# NSSC-2021

*National Students Space Challenge, IIT Kharagpur*

## CASE STUDY-1 (Round-1)

## *Exoplanets*

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# PROBLEM STATEMENT

## a) *Definition of Exoplanets and their classification:*

### *a) What are the criteria that classify a celestial object as a Planet?*

*In 2006, the IAU (International Astronomical Union) came up with three criterias to provide an official definition of Planet that would classify any celestial object as a Planet. Though the definition has remained controversial, it is still used as an official definition.*

*Therefore, the criterias that classify a celestial object as a Planet are:-*

1) *A planet is a celestial body that is in orbit around the sun or a central star.*
2) *A planet is a celestial body that has sufficient mass to have a nearly round shape. In other words, it has sufficient mass to assume hydrostatic equilibrium (a nearly round shape).*
3) *A planet is a celestial body that has "cleared the neighborhood" around its orbit (meaning it has cleared most of the mass from its orbital zone).*

*In 2017, a group of scientists, including Stern, proposed a new definition of planet, which they plan to submit to the IAU: "A planet is a sub-stellar mass body that has never undergone nuclear fusion and that has sufficient self-gravitation to assume a spheroidal shape adequately described by a triaxial ellipsoid regardless of its orbital parameters."*

### *b) What are the different types of exoplanets that have been discovered? Describe them on the basis of their distinct physical characteristics.*

*Four types of exoplanets have been discovered until now, namely: Gas giant, Neptunian, super-Earth and terrestrial.*

- ***Gas Giants:*** *These are planets like Jupiter and Saturn– mostly composed of hydrogen and helium gas. They don't have hard surfaces and instead, have swirling gases above a solid core. Gas giant exoplanets can be much larger than Jupiter, and much closer to their stars than anything found in our solar system. Gas giants nearer to their stars are often called "hot Jupiters." These large planets make such tight orbits that they cause a pronounced "wobble" in their stars, tugging their stellar hosts this way and that, and causing a measurable shift in the spectrum of light from the stars.*
- ***Neptunian Planets:*** *Neptunian exoplanets are similar in size to Neptune and Uranus in our solar system. Neptunian planets typically have hydrogen and helium-dominated atmospheres with cores of rock and heavier metals. Uranus and Neptune are often referred to as "ice giants", thus, Neptunian exoplanets are also called ice-giants. Neptunian exoplanets often have thick clouds that block any light from coming through, hiding the signature of the molecules in the atmosphere.*

- ***Super-Earths:*** *Super-Earths are planets whose mass ranges from 2-10 times the mass of the Earth. They are different from planets in our solar system, as in, are more massive than Earth yet lighter than ice giants like Neptune and Uranus, and can be made of gas, rock or a combination of both. "Super-Earth" only refers to the mass of the planet and has nothing to do with its similarity to Earth (although it can be similar).*
- ***Terrestrial Planets:*** *Terrestrial planets are rocky planets like Earth, Mars, Mercury or Venus. They are mostly made of rock or iron and have a solid or liquid surface and they may or may not be similar to Earth. Planets between half of Earth's size to twice its radius are considered terrestrial. Terrestrial planets (Earth sized and smaller) are rocky worlds, composed of rock, silicate, water and/or carbon. [NOTE:- Larger terrestrial exoplanets (those at least twice as massive as Earth) are classified as super-Earths].*

