



Trends and Behaviours of Exoplanets with respect to the star classifications

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Contents

PART A	8
1. Introduction	9
1.1. Background and literature survey	9
1.2. Classification Exoplanets	9
1.2.1. Classification with respect to mass	9
1.2.2. Classification with respect to temperature	10
1.3. Detection Methods	11
1.3.1. Radial velocity	12
1.3.2. Transit	14
1.4. Survey Telescopes	15
1.4.1. The Kepler Telescope	16
1.4.2. Ground based telescope	17
2. Objective I	18
2.1. Trends and Behaviours of Exoplanets with respect to the star classifications	18
2.1.1. Introduction	18
2.1.2. Flowchart	19
2.1.3. Database	20
2.2. Study and Characterization of Exoplanets	20
2.2.1. Stellar Age V/s Exoplanet mass	20
2.2.2. Orbital period of planet vs. Mass planet w.r.t. Star class	21
2.2.3. Planet population statistics for star age (0.003 - 9.8×10^9 years)	22
2.2.4. Stellar Effective Temperature v/s Mass of the Exoplanet v/s Stellar Age	23
2.2.6. Age Related Trends	25
2.2.7. Masses of Planets around Stars of varied Age and Temperatures	26
2.2.8. Mass Radius Relationships	27
2.2.9. Temperature, Mass Analysis	29
2.2.10. Understanding Orbital Period Trends	30
2.2.11. Distances from Earth	32
2.2.12. A Look into Stellar Metallicity of Exoplanet Stars	33
2.2.13. Population of exoplanets w.r.t star class	34
2.2.14. Density population of exoplanets w.r.t star class	35
2.3. Inference	36

3. Conclusion and Scope for Future work	38
References.....	39
Code Sheet	44
PART-B	67
1. INTRODUCTION	68
1.1. AIM AND OBJECTIVE	68
OBJECTIVE –II : Analysing the spectral data of stars using MATLAB.....	68
2. BACKGROUND&LITERATURE OVERVIEW	69
2.1. STAR	69
2.1.1. FORMATION OF STARS.....	69
2.1.2. PROPERTIES OF THE STAR	69
2.2. STELLAR CLASSIFICATION	71
2.2.1. LUMINOSITY CLASS	72
Late giant carbon-star classes	74
2.3. STELLER SPECTRUM ANALYSIS:.....	76
2.3.1. EXTRACTING INFORMATION FROM THE SPECTRA	76
2.3.2. EMISSION AND ABSORPTION LINES	77
2.3.3. DETERMINING THE SURFACE TEMPERATURE OF THE STAR USING ITS SPECTRUM	78
2.3.4. RADIAL VELOCITY	78
2.4. STARS AND EXOPLANETS	79
2.4.1. METHODS TO FIND ATMOSPHERIC COMPOSITION	79
2.4.2. STELLAR HABITABILITY	81
2.4.3. POTENTIAL HABITABILITY.....	81
2.5. BIOSIGNATURES.....	82
2.5.1. FUNDAMENTALS	Error! Bookmark not defined.
2.5.2. SIGNIFICANT GASES	82
2.6. METHODOLOGIES, SOFTWARES AND TOOLS	83
2.6.1. SOFTWARES	83
2.6.2. DATABASES	84
3. DATA ANALYSIS	85
3.1. CODE	85
3.2. GRAPHS	86
3.3. CALCULATIONS.....	87
4. RESULTS & CONCLUSIONS.....	88

4.1. RESULTS	88
4.2. CONCLUSIONS	88
5. FUTURE SCOPE	89
REFERENCES	90

List of Tables

Objective 1

Table 1 : Classification of Exoplanets based on Mass and Radius	10
Table 2: Classification with respect to temperature.....	11
Table 3: Exoplanet population	22
Table 4: Density population of exoplanets w.r.t star class	35
Table 1- Luminosity class	72
Table 2- star type	72
Table 3- Spectral lines of stars	75

Objective 2

Table 4- Spectral lines and the wavelength	75
Table 5 - Wavelengths of each element	76

List of Figures

Objective 1

<i>Figure 1: Exoplanet detection methods.</i>	11
Figure 2: Mass vs. semi major axis using different detection methods.....	12
Figure 3: Radial Velocity Method	13
Figure 4: The Transit Light Curve	15
Figure 6: Image of Kepler Field of View, K2 Campaign 10	16
Figure 5: Kepler's Field of View (Schematic).....	16
Figure 7: The Kepler Telescope	17
Figure 8: Stellar Age Vs. Mass of the exoplanet	20
Figure 9: Orbital period of planet vs. Mass planet w.r.t. Star class	21
Figure 10: Planet population statistics for star age ($0.003 - 9.8 \times 10^9$ years)	22
Figure 11: Stellar Temperature vs. Mass of the Exoplanets vs. Stellar Age.....	23
Figure 12: Stellar Effective Temperature v/s Mass of the Exoplanet w.r.t Star Class	24
Figure 16: Stellar Temperature vs. Mass of the planet.....	26
Figure 15: Mass of planet vs. Stellar Age	26

Objective 2

Figure 1- Spectra of star HD09280.....	86
Figure 2- Wavelength vs intensity graph	87

PART A

Trends and behaviours of Exoplanets w.r.t the star classification

1. Introduction

For centuries now, fictional illustrations of planets in different star systems have kept our creative minds curious. From Desserts of Dune to the wildernesses of Yoda's planet Dagobah in Star Wars! As Terrans we have consistently been intrigued with the possibility of outlandish, far away universes.

First discovery of Exoplanets orbiting Sun-like stars during the 1990's [1] opened doors to whole new World! Just in 3 decades we have plentiful information on these far of worlds, i.e. there are tons of planets orbiting their own stars or just loafing around. Till now more than 4,000 exoplanet candidates have been observed. Some exoplanets are shockingly like anecdotal universes we've envisioned, while others have ended up being more outlandish than anything we could have imagined. [2]

1.1. Background and literature survey

Planet formation can take from few to millions of years within the years of their parental star formation. [3][4] Planetary bodies in our very own solar system can be studied in their present state, whereas planets with different parental stars from varying star cycles permits us to study different stages of planetary evolution as well. For example; from the observations of more than 4k planets, we now know that there are range from planets at extreme spectrums; such as planets which are yet to be formed in a spheroidal shape (young proto-planetary disks)[5] to planets as old as 10 G years.[6]

1.2. Classification Exoplanets

Exoplanets can be studied in a very broader spectrum attributing to their physical properties such as; colour and brightness, magnetic field, plate tectonics, volcanism, rings, moons, atmospheres and habitability etc.

Though the Exoplanets can be categorised using the above mention parameters, they are popularly studied with classifications in terms of their mass on Temperature.

Most of the exoplanets are gigantic and they orbit around main-sequence stars similar to the spectral class of our own sun, finding methods of exoplanets are more favourable to find huge planets orbiting closer to the star. Some exoplanets have less orbital distance and some have large elliptical orbits. Most of the exoplanets which have been confirmed are gaseous in nature. Others have rocky features with terrestrial signs in them. [7]

1.2.1. Classification with respect to mass

Exoplanets are divided into classes according to their radius and mass. Presently, they are separated into the following types: Asteroideans, Mercurian, Subterran, Terran, Superterran, Neptunian and Jovian, as presented below. [8][9]

*(*This classification has been used for our trend analysis)*

Table 1 : Classification of Exoplanets based on Mass and Radius

Planet Type	Mass (Earth Units)	Radius (Earth Units)	Potential Atmosphere*
Asteroidian	0 - 0.00001	0 - 0.03	Asteroidian are small irregular bodies (below the hydrostatic equilibrium) that are not able to hold a stable atmosphere.
Mercurian	0.00001 - 0.1	0.03 - 0.7	Mercurians are only able to hold significant atmospheres in the cold zones beyond the snow line (i.e. Titan).
Subterran	0.1 - 0.5	0.5 - 1.2	Subterrains are able to hold significant atmospheres after the outer edges of the habitable zone (i.e. Mars).
Terran	0.5 - 2	0.8 - 1.9	Terrans are able to hold a significant atmosphere with liquid water within the habitable zone (i.e. Earth).
Superterran	2 - 10	1.3 - 3.3	Superterrains are able to hold dense atmospheres with liquid water within the habitable zone.
Neptunian	10 - 50	2.1 - 5.7	Neptunians can have dense atmospheres in the hot zone.
Jovian	50 - 5000	3.5 - 27	Jovians can have super dense atmospheres in the hot zone.

Source: Planetary Habitability Laboratory (PHL) University of Puerto Rico at Arecibo

1.2.2. Classification with respect to temperature [10]

The Planetary Habitability Laboratory, University of Puerto Rico at Arecibo classifies exoplanets based on their temperature as mesoplanets, psychroplanets and thermoplanets. Surface temperature of the exoplanets can be indirectly determined by its distance to the parent star together with the star's luminosity within the stellar habitable zone. They focus on constructing the simplest formulation, which is based on temperature and restricted to terrestrial exoplanets with abundant water on their surface. Their terrestrial nature can be inferred by their size and density.

To develop a planetary habitability classification based on temperature we need to consider our understanding of the thermal requirements of life in general. Microbial life forms such as bacteria can sustain in temperatures ranging from -15°C to 121°C and macroscopic life form like animals (metazoan) are restricted to 0°C to 50°C. Primary producers like cyanobacteria and plants which generate most of the energy for consumers also have similar temperature ranges for sustenance. Most plants are particularly efficient at temperatures close to 25°C. Water is found in liquid state between 0°C to 100°C at standard atmospheric pressures but is also at -50°C in supercooled states or in combination with antifreeze agents. Based on the above considerations, thermal tolerance of life can be divided in bins of 50°C around the freezing point of water. The thermal tolerance classifications of 50°C around the freezing point of water are as follows:

Table 2: Classification with respect to temperature

Class	Type of planet	Temperature
Class hP	Hyperpsychroplanet	-100°C to -50°C
Class p	Psychroplanet	-50°C to 0°C
Class M	Mesoplanet	0°C to 50°C
Class T	Thermoplanet	50°C to 100°C
Class hT	Hyperthermoplanet	100°C to 150°C

- Mesoplanets are Earth-like planets, which may be potentially habitable by complex life as we know it, such as plants and animals.
- Psychroplanets (cold) and thermoplanets (hot) may harbour microbial life.
- An extension of the classification as hypopsychroplanets or hyperthermoplanets might still be habitable for life forms other than carbon-based life in aqueous environments.

1.3. Detection Methods

To detect exoplanets, there are numerous techniques available. Methods such as radial velocities, transits, gravitational microlensing, direct imaging and astrometry have been able to detect exoplanets so far. Each of them being unique technique and extremely sensitive to various types of Exoplanets. [11]

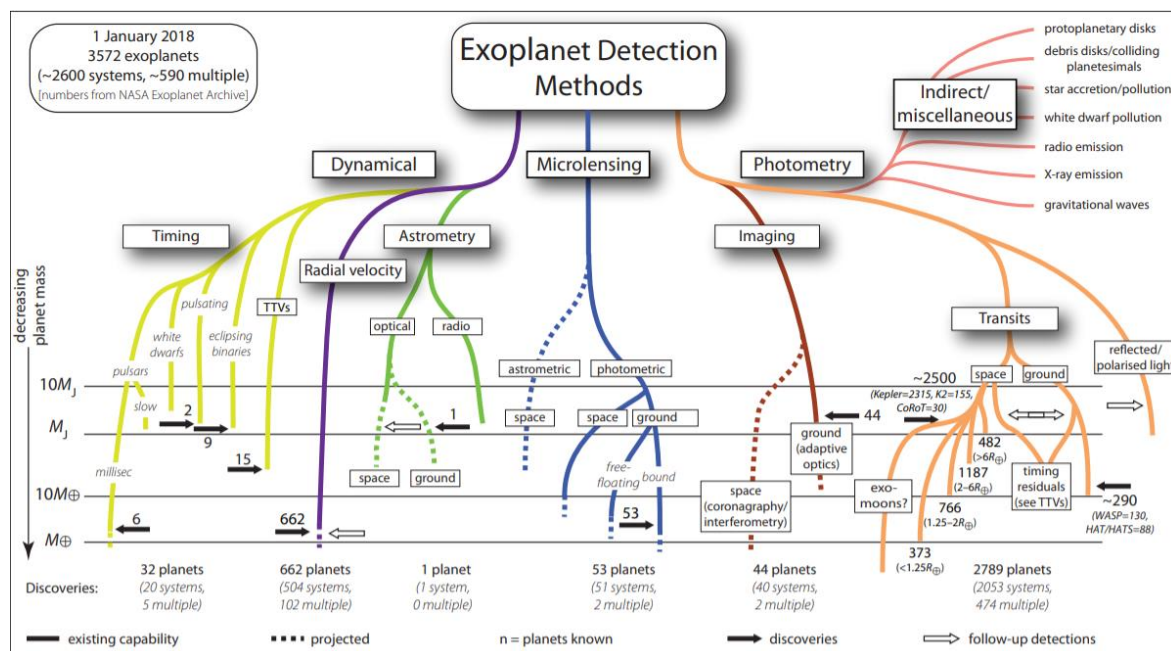


Figure 1: Exoplanet detection methods.

The lower limits of the lines indicate masses within reach of present measurements (solid lines), and those that might be expected within the next few years (dashed). The (Logarithmic) mass

scale is shown at left miscellaneous signature to the upper right are less well quantified in mass terms. Solid arrows show relevant discoveries. Open arrows indicate measurements of previously-detected systems. Numbers are from the NASA Exoplanet Archive [12]

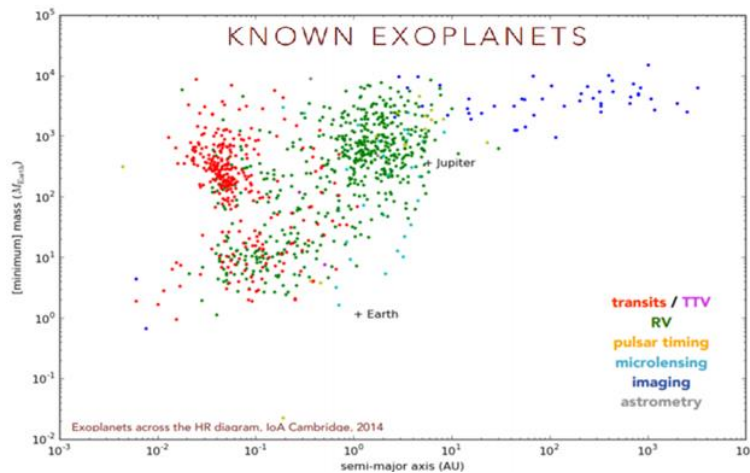


Figure 2: Mass vs. semi major axis using different detection methods

Evidently detection of Exoplanets using Transit and Radial Velocity method is huge in comparison to other techniques. [13]

1.3.1. Radial Velocity Method

1.3.1.1. Introduction

Radial velocity method is one of the methods used in the detection of exoplanets. There are other methods also but this method helps us to find information about the mass of the exoplanet. *'PRVs¹ complement other exoplanet detection methods, for example offering a direct path to obtaining the bulk density and thus the structure and composition of transiting exoplanets.* [14]

When a planet revolves around a star it's not just the planet that experiences the gravitational pull of the star, but the star also experiences the pull of the planet and it wobbles. Whenever the star is viewed from a distance there's a slight change in the star's spectrum due to the wobbling. The spectrum appears shifted, it shifts to blue when the star is moving towards the observer and appears red if the star is moving away. This is called the Doppler's shift. This detection *'measures the line-of-sight component of the space velocity vector of a star (hence the term "radial", i.e. the velocity component along the radius between observer and target)'* and is known as Radial Velocity Method. [15]

1.3.1.2. Detection method:

The detection of exoplanets involves spectral measurements. This requires highly sensitive spectrographs, which can search and measure the periodic shifts in the spectrum of the star. Here, we measure the relative shift rather than the absolute one (i.e. Continuum emission). We see the absorption lines and check that, how far they have shifted compared to the initial position. The shift here, not only occurs in the visible region but it occurs on the entire range of

¹ PRVs – Precise radial velocity.

the EM spectrum. Here this shift in frequency infers that there's some other mass present in the system, which has its gravitational effect on the star. It could be a star or a planet depending upon the shift that is produced. If it's a star the shift would be large and smaller if it is a planet. 'The result of a spectroscopic line-shift measurement may be expressed by means of the dimensionless redshift variable' (16)

$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{V_{obs} - V_0}{V_0}$$

Where λ_0 (ν_0) is the rest-frame wavelength (frequency). The redshift is often converted to a conventional velocity using some standard formula, the simplest being U_r , [14]-[16]

$$U_r = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = C_z$$

For a system of two gravitationally bound objects m_1 and m_2 in a circular orbit, the radial velocity semi amplitude K_1 of m_1 can be calculated by using:

$$K_1 = \frac{m_2 [\sin(i)]}{m_1 + m_2} \sqrt{G \frac{m_1 + m_2}{a}}$$

Where, m_1 is the more massive object and m_2 is the less massive secondary companion, i denotes the angle between the orbital plane and the plane of the sky, G is the gravitational constant, and a is the semi-major axis of the orbit. It is immediately clear that for face-on systems ($\sin i = 0$), K_1 is zero. [17]

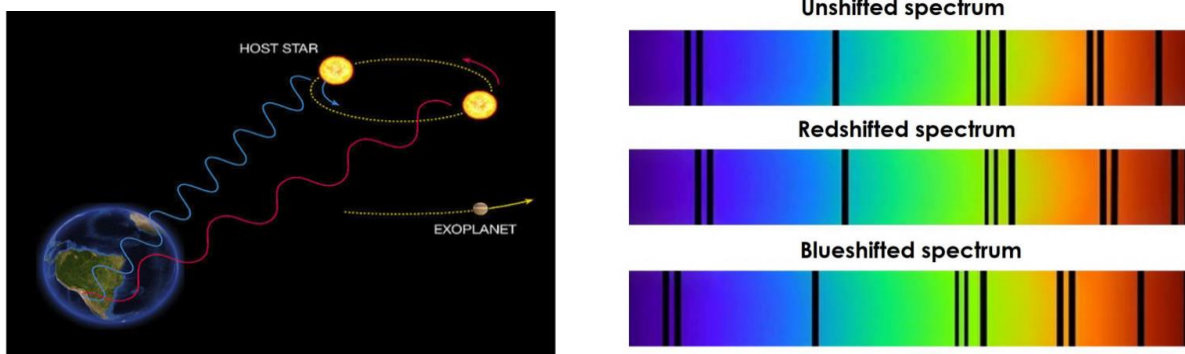


Figure 3: Radial Velocity Method

1.3.1.3. Detection problem/Limitations:

The detection problem can arise when instruments aren't calibrated and if there's a planet revolving the star at 90° , from our perspective, i.e. the whole system is facing towards us; in that

case, we cannot detect such planets using the radial velocity method. If the planet is revolving between 0° - 90° it might not give us the correct/ true value of radial velocity. This happens because we aren't measuring over the radius, but measuring on a particular angle. That is why this method is also known as the line-of-sight method. Here, the measurement accuracy, therefore, depends upon the orbital inclination from which the star is being observed. 'However, in order to deduce true velocities to high accuracy, all spectral observations – of "standard" stars and others – must undergo a detailed physical modelling of their emitted spectrum, and of its recording process'. As discussed in the earlier section the spectrum shift for a planet is quite small. [17] Therefore, the accuracy of measuring the spectrum (i.e. radial velocity) depends on the most miniscule changes which the telescopes can detect in the spectrum and on the number of objects present. 'If several planets are present, their signals will appear combined in the radial motion of the star, leading to potential misinterpretations of the data [18]

1.3.2. Transit Method

1.3.2.1. Introduction

Transit Method is one of the detection methods for exoplanets. This method detects the passage of a planet in front of its host star. This event is called a transit. Like Jupiter creates a transit of 1% depth in front of the Sun, and the Earth create a depth of 0.08%. One of the strengths of the transit method is that it allows to calculation of radius of the planet. By studying the spectrum of the star during transit and during eclipse (when planet behind the star) helps to know about the composition of the planet. The transit method is most sensitive to close-in planets as the probability of observing their transits is higher. [19]

In the mid-19th century, the radial velocity method was used to detect exoplanets. Since, the discovery of the first exoplanet HD 209458b, the transit method has become the most successful detection method among other methods. [20] Among the all planets had detected, 77% detected by using transit method. [21]

1.3.2.2. Detection

When a planet passes in front of the star, the brightness of the star as observed by us becomes dimmer; which depends on the size of the planet. During observation, the CCD (charge couple device) plays very crucial role. The array of CCD is used to continuously measure the variation in the brightness of star.[22] When we plot graph of Flux vs. time, we find that there is change in flux (depth of the light curve) for short period time. This enables us to detect planets around star. From these methods we can only determine the radius of the planet by using following formula.

$$\Delta F = \left(\frac{R_p}{R_s} \right)^2$$

(ΔF is fractional change in Flux of star light i.e. the depth of light curve. Here, R_p is the radius of planet and R_s is the radius of star)

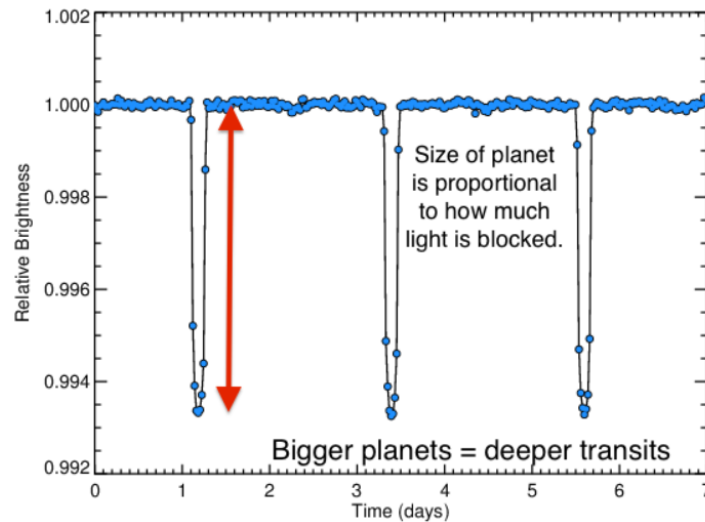


Figure 4: The Transit Light Curve [23]

1.3.2.3. Limitations

- Some transits don't last long. Here, the precision and accuracy matter a lot.
- For a transit to occur, the exoplanetary system needs to be seen from the edge of the system. Not all systems are in a plane w.r.t our point of view.
- Not only Planets can cause briefly dimmer in its light but other factors such as sun spots can also cause this. Such occurrences are known as called "false positive". The examples of false positive are binary star system, multiple star systems, stellar variability.[24][25]

1.4. Survey Telescopes

Since 1995, various telescopes have been employed to gaze the vast skies in search of planets residing in other solar systems. The ground-based and space telescopes work together in discovering exoplanets using various method such as direct imaging, gravitational microlensing, transit, radial velocity and transit timing.

