The Search for Exoplanets: Methods and History

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Abstract

The discovery of exoplanets, planets beyond the solar system, has raised key questions about extraterrestrial life and the technology needed to find it. While considerable progress in exoplanet detection has been achieved over the past three decades, the methods currently in use still face notable limitations. Indeed, the detection of exoplanets has come a long way since its first confirmation in 1992. At first, these celestial objects were considered as figment of movies and science fiction, but it is credible today that Radial Velocity, Transit, Gravitational Microlensing, Direct Imaging, and Astrometry approaches have found these planetary bodies. While each of the methods works well, all techniques possess specific systematic errors depending on orbital radius, planetary size, and so on. For the past few decades, missions like Hubble, Spitzer as well as Kepler have delivered the fundamental catalogs and enormously improved the knowledge in the field of exoplanets. Recent developments, specifically with the JWST, have provided new ideas with indications of biosignatures on planet exoplanet K2-18b. The future prospects for exoplanet discovery also look good, for example, with the help of the machine learning for analysis and planned instruments like Nancy Grace Roman Space Telescope and the concept of Habitable Worlds Observatory. These observatories are oriented towards the search of potentially habitable exoplanets and for exploration of other universal enigmatic processes. In this paper, the advancement of technique in identifying exoplanets is outlined with specific focus on significant accomplishments, trends, technologies, and future outlook, which shows a fairly promising field that holds great potential for finding more habitable planets.

1. INTRODUCTION

An exoplanet may seem like a common entity today but back in the 1990s, it was science fiction. It was not until 1992 that two astronomers, Aleksander Wolszczan and Dale Frail, announced to the world that they had observed two planets like Earth which seemed to be revolving not around a regular star (as one would expect) but a pulsar, marking the first confirmed exoplanet detection [1]. Many different methods have been developed since then to look out for detecting exoplanets. In this paper we describe five major detection techniques that have contributed significantly to the detection of exoplanets: Radial Velocity, Transits, Gravitational Microlensing, Direct Imaging and Astrometry.

Each method has its own biases, for example even though transit and radial velocity methods discovered most of the exoplanets, they are more favorable towards planets that have shorter orbital radius and are comparably larger in size whereas the microlensing and direct imaging methods are favorable for those with larger orbital radius [2]. The methods usually have different sets of planets as their biases are different.

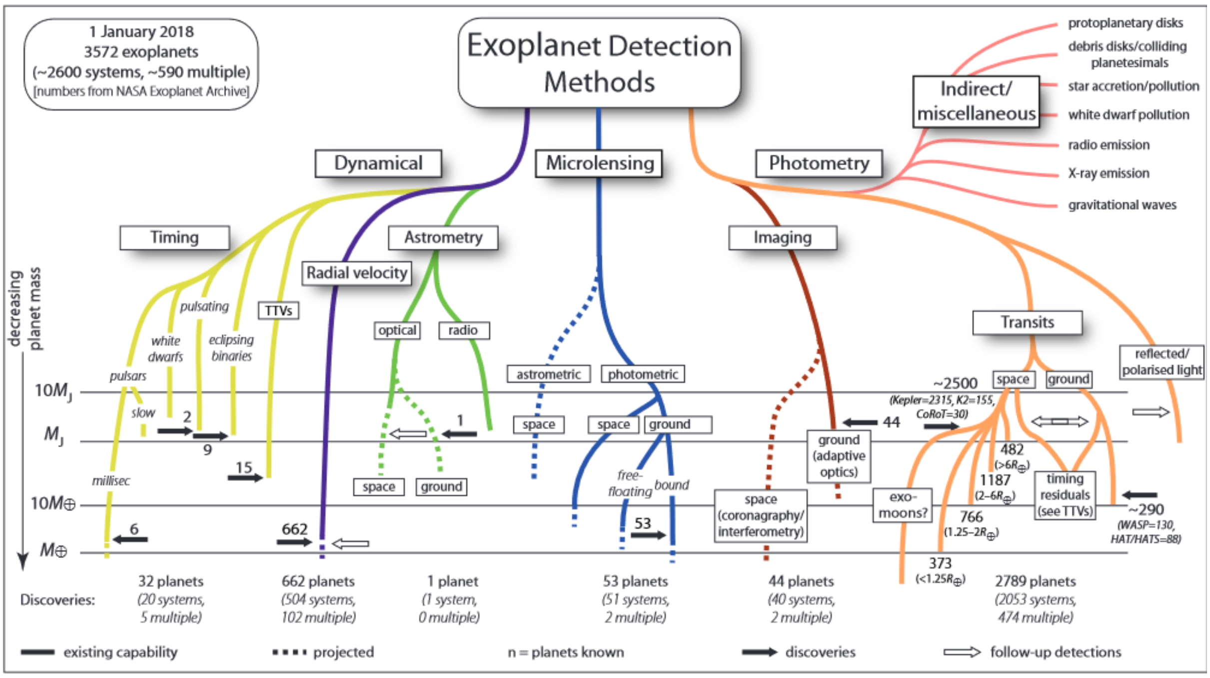

Figure 1: Exoplanet detection methods. The lower limits of the lines indicate masses within reach of present measurements by solid lines, and those that might be expected within the next few years are indicated by dashed lines [3].

