Physics Project Reading

PPr701

Beyond Our Solar System: Discovering the Exoplanets

Submitted by

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CERTIFICATE

This is to certify that the reading project entitled ”Beyond Our Solar System: Discovering the Exoplanets” is done by **Laxmi Prasoon Barik** under my guidance and supervision during November 2023 to February 2023 for the 7th Semester Project **PPr701** of Integrated M.Sc. in Physics at Center for Basic Sciences, Pandit Ravishankar Shukla University, Raipur, Chhattisgarh, India.

To the best of my knowledge and belief, this dissertation embodies the work done by the candidate.

Supervisor

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I sincerely behold the blessings of my parents for supporting me.

Laxmi Prasoon Barik

Contents

1 Introduction

1.1 Definition

Any planet beyond our solar system is called an exoplanet. Most of the exoplanets orbit stars. There are free-floating 'Rouge Planets' that do not orbit stars; instead, they orbit the galactic center. The definition of exoplanet, according to International Astronomical Union (IAU), is a changing topic which evolves as our understanding of the universe increases.

In 1930, Pluto was discovered and included as a planet. However, in 2003, the Working Group on ExtraSolar Planets (WGESP) gave a working definition, and Pluto was no longer classified as a planet. The need for a proper definition arrived from the inclusion and exclusion of Pluto as a planet of our solar system, according to the notion of the term 'Planet' as understood by the scientists.

In 2006, IAU General Assembly adopted the definition of planets in the solar system.[1]
The current working definition of a planet is:

1. Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars, brown dwarfs or stellar remnants are "planets" (no matter how they formed).

2. Sub-stellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "Brown Dwarfs (no matter how they are formed nor where they are located).

3. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "Planets" but are "Sub-Brown Dwarfs"(or whatever name is most appropriate).

1.2 Historical Context and Discovery

In the year 1984, the first planetary disk was observed. In January 1992, the discovery of the first exoplanets were announced by Aleksander Wolszczan and Dake Frail, orbiting PSR B1 257+12, a pulsar in the constellation Virgo. The discovery of an exoplanet orbiting a main-sequence star (51 Pegasi) dates back to October 1995. The first transiting exoplanet was discovered in 1999 across the star HD209458. The first exoplanet in the habitable zone was found in 2001. The first measurement of atmosphere on any exoplanet came in 2001, orbiting HD209458. A remarkable breakthrough was made in 2005 when light from an exoplanet was observed directly using the Spitzer Space Telescope. It observed direct infrared light from HD209458 and TrES-1.

In June 2019, NASA's Exoplanet Archive announced 31 newly confirmed exoplanets, which made the official count reach the 4000 mark. On March 21, 2022, the count passed the 5000 mark. There are many potential planets marked as candidates. However, some can turn out to be "false positives." The candidates are confirmed once they are verified by two other telescopes through additional observations.

2 Methods of Detection

2.1 Transit Method

If Earth lies in or near the orbital plane of an exoplanet, that planet transits its star once per orbit as viewed from Earth. When certain geometrical conditions are present, the transit of a planet attenuates the incoming radiation from the host star. This effect repeats with each orbit.
The probability of a randomly oriented planet being aligned for a transit is (Borucki and Summers, 1984).

$$P = \frac{R_*}{a} \approx 0.05(\frac{R_*}{R_\odot})(\frac{a}{1au})^{-1}$$

There are four principal observables which characterise the duration and profile of primary transit:

- The period P,
- The transit depth ΔF
- The interval between first and fourth contacts t_T

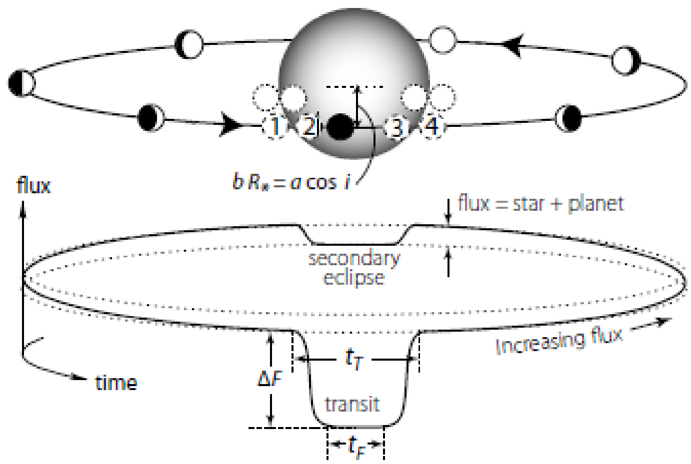

Figure 1: Schematic illustration of a transiting planet. The transit begins at first contact, where the planet is at position 1 in the upper diagram. The entire disk of the planet blocks light from the star from the time of second contact (2) through that of third contact (3), and the transit concludes at fourth contact (4). (Perryman 2011)

- The interval between second and third contacts t_F

[2] From these, three geometrical equations together describe the principal features of the transit light curve.(1)

2.1.1 Transit Light Curves

The fractional decrease in the star's apparent brightness, neglecting variations of brightness across the stellar disk, is given by:

$$\frac{\Delta L}{L} = \frac{R_P}{R_*}^2$$

Limb darkening affects the shape of the transit curve. It causes the edge to appear fainter than the central region. Thus, the planet blocks a smaller fraction of the star's light than the ratio of the area of the two bodies when it obscures light from near the star's limb.

