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Analysis the State-of-art Exoplanets Exploring Schemes: Radial Velocity, Transit and Gravitational Microlensing

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Abstract:

Since the first planet beyond the solar system managed to be examined in 1995, the concept of "exoplanet" has been created. The exoplanet, officially defined as extrasolar planets circling other stars that are not part of the solar system, quickly arose an influential curiosity, as scientists began to consider how many stars and planets truly exist in the periphery of the solar system and what the properties of these objects have. In the following years, a series of detection schemes appeared and applied to this theme. This study has listed five of them that are utilized most in current decades, providing a specific view of the Radial velocity method, Transit method, and Gravitational microlensing method. Each of these three explores exoplanets depends on different theories, like Doppler shifts of the RV method, the light variations of the transit method caused by the shadow of planets, and the subtle peaks of luminance of the microlensing method. By outlining the information of several instruments, the goal is to obtain a comprehensive understanding and concise synopsis of the methods employed in the exoplanetary area, which may provide with fresh inspiration to create more sophisticated appliances by understanding the underlying principles of the ones that already exist.

Keywords: Exoplanets; exoplanets detection; RV method; transit; microlensing.

1. Introduction

For decades, exoplanets have remained a mystery and aroused strong interests among specialists in the realms of stellar-planetary cosmogony and cosmochemistry, offering an extensive fresh category of objects for astronomical, physical, and dynamic study which are chiefly used for correlative research [1]. However, prior to the late 20th century, theoretical and philosophical arguments had persistently been the major basement of what one knew about exoplanets, developing astrometry, which is the oldest method of astronomy [2]. Therefore, it is unsurprising that most of the previous detections ended up in failures. It was not until the early 1990s that Aleksander Wolszschan and Dale Frail found the first exoplanet while studying the PSR B1257-12 pulsar, whose mass is 1.4 times that of the Sun in neutron star terms [1, 3]. Later, Michel Mayor and Didier Que Loz uncovered the first exoplanet in 1995 orbiting a main-sequence star when they identified a hot Jupiter circling 51 Pegasi [1, 4]. The next significant development in exoplanet monitoring occurred in 1999 when Charbonneau et al. discovered the first transiting signal in the radial velocity-validated planetary system HD 209458 [5]. The source of this signal was an exoplanet that was out of the direct line of sight and passing in front of the host star [5].

From then on, the consensus that the subject matter of exoplanets has experienced a greater influence from new instrumentation than any other topics in astrophysics has been promoting the great evolution of the primary astronomical techniques for exoplanet exploration, from radial velocity variations (1989, first success in 1995) to direct imaging and the microlensing method in 2004 [1, 2] To demonstrate, photons directly released from the exoplanets were first detected by astronomers in 2008. Nevertheless, only the high contrast imaging capabilities provided by the Keck and Gemini telescopes at the time, along with the exquisite spatial resolution offered by ground-based AO equipment, allow this to happen [5].

In fact, this increasing advance was not only devoted to updated instruments but also contributed by several efforts made by astronomical organizations. For instance, NASA's Kepler mission, with the usage of TESS and CHEOPS, stimulated the generation of computational systems for calculating the planet formation frequencies; similarly, the International Space Science Institute forums first held in 2012 assembled 24 experts of great renown to discuss a series of issues concerning exoplanets researches improvements [6-8]. The dramatic developments of astronomical approaches and observation tools, though the majority of the accessible instruments were space telescopes, opened the door to a new world and led to exciting remarkable progress: above 4000 exoplanets have been found in less than 25 years and are part of exceeded 3000 planetary systems [1]. Specifically, a hitherto number of exoplanets that have been confirmed to detect is around 5600 [9]. In recent years, since it is widely accepted that a lone theory will probably fail to be able to describe sophisticated planetary systems, a number of specific models have been advocated to create, including atmospheric codes for photochemical, thermospheric, and hydrodynamic processes, test-particle devices, Monte Carlo simulation implements, and multiple mathematical transit algorithms [8].

The field of exoplanetary studies has provided new perspectives on key issues in stellar-planetary cosmology, particularly the topic of the Solar System's birth and expansion [1]. Thus, this review aims to present a number of exoplanets exploring schemes with details in a comprehensive and logical version, providing an accessible overview due to the significant role that advanced observation techniques play in exoplanet detection. To demonstrate, the review will first compare the discrepancies between different methods of exoplanet research, focusing on the introductions of three approaches, especially, in detail. Ultimately, the future anticipations and the limitations of current exoplanet research are appended at the end of the review.

