ISSN 2959-6157

Comparisons for Different State-of-art Planet Searching Scenarios: Transit, Radial Velocity and Direct-imaging

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Abstract:

The vastness of the universe has inspired mankind's infinite imagination of the exoplanets with living. The exploration of them reflects human beings' yearning for possible life and the pursuit of a possible future home. From the first detection of an exoplanet in 1992 to the detection of 5,747 exoplanets on August 16, 2024, scholars have worked hard to explore. This study presents typical results of exoplanet detection in recent years, describing in general terms which planet retrieval methods have been used, what results are obtained by each method and which parameters of the planet can be detected. To be specific, three main methods for detecting exoplanets are detailly evaluated, namely the transit, the radial velocity and the direct imaging. By comparing these three methods, detection methods suitable for different types of exoplanets are summarized. According to the analysis, the limitations of current exoplanet detection are summarized based on the results, and future countermeasures are outlined. These results offer a guideline for exoplanet exploration and shed light on understanding the three main methods of detecting exoplanets.

Keywords: Exoplanet detection; transit; radial velocity; direct-imaging.

1. Introduction

With the continuous development of astronomy and space technology, the exploration of exoplanets by astronomers has gradually become a popular area of scientific research. The number of exoplanets, which are planets located outside of the solar system and orbiting other stars, is greater than has ever been thought. Exploring these planets has profound implications for understanding the universe, the search for life and a better future for mankind. With the environmental factors of global warming and pollution emissions, as well as the population crisis, human beings have to look at other planets. This has led to a better understanding of the evolution of these planets, which can be used to predict the eventual fate of the Earth and where humanity will go in the future [1]. In addition, in the process of detecting exoplanets, different aspects such as mass, radius, temperature and orbital parameters have been obtained through different methods of detection [2]. Such extreme diversity in the macroscopic nature of exoplanets places the solar system in a cosmic context for the first time [2]. This led to the creation of the theory of planet formation. Its goal was to develop a single theory that explains how the different planets formed [3].

In January 1992, the first exoplanet was discovered [4]. However, it wasn‘t just one exoplanet that was discovered.The 6.2-ms pulsar PSR1257-12 was shown to be surrounded by three planets. Then in 1995, scientists found a Jupiter-mass companion to a solar-type star [5]. Over the next fourteen years, new planets continued to be discovered, but the total number of discoveries was not large. This situation was completely changed when the Kepler planet-finding mission was launched. In March 2009, the Kepler probe was launched into a heliocentric orbit trailing the Earth, with the aim of probing the abundance and characteristics of the planetary system [6]. Kepler‘s first operation ended in May 2013 when its second re-action wheel failed [6]. The Kepler probe‘s second mission, k2, ran from March 2014 through September 2018. Thousands of planets, including hundreds of planetary systems, have been discovered in the nearly ten years that the Kepler probe has been in operation [6]. There is no doubt that Kepler has contributed greatly to the detection of exoplanets. Later, the TESS mission emerged after the Kepler mission to continue the planets. The TESS mission was launched in April 2018 [7]. By August 16, 2024, a total of 5,747 exoplanets had been discovered [8].

The purpose of this article is to present three methods of finding exoplanets, which are the most promising methods of detecting exoplanets today. By analyzing and comparing the three methods, one can be made aware of the advantages and disadvantages of the three methods and is given some idea of the principles of the detection methods and the facilities used. Sec. 2 will present what are the methods of planetary detection, what are the results obtained by each one of them and what are the parameters of the planets that can be specifically detected. Sec. 3, Sec. 4 and Sec. 5 will demonstrate the principles of the detection methods and the utizlied equipment as well as the typical results obtained with the three methods, respectively. In Sec. 6, the three approaches will be compared and contrasted, exploring the applicability of each, the limitations of current exoplanet exploration, and the outlook for the future. Finally, a conclude remark will be presented in Sec. 7.

2. Description of Exoplanet Detection

There are a variety of methods that can be used to detect exoplanets either directly or indirectly. The main ones are transit, radial velocity, direct imaging, gravitational microlensing, astrometry, pulsar timing , transit timing, eclipse timing, orbital brightness modulations and disk kinematics. The most common and well-known of these are the transit as well as the radial velocity. The number of exoplanets detected by these two methods are the most.