2.1.2 Advantages and Disadvantages

The transit method is used to measure properties that are not detectable using other methods. It can provide the size and orbital period of the detected planet.
The major disadvantage is that the geometrical considerations limit the fraction of planets detectable by this method.

2.2 Radial Velocity or Doppler Method

Radial velocity measurement is the most successful method for detecting planets around main sequence stars. The velocity at which the star is moving in the direction or opposite to the direction of the observer can be measured by fitting the Doppler shift of a large number of features, such as the red shift.

2.2.1 Spectroscopic Observations

The observed factors include the motion of the observer relative to barycenter of the solar system and other known motions, along with the radial motion of the target star. After subtracting other factors, the radial motion can be calculated.
If K is the amplitude of the radial velocity variation, M_* is the mass of the star, and M_P is the mass of the orbiting planet, then:

$$K = (\frac{2\pi G}{P_{orb}})^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

Where P_{orb} is the orbital period, i is the angle between the normal to the orbital plane and the line of sight, and e is the eccentricity of the orbit.[3]

2.2.2 Advantages and Limitations

The radial velocity method is most sensitive to massive planets and to planets in short orbital periods.
The major disadvantages are stellar rotation and intrinsic variability of the star, such as star spots, which cause a lot of noise.

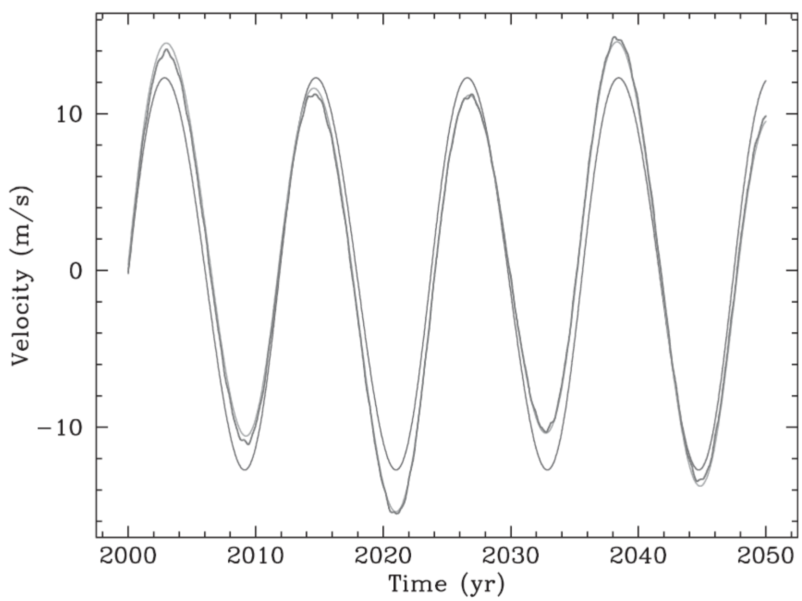

Figure 2: COLOR PLATE Velocity variations of the Sun in response to Jupiter (nearly sinusoidal narrow blue curve), Jupiter plus Saturn (faint green curve), and all eight planets plus Pluto (thick red curve). Jupiter's tug dominates the variations, with Saturn having much less influence than Jupiter but still far more than all of the remaining planets combined. The pull of Earth and Venus is evident in the short-period variations seen in the thick red curve. (Courtesy Elisa V. Quintana)

2.3 Direct Imaging

Extrasolar planets are very difficult to image since the light emitted by them is very faint in comparison to much brighter objects like stars.

2.3.1 Techniques and Instruments

Reflected light by planets that have a size and orbit similar to our solar system is roughly one-billionth as large as the stellar brightness. However, the contrast is $\sim$3 order of magnitude more favorable in the thermal infrared shown by figure (3)

2.3.2 Advantages and Limitations

Sub-stellar objects that do not orbit stars have also been imaged in the infrared using this technique. This enabled discovery of free-floating giant planets which may have members less massive than deuterium burning limit. The variability caused by the atmosphere and diffraction by the telescope makes detection harder. Exozodiacal clouds (asteroids and comets form dusk disks by erosion) make the imaging complicated.