2. Comparison of Schemes

Until now, there are mainly five ways invented to detect the exoplanets along with the exoplanet's research history: Astrometry, Radial velocity, Transit, Direct imaging, and Gravitational microlensing. Astrometry is the earliest tool used to explore exoplanets by noticing the star's minute oscillations in space when wobbling around due to the existence of a planet or planets (seen from Fig. 1) [1]. Yet considering the way that light is bent and twisted by the atmosphere, astrometry is particularly difficult to do from Earth's surface and calls for exceptionally accurate lenses [10]. Therefore, the RV (radial velocity) method was brought into reality as the situation requires. The basic principle behind it is the assessment of periodic fluctuations in a star's radial speed using changes in its spectra lines. [1] However, compared to other observation schemes, the deficiency of the RV method is also obvious: when the system of planets is viewed virtually face-on, the real weight may be substantially greater because the slope of the planetary rotation is still unable to be determined accurately, which means that the interpreted planetary mass continuously maintains its lowest number [8].

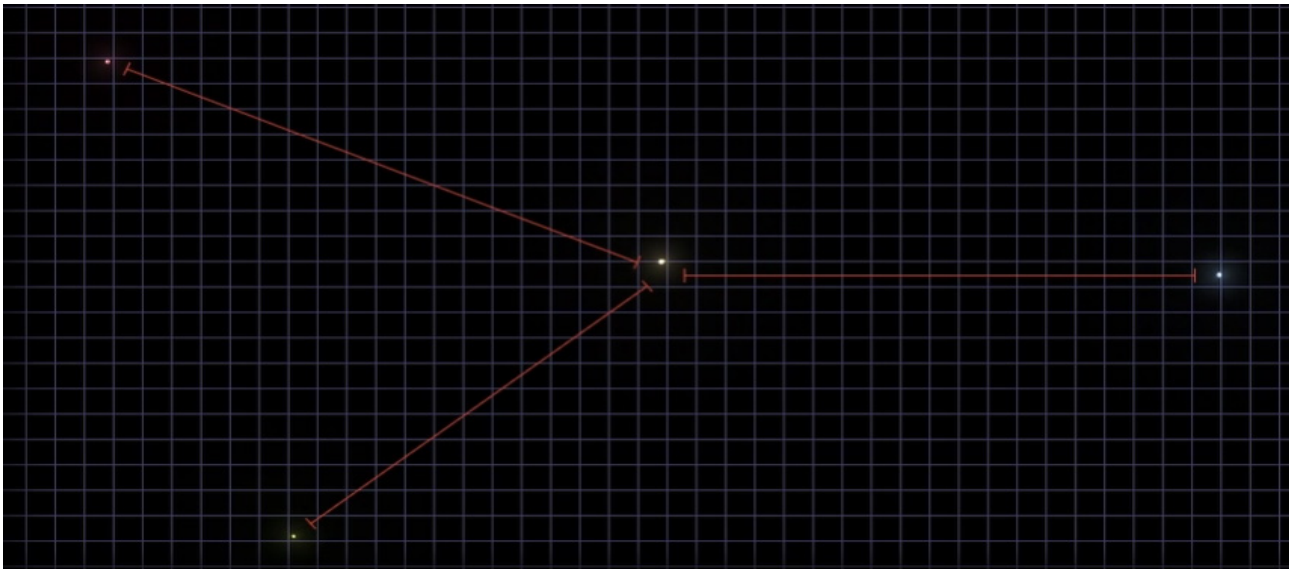

Fig. 1 A sketch of minuscule movement of a star. A star's wobbling in space with respect to other neighboring stars in the sky can result from a planet's orbit [10].

In the end, with the gradual development of the space industry, the transit method was then introduced to the field of exoplanets, which has been regarded as one of the most widely used approaches. The transit method is always praised for its ability to provide exoplanet atmospheres with a lot of leverage [8]. Still, the only concern is the strict demand for the photometric accuracy needed to identify the exoplanet using this technique, which is found to be challenging to achieve this level of photometric precision from Earth due to atmospheric turmoil [8]. In short, the brilliant stars become the only targets [8]. While enjoying the advantages that are contributed to the transit method, another exotic method named Gravitational microlensing (GM) was discovered accidentally. Its lone drawback is that, in contrast to other techniques, the transmission from outer space won't reoccur, giving us a single opportunity to recognize the planetary nature of light waves produced by microlensing (as depicted in Fig. 2). What makes the GM method so special, is that the selection effects have a negligible impact on it, meaning that only with this approach is it currently possible to find planets with such modest masses [1, 8].