Figure 1 shows the contribution of various methods towards detecting exoplanets till 1 January 2018. There is a clear domination of detections by transits which sits at roughly about 78% of the total detections. The dashed lines show the possibilities of future paths taken by these methods to improve their detection rates.

2. RADIAL VELOCITY

This is one of the earliest and widely employed methods of planet, this method is also known as 'Doppler Wobble.' This technique utilizes the Doppler Effect; the light coming from an object can be seen in a spectrum using spectroscopy. When the object is moving closer to the observer, its wavelength decreases, this is termed as blueshift (violet is the shortest wavelength and it should be called violet shift, but blue is a more prominent color) and when the object is going away from the observer, its wavelength increases and approaches the red end of the spectrum, this is given the name of redshift.

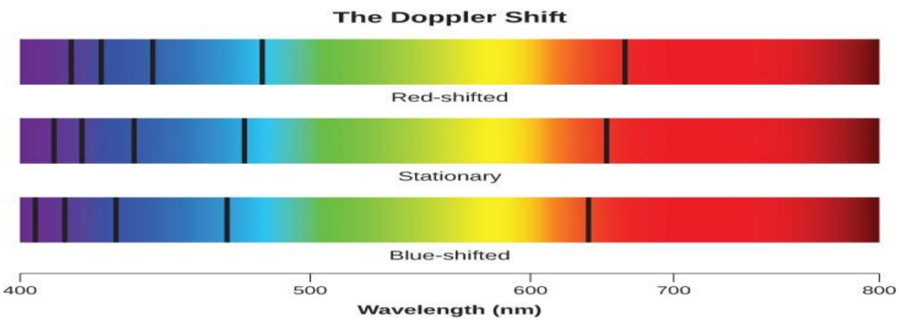

Figure 2: The image clearly shows the wavelength shifted towards the red spectrum in the first band i.e., the object going away. The middle strip shows the object at rest and the last strip shows the wavelength shifted towards the blue end, i.e., the object is approaching the observer.

If a planet candidate exists in the orbit of its parent star, it exerts a gravitational influence on the star, resulting in the seen reflex motion or wobble effect. The star in response to its companion does not remain completely stationary which causes the starlight to be alternately squeezed hinting towards the presence of a potential planet candidate. After verifying the stellar wobble, there remains a possibility that it is caused by something other than the gravitational force exerted by a companion object. This phenomenon could be attributed to a binary star located far away but sharing the same orbital period as the supposed planet candidate. However, these instances can only imitate the presence of low-mass planets on expansive orbits, which are currently beyond our ability to detect.

2.1 Limitations

Mass restriction

Radial Velocity does not give confirmation on the planet's mass; this is due to the difficulties in calculating the angle of inclination of an exoplanet system. The information retrieved is in the form of M_P sin(i) which only places a lower limit on the mass of the planet [4]. Since the measurement relies on the wavelength from the star, this opens possibilities for a lot of redundant noise in the data in the form of stellar jitter [5], such as changes in star spots or magnetic fields.

Equipment heating

The use of electrical devices produces variable temperatures in the mechanical components of the spectrograph which could affect the Point Spread Function; this could resemble changes in wavelength in the detector. Additionally, reconfiguring the structural body of the detector can lead to similar differences. These minor variations can reach noticeable figures.

Varying refractive index in the atmosphere

The Earth's atmosphere is heterogeneous; when one ascends into the exosphere, its density varies, thereby altering the refractive index. Although this factor can be accounted for, the bigger problem is air turbulence, the warm and cold pockets in the atmosphere, these come and go in random patterns which bend the light (even the slightest of bends can cause observations of these distant objects to become inaccurate).

3. TRANSIT

Planets which have an edge-on orbit with their star (meaning they eclipse their star for an observer from Earth) have been known to cause a measurable dip in the brightness from the system; the transit method employs this fact to detect the existence of an exoplanet. This uses indirect detection of the brightness to discover exoplanets, yet it provides significant information about the relationship of the planet-star system.