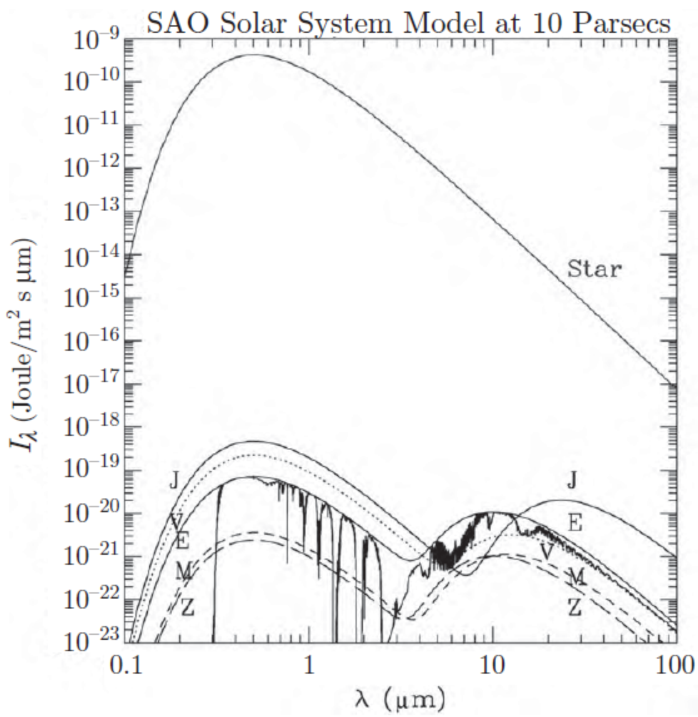

Figure 3: Spectral energy distribution of the Sun, Jupiter, Venus, Earth, Mars and the zodiacal cloud. The bodies are approximated by blackbodies of uniform albedo, with an additional curve showing Earth's atmospheric absorption features. (Adapted from Des Marais et al. 2002)

2.4 Gravitational Microlensing

The bending of starlight by a massive object (acting as a lens) between the source and the observer is called gravitational microlensing.

2.4.1 Principle of Operation

The phenomenon of gravitational microlensing is based on the general theory of relativity. Light from the source located behind the lens appears to form a circular region known as Einstein's Ring. This ring is not resolvable. However, it magnifies the light from the source by a considerable factor, given it passes closer to the line of sight than the radius of Einstein's ring(R_E)

$$R_E = \sqrt{\frac{4GM_L r_{\Delta L}}{c^2}}(1 - \frac{r_{\Delta L}}{r_{\Delta S}})^{\frac{1}{2}}$$

Where M_L is the mass of the lens, $r_{\Delta L}$ is the distance of earth to the lens, and $r_{\Delta S}$ is the distance of earth to the source.

2.4.2 Advantages and Limitations

This method is quite useful in the detection of faint stellar and sub-stellar mass bodies in our galaxy. It provides information about the mass ratio and projected separation of the planet and star. This technique is capable of detecting systems with multiple planets and/or more than one star. If the circumstances are favorable, planets as small as Earth can be detected.
The problem with this method is that they are observed only when the source and lens are very well aligned. The follow up observation is also very difficult due to the faintness of distant systems.

