Analysis of the State-of-art Planet Searching Results: Evidence from Radial Velocity, Relativistic Beaming and Polarimetry

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Abstract. The present research describes some of the newest techniques being used in exoplanetary detection, with a focus on radial velocity, (RV), relativistic beaming, (RB), and polarimetry. In light of worsening environmental conditions due to global warming, and an increased need for assessing the habitability of Earth, the investigation into plausibly habitable planets has become a priority area for modern scientific investigations. Over the last several decades, improvement in observational methodologies has turned the detection of exoplanets from a theoretical speculation into an objectively viable scientific domain. Empirical discoveries have extended the catalog of planetary diversity by showing a variety of worlds with diverse characteristics. Each technique discussed in this paper provides aggregate information on the detection, measurement, and characterization of distant planets by their properties, including their mass, orbit, atmospheric properties, and possible habitability. This research combines these approaches to underline their respective strengths and importance in investigating crucial questions related to the possibility of life beyond Earth.

Keywords: Exoplanet detection, radial velocity, relativistic beaming, polarimetry, planetary systems.

1. Introduction

The search for exoplanets, those planets moving outside the solar system, is an exciting, transformative aspect of modern astronomy. This area combines burgeoning detection techniques with more modern interpretational technology, making sense of the night sky at a faster rate than at any other time in history. Since the early 1990s with the discovery of exoplanets such as 51 Pegasi b, the discovery of exoplanets not only expanded humanity’s understanding of local planetary systems, but also revealed a wider range of options to look for farther in space. From gas giants such as Jupiter to rocky planets resembling Earth, exoplanet research has reshaped humanity’s vantage on the universe and the potential for sentient life beyond Earth [1-3].

Historically, 51 Pegasi b, was the first exoplanet around a Sun-like star confirmed through RV [4]. RV successfully detected it by monitoring a nearby star’s barely perceptible shifting spectral lines caused by the gravitational effect of this otherwise undetected nearby planet. Since then, observational technical improvements have promoted RV measurement accuracy significantly, allowing detection of planets of smaller masses [5]. Additionally, complementary techniques including Transit Photometry (TP) and Microlensing detected planets through observing periodic reduction in stellar brightness when a planet crosses in front of its host star. Microlensing detects planets through gravitational lensing effects, also playing a crucial role in the exponential growth of exoplanet detection. The Kepler space telescope, launched in 2009, had discovered more than 2600 confirmed exoplanet planets using this technique [2].

More recently, since the 2010s, exoplanet detection techniques have reached an unprecedented accuracy, making the planets with Earth-like characterization discoverable. For instance, the advent of high-resolution spectrographs in such as Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope (VLT), has pushed RV sensitivity to 0.5 meter per second [3]. These advancements have expanded the scope of exoplanet research from detecting large, gaseous planets in closer orbits to exploring smaller, potentially habitable rocky planets. Similarly, new space missions such as Transiting Exoplanet Survey Satellite

(TESS) have shifted the focus to searching for planets around brighter and closer stars, facilitating detailed atmospheric studies [4].

This summary outlines three advanced exoplanet detection methods: i.e., radial velocity (RV), relativistic beaming (RB), and polarimetry; they provide complementary perspectives for the research on characterization of exoplanet detection separately. RB, a more recent tool, detects periodic brightness variations in a host star caused by the Doppler effect, due to its motion under gravitational forces, and polarimetry studies the polarization of the light reflected from exoplanetary atmospheres, providing the insight of atmospheric properties. Combining these three methods comprises a powerful, multi-data approach to exoplanet detection. These methods can make effective, detailed models from their complementary data. RV makes the measurement of mass possible, while RB helps make an accurate orbit parameter polarimetry adding atmospheric details. The continuous development of these methods is considered important for determining the frequency of human-habitable planets in the universe. These multiple methods, especially polarimetry, allow the detection of biosignatures, such as oxygen, methane and water vapor, as necessary indicators in biosphere and biological activities [5]. As environmental challenges on Earth intensify, it has become a pressing scientific priority to searching for livable planets. By combining RV, RB and polarimetry, research aims to construct a comprehensive framework, using more exoplanetary detection and characterization. Each method's specific contribution lets this multidimensional method make it more complete to solve the frequency of livable planets, the atmospheric type suitable for life and the problems on distant planetary systematic characterization.