The most successful planet-hunting technique to date has been radial velocity. HARPS (High Accuracy Radial Velocity Planet Searcher) spectrometer at the ESO 3.6-meter telescope in La Silla Observatory, Chile, and the HIRES spectrometer at the Keck telescopes use this method to measure variations in parent star's spectral lines due to the Doppler Effect.

CHEOPS (CHaracterising ExOPlanets Satellite) uses ultrahigh-definition transit photometry to detect the minute dimming of a star as a planet passes in front of it. Several other surveys have taken this approach, such as the ground-based MEarth Project, SuperWASP, KELT, and HATNet, as well as the space-based CoRoT, Kepler and TESS missions.

Gravitational microlensing occurs when one star passes directly in front of a background star, as seen from Earth. The gravitational field of the foreground star acts like a lens, magnifying the light of the background star. This effect occurs only when the two stars are almost exactly aligned. The

European Research Council-funded OGLE (Optical Gravitational Lensing Experiment) and the MOA (Microlensing Observations in Astrophysics) group are working to perfect this approach.

European Southern Observatory's Very Large Telescope array in Chile, the Keck Observatory telescope, Gemini Observatory telescope, the Subaru Telescope in Hawaii are some of the telescopes that use Direct imaging method.

Transit-timing variation is a method for detecting exoplanets by observing variations in the timing of a transit. Multiple transiting planets can be confirmed with the transit timing variation method [26]-[30]

1.4.1. The Kepler Telescope

The scientific objective of Kepler Mission is to explore the structure and diversity of the planetary systems. Such a goal is achieved by the survey of a large data of a sample of stars.

The Kepler Mission went up with the goal of achieving the following. It helped us:

1. In the determination of the percentage of terrestrial planets, as well as the larger planets which do exist in or near the habitable region of a wide diversity of stars
2. To understand the distribution of shapes and sizes of the orbits of these planets
3. In the estimation of the number of planets which exist in multiple-star systems
4. In the determination of the various orbit of varied sizes along with the planet reflectivities, their sizes, masses and the densities of the short-period giant planets
5. In the identification of the additional members of every planetary system discovered using other techniques
6. And lastly it helped us to understand the properties of those stars which are capable of harbouring planetary systems. [31]

Field of view

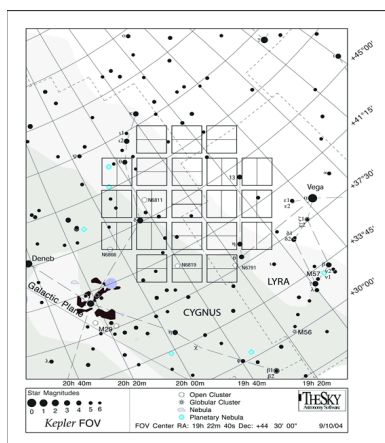


Figure 5: Kepler's Field of View (Schematic)

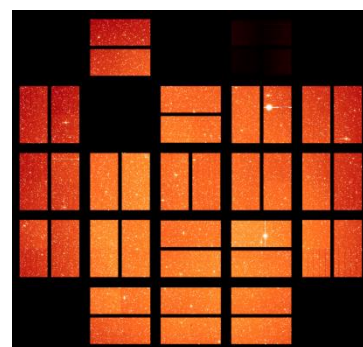


Figure 6: Image of Kepler Field of View, K2 Campaign 10

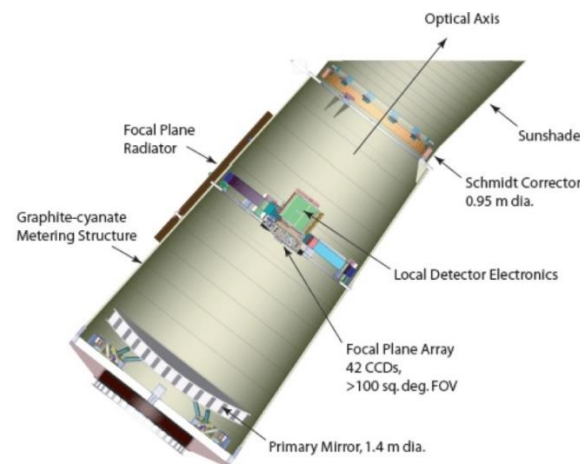


Figure 5: The Kepler Telescope

The Kepler photometer contains 21 CCD modules (each with two 2200x1024 pixel CCDs). Each of the modules cover 5 square degrees of the sky. The net 116 square degree field of view on the sky is given below; specifically, for the single field which was observed during the prime Kepler mission. [32]

1.4.2. Ground based telescope

Space based telescopes are more preferred over the ones on the ground due to atmospheric distortion. This results in blurred images of celestial objects. However, ground based telescopes have an upper hand when it comes to cost efficiency and maintenance. Recent technologies have implemented adaptive optics which sharpens the blurry images as they are being taken. The adaptive optics system uses lasers, supercomputers, and an array of mirrors to correct atmospheric distortion. Adaptive optics technology can be seen on the ground-based Giant Magellan Telescope that's slated for completion in 2021. Ground based telescopes play a major role in follow up studies of the exoplanets discovered by space telescopes using transit method.

Some major ground-based telescopes that focus on finding exoplanets are:

- a. **WASP** (Wide Angle Search for Planets) uses eight wide-angle cameras to search for exoplanets using photometry. It consists of an array of robotic telescopes that survey the entire sky, simultaneously monitoring thousands of stars of visual magnitude from about 7 to 13. WASP is an optical telescope that collects data by using transit method.
- b. The WASP has discovered about 118 exoplanets planets according to Extrasolar Planets Encyclopaedia, 2016.
- c. **HAT** (The Hungarian Automated Telescope Network) is a network of six small fully automated "HAT" telescopes. HAT detects and characterizes exoplanets using the transit method. It also finds and follows bright variable stars. The HAT has so far discovered 143 exoplanets.

- d. **HARPS** (High Accuracy Radial Velocity Searcher) is a high precision, second-generation spectrograph installed on the **ESO's** 3.6m telescope at **La Silla Observatory in Chile**. It detects exoplanets using radial-velocity method. HARPS can attain a precision of 0.97 m/s due to its intricate design. **HARPS** has discovered over 130 exoplanets to date.[33]-[37]

2. Objective I

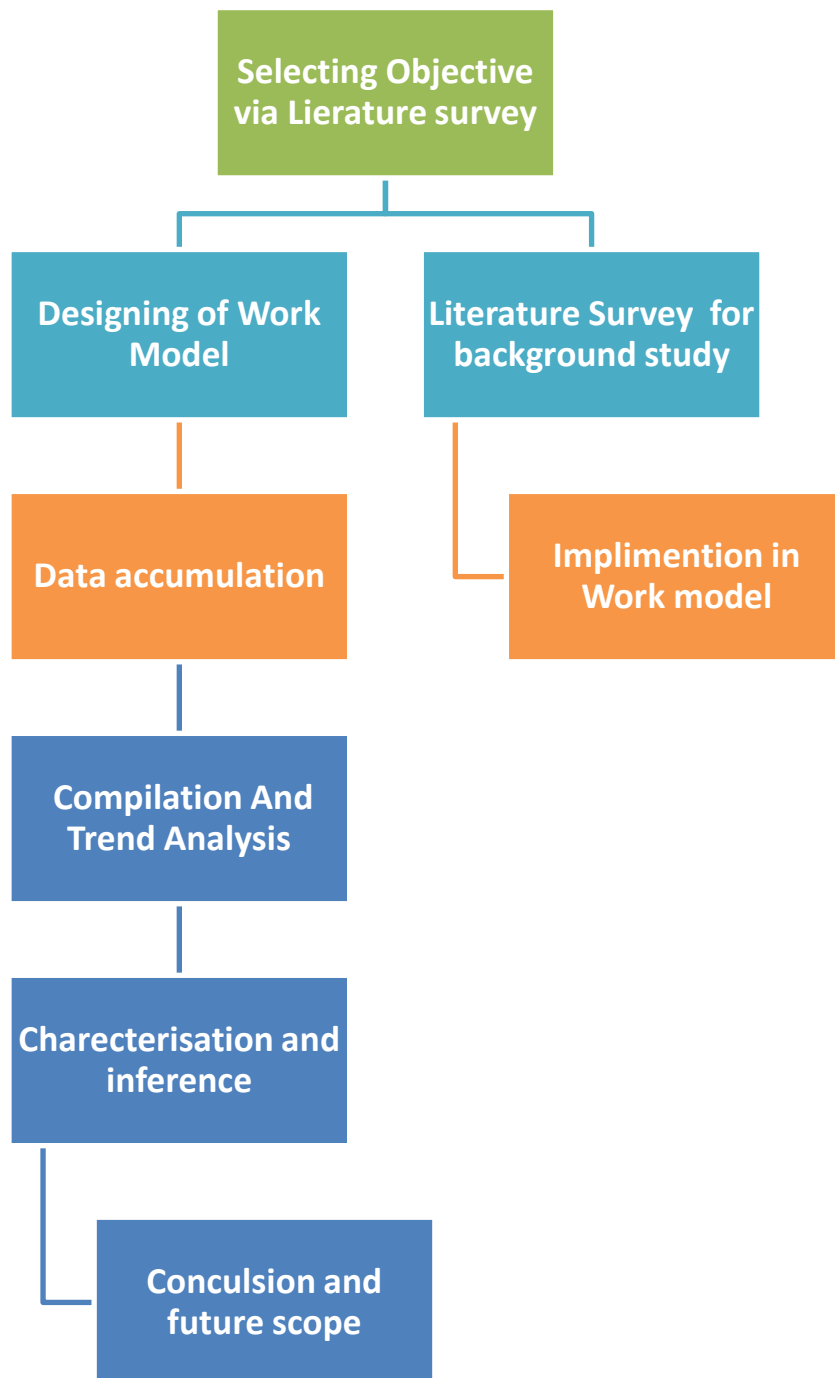
2.1. Trends and Behaviours of Exoplanets with respect to the star classifications

2.1.1. Introduction

We have aimed to gather data of transits and variations in the Doppler shift of radial velocity to determine the characteristics of an exoplanets orbiting a particular class of star. By characterisation we mean classification based on its properties such as mass, metallicity, radius, orbital period etc.

***, Python and MATLAB have been used for *data analyses and graphing*.

2.1.2. Flowchart



2.1.3. Database

To study the trends and behaviours of Exoplanets with respect to star classes, we have accumulated data from Extrasolar Planets Global Searches archive: <http://exoplanet.eu/catalog/>

2.2. Study and Characterization of Exoplanets

2.2.1. Stellar Age V/s Exoplanet mass



Figure 6: Stellar Age Vs. Mass of the exoplanet

Amongst 1300 of data points, as we can see from the graph the cluster of data points tends towards the older stars indicating the fact that most planets which have been observed till date are found around the older stars. The planets' masses which are formed near younger stars as we can observe from the graph tend to be higher. The trends which we can observe from this graph tell us that heavier planets tend to form near younger stars while planets with lower masses tend to occur near older stars.

Basic conclusion that can be drawn from this graph is, that we have observed more planets near sun like or 0.1 → 10 billion years old stars with highly varied masses while there is a tendency of heavier planets being formed around younger stars as per the data collected till date. Also, we can infer that **Neptunian** and **Jovian** type of planets are more densely populated at main sequence region.

2.2.2. Orbital period of planet vs. Mass planet w.r.t. Star class

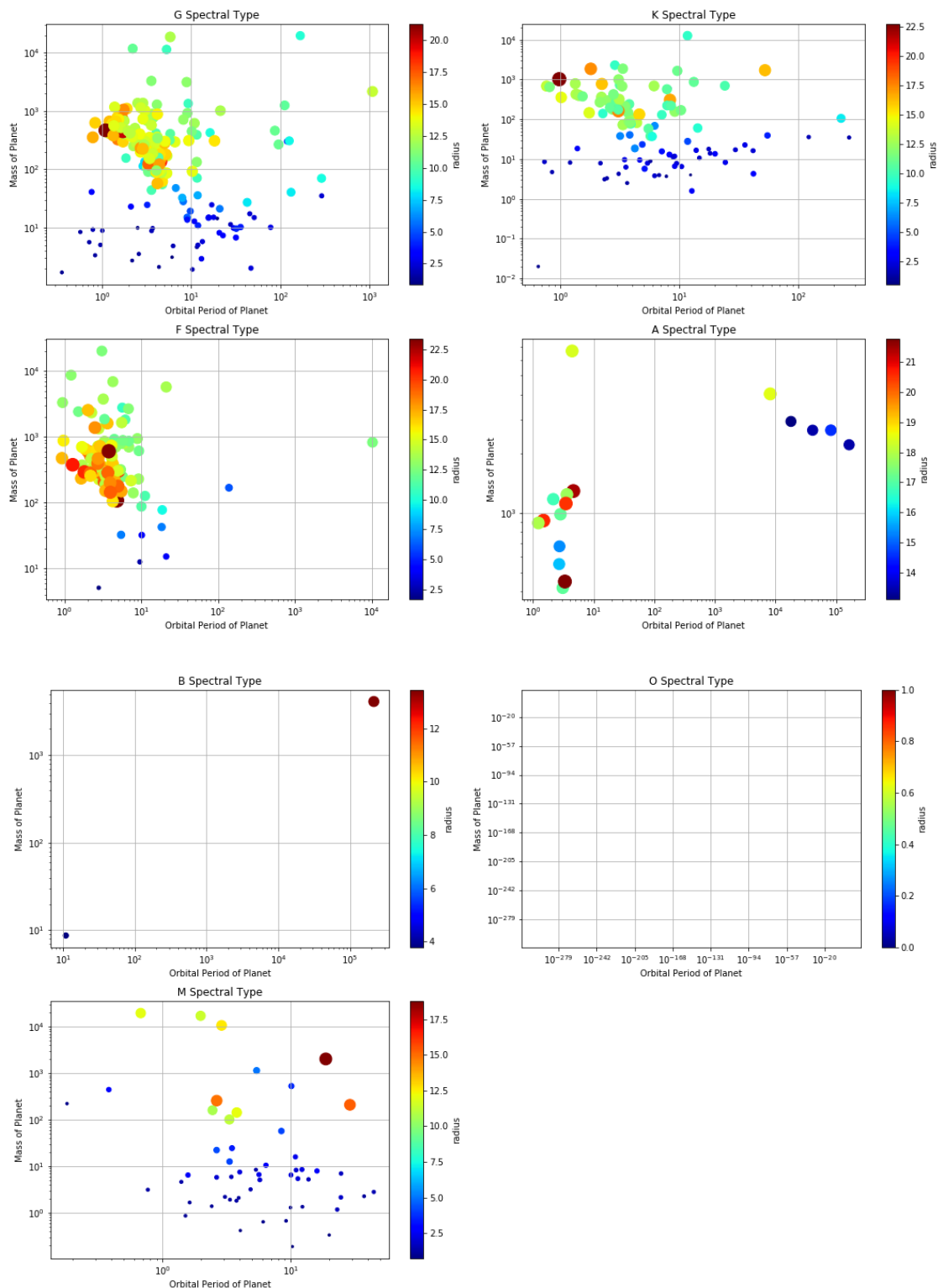


Figure 7: Orbital period of planet vs. Mass planet w.r.t. Star class

From H-R classification of star we know the type of stars distributed throughout their life cycles, above graphs have captured the Orbital period and Mass of the planet relation with respect to

the Star class. Size of the dots are directly proportional to the radius of the exoplanets. It is clearly evident that **G, K, F, A** and **M** class star is populous with Exoplanets, ranging from Asteroidean, Neptunians and Jovians. On the other hand, **O** class, which are amongst highest temperature are not harbouring planets in comparison to another star class

****It is to be noted that O class does have planets (2). Which are significantly less in comparison n to other star class.*

2.2.3. Planet population statistics for star age (0.003 - 9.8×10^9 years)

Table 3: Exoplanet population

Size Range	Planet Type	Counts
0 - 0.00001	Asteroidean	583
0.00001 - 0.2	Mercurian	1
0.1 - 0.5	Subterran	4
0.5 - 2	Terran	12
2 -10	Superterran	79
10 - 50	Neptunian	81
50 - 5000	Jovian	467
>5000	Super Jovians	73

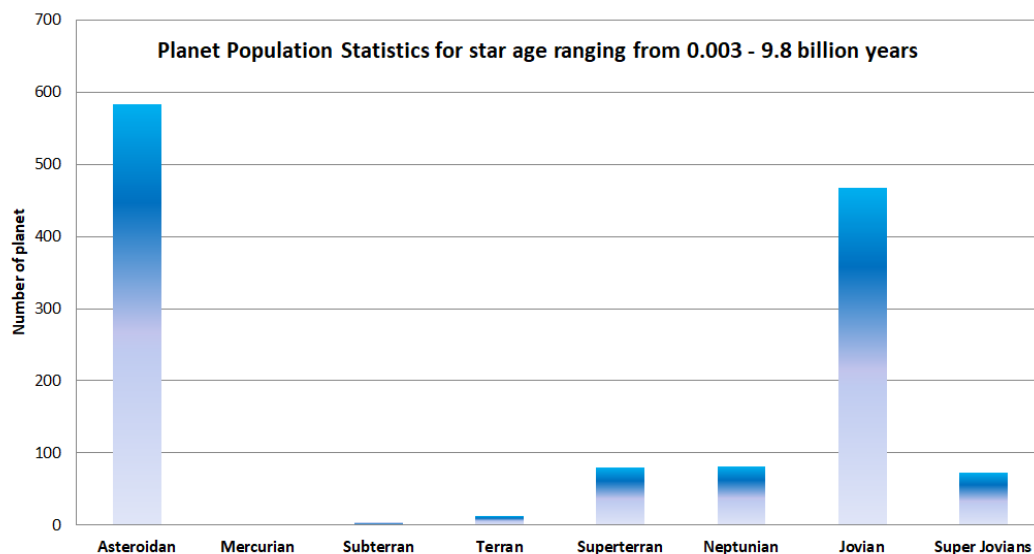


Figure 8: Planet population statistics for star age (0.003 - 9.8×10^9 years)

The bar graph plotted above shall act as a wholesome reference to prove our observations based on the collection of graphs which have been plotted in this report as well as the literature surveys executed by us. It gives us a basic idea about the kind of planets which have been discovered so far, and it states the number of planets each classification holds. As we can see from the data, the most prominent kind of planets right after the ginormous numbers of asteroidean planets is the

Jovian type. This happens due to the simple fact that when stars tend to lose materials due to various reasons (due to an external gravitational entity or due to its inner dynamics), the matter they eject tries to fall back towards itself and then they tend to fall into an orbit around the star. When such processes occur often the orbiting mass accumulates into a Jovian planet, since they are mostly made up of gasses such as H and He like their parent stars. The Jovian class is consequently followed by the hot Jovians and the Neptunians. This is rather intuitive since the Neptunians are also gas giants but with dense amounts of gasses and liquids such as ammonia and methane. Hence; these planets which follow up behind the jovians with respect to the populations; have slightly heavier elements present within them and take longer to form as compared to the jovians.