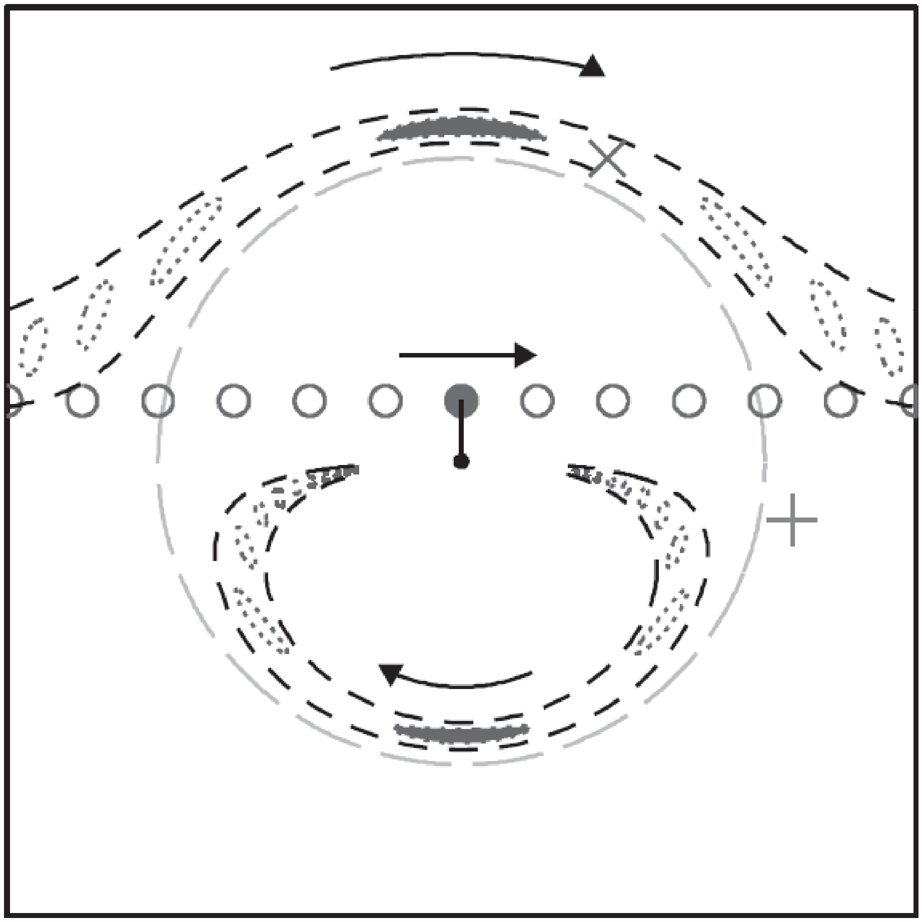

Figure 4: Schematic of a microlensing event illustrating the effect of the light from a distant source being bent by a lensing star that possesses a planetary companion. The images (dotted ovals) are shown for several different positions of the source (solid circles), along with the primary lens (black dot) and Einstein ring (long-dashed circle). The source is moving from left to right relative to the lens, and the images of its bent light move in a clockwise sense, as indicated by the arrows. The filled ovals correspond to the images of the source when it is at the position of the filled circle. If the primary lens has a planet near the path of one of the images, i.e., within the short-dashed lines, then the planet will perturb the light from the source, creating a deviation to the single lens lightcurve.

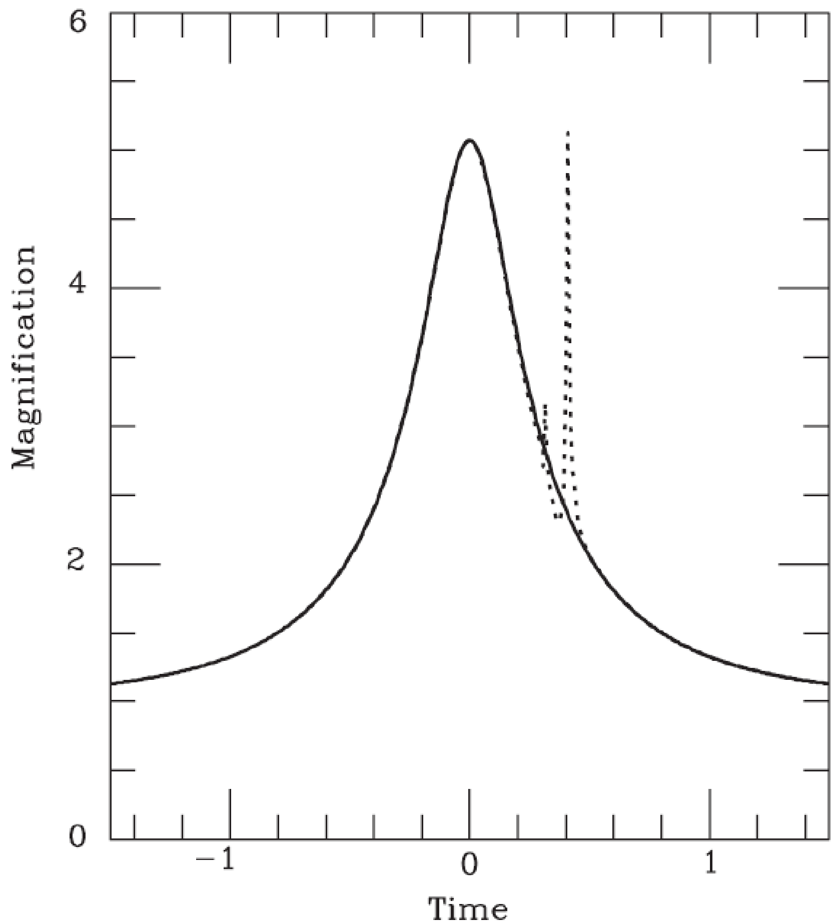

Figure 5: The observed amplification of the amount of light from the source received at the telescope as a function of time is shown for the case of a single stellar-mass lens (solid line) and a star with an accompanying planet located at the position of the × (dotted line). If the planet was located at the + instead, then there would be no detectable perturbation, and the resulting lightcurve would be essentially identical to the solid curve. The units of the time are RE/v, where v is the velocity of source's location relative to the lens on the plane of the sky. (Courtesy Scott Gaudi)

3 Characteristics of Exoplanets

3.1 Density and Masses

Small planets are made up of either rock or iron. The density of iron planets is higher than that of rocky planets. On the other hand, gas giant planets have a higher density than expected, indicating the presence of heavy elements, as is found on Jupiter and Saturn.