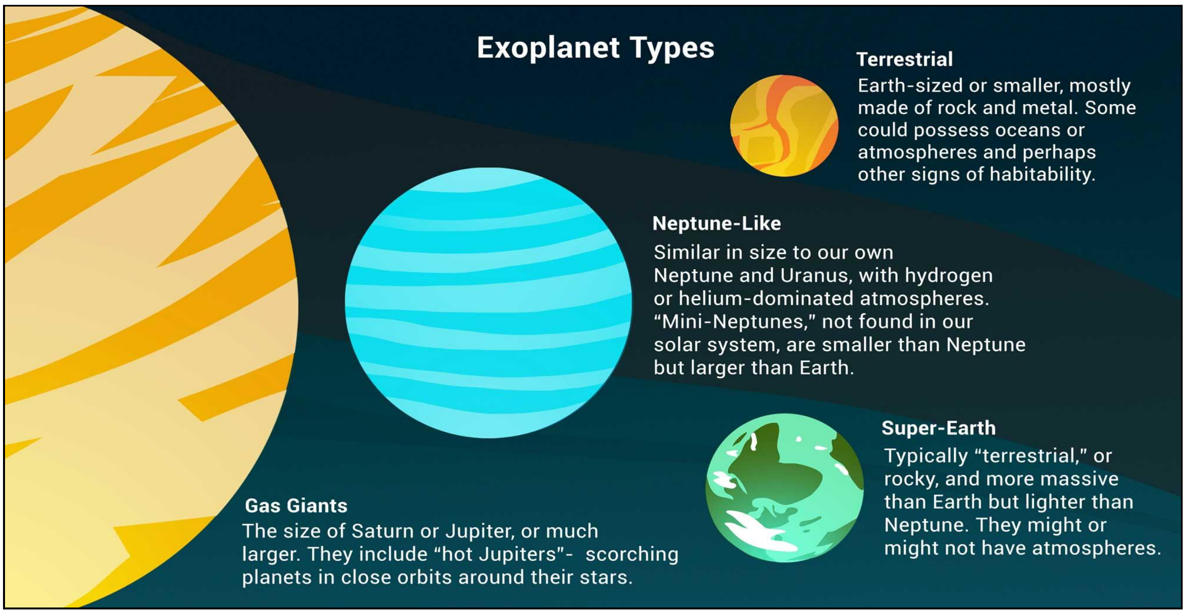



***Image Credit:-*** *[https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/overview/](https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/overview/)*

### *c) What are rogue planets? What are the possible ways in which these might be formed?*

*Rogue Planet is a celestial object that is classified as a planet but does not orbit a star or simply we can say, it is a planet without a host planetary system. They are also known as free-floating planets.*

***The possible ways in which the rogue planets might be formed:-***

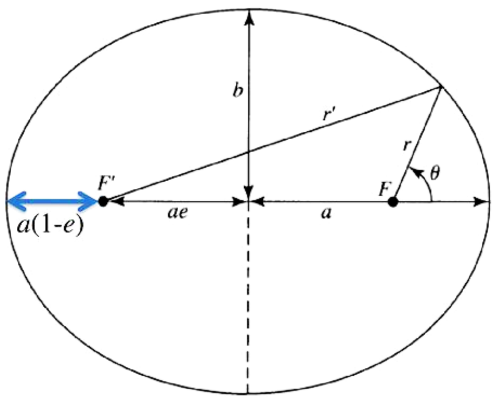
1) *Rogue planets could form in the gaseous disks around young stars, similar to those planets still bound to their host stars. After formation, they could later be ejected through interactions with other planets in the system, or even fly-by events by other stars. Sometimes collisions and close encounters can fling (throw) a planet clear out of the gravitational grip of its parent star.*
2) *Rogue planets may also form in isolation from clouds of gas and dust, similar to how stars grow. A small cloud of gas and dust could collapse to form a central planet instead of a star, with moons instead of planets surrounding it.*

*d) In the dataset provided, consider the exoplanet HD 10697 b. (Data entry no. 13) Formulating it as a two-body problem, describe its orbit around its host star and find out the maximum and the minimum speed of the planet w.r.t the barycentre?*

***Using Dataset (python data analysis) we got to know following details for given exoplanet HD 10697 b:-***

*Mass (m1) of exoplanet= 6.837 Jupiter mass = 0.006526521 M⊙ (M⊙=Solar mass)*
*a (semi-major axis)=2.14 A.U.*
*e (eccentricity)=0.1043*
*Inclination (θ)=69.0 Degrees*
*Host Star=HD 10697*
*Star Mass (m2)=1.13 M⊙ (M⊙=Solar mass)*
*M=m1+m2 = 1.136526521 M⊙*

***Orbit of exoplanet around its host star can be defined by geometry of ellipse orbit:-***




$$r = \frac{a\left(1 - e^2\right)}{1 + e\cos\theta}$$

$$(0 \leq e < 1)$$

$$e = \sqrt{(1 - b^2/a^2)}$$

*After putting all the values in formula of r :-*

$\mathbf{r = a(1\text{-}e^2)/(1+e\cos(\theta))}$ *-> eq(1)*

*r (distance between host star and exoplanet for given θ)= 2.040452993661945 A.U.*

***For Speed (v) of exoplanet:-***

$v^2$**=GM((2/r) – (1/a))** *,where G is gravitational constant.*

*So from the above equation we can say, for max speed ($v_{max}$) r should be minimum (means θ=0 Degrees in eq(1)) and similarly, for min speed ($v_{min}$) r should be maximum (means θ=180 Degrees in eq(1)).*