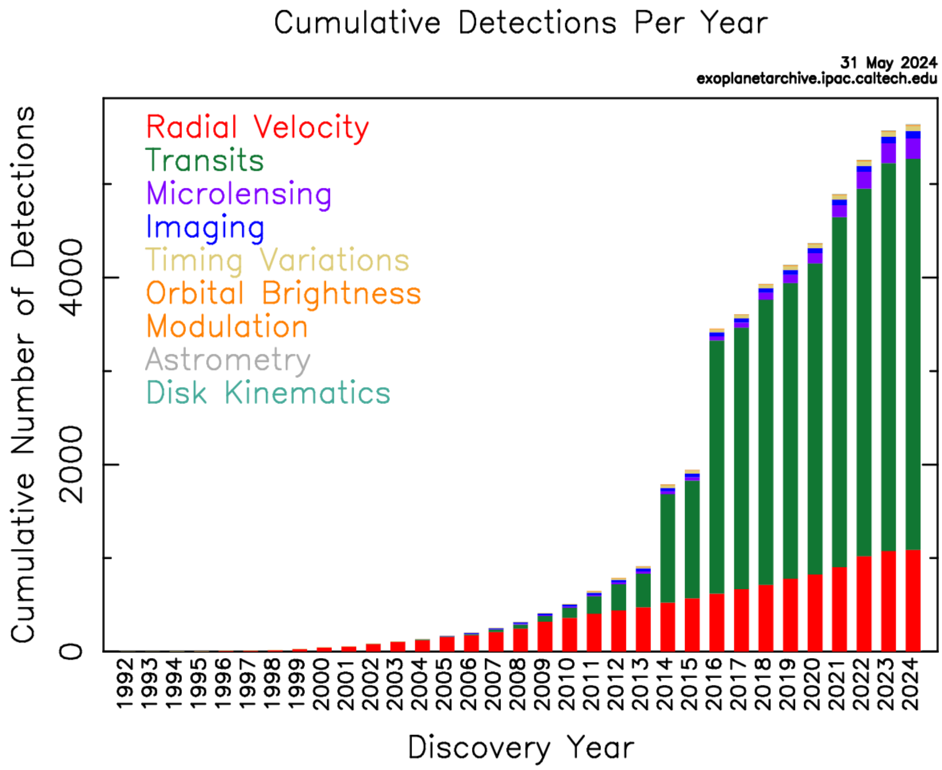

Figure 3: The cumulative histogram shows the classification of methods through which the exoplanets were discovered. Image is sourced from Caltech Exoplanet Archives.

Radial velocity used to be the main technique for identifying exoplanets until the first decade of the 21st century (see Fig. 3). David Charbonneau [6], first introduced the transiting method which detects periodic dips in a star's brightness as a planet transit in front of it. Notably, a plethora of information can be inferred from this method which allows for a deeper scrutiny of the nature of the system.

The planet detected by him - HD 209458b, was already discovered through the radial method. This method is the most common way to detect and characterize exoplanets. This slowly became the method to confirm planets which could not be found with radial velocity method and a lot of ‘blind hunts’ were organized which involved dedicated instruments to collect a lot of ‘light curves’ from a portion of the sky, starting from the sky then ground based telescopes [3]. The path involved detecting these planets only from dips in the stellar luminositv.

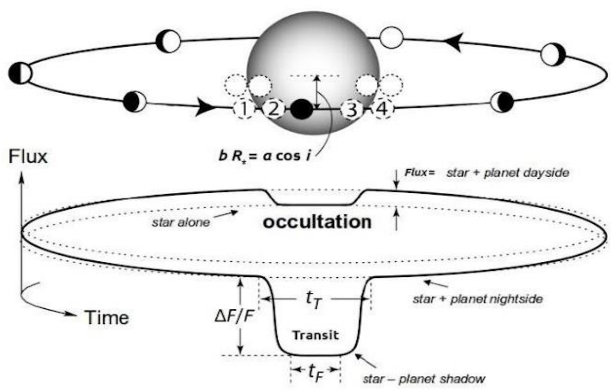

Figure 4: Depiction of a transit light curve [7]

Radius of the planet-

Fraction of light lost is given by,

$$\frac{\Delta F}{F} = \left(\frac{r_p}{r_s}\right)^2 \qquad (1)$$

$$r_p = r_s\sqrt{\frac{\Delta F}{F}} \qquad (2)$$

Where,

r_p: Radius of planet

r_s: Radius of star

Kepler's third law-

For the approximation of the radius of the orbit, we have to make an assumption on the relation of the masses, which is that the mass of the star is way greater than that of the planet.

$$M_s \gg M_p \qquad (3)$$

To determine the period of revolution (P), we simply need to collect light curve with periodic dips, the time between the dips is the period of the planet to complete a full revolution.

$$r_0 = \sqrt[3]{\frac{GM_sP^2}{4\pi^2}} \qquad (4)$$

Where,

r_o: Radius of orbit

P: Time period taken for full revolution

Average Velocity of planet during transit-

This equation comes right out of kinematics,

$$v = \frac{2r_s}{t_t} \qquad (5)$$

Here,

t_t: Time taken for the planet to transit

This method is quite unique in terms of the information it provides, only via this process is it possible to determine the radius of the exoplanet which helps in classifying the planet by the mass to size ratio. Careful observation of the light curves also shows a minor secondary dip in brightness (when the planet goes behind the star), by processing this, we can take a peek into the upper atmospheric spectrum of the planet. The transition method also works fabulously with radial velocity since combining these two methods allows us to measure the inclination of the orbit of the planet. All these unique features make transiting the best method till now to identify exoplanets, but as with everything even it has its cons (as discussed later).

OGLE-TR-56b, detected by Maciej Konacki [8] was the first to be discovered by transit method. Soon the first space mission dedicated to exoplanetary research was CoRoT (Convection, Rotation, and planetary Transits) launched by French space agency CNES [9], and this, as the name suggests, uses transit method to detect extrasolar planets. NASA's Kepler space telescope also utilizes a variation of transit method, and it stares at a small patch of space patiently waiting to catch small dips in the luminosity of the stars. NASA's TESS (Transiting Exoplanet Survey Satellite) has also been deployed to search exoplanets using the same detection technique.