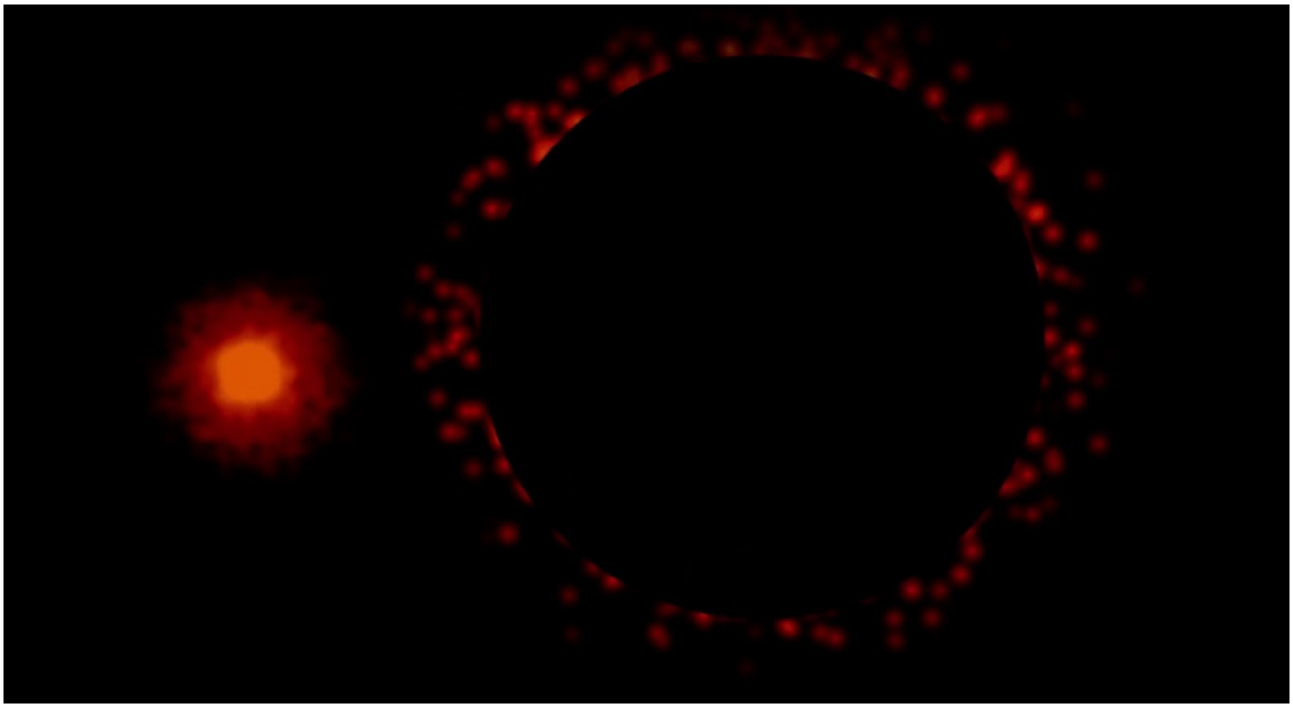

Fig. 2 Capturing images of a planet, by lowering the intense brightness of the stars that this exoplanet rounds [10].

Although the direct imaging method is currently in its early phases, it has great expectations for being one of the important instruments in the future, as the examination of the exoplanetary atmospheric conditions in-depth can be supported by the superior spatial accuracy that AO, utilized in direct imaging, provides [10]. Nevertheless, one of the weaknesses is that the conditions of its application are harsh, for only glowed stars or those at greater circular distances [8]. Concerning the differences in measurement resolutions and limited conditions between different types of techniques, the results of the stellar magnitude are distinguished. The results are presented in the following: the number of planets that the Astrometry means has found is 3, and which of those that RV method, Transit, Direct imaging, and Gravitational microlensing uncovered is respectively 1091, 4276, 82, and 224, as listed in Table 1.

Table 1. The number of planets that have been retrieved through each scheme

Scheme types	Astrometry	RV method	Transit	Direct imaging	Gravitational microlensing
The number of Planets detected	3	1091	4276	82	224

3. Detection Schemes

3.1 RV

The RV method is known by another name, Doppler spectroscopy, which measures periodic shifts in a star's radial velocity caused by planets [1]. To know more about this time-constant change, a perspective called the 'size rule' has to be understood first. The size rule is that, when there is a considerably small planet, which has far less gravity, surrounding a large star with a strong gravitational field in the middle, this host star would 'wobble' around slightly by the force its planet implemented (as illustrated in Fig. 3), and the size of the planet is in direct proportion to the impact that imposed on its star [10]. Therefore, the 'wobble' of a star is an excellent reference to reveal information about its planet count and size [10].