*Therefore after putting required values for vmax and vmin we get,*

$v_{max}$=*2.142410908086144 (√G) M⊙ /A.U.*

$v_{min}$= *1.7377138914903185 (√G) M⊙ /A.U.*

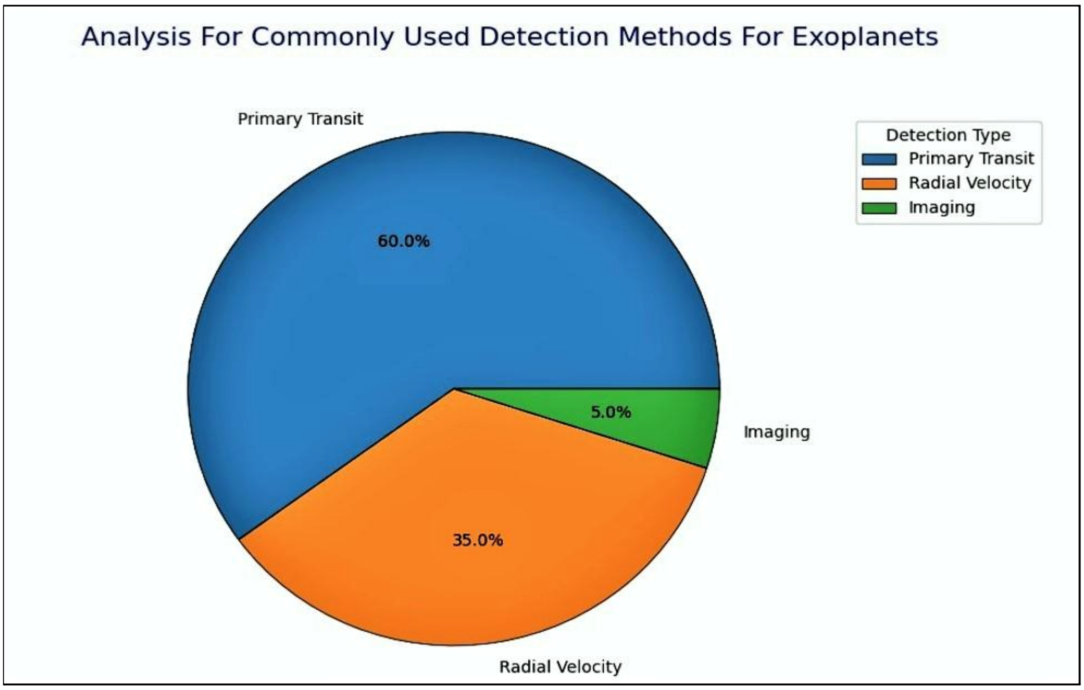
*where, G is Gravitational constant, M⊙ is solar mass and A.U. is astronomical unit.*

## *b) Methods used for detection of Exoplanets:*

*a) Refer to the dataset, and obtain the two most commonly used detection methods for exoplanets. Describing the principle for each, highlight what classes of planets are more likely to be discovered from each method. Compare*

***their limitations.***

*After analysing the given dataset using python data analysis we concluded that two most commonly used detection methods are Primary Transit and Radial Velocity. This conclusion is shown below with help of a pie chart:-*




- ***Primary Transit:*** *Transit method is a photometric method that aims to indirectly detect the presence of one or more exoplanets in orbit around a star. Most known exoplanets have been discovered using the transit method. "Primary" transit occurs when a planet passes between a star and its observer. This method measures the periodic dimming of the star caused by a planet passing in front of the star along the line of sight from the observer. With the transit method, it is easier to detect Giant Planets, Super-Jupiters, Super-Earth and Mini-Neptunes orbiting close to their parent star than other planets as these planets catch more light from their parent star. Mars-size planets may also be detected in Mercury-like orbits with four years of observing. Transits reveal an exoplanet not because we directly see it from many light-years away, but because the planet passing in front of its star ever so slightly dims its light. This dimming can be seen in light curves – graphs showing light received over a period of time. Below figure will help to understand this point.*