3.1 Limitations

False positive trends-

False positive detections of eclipsing binaries are usually the only concern for corruption of data from transits [10], for many transit satellites and radios. The False Positive rate has been identified as 9.4% ± 0.9 % [11], this requires a thorough check of the possible candidates, also referred to as Kepler Objects of Interest (KOIs) for the Kepler Mission [11].

4. GRAVITATIONAL MICROLENSING

It was first defined by Albert Einstein in his general theory of Relativity which said that objects which have any mass generate a dip in the space-time curvature around them which causes light to bend around the object. This method leverages the gravitational potential energy of the lens to magnify the amount of light that is coming from the source. It is a very delicate method which can detect the smallest of exoplanets with great precision.

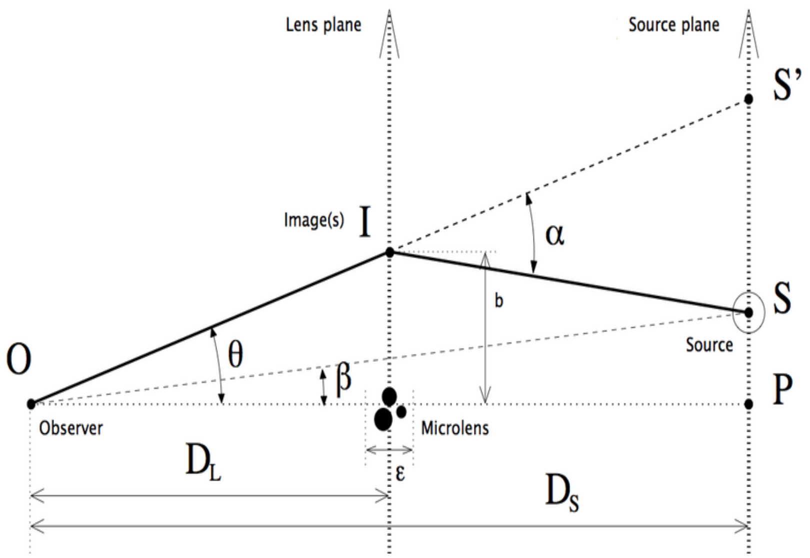

Figure 5: The figure shows the process of microlensing. Image taken from [12].

The alignment between the source, lens, and the observer changes as a function of time; this gives a symmetric curve of increased brightness over a sufficiently long period. Astronomers notice a sharp spike in the curve for an extremely short amount of time which occurs due to the temporary magnification from the gravitational field of an exoplanet in the orbit of the lensing object. The first exoplanet discovered by microlensing was in 2004 by a team led by Ian Bond at the University of Edinburgh [13].

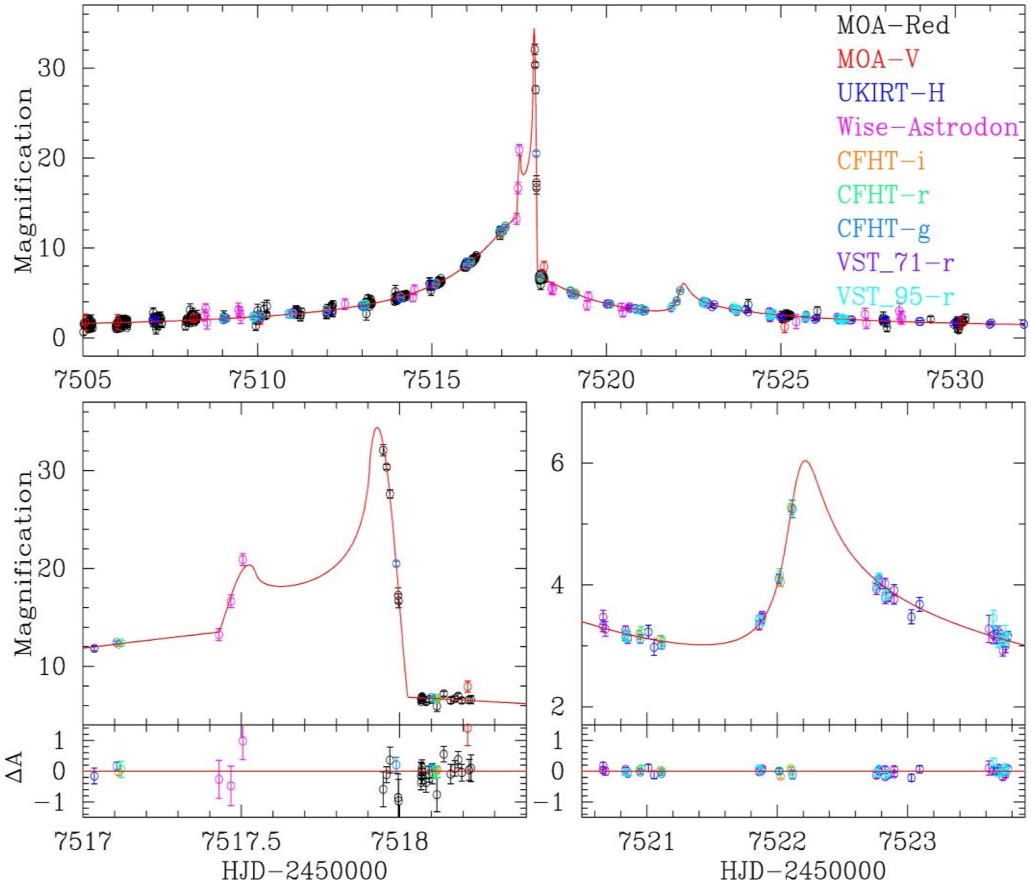

Figure 6: This shows a light curve of planet MOA-2016-BLG-227 discovered by [14].

