Analysis of Planet Searching Scenarios: Radial Velocity, Gravitational Microlensing and Transit

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Abstract. As a matter of fact, since extrasolar planets are crucial celestial bodies for understanding stellar evolution and the starting point for investigating the origin of life, they have long been a focus of astronomical frontier research. So far, approximately ten different exoplanet detection techniques have been proposed based on various advanced detectors. In reality, with the improving accuracy of astronomical observational tools, more than 4,000 exoplanets have been found since 1992 according to the NASA. With this in mind, in this paper, three methods of detecting planets are introduced, and their working principles and geometric representations are introduced, respectively. To be specific, the radial velocity, transit, gravitational microlensing, the theory of the doppler effect, planetary spectra orbit, lens equation and observed values interpreted and analyzed. According to the analysis, the current detection limitations are clarified and demonstrated. At the same time, the development trend of exoplanet exploration in the next 5 to 10 years is also prospected.

Keywords: Planet searching; radial velocity; gravitational microlensing.

1. Introduction

Planetary exploration is a crucial tool for advancing human understanding of the cosmos. These detection missions have produced impressive findings [1]. Almost throughout the entire history of spaceflight, planetary exploration has been conducted by space probes. The first planetary probe started its exploration mission with a flyby, orbit, and landing not long after humans were able to escape the gravity of the earth. Humans have achieved the scientific detection of the eight planets of the solar system and their satellites, asteroids, dwarf planets, comets, and other celestial bodies thanks to the gradual development of various detection techniques like inspection, inspection, and sampling return. It has enhanced human understanding of the solar system's genesis and development.

In the middle of the 20th century, with the development and improvement of celestial mechanics and astrometry, the accuracy of celestial body positions obtained by astronomical observations gradually increased. In the 1990s, the emergence of space telescopes greatly promoted the accuracy of astrometry and astrophysical observations. At this time, the astrometric accuracy of stars an planets has reached the order of 0.001 [1]. Accuracy, spatial and temporal resolution of celestial imaging. Through the observation and research of some stars, the "companion stars" of suspected exoplanets have been discovered. Astronomers believe that these companion stars may be extrasolar planets orbiting the stars, so people turn their attention to the universe outside the solar system in search of planets. In 1992, Wolszczan and Frail detected the periodic variation of the pulse arrival time of the pulsar PSR 1257+ 12, and thus discovered that two pulsars with a mass of 4.3M ⊕ revolving around this millisecond pulsar (M⊕ represents Earth mass) and the companion star PSR 1257+ 12 c, d with a mass of 3.9M⊕; in subsequent observations, Wolszczan discovered another planet PSR 1257+ 12 b with a mass of 0.02M⊕. In 1995, Mayor and Queloz discovered the first exoplanet 51 Pegasi b orbiting a sun-like star by monitoring the radial velocity changes of a group of K-type and G-type dwarf stars; this important discovery It means the beginning of the era of exoplanet exploration. In October 2019, Mayor and Queloz were also awarded the Nobel Prize in Physics for this discovery. Since then, the detection methods and technologies of exoplanets have also been continuously developed and matured. However, because exoplanets are too far away from the earth and do not emit light, the ability of ground-based telescopes to detect exoplanets is limited. Since the discovery of the first extrasolar planet in 1992, Before the launch of the Kepler telescope in 2009, humans had only discovered more than 400 exoplanets.

In 2000, Henry et al. and Charbonneau et al. independently discovered the transiting exoplanet HD 209458 b. This exoplanet is similar to 51 Pegasi b, and it also revolves around a A sun-like star orbits. Before the launch of the Kepler space telescope [2], the photometry accuracy of celestial bodies has reached the level enough to detect the light variation of the host star when the exoplanet transits. Limited by the Earth's atmosphere, Ningdu and others discovered only more than 50 exoplanets using the transit method during 2000-2009. In 2009, the Kepler telescope was launched into space and is planned to serve for 4 years. During the 9 years of actual service, about 500,000 stars were monitored for luminosity changes, searching for candidate targets that may have exoplanets. The launch of the Kepler telescope has increased the number of exoplanet discoveries by an order of magnitude, expanding the research sample of exoplanets. The Kepler telescope ended its mission to detect exoplanets in November 2018. Using the Kepler telescope to carry out large-scale exoplanet searches, one has discovered a large number of exoplanets in the universe, and observed that planets are commonly found around stars. In order to carry out a larger-scale exoplanet search, in April 2018, as the successor of the Kepler telescope, the transiting exoplanet survey telescope TESS (transiting exoplanet survey telescope) was launched into space.Search and study of exoplanets. As of November 10, 2020, astronomers have discovered and confirmed a total of 4,301 exoplanets by using different detection instruments and methods.