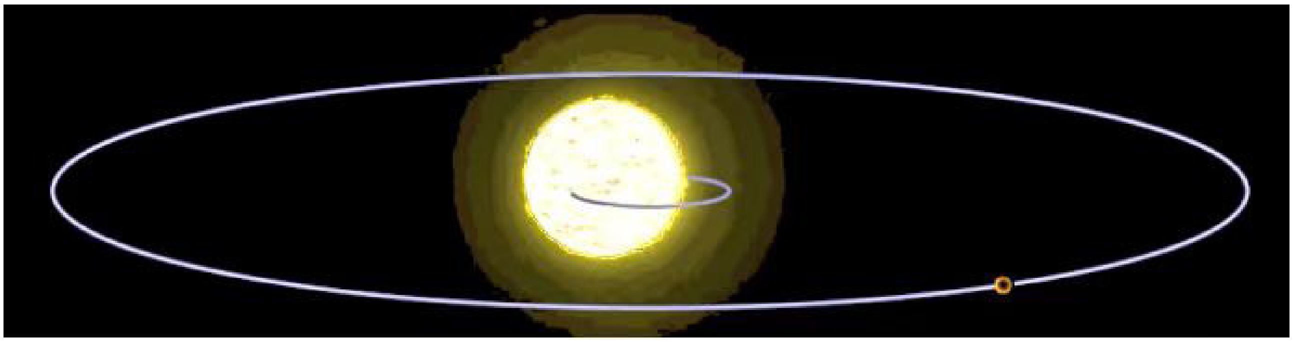

Fig. 3 When a massive star is surrounded by a significantly smaller planet with much less gravity, the star will 'wobble' somewhat due to the pull exerted by the planet [10].

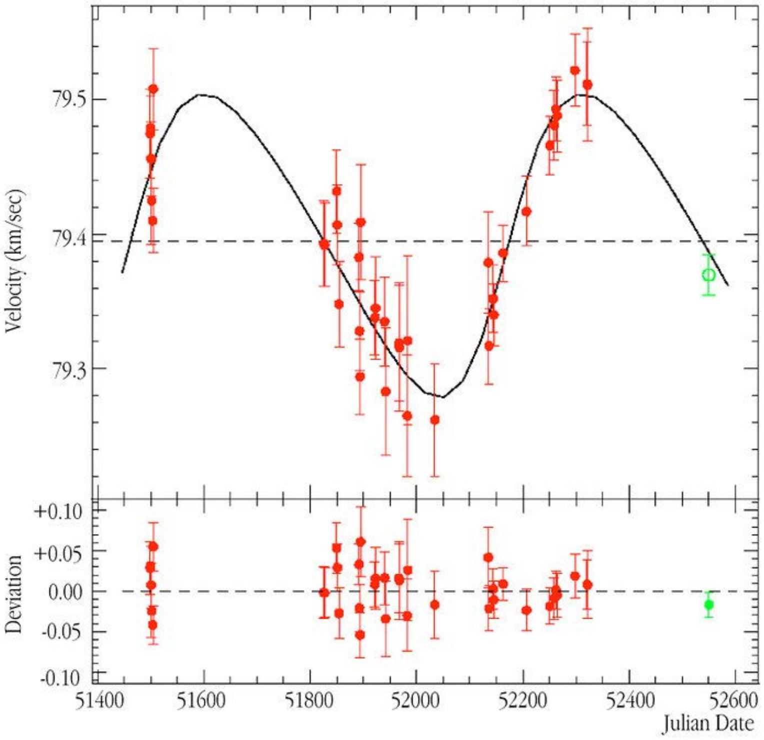

Fig. 4 The RV curve of HD 47536, the result of the planet's attraction over a time frame of 712 days [13].

Astronomers then crystallized the abstract process of 'wobbling' into the radial velocity to help a convenient measurement, whereas the radial-velocity change was too rapid to capture. To concur with this issue, the phenomenon of Doppler shift was applied and later developed into the Doppler technique: the process of calculating a spectral line›s wavelength and contrasting it to the amount it would theoretically have when transported into the rest frame of the solar system [2, 10]. These two compared values, ultimately, are connected through the Doppler equation with the RV vector as an auxiliary [2]. Detecting the imperceptible variation relies tightly on high-resolution spectrographs. Take HARPS-N as an exemplification. Although spectrographs have been used in the RV method since many years ago, scientists are trying their best to ameliorate its function in order to acquire a more precise accurate result. Around two years ago, the widely accessible ESPRESSO DRS was configured to function with HARPS-N to increase the reliability of the HARPS-N RVs [11]. Another spectrograph that currently has been put into use is EXPRES (EXtreme-PREcision Spectrograph), which achieves an RV precision of 30 cm^{-1} [12]. To be more specific, the most invaluable function that it offers is a comprehensive pipeline for scientific diminution, ex-

traction, and evaluation, playing an important role in producing erroneous assessments through its data reduction processes [12].
Using the planet HD 47536 learned through the RV method as an example, Fig. 4 explains the specific detection results derived from the RV method. The precision of the observations is indicated by error bars [13] The continuous black lines are the programmed velocity wave with computational technology [13]. In addition, the diagram's bottom section indicates how far the measurements diverge from this wave [13]. By taking the data of RV and then plotting them, the number of planets that are near a star can be soon confirmed rightly.