The figure above shows the complete timeline of the magnification by a lens, it shows a general parabolic curve but with a spike in the starting, this indicates the presence of a massive planet MOA-2016-BLG-227 [14].

Microlensing is unique in its ability to confirm the existence of free-floating planets, every now and then a small increase in brightness is seen telescopes while observing the bulge of our Milky Way, this disruption has been attributed to exoplanets which are moving around without an orbit or which have a very eccentric orbit around their star. The only major disadvantage of this method is that it will not be repeated frequently since it requires a precise alignment of the planet with a background light source.

5. DIRECT IMAGING

This method gives direct evidence for the presence of an exoplanet as a luminous object. It directly takes the emitted photons and identifies little blobs that represent planets.

The brightness ratio of our sun to Jupiter is roughly a billion, this makes it almost impossible to image them in the optical wavelength but astronomers have figured out that most of the light emitted from the star is in the optical spectrum and planets (especially young) produce their light in the infrared spectrum which is the leftover heat from the disc of gas that made the planet.

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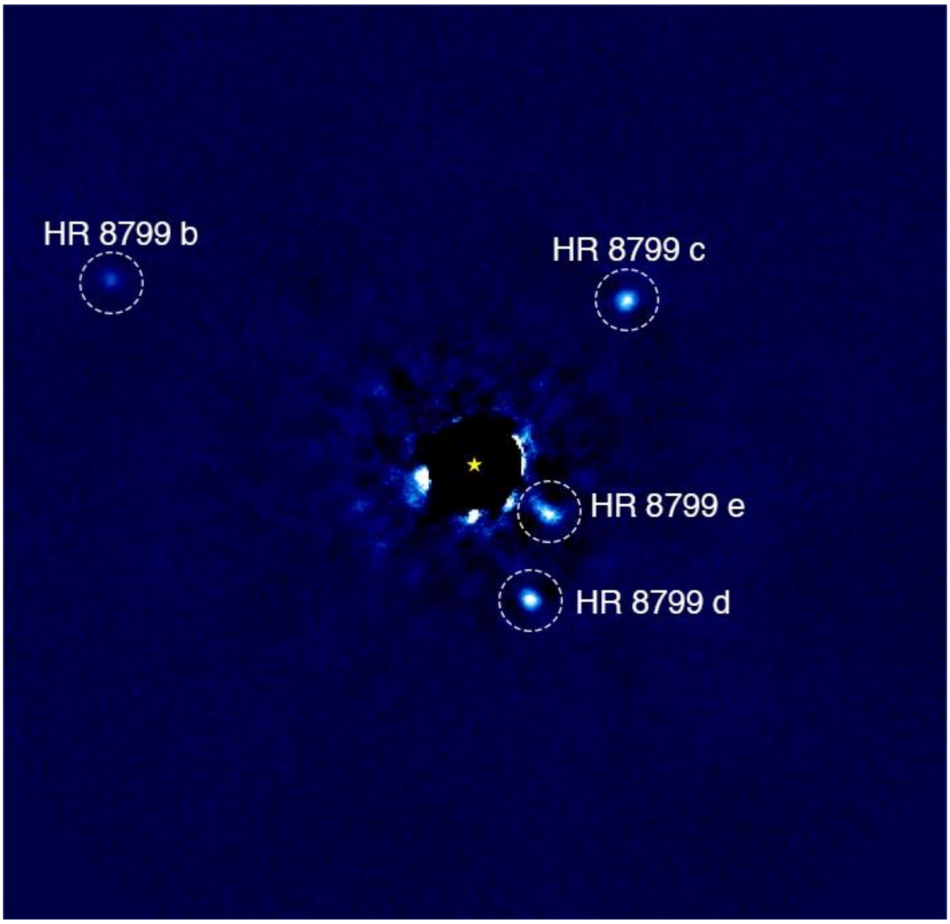

Figure 7: Displays 4 exoplanets in system HR 8799, detected by Direct imaging method. The circled object displays the exoplanets with their star in the middle.

One can use spatial coherence [15] with this to maximize the information received about the system. Fig 7 displays the HR 8799 system [16] which is the best example to show that we can detect many exoplanets at the same time and track their orbits.

5.1 Limitations

Limited candidate pool-

This technique only detects very distant exoplanets which are young, hot, and bright (self-luminous gas giants) with wide orbits d > 5 AU and contrast values ~ $10^6 - 10^{10}$. These restrictions are being overcome with improvements in technology but remain a big factor in the lack of discoveries through this method.