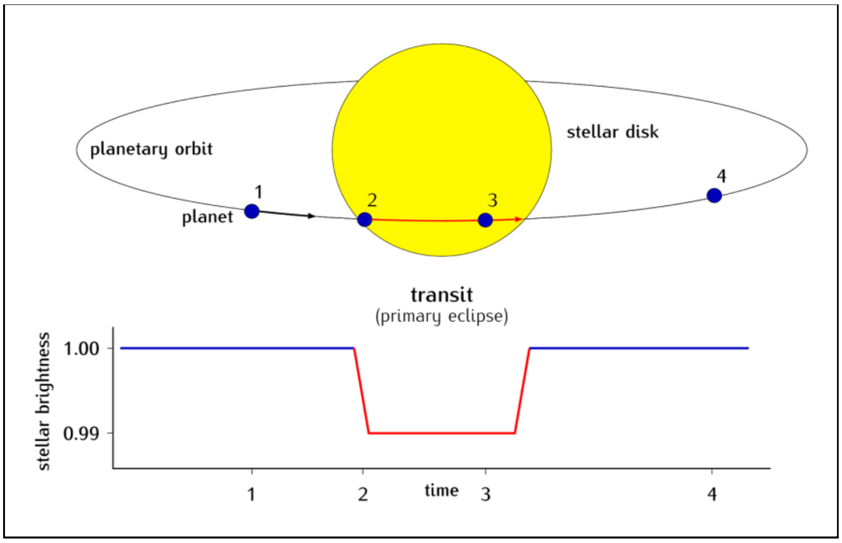



*Image Credit:* *https://www.pngitem.com/middle/hiboiwJ_the-transit-method-transit-diagram-of-exoplanet-hd/*

***[Note:-** Stellar variability on the time scale of a transit limits the detectable size to about half that of Earth (lower limit) for a 1 A.U. orbit about a 1 M⊙ star (M⊙ is solar mass). Planets with orbital periods greater than two years are not readily detectable, since their chance of being properly aligned along the line of sight to the star becomes very small.**]***

- ***Radial Velocity:*** *The radial-velocity method for detecting exoplanets relies on the fact that a star does not remain completely stationary when it is orbited by a planet. A star with a planet will move in its own small orbit in response to the planet's gravity. It is an indirect method for finding extrasolar planets from radial-velocity measurements via observation of Doppler shifts in the spectrum of the planet's parent star. The radial velocity signal is distance independent, but requires high signal-to-noise ratio spectra to achieve high precision, and so is generally used only for relatively nearby stars. Super-Jupiters are most likely to be discovered by this method. The radial velocity technique is able to detect planets around low-mass stars, such as M-type stars (0.08-0.45 M⊙). This is due to the fact that low mass stars are more affected by the gravitational tug of planets and also because such stars generally rotate more slowly leading to more clear spectral lines. This method is also known as Doppler spectroscopy.*

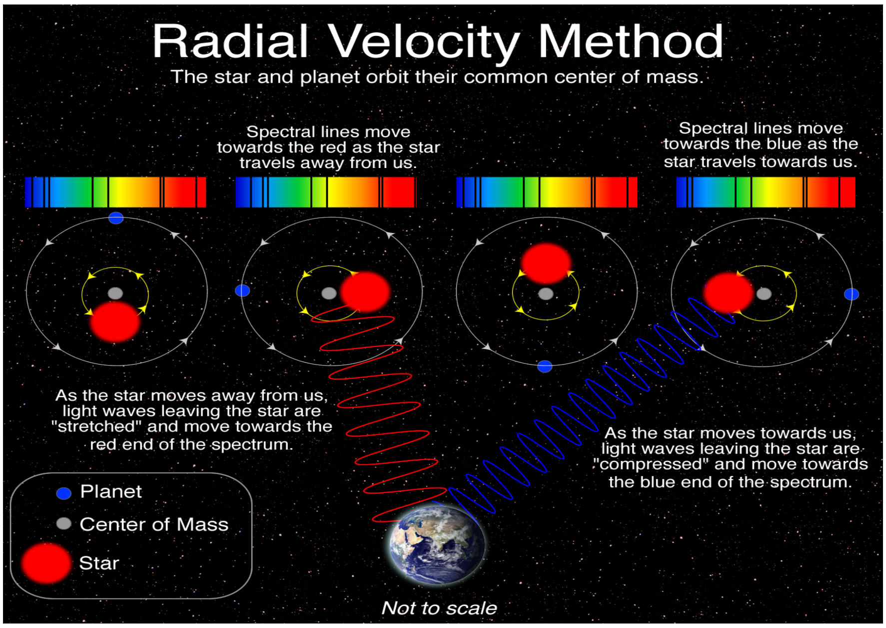



**Image Link:** [https://www.universetoday.com/138014/radial-velocity-method/](https://www.universetoday.com/138014/radial-velocity-method/)

