Exoplanets and Earth-like exoplanets

Our ancients knew about the solar system planets for quite a long time. They discover Mercury, Venus, Mars, Jupiter and Saturn by looking at them in the sky and monitoring their motion with the rest of the stars. Initially, they counted Earth's moon and Sun as planets along with other five planets (Mercury, Venus, Mars, Jupiter and Saturn). Everything was thought to be rotating around the Earth until the 16th century when Nicolaus Copernicus gave the model where the Sun was placed at the centre of the known universe, and the Earth revolved around it. By the 17th century, astronomers, aided by the invention of the telescope, discovered outer planets such as Uranus, Neptune & Pluto. In 2006 the International Astronomical Union (IAU) demoted Pluto from its position as the ninth planet from the Sun to one of five dwarf planets.

In 1992, the discovery of two exoplanets around the pulsar PSR B1257+12 using pulsar timing was announced by two astronomers, Aleksander Wolszczan and Dale Frail. These were the first confirmed exoplanets, although they were not orbiting a typical main-sequence star (stars which burn hydrogen in their core). Later in 1995, the first exoplanet was discovered around sun-like stars called 51 Pegasi b by Michel Mayor and Didier Queloz (they received the Nobel Prize in 2019 for that discovery). Since then, nearly 5300 exoplanet systems have been known/confirmed worldwide. With all these discoveries, exoplanetary science opens a window to seek answers to various human quests, such as: How diverse are the planets? Is there any life outside the Solar System?

The recent definition of exoplanets is as follows: objects with true masses below the limiting mass for thermonuclear fusion of deuterium (i.e. 13 Jupiter masses for objects revolving sun-type composition) that orbit stars, brown dwarfs or stellar remnants.

There are several methods used to detect exoplanets. Here are some of the main techniques:

1. Direct Imaging: This is the only method which involves the effort to detect and study exoplanets from the light emitted or scattered by the planets themselves. Direct imaging involves capturing actual images of exoplanets. In this method, coronagraphs are used to block the light from the host star so that emissions from the planet can be detected (see figure 1). In this technique, the brightness ratio between the planet and the host star depends on the planet's size, the distance between the planet and the star, and the scattering characteristics of the planet's surface. The few planets that have been detected by direct imaging are HR8799 , HD 106906 b.

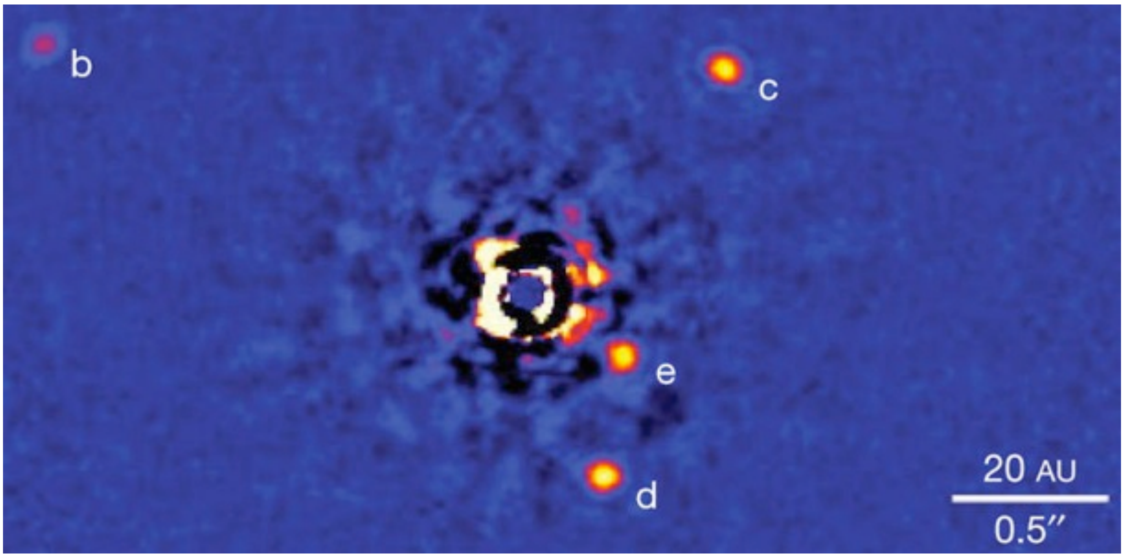

Figure 1 : HR8799 direct imaging planet detections Credit: Marois et al (2010).