Mass restriction-

Only data related to the apparent brightness of an object is collected via direct imaging. The lack of other types of data results in people not knowing the mass of the object.

Varying refractive index in the atmosphere-

Earth's atmosphere is not uniform, as we approach the exosphere, its density changes which in turn change the refractive index. Although this factor can be accounted for, the bigger problem is air turbulence, the warm and cold pockets in the atmosphere, these come and go in random patterns which bend the light (even the slightest of bends can cause observations of these distant objects to become inaccurate).

6. ASTROMETRY

It is the oldest technique used for detecting exoplanets in other star systems. Similar to other indirect measurement techniques, it depends on the relative movement of a star due to its companion mass. Unlike radial velocity, astrometry uses direct measurement of the position of a star to deduce its period and related qualities of the system. A distant star is usually taken as a source of reference, defined as an astrometric frame reference [18].

The Gaia space mission by the European Space Agency acted as a steppingstone for the technology needed to use astrometry. Launched in 2013, it has released three massive datasets, observing over two billion objects in deep space, with the latest one in 2022 [19] and is expected to continue till 2025.

The amplitude S of an astrometric signal is expressed as –

$$S = \frac{m.r}{M.D} \qquad (6)$$

Where m is the mass of the exoplanet, r is the semi-major axis of the planet's orbit, M is the mass of the host star, and d is the distance from the observer to the star system. This equation shows that astrometry is biased for Jupiter-like gas giants around small stars (to give a small mass ratio), at a long distance and around nearby stars.

It is better suited to observe systems which are face on, whereas the spectroscopic method is appropriate for edge-on orbits. Another distinction is that while radial velocity is effective for detecting planets in close-in orbits, astrometry is more suited for identifying planets with longer orbits. This is because astrometry detects the component of a star's movement that changes its position in the sky, which is perpendicular to the observer's line of sight from Earth. These distinctions make them the perfect complementary methods to observe.

6.1 Limitations

Static interference

Increase in sensitivity in instruments can degrade the accuracy of measurements. Phenomena such as star spots and cool patches on the surface of a star could be detected by advanced technology. It could falsely represent the movement of a star by a companion when its stationary.

Period Length

Though observing long period objects is an astronomer’s long-sought wish, it presents another challenge. To support the claim of a planet, it is necessary to show repeated periodic movement of the star, this means observatories will have to look at these objects for many years before arriving at a confident analysis.

Range

Astrometry requires extremely delicate observations to see any reasonable pattern. As deduced from the equation for amplitude S, the magnitude of observation decreases with an increase in distance. This limits the range of detection by astrometry to our neighborhood systems.

7. PRESENT ADVANCEMENTS

To understand the potential that we have for detecting extrasolar planets it is necessary to first get familiarized with the present capabilities and the path that we paved to lead us to this point.

The use of pulsar timing in 1992 [1] marked a significant milestone in detecting planetary mass bodies outside our solar system. In 1988, precise radial velocity measurements (using the Doppler effect) hinted at the presence of planetary-mass objects around main sequence stars. However, it was not until 1995 [20] that the first definitive detection of such objects was reported.

The proof that there are planets outside our solar system motivated scientists and astronomers to improve upon the existing methods of detection. In 1998, the method of gravitational microlensing was used to gather support for the existence of a planet with low mass [21], which was found to be orbiting a star located close to the center of the Galaxy at approximately 30,000 light-years. The first officially confirmed microlensing planet was announced in 2004 [13].

The search for exoplanets using photometric methods has yielded significant milestones. In 1999, the first transit of an exoplanet that had been detected earlier was officially recorded [6]. Subsequently, in 2003, the first discovery of an exoplanet using transit photometry was reported [8]. After these unprecedented discoveries, space agencies stirred up the search for exoplanets by launching space observatories above our heads to detect them so let's go on a trip back in time to really understand where we stand today.

The Humble Beginnings

It starts with our best friend The Hubble Telescope, which has spent years up above the Earth’s atmosphere consistently delivering groundbreaking data. In 2000, it studied HD 209458 b which is an exoplanet in the constellation of Pegasus. HST was the first telescope to directly measure an exoplanet’s atmosphere by using the background light from its star. The Microvariability and Oscillations of Stars Telescope (MOST) was a Canadian satellite dedicated for studying asteroseismology and exoplanets which transit in front of their stars [22].

Spitzer was an infrared space observatory launched by NASA in 2003 and has given incredible hopes for the existence of more Earth-like planets by discovering the TRAPPIST system which consists of seven exoplanets revolving around a red dwarf star [23].

Convection, Rotation and Planetary Transits Satellite (CoRoT) was launched by a France space agency (CNES) which uses transit method as the primary method for detecting exoplanets and it has found a total of 34 confirmed extrasolar planets during its lifetime.

