Analysis of Planet Searching and Detection Based on Radial Velocity, Direct Imaging and Transit

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Abstract. As a matter of fact, significant progress has been made in the discovery and research of exoplanets over the years. In reality, the discovery of thousands of exoplanets outside the solar system are achieved based on the state-of-art approaches as well as detectors. With this in mind, understanding the detection scenarios of the exoplanets are crucial to delve deep into astrophysics as well as cosmology study. Among various approaches, the three prominent techniques used in this pursuit are radial velocity, direct imaging, and transit method. On this basis, this study comprehensively analyzes these methods. To be specific, this study delves into their principles, applications as well as detection features. According to the analysis, the limitations of these methods will be demonstrated in detail. At the same time, the current and future developments for the three approaches will also be presented. Overall, these results shed light on guiding further exploration of planet searching.

Keywords: Transit method; radial velocity; direct imaging.

1. Introduction

As long as humans look up at the night sky, human beings will be attracted by the celestial bodies dotted in the night sky. Planetary research refers to the scientific study of planets, satellites, and other celestial bodies inside and outside the solar system. In the 19th century, with the emergence of more powerful telescopes, planetary research rose again. Pioneering astronomers, including Sir William Herschel and Giovanni shaparelli [1], made significant contributions. Herschel discovered Uranus [2] and studied its moon. Shaparelli's careful observation of Mars led to the description of the "canal", which was later exposed, but aroused interest in the possible existence of life on other planets. The 20th century marks the arrival of the space age, and planetary research has entered an era of change. In 1957, the launch of man-made satellite 1 heralded the beginning of space exploration. NASA's Apollo program sent humans to the moon, and robotic spacecraft such as Voyager [3], Mars rover [4] and Hubble Space Telescope have provided us with unprecedented information about the solar system and other aspects. In terms of Significance of Planetary Research:

Understanding Earth. Planetary research not only expands the knowledge of other worlds but also provides crucial insights into the Earth's history, climate, and potential for life. Comparative planetary science helps us appreciate the uniqueness of the planet.

Origins of Life. Exploring other planets and moons informs the search for life beyond Earth. The discovery of extremophiles on Earth and the possibility of subsurface oceans on moons like Europa offer tantalizing clues.

Habitability and Potential for Colonization. Understanding the habitability of other planets and celestial bodies is crucial for future human exploration and potential colonization. It informs us about resources, the potential for human survival, and the possibility of establishing sustainable habitats beyond Earth.

Technology Development and Innovation. The challenges of extraterrestrial exploration drive the development of cutting-edge technologies. Innovations in robotics, artificial intelligence, spacecraft design, propulsion systems, life support systems, and more are often a direct result of space exploration efforts.

In recent years, the exploration of exoplanets (planets outside the solar system) has seen remarkable progress and breakthroughs thanks to advancements in technology, observational

techniques, and the launch of new space missions. Here are some key areas of progress in exoplanet exploration. The number of confirmed exoplanets has soared. Thousands of exoplanets have been found, and more candidate planets are waiting to be confirmed. The Kepler space telescope and the transit exoplanet survey satellite (TESS) played an important role in these discoveries. Identification of Potentially Habitable Worlds: Scientists have identified numerous exoplanets located in the "habitable zone" of their host stars, where conditions may be suitable for liquid water and potentially life as one knows it. These include planets like Kepler-442b [5], Kepler-186f [6], and TRAPPIST-1e [7].

In this article, the three methods (transit, radial velocity, direct imaging) for detection exoplanet are introduced. Each method is described in three separate parts, fundamental theory, basic instruments and applications. Lastly, the limitation of each method and potential developing in future are mentioned.

2. Basic Description

Exploring exoplanets is a challenging but exciting task. Astronomers use several methods to explore these distant worlds, each providing different types of exoplanet information. The following are the main methods and related detection indicators for detecting exoplanets. To start with the main method for detection exoplanet:

Transit method. Exoplanets passing in front of their host stars (transiting) cause a temporary dip in the star's brightness. By measuring the depth and duration of these transits, astronomers can determine the exoplanet's size (radius) and orbital period.

Radial Velocity Method (Doppler Spectroscopy). Exoplanets gravitationally tug on their host stars, causing the star to wobble slightly. This motion results in a Doppler shift in the star's spectral lines. By analyzing these shifts, astronomers can deduce the exoplanet's mass and orbital period.