Major spaceflight nations have developed their own planetary exploration routes, organized in accordance with planned Scientific exploration activities, since the 1960s. These countries and organizations include the United States, the Soviet Union/Russia, the European Space Agency, Japan, India, China, and the United Arab Emirates. The mysteries of the sun, the earth, and the moon are continually being investigated by humans.It has carried out numerous asteroid sampling and return missions, three Mercury explorations, 46 Venus explorations, 47 Mars explorations, nine Jupiter explorations, four Saturn explorations, one Neptune exploration, two dwarf planet explorations, and numerous asteroid explorations. These exploration missions have produced valuable scientific findings and advanced the field of aerospace system engineering. As seen from the perspective of development history, asteroid exploration has gone from close flybys (such as "Deep Space 1," "Stardust," and "Rosetta" missions) to asteroid orbiting detection (such as the Near Earth Asteroid RendezvoHs (Near Earth Asteroid RendezvoHs, NEAR) probe and the "Dawn" Dawn detection mission), and then to the attachment detection (such as the Rosetta mission),this has led to the current asteroid surface sample return programs (e.g,m Hayabusa 1, Hayabusa 2 and OSIRIS-REx missions).

In terms of scientific accomplishments, several detecting tasks have allowed for the precise determination of the target small celestial body's orbit, motion speed, volume, material composition, and interior structure. For instance, the US "Deep Space 1" mission flew over the comet =19P/Borrelly and measured its size, shape, surface features, brightness, mass, density, and rotation state. It also studied the plasma characteristics of the coma, interactions between the coma and solar wind, brightness, and the characteristics of the dust and gas streams that were ejected from the comet's nucleus. These missions expand our understanding of the origin of the solar system and the principles governing planetary formation and evolution and research the origin of life. These missions are directly tied to scientific concerns like the creation of the solar system and the origin of life.

2. Basic Decsriptions

Before the NASA launched the Kepler Space Telescope in 2009, the radial velocity method dominated the detection of exoplanets, whereas the predation event observation approach swiftly replaced the Kepler space survey data release method. All of this is credited to the Kepler Space Telescope's excellent design, which ensures the ability to discover planets that are terrestrial and even smaller exoplanets thanks to its unmatched pointing precision and photometric precision of one millionth (ppm). The technology for finding extrasolar planets today goes beyond the radial velocity method and the pulsar timing method, which were used to find the first exoplanets. Additionally, it covers astrometry, a direct imaging method, a transit event observation method, and the recently proposed gravitational microlensing method.

Given the tiny angular separation and a star and its planets have a sharp brightness difference, direct observation of extrasolar planets is quite challenging. For instance, according to previous study, if the own Solar System were to be seen at, say, a distance of 5 parsecs, the Sun and Jupiter would be only 1 arcsecond apart at their greatest angular distance, at visible wavelengths, the Sun appears to be 109 times brighter. Jupiter would be impossible to distinguish from the Sun's glare under these circumstances. There have already been four planets/brown dwarfs directly imaged about brown dwarfs. The search for extrasolar planets orbiting white dwarfs has so far come up empty. Another approach is to look for the planet at wavelengths close to its Planck function peak. The Sun-Jupiter system's flux ratio is reduced to 104 by observing at 50 meters instead of 0.6 meters, however at these longer wavelengths, any useable telescope's diffraction-limited angular resolution would be insufficient.It was realized that, despite the fact that the direct visual detection of extrasolar planets first thought to be highly challenging, it would be able to discover them indirectly through their impact on the center star's velocity. Two strategies exist for doing this: 1) by watching the star's the planetary system's radial velocity revolves around its center of mass, and 2) by using astrometry to track the actual reflex motion of the star against the sky. In addition, while other detection methods, such as gravitational lensing, were discovered by accident, it was possible to identify an extrasolar planet if it transited in front of its star. The many techniques for finding extrasolar planets that are now available will be briefly summarized.