2. Description of Planet researching

In past decades, innovative methods and advanced techniques have made the detection of exoplanets easier. Presently, several types of major detection techniques have matured, where each one provides more unique information about planetary characteristics, including mass, orbit, density and surface temperature. Radial velocity, (RV), and transit photometry, (TP), are the two most widely applied methods, and the new generated methods such as direct imaging, gravitational microlensing, and astrometry offer comprehensive supplements aiding planetary detections [6-8].

RV is one of the central techniques of exoplanet detection. By analyzing Doppler shifts due to the planetary gravitational force effect, RV can detect the mass and orbital period of the planets accurately. Advanced spectrographs, such as ESPRESSO on the Very Large Telescope, (VLT), greatly improve RV's sensitivity, allowing detection of tiny Earth-like planets with a velocity less than one meter per second [7]. Unfortunately, RV is relatively weak for detection of more massive planets in higher stellar activity systems [6].

TP identifies planets through the periodic reduction in stellar brightness as planets go through the stellar surface.TP is also a process by which planets are hunted for through observing small, periodic drops in the brightness of a star. This occurs when a planet has passed in front of its star, as viewed from Earth, blocking a minute portion of the star's light-the effect being somewhat like trying to notice a shadow passing momentarily across a lightbulb. With such dips, scientists can reduce the size of the exoplanet, its orbit, and even some characteristics of its atmosphere. This method is well suited for detecting planetary radii, orbital inclination, and even atmospheric composition when combined with spectroscopy. The Kepler space telescope's monitoring changes in stellar brightness whilst discovering thousands of exoplanets, greatly advanced the development of TP techniques.[8] Regrettably, TP must accurately align between planetary orbits and observers' sight, limiting its available range [6].

Direct imaging can perform visible observations, which is especially useful in researching planetary brightness, albedo, the surface reflectivity, and atmospheric characteristics. Although this method can only observe young, large mass planets which are far from stars, the advancement of adaptive optics, tech correcting atmospheric distortions, and coronagraphs which block starlight to reveal nearby objects. Technology has aided detection of small Earth-like planets [7]. Gravitational microlensing, using the effect of planetary gravitation bending light, is appropriate for detecting distant or freely floating planets. Astrometry, which tracks minute changes in position of a star due to a planet's gravitational influence, is getting continuous technical improvement from tasks like Gaia. Gaia is a space observatory launched by the European Astronaut Corps to map the positions, motions, and characteristics of stars [8]. The data gained by each method buffets the next, comprising a multi-dimensional planetary system. RV and TP work well to measure mass, orbital characteristics and density while direct imaging and polarimetry reveal the atmospheric conditions and temperature of planets [6, 7].

3. Radial Velocity

RV techniques are an effective tool for exoplanet detection. Through observing orbitally moving planets, which causes tiny periodic motions or “pendulums” in the host star, RV offers another method for indirect exoplanet detection. A pendulum indicates slight changes in stars along the velocity of the observers’ sights. Using the Doppler effect, where light from an object moving toward the observer is slightly compressed (blue-shifted) and light moving away is expanded (red-shifted), astronomers can detect these changes in velocity in the stellar spectrum. By analyzing these changes carefully, researchers are able to speculate about planetary existence, orbital characteristics and even an estimation of its mass. The value of this method is that it can detect planets indirectly, providing one way for solving the situation where direct imaging is impossible due to the extreme distance and faintness of planets relative to their stars. For decades, RV has been the main key to discovering and researching new planetary systems, as crucial for scientists to understand exoplanetary science [9, 10]. In the 1990s, as the 51 Pegasi b was discovered, marking as the formal beginning of the astronomical use of radial velocity (RV) for exoplanet detection. This discovery was not only one of the first certified exoplanets, but also certified the reliability of RV detection. Since that time, there has been development in improving RV’s velocity measurement.