The Superterrans, terrans and subterrans follow behind the population of the gas giants. Since formation of these dense rocky planets with heavier planets take time and specific conditions, they end up less likely to be formed hence the data which has been used has lower numbers of records of these kinds of planets.

And as for the asteroideans, since orbiting bodies have a high tendency to collide into each other as often predicted by the restricted three body problem, asteroids have a very high tendency to form, as they fall into an orbit around the host star and often with the occurrence of collisions which can give rise to the sheer number of this category of planets which we have observed especially around sun-like G spectral type stars.

2.2.4. Stellar Effective Temperature v/s Mass of the Exoplanet v/s Stellar Age

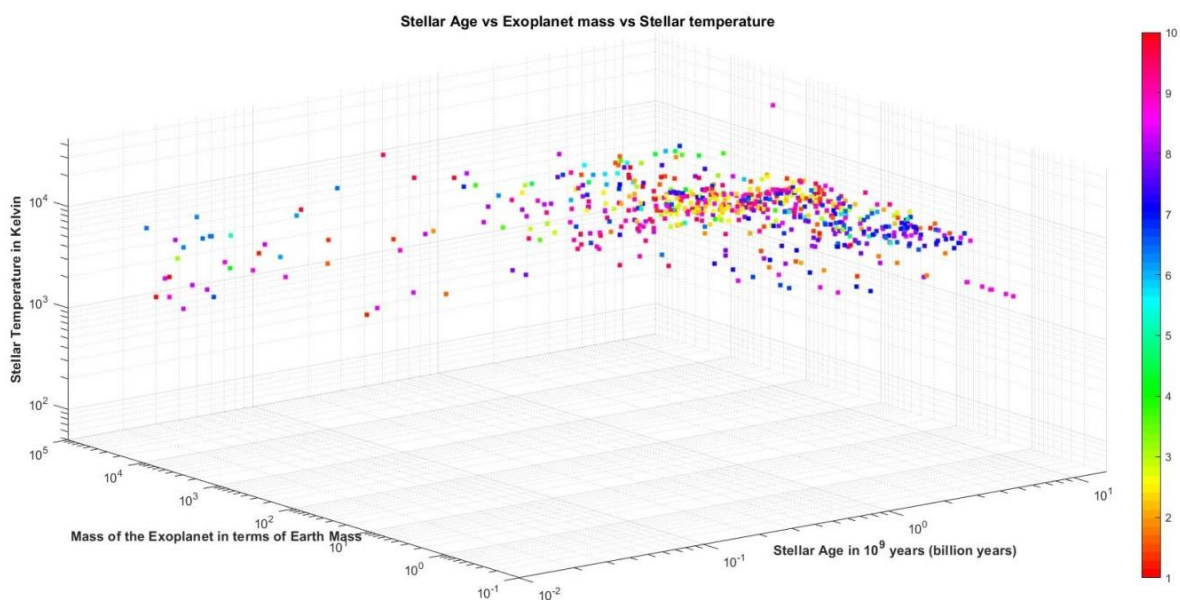


Figure 9: Stellar Temperature vs. Mass of the Exoplanets vs. Stellar Age

In the above 3-D plot of Stellar Temperature vs. Mass of the Exoplanets vs. Stellar Age, mass of the Exoplanet and also the count number of planets increase as the temperature increases and

span of star increases, after the its peak point through main sequence G class to K class it dips down in numbers in terms count number, but greater mass planets such as jovians are still existent at even hottest stars at O class.

2.2.5. Planet Class population w.r.t Star Classification

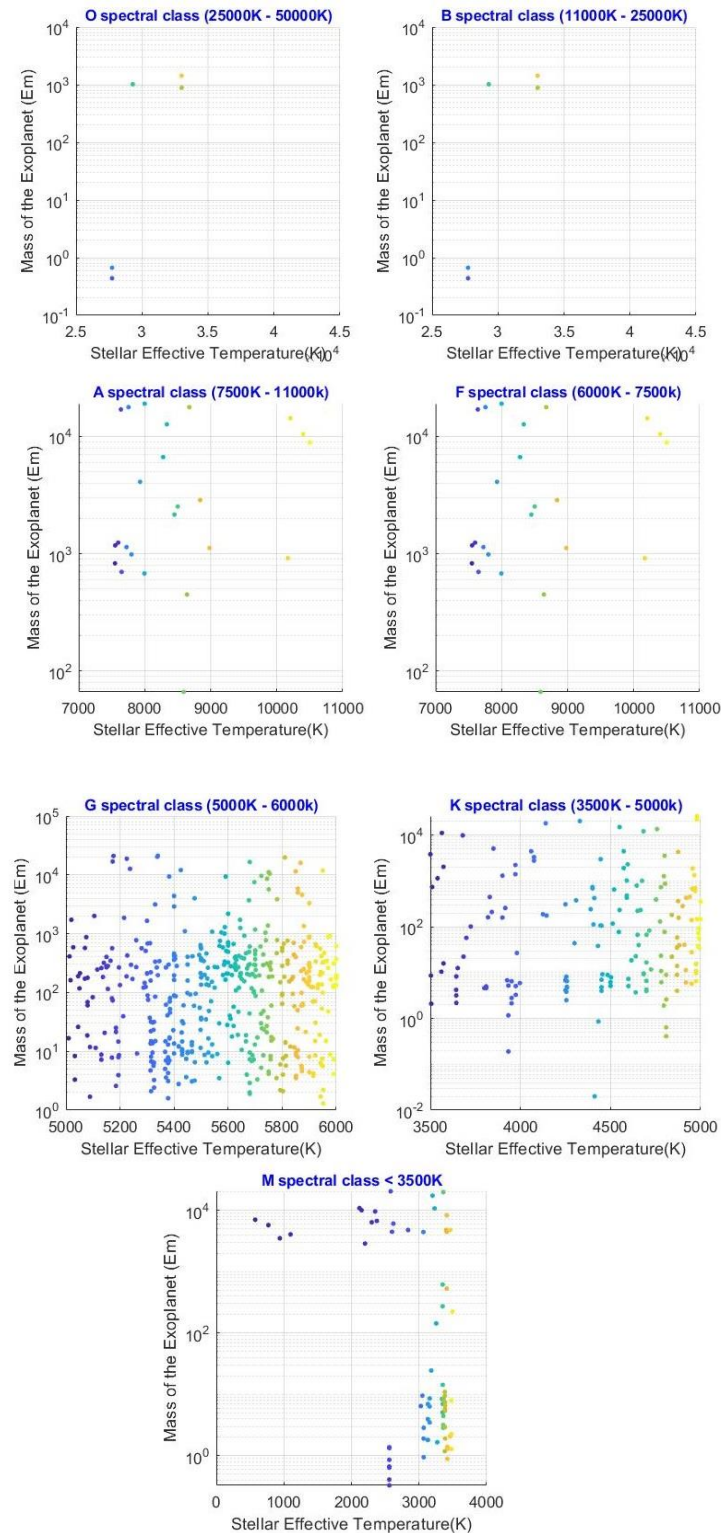


Figure 10: Stellar Effective Temperature v/s Mass of the Exoplanet w.r.t Star Class

Above graph is a scatter plot for population of exoplanets with respect to star classification.

The hottest star in the HR diagram starts with **O classification** ranging from 25000K – 50000k, here the star population density is very few in comparison to other classification of stars, amongst them we can find one or two Subterran and few Jovian-like bodies.

B spectral class follows a similar trend which has temperature from 11000k – 25000k, this classification star also has a smaller number of exoplanet spectral class much similar to O class.

A and F spectral class shows prominent increase in number of exoplanets. In these star classifications, temperature ranges from 7500K - 11000K and 6000K to 7500K.

Significant amongst all of these graphs are **G spectral class** from main sequence which is heavily populated with exoplanets ranging from asteroidean to Jovians, the temperature of this spectral class is 5000K to 6000K, these types of stars are very similar to our very own sun.

K spectral class follows a similar trend as G spectral class but the population is lesser than the G spectral class. This class of star has a temperature from 3500K to 5000K.

At the lowest spectral class having temperature below 3500 Kelvin shows decrease in harbouring exoplanets. Even so it promises to have a greater number of asteroids and Jovians together in comparison to Spectral Class at the extreme end of an H-R graph.

2.2.6. Age Related Trends

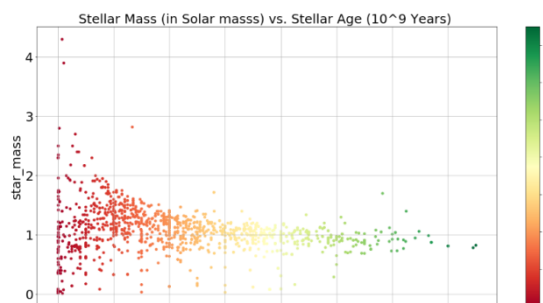


Figure 13: Stellar Age vs. Stellar Mass

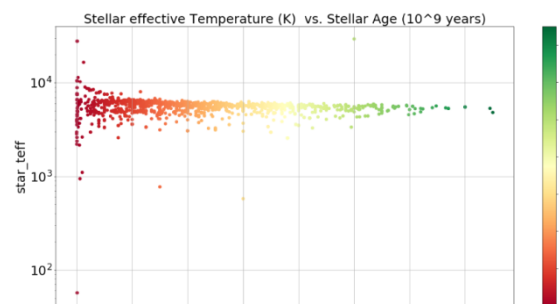


Figure 14: Stellar Temperature vs. Stellar Age

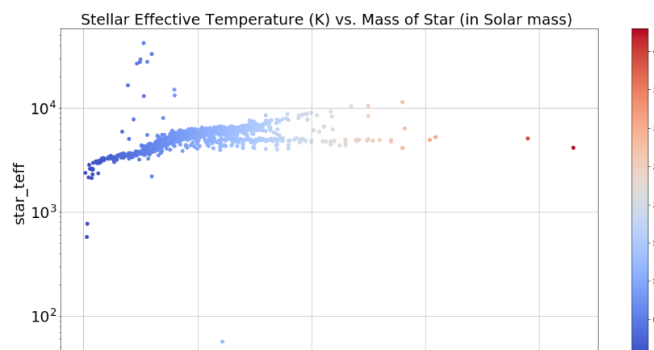


Figure 15: Stellar Temperature vs. Mass of star

It must be kept in mind that all the plots regarding the stars themselves also give us a certain amount of information about the planets as well, since all these stars whose data have been plotted in these graphs are host stars to exoplanets.

The above graphs show the variance of stellar temperature and mass with respect to their ages. Here, primarily two concepts need to be taken into consideration. First, the more massive a star is at its birth, the faster it burns out and hence they do not grow to be very old and die out comparatively quicker than other stars. Hence, if exoplanets were found around young, massive stars, they are likely to not be habitable (with respect to human standards) or remain the way they are for a long time. Figure 14 shows that, most stars which have been found to host exoplanets are young and massive and the older the stars become, the lesser is their temperature and mass (as a generalized trend as observed in the above two figures 13 and 14). Also, notice that the number of exoplanets dwindle with the increasing age of the star and both the lower and higher values converge at a certain point in both cases when plotting against stellar age.

With this we can infer, given the data we have collected so far, older stars seem to have lesser number of planets than the younger ones.

Figure 15 shows two kinds of trends in the stellar temperature with the increase in mass. Initially, the trend increases in a linear manner up to stars which are as big as 1 solar mass. As the mass approaches the 1.5 solar mass value, it branches off into a constant and a growing curve. Hence for most cases the effective stellar temperature is directly proportional to its mass and stars larger than 1.5 solar masses can have different temperatures for their individual scenarios but the basic trend of the graph remains as an increasing trend. Hence it is highly probable for a massive star to have a proportionately high temperature.

2.2.11. Distances from Earth Distances from Earth, figure (32) for confirmation of the fact that we have almost just as much data about stars which are farther away from earth as compared to the ones near earth.

2.2.7. Masses of Planets around Stars of varied Age and Temperatures

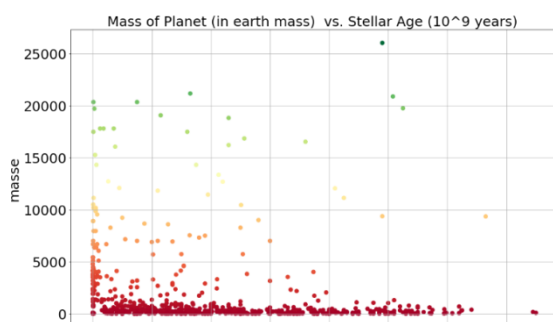


Figure 12: Mass of planet vs. Stellar Age

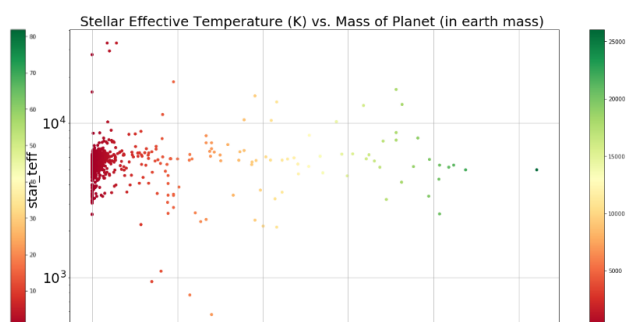


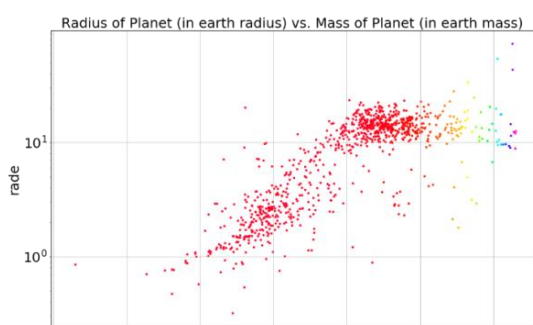
Figure 11: Stellar Temperature vs. Mass of the planet

The above Figures, namely, (16) and (17) show that the fact that most exoplanets discovered so far have a high fraction of hot Jovians amongst them. In an oversimplified manner one may say that, if there does exist a newly discovered exoplanet whose mass and radius or any other such relevant details are still unknown to us, the probability of that planet turning out to be a hot Jupiter is more likely than the other categories. But though the previous statement is not as scientifically sound, it serves the purpose to state that the number of hot Jovians are quite high compared to other planets.

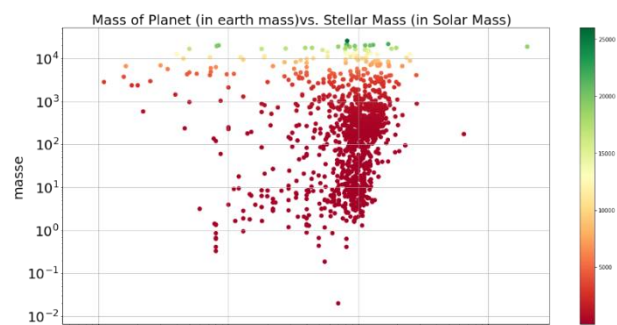
The formations of hot Jovians are comparatively more common than any other planets. To a certain extent this is because they can form due the interference of a third body in a two-body system and gasses of hydrogen and helium along with dust particles can be stripped away from the stars and can revolve around till they collide with each other and over time form into a Jovian planet. This is also put into effect by the Lidov-Kozai mechanism.

The Jovian planet so formed around stars with high stellar temperatures begins to migrate towards the star till by and by it becomes tidally locked. Because of this hot Jupiters come into existence with highly varied temperatures of atmospheres on the sides facing towards and away from the star.