Direct Imaging. The light from the star is blocked by specialised equipment, enabling astronomers to take pictures of exoplanets. For young, huge planets that radiate their own light, this technique works well.

Besides, Detecting and characterizing extraterrestrial objects, including exoplanets and other celestial bodies, involves analyzing various indicators and parameters. Here are key indicators used to detect and characterize these objects:

Atmospheric Composition. Analyzing the spectrum of electromagnetic radiation emitted or absorbed by an object to determine its chemical composition. Different elements and molecules have unique spectral signatures [8].

Mass and Size. Observing the gravitational interactions between celestial objects to infer their mass. For example, gravitational effects on nearby stars can indicate the presence of a massive exoplanet.

Orbital Characteristics. The time taken for an object to complete one orbit around another. This provides information about the object's distance from the host body and its mass [9].

Orbital Eccentricity: The measure of the orbit's deviation from a perfect circle. Eccentricity provides insights into the object's orbit shape and stability.

Temperature. Measuring the thermal radiation emitted by an object to determine its temperature and surface properties.

3. Transit Method

At its core, the transit method hinges on a fundamental concept in astronomy: as an exoplanet orbits its parent star, it occasionally crosses the line of sight between that star and an observer on Earth. This alignment creates a unique event known as a transit, wherein the exoplanet passes in front of its host star as seen from the vantage point. During this fleeting celestial choreography, the

exoplanet partially obscures a portion of the star's light. This temporary dip in the star's brightness can be detected and analyzed, serving as the hallmark of an exoplanet's presence.

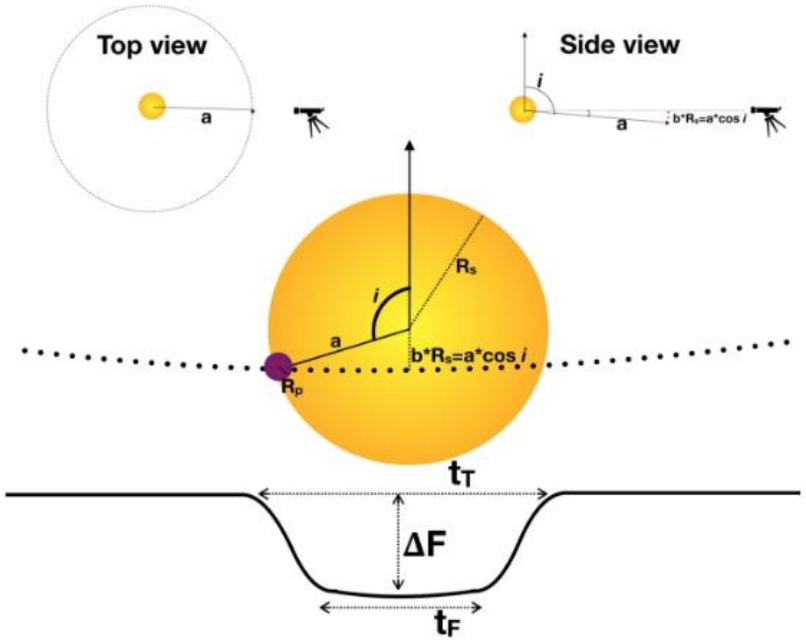


Fig. 1 The transit profile of exoplanets, including the main quantities used to describe the orbital structure, from the observable values given in the lower entity curve (observed light curve) to the model representation of the observer's perspective (center panel) or other perspectives (top panel).

Fig. 1 illustrates the principle of transit method. The concept is analogous to a miniature solar eclipse, but instead of the Moon blocking the Sun's light, one observes a distant exoplanet casting its shadow on its host star. These elusive dimmings of starlight are the key to unlocking the mysteries of exoplanets through this method. Here, a is orbital semimajor axis, i the orbital inclination, Rs the radius of the star, Rp the radius of the planet, and P the orbital period. When the planet passes in front of the star, its flux decreases by a fraction. The total duration of the transit event is expressed as tT and the time of totality (or, in terms of an eclipse, the interval between the second and third contacts), during which the complete planet disk is in front of the star disk, is given by tF. Specifically, the impact parameter b, defined as the shortest projected path to the star disc's center during transit [10]. Thus, several equations can be obtained:

$$\Delta F \sim \left(\frac{R_p}{R_s}\right)^2 = k^2 \tag{1}$$

where ΔF is given by the ratio of the areas of the planet and the star.