Spectrography has greatly increased RV’s precision. Early RV instruments could only measure the change in stellar velocity, down to several meters per second, enough to detect immense massive planets. Modern spectrographs have achieved precision levels within 1 meter per second or better, allowing detection of much smaller planets. In addition, improving the telescopic stability, atmospheric interference control and advanced data processing lowered the error and noise significantly, improving the effectiveness of this method [10, 11]. The radial velocity (RV) curve of 51 Pegasi b is shown in Fig. 1 [9], where the data points represent the observed radial velocity measurements for 51 Pegasi. The solid line illustrates the best-fit Keplerian orbital model for the system.

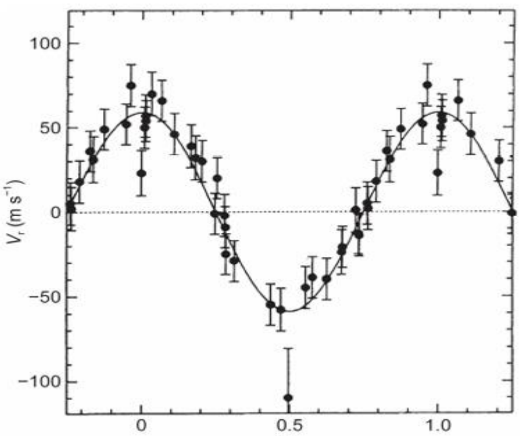

Figure 1. Radial velocity curve of 51 Peg b [9]

This improvement in sensitivity is crucial in detecting low-mass planets as well as bigger planets on wider orbits. With improved RV functionality, researchers can now detect previously unnoticed planetary signals. RV data is complicated to explain, being extremely dependent on statistical models to correctly identify the planetary signal distinct from background noise. Once RV measurements capture the tiny changes in stellar velocity, scientists must analyze the data carefully to confirm the existence of orbital planets. The key to accurate RV analysis is to distinguish the real planetary signal with various noise sources, including stellar movements, instrument effect and observational error.

Statistical methods are crucial in this type of research. Researchers use statistical methods dividing the indicated planet's periodic signals and non-periodic disturbances. For instance, Bayesian inference is the common tool for analyzing RV data, as it allows scientists to use a reliable interval estimating planets' parameters such as planetary mass and orbital distance. Through building the probability model, researchers can quantify the possibility of planetary characterization, and provide a more credible conclusion about its existence and property [12]. Denoise is another important part of RV analysis data. Caused by phenomena such as stellar spots, pulsations, or magnetic activity, stellar noise can lead a transformation in RV measurement, thus imitating or concealing the planetary signals. Advanced noise filtering techniques, such as Gaussian processes, are generally used to separate these planetary effects from real planetary signals. These statistical methods can explain RV data much more accurately and precisely, aiding researchers to detect planets possibly hidden in the noise [13, 14].

Although RV is a powerful tool, it has limitations. RV is less effective in detecting planets with very low mass and planets located on a wider, more distant orbit. RV measurement is sensitive with the ratio of stellar and planetary mass, meaning the planets which own greater masses or closer to stars will produce more powerful, more easily detected signals. Detecting the planets with Earth's Mass, especially on the distant orbit around a sun-like star, is still a challenging topic even though progress is continuously pushing these boundaries [15]. One major challenge for RV is its interference by stellar movements. Stellar movement such as the stellar internal magnetic changes or oscillations, produce changes in velocity, imitating the influence of orbital planets. This interference may cause false positive reporting, or "coving", of actual planetary signals, making the detection process unclear. To address this challenge, researchers always use other instruments' synchronous observation, such as the photometer, which is better to distinguish stellar noise and plenary signals. Additionally, using advanced algorithms to stimulate and decrease these influences, one can improve the reliability of RV measurement [16]. Even with these challenges, RV keeps developing and adapting. With technical improvement and complicated analyzing techniques, RV is still the most reliable method for discovering exoplanets, especially when combined with other detection methods [15, 16].

RV is not only a tool of detection, but also vital for researching the various data from exoplanets. By analyzing large quantities of RV data from various stars, scientists can determine the planetary characterization and the trend of distribution, thus gaining a deeper understanding of the diversity of planetary systems. RV data reveals an important discovery of various types of planetary, (such as gas giants, super Earths, and smaller rocky planets), incidence rate. These observations are critical for understanding the process of planetary formations and transformations and identifying the typical structure of planetary systems [13, 16].