2.2.8. Mass Radius Relationships



**Figure 18: Radius of the planet
vs. Mass of the planet**



**Figure 19: Mass of Planet
vs Stellar Mass**

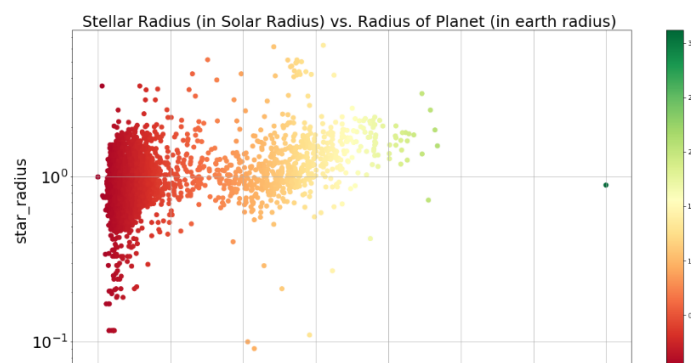


Figure 20: Stellar Radius vs. Radius of Planet

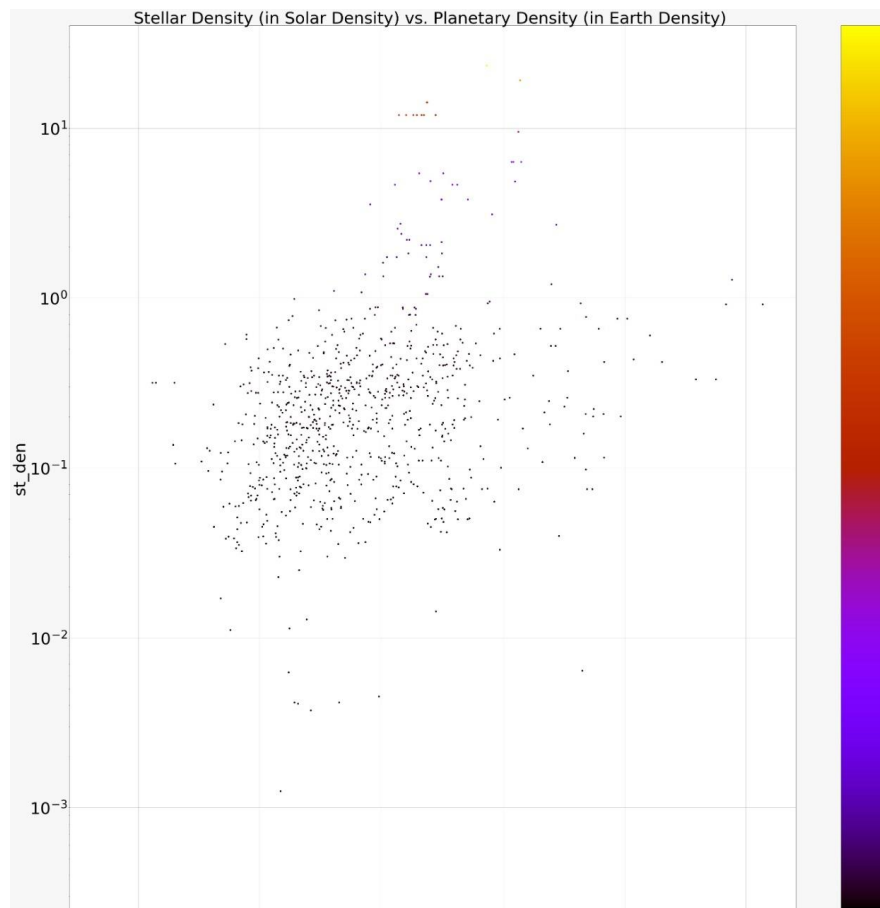


Figure 21: Stellar Density vs. Planetary Density

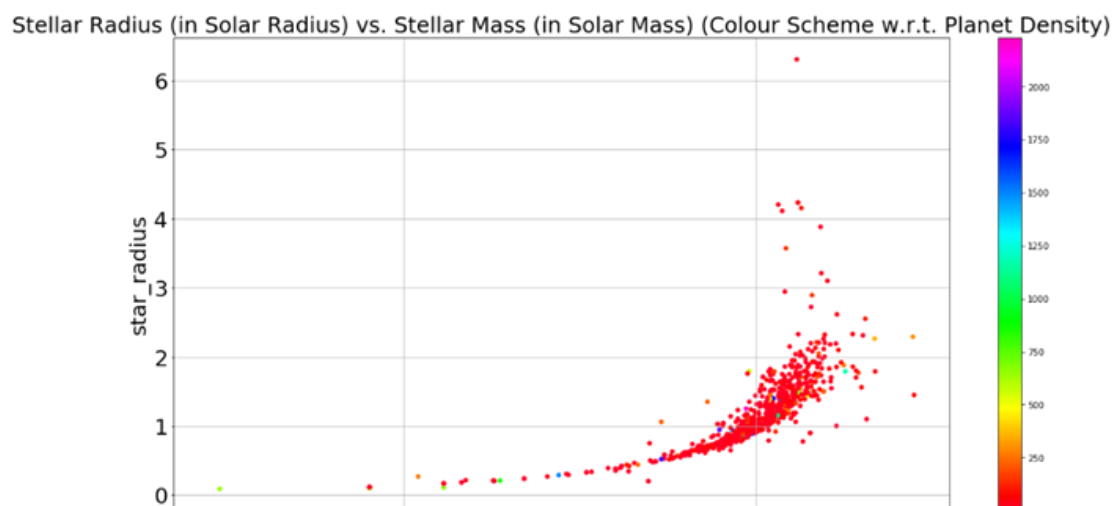


Figure 22: Stellar Radius vs. stellar mass

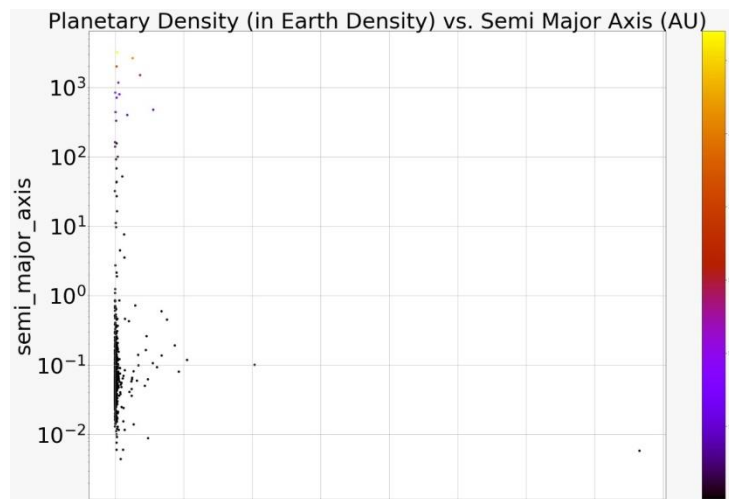


Figure 23: Planetary Density vs. Semi Major Axis

In figure (21), (22) 927 data points exist for planet density in (earth density units).

The above figures (18), (19), (20), (21) and (22) give an idea about the mass and radius relationships of the host stars and exoplanets. The graph (22) exhibits an exponential relationship between the stellar mass and radius. From the compiled data we have found that this dataset contains a high number of asteroidean exoplanets recorded in it. This high number of asteroidean planets is followed by the second highest number of Jovian planets which are most likely to form around other stars. The formation of such Jovians has been discussed in the following section:

2.2.7. Masses of Planets around Stars of varied Age and Temperatures.

Figure (23) here shows that there exist a huge number of planets with lower densities which reside closer to the host star and most of the planets residing away from the stars, tends to have low densities. As we can see, higher density planets tend to reside close to the host star, this occurrence can be explained by the concept of migration of planets. That being said this graph also shows a significant number of dense planets which reside near the stars as well.

2.2.9. Temperature, Mass Analysis

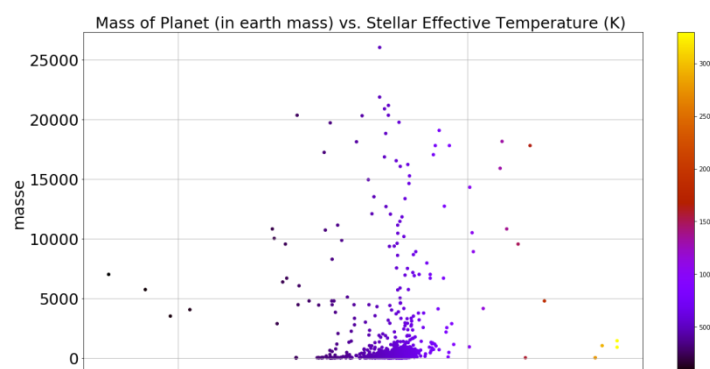


Figure 24: Mass of the planet vs. stellar Temperature

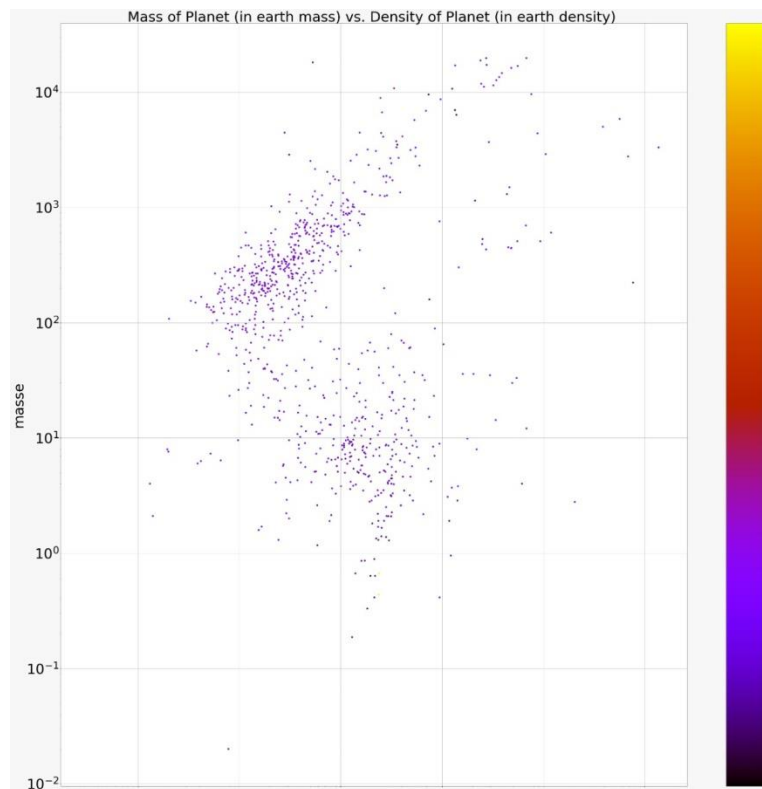


Figure 25: Mass of the planet vs. Density of the Planet

The graph (24) and (25) serves the purpose of merely displaying; first, planets of various masses are distributed evenly across stars of varied temperatures; and second, the mass and densities of the planets follow a linear pattern with variation in their classes. However, one can see the slight increase in the number of massive planets with host stars of high stellar temperatures, followed by a sudden drop in stars which have very high effective temperatures. Hence most planets tend to exist within a certain range or limit of stellar temperatures. This is also supported by our graphs which display that most exoplanets have been discovered around G and K spectral classes, the range of whose effective temperatures is from about 3500 K to 6000 K.

2.2.10. Understanding Orbital Period Trends

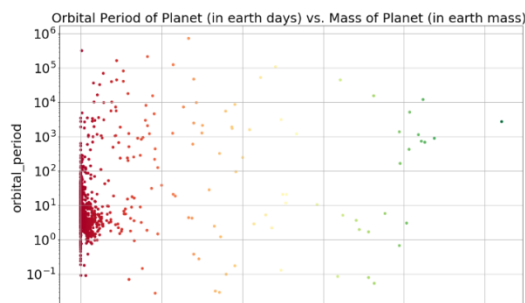


Figure 26: Orbital period vs. Mass of the planet

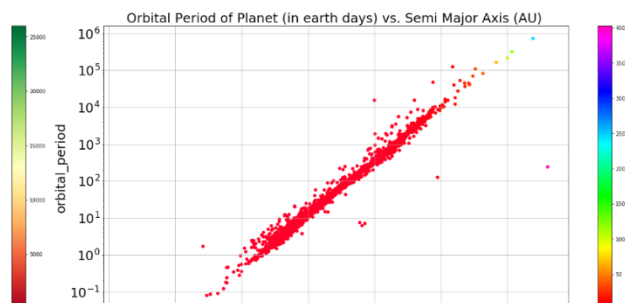


Figure 27: Orbital Period vs. Semi Major Axis.

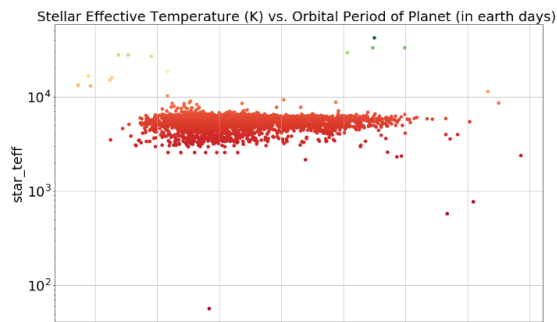


Figure 28: Star Temperature vs. Orbital Period of planet

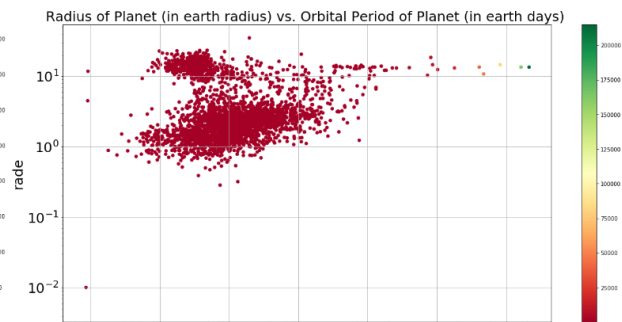


Figure 29: Radius of Planet vs. Orbital Period of Planet

The above graphs exhibit the variation of exoplanetary properties with respect to their orbital periods.

Graph (28) shows that there exists a great number of planets orbiting stars of high temperatures and that number decreases with increase in orbital period. Most planets observed by us are via the transit method, which relies upon the transit of a planet across the star in relatively short amounts of time. The measurement of this time period or orbital period at times exhibit harmonic motions and can tell us about the orbital mechanics of the planets, via Bayesian analytical methods. [40]

Similarly, Graph [27] exhibits the fact that the orbital period of any planet is directly proportional to the semi major axis of the planetary body. Such analysis is helpful in the fields of the restricted three body problems which have further studies going on to analyse the prograde and retrograde orbital motions of the planets. [41]

Graph (29) and graph (26) show the masses and radii of planets detected whose orbital time periods are known to us. Since the transit method has the highest success rate of planet detection; and it is capable of determining both the time period (via repeated collection of data and measuring the time taken by that light curve to repeat itself) and the radius of a given planet (via the formula: $\text{Flux} = \left(\frac{R_{\text{planet}}^2}{R_{\text{star}}^2} \right)$); the data for the radii versus time period graph is the most clustered. Hence, we have a fair idea about the trends exhibited by the planets with varied radiuses and their orbital periods. Since the Jovians have a tendency of migrating towards the host star and then getting tidally locked, one can observe the cluster obtained above the 10^1 line of y axis. And the fact that the data conveys that larger planets can have large orbital periods is rather intuitive since the type of planets such as the asteroidean or the Mercurian planets will be flung out of their orbit if their distance from the host star is too great.

These basic interpretations can be used as a skeletal reference for future research on orbital mechanics.

2.2.11. Distances from Earth

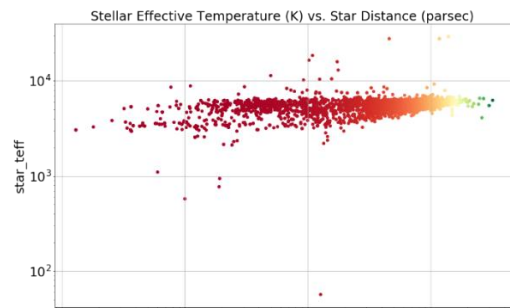


Figure 30: Star Distance vs. Stellar Effective Temperature

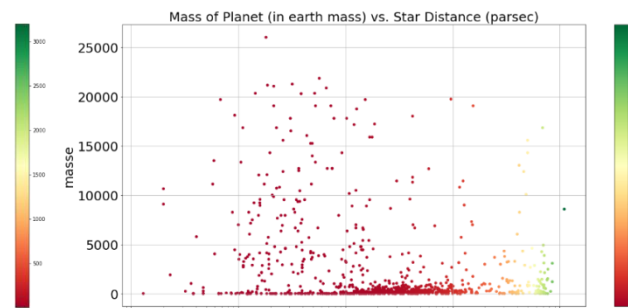


Figure 31: Star Distance vs. Planetary Mass

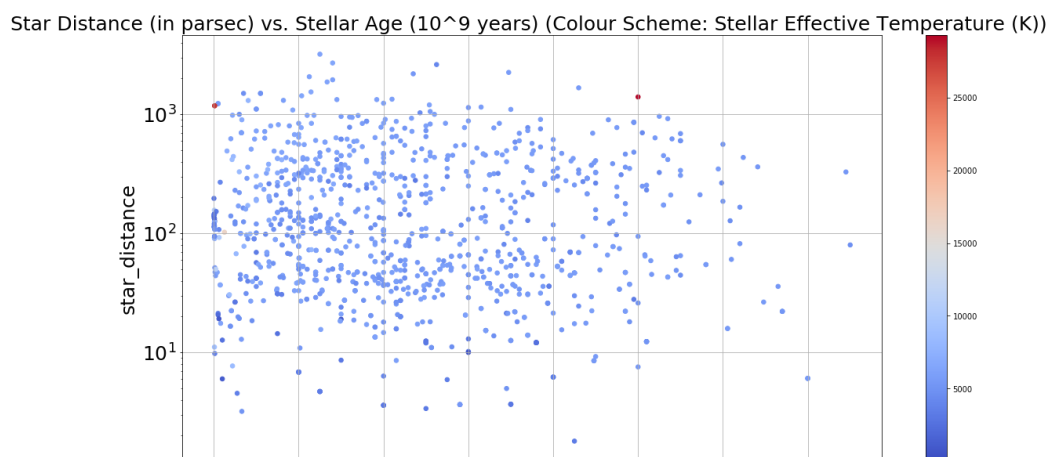


Figure 32: Star Distance vs. Stellar Age

The above graphical data of (30) and (31) gives us a basic idea about the variance of exoplanets and their stars as we go farther away from the vicinity of our planetary system. As (30) portrays, a general increasing trend can be observed in the effective stellar temperature of stars as we go farther away from our planet. However, this increasing change is very minute. However, on the other hand one can observe something rather intuitive which is that the number of exoplanets discovered decreases with increase in the distance from earth; this fact can also be seen in (31). Graph (31) also tells us that we have discovered relatively massive exoplanets within closer distances while the farther we go from earth, the mass of the exoplanets seemingly tend to fall. Hence from our present data we can conclude that the population of massive planets tend to decline as we go further away from earth. But one can notice a slight increase in the number of low mass planets at the centre of graph (31), which enables us to gain some perspective about the distances of super earths from our planet.

2.2.6. Age Related Trends *Age Related Trends*, for graph (32), the observation of dwindling number of planets can be related with the corresponding graph, by making the observation that our data is not very biased towards stellar age being proportionate with star distance. This means that the data collected is not limited or erred by the lack of fair observation due to the time taken by the

starlight to reach us. Since from the graph it is visible that we have new and old stars of varied temperatures and distances. Hence the data collected is as much available for older stars as they are for younger stars since both are roughly, uniformly distributed over the graph with respect to the star distance.

2.2.12. A Look into Stellar Metallicity of Host Stars

A star can be essentially considered as a massive scale fusion reaction. At first hydrogen atoms

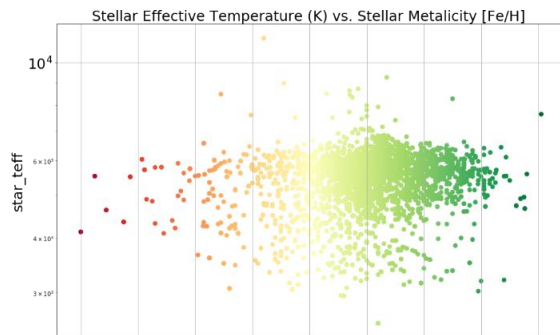


Figure 33: Stellar Temperature vs. Stellar Metallicity

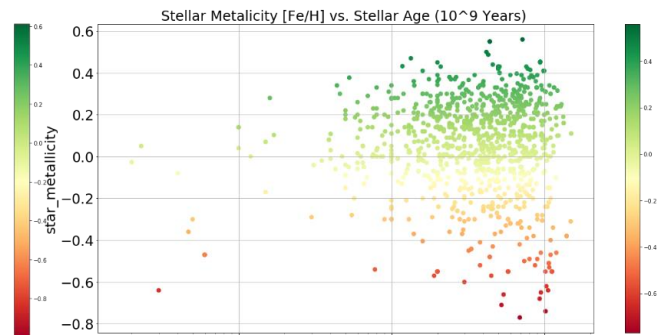


Figure 34: Stellar Metallicity vs. Stellar Age

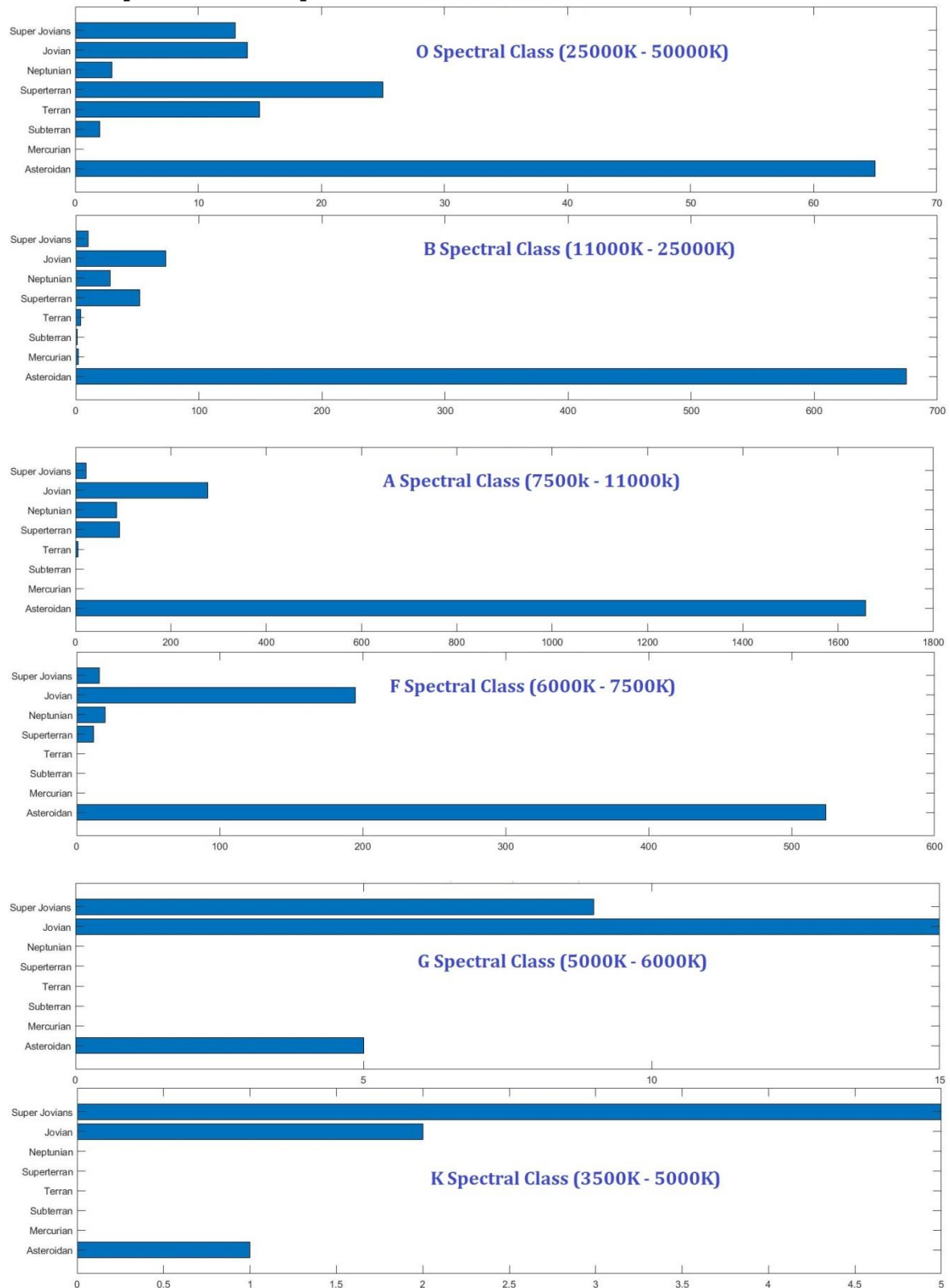
fall into a gravitational concentration and then as the concentration of hydrogen reaches a point such that the gravity of that body is sufficient to ignite a fusion reaction, a star is born. The hydrogen nuclei fuse to form helium. Then three helium nuclei fuse to form carbon nuclei. And in this process (also known as the onion skin model) fusion takes place throughout the star's life and it continues till a Fe nuclei core is formed. After the formation of the heavy metallic Fe nuclei, further fusion is terminated in stars. The metallicity of a star is a logarithmic ratio of the amount of Fe to the amount of H present in the star. This scaling in turn is done with respect to the metallicity of our sun. the following is the formula used to calculate the metallicity:

$$\left[\frac{Fe}{H} \right] = \log_{10} \left[\frac{\left(\frac{Fe}{H} \right)_{star}}{\left(\frac{Fe}{H} \right)_{sun}} \right]$$

Naturally, older stars have higher metallicities. In both the data sets of the graphs (19) and (20) we can observe that the metallicity levels of most of the stars in the dataset are comparatively higher than that of our sun, hence the part greater than 0 dex has a higher concentration of data points.