3.2 Atmosphere and composition

Information about the temperature and atmosphere can be obtained by comparing spectra during transit and outside of transit. Some light is partially absorbed by the atmosphere of the planet, which can be calculated by observing stellar light during transit. The constraints on atmosphere and clouds is provided by measuring the phase variation of the extrasolar planet.
For example, optically thick clouds of Venus lead to small brightness variations with phase angle.

3.3 Habitability

Huang (1959) presented a general discussion of the 'habitable zone of a star' and considered time scales of stellar evolution, dynamical constraints in multiple stellar systems, and the stellar galactic orbit. Dale (1964) gave a broader description. Currently, habitability is based on known life i.e. on Earth.

Circumstellar habitable zone is loosely defined by range of star-planet distances where liquid water can exist in the surface. The other factors also affect such as atmospheric properties and orbital effects including eccentricity. Other sources of heat like X-ray heating, heating by long-lived radionucleides , eg. U^{235},U^{238} and K^{40} are also considered.

Kasting(1993) found an almost constant inner boundary defined by water loss and the runaway greenhouse effect for Earth like planets. For 1 $M_{\odot}$ star, inner boundary at $\sim 0.75 - 0.95$au and outer boundary at $\sim 1.37 - 1.77$au. There are several other models based on other characteristics.

Continuously habitable zone moves outwards with time, dependent on stellar mass, because of increasing stellar luminosity with age. It can be defined as range of orbital distances over which liquid H_2O could have existed continuously over sufficient time for evolution of life.

4 Notable Exoplanets

4.1 TRAPPIST-1 System

Discovered by 0.6-meter robotic Transiting Planets and Planetestimals Small Telescope (TRAPPIST), Chile, as a three-planet system (as known at that time) around an M-type star at a distance of 40 light years, TRAPPIST-1 system consists of seven planets orbiting at the habitable zone of its star.

In February 2018, a closer study suggested the presence of a huge quantity of water, greater than that on Earth, on some of the planets. Using the transit method, the mass and diameter of the planets were known, which were used in the calculation of densities.

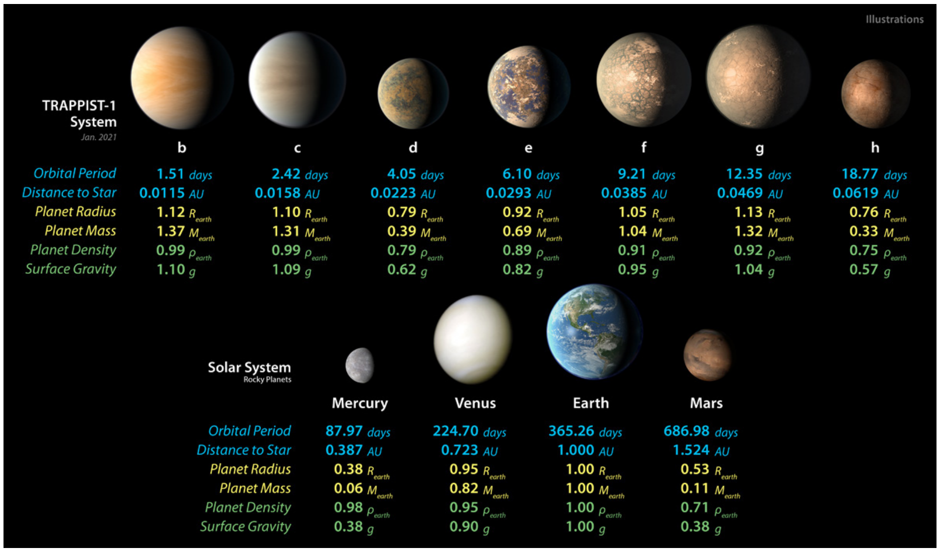

Figure 6: Detailed measurements of the physical properties of the seven rocky TRAPPIST-1 planets and the four terrestrial planets in our solar system help scientists find similarities and differences between the two planet families. Credit: NASA/JPL-Caltech