★ ***Comparison of above two mentioned detection methods limitations:-***

- *Radial velocity method is ideal for ground-based telescopes because (unlike for transit photometry) stars do not need to be monitored continuously.*
- *The main difficulty with the transit method is that in order for the photometric effect to be measured,* ***a transit must occur****. Not all planets orbiting other stars transit their stars as seen from Earth; a distant planet must pass directly between its star and Earth. Thus, in such cases we prefer the radial velocity method which is done via observation of Doppler shifts in the spectrum of the planet's parent star.*
- *The Radial velocity method cannot accurately determine the mass of a distant planet, but only provide an estimate of its minimum mass while the Transit method can accurately determine mass of a distant planet.*
- *Transit method is not used for low-mass planetary systems while the radial velocity method can be used there.*
- *The Radial velocity method is not very useful and trustworthy in the case of multi-planet, multi-star systems as this technique is primarily based on the splitting of lights from the star and teasing apart the individual planet or star signals is more difficult.*
- *Giant outer planets that produce a transit signal of 1% but have orbital periods greater than 2 years can be followed up with Doppler spectroscopy (radial velocity method) since, planets with orbital periods greater than two years are not readily detectable as their chance of being properly aligned along the line of sight to the star becomes very small.*
- *Although the transit method has surpassed the radial velocity method in terms of sheer number of exoplanet discoveries largely due to NASA's Kepler mission, the radial velocity method still plays an important role in transit discoveries by providing the  radius of the planet. Without this, one cannot calculate the bulk density of the planet needed to determine its structure.*

***b) How are these classes of planets differentiated based on their physical parameters (as given in the dataset)? Justify by mentioning which parameters are used and how these differentiate between the two classes of planets as detected from respective methods.***

- ***Giant Planets:*** *All massive planets in outer space which have masses more or several times more than earth mass are considered giant planets. They are usually primarily composed of low-boiling-point materials (gases or ices), rather than rock or other solid matter, but massive solid planets can also exist.*
- ***Super-Jupiter:*** *Super-Jupiter, also known as super-jovian planet, is a classification of planets with mass ranging from 2 to 13 Jupiter masses. Super-Jupiters are gaseous with no solid surface, but they have rock/iron cores surrounded by three layers of mantle.*
- ***Mini-Neptune****: A mini-Neptune (sometimes known as a gas dwarf) is a planet less massive than Neptune but resembles Neptune in that it has a thick H–He (Hydrogen-Helium) atmosphere, probably with deep layers of ice, rock or liquid oceans (made of water, ammonia, a mixture of both, or heavier volatiles). These planets have masses several to 10 or more times that of Earth but below 17.1 Earth mass, plus a radius more than 1.6 times that of Earth.*
- ***Super-Earth****: It is also known as super-terran planet, is a classification of planets with mass ranging from 2 to 10 Earth masses or 0.0063 to 0.0315 Jupiter masses. They're generally between 1.2 and 2 Earth-radii and have mass up to four times the mass of Earth.*

★ ***The physical parameters by help of which we differentiate between classes of planets as detected by respective methods are:-***

1. *Mass of Planet and Radius of planet*
2. *Period (which tells revolution period of planet around its star)*
3. *Semi-major axis and eccentricity (which are used to define orbit of planet)*
4. *Mass of Star*

- *Star (orbited by the exoplanet) that having mass which fall unders M-type star (0.08-0.45 M☉) category or low mass star category and by knowing mass and radius of exoplanet which falls under super-jupiter category, we can say exoplanet (orbiting that star) was most probably detected by radial velocity method.*
- *By finding the orbit of the planet (using semi-major axis and eccentricity from the dataset) which falls under or upto 1A.U. and by knowing mass and radius of planet from dataset which falls under super-jupiter, super-earth, mini-neptune or giant planet category and by knowing period of planet (using dataset) which is upto two years then we can say, exoplanet was most probably detected by Primary Transit method.*

***[Note that both these methods require the planets to be big for us to detect.]***

***c) Other than the above two, describe two more methods that are applied or could be used for detection. When are these methods feasible?***

- ***Gravitational Microlensing:*** *The gravitational microlensing method allows planets to be found using light from a distant star. The path of the light from this star will be altered by the presence of a massive lens – in our case, a star and a planet. Thus, for a short period of time, the distant star will appear brighter. In accordance with Einstein's Theory of General Relativity, gravity causes the fabric of spacetime to bend. This effect can cause light affected by an object's gravity to become distorted or bent. It can also act as a lens, causing light to become more focused and making distant objects (like stars) appear brighter to an observer. This effect occurs only when the two stars are almost exactly aligned relative to the observer (i.e. one positioned in front of the other).*
    - *Microlensing is the only known method capable of discovering planets at truly great distances from the Earth.*
    - *This method is capable of finding the smallest of exoplanets.*
    - *Microlensing is also the only proven means of detecting low-mass planets in wider orbits, where both the transit method and radial velocity are ineffective.*