3. Radial Velocity

The star "wobbles" a little due to the planet's gravitational pull. The larger the planet,the greater its influence on the star. Asteroids like Earth wobble their stars just a little. The influence of larger planets,such as Jupiter, is much stronger. A star’s wobble can tell us whether it has planets, how many planets it has, and how big they are. Doppler shift is the name of the technique. When an object that emits energy is close to you, the waves gather and squeeze together. When the object moves away,the wave sttretches. When visible light waves come together,their color appears bluer. As sound waves stretch,their pitch becomes lower. When visible light waves stretch,they make objects appear redder.Scientists can utilize the "redshift" effect, which causes a change in color, to determine whether an object in the sky is traveling toward or away from us.

The dimensionless redshift variable can be used to express the outcome of a spectroscopic line-shift approach [3]:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_0 - v}{v} \tag{1}$$

When the rest-frame wavelength (frequency) is 0 (v0).Using a standard formula, It is common practice to translate the redshift to a conventional velocity. Instead of considering the relative change in wavelength, an alternate conversion is derived:

$$v_r = \frac{cz}{1+z} \tag{2}$$

The Doppler effect allows us to determine a star's radial velocity—its speed as projected onto the line of sight. The wavelength of the photon received is given by if a source emits a photon with wavelength λ0 and v of modulus in relation to the observer:

$$\lambda = \lambda_0 \frac{1+v/c}{\sqrt{1+v^2/c^2}} \tag{3}$$

The Doppler method counts the speed of a planet's reflection off of a star. Larger and easier to detect stellar velocity amplitudes are produced by more massive planets because gravity plays a role in the interplay between stars and planets. Additionally, it is simpler to find nearby planets since their orbital periods are shorter and enable quicker detection as well as the fact that their gravitational pull increases with the square of their distance. The technical features of Doppler analysis using a thorium-argon simultaneous reference source and an iodine cell are thoroughly discussed by Lovis and Fischer [4]. If the mass of the star M is known, the observable parameters (velocity semi-amplitude K*, orbital period P, eccentricity e, and orientation angle ω) are used to determine the minimal mass of the planet MP sin i. It is possible to determine a star's radial reflex motion in reaction to an orbiting planet using Doppler measurements. This movement reveals the period, distance, and shape of the orbit as well as details on the mass of the planet that is in orbit [5].

$$v_r = K[cos(\nu + \omega_3) + ecos\omega_*] + \gamma \tag{4}$$

Here, T0 and are mathematically undefinable for circular orbits with e = 0, since there isn't a periastron strategy. In these circumstances, a nominal value for ω*,like 0 or π/2,establishes T0; alternatively, one might define the angle's value at a particular epoch. As illustrated in Figure 3, the variables and e dictate the shape of an orbiting companion's radial velocity signature, while P, T0, and K regulate an RV curve's period, phase, and amplitude, respectively. When describing the orbits of solitary unseen companions. T0 and are mathematically undefinable for circular orbits with e = 0, since there is no periastron approach. In these circumstances,T0 is established by a notional value of ω*(such as 0 or π/2); alternatively, one might define the angle's value at a particular epoch.

4. Transit

The star's spectroscopic orbit (radial velocity curve) and photometric transit measurements (light curve) are the fundamental pieces of information for a transiting planet [6]. With these facts, it is impossible to estimate the planetary mass and radius apart from the stellar features. The extra planet's orbital period and mass can only be determined from transit data due to variations in transit times brought on by gravitational interactions with other planets. The transiting planet and a second planet interact gravitationally with each other and exchange energy and angular momentum during their orbits. This contact, which is strongest during each planetary conjunction, causes the eccentricities and semimajor axes of the planets to briefly oscillate, which changes the time gap between transits. By thinking about our solar system, one can demonstrate this impact (seen from Fig. 1). The transit period differences caused by gravitational alterations range from tens of seconds for Mercury to thousands of seconds for Mars between the planets in the solar system [7].