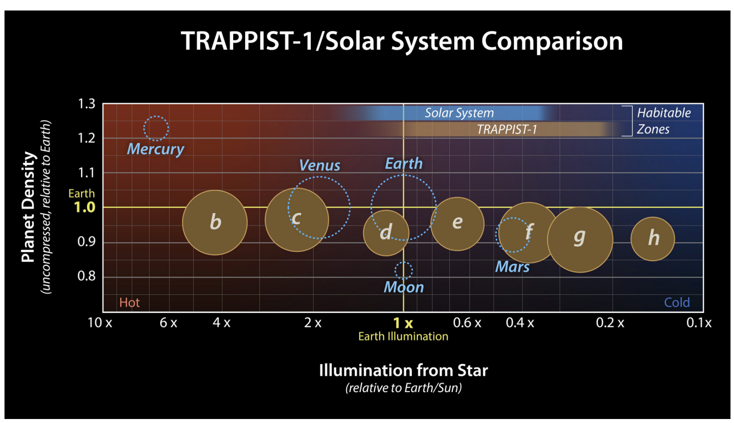

Figure 7: A planet's density is determined by its composition as well as its size: Gravity compresses the material a planet is made of, increasing the planet's density. Uncompressed density adjusts for the effect of gravity and can reveal how the composition of various planets compare. Credit: NASA/JPL-Caltech

4.2 Proxima Centauri b

An extrasolar planet orbiting an M-type star with a mass equivalent to $\sim$1.07 $M_\odot$. It takes 11.2 solar days to complete one orbit of its star. It is located 0.04856 AU from its star. This planet was discovered in 2016 by the European Southern Observatory (ESO) using the radial velocity method by analyzing previously obtained Doppler measurements. The search and significance of signals were performed using frequentist and Bayesian methods.

The host star Proxima Centauri is located at 4.2 light years away from us in the constellation Centaurus. This makes Proxima Centauri b closest exoplanet to us.

4.3 Kepler-22b

Kepler-22b is an exoplanet that orbits the G-type star Kepler-22 (a star in the constellation Cygnus) at a distance of 640 light years from Earth. It is situated at the habitable zone of its star.

It is the first known transiting planet discovered in December 2011 by NASA's Kepler Space Telescope. The radius of Kepler-22b is 2.1 $R_\oplus$ i.e. it is a Super Earth that could be covered in oceans. The orbital period of this planet in 290 days and its mass is approximated to be 9.1 $M_\oplus$.

4.4 Other Significant Discoveries

In the image (9), Of the 1,030 confirmed planets from Kepler, a dozen are less than twice the size of Earth and reside in the habitable zone of their host stars. In this diagram, the sizes of the exoplanets are represented by the size of each sphere. These are arranged by size from left to right, and by the type of star they orbit, from the M stars that are significantly cooler and smaller than the sun, to the K stars that are somewhat cooler and smaller than the sun, to the G stars that include the sun. The sizes of the planets are enlarged by 25 times compared to the stars. The Earth is shown for reference.

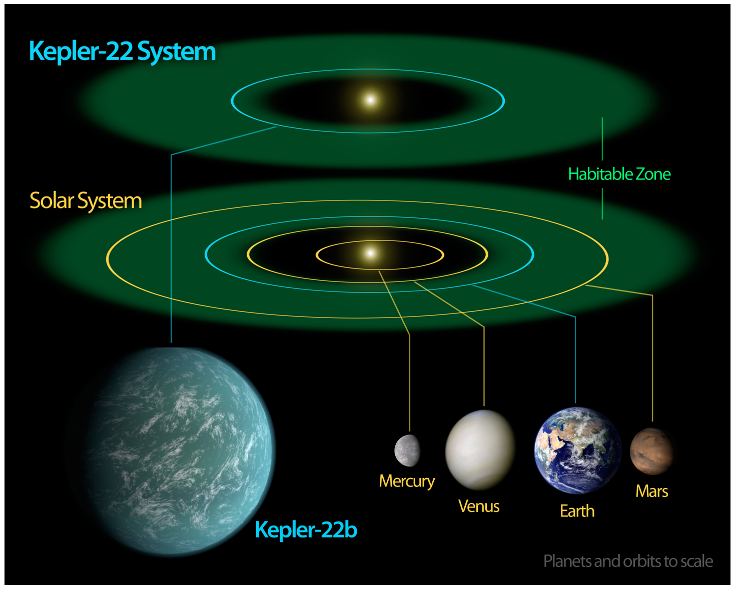

Figure 8: Artist's impression of the Kepler-22 system and its planet (sizes to scale) compared to the planets of the inner Solar System with their respective habitable zones