*Below figure will help to understand this method more better:-*

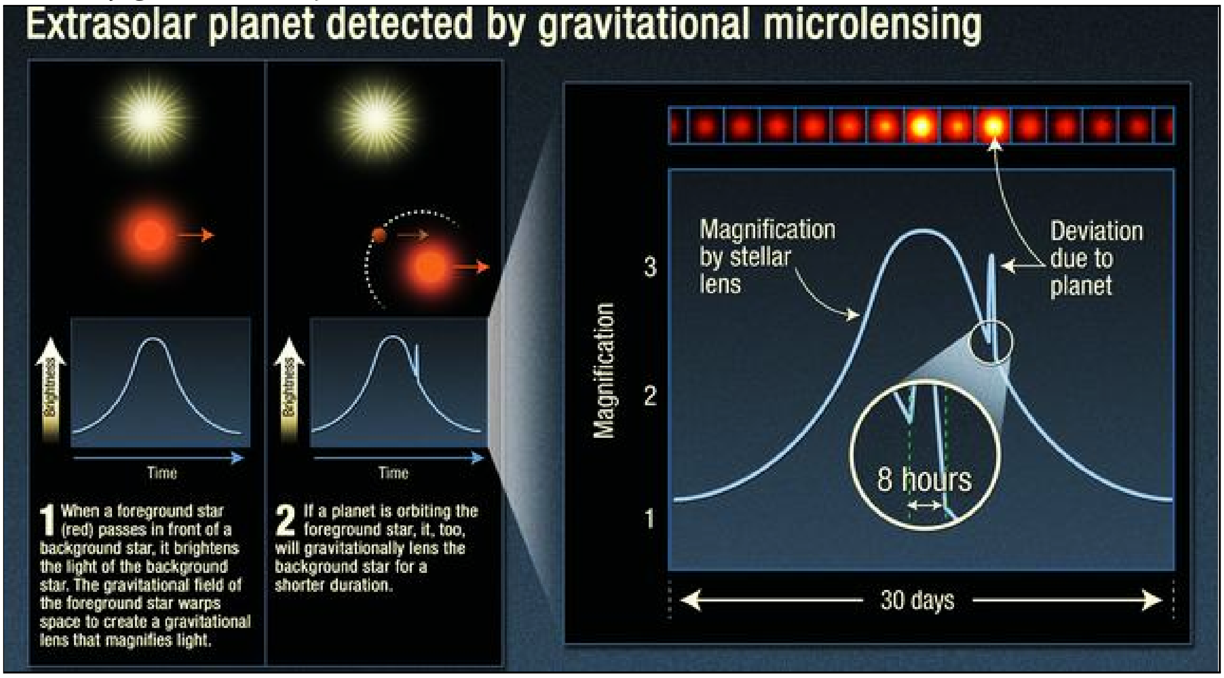



*Image Link: [https://www.universetoday.com/138141/gravitational-microlensing-method/](https://www.universetoday.com/138141/gravitational-microlensing-method/)*

- ***Direct imaging:*** *Direct Imaging consists of capturing images of exoplanets directly, which is possible by searching for the light reflected from a planet's atmosphere at infrared wavelengths. The reason for this is because at infrared wavelengths, a star is only likely to be about 1 million times brighter than a planet reflecting light, rather than a billion times (which is typically the case at visual wavelengths). Direct Imaging works best for planets that have wide orbits and are particularly massive (such as gas giants).*

- *One of the most obvious advantages of Direct Imaging is that it is less prone to false positives.*
- *Direct Imaging allows astronomers to actually see the planets they are searching for.*
- *It is very useful for detecting planets that are positioned "face-on", meaning that they do not transit in front of the star relative to the observer.*
- *This method works for planets that are very far from their stars, so an orbit might take hundreds or thousands of years for a planet discovered by this method.*

**c) *Spectroscopy of Exoplanets: The detection methods can only give some physical information about the planet (such as its mass, radius, orbital period, distance from the star, range of temperature, etc). But to determine its composition or the possibility of it to support life, we need to learn about its surface and atmosphere. This is where spectroscopy comes in.***

***a) What is meant by transmission and reflectance spectroscopy? How can these be used to determine the composition of the exoplanet's atmosphere? How are these two methods different?***

*A background light source is required for transmission spectroscopy. Light from the source that has travelled through the object of interest on its way to the observer, is compared with the light received directly from the source. As a planet passes in front of its star, light from the star has to travel through the atmosphere of the planet and this transmitted light carries information about the atmosphere, which can be understood with reference to the light received directly from the star. The resulting spectrum would depend, for example, on the thickness of the planet's atmosphere and the absorption coefficient of the elements constituting the atmosphere of the planet.*