3.2 Transit

The transit method is an inspiration generated from the solar eclipse or the lunar eclipse, of the basic principles behind it are similar to each other. Particularly, it skillfully exploits a partial blockage of a planet, when the light of its orbiting star therefore becomes darker, produced due to the planet orbiting [10]. Even though the variation is slight, it provides researchers with sufficient evidence to conclude that an exoplanet is orbiting a far-off star [10]. There are actually two methods that exist for spotting planetary transits. The first one is to scan a large number of stars with a few photometers in the hopes of finding potential exoplanets. The key point is that what the level of the photometric accuracy required depends on the projected length of the transit light pattern [2]. Moreover, the demand for several optical resolutions at the same time brings respective issues that are likely to be solved by distinct instruments. To illustrate, telescopes with a tiny diameter and charge-coupled devices (CCDs) work well for measuring as many planets as possible; similarly, when discussing the extended period of the nighttime that precludes observations from one position, tiny telescope networks that transfer data from various longitudes comes to the first place, like the Hungarian Automated Telescope Network (HATNet) [2].
Focusing on densely populated stellar fields is the alternative tactic, taking advantage of a 1.3-m telescope in the Optical Gravitational Lensing Experiment (OGLE) operated in this tactic [2]. To supplement, besides this telescope, another telescope is of great significance to the transit method. That is the Kepler space telescope, which is frequently praised for its ongoing observation and extremely accurate photometry [8]. The results of the transit method are presented in Fig. 5. As the graph interprets, the sudden drop in the light curve suggests a decrease in luminosity [10]. The shape of the light curve is likely to be affected by the other two factors. One of the strongly influential parameters is the scale of the planet, causing the following changes in the dimensions and duration of the transits method [10]. It can be seen in Fig. 6 that the light curve of the larger planet has a deeper groove and longer interval, whereas that of the smaller planet is the opposite. Therefore, it can be summarized that the deeper the fissure is, the more amount of light is hindered the bigger the planet is; additionally, a planet's orbital period and time to have a transit completed increase with its distance from the star. Another factor is a condition set up by a couple of planets across at the same moment, leading to the complexity of the graph (seen from Fig. 7) [10]. All these relationships mentioned above provided important data regarding the galactic distribution of exoplanets by making use of the transit method.

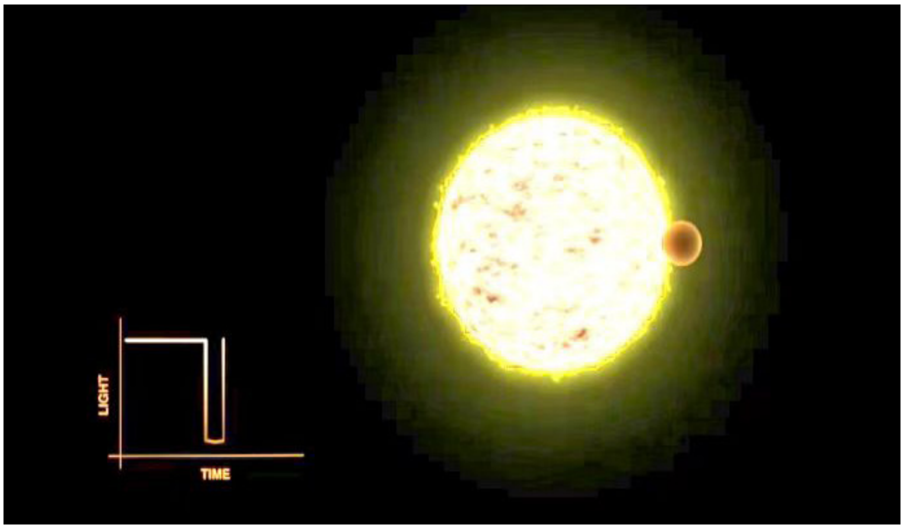

Fig. 5 The animation on the right side depicts the process of the light from a star being diminished when a planet travels in front of the star, the chart on the left side shows how much light is coming from the star [10].