Advantages of the Direct Imaging Method:

i. Direct imaging allows astronomers to capture actual images of exoplanets. This provides direct evidence of the planet's existence and offers valuable information about its characteristics, such as its size, color, and orbital position.
ii. With the help of direct images one can explore planet's atmospheric properties, including the presence of clouds.
iii. This technique is very effective in detecting large, young exoplanets. These planets are often located farther away from their host stars and have larger separations, making them more amenable to direct detection.
iv. Using this technique one can collect the planet's spectrum directly, which can be used to analyze its composition and atmospheric properties.

Disadvantages of the Direct Imaging Method:

i. Direct imaging is challenging because exoplanets are significantly fainter than their host stars, making their detection difficult. The contrast ratio between a star and its planet can be as extreme as a billion to one or more, depending on the separation and properties of the system.
ii. This method is most effective for detecting young and massive planets located farther away from their host stars. This method is biased towards a specific population of exoplanets, potentially missing smaller planets or those in closer orbits.

2. **Transit Method:** The majority of exoplanets have been discovered using this technique. This method only works for star-planet systems that have orbits aligned in such a way that, when the planet is between the earth (observer) and the host star, the planet will pass through in front of the host star, temporarily blocking some of the light from the star once every orbit. This blocking of light will be shown in the photometric measurement of the star. This is called a transit event, as shown in Figure 2 below. By monitoring these periodic changes in brightness, scientists can infer the presence of an exoplanet and gather information about its size, orbit, and other characteristics.

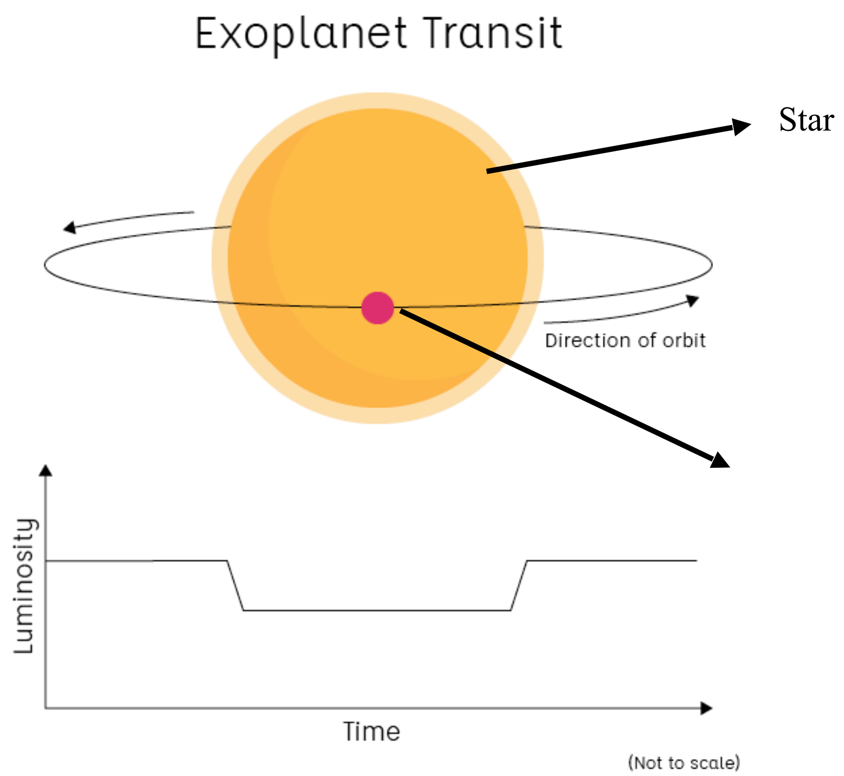

Figure 2 : Example of an exoplanet transit. Credit: LCO

Advantages of the Transit Method:

i. This method is sensitive to detecting relatively small exoplanets. By observing the transit. This sensitivity has led to the discovery of numerous exoplanets in a wide range of sizes, such as planets bigger than our Jupiter and planets including Earth-sized.