$$\mathrm{b} = a/R_s cosi \tag{2}$$

The so-called scale of the system, or the ratio between the semimajor axis and the star's radius, is a frequently used quantity that can be determined only from photometric data:

$$\frac{a}{R_s} = \frac{1}{\tan\left(t_T \pi/P\right)} \sqrt{(1+k^2) - b^2} \tag{3}$$

This may be converted into a measurement of the mean stellar density using Kepler's laws of motion, reasonable estimates, and the mass of the planet being significantly less than that of its host star:

$$\rho_s = \frac{3\pi}{GP^2}\left(\frac{a}{R_s}\right)^3 \tag{4}$$

The measuring of light intensity, or precise photometry, is at the heart of the transit method. Astronomers use specialist equipment like CCD (Charge-Coupled Device) cameras and photometers

to spot the minute fluctuations in a star's brightness that occur during an exoplanetary transit. The light from a target star is captured by these sensors over time, creating a light curve, a graph that shows the star's brightness as a function of time. Exoplanetary transits are indicated by the recurring periodic dips in the light curve [10]. Careful follow-up observations are necessary to confirm the existence of an exoplanet through transits. Astronomers frequently use additional telescopes and tools to confirm their preliminary findings. This process is necessary to weed out false positives and confirm that the observed brightness dips are brought on by exoplanetary transits rather than other causes such as inherent star variability or sensor errors. This method's capabilities have significantly increased thanks in large part to space telescopes. Observations have been particularly reliable and unbroken thanks to missions like NASA's Kepler and TESS (Transiting Exoplanet Survey Satellite), which have operated above Earth's atmosphere. Thousands of exoplanets, including smaller ones and those with longer orbital periods that would have been difficult to distinguish from Earth, have been discovered as a result. This approach offers insights into the dynamics of exoplanetary systems in addition to exoplanet discovery. The study of variations in transit timing is known as transit timing variations, or TTVs. Gravitational interactions between numerous exoplanets in a system may be the root of these changes. Astronomers have found previously unidentified planets and learned important details about their orbits and masses by carefully examining TTVs. The transmission spectroscopy approach advances the basic method by focusing on changes in starlight. A part of the starlight traverses the exoplanet's atmosphere during a transit. Astronomers can determine the makeup of the exoplanet's atmosphere by dissecting and examining the transmitted light's spectrum. Important chemicals including water, methane, and carbon dioxide have been found using this technique, providing critical information on the possible habitability of exoplanets.

The research of exoplanet atmosphere can be greatly facilitated by this method. This is due to the fact that during a transit, light from the host star will penetrate the exoplanet's atmosphere and disclose aspects of the exosphere's molecular absorption. One can explore the exosphere with high S/N by contrasting the spectra of the host star during and without the passage. Additionally, differences in exospheric absorption characteristics across several transit cycles can provide insight on the exoplanets' weather. The timing and duration of transit events help astronomers determine the orbital period of the exoplanet (time taken to complete one orbit around the star) and its distance from the host star. These parameters provide critical insights into the exoplanet's orbit, its proximity to the star, and potentially its habitability. This method offers valuable information about the physical properties of exoplanets, particularly their size or radius. The depth of the brightness dip during a transit directly correlates with the size of the exoplanet relative to the host star. By analyzing the depth and shape of the transit light curve, astronomers can determine the exoplanet's radius and, consequently, its volume and density.

4. Radial Velocity

A key idea in astronomy and astrophysics, the principle of radial velocity provides a potent tool for locating and characterizing celestial objects, notably exoplanets. The Doppler effect, which describes the change in the apparent frequency (or wavelength) of light or other electromagnetic waves when the source of those waves is in motion relative to the observer, serves as the foundation for this theory.

