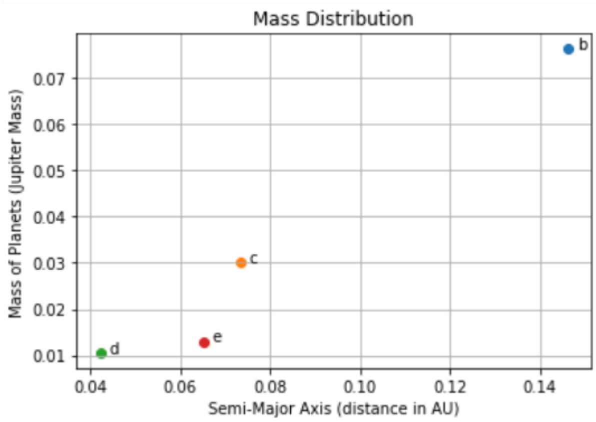


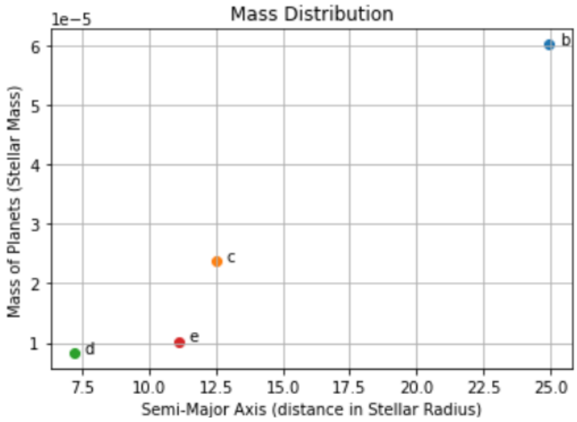
4. DMPP-1:

Star Name:	DMPP-1
Number of Planets:	4
Stellar Effective Temperature:	6196.0 K
Stellar Mass [Solar Mass]:	1.21
Stellar Radius [Solar Radius]:	1.26
Stellar Luminosity [log(Solar)]:	0.32
Distance to star in parsec:	62.5388
Spectral Type:	F8 V

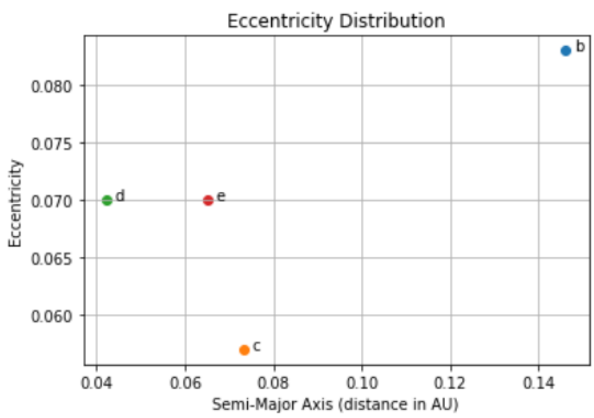
Planet Name	Planet Letter	Orbit Semi-Major Axis [au]	Planet Mass or Mass*sin(i) [Jupiter Mass]	Eccentricity
DMPP-1 b	b	0.1462	0.07636	0.083
DMPP-1 c	c	0.0733	0.0302	0.057
DMPP-1 d	d	0.0422	0.01054	0.07
DMPP-1 e	e	0.0651	0.01299	0.07

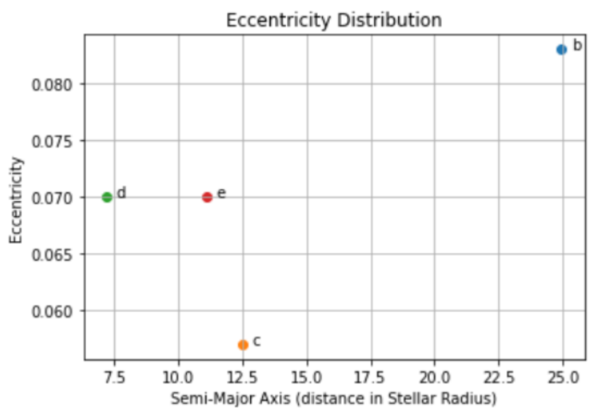
a. Mass Distribution:





b. Eccentricity Distribution:





5. Habitable Zone:

   a. Solar System:

      The inner limit of habitable zone is: **0.9534625892455924** AU
      The outer limit of habitable zone is: **1.37360563948689** AU
      The number of planets in habitable zone in our solar system are: **1**

   b. Kepler-186:

      The inner limit of habitable zone is: **0.1935546714161919** AU
      The outer limit of habitable zone is: **0.27884448871420914** AU
      The number of planets in Habitable zone of star Kepler 186 are: **0**