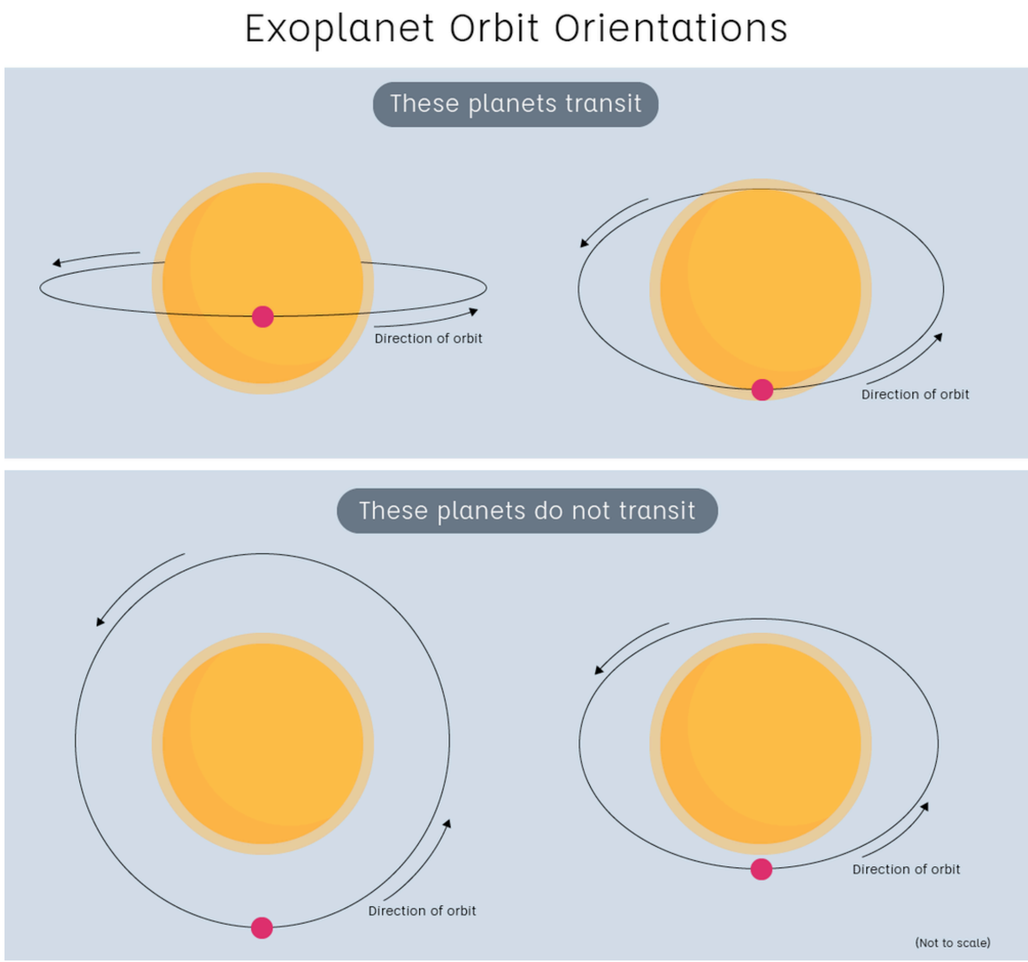

Figure 3 : Examples of different exoplanet orbit orientations, showing exoplanets that do transit and ones that don't. Credit: LCO

ii. During transit, some of the star's light passes through the exoplanet's atmosphere, leaving a signature in the star's spectrum. By analyzing this light, scientists can gain insights into the composition and properties of the exoplanet's atmosphere, such as the presence of certain molecules. This provides valuable information for studying exoplanetary atmospheres and their potential habitability.
iii. By observing a large number of stars and monitoring their brightness over time, astronomers can estimate the occurrence rates of different types of exoplanets. This statistical approach helps us understand the prevalence and diversity of exoplanets in the galaxy.