Transit is the most effective method. The Kepler planet-finding mission has detected thousands of exoplanets using this approach. In total, 4279 exoplanets have been discovered through TRANSIT so far [8]. The orbital period of a planet can be determined by measuring the elapsed time between transits. Kepler‘s third law of planetary motion can then be applied to determine the average distance of the planet from its star. It is also possible to derive planetary radii from measurements of transit depths [9]. The radial velocity method was one of the first successful searches for exoplanets and remains one of the most effective. This method is also used to identify planets discovered by other methods. Up to now a total of 1092 exoplanets have been discovered by radial velocity [8]. RV varies in magnitude proportional to the planetary mass, whose shape depends on the orbital eccentricity [10]. The amplitude of the radial velocity profile can therefore be used to infer the minimum mass of the planet. Radial velocity also measures orbital period [9]. Direct imaging is still at the beginning stages as an exoplanet finding method. A total of 82 exoplanets have been discovered today using direct imaging [8]. Direct imaging allows direct measurements of the orbits of exoplanets as well as the phase changes as the planets rotate around their stars [9]. Atmospheric characterization is also possible through direct imaging. Gravitational microlensing comes from the general theory of relativity proposed by Einstein. A total of 224 exoplanets have been discovered through gravitational microlensing to date [8]. Gravitational microlensing probes the mass ratio between an exoplanet and its host star. Astrometry requires extremely sophisticated optics, which makes detection difficult. Thus only three exoplanets have been discovered by astrometry so far [8]. The mass of the exoplanet as well as its orbital inclination can be obtained through astrometry [11].

These five methods are now the most popular methods of detecting exoplanets. The remaining exoplanets are 30 with transit timing, 17 with eclapse timing, 8 with pulsar timing, 2 with pulsation, 9 with orbital brightness modulations, 1 with disk kinematics [8].

3. Transit

The basic principle of the transit is that when a planet passes directly between an observer and the star which the planet orbits, the planet blocks some of the star‘s light, dimming the observed star.Transit can be understood through the more obvious phenomenon of solar eclipse. The principle of transits is similar to that of solar eclipses. According to the principle of transits, transits can occur within the solar system as well as outside of the system. Transits in the solar system can be observed from Earth as Mercury or Venus passes between the Sun and Earth. Transits work by observing changes in the brightness of a star to detect possible exoplanets. When a star is observed to dim, if this change in brightness is detected at regular intervals and the duration is fixed and repetitive, then it is likely that another fainter object is orbiting the star. A small percentage of these fainter objects are small, dim stars, and most are exoplanets. Fig. 1 presents the propabaility for star with different masses [8].

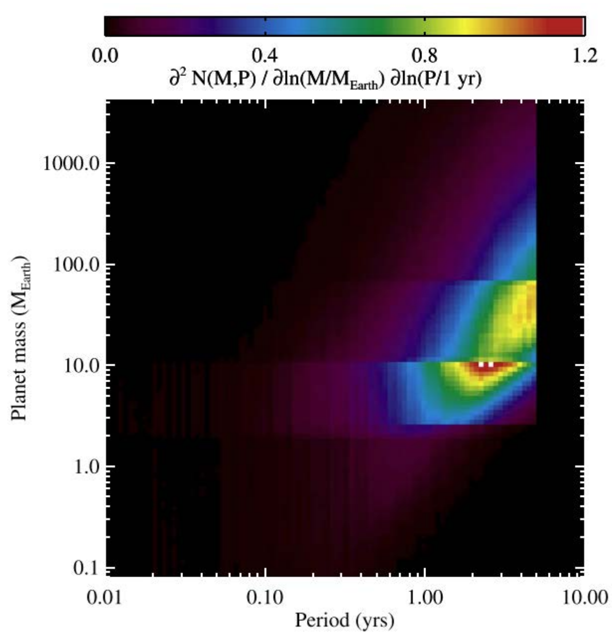

Fig. 1 Probability distribution of transiting exoplanets [8].