This tells us that a relatively larger number of exoplanets have stars which have a metallicity higher than our sun.

2.2.13. Population of exoplanets w.r.t star class.



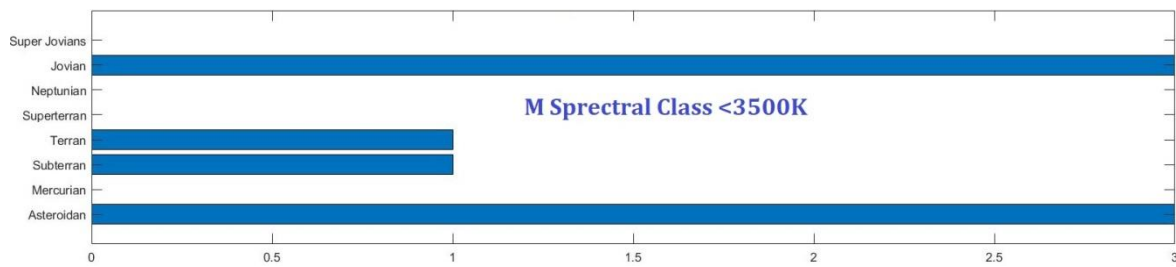


Figure 35: Populations of Exoplanets w.r.t star class

The following graphs shall serve as a referential documentation of data, and will act to serve the purpose of neat documentation of data via visual representation. These graphs will act as references for the further compilation of studies of trend analysis of which the project is comprised of.

2.2.14. Density population of exoplanets w.r.t star class

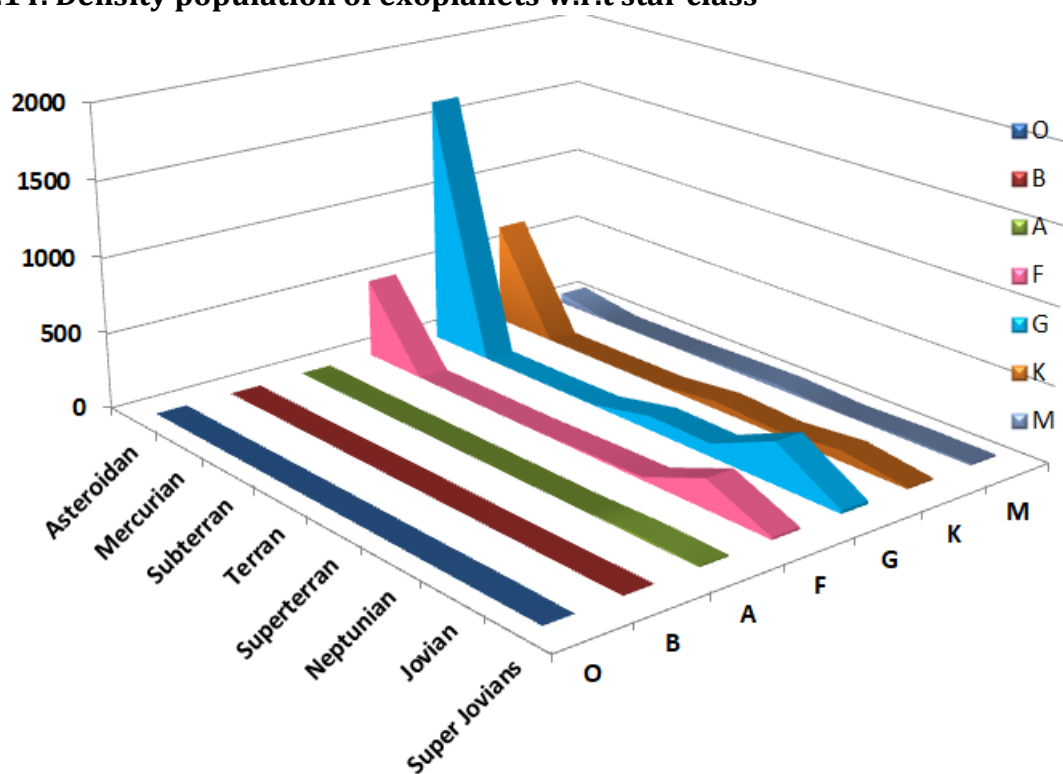


Figure 36: Density population of exoplanets w.r.t star class

Table 4: Density population of exoplanets w.r.t star class

	O	B	A	F	G	K	M
Astroidean	3	1	5	524	1658	675	65
Mercurian	0	0	0	0	0	2	0
Subterran	1	0	0	0	0	1	2
Terrian	1	0	0	0	5	4	15
Superterran	0	0	0	12	93	52	25

Neptunian	0	0	0	20	86	28	3
Jovian	3	2	15	195	278	73	14
Super Jovians	0	5	9	16	22	10	13

It is evident from the area plot that **G type spectral class** star harbour maximum number of Asteroidean, Superterran, Neptunian and Jovians type planets. G type star is similar to our very own sun which is in its main sequence. The stars of F and K spectral classes are quite similar to the G type stars in terms of the number of planets they harbour in their system. The temperature ranges from 3500 K to 7500 K from the K to F type stars, wherein most planets are found to exist.

2.3. Inference

Sl. No	Trend	Data points	Type of plot	Analysis	Platform
1	Stellar Age V/s Exoplanet mass	1206	Scatter	Heavier planets tend to form near younger stars while planets with lower masses tend to occur near older stars.	MATLAB
2	Orbital period of planet vs. Mass planet w.r.t. Star class	4153	Scatter	G, K, F, A and M class star is populous with ranging from Asteroidean, Neptunians and Jovians while O class are not harbouring planets.	Python
3	Planet population statistics for star age	1301	Bar	Asteroidean and Jovian are populous towards older stars.	MATLAB
4	Stellar Effective Temperature v/s Mass of the Exoplanet w.r.t Star Class	1246	3D Scatter	Mass and the count of number of exoplanets increase as the temperature increases and span of star increases.	Python
5	Planet Class population w.r.t Star Classification	3936	Scatter	For G spectral class the population is maximum to the O spectral class having least population of exoplanets.	MATLAB
6	Age Related Trends		Scatter	Older stars seem to have lesser number of exoplanets than the younger ones.	Python

7	Masses of Planets around Stars of varied Age and Temperatures		Scatter	Most exoplanets discovered so far have a high fraction of hot Jovians. The probability of the planet turning out to be a hot Jupiter is more likely than the other categories.	Python
8	Mass Radius Relationships		Scatter	High number of asteroidean exoplanets have recorded followed by the Jovian planets which are most likely to form around other stars.	Python
9	Temperature, Mass Analysis		Scatter	Most planets tend to exist within a certain range or limit of stellar temperatures.	Python
10	Understanding Orbital Period Trends		Scatter	Planets orbiting stars of high temperatures and that number decreases with increase in orbital period. Orbital period of any planet is directly proportional to the semi major axis of the planetary body.	Python
11	Distances from Earth		Scatter	Population of massive planets tend to decline as we go further away from earth.	Python
12	A Look into Stellar Metallicity of Exoplanet Stars		Scatter	Relatively larger number of exoplanets have stars which have a metallicity higher than our sun.	Python
13	Population of exoplanets w.r.t star class	3936	Bar	G class is densely populated	Ms Excel
14	Density population of exoplanets w.r.t star class	3936	3D Bar	G type spectral class star harbour maximum number of	Ms Excel

Asteroidean,
Superterran,
Neptunian and
Jovians type planets.

3. Conclusion and Scope for Future work

- I. More planets tend to form near younger stars than older stars.
- II. G, K, F, A and M class star is populous with ranging from Asteroidean, Neptunians and Jovians while O class are not harbouring planets.
- III. Asteroidean and Jovian are populous towards older stars.
- IV. Mass and the count of number of exoplanets increase as the temperature increases and span of star increases.
- V. For G spectral class the population is maximum to the O spectral class having least population of exoplanets.
- VI. Older stars seem to have lesser number of exoplanets than the younger ones.
- VII. Most exoplanets discovered so far have a high fraction of hot Jovians. The probability of the planet turning out to be a hot Jupiter is more likely than the other categories.
- VIII. High number of asteroidean exoplanets have recorded followed by the Jovian planets which are most likely to form around other stars.
- IX. Most planets tend to exist within a certain range or limit of stellar temperatures.
- X. Planets orbiting stars of high temperatures and that number decreases with increase in orbital period. Orbital period of any planet is directly proportional to the semi major axis of the planetary body.
- XI. Population of massive planets tend to decline as we go further away from earth.
- XII. Relatively larger number of exoplanets have stars which have a metallicity higher than our sun.
- XIII. G class is densely populated
- XIV. G type spectral class star harbour maximum number of Asteroidean, Superterran, Neptunian and Jovians type planets.

The interpretations provided herein can act as a referential backbone, as a recollection or starting point for further research in the future. The future scope for this research lies in the fact that this can be further cross checked with new data which would be provided to us by newer missions such as the JWST (James Webb Space Telescope) and the perturbational trends can be analysed to obtain a better understanding of our models of orbital mechanics and exoplanet characterizations.

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Code Sheet

A. MATLAB

%%%%%%%%%Plot for Stellar Age V/s Exoplanet mass%%%%%%%%%

```
clear all;
close all;
clc
A=dlmread('StaragevsplanetMass.csv')
x=A(:,1);
y=A(:,2);
sz = 25;
c = linspace(1,10,length(x));
scatter(x,y,sz,c,'filled')
set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('Stellar Age V/s Mass of the exoplanet')
xlabel('Stellar Age in 10^9 years (billion years)')
ylabel('Mass of the Exoplanet in terms of Earth Mass')
```

%%%%%%%%%Plot for Stellar Age vs Exoplanet mass vs Stellar temperature%%%%%%%%%

```
clear all;
close all;
clc
A=dlmread('Temp0mass0age.csv')
x=A(:,1);
y=A(:,2);
z=A(:,3);
sz = 25;

c = linspace(1,10,length(x));
scatter3(x,y,z,sz,c,'filled')
set(gca,'xscale','log')
set(gca,'yscale','log')
set(gca,'zscale','log')
grid on
title('Stellar Age vs Exoplanet mass vs Stellar temperature')
xlabel('Stellar Age in 10^9 years (billion years)')
ylabel('Mass of the Exoplanet in terms of Earth Mass')
zlabel('Stellar Temperature in Kelvin')
```

%%%%%%%%%Star class subplot and planet mass%%%%%%%%%

```
clear all;
close all;
clc
```

```
%%%%%%%%%%%% O spectral class %%%%%%%%%%%%%%
```

```
O=dlmread('Oclass.csv')
x1=O(:,1);
y1=O(:,2);
sz = 10;
c = linspace(1,10,length(x1));
subplot(2,4,1)
scatter(x1,y1,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('O spectral class (25000K - 50000K)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%% B spectral class %%%%%%%%%%%%%%
```

```
B=dlmread('Oclass.csv')
x2=B(:,1);
y2=B(:,2);
sz = 10;
c = linspace(1,10,length(x2));
subplot(2,4,2)
scatter(x2,y2,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('B spectral class (11000K - 25000K)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%% A spectral classes %%%%%%%%%%%%%%
```

```
A=dlmread('Aclass.csv')
x3=A(:,1);
y3=A(:,2);
sz = 10;
c = linspace(1,10,length(x3));
subplot(2,4,3)
scatter(x3,y3,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('A spectral class (7500K - 11000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
```

```
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%% F spectral class %%%%%%%%%%
```

```
F=dlmread('Fclass.csv')
x4=A(:,1);
y4=A(:,2);
sz = 10;
c = linspace(1,10,length(x4));
subplot(2,4,4)
scatter(x4,y4,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('F spectral class (6000K - 7500k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%% G spectral class %%%%%%%%%%
```

```
G=dlmread('Gclass.csv')
x5=G(:,1);
y5=G(:,2);
sz = 10;
c = linspace(1,10,length(x5));
subplot(2,4,5)
scatter(x5,y5,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('G spectral class (5000K - 6000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%% K spectral class %%%%%%%%%%
```

```
K=dlmread('Kclass.csv')
x6=K(:,1);
y6=K(:,2);
sz = 10;
c = linspace(1,10,length(x6));
subplot(2,4,6)
scatter(x6,y6,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('K spectral class (3500K - 5000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
```

```
ylabel('Mass of the Exoplanet (Em)')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% M spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
M=dlmread('Mclass.csv')
x7=M(:,1);
y7=M(:,2);
sz = 10;
c = linspace(1,10,length(x7));
subplot(2,4,7)
scatter(x7,y7,sz,c,'filled')
%set(gca,'xscale','log')
set(gca,'yscale','log')
grid on
title('M spectral class < 3500K','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
xlabel('Stellar Effective Temperature(K)')
ylabel('Mass of the Exoplanet (Em)')
```

%Star class subplot and planet mass

%%part 01%%

```
clear all;
close all;
clc
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% O spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
subplot(4,1,1)
Earthmass=[65 0 2 15 25 3 14 13];
Category={'Asteroidan';'Mercurian';'Subterranean';
'Terran';'Superterranean';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('O spectral class (25000K - 50000K)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% B spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
subplot(4,1,2)
Earthmass=[675 2 1 4 52 28 73 10];
Category={'Asteroidan';'Mercurian';'Subterranean';
'Terran';'Superterranean';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('B spectral class (11000K - 25000K)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% A spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
subplot(4,1,3)
Earthmass=[1658 0 0 5 93 86 278 22];
Category={'Asteroidan';'Mercurian';'Subterranean';
'Terran';'Superterranean';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
```

```

set(gca,'yticklabel',Category)
title('A spectral class (7500K - 11000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% F spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
subplot(4,1,4)
Earthmass=[524 0 0 0 12 20 195 16];
Category={'Asteroidan';'Mercurian';'Subterran';
'Terran';'Superterran';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('F spectral class (6000K - 7500k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')

```

%Star class subplot and planet mass

%%part 02

```

clear all;
close all;
clc

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% G spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
subplot(4,1,1)
Earthmass=[5 0 0 0 0 0 15 9];
Category={'Asteroidan';'Mercurian';'Subterran';
'Terran';'Superterran';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('G spectral class (5000K - 6000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% K spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
subplot(4,1,2)
Earthmass=[1 0 0 0 0 0 2 5];
Category={'Asteroidan';'Mercurian';'Subterran';
'Terran';'Superterran';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('K spectral class (3500K - 5000k)','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% M spectral class %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
subplot(4,1,3)
Earthmass=[3 0 1 1 0 0 3 0];
Category={'Asteroidan';'Mercurian';'Subterran';
'Terran';'Superterran';'Neptunian';'Jovian';'Super Jovians' }
barh(Earthmass)
set(gca,'yticklabel',Category)
title('M spectral class <3500K - 5000k','FontSize', 10, 'Color', 'b', 'FontWeight', 'bold')

```

B. Python

Mass of the planet vs. Orbital period

```
import numpy as np
```



```
import matplotlib.pyplot as plt
import pandas as pd
%matplotlib inline

data = pd.read_csv('exoplanet.eu_catalog.csv')
data['mass'] = data['mass']*317.93842034806
data['radius'] = data['radius']*11.2089

new_data = data.dropna(subset=['star_sp_type', 'star_teff'], how='all')

new_data.loc[(new_data['star_teff']>=3500) & (new_data['star_teff']<5000), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=3500) & (new_data['star_teff']<5000),
'star_sp_type'].fillna('K')

new_data.loc[(new_data['star_teff']>=5000) & (new_data['star_teff']<6000), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=5000) & (new_data['star_teff']<6000),
'star_sp_type'].fillna('G')

new_data.loc[(new_data['star_teff']>=6000) & (new_data['star_teff']<7500), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=6000) & (new_data['star_teff']<7500),
'star_sp_type'].fillna('F')

new_data.loc[(new_data['star_teff']>=7500) & (new_data['star_teff']<11000), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=7500) & (new_data['star_teff']<11000),
'star_sp_type'].fillna('A')

new_data.loc[(new_data['star_teff']>=11000) & (new_data['star_teff']<25000), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=11000) & (new_data['star_teff']<25000),
'star_sp_type'].fillna('B')

new_data.loc[(new_data['star_teff']>=25000) & (new_data['star_teff']<50000), 'star_sp_type'] =
new_data.loc[(new_data['star_teff']>=25000) & (new_data['star_teff']<50000),
'star_sp_type'].fillna('O')

new_data.loc[new_data['star_teff']<3500, 'star_sp_type'] =
new_data.loc[new_data['star_teff']<3500, 'star_sp_type'].fillna('M')

data_upd = new_data.copy()
data_upd['spect_first'] = data['star_sp_type'].dropna().apply(lambda x: x[0])

data_upd['spect_first'].value_counts()

fig = plt.figure()

ax = plt.subplot(221)
data_upd[data_upd['spect_first'] ==
'G'].plot.scatter('orbital_period', 'mass', s=data_upd[data_upd['spect_first'] ==
'G']['radius']*10, c='radius', cmap = 'jet', marker='o', ax=ax)
plt.xscale('log')
```

```
plt.yscale('log')
plt.title('G Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

ax = plt.subplot(222)
data_upd[data_upd['spect_first'] ==
'K'].plot.scatter('orbital_period','mass',s=data_upd[data_upd['spect_first'] ==
'K']['radius']*10,c='radius',cmap = 'jet',marker='o', ax=ax)
plt.xscale('log')
plt.yscale('log')
plt.title('K Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

ax = plt.subplot(223)
data_upd[data_upd['spect_first'] ==
'F'].plot.scatter('orbital_period','mass',s=data_upd[data_upd['spect_first'] ==
'F']['radius']*10,c='radius',cmap = 'jet',marker='o', ax=ax)
plt.xscale('log')
plt.yscale('log')
plt.title('F Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

ax = plt.subplot(224)
data_upd[data_upd['spect_first'] ==
'A'].plot.scatter('orbital_period','mass',s=data_upd[data_upd['spect_first'] ==
'A']['radius']*10,c='radius',cmap = 'jet',marker='o', ax=ax)
plt.xscale('log')
plt.yscale('log')
plt.title('A Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

fig.tight_layout()
plt.savefig('GKFA.png', transparent=False)

fig = plt.figure()

ax = plt.subplot(221)
data_upd[data_upd['spect_first'] ==
'B'].plot.scatter('orbital_period','mass',s=data_upd[data_upd['spect_first'] ==
'B']['radius']*10,c='radius',cmap = 'jet',marker='o', ax=ax)
```

```
plt.xscale('log')
plt.yscale('log')
plt.title('B Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

ax = plt.subplot(222)
data_upd[data_upd['spect_first'] ==
'O'].plot.scatter('orbital_period', 'mass', s=data_upd[data_upd['spect_first'] ==
'O']['radius']*10, c='radius', cmap = 'jet', marker='o', ax=ax)
plt.xscale('log')
plt.yscale('log')
plt.title('O Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

ax = plt.subplot(223)
data_upd[data_upd['spect_first'] ==
'M'].plot.scatter('orbital_period', 'mass', s=data_upd[data_upd['spect_first'] ==
'M']['radius']*10, c='radius', cmap = 'jet', marker='o', ax=ax)
plt.xscale('log')
plt.yscale('log')
plt.title('M Spectral Type')
plt.xlabel('Orbital Period of Planet')
plt.ylabel('Mass of Planet')
plt.grid(True)

fig.tight_layout()
plt.savefig('BOM.png', transparent=False)
```