*In reflectance spectroscopy, the light that has been reflected (or scattered) from a solid, liquid, or gas medium, is studied. Photons that are reflected from surfaces or refracted through a medium are said to be scattered. Scattered photons can then be detected and measured. In the case of stars, the light gets reflected from the surface of the planet and is received by the observer alongwith the direct light from the star.*

*During a primary eclipse, i.e. when the planet is crossing the stellar disk, the stellar spectrum picks up features of the planet's atmosphere, leading to a combined spectrum. The reflectance or transmission spectrum of a planet contains information about the composition of the atmosphere. The absorption lines or bands would reveal the main chemical constituents and would help to analyse the probability of habitability on the given planet.*

*Briefly before the planet is behind the star during a secondary eclipse, the stellar light is reflected by the planet's dayside and produces the reflectance spectrum.*

*Both transmission and reflectance spectra contain information about the planet's atmospheric composition but if the atmosphere is optically thin, the reflectance spectrum also contains features of the surface.*

***b) Why is a spectral analysis of exoplanets so difficult as compared to stellar spectroscopy?***

*The signals from the exoplanets are tiny in comparison to the stellar flux which is overwhelmingly bright making it extremely challenging to directly observe the spectrum of an exoplanet. Thereby, the light transmitted or reflected from the exoplanet is buried inside the spectrum of the host star. Exoplanets are typically located at sub-arcsecond orbital separations and are thousand to million times less bright than the stars. Therefore, to be able to detect such faint sources, big telescopes are required to maximize photons received.*

***c) Briefly elaborate on spectroscopic errors that are typically observed from the exoplanet's spectra, such as telluric contamination. How are these corrected?***

*Ground based observations for exoplanet detection have to account for errors due to atmospheric turbulence that adds systematic noise to light curves and thermal background noise in the infrared. Other systematic errors could be:*

1. *Telluric Noise*

   *The light that can be absorbed and emitted by earth's atmospheric constituents, like water vapor and oxygen, lead to telluric (earth borne) contamination.*

   *Correction: One approach is to use comparison stars to correct for systematic trends in the target light curve. The path of their flux traverses similar parts of the Earth's atmosphere, so their light curves exhibit nearly identical systematic trends as the target. The target light curve can then be divided by the sum of the comparison star light curves to remove systematics.*

2. *Photon Noise*

   *Stars emit $N \pm \sqrt{N}$ photons per unit time. The $\sqrt{N}$ noise (photon noise), arises because each atom in the star emits a photon with some small probability per unit time. Photon noise is the fundamental limit on the precision of a light curve.*

   *Correction: The only way to improve the precision on a planet's spectrum is to stack many observations together*

3. *Variable Illumination*

   *The position of the spectrum on the detector can shift slightly over the course* *of an observation, either due to pointing drift or changes in telescope focus. These shifts cause light to fall on pixels that may have different sensitivity. Correction: This effect can sometimes be corrected with a polynomial fit.*

4. *Background Stars*
   *Most stars have one or more bound companions. If the companion flux is blended with that of the host star, it dilutes the planet signal.*
   *Correction: High contrast imaging is needed to detect close companions, and should be obtained for systems that are targets for atmosphere characterization.*
5. *Stellar Activity*
   *Variations in star spot coverage are also a source of bias in transit depth Measurements.*
   *Correction: To correct transit depths taken at different epochs, one can obtain photometric monitoring of the host star to estimate changes in s and correct the depths with the above scale factor*
6. *Nightside emission from the planet*
   *For the hottest planets, thermal emission from the nightside may contribute significant flux during the transit.*
   *Correction: To correct for nightside flux, the transit depths should be multiplied be a factor* $(1 + \frac{F_P}{F_S})^{-1}$ *, where Fp is the planet nightside flux and Fs is the stellar flux.*

**d) Circumstellar Habitable Zone (CHZ) : The Circumstellar habitable zone is the zone around a star where a habitable environment is considered possible. Although being in the CHZ is one of the factors in making a planet habitable, Scientists argue that it is only one of the many factors that contribute to life.**