There are six main projects that use transit to study exoplanets. These programs are HATnet, WASP, NGTS, Kepler Mission(Kepler probe and Kepler probe's second mission), TESS and CHEOPS. The first three of these programs started much further back in time, so the telescopes used for observing exoplanets in these three programs are spread out on the ground, whereas the last three programs all operate in space. The first five of all the projects are aimed at detecting exoplanets, while the last one focuses on follow-up observations of known exoplanets. As a result, the most popular programs using TRANSIT to detect exoplanets are now the Kepler Series and TESS. By August 16, 2024, there are 2,773 confirmed and 1,982 unconfirmed exoplanets detected by Kepler; 548 confirmed and 976 unconfirmed exoplanets detected by K2; and 545 confirmed and 7,208 unconfirmed exoplanets detected by TESS [8].

An important application of transits is the study of the atmospheric composition of exoplanets. Planet transmission spectroscopy can reveal exoplanet atmospheric compositions, described in terms of wavelength-dependent planetary radii. A small portion of the star's light will pass through the planet's translucent atmosphere as the planet passes in front of the star it orbits [12]. Since the optical thickness of the atmosphere is wavelength-dependent, the proportion of stellar light that can penetrate the atmosphere varies over the observed wavelength range [12]. By comparing the spectroscopy during a stellar transit with the spectroscopy when the planet is not in front, scientists can detect specific absorption lines. These lines indicate the presence of certain molecules, such as carbon dioxide. The final result of the analysis is the planetary transmission spectrum.

4. Radial Velocity

Radial velocity bases on the interaction of the gravitational forces between the planet and the star it orbits, as well as the Doppler shift. Gravitational interactions can be understood by analogizing a tug of war. Suppose there is a planet at the one end and the star it orbits at the other. The mass of the star is much greater than that of the planet, so the effect of the planet's gravity on the star's manifestation is very small. This is the reason why planets orbit stars. It's worth noting that even though planets have little effect on stars, they can still be detected. Another key principle Doppler shift is based on the Doppler effect. The Doppler effect describes how the frequency or wavelength of a light or sound wave varies depending on the motion of the emitting source relative to the observer. The wavelength is compressed (blueshifted) as the object moves toward the observer and stretched (redshifted) as the object moves away. With the above in mind, the radial velocity method can be explained as to how it works. Imagine a total of two circles nested together. The larger circle is the orbit of a planet and the smaller circle is the orbit of the star. When a planet orbits a star, the gravitational pull between the two objects causes the star to move slightly in a small orbit or swing around a common center of gravity. Light from a star is slightly blueshifted (wavelengths are compressed) as the star moves toward the observer. In contrast, light is redshifted (the wavelength is stretched) when the star is farther away. The change in wavelength due to the Doppler effect is what astronomers measure as radial velocity. By observing periodic changes in stellar spectral lines over time, astronomers can infer the presence of planets.

Two famous observatories that use radial velocities are the Keck Telescope and the La Silla Observatory. The Keck Observatory has two nearly identical 10-meter telescopes, Keck I and Keck II. Recently, Keck Observatory installed the Keck Planetary Finder (KPF), one of the most advanced spectrometers of its kind in the world. KPF is a fiber-fed, high-resolution step spectrometer dedicated to the discovery and characterization of exoplanets using Doppler spectroscopy [12]. The guiding principles in the design of the KPF were high throughput to facilitate survey speed and acquisition of weak targets, and high stability to maintain uncalibrated systematic Doppler measurement errors below 30 cm s. The KPF was designed to provide a high degree of stability to the system, and to provide a high degree of stability to the system [12]. The La Silla Observatory in the Atacama Desert was also upgraded a few years ago. ESPRESSO is the next generation of high-resolution spectrographs for VLT. It is designed to achieve ultra-high radial velocity (RV) accuracy and very high spectral fidelity [13]. A typical observation results are shown in Fig. 2 [13].