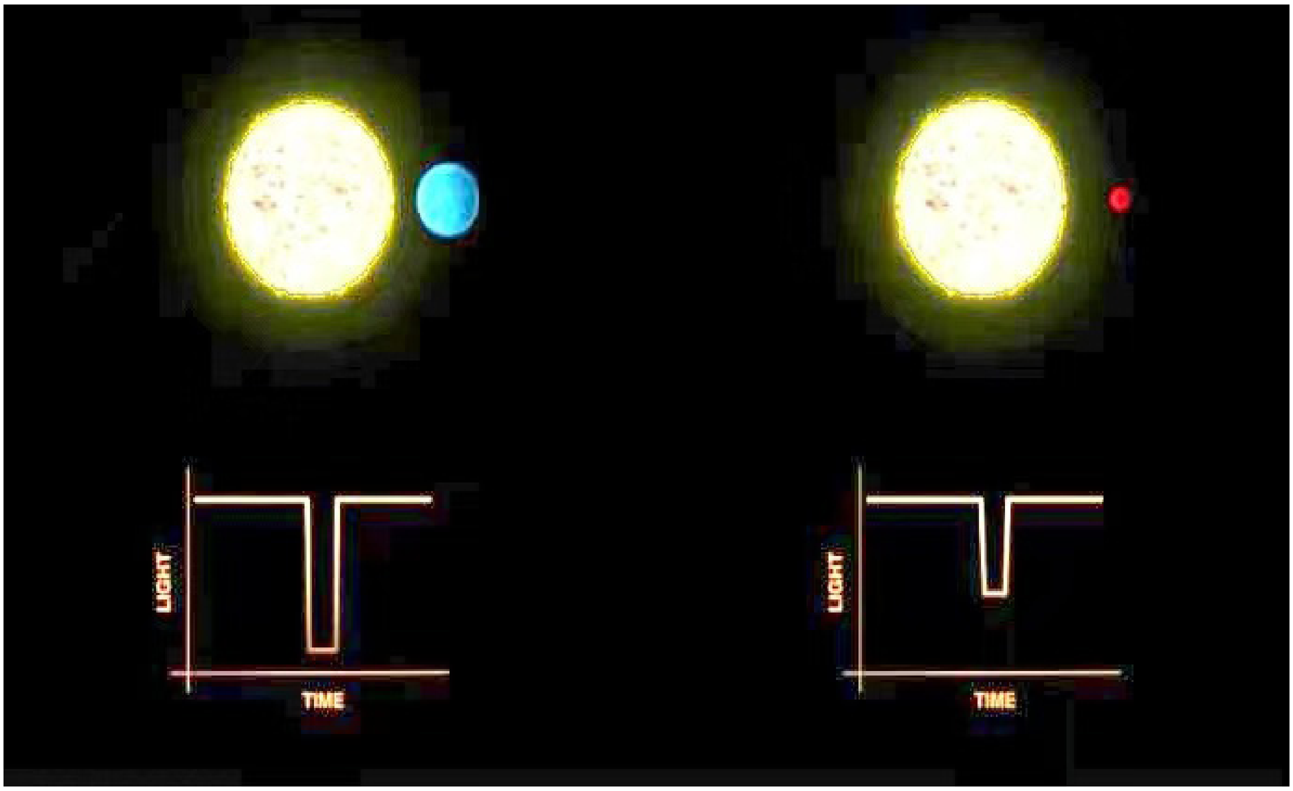

Fig. 6 The two pictures describe the same process in the figure with the only difference of the planet's size [10].