Doppler effect has long been known. When the light source or radiation source moves towards the observer, its wave is compressed, resulting in a blue shift. At this time, the observed wavelength becomes shorter and the light becomes blue. On the contrary, when the light source is far away from the observer, the wave will be stretched, causing a red shift. At this time, the observed wavelength will be longer, and the light will be redder. When a celestial body moves, due to its radial velocity relative to the observer, the light emitted or reflected by it will have Doppler shift. This displacement can be measured as the change of the spectral line of the object, that is, the light of a specific

wavelength absorbed or emitted by the object. As the unique fingerprint of elements and molecules, spectral lines enable astronomers to detect and analyze the movement of objects in space.

The accurate assessment of these shifts in an object's spectrum, which are frequently stated in meters per second (m/s) or kilometers per second (km/s), is necessary for RV measurements. Astronomers are able to produce ground-breaking discoveries thanks to these measurements, which offer invaluable information about the motion, mass, and characteristics of celestial objects. The development of the RV is seen in Fig. 2. A time-dependent function of measurement inaccuracy. Using single-order spectrographs and photographic plates, it was uncommon to attain RV measurement precision better than 1 kms^{-1}, which is around the speed of the fastest military aircraft (SR-71 Blackbird), in the middle of the 1950s. The measurement inaccuracy was about 15 $ms^{-1}$by the end of the 1980s, or roughly the speed of a world-class sprinter. Electronic detectors with high quantum efficiencies were now in widespread usage. At this period, the first simultaneous wavelength calibration techniques were also used. However, single-order spectrographs continued to be employed, and because of their limited wavelength coverage, the RV precision was constrained. At this time, current methods can reach an RV precision of 0.5-1ms^{-1}, or roughly the speed of a quick crawl. The horizontal line represents the 10 ms^{-1} nominal RV precision one required to detect the solar-like star's reflex motion caused by Jupiter at 5 AU. It should not come as a surprise that the first exoplanets were discovered about the time when this 10 ms^{-1} measuring inaccuracy was attained [11].

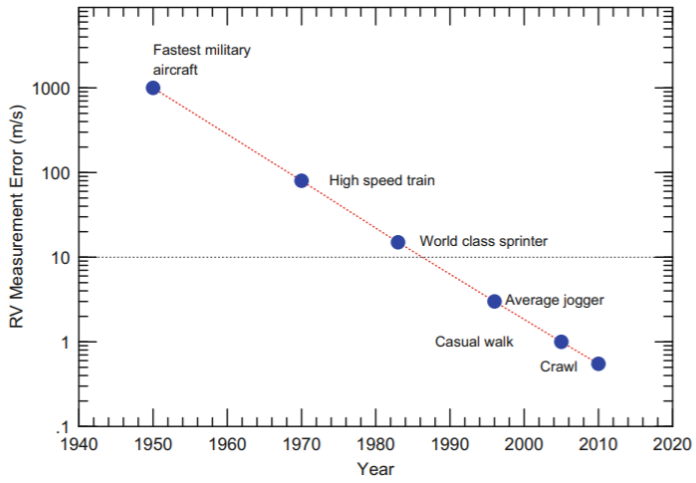


Fig. 2 The temporal evolution of the measurement inaccuracy of radial velocity. The horizontal line indicates the velocity of a solar-mass star that is comparable to Jupiter.

Spectrographs are the cornerstone of RV measurements. They split incoming light into its constituent colors or wavelengths, creating a spectrum that can be analyzed in detail. Spectrographs can be attached to various types of telescopes, making them essential tools for astronomers. Two primary types of spectrographs used for RV measurements are:

Echelle Spectrographs. These high-resolution spectrographs are designed to disperse light into an array of closely spaced spectral lines, facilitating precise measurements of the Doppler shift. Echelle spectrographs are often used in dedicated RV surveys.

Cross-Dispersed Spectrographs. These instruments are equipped with multiple diffraction gratings or prisms to disperse light in both the horizontal and vertical directions. Cross-dispersed spectrographs allow for the observation of a broad range of wavelengths in a single exposure, making them efficient for RV surveys.