C. Python

```
#!/usr/bin/env python

# coding: utf-8

# In[1]:

import numpy as np

import matplotlib.pyplot as plt

import pandas as pd

import math as mt
```

```
from pandas import DataFrame as df
```

```
# In[2]:
```

```
exo=pd.read_csv(r'C:\Users\TISYAGUPTA PYNE\Desktop\TURN\SSERD  
Internship\Data\exoplanet.eu_catalog.csv')
```

```
# In[4]:
```

```
exop = df(exo)
```

```
# In[5]:
```

```
def datap(col1, col2):
```

```
    if col1.count() < col2.count():
```

```
        return(col1.count())
```

```
    else:
```

```
        return(col2.count())
```

```
# In[6]:
```

```
plt.scatter(exop['star_age'], exop['star_teff'], c='None', cmap='None')
```

```
plt.grid(True)
```

```
# In[7]:
```

```
exop['rade'] = np.array(exop['radius'])*11.2089
```

```
# In[8]:
```

```
massj=np.array(exop['mass'])
```

```
# In[9]:
```

```
massj
```

```
# In[10]:
```

```
masse= 317.93842034806*massj
```

```
# In[11]:
```

```
masse

# In[12]:

exop['masse']=masse

# In[29]:

exop.plot(x='star_age', y= 'star_teff', kind='scatter', c=exop['star_age'], cmap='RdYlGn', s=30)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Stellar effective Temperature (K) vs. Stellar Age (10^9 years)')

fig= plt.figure(figsize=(6,3))

# In[30]:

datap(exop['star_age'],exop['star_teff'])

# In[31]:

exop.plot(x='star_age', y= 'masse', kind='scatter', c=exop['mass'], cmap='RdYlGn', s=50)

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Stellar Age (10^9 years) ')

# In[32]:

datap(exop['star_age'],exop['masse'])

# In[33]:
```

```
exop.plot(x='masse', y='star_teff', kind="scatter", c=exop['masse'], cmap='RdYlGn_r', s=20)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Mass of Planet (in earth mass) ')

# In[34]:

datap(exop['star_teff'],exop['masse'])

# In[35]:

plt.figure(figsize=(60,30))

exop.plot(x='star_mass', y='star_teff', kind='scatter', c=exop['star_mass'], cmap='coolwarm',
s=30)

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.yscale('log')

plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Mass of Star (in Solar mass) ')

# In[36]:

datap(exop['star_teff'],exop['star_mass'])

# In[37]:

exop.plot(x='masse', y='rade', kind='scatter', c=exop['masse'], cmap='gist_rainbow', s=10)

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)
```

```
plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.yscale('log')

plt.xscale('log')

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Radius of Planet (in earth radius) vs. Mass of Planet (in earth mass) ')

# In[38]:

datap(exop['masse'],exop['radius'])

# In[39]:

exop.plot(y='star_mass', x='star_age', kind='scatter', c=exop['star_age'], cmap='RdYlGn', s=20)

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Stellar Mass (in Solar masss) vs. Stellar Age (10^9 Years) ')

# In[40]:

datap(exop['star_mass'],exop['star_age'])

# In[41]:

exop.plot(y='star_teff', x='star_age', kind='scatter', c=exop['star_age'], cmap='RdYlGn', s=20)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)
```

```
plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Stellar Age (10^9 Years)')

# In[26]:

datap(exop['star_teff'],exop['star_age'])

# In[27]:

exop.plot(x='star_teff', y='masse', kind='scatter', c=exop['star_teff'], cmap='gnuplot', s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Stellar Effective Temperature (K) ')

# In[42]:

exop.plot(x='star_teff', y='dens', kind='scatter', c=exop['star_teff'], cmap='gnuplot', s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Stellar Effective Temperature (K) ')

# In[43]:

datap(exop['star_teff'],exop['masse'])

# In[44]:

exop.plot(y='orbital_period', x='masse', kind='scatter', c=exop['orbital_period'], cmap='RdYlGn',
s=30)
```



```
plt.yscale('log')

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Orbital Period of Planet (in earth days) vs. Mass of Planet (in earth mass)')

# In[45]:

exop.plot(y='orbital_period', x='masse', kind = 'scatter', c=exop['masse'], cmap='RdYlGn', s=20)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Orbital Period of Planet (in earth days) vs. Mass of Planet (in earth mass) ')

# In[46]:

datap(exop['orbital_period'],exop['masse'])

# In[47]:

exop.plot(y='mag_v', x='star_teff', kind = 'scatter', c=exop['mag_v'], cmap='RdYlGn', s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)
```

```
plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Apparent magnitude V vs. Stellar Effective Temperature (K)')

# In[48]:

exop.plot(y='orbital_period', x='semi_major_axis', kind = 'scatter', c=exop['semi_major_axis'],
cmap='gist_rainbow', s=30)

plt.yscale('log')

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Orbital Period of Planet (in earth days) vs. Semi Major Axis (AU) ')

# In[49]:

datap(exop['orbital_period'], exop['semi_major_axis'])

# In[50]:

exop.plot(x='orbital_period', y='star_teff', kind = 'scatter', c=exop['star_teff'], cmap='RdYlGn',
s=30)

plt.yscale('log')

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)
```

```
plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Orbital Period of Planet (in earth days) ')

# In[51]:

datap(exop['orbital_period'], exop['star_teff'])

# In[52]:

exop.plot(x='orbital_period', y='rade', kind = 'scatter', c=exop['orbital_period'], cmap='RdYlGn',
s=30)

plt.xscale('log')

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Radius of Planet (in earth radius) vs. Orbital Period of Planet (in earth days) ')

# In[72]:

datap(exop['radius'], exop['orbital_period'])

# In[73]:

exop.plot(x='star_distance', y='star_teff', kind = 'scatter', c=exop['star_distance'], cmap='RdYlGn',
s=30)

plt.yscale('log')

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)
```

```
plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Star Distance (parsec) ')

# In[74]:

datap(exop['star_teff'], exop['star_distance'])

# In[75]:

exop.plot(x='star_distance', y='masse', kind = 'scatter', c=exop['star_distance'], cmap='RdYlGn',
s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Star Distance (parsec)')

# In[76]:

datap(exop['masse'], exop['star_distance'])

# In[77]:

exop.plot(x='star_mass', y='masse', kind = 'scatter', c=exop['masse'], cmap='RdYlGn', s=50)

plt.yscale('log')

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)
```

```
plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Mass of Planet (in earth mass)vs. Stellar Mass (in Solar Mass) ')

# In[78]:

datap(exop['masse'], exop['star_mass'])

# In[79]:

exop.plot(y='star_radius', x='rade', kind = 'scatter', c=exop['radius'], cmap='RdYlGn', s=50)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Radius (in Solar Radius) vs. Radius of Planet (in earth radius) ')

# In[80]:

datap(exop['star_radius'], exop['rade'])

# In[81]:

exop.plot(y='star_teff', x='star_metallicity', kind = 'scatter', c=exop['star_metallicity'],
cmap='RdYlGn', s=50)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)
```

```
plt.grid(True)

plt.title('Stellar Effective Temperature (K) vs. Stellar Metallicity [Fe/H] ')

# In[82]:

datap(exop['star_teff'], exop['star_metallicity'])

# In[83]:

exop.plot(x='star_age', y='star_metallicity', kind = 'scatter', c=exop['star_metallicity'],
cmap='RdYlGn', s=50)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Metallicity [Fe/H] vs. Stellar Age (10^9 Years) ')

# In[84]:

datap(exop['star_metallicity'], exop['star_age'])

# In[85]:

exop.plot(x='star_mass', y='star_radius', kind = 'scatter', c=exop['dens'], cmap='gist_rainbow',
s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)
```

```
plt.title('Stellar Radius (in Solar Radius) vs. Stellar Mass (in Solar Mass) (Colour Scheme w.r.t.  
Planet Density)')
```

```
# In[86]:
```

```
datap(exop['star_mass'],exop['star_radius'])
```

```
# In[54]:
```

```
den=np.array(exop['masse'])/np.array(exop['rade'])
```

```
# In[55]:
```

```
den
```

```
# In[56]:
```

```
datap(exop['masse'], exop['rade'])
```

```
# In[57]:
```

```
exop['dens']=den
```

```
# In[58]:
```

```
exop['dens'].count()
```

```
# In[59]:
```

```
exop['rade'].count()
```

```
# In[60]:
```

```
st_dens=np.array(exop['star_mass'])/np.array(exop['star_radius'])
```

```
# In[61]:
```

```
st_dens
```

```
# In[62]:
```

```
exop['st_den']=st_dens
```

```
# In[63]:
```

```
exop['st_den'].count()
```

```
# In[64]:
```

```
exop['denj']=np.array(exop['mass'])/np.array(exop['radius'])
```

```
#added new column to dataframe
```

```
# In[65]:

exop.plot(y='st_den', x='dens', kind = 'scatter', c=exop['dens'], cmap='gnuplot', s=20)

plt.xscale('log')

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Density (in Solar Density) vs. Planetary Density (in Earth Density) ')

# In[66]:

exop.plot(x='star_mass', y='star_radius', kind = 'scatter', c=exop['denj'], cmap='RdYlGn', s=20)

plt.xscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Stellar Radius (in Solar Radius) vs. Stellar Mass (in Solar Mass) (Colour Scheme w.r.t.
Planet Density)')

# In[67]:

w=exop['denj']/exop['dens']

#experimental operation success proof

# In[68]:

for i in w:
```



```
print(i)

#proof for proper operations

# In[69]:

exop.plot(y='dens', x='semi_major_axis', kind = 'scatter', c=exop['semi_major_axis'],
cmap='gnuplot', s=20)

plt.xscale('log')

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.rcParams["figure.figsize"] = (20,10)

plt.grid(True)

plt.title('Planetary Density (in Earth Density) vs. Semi Major Axis (AU)')

# In[70]:

exop.plot(x='dens', y='masse', kind='scatter', c=exop['star_teff'], cmap='gnuplot', s=20)

plt.xscale('log')

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Density of Planet (in earth density) ')

# In[71]:

exop.plot(x='dens', y='rade', kind='scatter', c=exop['star_teff'], cmap='gnuplot', s=20)

plt.xscale('log')
```

```
plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Mass of Planet (in earth mass) vs. Stellar Effective Temperature (K) ')

# In[101]:

exop.plot(y='star_distance', x='star_age', kind='scatter', c=exop['star_teff'], cmap='coolwarm',
s=30)

plt.yscale('log')

plt.rc('axes', titlesize=25)

plt.rc('axes', labelsiz=25)

plt.xticks(fontsize=25)

plt.yticks(fontsize=25)

plt.grid(True)

plt.title('Star Distance (in parsec) vs. Stellar Age (10^9 years) (Colour Scheme: Stellar Effective
Temperature (K)) ')
```

PART-B

ANALYSING STAR THROUGH THEIR SPECTRA

1. INTRODUCTION

Since centuries, Mankind's biggest questions have led to its progress and evolution. The whole dawn of space revolution has come into existence because of chasing the biggest questions out there like, what lies beyond the skies we daily look unto? Are there other worlds like ours? Are we alone? What makes life possible? We set out to do the impossible and with decades worth work and many heads put together have surely made it now possible to step out of our world and go on a mission to explore other ones out there.

Just like that our team has had the same curiosity to understand what lies beyond us, hence our motto to infinity and beyond. Our hunt to search Exoplanets began. We looked into data of various found exoplanets by TESS, KEPLER, HST etc. We realized there's a lot more to look into and understand besides the exoplanet itself to comment more on its habitability or its atmosphere. The host star has a plethora of information as well, that influences the planetary system. Its size, mass, temperature, age, spectral type and a lot more tells us about the planets around it, its formation process, its orbit, its composition and atmosphere. There might be various relations between them that are yet to be found and established. So, we decided to go into detail about studying the host stars of such found exoplanets and began by venturing into the topic of stars and their spectra. After all they might be far and beyond but as long as we have its light, there's a lot that can be unravelled and analysed once looked at deep enough.

1.1. AIM AND OBJECTIVE

OBJECTIVE –II: Analysing the spectral data of stars using MATLAB.

The relationship between a host star and its exoplanets is very much interlinked. When we address or question an exoplanet's habitability or its atmosphere, it's important to look at the host star as well. The host star tells us about the formation of planets around it, the chemical composition, its atmosphere and a lot more. The exoplanets are subjected to the host star's wind and high energy radiation of UV and X-radiation which determines what kind of atmosphere it will end up having or if it can survive it.

Our objective focuses on finding the atmospheric composition of the stars using MATLAB, mainly the G type main-sequence star. A G-type star (Spectral type: G-V), also called a yellow dwarf or G dwarf star, is a main-sequence star (luminosity class V) of spectral type G. The star is defined to be having about 0.84 to 1.15 solar masses and surface temperature of between 5,300 and 6,000K. We initially began with the objective of finding the atmospheric composition of the planets transiting through these stars but due to insufficient databases about the spectroscopy of planets we thereby decided to look for the atmospheric composition of the host stars. Stars are surrounded by the clouds of hot gases so when the light or photons radiated by the stars, hits through the atoms, the electrons in their lowest-energy configuration get boosted to their higher energy levels, this is absorption. Since the electrons tend to go back to their original levels, they

emit the energy, in the form of photons with the same wavelengths of light that were absorbed in the first place. Most of the light emitted by the atom is in the direction that is away from our line of sight. Therefore, a dark line appears in the spectrum at that particular wavelength. Since the wavelengths at which absorption lines occur are unique for each element, we can measure the position of the lines to determine elements present in the target. The amount of light that is absorbed provides information about how much of each element is present.

- Collect spectral data of stars from STELIB (stellar library)
- Use MATLAB codes to create the plots between the stellar properties collected.
- Inferring about the temperature, Doppler shift, speed and chemical composition present in the atmosphere of the star through the plots obtained.

2. BACKGROUND&LITERATURE OVERVIEW

2.1. STAR

A star is an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity. They are the astronomical objects that represent the fundamental frame for the existence or formation of galaxies. Stars are huge and mostly consist of hydrogen and helium that produce light and heat from the churning nuclear forges inside their cores. [1] [2]

2.1.1. FORMATION OF STARS

Stars are formed within the clouds of hydrogen-based dust that are dispersed throughout galaxies called nebulae. Within the course of some years, the surge of turbulence deep within these clouds gives rise to clusters with the mass that the gas and dust can begin to collapse under its own gravitational attraction.[3] As the cloud collapses, the centre gets to begin heating up. Known as a protostar, some of it is massive such that the core temperature will eventually reach 10 million kelvins, initiating the proton-proton chain reaction and allowing hydrogen to fuse, first to deuterium and then to helium. As this protostar gets smaller, properties of the star gets to be defined, it spins faster because of the conservation of angular momentum.[4] Increasing pressure creates rising temperatures, and during this time, a star enters T Tauri phase. [5] Following all the stages eventually a star is formed one day.

2.1.2. PROPERTIES OF THE STAR

A) Physical

Almost everything about a star is determined by its initial mass, including such characteristics as luminosity, size, evolution, lifespan, and its eventual fate. [6]

- Age
- Diameter
- Chemical composition

When stars form in the present Milky Way galaxy, they are composed of about 71% hydrogen and 27% helium, as measured by mass, with a small fraction of heavier elements. There also exist chemically peculiar stars that show unusual abundances of certain elements in their spectrum; especially chromium and rare earth elements. Stars with cooler outer atmospheres, including the Sun, can form various diatomic and polyatomic molecules. [7]

B) Kinematics

The motion of a star relative to the Sun can provide useful information about the origin and age of a star, as well as the structure and evolution of the surrounding galaxy. The components of motion of a star consist of the radial velocity toward or away from the Sun, and the traverse angular movement, which is called its proper motion. [8]

- **Radial velocity**

Radial velocity is measured by the Doppler shift of the star's spectral lines, and is given in units of km/s. The proper motion of a star, its parallax, is determined by precise astrometric measurements in units of milli-arc seconds (mas) per year. With knowledge of the star's parallax and its distance, the proper motion velocity can be calculated. Together with the radial velocity, the total velocity can be calculated. Stars with high rates of proper motion are likely to be relatively close to the Sun, making them good candidates for parallax measurements. [8]

- **Magnetic field**

The magnetic field of a star is generated within regions of the interior where convective circulation occurs. This movement of conductive plasma functions like a dynamo, wherein the movement of electrical charges induce magnetic fields, as does a mechanical dynamo. [9]

- **Mass**

Mass are due to elements present in them. The combination of the radius and the mass of a star determines its surface gravity.

- **Rotation**

The rotation rate of stars can be determined through spectroscopic measurement, or more exactly determined by tracking their star spots. The rotation rate of the pulsar will gradually slow due to the emission of radiation.

- **Temperature**

The surface temperature of a main sequence star is determined by the rate of energy production of its core and by its radius, and is often estimated from the star's colour index. The temperature is normally given in terms of an effective temperature, which is the temperature of an idealized black body that radiates its energy at the same luminosity per surface area as the star.

- **Radiation**

The energy produced by stars, a product of nuclear fusion, radiates to space as both electromagnetic radiation and particle radiation. The production of energy at the core is the

reason stars shine so brightly: every time two or more atomic nuclei fuse together to form a single atomic nucleus of a new heavier element; gamma ray photons are released from the nuclear fusion product.

- **Luminosity**

The luminosity of a star is the amount of light and other forms of radiant energy it radiates per unit of time. It has units of power. The luminosity of a star is determined by its radius and surface temperature.

- **Magnitude**

The apparent brightness of a star is expressed in terms of its apparent magnitude. It is a function of the star's luminosity, its distance from Earth, the extinction effect of interstellar dust and gas, and the altering of the star's light as it passes through Earth's atmosphere.

Here in this project Properties of star like Chemical composition, Radial velocity and temperatures is being focused.

2.2. STELLAR CLASSIFICATION

The classification of stars based on their spectral characteristics is known as the stellar classification.

A spectral line is a dark or bright line in a uniform and spectrum, which is due to emission or absorption of light in a narrow frequency range, compared with the nearby frequencies. They are used to identify atoms and molecules. They are also called as “fingerprints” as every element happens to have its own unique spectral signature just as our fingerprints are unique. These “fingerprints” can be compared to the previously collected ones of atoms and molecules, and are used to identify the atomic and molecular components of stars and planets.

Each line indicates a particular chemical element or molecule, the line strength indicates the abundance of that element. The strengths of the different spectral lines vary mainly due to the temperature of the photosphere, although in some cases there are true abundance differences. The *spectral class* of a star is simply a short code for the ionization state, giving an objective measure of the photosphere's temperature.

The Morgan–Keenan (MK) system is a system built that is used to classify most of the stars using the letters *O*, *B*, *A*, *F*, *G*, *K*, and *M*, a sequence from the hottest (*O* type) to the coolest (*M* type). Each letter class is then subdivided using a numeric digit with *0* being hottest and *9* being coolest (e.g., *A8*, *A9*, *F0*, and *F1* form a sequence from hotter to cooler). The sequence has been expanded with classes for other stars and star-like objects that do not fit in the classical system, such as class *D* for white dwarfs and classes *S* and *C* for carbon stars.