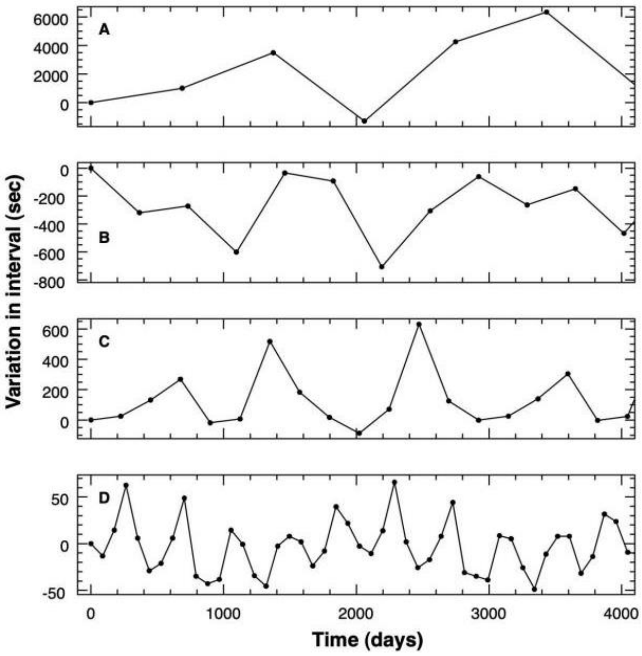

Fig. 1 The changes in the time between successive terrestrial planet transits brought about by the solar system's other planets.

Fig. 1 depicts a schematic representation of a transit event, with the bottom portion representing the system's observed flux. The flux of the planet decreases by a fractional, represented as ΔF, as it moves in front of the star [8]. The surface area ratio between the planet and the star provides ΔF under the conditions of minimal flow and spherical from the planet forms for both:

$$\Delta F \sim \left(\frac{R_p}{R_s}\right)^2 = k^2 \tag{5}$$

where Rp is the radius of planet, Rs is the radius of star, and k is the radius ratio. The period of totality, the entire planet disk is in front of the star disk at this time.To use eclipse terminology, the distance between the second and third encounters is given by tF, and occurs when the light curve is comparatively flat. The transit event's duration is denoted by tT. The study by Seager and Malle n-Ornelas deduced analytical formulas that link these measurements to the orbital parameters using simple geometry (seen frm Fig. 2). This might be used to calculate the mean star density using Kepler's laws of motion, reasonable estimates, and the mass of the planet being significantly less than that of its host star:

$$\mathrm{p_s} = \frac{3\pi}{GP^2}\left(\frac{a}{R_s}\right)^3 \tag{6}$$

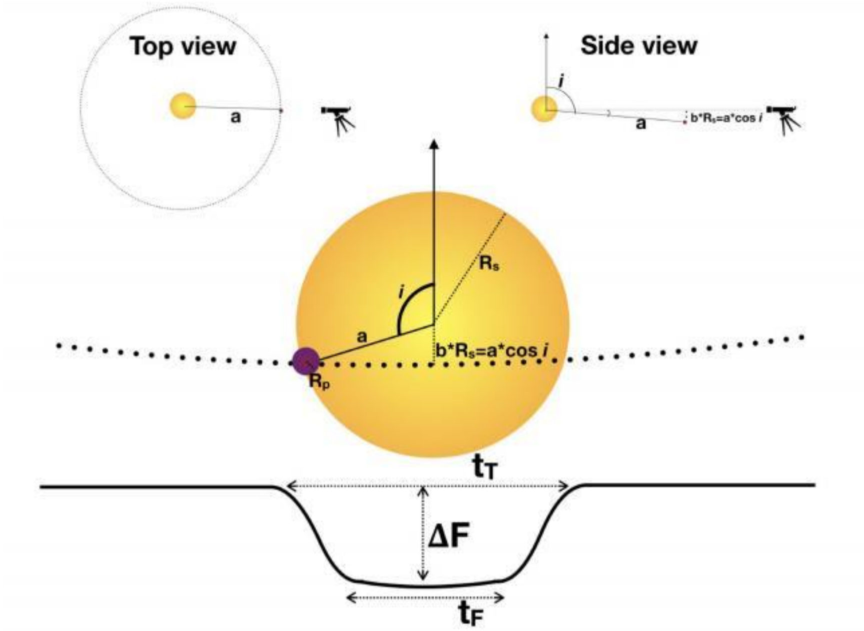

Fig. 2 Describes the main metrics of the track configuration.