One of the significant contributions is the deep understanding of the multiplanetary system. Through RV observation, researchers discover the multiple planets around one single star, revealing the complicated, various systematic structure. These findings provide the model of planetary system's formation, indicating some types of system might be more common than other types [11, 16]. These demographic research offers a wider background for a single planetary detection, and helps the corpus of developing planetary theory. As innovation keeps improving RV's accuracy and applicability, the future is full of hope. One developing field is producing laser-combed spectrographs which offer higher accuracy by providing stable and accurate wavelength references. These instruments can perform more highly accurate RV measurement, and are reliable to improve the detection for low-mass planets, or these planets will be barely detectable [9, 10, 13, 15]. Machine-learning technology could be also applied in RV data analysis, enhancing the ability of identification and characterization of weak planetary signals under noises. These algorithms can collate with large data sets, offering more efficient data procession while lowering the risk of human error. Machine learning can also help improve noise reduction technology and make RV data cleaner [10, 12].

In the future, RV may possibly play a key role in researching planets within the habitable zone of stars. The upcoming surface and space-based telescope will expand the range of RV observations. As RV techniques progress, it would be helpful to research the exoplanetary atmospheres, especially when combined with other methods of detection. Such may reveal the details of exoplanetary livability one day, and perhaps even the potential biological characterization, deeper the understanding of the planets outside the solar system [14, 16].

4. Relativistic Beaming: A Supplementary Method for Planetary Exploration

RB, also called as Doppler Boosting, is an advanced photometric technology used for assisting RV methods in performing exoplanetary detection and characterization. Unlike detecting planets by stellar spectral line shift caused by planetary gravitation such as RV methods, RB is based on the tiny stellar changes in brightness when the star moves due to the gravitational influence of its companion stars. This fluctuation in brightness provides key information for researching planetary mass and orbital characterizations [17-21].

RB originates from the combination of relativistic effect and Doppler effect; these effects jointly influence the observational strength of stellar lightness. When the star moves towards the Earth, the frequency of its light increases slightly (blue shift), thus it seems brighter; when the star moves far away from the Earth, the frequency of its light decreases slightly (red shift), and its brightness relatively reduces. This change in brightness is periodic, directly related to the orbital period of a star-planet system moving around its center of mass [18, 22]. Photometric variation Caused by relativistic beaming (PVCBRB) is extremely weak, generating only a few parts per million (PPM) in the stellar light variation curve. Detecting such tiny signals like this, scientists need highly sensitive photometric measuring instruments, for example, space telescopes such as Kepler, characterizing exoplanets satellite (CHEOPS) and Transiting Exoplanet Survey Satellite (TESS), which can both achieve extremely high observational precision [23-25].

The center of RB is the movement on planetary orbits, this movement determines the direction and amplitude of the beaming effect. When the star approaches, its light is compressed into a slightly higher-energy range (blue-shifted), increasing its perceived brightness. When it recedes, the light is stretched (red-shifted), resulting in dimming [20, 24, 26]. The amplitude of the PVCBRB is influenced by three key factors, i.e., stellar radial velocity, stellar characterization and observational band. The greater the velocity of stars along the sight's direction, the more obvious PVCBRB works; The star's mass, temperature and spectral type, this property would determine the stellar radiation flux and the changes in amplitude of observed brightness; The telescope's sensitivity for specific lights' wavelength affects the measurability of the effect. For instance, CHEOPS and TESS are more sensitive to visible light and near-infrared bands, respectively, which can affect their measuring ability of PVCBRB [23]. Mathematically, the PVCBRB can be described through the relationship between observational luminous flux and the stellar movements. In a simplified form, the observed flux (F_b), at a given time is proportional to the intrinsic stellar flux, (F_*), modified by the star's velocity relative to the observer:

$$F_b(t) \sim F_* \left(1 + \frac{4v_r}{c}\right) \tag{1}$$

Where v_r represents the stellar radial velocity, c is the speed of light. This formula above indicates that the amplitude of PVCBRB is directly proportional to the motion of stars [21, 27]. For the planetary systems with companion stars, the stellar radial velocity transformed into sine waves, causing periodic changes in brightness which can be observed and measured.