Disadvantages of the Transit Method :

i. The transit method is most effective when the exoplanet's orbit is aligned in such a way that it transits across the face of its host star as viewed from Earth. This means the method is biased towards detecting exoplanets in systems with orbits that are edge-on relative to us (see Figure 3). Exoplanets in systems with inclined or non-transiting orbits may be missed by the transit method.
ii. While the transit method provides information about the size of an exoplanet, it does not directly determine its mass. Additional follow-up observations, such as the radial velocity method, are often needed to measure the planet's mass and confirm its existence.
iii. The transit method can sometimes produce false positives, where other astrophysical phenomena or instrumental effects mimic the signature of a planet's transit. Careful analysis and follow-up observations are necessary to confirm the presence of an exoplanet and rule out false positives.

3. **Radial Velocity Method:** This is also known as the Doppler spectroscopy method. This technique detects exoplanets by observing the tiny wobbles in a star's motion caused by the gravitational pull of an orbiting planet. As the planet moves around the star, it exerts a gravitational force on the star, causing it to undergo slight velocity shifts. This shift in the velocity of a star makes it appear bluer or redder (see Figure 4). By measuring these bluer or redder shifts in the star's spectrum, one can deduce the presence of an exoplanet and determine its mass and orbit.

Advantages of the Radial Velocity Method :

i. Using RV method, one can determine the mass of the exoplanets directly.
ii. The RV method is sensitive to a wide range of exoplanets, including both massive gas giants and smaller rocky planets. This makes it suitable for studying the overall population of exoplanets.
iii. The RV method, along with the transit method, helps to confirm/verify the existence of exoplanets and gather additional information about their properties. Combining the data from both methods can give more accurate measurements of the exoplanet's mass, radius, and orbital characteristics.

Disadvantages of the Radial Velocity Method:

i. While the RV method provides valuable information about an exoplanet's mass and orbital parameters, it does not directly measure its size or composition. Additional observations or complementary methods are required to determine these characteristics.
ii. The RV method is more sensitive to detecting exoplanets with short orbital periods, particularly those close to their host stars. This is because the

gravitational tug on the star is more significant in such cases, resulting in a larger radial velocity shift. This bias can make it challenging to detect planets with longer orbital periods or those located farther from their host stars.

iii. The RV measurements can be affected by various factors, such as stellar activity, instrumental noise, and other astrophysical phenomena. These factors can produce false signals that mimic the signature of an exoplanet.

iv. The RV method is less sensitive to detecting low-mass exoplanets, particularly those similar in mass to Earth, due to their smaller gravitational influence on their host stars and the limitation of current instruments.