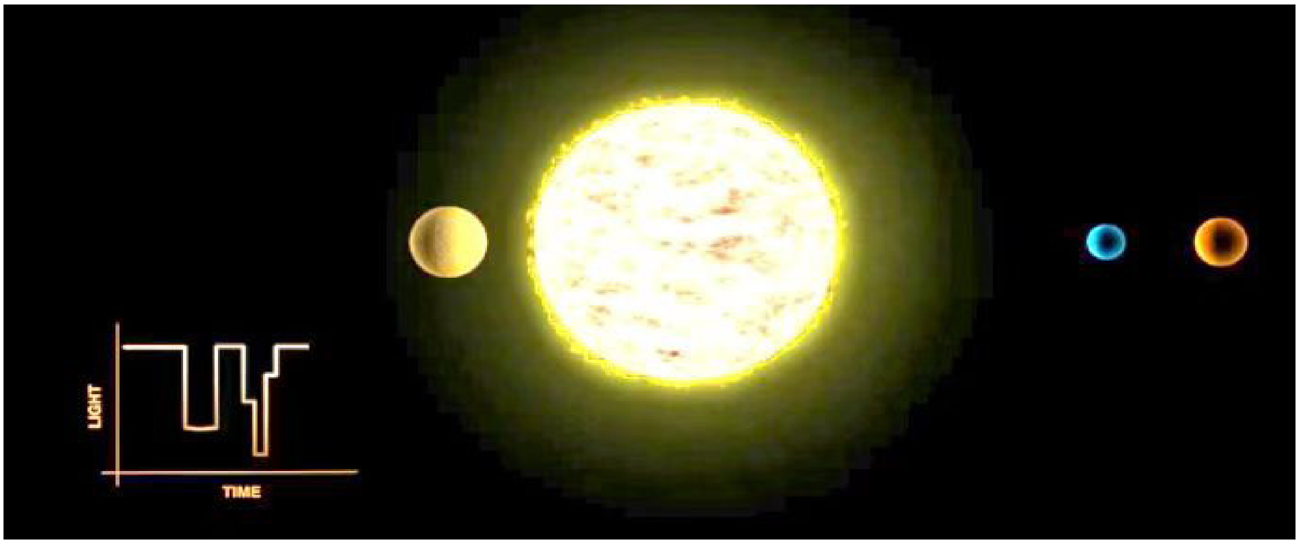

Fig. 7 The picture describes the same process in the figure with multiple planets [10].

3.3 Gravitational Microlensing

The gravitational microlensing method relies on photometric measurements of a far-off star's luminosity increasing as a result of gravity's lensing effect [1]. Before understanding it in detail, the phenomenon of gravitational lensing is paramount to know beforehand. Based on a feature of gravity-it may be thought of as a curvature in space-time-proposed by Albert Einstein in his Theory of General Relativity, any huge star object will divert light beams that are approaching it [14]. This variation of orientation features gravity the ability to bend and concentrate light, eventually emerging a convergence of the light which momentarily makes the focus appear brighter [10]. Thus, the microlensing method finely takes advantage of this brief flash to confirm the existence of planets. In Fig. 8, the star begins to brighten, followed by a momentary burst of brilliance caused by the planet's lensing activity which is a thin secondary signal if there is a planet orbiting the lensing star. After the planet gets lensed, the light levels decrease, but the star's lensing activity keeps the light levels rising [10]. The luminous power of the farther-off star immediately disappears as long as the lensing star departs from its ideal location. Nevertheless, these lensing events are unpredictable in terms of timing and location for researchers, meaning that they must therefore observe vast swaths of the sky for an extended amount of time in order to obtain details regarding the star's approximate size [10].