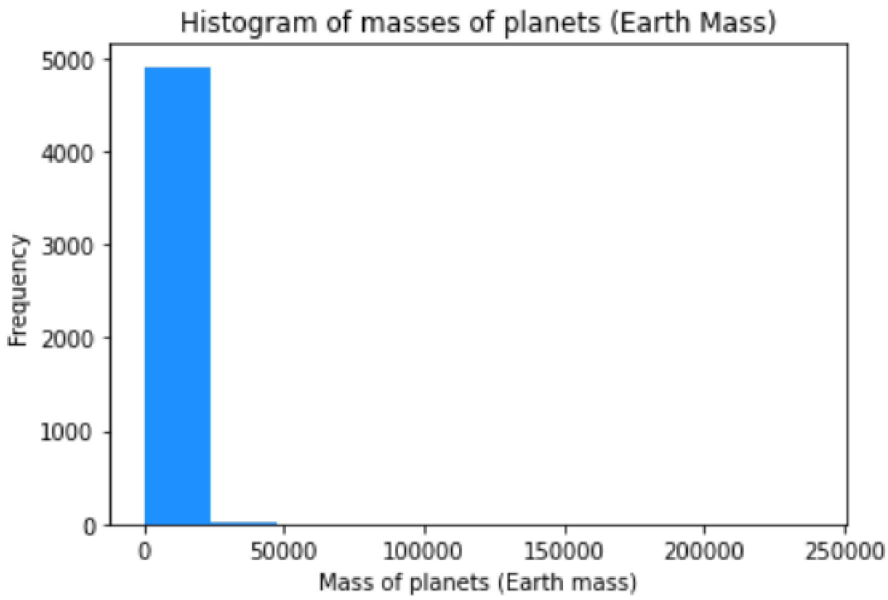
   c. HD 10180:

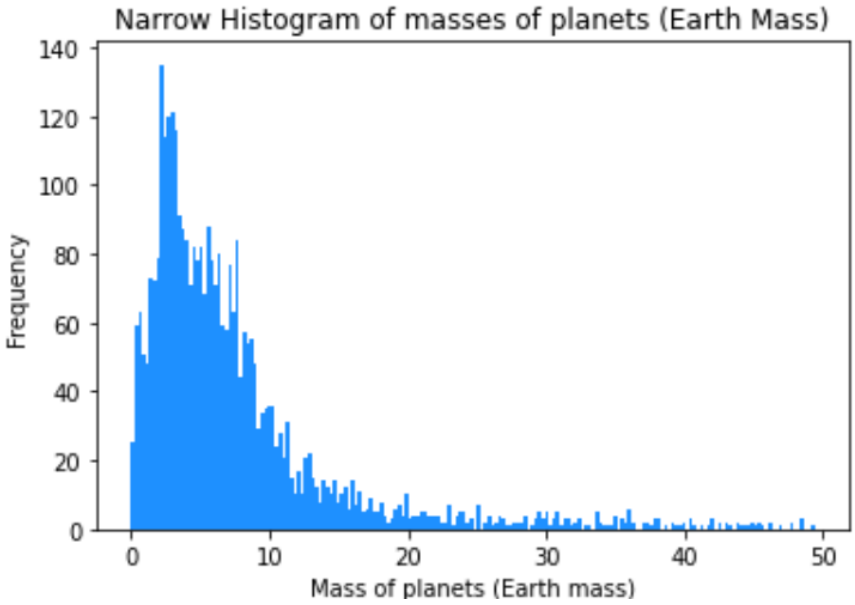
      The inner limit of habitable zone is: **1.1635998522261988** AU
      The outer limit of habitable zone is: **1.6763398345693485** AU
      The number of planets in Habitable zone of star HD10180 are: **1**

   d. DMPP-1:

      The inner limit of habitable zone is: **1.3781727464139675** AU
      The outer limit of habitable zone is: **1.9854642206352437** AU
      The number of planets in Habitable zone of star DMPP1 are: **0**

6. Histogram Plot:





7. Search for Earth-like planet:
   The conditions that were imposed upon the Exoplanetary data to get an Earth-like planet were:
   1. $0.8 \times R_{Earth} \leq R_{planet} \leq 1.2\times R_{Earth}$
   2. $0.8 \times M_{Earth} \leq M_{planet} \leq 1.2\times M_{Earth}$
   3. $250K \leq T_{planet} \leq 323K$

Planet Name	Star Name	Planet Letter	Number of Stars	Discovery Method	Discovery Year	Orbital Period [days]	Orbit Semi-Major Axis [au]	Planet Radius [Earth Radius]	Planet Mass or Mass*sin(i) [Earth Mass]	Eccentricity	Equilibrium Temperature [K]	Stellar Effective Temperature [K]	Stellar Mass [Solar mass]	Stellar Luminosity [log(Solar)]	Distance [pc]
Kepler-1649 b	Kepler-1649	b	1	Transit	2017	8.689099	0.0514	1.017	1.03	0.0	307.0	3240.0	0.2	-2.287	92.1913

Yayy!!! We found ***EARTH 2.0!!***

XI. CONCLUSIONS:

1. In the case of solar system, we do not see any trend or formula that can describe the eccentricity vs distance & mass vs distance plots. But we can still infer one thing, that inner planets show bigger difference in eccentricities of the orbits between them than compared to the Giant planets and reverse can be seen in the case of giant planets, they show bigger difference in mass (in terms of Jupiter mass) content between them (if we ignore Neptune) as compared to that of the rocky planets.
2. The analysis of three extrasolar planetary systems (Kepler-186, HD 10180, DMPP-1) also do not show any trend or a rule that can describe them. The plots are scattered. We can confidently say, Eccentricity and Masses distributed are randomly distributed with respect to their average distance from the host star.

3. The Normalization of masses and average distances with respect to host stars, do not serve much purpose. It just changes the scale of the graph.
4. The histogram plot verifies the relation $\frac{dN}{dM} \propto M^{-1}$

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Bibliography:

1) Introduction to Modern Astrophysics by B. W. Carroll & D. A. Ostlie, Second Edition, Chap. 23.

2) Astronomy: Principles and Practice by A. E. Roy & D. Clarke, Fourth edition, Chap. 13.

References:

1. https://www.kaggle.com/jaredsavage/solar-system-major-bodies-data

2. https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PSCompPars

3. https://www.planetarybiology.com/calculating_habitable_zone.html

Python Code File.
Data Files.