Many RV instruments use fiber optic coupling to reduce the impacts of atmospheric turbulence and instrument instability. Using optical fibers, this method directs light from the target item into the spectrograph. High-accuracy RV measurements are made possible by the instrument's improved stability and precision thanks to fiber optic connectivity. For the measurement of RV, accurate calibration is essential. The spectral lines that calibration lamps, such thorium-argon or iodine lamps, generate have well-defined wavelengths. To make sure that observed shifts in spectral lines are

correctly attributed to variations in RV, these lamps are employed to calibrate the spectrograph's response and measure any experimental drifts. The stability of spectrographs is paramount in RV measurements, as even minute changes in the instrument can introduce errors. Spectrographs are often equipped with temperature control systems, vibration isolation, and mechanical stabilization to minimize instrumental drift and ensure accurate results. In some cases, adaptive optics systems are employed to compensate for atmospheric turbulence, which can distort the observed spectral lines. By dynamically adjusting the shape of a deformable mirror, adaptive optics can correct for these distortions, enhancing the precision of RV measurements. High resolution detectors, such as CCD (charge coupled device) camera and CCD spectrometer, are used to capture the spectrum generated by the spectrometer. These detectors are essential for achieving the high level of accuracy required for RV measurements.

The RV method is a powerful tool used to characterize binary star systems. Two stars make up binary star systems, which orbit a single mass center as a result of their gravitational pull on one another. These systems provide important information about the characteristics of stars, including their masses, orbital parameters, and even the potential for finding exoplanets [12]. This method has revealed crucial insights, including the Milky Way's rotation, the presence and distribution of dark matter, and the dynamics around the supermassive black hole at the galactic center. RV measurements are instrumental in understanding the structure, composition, and evolution of the galaxy [13].

5. Direct Imaging

Astronomers can obtain precise photos of far-off astronomical objects, such as planets, stars, galaxies, and even exoplanets, using the astonishing technology known as direct imaging. Direct imaging entails capturing the actual photons of light emitted or reflected by these objects, as opposed to other observational techniques that depend on indirect measurements or the analysis of light and radiation [14]. In essence, astronomical direct imaging is similar to taking a picture of a far-off object. Direct imaging enables us to visually see these items in the same way one might take a picture of a scene or a friend, rather than inferring their existence or properties from their effects on the environment or the light they emit. Direct imaging's strength rests in its capacity to offer direct visual proof of cosmic phenomena, leading to a deeper comprehension of the cosmos. There are three important ideas in direct imaging:

Collecting Photons. The photons (light particles) that the target object emits or reflects are actually collected by direct imaging equipment. This differs significantly from many other observational methods in that it directly captures photons as opposed to monitoring their effects.

Resolution and Contrast. Achieving high-resolution images is essential in direct imaging. It enables astronomers to make out subtle features and details of far-off objects. Techniques for increasing contrast are frequently used to separate things from the glare of surrounding stars or other bright sources.

Multiple Wavelengths. Direct imaging is done using a variety of wavelengths, including radio waves, X-rays, and visible light. Observing at multiple wavelengths can provide important details about the temperature, composition, and magnetic fields of astronomical objects [15].

Telescopes are the primary tools used in direct imaging. Ground-based optical telescopes and space-based observatories like the Hubble Space Telescope are equipped with advanced optics and detectors optimized for capturing images of celestial objects. Adaptive optics systems, which compensate for atmospheric turbulence, enhance the image quality of ground-based telescopes. Modern direct imaging instruments use highly sensitive detectors, such as charge-coupled devices (CCDs) and complementary metal-oxide-semiconductor (CMOS) sensors. These detectors capture and record the photons of light, allowing astronomers to convert them into digital images. To gain a comprehensive view of celestial objects, astronomers often use multi-band imaging, where observations are conducted across multiple wavelengths. This approach reveals different aspects of the object's properties, such as its temperature, chemical composition, and the presence of specific

molecules. Direct imaging typically involves complex image processing techniques to improve image quality. This includes removing noise, correcting distortion, and sharpening features of interest. Image processing is crucial for extracting valuable scientific information from raw image data

Direct imaging has revolutionized the ability to discover and study exoplanets—planets outside the solar system. By blocking out the intense light of parent stars, direct imaging instruments can reveal exoplanets that would otherwise be lost in the glare. This method provides insights into exoplanet atmospheres, temperatures, and even the potential presence of life-supporting conditions. For instance, HD 131399 was observed on 12 June 2015 [16], achieving a broad spectrum coverage of the near-infrared region, from the Y band to the K band (0.95 to 2.25 μm) and diffraction-limited imaging with an 8.2-m telescope aperture. The observations resulted in the discovery of HD 131399Ab, a point source with a 10−5 contrast to HD 131399A and a projected separation of 0.84 arc sec, or 82 ± 6 AU (seen from Fig.3). Direct imaging enables the observation of distant objects such as quasars, active galactic nuclei (AGNs), and gravitational lensing phenomena. These observations shed light on the behavior of matter and energy in extreme environments. Direct imaging is used by probes and spacecraft with cameras and imaging equipment to study the own solar system. This includes taking pictures of the solar system's planets, moons, asteroids, comets, and other celestial bodies.