RB offers a crucial supplement for RV methodology; it can individually verify the measurement of planetary mass. Although RV measurement is very efficient, false reports exist occasionally, such as the signals caused by binary star systems disguised as planetary signals. Also, PVCBRB based on

Photometric observation provides additional tools to verify this situation [17, 26]. Additionally, combining the photometric variation data with RV measurement, scientists are able to more accurately estimate planetary orbit and mass. For instance, when RB paired with transit photometry, beaming can help distinguish between small, rocky planets and more massive gas giants, enabling more accurate characterizations of planetary systems [20].

RB's observational height crucially depends on the ability of modern space telescopes. The Kepler telescope, with unprecedented photometric accuracy, successfully detected this weak brightness variation in systems such as Kepler-76b [18, 25]. In a recent task, CHEOPS and TESS expand their detecting potential for PVCBRB. CHEOPS, with its high sensitivity and targeted observations of known exoplanet-hosting stars, is particularly suited for discovering the PVCBRB in the planetary systems with great mass and short orbital period. For TESS, although it has a slightly lower accuracy, its spacious view and the monitoring of large areas of the sky, providing it great advantages in detecting the light variation signals in bright neighbor stars (seen from Fig. 2) [18, 23].

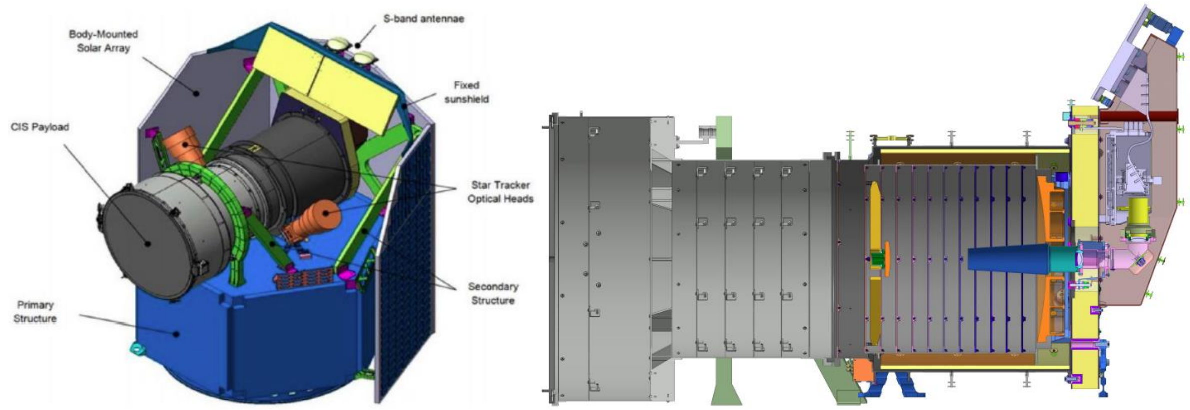

Figure 2. The configuration of the CHEOPS spacecraft and the integration of its units within the platform are illustrated [18]

Despite all this advancement, the RB method still faces challenges. This effect is generally covered by other photometric signals (such as stellar movements or instrument noises), making it difficult to be extracted and analyzed separately. In addition, the amplitude of photometric variation is relatively small, limited to systems with large RV amplitudes, or requires a longer observation time to be detected [27]. One typical case of RB is the detection of hot Jupiter Kepler-76b. In this system, the PVCBRB's contribution for the photometric curve is about 12 ppm; other photometric signals also existed at the same time, such as ellipsoidal variations and thermal reflection from the planet's dayside. By analyzing these combining signals, astronomers not only confirmed the mass of the planet, but also accurately determined its orbital parameters [22, 25, 26]. The case of Kepler-76b completely exhibited the crucial role of RB in the exoplanetary systems, especially combining with other detection methods as illustrated in Fig. 3. The Kepler light curve of Kepler-76b, where the relativistic beaming effect accounts for a 12-ppm contribution to the total observed variation [19].