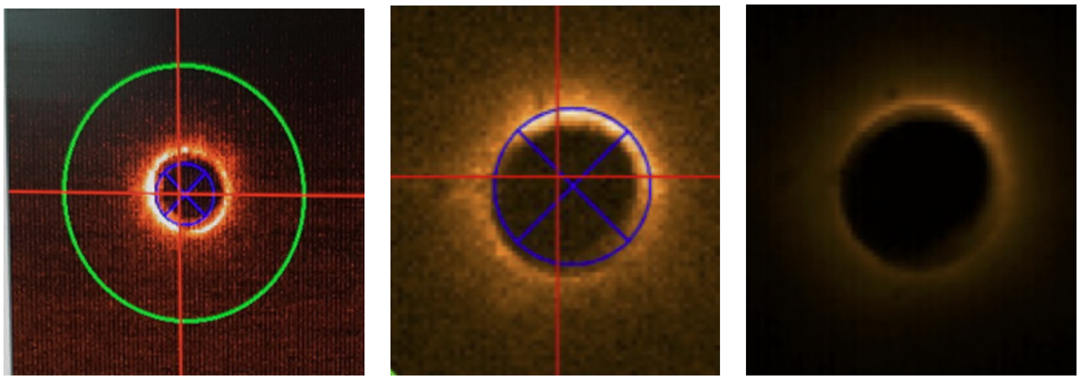

Fig. 2 Typical observation results for ESPRESSO of VLT [13].

5. Direct Imaging

The difference between the direct imaging method and the previous two detection methods lies in the fact that direct imaging is a direct observation of the presence of exoplanets, instead of an indirect detection of exoplanets. The key to this method is the need to block the light from the star that the exoplanet is orbiting, since exoplanets are typically millions of times fainter than stars. The direct imaging method can be analogous to the principle of sunglasses and visors blocking sunlight for solutions to excessive stellar light. By reducing the intensity of the light, one can more easily see other things that are near the source of the light emitted. There are two main types of instruments that block the light from stars. The first is the coronagraph. The essential components of the coronagraph are the Occulting Mask, the Lyot Stop and the Wavefront Control. Occulting Mask is a small disk or shape placed within the telescope‘s optical path, positioned to cover the star‘s image. By blocking the star‘s light, the occulting mask reduces the glare and allows astronomers to see the dimmer objects around the star.After the starlight is blocked by the occulting mask, some residual light still reaches the telescope. The Lyot stop is a mask placed in the pupil plane of the telescope to block diffracted starlight and enhance the contrast further.Imperfections in the telescope‘s optics can cause light to scatter, reducing the effectiveness of the coronagraph. Wavefront control systems, such as deformable mirrors, are used to correct these imperfections in real-time, improving the coronagraph‘s performance. The other instrument is the starshade. A starshade is an external occulter, a large structure located in the space between the telescope and the star. The starshade is usually a separate spacecraft. Star shields are designed in specific shapes, such as flowers with petal-like structures, to minimize distortion of the starlight by means of light leakage through the edges. This complex design helps to reduce the brightness of the star to a level where the fainter light reflected from the exoplanet becomes visible.

JWST uses direct imaging as one of the methods for detecting and studying exoplanets. JWST‘s Near Infrared Camera (NIRCam) is equipped with a coronagraph. JWST conducted coronal observations of the super-Jupiter exoplanet HIP 65426b with NIRCam from 2 to 5 microns and with MIRI from 11 to 16 microns [14]. A typical wavelength detection results (HIP 65426b) of JWST and other facilities are shown in Fig. 3 [14].The results showed that JWST successfully detected an exoplanet. This is the first time JWST has detected an exoplanet using direct imaging and the first ever direct detection of an exoplanet beyond 5 μm [14].