5. Gravitational Lensing

The light from the background source star is distorted by the gravitational "pull" of the foreground star when it appears to pass practically in front of another star in the sky. This study refers to the foreground star as a lensing star because it acts as a kind of virtual magnifying glass, enhancing the brightness of the background source star. If the lensing star is part of a planetary system, the planets in the system can also serve as lenses, each one causing a temporary change in the brightness of the light source. As a result, one finds each exoplanet and determine its mass and distance from the star [9]. The publication written by Paczynski in 1986 that proposed the detection of the lensing of a source star by another star in the Milky Way galaxy gave rise to the contemporary field of microlensing [10]. The separation between the lensed pictures in this sort of lensing is too narrow for ground-based telescopes to resolve. The backdrop star's enlargement during lensing may be seen, though. In contrast to cosmological lensing, gravitational lensing within the Milky Way galaxy results in a temporary lensing effect known as gravitation microlensing because the positions of the observer, lens, and source are moving with regard to one another. In this kind of gravitational lensing, the background star is magnified by the lens over the course of one month.

This study employs the straightforward geometry depicted in Figure 3 for the gravitational lensing formalism. Here, $\hat{\alpha}$ determines the deflection angle, which is created by a single lens, but one can also apply it to numerous lenses [11]. One may express the relationship between the location of the unlensed source and the images after lensing using a straightforward geometrical connection as follows:

$$\hat{\theta} D_s = \hat{\beta} D_s + \hat{\alpha} D_{ds} \tag{7}$$

Simple steps can be used to derive the lens equation. Simple geometry provides the lensing setup seen in Fig. 4:

$$\eta + D_{ds}\hat{\alpha} = \xi \cdot \frac{D_s}{D_d} \tag{8}$$

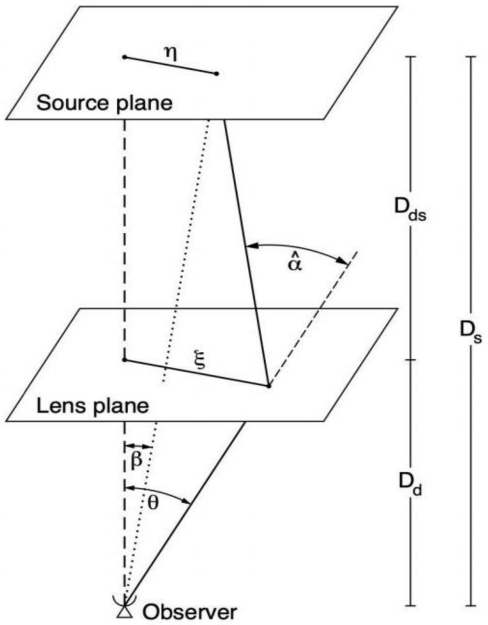

Fig. 3 A schematic illustration of gravitational lensing with the observer.

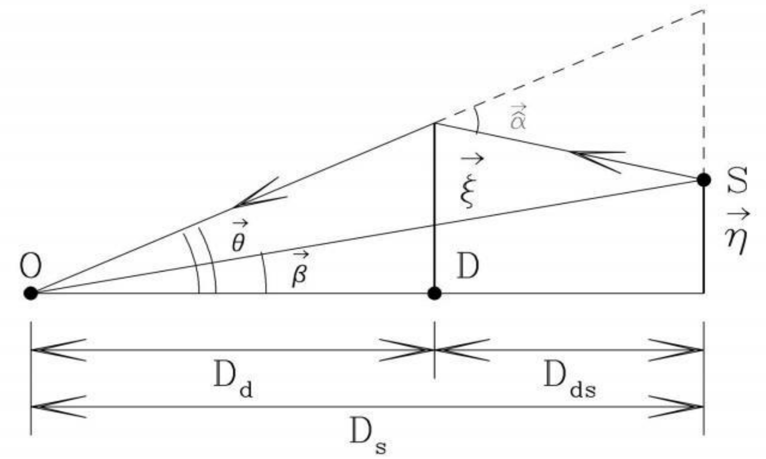

Fig. 4 Illustration of various distances and angles in the lens equation.