The Modern era

This era was signified with the launch of Kepler telescope in 2009 which has made the greatest contribution in the field of exoplanets as it discovered more than 2500 exoplanets in its lifetime that lasted about nine years. It was launched in the heliocentric orbit above Earth and was fixed to observe a certain patch of the space for a long time where it will detect planets as they transit in front of their parent star and cause a dip in their brightness, the amount of time it takes to transit will help us to determine its orbital period. After facing some technical difficulties, Kepler started anew as K2 on an extended mission which forced it to look at a new patch every 3 months. It has helped to discover an 8-planet system similar to ours with each planet orbiting closer to its star than the distance between Earth and Sun. It finally retired in 2019 leaving behind an indelible mark, revolutionizing our understanding of exoplanets, and unveiling a treasure trove of celestial marvels. Nevertheless, the hunt for exoplanets continues as NASA launched the Transiting Exoplanet Survey Satellite (TESS) which, as the name suggests, uses the transit method as the primary method of detecting exoplanets. The conclusion of this period was given in 2022 with the exoplanetary count breaking the 5000 milestone.

The Advanced era

This period has started off with the mind-blowing discoveries which are being made by humanity's most advanced space observatory – 'James Webb Space Telescope' (JWST). It was launched by NASA in December of 2021 and became functional to carry out missions in 2022. It works in the infrared spectrum which is invisible to the human eye but will allow the telescope to look further away or back in the past, it orbits in the Lagrange 2 or L2 point around the Sun.

K2-18b

This particular exoplanet was first found in the data from Kepler satellite's K2 mission [24]. Recently, another observation of this exoplanet by the JWST has spurred a lot of attention due to a paper claiming to find life signatures on this planet. The existence of dimethyl sulfide [25] is only associated with known biological processes. Since then, two more groups have published their own hypothesis of this unusuality. The first one claims that although the atmosphere is dominated by hydrogen, the surface is made of magma which covers for the excess of CO2 [26]. Whereas the second group presents different models that might be possible on the planet and then deduces that a mini-Neptune without any surface is the most probable theory [27]. More observations and research are required to confirm any of the proposals.

8. FUTURE SCOPE

Exoplanet detection has come a long way since its inception and will continue to improve. Technology has also been growing at a rapid pace with machine learning now making its way in exoplanet detection as well. With the instruments getting more precise, the amount of data needed to be processed is growing manifold but new solutions with machine learning are coming into play. This paper by A. Barboza [28] describes using a machine learning algorithm called K-means to classify exoplanets from data into 3 groups - Hot Jupiters, Long Period Giants and Small Planets. Since the beginning, scientists have been finding ways to address many problems such as the noise from the atmosphere. This paper by Baranne [29] discusses the first possibility to replace the iodine cell method with another instrument that will give the exact changes in atmosphere.

The development of the Nancy Grace Roman Space Telescope is currently underway, with an expected deadline . This great observatory will primarily focus on discovering the truth about dark matter. Another great observatory which has been recommended by National Academies of Sciences [30] is the Habitable Worlds Observatory for launch in the 2040s. The primary objective for this observatory is to detect, study and categorize habitable exoplanets. To achieve this, they have suggested a large telescope (~ 6 m diameter) with a high contrast imaging (~ 10-10). This is not possible with the existing technology, but we have already reached a contrast of up to a factor of millions, so this might not be that far.

9. CONCLUSION

In this paper we discussed the ever-evolving domain of extrasolar planets, beginning with a brief about the first discovered exoplanet and methods. We discussed key detection methods including Radial Velocity, Transit, Gravitational Microlensing, Direct Imaging, and Astrometry, each with its unique strengths and limitations. Subsequently, we noted the progress of exoplanetary research through pivotal missions, from the early triumphs of the Hubble Space Telescope and observatories like MOST and Spitzer, to the transformative discoveries made by Kepler, which unveiled over 2500 exoplanets.

Kepler's legacy is now carried forward by TESS, and the cutting-edge James Webb Space Telescope (JWST), which promises to revolutionize our understanding of exoplanetary atmospheres and potential habitability.
We then discussed the intriguing case of K2-18b, an exoplanet that has sparked significant interest due to potential biosignatures detected by JWST, though further observations and analyses are needed to confirm these findings.
Finally, we looked at the future of exoplanet detection, which promises to be bright with the integration of advanced technology and machine learning. New algorithms are being developed to handle the vast amounts of data generated by modern instruments, allowing for more efficient and accurate exoplanet detection and classification. The application of machine learning and upcoming telescopes, like the Nancy Grace Roman Space Telescope and the proposed Habitable Worlds Observatory, signify the ongoing advancements that promise to address present limitations and explore the depths of our universe further. These efforts underscore a rapidly advancing field, poised to unveil deeper insights into planetary formation, the nature of distant solar systems, and the potential for life beyond Earth.