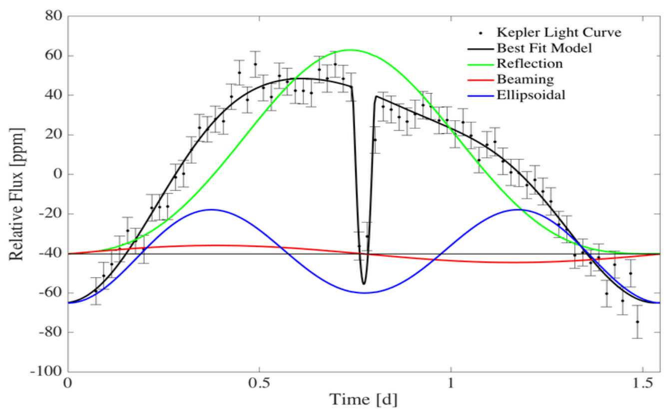

Figure 3. The Kepler light curve of Kepler-76b [19]

As observational technology advances, the role of RB in exoplanet detection will undoubtedly expand. The new generation of telescopes, such as James Webb Space Telescope (JWST) and the European Extremely Large Telescope (E-ELT), with higher photometric accuracy and sensitivity, can detect smaller beaming amplitudes, thus applying this method into a wider planetary system [24]. In addition, combining RB with other methods such as polarimetry and direct imaging, holds the potential for transformative discoveries. Through offering the complementary data about planetary mass, orbits and atmospheric characterization, these methods together can paint a more comprehensive picture of exoplanetary systems and their potential for habitability [19, 27].

5. Polarimetry: Insights into Exoplanetary Atmospheres

Polarimetry, the research on polarization characteristic of light, is a technique with unique advantages in exoplanet detection and characterization. Unlike focusing on the gravitational or photometric effects of planets on their host stars such as RV and RB, polarimetry investigates the interaction effect between planetary atmosphere, surface and clouds, revealing its characteristics. Through researching the polarization characteristics of reflected light, this method provides precious clues about atmospheric composition, cloud distribution and potential livability for exoplanets, holding significant importance in the detection of biomarkers [28, 29].

When the stellar light interacts with the exoplanetary atmosphere or surface, the light will partly polarize. This polarization is mainly caused by the scattering of light by molecules, aerosols, or cloud particles in the atmosphere. Tiny particles in the atmosphere can let the electric field of light oscillate along a specific direction in the scattering process, forming the polarization phenomenon. In addition, the reflection of light from planetary surfaces can also cause polarization characteristics, specifically depending on the composition and texture of the planetary surface [30].

The characteristics of polarized light include the degree and angle of polarization, through measuring these two indexes, the planetary atmospheric physical property, such as chemical components, particles' sizes' distribution, cloud coverage and surface reflectivity (albedo), can be determined. One key point is, some polarization characteristics may indicate the existence of water drop, organic compounds and other matters related to life, which make the polarization measurement become one crucial tool for discovering livability [31]. The polarized signals of exoplanets are generally extremely weak, these signals only have around 1 ppm strength compared to the direct light from their host stars in most cases. This low signal strength needs an extremely high requirement on the observational instruments' sensitivity. Polarimeter with high accuracy should be able to separate the polarization light reflected by exoplanets and unpolarized or weakly polarized light of the star itself [29]. The change in polarization signals is also highly related to planets' phase angles, which means the included angle between stars, planets and observers. For instance, when planets are presenting bright crescent shapes, the polarization degree would reach a peak value, providing important data for atmospheric modelling [30, 31].

Progress in polarization instruments significantly improves the availability of detecting polarization signals. Using ground telescopes for high precision polarimeters, such as SPHERE at the VLT, has got significant achievements in filtering stellar light and isolating planetary signals. These instruments combine adaptive optics technology and advanced polarization filters to effectively suppress the interference of starlight, thereby capturing the polarization signals of planets [28, 31]. Upcoming space tasks can probably push the boundary of polarimetry measurement further. The novel generated astronomic devices such as the Roman Space Telescope (formerly WFIRST) and the European Extremely Large Telescope (E-ELT), planning to bring polarization measurement functions in the observational abilities to achieve the direct imaging and characterizing for the exoplanetary atmosphere. This progress in techniques will probably improve sensitivity, creating new possibilities for detecting distant planets' weak polarized signals [29, 31].