**a) What are the other possible factors that can contribute to life on the exoplanet?**

*Possibility of life on exoplanets is linked to the presence of surface liquid water. Whether or not an exoplanet is able to maintain liquid water on its surface is due to a complex interplay of planetary, stellar, and planetary system characteristics over the planet's lifetime. Although a planet's habitability depends critically on the effect of stellar type and planetary semimajor axis on climate balance, many additional factors can also impact habitability. Processes which can modify a habitable planet's environment include photochemistry; stellar effects on climate balance; atmospheric loss; gravitational* *interactions with the star, moons, other planets and minor bodies; and galactic phenomena.*

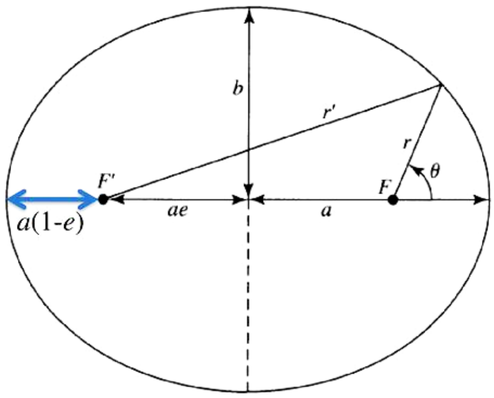
***b) What are the cases that the CHZ region is dependent on the spectral class of the host star?***

*Stars being the dominant force in any planetary system, habitable zones would strongly depend on the spectral class of stars. Habitable zones, potentially capable of hosting life-bearing planets, are wider for hotter stars. Smaller, dimmer red dwarfs, the most common type in our Milky Way galaxy, have much tighter habitable zones. Planets in a red dwarf's comparatively narrow habitable zone, which is very close to the star, are exposed to extreme levels of X-ray and ultraviolet (UV) radiation, which can be up to hundreds of thousands of times more intense than what Earth receives from the Sun.*

***c) To determine the CHZ around a star, one should first consider the power output from the star itself - its Luminosity which can be obtained using Stefan's Law on the blackbody model of star. Now we define the CHZ around a star as the region where the stellar radiative flux (S) at a distance R ( = Luminosity / Surface area of sphere of radius R) is within the range -***

$$0.01\,\frac{L_\odot}{AU^2} < S < 0.32\,\frac{L_\odot}{AU^2}$$

***Where L⊚ is Solar Luminosity ($3.828\times10^{26}$ W). This gives the inner and outer radius of the Habitable Zone of each Star. Using the modelling as stated, determine which of the exoplanets in the given dataset fall into the habitable zone.Which of them lies closest to Earth? Present all the findings in a tabular form.***




$$r = \frac{a\left(1 - e^2\right)}{1 + e\cos\theta}$$

$$(0 \le e < 1)$$

$$e = \sqrt{(1 - b^2/a^2)}$$

$r_{min}$ *corresponds to the minimum distance of the planet from the star which happens at* $\theta = 0°$

$r_{max}$ *corresponds to the maximum distance of the planet from the star which happens at* $\theta = 180°$

*Luminosity of the star is given by*

$$L = \sigma A T^4$$

*where*
*σ is Stefan-Boltzmann constant*
*A is the surface area of the star*
*T is the effective temperature of the star*

*The stellar flux at a distance r from the center of the star would be given by*

$$\frac{L}{4\pi r^2}$$

*The given limits for the habitable zone would then correspond to the following two limits on the radial separation from the star:*

$$\frac{L}{4\pi R_{max}^{2}} = 0.01$$

$$\frac{L}{4\pi R_{min}^{2}} = 0.32$$

*where L is in units of Solar Luminosity*

*To find the candidates which fall in the CHZ of their host stars, we looked for planets whose $r_{min}$ or $r_{max}$ lies between the allowed radius of habitable zones, namely, $R_{min}$ and $R_{max}$.*

*We found only one such candidate, with the following values of the distances.*

| | target_name | r_min | r_max | R_min | R_max |
|---|---|---|---|---|---|
| **12** | HD 10697 b | 1.916798 | 2.363202 | 0.831474 | 4.703529 |

*(The above screenshot is the result we obtained on running the following code on our dataset.)*

```
L=df['star_lum(Solar Luminosity)']
R_max=pd.DataFrame(pow(L/(4*3.1415*0.01),1/2))
R_min=pd.DataFrame(pow(L/(4*3.1415*0.32),1/2))
R_=pd.merge(R_min,R_max,left_index=True, right_index=True)
R_.columns = ["R_min","R_max"]
df2=pd.merge(r_all,R_,left_index=True, right_index=True)
new = df2[((df2.r_min > df2.R_min) & (df2.r_min < df2.R_max)) | ((df2.r_max > df2.R_min) & (df2.r_max < df2.R_max))]
new
```

## *REFERENCES:-*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