REFERENCES

1. Wolszczan, D. A. Frail. "A planetary system around the millisecond pulsar PSR1257 + 12". Nature, vol. 355, pp. 145–147, Jan. 1992
2. D. A. Fischer, A. W. Howard, G. P. Laughlin, etal. "Exoplanet Detection Techniques." Protostars and Planets VI, pp. 715-737, 2014
3. M. Perryman. The exoplanet handbook. Cambridge university press, 2018
4. Lovis, D. Fischer. "Radial Velocity Techniques for Exoplanets." Exoplanets, pp. 27–53, 2011
5. S. S. Brems, M. Kürster, T. Trifonov, S. Reffert, and A. Quirrenbach. "Radial-velocity jitter of stars as a function of observational timescale and stellar age." Astronomy and Astrophysics, vol. 632, Art. no. A37, 2019.
6. Charbonneau, T. M. Brown, D. W. Latham, and M. Mayor. "Detection of Planetary Transits Across a Sun-like Star." The Astrophysical Journal, vol. 529, pp. L45–L48, 2000.
7. H. Essamlali, O. Yassine & O. Rachida. "Pfe-exoplanets detection methods." Thesis, Jun. 2023
8. M. Konacki, G. Torres, S. Jha, D. Sasselov. "An extrasolar planet that transits the disk of its parent star." Nature, vol. 421, pp. 507-509, Jan. 2003
9. M. Auvergne, P. Bodin, L. Boisnard et al. "The CoRoT satellite in flight: description and performance." Astronomy & Astrophysics, vol. 506, pp. 411-424, Mar. 2009
10. T. M. Brown. "Expected Detection and False Alarm Rates for Transiting Jovian Planets." The Astrophysical Journal, vol. 593, pp. L125, Jul. 2003
11. F. Fressin et al. "The false positive rate of Kepler and the occurrence of planets." Astrophysical Journal, vol. 766 (2), pp. 81, Mar. 2013
12. A. Cassan. "Extrasolar planets detections and statistics through gravitational microlensing." Hal Thesis, Sep. 2014
13. I. A. Bond, A. Udalski, M. Jaroszyński, N. J. Rattenbury, B. Paczyński, I. Soszyński et al. "OGLE 2003-BLG-235/MOA 2003-BLG-53: A planetary microlensing event". The Astrophysical Journal, vol. 606(2), pp. L155, Apr. 2004
14. N. Koshimoto, Y. Shvartzvald, D. P. Bennett., et al. "MOA-2016-BLG-227Lb: A Massive Planet Characterized by Combining Light-curve Analysis and Keck AO Imaging". The Astronomical Jour-

nal, vol. 154(3), pp. 15, Jun 2017
15. NASA, "Astro2020 Science White Paper", Available: https://lisa.nasa.gov/documentsAstro2020.html, 1/1/2020
16. J. J. Wang, J. B. Ruffio, E. Morris et al. "Detection and Bulk Properties of the HR 8799 Planets with High-resolution Spectroscopy". The Astronomical Journal, vol. 162(148), pp. 24, Sep 2021
17. G. Chauvin. "Direct imaging of exoplanets: Legacy and prospects". Académie des sciences, vol. 24, pp. 129-150, Jun. 2023
18. M. Endl & W. D. Cochran. (2007, Sep. 2). "Encyclopedia of the Solar System" (2nd edition) Ch. 47, 887–902 (Academic Press, 2007). Available: https://doi.org/10.1016/B978-012088589-3/50051-7
19. Vallenari, A. G. A. Brown, T. Prusti. "Gaia data release 3-summary of the content and survey properties". Astronomy & Astrophysics, vol. 674, A1. Jun. 2023
20. M. Mayor, & D. Queloz. "A Jupiter-mass companion to a solar-type star." Nature, vol. 378, pp. 355–359, Nov. 1995
21. J. Wambsganss. "Gravitational Lensing in Astronomy." Living Reviews in Relativity, vol. 1, pp. 12, Dec.1998
22. J. M. Matthews. "Asteroseismology from Space: Getting the MOST Science for the Least Money." Structure and Dynamics of the Interior of the Sun and Sun-like Stars, vol. 418, p. 395, 1998.
23. M. W. Werner et al. "The Spitzer Space Telescope Mission." The Astrophysical Journal Supplement Series, vol. 154, pp. 1-9, May. 2004
24. Foreman-Mackey, B. T. Montet, D. W. Hogg, T. D. Morton, D. Wangand & B. Schölkopf. "A Systematic Search for Transiting Planets in the K2 Data." Astrophysical Journal, vol. 806, no. 2, p. Art. No. 215, Jun. 2015
25. N. Madhusudhan, S. Sarkar, S. Constantinou, M. Holmberg, A. Piette & J. Moses. "Carbon-bearing Molecules in a Possible Hycean Atmosphere." The Astrophysical Journal Letters, vol. 956, pp. 16, Oct 2023
26. O. Shorttle et al. "Distinguishing Oceans of Water from Magma on Mini-Neptune K2-18b". The Astrophysical Journal Letters, vol. 962, pp. 9, Feb 2024
27. N. F. Wogan et al. "JWST Observations of K2-18b Can Be Explained by a Gas-rich Mini-Neptune with No Habitable Surface". The Astrophysical Journal Letters, vol. 963, pp. 10, Mar 2024
28. Barboza, S. Ulmer-Moll, and J. Faria. "Classifying Exoplanets with Machine Learning." Europlanet Science Congress, 21 September–9 Oct 2020
29. Baranne. "ELODIE: A spectrograph for accurate radial velocity measurements." Astronomy and Astrophysics Supplement Series, vol. 119, pp. 373–390, Oct 1996
30. National Academies of Sciences, Engineering, and Medicine. (2023). "Pathways to Discovery in Astronomy and Astrophysics for the 2020s". Available: https://doi.org/10.17226/26141