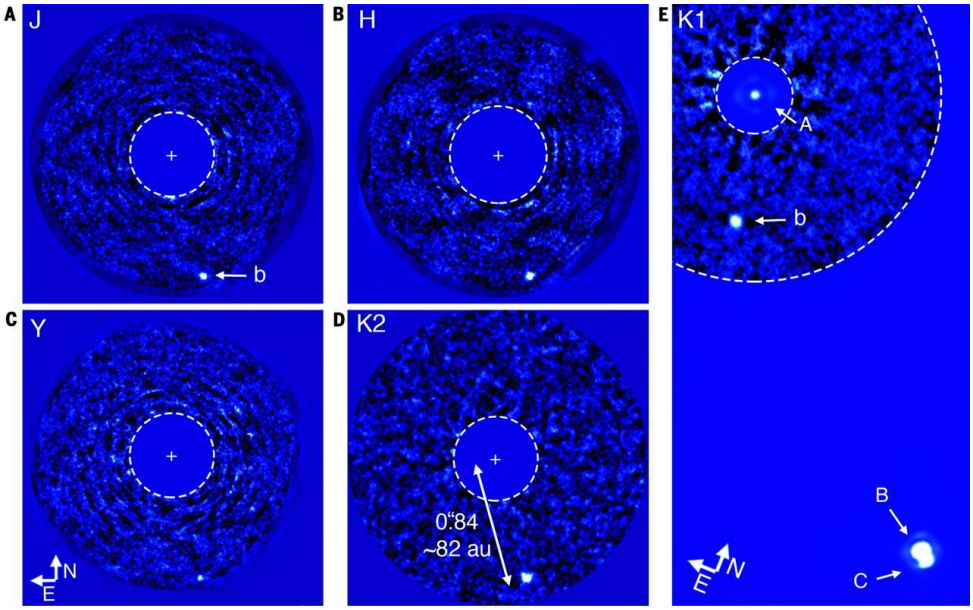


Fig. 3 Near-infrared VLT-SPHERE images of HD 131399Ab and the hierarchical triple-star system HD 131399ABC.

Table 1. Comparison of the method.

Method	Limitation	Future development
Direct imaging	low sensitivity to smaller planets	Ongoing development of high-contrast imaging techniques will enable the detection of smaller, potentially habitable exoplanets
Transit	Limited to detecting exoplanets in systems with nearly edge-on orbits relative to Earth.	Increased use of ground-based facilities with high cadence observations
Radial velocity	high-precision spectrographs and stable observational conditions are required.	Development of next-generation spectrographs

6. Limitations and Prospects

Each of these techniques for finding planets has advantages and disadvantages. While creating finely detailed photos of exoplanets, direct imaging has issues with sensitivity and star closeness. A large variety of exoplanets can be found using the RV method, although it has inclinational

restrictions and necessitates accurate spectroscopy. The orientation of planetary orbits places restrictions on the transit method, which nevertheless provides effective surveying capabilities. Future innovations in these techniques look promise, with many current constraints anticipated to be addressed by advancements in technology, equipment, and space missions. These developments will probably result in the identification and characterization of a wider variety of exoplanets, including those that resemble Earth and may be habitable, increasing the knowledge of planetary systems outside of the solar system (seen from Table 1).

7. Conclusion

In short, due to the development and evolution of various methods, great progress has been made in the research and detection of exoplanets. Radial velocity method, direct imaging method and theodolite method have all made great contributions to this field, and each method has its unique ability and potential. The continuous progress of technology and methods is expected to promote further discoveries and pave the way for in-depth understanding of extrasolar planets and various planetary systems outside the solar system. Exploring and describing exoplanets remains an exciting and promising effort in the field of astrophysics.

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