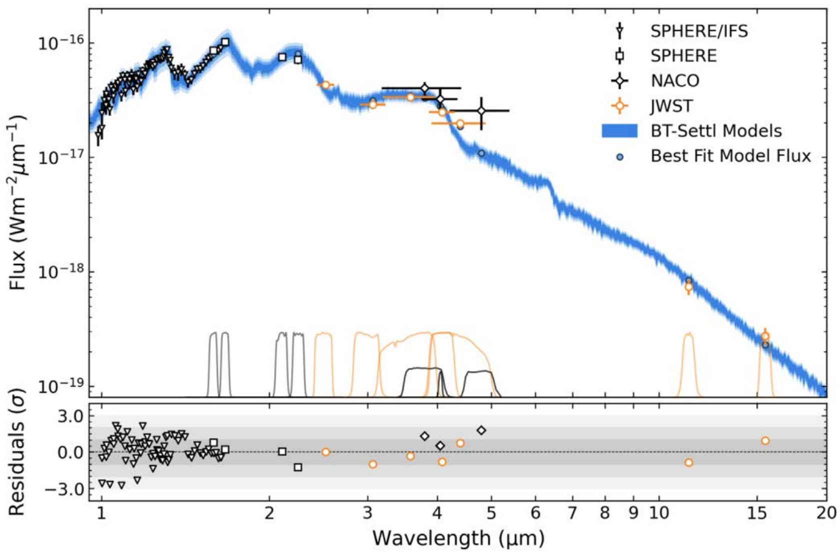

Fig. 3 The wavelength detection of HIP 65426b based on JWST and other facilities [14].

6. Comparisons, Limitations and Prospects

Each of the three methods of detecting exoplanets has its own advantages and disadvantages. First is TRANSIT. The first advantage of the transit method is that it can provide important parameters about exoplanets. The transit method combined with stellar parameters and radial velocity measurements gives the mass, radius and density of the planet [15]. The second point is that the transiting method can survey many stars at once, which makes the discovery of a large number of exoplanets very effective, especially in large surveys like those conducted by Kepler or TESS. For example, Kepler can continuously and simultaneously monitor the brightness of about 150,000 main sequence stars [16]. The third point is that spectroscopy can be used to analyze the atmospheric composition of exoplanets. There are also limitations to using the transit method. First, the orbital plane must be almost exactly edge-on to the observer, which is the case for only a few distant planets. Secondly, cases such as the double star system can create signals that mimic transits, requiring additional observations to confirm the existence of a planet. Radial velocity can also provide key parameters for exoplanets. The use of the radial velocity method enables the determination of the minimum mass of the planet as well as the orbital eccentricity. In addition, the radial velocity method has limitations. Radial velocities are more sensitive to large, massive planets close to the star and less effective at detecting smaller, Earth-sized planets, especially those that are farther away. This means that it is most likely to find the types of planets that are least likely to be hosts for life. The advantage of using direct imaging to detect exoplanets is that the position and orbit of the planet can be observed directly. In some cases it is also possible to observe its atmosphere and surface conditions. Another advantage is that objects that are detected using direct imaging are less prone to false positives. The disadvantages of direct imaging are also obvious as it is technically demanding. Another limitation is that the direct imaging method is mainly effective for large planets far from the star. It is difficult to detect smaller terrestrial planets, especially those closer to the star.

In summary, different detection methods have different strengths and weaknesses, so one can summarize what methods are applicable to different kinds of planets according to the type of exoplanet. Firstly for gas giants, the transit method is highly suitable because the large size of gas giants causes the brightness of the star to drop significantly during the transit, making it easy to detect. The radial velocity method is also very appropriate for detecting gas giants, whose large masses exert a strong gravitational pull on the host star, leading to pronounced stellar wobbles. The direct imaging method is also valid for gas giants. For terrestrial planets, only the transiting method is suitable. The small mass of terrestrial planets results in a weak gravitational effect on the host star, which is difficult to detect using the radial velocity method. Similarly, the small size and low brightness of terrestrial planets make them difficult to image directly, especially when close to a star. Both the transit method and the radial velocity method are suited for super-Earth detection. Super-Earths are larger than terrestrial planets and cause a more pronounced decrease in stellar brightness during transits, which is why the transiting method applies. The reason for applying the radial velocity method is that super-Earths cause detectable gravitational oscillations, especially when they are close to the star. However, super-Earths are still difficult to detect directly unless they are in wide orbits and orbiting faint stars. Finally for Neptune-like planets, all three methods can be used. The transit method is the most applicable for detecting Neptune-like planets. Similar to gas giants, Neptune-like planets are large enough to cause a significant drop in starlight during transits.

Current exoplanet exploration also has limitations. The above findings suggest that current detection methods are biased towards large near-neighboring planets, which has led to the current under-exploration of terrestrial and distant planets. Another limitation is that most detection methods require long observation periods to confirm the presence of planets, especially for planets with long orbital periods. Beyond that, current detection methods are basically indirect for exoplanets. This results in a lack of direct observations of planets.