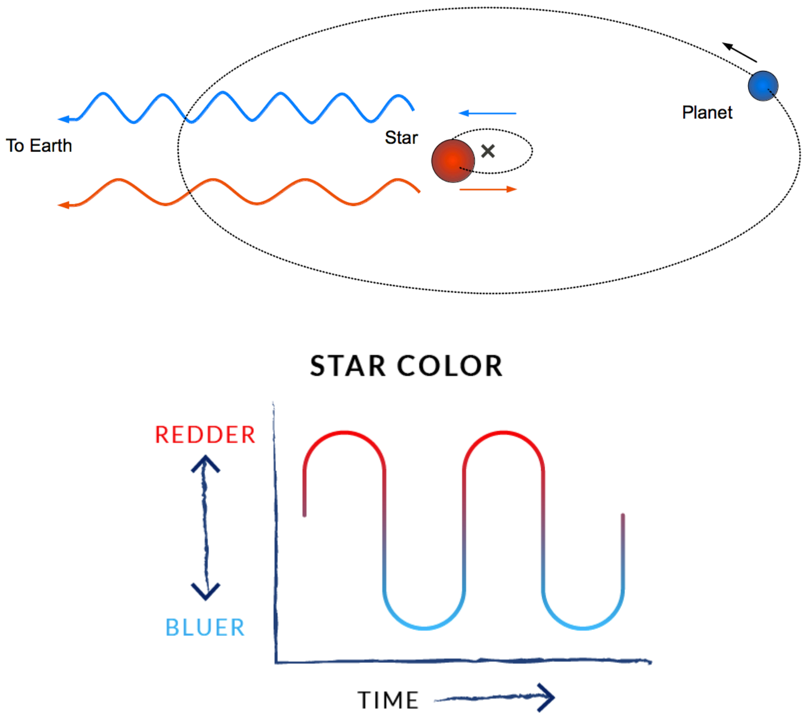

Figure 4 : Illustration showing how the radial velocity method (also known as Doppler spectroscopy) works.

The other two indirect methods to detect the exoplanets are :

1. **Gravitational Microlensing:** This method utilizes the gravitational bending of light to detect exoplanets. When a star with an exoplanet passes in front of a background star, the star's gravity acts as a lens, magnifying and brightening the light from the background star. By observing this change in brightness, astronomers can deduce the presence of the exoplanet.

2. **Astrometry:** Astrometry involves measuring a star's precise position and its motion to infer the presence of an exoplanet. As a planet orbits its host star, it induces a small back-and-forth wobble in the star's position. By monitoring this motion, astronomers can determine the presence of an exoplanet and estimate its mass and orbit. Astrometry is most effective for detecting massive planets with long orbital periods.

Diversity of Exoplanets: When considering the diversity of exoplanets based on their mass and radius, one often refers to the mass-radius diagram (see Figure 5), also known as the mass-radius relation. This diagram helps categorize exoplanets into different classes based on their compositions. Broadly the diversity of exoplanets can be categorized as follows :

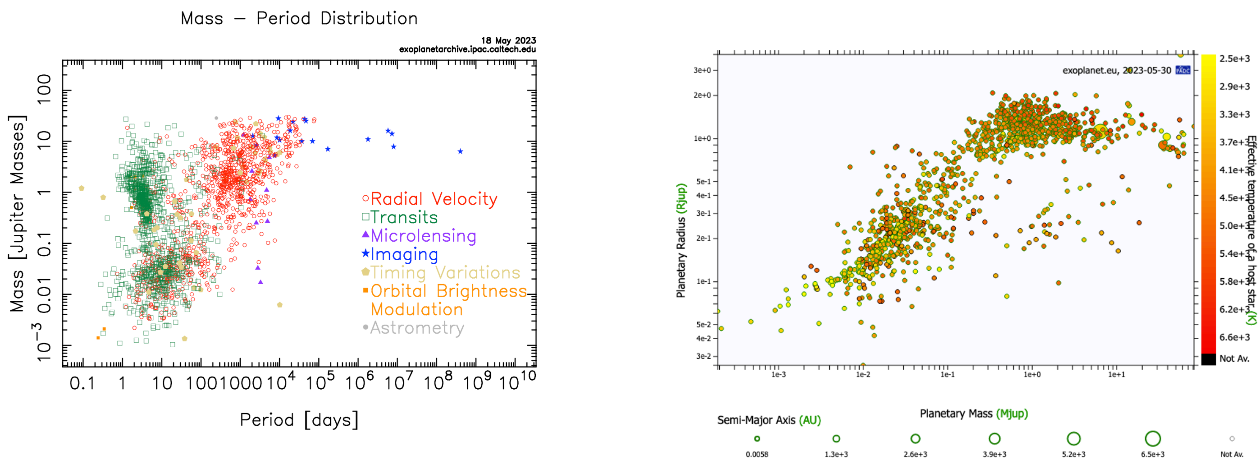

Figure 5 : Mass - Period and Mass - Radius distribution of confirmed exoplanets.

1. **Terrestrial Planets**: Terrestrial planets are rocky worlds similar to Earth, with solid surfaces. They have a relatively low mass and radius compared to gas giants. Examples include Mercury, Venus, Earth, and Mars in our solar system (examples: TRAPPIST -1 e, TRAPPIST -1 d)

2. **Super-Earths:** Super-Earths are exoplanets that have a mass and radius larger than Earth but are still predominantly rocky. They can range from a few times Earth's mass to several times larger. Super-Earths may have thicker atmospheres, including hydrogen and helium, or a significant amount of water. These planets are considered to be potentially habitable if they are within the habitable zone of their star (examples: GJ 15 Ab, 55 Cancer e).