Planetary microlensing occurrences are simply binary lenses with very small mass ratios between the two lens components. In more complicated systems with three or more lensing objects, they can technically exist (and have), although they are considerably less common. The planets' light curves mostly resemble those of single lenses because their mass is so modest relative to that of the host star. When one of the source images created by the lensing effect'sweeps' through the planet's location, the planet will become visible. This will result in transient planetary anomalies, also known as binary-lens type perturbations on the light curve, which, after careful observation and analysis, can be utilized to determine the features of the system. The likelihood of seeing a planet, if one exists, is highest where the images appear near to the lens' Einstein ring. This translates into a physical distance from the host star of roughly 1 to 10 AU for average lens and source distances. The detection probability grows roughly as q1/2 near the planetary caustics or as q close to the core caustic, despite the fact that the amplitude of the planetary signal can be considerable regardless of the mass of the planet.

6. Limitations and Prospects

In the subsurface follow-up observation of exoplanets, the transit method and radial velocity method are currently most frequently used. As new large-aperture telescopes are constructed for use in ground-based astronomical surveys, one will be able to observe more exoplanets in greater detail and surpass the detection accuracy of the first two indirect techniques of finding exoplanets. Currently, models are used to fit the results of indirect observations and then make assumptions in order todiscover the atmospheres, interior structures, and other aspects of exoplanets. Many fundamental characteristics of the identified exoplanets, including period, mass, and radius, are still unknown due to a lack of detecting techniques. To gather further information, it is wished to scan with modest diameters, such as planets similar to Earth. The extent of an exoplanet's occultation, which is roughly proportional to the apparent area of the planet-host star, directly dictates the magnitude of the luminosity reduction. The smallest light variation amplitude that can be resolved during the observation depends on the measurement accuracy of the equipment. The observation of the exoplanet candidate can only be assured when the photometric drop brought on by the exoplanet's occultation exceeds the measurement accuracy of the equipment. The transit method is employed with ground-based telescopes to observe exoplanets with limited visibility and a maximum size restriction.

Although the Milky Way galaxy has the majority of planets, there are still many undiscovered exoplanets in the deeper universe. This study will employ increasingly sophisticated observational technologies to conduct in-depth research on these exoplanets. To give more precise data for the study of nature and evolution theory, it is important to change and confirm the observed planetary mass, radius, and orbit parameters for the identified exoplanets in addition to further supplementing the observational data and basic parameters. The study findings on exoplanets are evolving quickly due to the maturity of large-aperture observation instrument construction technology, the enhancement of instrument stability and accuracy, and the continuous improvement of observation and analysis methods. The sample of exoplanets is expanding as more and more space telescopes and satellites are in service. More in-depth observation and characterization of these samples are crucial for the advancement of the theoretical framework describing exoplanet creation and development. The study of extraterrestrial qualities will also benefit greatly from enhancing the effectiveness and accuracy of data analysis, as well as attempting to apply other novel analytical techniques.The volume of exoplanet-related scientific study is exploding with each new generation of observational instruments and advancement of observational techniques. The objectives of exoplanet exploration and research in the coming years include furthering the discovery of habitable planets in nearby stars, optimizing planetary system parameters, and elaborating their characteristics.

7. Conclusion

To sum up, the study of exoplanets has advanced into one of the most active fields of astronomical research approximately twenty years since the earliest extrasolar planets were discovered. Over 700 planets have been confirmed, and at the current rate, the sample will double in size every few years. Exoplanet detection techniques, methodologies, tests, tools, telescopes, and satellites are continually being improved, allowing for the identification and characterization of a larger and larger variety of planets orbiting a larger and larger variety of hosts. These studies are not only consistently revealing novel and surprising sorts of planetary systems, but they are also starting to make it possible to characterize the demographics of several exoplanet samples throughout a wide range of parameter space statistically robustly.

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