In the MK system, a luminosity class is added to the spectral class using Roman numerals which is based on the width of certain absorption lines in the star's spectrum, which vary with the density of the atmosphere and so distinguish giant stars from dwarfs. [10]

2.2.1. LUMINOSITY CLASS

Table 5- Luminosity class

LUMINOSITY CLASS	STAR TYPE
<i>O or Ia+</i>	<i>Hypergiants</i> (extremely luminous giants)
<i>class I</i>	<i>supergiants</i> , (luminous supergiants- to less luminous giants)
<i>class II</i>	<i>bright giants</i>
<i>class III</i>	<i>regular giants</i>
<i>class IV</i>	<i>sub-giants</i> ,
<i>class V</i>	<i>main-sequence stars</i> , (dwarfs)
<i>class sd (or VI)</i>	<i>sub-dwarfs</i> ,
<i>class D (or VII)</i>	<i>white dwarfs</i> .

e.g. The full spectral class for the Sun is then G2V, which basically says that it's a main-sequence star with a surface temperature of about 5,800 K.

Table 6- star type

CLASS	EFFECTIVE TEMPERATURE	CHROMACITY (D65)	MAIN SEQUENCE MASS (SOLAR MASS)	MAIN SEQUENCE LUMINOSITY (BOLOMETRIC)	HYDROGEN LINES
O	≥30,000K	Blue	>16M	>30,000L	Weak
B	10,000-30,000K	Deep blue white	2.1-16M	25-30,000L	Medium
A	7,500-10,000K	Blue white	1.4-2.1M	5-25L	Strong
F	6,000-7,500K	White	1.04-1.4M	1.5-5L	Medium
G	5,200-6,000K	Yellowish white	0.8-1.04M	0.6-1.5L	Weak
K	3,700-5,200K	Pale yellow orange	0.45- 0.8M	0.08-0.6L	Very weak
M	2,400-3,700K	Light orange red	0.08-0.45	<0.08L	Very weak

Class O

O-type stars have dominant lines of absorption and sometimes emission for He II lines, prominent ionized (Si IV, O III, N III, and C III) and neutral helium lines, strengthening from O5 to O9, and prominent hydrogen Balmer lines, although not as strong as in later types. Because they are so massive, O-type stars have very hot cores and burn through their hydrogen fuel very quickly, so they are the first stars to leave the main sequence. [11]

Class B

B-type stars are very luminous and blue. Their spectra have neutral helium lines, which are most prominent at the B2 subclass, and moderate hydrogen lines. As O- and B-type stars are so energetic, that they are relatively short lived due to the low probability of kinematic interaction during their lifetime, they are unable to stray far from the area in which they formed. [12]

Class A

A-type stars are among the more common naked eye stars, and are white or bluish-white. They have strong hydrogen lines, at a maximum by A0, and also lines of ionized metals (Fe II, Mg II, Si II) at a maximum at A5. The presence of Ca II lines is notably strengthening by this point.

Class F

F-type stars have strengthening spectral lines *H* and *K* of Ca II. Neutral metals (Fe I, Cr I) beginning to gain on ionized metal lines by late F. Their spectra are characterized by the weaker hydrogen lines and ionized metals. Their colour is white.

Class G

G-type stars (like our sun) have prominent spectral lines *H* and *K* of Ca II, which are most pronounced at G2. They have even weaker hydrogen lines than F, but along with the ionized metals, they have neutral metals. There is a prominent spike in the G band of CH molecules.

Class G contains the "Yellow Evolutionary Void". Supergiant stars often swing between O or B (blue) and K or M (red). While they do this, they do not stay for long in the yellow supergiant G class, as this is an extremely unstable place for a supergiant to be.

Class K

They have extremely weak hydrogen lines, if those are present at all, and mostly neutral metals (Mn I, Fe I, Si I). By late K, molecular bands of titanium oxide become present.

Some theories also suggest that such stars have an optimum chance of life being evolved at (i.e. if it all the life we talk of is anything like our earth) such orbiting planets because it has a greater habitable zone with lower chances of harmful emissions.

Class M

The spectrum of a class M star contains lines from oxide molecules (in the visible spectrum, especially TiO) and all neutral metals, but absorption lines of hydrogen are usually absent. TiO bands can be strong in class M stars, usually dominating their visible spectrum by about M5. Vanadium (II) oxide bands become present by late M. [13]

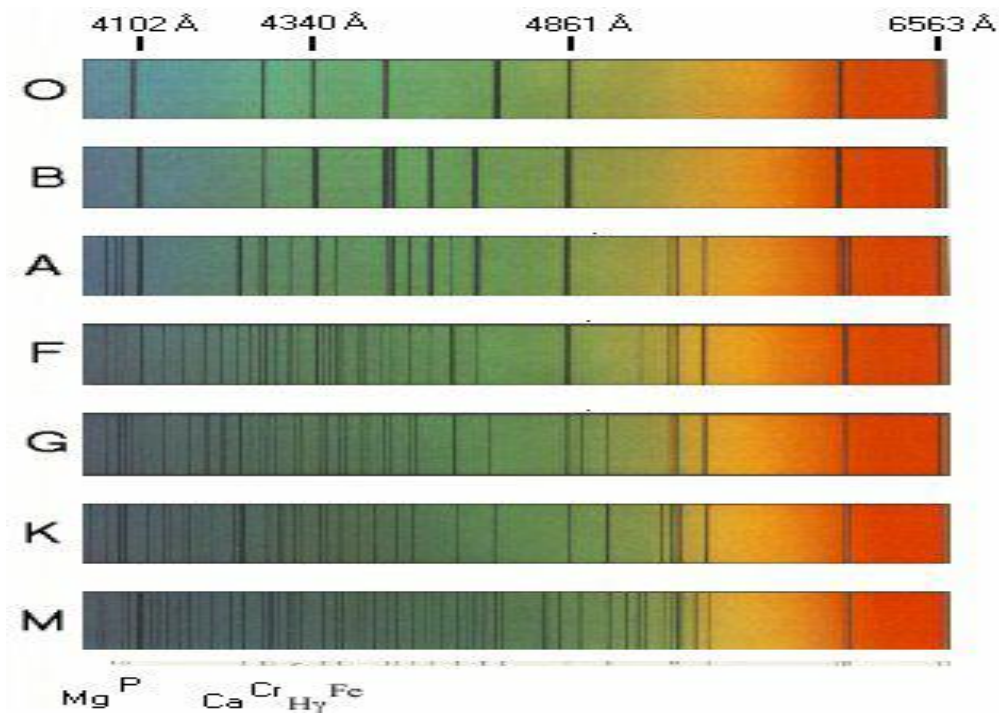


Image credit: Wikipedia

Class L

Class L dwarfs get their designation because they are cooler than M stars and L is the remaining letter alphabetically closest to M. Some of these objects have masses large enough to support hydrogen fusion and are therefore stars, but most are of sub stellar mass and are therefore brown dwarfs. They are a very dark red in colour and brightest in infrared. Their atmosphere is cool enough to allow metal hydrides and alkali metals to be prominent in their spectra

Due to low surface gravity in giant stars, TiO- and VO-bearing condensates never form. Thus, L-type stars larger than dwarfs can never form in an isolated environment.

Class T: methane dwarfs

Class T dwarfs are cool brown dwarfs with surface temperatures between approximately 550 and 1,300 K (277 and 1,027 °C; 530 and 1,880 °F). Their emission peaks in the infrared. As the name suggests Methane is prominent in their spectra.

Class Y

Brown dwarfs of spectral class Y are cooler than those of spectral class T and have qualitatively different spectra from them. Coolest Y dwarf currently known is WISE 0855–0714 with an approximate temperature of 250 K.

Late giant carbon-star classes

Carbon-stars are stars which have a spectrum indicating the production of carbon—a by-product of triple-alpha helium fusion. With increased carbon abundance, and some parallel s-process heavy element production, the spectra of these stars become increasingly deviant from the usual late spectral classes G, K, and M. Equivalent classes for carbon-rich stars are S and C.

The giants among those stars are presumed to produce this carbon themselves, but some stars in this class are double stars, whose odd atmosphere is suspected of having been transferred from a companion that is now a white dwarf, when the companion was a carbon-star.

Class C: carbon stars

These are red giants, near the end of their lives, in which there is an excess of carbon in the atmosphere. The old R and N classes ran parallel to the normal classification system from roughly mid G to late M.

Class S

Class S stars form a continuum between class M stars and carbon stars. Those most similar to class M stars have strong ZrO absorption bands analogous to the TiO bands of class M stars, whereas those most similar to carbon stars have strong sodium D lines and weak C₂ bands. Class S stars have excess amounts of zirconium and other elements produced by the s-process, and have more similar carbon and oxygen abundances than class M or carbon stars. Like carbon stars, nearly all known class S stars are asymptotic-giant-branch stars. [14]

Table 7- Spectral lines of stars

SPECTRAL TYPE	TEMPERATURE(K)	SPECTRAL LINES
O	28,000-50,000	Ionized helium
B	10,000-28,000	Helium, hydrogen
A	7,500-10,000	Strong Hydrogen, some ionized metals
F	6000-7500	Hydrogen, ionized Calcium (H & K) and Iron
G	5000-6000	Neutral and ionized metals, Calcium G band
K	3500-5000	Neutral metals, sodium
M	2500-3500	Strong titanium oxide, strong sodium

Table 8- Spectral lines and the wavelength

SPECTRAL LINES	WAVELENGTHS
H_a, H_b, H_g	6600, 4800, 4350
Ionized Calcium H & K lines	3800-4000
Titanium Oxide	4900-5200, 5400-5700, 6200-6300, 6700-6900
G band	4250
Sodium	5800
Helium(neutral)	4200
Helium (ionized)	4400

2.3. STELLER SPECTRUM ANALYSIS:

Stars are surrounded by the clouds of hot gases so when the light or photons radiated by the stars, hits through the atoms, the electrons in their lowest-energy configuration get boosted to their higher energy levels, this is absorption. Since the electrons tend to go back to their original levels, they emit the energy, in the form of photons with the same wavelengths of light that were absorbed in the first place. Therefore, a dark line appears in the spectrum at that particular wavelength. Since the wavelengths at which absorption lines occur are unique for each element, we can measure the position of the lines to determine elements present in the target. The amount of light that is absorbed provides information about how much of each element is present. Using the stellar spectrum, astronomers can also determine the surface temperature, surface gravity, metallicity and rotational velocity of a star. If the distance of the star is found, such as by measuring the parallax, then the luminosity of the star can be derived.

Some of the chemicals /elements that correspond to the wavelength of light obtained through spectrum is given in Table.

Table 9 - Wavelengths of each element

Element		Wavelength (nm)					
Fe	495.761	O2	686.719	Fe	382.044	Na	589.592
H	486.134	O2	822.696	Ni	299.444	Na	588.995
Fe	466.814	O2	759.370	Fe	358.121	Hg	546.073
Fe	438.355	Mg	518.362	Ti+	336.112	Ca+	396.847
H	434.047	O2	627.661	Fe	516.891	Ca+	393.368
Fe	430.790	He	587.5618	Mg	517.270	Mg	516.733
Ca	430.774	H	656.281	Fe	302.108	O2	898.765
H	410.175	Fe	527.039				

2.3.1. EXTRACTING INFORMATION FROM THE SPECTRA

The wavelength at which known emission and absorption lines are detected can be used to measure the redshift of the observed object. Apart from measuring distances, this type of analysis can also be used to detect spectroscopic binaries and Extrasolar planets.

1. Through spectral broadening the velocity broadening can be calculated using the widths of both the absorption or emission line that helps in finding the average velocity of the star within galaxies
2. Most absorption and emission lines are produced by metals. The *depths* or *heights* of these lines can be used to estimate the abundances of the metals responsible. In stars, these also permit the measurement of the temperature and pressure of the stellar atmosphere. In objects such as galaxies, they permit an estimation of age, though the spectra are somewhat susceptible to the age-metallicity degeneracy making this a difficult procedure.
3. Finally, the overall shape of the spectrum contains clues to many other aspects of the observed population including age and interstellar reddening (extinction).

4. The wavelength at which known emission and absorption lines are detected can be used to measure the redshift of the observed object. Apart from measuring distances, this type of analysis can also be used to detect spectroscopic binaries and Extrasolar planets. [15]

Spectroscopic Binaries

Single-lined spectroscopic binaries have a characteristic emission or absorption line that helps us to characterize their orbits using the mass function. In these systems, the spectrum is dominated by one of the two stars. Spectroscopic binary systems are usually detected due to the movement of the emission and absorption lines in the observed spectrum, caused by the Doppler Effect as the stars move in their orbit. Dual-line spectroscopic binaries can have spectroscopic features from both stars identified and followed around the orbit. These binaries allow determination of their mass ratio. [16]

2.3.2. EMISSION AND ABSORPTION LINES

The spectra aren't always smooth there are certain breaks in between which is due to the emission or absorption of the electromagnetic radiation of an element or compound which occurs at specific wavelengths. [17]

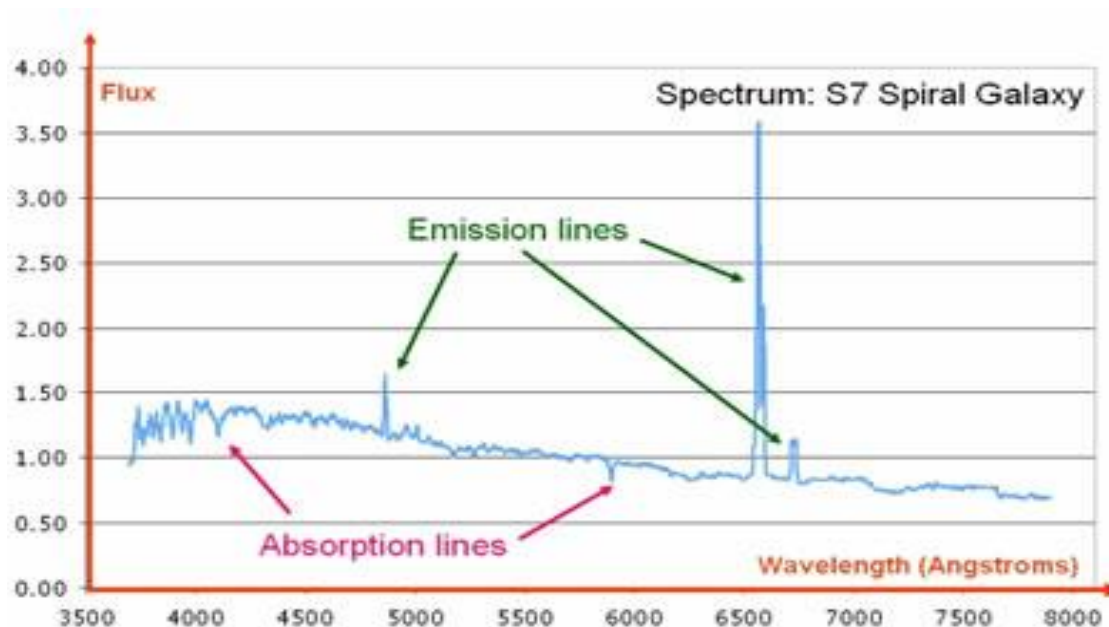


Image credit: Swinburne

2.3.3. DETERMINING THE SURFACE TEMPERATURE OF THE STAR USING ITS SPECTRUM

The sun's spectrum can be closely approximated to a blackbody spectrum, likewise so are the other stars. The temperature of a blackbody can be calculated by the formula

$$T = 0.0029/\lambda_{max}$$

T- Temperature of the blackbody (in Kelvin)

λ_{max} - Wavelength of the maximum emission (In meters)

With this formula, we can compute the surface temperature of the star by the wavelengths that emit the maximum amount of light.

One can also compute knowing the star's colour. The redder a star is the colder the temperature, the bluer the hotter.

2.3.4. RADIAL VELOCITY

When we measure the spectrum of a star, we determine the wavelength of each of its lines. If the star is not moving with respect to the Sun, then the wavelength corresponding to each element will be the same as those we measure in a laboratory here on Earth. But if stars are moving toward or away from us, we must consider the *Doppler Effect*. We should see all the spectral lines of moving stars shifted toward the red end of the spectrum if the star is moving away from us or toward the blue (violet) end if it is moving toward us. The greater the shift, the faster the star is moving. Such motion, along the line of sight between the star and the observer, is called **radial velocity** and is usually measured in kilometres per second.

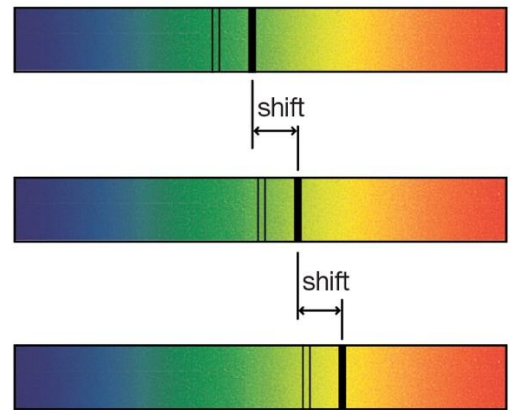
The Doppler shift

The amount of shift depends on the velocity of the object in relationship to the observer: the greater the velocity, the greater the shift.

Absorption lines from an approaching object shift toward the violet (shorter wavelength).

Absorption lines from the sun are used for comparison.

Absorption lines from a receding object shift toward the red (longer wavelength).



The colored bands are standard spectra. The black lines are absorption lines.

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Image credit: Britannica

2.4. STARS AND EXOPLANETS

As the cloud collapses, a dense, hot core forms and begins gathering dust and gas. Not all of this material ends up as part of a star — the remaining dust can become planets, asteroids, or comets or may remain as dust.

Stars are the reason for the formation and distribution of some of the heavy elements such as carbon, nitrogen, and oxygen, and their characteristics are closely related to the characteristics of the planetary systems within them. The properties of the stars such as their age, distribution, and composition give the evidence of the history, dynamics, and evolution of the galaxy. The study of stars is a central field of astronomy.

2.4.1. METHODS TO FIND ATMOSPHERIC COMPOSITION

Some of the most preferred methods are

1. Transit spectroscopy method
2. Radial velocity method
3. Phase curve variations

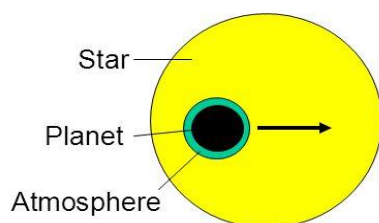
TRANSIT SPECTROSCOPY:

When a planet transits in front of its host star, the planetary atmosphere absorbs some of the star light and since atoms and molecules absorb photons at specific energies, this results in slight differences in the observed flux at different wavelengths. As a direct consequence of these changes in flux, the depth of the transit will suffer an equivalent change in different wavelengths, this enables us to deduce the elements and molecules present in the atmosphere of the exoplanets.

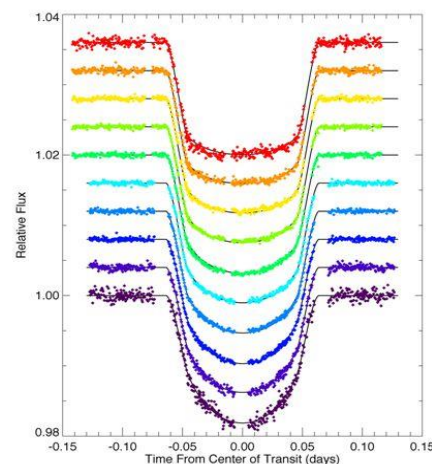
In simple terms, most stars have a reasonably constant brightness, so if there is any dip in brightness, we can know that some object has passed in between us and the star. If the dip is repeated periodically, it means that an object (i.e. in our case a planet) is in orbit around the star. This dip in the observed spectra varies depending on the atmospheric composition of the orbiting object.

An alternate method is to get the combined spectra of the host star's light and the absorption spectrum of the transiting planets' atmosphere, and subtracting the background star's light. [18]

Characterizing Atmospheres With Transmission Spectroscopy



- Probes composition of atmosphere at day-night terminator
- Can search for clouds, hazes, condensates



HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)

Image credits: Google images

In transit method if the planet is in front of the star the study is called primary eclipse method.

RADIAL VELOCITY METHOD:

Consider an observer observing a star. As the star moves away from the observer, the light will be slightly shifted towards the red and as the star moves towards the observer, the light will be slightly shifted to the blue. This wobbling caused by the presence of a planet around the star can therefore be detected by the slight change in the wave length of the star. And this method is called radial velocity or Doppler shift method. The amount by which the starlight is Doppler shifted is directly proportional to the radial velocity of the star, and so the measurement is quite simple to convert from spectroscopy into velocity in space, and the amplitude of this radio velocity measured by spectroscopy is a direct indication of the mass of the planet.