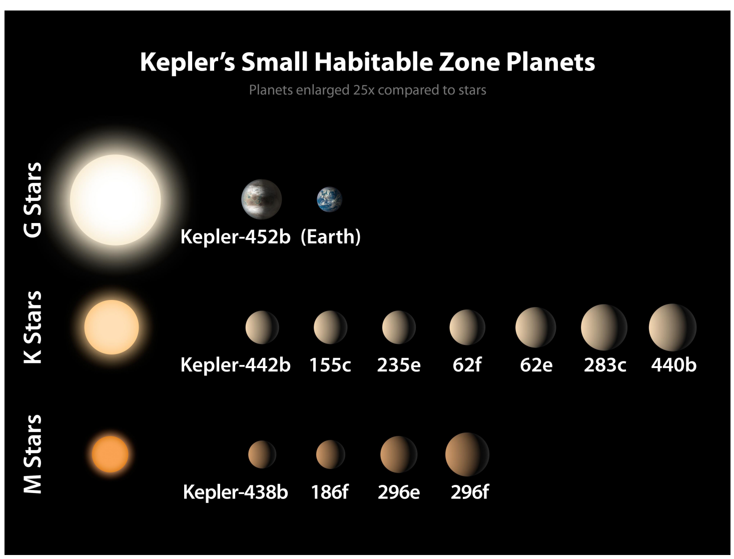

Figure 9: PIA19827: Kepler's Small Habitable Zone Planets

5 Implications for Life Beyond Earth

5.1 Goldilocks Zone and Habitability

Habitable zone (HZ) is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure. Factors such as the position of the planet from the star and the solar radiance received. The concept was first introduced by Edward Maunder in the year 1913. The concept of habitable zones was further developed in 1964 by Stephen H. Dole. Astronomer James Kasting coined the phrase "circumstellar habitable zone" in 1993. He was also the first to present detailed model for the habitable zone for exoplanets.

This zone is also called 'Goldilocks zone', a metaphor for the children's fairy tale "Goldilocks and the Three Bears." In the 1970s, the phrase "Goldilocks zone" first appeared, referring to an area surrounding a star where the temperature is "just right" for liquid water to exist. The criteria is still evolving as our understanding of the universe grows.

As stars evolve, circumstellar habitable zones shift throughout time. As an example, hot O-type stars, which might stay on the main sequence for less than 10 million years, would have habitable zones that change quickly, making them unsuitable for the emergence of life. To address this luminosity increase, the idea of a 'continuously habitable zone' has been proposed. The continuously habitable zone, as its name suggests, is an area surrounding a star where planetary mass bodies can support liquid water for a certain period of time.

5.2 Astrobiology and Potential Biosignatures

Astrobiology aims for the detection of life in the universe. Direct detection of life is not possible with our current technological advancements. We detect the biosignatures that might lead to life. But there is no definite theory of life or living things. For example, both biotic and abiotic proccesses produce oxygen. We do not have a method to know the truth about claims beyond the atmospheric composition. However, life on any planet might include the signature of life with its spectra, like the presence of a gas, which can be interpreted as originating from living organisms.[4] [5]

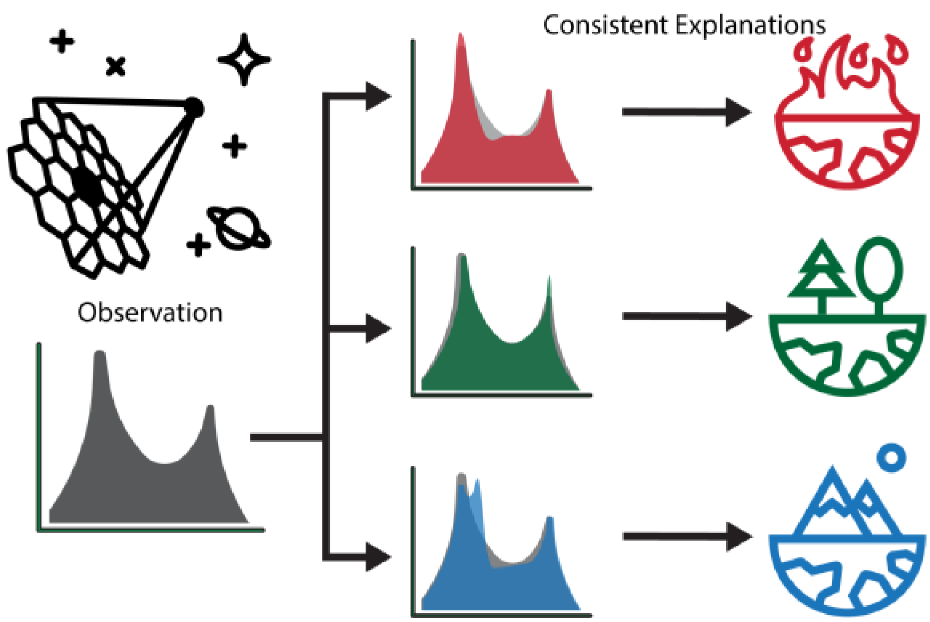

Figure 10: Different underlying planetary processes can lead to the same atmospheric observables, which means that a specific observation of an atmosphere cannot unambiguously identify the surface processes, including biological ones. Uncertainty in the types and scale of novel chemistry, planetary processes, and biotic processes amplify this problem.[5]

6 Current State of Exoplanet Research

6.1 Kepler Mission

Launched in 2009, the Kepler space telescope was designed to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine the fraction of stars that might have such planets in a three-and-a-half-year time period. It gave a significant result with the discovery of Kepler 4b, 5b, 6b, 7b, and 8b within six weeks of operation.