One typical example of the potential of polarimetry measurement is the research of hot Jupiter HD 189733b. The observation indicates that there are some changes in polarized level at different positions on the orbit of this planet, which is determined to be caused by the atmospheric scattering with silicate particles and clouds. These discoveries not only confirmed the atmosphere composition for planets, but also showed how polarimetry measurement can reveal details which cannot be detected by traditional photometric techniques [28]. Another interesting possibility is using polarimetry measurement to identify livable evidence. For example, from the Earth's perspective as an exoplanet, its polarization signals show the characterizations of water clouds, oceans, and vegetation. This observation suggests that polarimetry's potential in discovering prospective biosignatures on Earth-like exoplanets

The unique advantage of polarimetry measurement makes it a crucial supplement of RV method and RB method. Even though RV and RB do well in confirming orbital parameters and planetary mass, polarimetry provides detailed information of atmospheric characterization. Combining these methods can achieve the complete characterization for exoplanets, bridging gaps in understanding their physical and chemical properties [29]. For example, combining polarized data with transit spectroscopy can provide constraints on atmospheric composition and dynamics. And if combining the polarimetry measurement with direct imaging techniques, the contrast ratio of planets and stars can be enhanced, improving the detecting ability on weak signals [28, 31].

The continuous development on polarization measurement is expected to change the research on exoplanets completely. As an improvement in detection techniques, polarimetry measurement plays an important role in discovering and characterizing earth-like exoplanets. The future observation may even detect polarized signals consistent with biological activity, offering direct providence for searching extraterrestrial life. Through revealing planetary atmospheres and surface characterization which are not able to be detected by other methods, polarimetry stands as a cornerstone in the quest to understand distant worlds. Its combination with other techniques also highlighted its importance in building a comprehensive picture of exoplanetary systems further, paving the way to the breakthrough in the field of planetary science and astrobiology [29-31].

6. Limitations and Prospects

Although there is significant progress in detection techniques, they still faced such a lot technical challenges and observational limitations. RV is very sensitive for large mass, near orbit planets, but it has troubles in detecting earth-like planets or orbital planets with a lower mass. RV's accuracy is easily affected by planetary movements such as magnetic field oscillation; these movements may imitate or cover planetary signals. Though complex statistical methods such as Gauss Process can relieve these problems in some way, planetary noise is still the main obstacle for getting completely available data. RB works as a valuable assistant method, depending on detecting tiny variations in stellar brightness, which requires highly sensitive photometric instruments. These signals are often covered by other photometric noise, demanding precise calibration and long observation periods. Current space telescopes like TESS and CHEOPS have improved sensitivity, but the method's reliance on ideal conditions limits its universality.

Polarimetry reveals the information of planetary atmospheres through research of the polarized characteristics, but it is actually limited by the weakness of polarized signals, which is generally extremely weak compared to stellar light. Even if those advanced instruments such as the SPHERE polarimeter on the VLT have made progress, they need specific geometrical alignment for the best data due to the influences of planetary phase angle which limited the polarimetry measurement. Looking to the future, integration of advanced techniques may solve these challenges. Developments, such as laser-combed spectrographs, machine learning algorithms for noise reduction and next-generation telescopes like the JWST and the E-ELT, could further improve detection accuracy further, expanding the range of planetary systems which are available to detect. Combining RV, RB and polarimetry with direct imaging and transit spectroscopy, will achieve the complete characterization for planets, including the detection of life signs. These progresses are hopeful to reveal Earth-like planets and provide observations about livability, paving the way for revolutionary discovery of planetary science.

7. Conclusion

To sum up, this paper discusses the three advanced methods for planetary detection, i.e., RV, RB and polarimetry, indicating their effects in advancing the field of exoplanet detection and characterization. RV performs excellently in detecting planetary mass; RB and PVCBRB improve the orbital parameters; Polarimetry measurement reveals the atmospheric characterization. They, together form a complementary frame, improving the understanding of distant planetary systems. The research result emphasizes these methods' increasing precision and potential in solving problems about planetary livability and diversity. Looking forward, technical progress and functional integration expect to break the current limitation, discovering more earth-like planets. This research not only pushes the identification of livable planets, but also deepens humans' understanding of the universe, offering a solid foundation for discovering extraterrestrial life in the future.

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