PHASE-CURVE VARIATIONS: (Thermal phase variation)

In close-in planets, the side opposite to the host star shows very high temperature during day time due to its close orbit around the star and has extremely cool conditions during night time. This thermal variation helps to detect the exoplanet by phase-curve variation method.

2.4.2. STELLAR HABITABILITY

For a host star to be able to have better chance of harbouring life in its system of planets (i.e. terrestrial) there are many factors to consider. Some of which are Stability, luminosity, and lifespan. We only know of one star that hosts life, and that is our own—a G class star with an abundance of heavy elements and low variability in brightness.

Working from these constraints and the problems of having an empirical sample set of only one, the range of stars that are predicted to be able to support life as we know it is limited by a few factors. Of the main-sequence star types, stars more massive than 1.5 times that of the Sun (spectral types O, B, and A) age too quickly for advanced life to develop (using Earth as our reference). On the other extreme, dwarfs of less than half the mass of our Sun (spectral type M) are likely to tidally lock planets within their habitable zone, along with other problems.

For these reasons NASA's Kepler Mission is searching for habitable planets at nearby main sequence stars that are less massive than spectral type A but more massive than type M -- making the most probable stars to host life dwarf stars of types F, G, and K.

2.4.3. POTENTIAL HABITABILITY

HABITABLE ZONE

The habitable zone or Goldilocks zone is generally characterized by the region around a host star where liquid water exists. Habitable zone is mostly defined based upon the availability of water in liquid state, as water is considered as the supreme necessity for life to exist. This is because water is a universal solvent and also it acts as a medium for biochemical reactions to take place.

The habitable zone also depends on the stellar spectra of the host star, planetary rotation, and the atmospheric properties of the planets, the initial water content and the evolutionary history of the surface environment.

The planets orbiting outside these regions are not necessarily habitable, they maybe habitable in their subsurface, but they will be difficult to observe. This shows that it is difficult to search for life in gas and ice giants remotely.

POTENTIAL HABITABLE PLANETS

Years of observational study and SETI (Search for extra-terrestrial intelligence) have shown us that potential habitable planets are situated in the habitable zone. We for instance live on a rocky terrestrial planet situated in the habitable zone. This makes us question whether the rocky

planets most apt for habitability? The answer is yes. Because these planets not only possess liquid water but also show possible biosignatures mostly from the surface if any. This makes them the right choice for biosignature search via remote methods. [23]

2.5. BIOSIGNATURES

Biosignatures are the indications of presence of life or biosphere in any planet. For instance, we all know that oxygen is the second highest constituent of our atmosphere next to nitrogen. This proves that oxygen is a significant biosignature of earth, because it is primarily produced through biological processes. In some cases, the remaining abiotically originated oxygen always leads to false interpretations. We will study about those misleading in the upcoming sections. [19]

Useful biosignatures have three main properties, which are as follows:

1. Reliability
2. Survivability
3. Detectability

Reliability – This questions the biotical origin of the biosignatures. If these are true signs of life they should be of biological origin, or else they must have been produced by planetary processes (i.e. geology, photochemistry).

Survivability – Can they escape the sinks (i.e. crustal oxidation, photolytic destruction in the stratosphere, reaction with volcanic gases, etc.) and build up to detectable levels?

Detectability - Whether the biosignatures are observable by the search techniques? Whether they are spectrally active and clear of overlap with other chemical species in the wavelength region to be observed?

2.5.1. SIGNIFICANT GASES

Though oxygen and methane are prominent gases in the atmosphere our main focus is on oxygen. We also look out for ozone produced from the oxygen, as oxygen is mostly of biological origin. But oxygen can be of abiotic origin as well. Some of the gases with abiotic source of origin are as follows:

Oxygen, Ozone, Nitrogen, Carbon dioxide, Carbon monoxide, Methane, Nitrogen dioxide, Ammonia, Nitrous oxide, Sulphur dioxide, Hydrogen sulphide, Carbonyl sulphide, Dimethyl sulphide and various non-methane hydrocarbons.

The availability and biological origin of oxygen are difficult to find and confirm. When we have a look at the detailed evolutionary history of our earth, we find that oxygen was not abundant in our planetary atmosphere for several billion years, rendering earth's life undetectable by current methods during the time. This is what we call as a false positive. As we discussed earlier, oxygen can be of abiotic origin too. Hence, it is possible for planetary atmospheres to possess high oxygen levels without the presence of biosphere. This high oxygen content is often mistaken as an indication of life and a false positive result is obtained.

Nitrogen is also an ambiguous indicator of life as it can be produced from both biotic and abiotic processes. But they have relatively poorer biosignatures because it exhibits strong absorption only in the extreme UV region at a wavelength less than 0.1 micro meters, where several other molecules also absorb and the stars are also much less luminous, reducing the reflection and transmission signals from the planetary atmosphere in this region. [22]

2.6. METHODOLOGIES, SOFTWARES AND TOOLS

2.6.1. SOFTWARES

GALA

GALA is a freely distributed FORTRAN code. It is specifically designed for automatically determining atmospheric parameters by using the observed equivalent widths (EWs) of metallic lines in stellar spectra. It is a five-year project funded by the European Research Council, developed within the Cosmic Lab and is freely available at the project Web site. [24]

LASSO algorithm

The fundamental idea of LASSO Algorithm is to statistically detect typical wavelength positions that are significant/necessary for discriminating stellar spectra with different atmospheric physical parameters. [25]

CHORIZOS

CHORIZOS is a powerful code. This software allows one to estimate T_{eff} , $\log g$, the extinction A_V , as well as the reddening parameter R_V from multi-band colours, using a Bayesian approach. [26]

Tool for Astrophysical Data Analysis (TA-DA)

Tool for Astrophysical Data Analysis (TA-DA), is a new software aimed to greatly simplify and improve the analysis of stellar photometric data in comparison with theoretical models, and allow the derivation of stellar parameters from multi-band photometry. It is developed using the ITTVIS Interactive Data Language. [27]

Functionalities:

Integration with stellar evolutionary models.

Automatic and universal synthetic photometric engine.

Data visual quick look in comparison with models or theoretical stellar parameters.

Automatic parameter fitter.

Generative Spectrum Networks (GSN)

Many researchers design traditional artificial neural networks structures with the fluxes of the spectra as the input and the stellar atmospheric parameters as the output, for analysis of spectra. Dafonte suggested the innovative idea of inverting the inputs and outputs of the ANNs, with the parameters as inputs and the flux values as outputs. [28]

Generative Spectrum Networks can produce model spectra when a team of parameters is given.

MATLAB

MATLAB is one of the multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages. Here in this project MATLAB interface is used in plotting the graphs and extracting other properties of the star like radial velocity and others.

2.6.2. DATABASES

Belgian repository of fundamental atomic data and stellar spectra (BRASS)

The Belgian repository of fundamental atomic data and stellar spectra (BRASS) aims to provide a large systematic and homogeneous quality assessment of the atomic data available for quantitative stellar spectroscopy. BRASS compares theoretical spectrum calculations to very high-quality observed spectra of FGK-type stars in order to critically evaluate the atomic data available for over a thousand atomic lines[29]

The Spitzer Atlas of Stellar Spectra

The Spitzer Atlas of Stellar Spectra (SASS), which includes 159 stellar spectra (5 to 32 mic; $R \sim 100$) taken with the Infrared Spectrograph on the Spitzer Space Telescope. This Atlas gathers representative spectra of a broad section of the Hertzsprung-Russell diagram, intended to serve as a general stellar spectral reference in the mid-infrared. It includes stars from all luminosity classes, as well as Wolf-Rayet (WR) objects. Furthermore, it includes some objects of intrinsic interest, like blue stragglers and certain pulsating variables. All the spectra have been uniformly reduced, and all are available online. [30]

Others

Sloan Digital Sky Survey (SDSS)

Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST/Guo Shoujing Telescope)

And *Gaia*. [31]

3. DATA ANALYSIS

To utilize the spectrum data, primarily Wavelength and Intensity of Light at that particular Wavelength were taken into consideration to compute the data and obtain the said results and draw inferences such as the atmospheric composition of Stars, Redshift Factor, Radial Velocity and the Temperature of Stars.

3.1. CODE

Following MATLAB Code was used to obtain the same

```
function speed=WithTemp

a=xlsread("file_name.xlsx");

obser = size(a(:,1));

lamFirst = 3200;

lamDel = 1;

lamLast = lamFirst + (obser-1)*lamDel;

lam = (lamFirst:lamDel:lamLast)';

s = a(:,2);

loglog(lam,s,"r.-");

xlabel("Wavelength");

ylabel("Intensity");

[sHa,idx] = min(s);

lamHyd = lam(idx);

hold on

loglog(lamHyd,sHa,"rs","MarkerSize",1);

hold off

z = lamHyd/6562.8 - 1;

speed = z*299792.458

[inte,ind]=max(s);

wav=a(ind,1)
```

```
tem=(2.898*(10^7)/wav)+" K"
```

```
end
```

3.2. GRAPHS

Using Spectral Data taken from Laboratoire D'astrophysique, OMP, Toulouse, France for various Stars to compute the data.

The spectral data was taken at evenly-spaced wavelengths of 1 Å, starting from 3200 Å and going up to 9899 Å. So about 6700 readings for every Star. The graph between wavelength and intensity of light was plotted to better understand the spectral data.

Plot for Spectral Data of HD094028 Star.

Figure 13- Wavelength vs. intensity graph of star HD094028

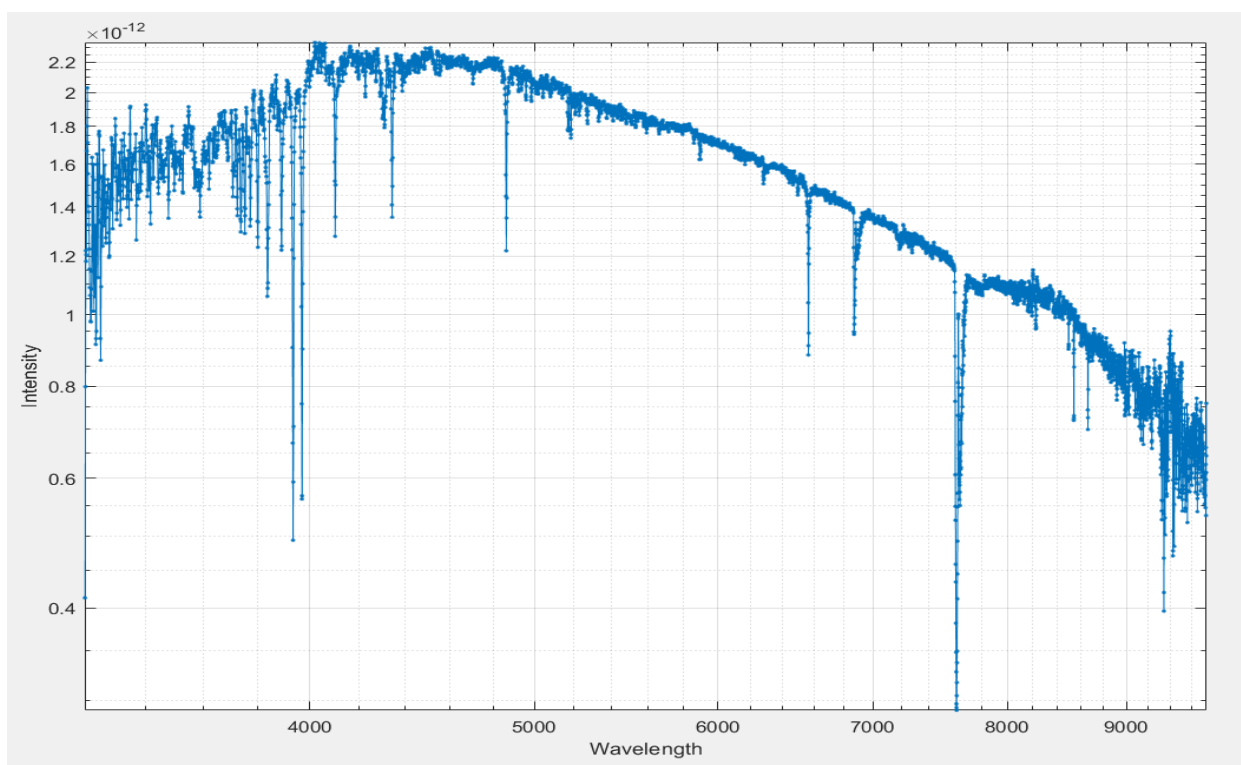
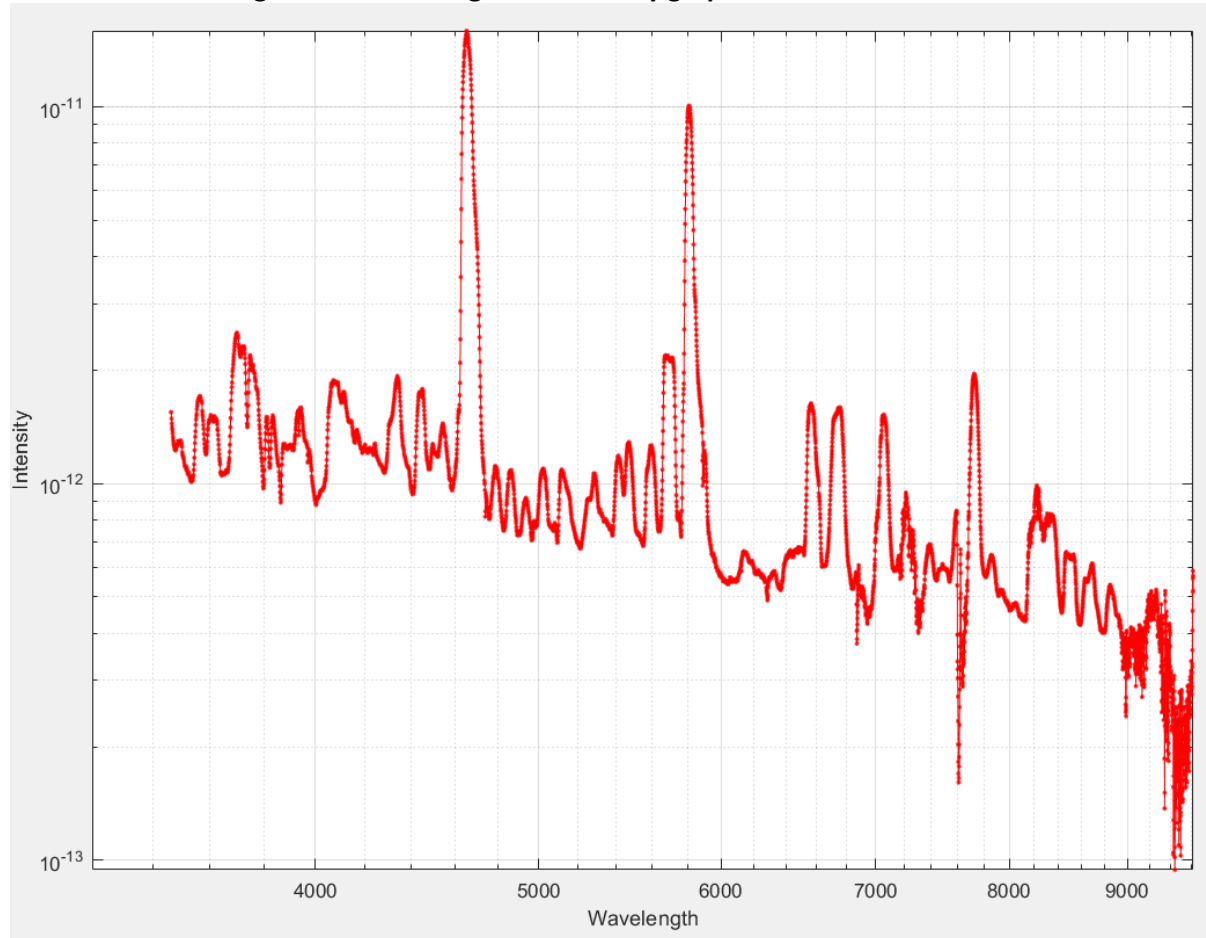


Figure 14- Wavelength vs. intensity graph of star HD092809



Here in the Spectral Data of HD94028 Star, A drop at 6566.2 \AA can be noticed, which is the Hydrogen-alpha line for this star. It can be seen that there is some difference between the theoretical Hydrogen-alpha line which is at 6562.8 \AA . The difference is small but this value can help us evaluate the Redshift Factor.

3.3. CALCULATIONS

To find the Redshift Factor, the index corresponding to the location of the Hydrogen-alpha line was taken. The laboratory value of Hydrogen-alpha line is noted to be 656.28 nm . But a certain difference in wavelengths can be observed in the spectral data of the stars. This difference can be used to measure the Redshift Factor.

$$\text{Redshift Factor } (z) = (\lambda_{\text{Ha}}/656.28) - 1$$

The speed at which the star is moving can be found by

$$\text{Speed} = z \times c$$

Where, $c = 299792.458 \text{ km/s}$ (Speed of Light)

The temperature of the Star can be found out using

$$\text{Temperature} = 2.898107\lambda_{\text{int}} = \text{max}$$

λ_{int} = max is the wavelength at which the intensity of light is maximum.

Here it was noted that the Redshift Factor was 5.1807155×10^{-4} and the speed of Star was found out to 155.3139 km/s.

To determine the atmospheric composition, the spectral data can be used to see at which wavelengths does the intensity of light fall down significantly. This implies that the Star would have certain gases or elements which absorbs light at that particular wavelength. Same as how it has been shown in the case of Hydrogen in this study.

This also shows the same method can be used for various star and to compute similar data from the same. For this, the temperature of the star was found to be 6229.5787 K.

4. RESULTS & CONCLUSIONS

4.1. RESULTS

Using the spectral data of the star HD094028, we have plotted the wavelength vs. intensity graph. As seen in Figure 15 & 16.

- About 6700 readings were taken of the star HD094028 with evenly-spaced wavelengths of 1 Å, starting from 3200 Å and going up to 9899 Å.
- The wavelength Vs. Intensity graph was plotted to calculate the redshift, radial velocity and the temperature of the star.
- The temperature of the star was found to be 6229.5787 K (using the Wien's displacement law)
- The H α - line for the star HD094028 is observed to be 6566.2 Å, whereas the theoretical value for H α line is 6562.8 Å.
- Using the information of the hydrogen alpha line, we got our red shift factor (z) = 0.00051807155.
 $z \sim 5.1 \times 10^{-4}$
- The speed of the star was found to be 155.3139 km/s.

4.2. CONCLUSIONS

- The code run on MATLAB and the graphs produced were successful with no errors or glitches.
- The theoretical and apparent Hydrogen alpha line were compared and used to calculate the redshift which is of a factor (z) = 0.00051807155.
- The redshift factor suggests that the star HD094028 is moving farther away with respect to our frame of reference.
- The speed of the star HD094028 is found to be 155.3139 km/s.

- The temperature of the star HD094028 is found to be 6229.5787 K
- Based on the temperature we can guess the star to be of the AGB type (asymptotic giant branch).
- This methodology can be used to study the elemental composition of stars and its atmosphere.

5. FUTURE SCOPE

- This study can be further extended to doing a lot more than just finding the temperature, Redshift and the speed of the star.
- Spectral data of Stars can be used to compute numerous things such as the Atmospheric Composition, Redshift Factor, Radial Velocity, Temperature of Stars, distance from the star, rotation of a star, rotation of a galaxy that the star is in, orbital motion of a star due to a planet.
- Knowing other parameters like Luminosity, colour of the star, absolute magnitude and star class. An HR diagram could be plotted which would help understanding the star classification better.
- The HR diagram could be used to study the properties of stars, stellar evolution and structure, its age, stellar radius and mass, binary system of stars, mass luminosity relationships, and chemical composition.
- Since the methodology used in this study uses Spectral Data, it does not limit it to only be used for Stars. Similar spectral data can be obtained for other celestial bodies such as exoplanets, to find their properties. Making this methodology flexible to analyse and study various celestial bodies.
- When extended to exoplanets, we can study more about an exoplanet's atmosphere by the spectroscopy methods with several databases available online of TESS, KEPLER and HST. Knowing the type of exoplanet, it is and its atmosphere, we can study the exoplanet's habitability and look at its biosignatures to comment on the possibility of life.
- Software like GALA, CHORIZOS, GSN, and TA-DA are some real good tools to help plot and understand spectra in greater detail.

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