3. **Neptune-like:** Neptune-like exoplanets with radii between that of Earth and Neptune but with masses higher than Earth's. They have a rocky core

made up of rock and heavier metals. They are surrounded by a thick atmosphere composed mainly of hydrogen and helium, similar to Neptune and Uranus in our solar system (examples: HAT-P-26b , GJ 436 b).

4. **Gas Giants:** Gas giants are massive planets predominantly composed of hydrogen and helium. They have both larger mass and radius than Jupiter in the solar system. Gas giants can have a range of sizes, from those similar to Jupiter to much larger and more massive ones. Gas giants are often called "hot Jupiters" when they orbit very close to their star, resulting in high temperatures (examples: KELTP-9b , Kepler- 7b).

Earth-like Exoplanets : Earth-like exoplanets are often referred to as "potentially habitable" or "Earth analogs" due to their potential to support liquid water and, potentially, life as we know it. Here are a few notable Earth-like exoplanets:

Proxima Centauri b: Discovered in 2016, Proxima Centauri b is the closest known exoplanet to Earth, orbiting the red dwarf star Proxima Centauri. It is approximately 1.3 times the mass of Earth and resides within the habitable zone, where conditions might allow for liquid water on its surface.

TRAPPIST-1 System: The TRAPPIST-1 system, located about 39 light-years away, gained significant attention because it hosts seven Earth-sized planets. Three of these planets, namely TRAPPIST-1e, f, and g, reside within the star's habitable zone. TRAPPIST-1e is particularly intriguing due to its similar size to Earth.

Various Space missions for exoplanet detections: Several space missions have been dedicated to detecting and studying exoplanets. These missions have significantly expanded our knowledge of exoplanetary systems and have provided invaluable data for understanding their diversity. Here are some notable space missions for exoplanet detections. 1) Kepler Space Telescope: The Kepler mission was launched by NASA in 2009. It used the transit method to detect exoplanets. Kepler discovered thousands of exoplanet candidates, including rocky planets and super-Earths, as well as the first Earth-sized planets in the habitable zone of their stars. 2) Transiting Exoplanet Survey Satellite (TESS): Also operated by NASA, launched in 2018. Like Kepler, TESS also used the transit method to detect exoplanets. TESS scans the entire sky, observing hundreds of thousands of bright sun-like stars.

These are just a few examples of space missions that have significantly contributed to our understanding of exoplanets. Future space missions, such as the PLATO (Planetary Transits and Oscillations of Stars) mission, are also planned to further explore and study exoplanetary systems.

Facilities available in India for Exoplanet studies: India has made significant contributions to the field of exoplanet detection and exploration. Scientist from India has been involved in various ground-based observational efforts and collaborations to detect and characterise exoplanets. Physical Research Laboratory (PRL), a leading institute in India, initiated the study of exoplanets. PRL has indigenously developed and operates the PRL Advanced Radial-velocity Abu-sky Search (PARAS) spectrograph attached to the 1.2-meter telescope at Mount Abu, Rajasthan. PARAS is primarily used for precise radial velocity measurements to detect exoplanets. It can detect sub-Neptune type exoplanets around Sun-like stars. It discovered the first sub-Saturn type exoplanet name EPIC 211945201 b (also known as K2 236 b), using the RV method in 2018. Later, PRL scientists discovered two more exoplanets and contributed to the first Brown dwarf discovery with TESS.

Scientists from PRL have recently developed a new indigenous facility called PARAS-2 attached to the newly installed 2.5-meter telescope at Mount Abu, Rajasthan. PARAS-2 is the only high-resolution spectrograph with R~110000 in Asia that aims to detect super-Earth planets around Sun-like stars.

Moreover, other institutes in India, such as the Indian Institute of Astrophysics (IIA) and Tata Institute of Fundamental Research (TIFR), also involve studying exoplanets and their exploration.