In 2013, it lost one of the four gyroscope-like reaction wheels, thus beginning the extended mission as K2. It was retired in 2018.

6.2 TESS Mission

Transiting Exoplanet Survey Satellite (TESS), launched in 2018 as a successor to Kepler to discover exoplanets in orbit around the nearby brightest dwarf stars ($\sim$ 200 light years). It observes 85 percent of the sky from the High Earth Orbit (HEO) to obtain continuous light curves and more precise photometry than the low Earth orbit.

6.3 Spitzer Space Telescope

Operable between 2013 to 2020, it was not originally designed to search for exoplanets, but its infrared instruments made it a excellent exoplanet explorer. This telescope discovered the TRAPPIST-1 system.

6.4 Other missions

There are several other missions useful for the detection and study of extra-solar planets. Gaia, short for Global Astrometric Interferometer for Astrophysics, launched in 2013, is expected to detect thousands of Jupiter-sized exoplanets.
The Convection, Rotation, and Planetary Transit (CoRoT) mission by ESA was used for the detection of exoplanets with short orbital periods using the transit method by the help of CCD. CoRoT-7b, showing a rock or metal dominated composition, is one of the notable discoveries of this mission. The Hubble telescope was one of the early telescopes.

7 Future Prospects and Challenges

Space programs such as the James Webb Space Telescope are responsible for continuously increasing the discoveries of exoplanets and their studies. James Webb telescope uses the transit method. Combined with other ground-based telescopes, it can be useful for detection of atmospheric compositions.

The Nancy Grace Roman Space Telescope, formerly known as the Wide Field InfraRed Survey Telescopec(WFIRST) is a NASA observatory expected to be launched in mid-2020s.

CHaracterising ExOPlanet Satellite (CHEOPS) is launched in 2019. It focuses on the study of small exoplanets previously detected by Doppler surveys and known transiting Neptune-sized planets detected by ground-based surveys.

PLAnetary Transits and Oscillations of stars (PLATO) is scheduled to be launched in 2026 based on the theme of studying terrestrial planets in the habitable zone of Sun-like stars.

ARIEL is an M-class project by the European Space Agency expected for launch in 2028. It will study the chemistry and thermal structures of exoplanet atmosphere.

There are NASA cube or Small Satellites such as ASTERIA (retired), CUTE, SPRCS, and Pandora.

Some ground-based observatories are W.M. Keck Observatory at the summit of Maunakea on Hawaii, The Large Binocular Telescope Interferometer, or LBTI on Mount Graham in Arizona, WIYN Telescope on Kitt Peak National Observatory near Tucson, Arizona, Small and Moderate Aperture Research Telescope System (SMARTS) on Cerro Tololo, Chile, and MINERVA telescope located at the Fred Lawrence Whipple Observatory at Mt. Hopkins, Arizona.

The major challenge faced by scientists during the study of exoplanets is the observation and separation of data. For instance, it is necessary to verify that the planet under hypothesis is not the result of atmospheric noise or any other anomaly that occurred during the observation process. Other challenges include producing spectral libraries for the purpose of comparison, accurate mass and radius measurement, and the challenge of bias. [6]

8 Conclusion

Extrasolar planets are the planets that are not in our solar system. There are planets that orbit other stars, multiple star systems, pulsars, or other stellar objects. Some planets are rouge planets. The late 20th and early 21st centuries are proving to be a golden era for the discovery and study of exoplanets. In the 1990s, the first exoplanet was discovered and since then, thousands of other planets have been discovered. The transit method and radial velocity, or Doppler method have been the most useful detection techniques. Some planets have also been detected by other methods, such as gravitational microlensing. The study of atmosphere, mass, density, and composition proves to be a vital aspect in the exploration of exoplanets. There are certain exoplanets that catch the attention of space enthusiasts. Proxima Centauri b is the closest exoplanet to Earth. The TRAPPIST-1 system, with its seven planets orbiting the Goldilocks zone, is an interesting system. Space missions have also developed from time to time. Kepler, TESS, and Spitzer telescopes have enriched the data on exoplanets. There are several ground-based observatories with different aspects of planetary research going on. The future of exoplanets depends on missions such as the James Webb Space Telescope, the Roman Telescope, CHEOPS, PLATO, and ARIEL by space agencies around the world.

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