In the future, the launch of powerful telescopes (e.g., ELT and NGRST), in conjunction with today‘s JWST surveys, will enhance the ability to detect and study exoplanets, especially small Earth-like planets and their atmospheres. Moreover, combining hybrid methods will also show great ability in accruacy searching. Together with this, further collaboration between astrophysics, planetary science and biology will advance the search for life on exoplanets by combining atmospheric data, habitability assessments and potential biosignature detection.

7. Conclusion

To sum up, this study describes typical results of exoplanet exploration in recent years, giving a rough idea of what methods of planetary retrieval are used, what results are obtained by each, and what parameters of the planets can be detected in particular. This research also details three methods of detecting exoplanets, the transiting method, the radial velocity method, and the direct imaging method. By comparing these three methods, the suitable detection methods for different kinds of exoplanets are summarized. Afterwards, the limitations of the current exoplanet exploration are summarized from the results, and future countermeasures are briefly described. With these results, the reader will gain an understanding of current exoplanet exploration, especially the transiting method, the radial velocity method, and the direct imaging method. Human curiosity about life has motivated the continued exploration of exoplanets. In the future, more sophisticated instruments and advanced methods will be invented to explore exoplanets. By analyzing more accurate and comprehensive data, the knowledge of exoplanets will be further enhanced.

References

[1] Bozza V, Mancini L, Sozzetti A. Methods of detecting exoplanets. Astrophysics and Space Science Library: Berlin, Germany, 2016, 428.

[2] Madhusudhan N, Agúndez M, Moses J I, et al. Exoplanetary atmospheres—chemistry, formation conditions, and habitability. Space science reviews, 2016, 205: 285-348.

[3] Mordasini C, Alibert Y, Klahr H, et al. Characterization of exoplanets from their formation-i. models of combined planet formation and evolution. Astronomy & Astrophysics, 2012, 547: A111.

[4] Wolszczan A, Frail D A. A planetary system around the millisecond pulsar PSR1257+ 12. Nature, 1992, 355(6356): 145-147.

[5] Mayor M, Queloz D. A Jupiter-mass companion to a solar-type star. nature, 1995, 378(6555): 355-359.

[6] Lissauer J J, Batalha N M, Borucki W J. Exoplanet Science From Kepler. arXiv preprint arXiv:2311.04981, 2023.

[7] Guerrero N M, Seager S, Huang C X, et al. The TESS objects of interest catalog from the TESS prime mission. The Astrophysical Journal Supplement Series, 2021, 254(2): 39.

[8] NASA Exoplanet Archive. Retrieved from: https://exoplanetarchive.ipac.caltech.edu/.

[9] Stark C C, Dressing C, Dulz S, et al. Toward complete characterization: prospects for directly imaging transiting exoplanets. The Astronomical Journal, 2020, 159(6): 286.

[10] Hara N C, Ford E B. Statistical methods for exoplanet detection with radial velocities. Annual Review of Statistics and Its Application, 2023, 10(1): 623-649.

[11] Dai Z, Ni D, Pan L, et al. Five methods of exoplanet detection. Journal of Physics: Conference Series. IOP Publishing, 2021, 2012(1): 012135.

[12] Gibson S R, Howard A W, Rider K, et al. System design of the Keck Planet Finder. Ground-based and Airborne Instrumentation for Astronomy X. SPIE, 2024, 13096: 42-70.

[13] Pepe F, Cristiani S, Rebolo R, et al. ESPRESSO at VLT-On-sky performance and first results. Astronomy & Astrophysics, 2021, 645: A96.

[14] Carter A L, Hinkley S, Kammerer J, et al. The JWST Early Release Science Program for Direct Observations of Exoplanetary Systems I: High-contrast Imaging of the Exoplanet HIP 65426 b from 2 to 16 μm. The Astrophysical journal letters, 2023, 951(1): L20.

[15] Koch D G, Borucki W J, Basri G, et al. Kepler mission design, realized photometric performance, and early science. The Astrophysical Journal Letters, 2010, 713(2): L79.

[16] Borucki W J, Koch D, Basri G, et al. Kepler planet-detection mission: introduction and first results. Science, 2010, 327(5968): 977-980.