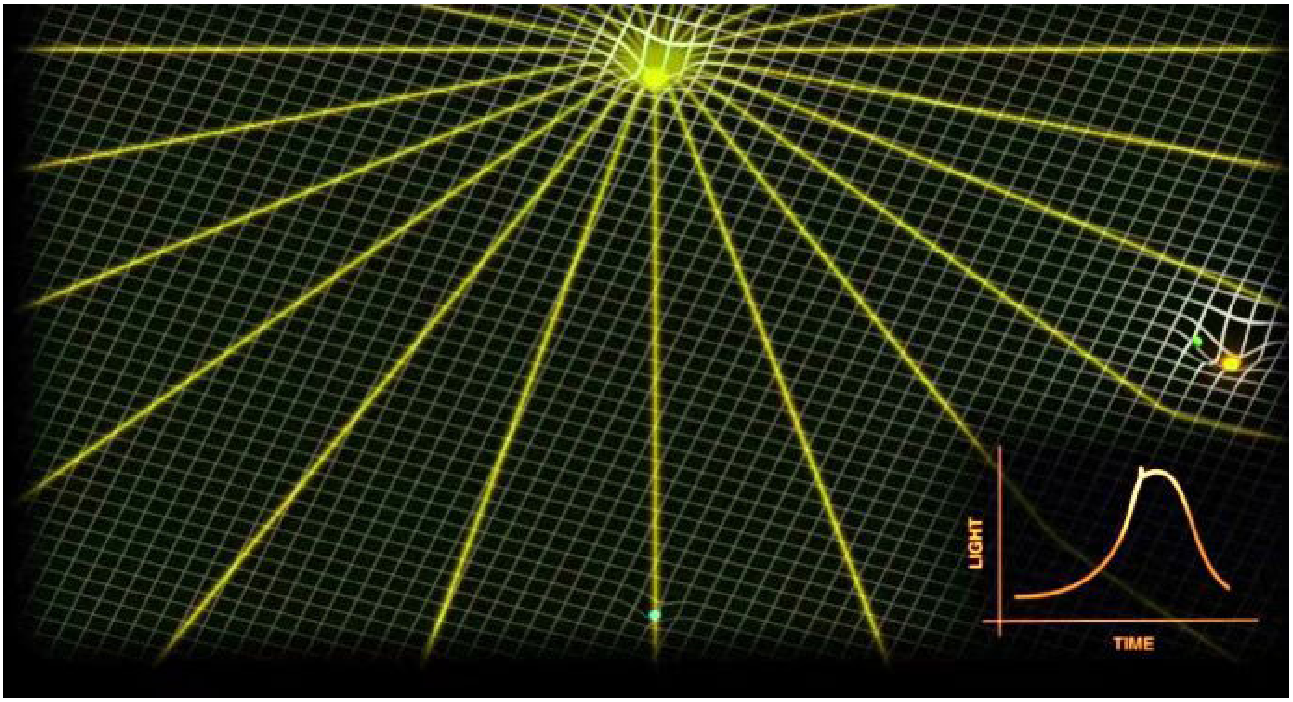

Fig. 8 The star's light is twisted and centered by gravity when a planet moves between a far-off star and Earth. Regarding the graph in the left corner, the first tiny apex is referred to as the "planetary signal" [1].

On the other hand, since the lensing phenomenon produces pictures with angular separations on a scale of milli-arcseconds, currently available telescopes are unable to independently clear the photos [14]. A future upcoming mission launched into space, WFIRST, has been placed great hopes on thereby, benefiting a lot potentially [8]. It, particularly with its excellent spatial accuracy and broad scope of vision, is not only anticipated to produce great cadence, and superior light curves that lead to the discovery of hundreds of exoplanets, but also permit the discovery of planets other than Earth with masses comparable to those of Jovian satellites [8]. Moreover, the function of simultaneous monitoring from above and below assists astronomers in overcoming microlensing degeneration and determining the lens technique's overall weight -consisting of the host stars and exoplanets.

4. Limitations and Prospects

Since the late 19th century, one has been persistently exploring the unknown world of exoplanets and have made considerable amazing achievements both in the realm of technique developments and invaluable discoveries. However, there are still a certain number of limitations and challenges that are supposed to be overcome. One takes specific schemes of exoplanet detection as examples. The RV method is one of the most relatively reliable and successful methods with a long-developed history, but nowadays it has been limited by multiple possible sources of issues, in spite of assiduous efforts made to figure out the solution, ranging from instrumental mistakes, and photonic interference to light pollution [2]. Another exploration approach is the transit approach. Despite the accomplishment of finding the majority of exoplanets detected to date, extensive observational work is needed when dealing with specific types of exoplanets, such as hot stars of early spectral types or stars with dim visual brightness [1, 2]. Microlensing instruments are the most challenging. As mentioned above, since the exact location and timing of such lensing events are unknown to observers, a large amount of time and energy would be consumed [10]. After all, the accuracy of the results provided by the RV method can be highly improved if these problems are solved properly in future development.

Previously, the emphasis was on finding new exoplanets and gathering data regarding their variety, which mostly involved exterior factors [2]. However, these days, the focus is shifting to a thorough characterization of particular planets and planetary systems, consisting of orbital variables, host star properties, synchronization, physical circumstances, etc. [2]. These features are extremely significant references to the following research on exoplanets, especially the endeavor to find life, which might be the most popular field of study for this topic today [5]. Human beings are looking forward to answering questions that are potentially resolved soon, like the existence of a standard design for planets, the reasons that force the planets to form and evolve, or the connection between the creation of planets and the development of environments similar to Earth, with these sophisticated schemes [7]. This study also highly expected that these schemes, in addition to having a more outstanding spectral and spatial sensitivity, will not compete with one another like old times, but will make a major contribution to the study of exoplanets when working mutually [2].

5. Conclusion

To sum up, this study analyzes and extends the previous instruments used to make discoveries, introducing three of them in detail, which are the RV method, transit, and gravitational microlensing. Regarding the number of exoplanets that are explored, the RV is based on the magnitude of gravitational force that drives between a star and its orbiting planets reflected by spectrum. The transit, in contrast, takes advantage of the star's luminance when covered by its planet. The microlensing, which hasn't been fully developed, makes good use of the gravitational lensing phenomenon. It is eager to see more explorations of new exoplanets along with the meliorative technology in the future. In this regard, the research is aimed to gain a broad insight and clear summary of the approaches used in the exoplanetary field, which might inspire viewers with new ideas to invent more advanced appliances by learning the principle behind the existing ones.

References

[1] Marov M Y, Ivan I Shevchenko. Exoplanets: nature and models. Physics-Uspekhi, 2020, 63(9): 837.

[2] Pepe F, David E, Michael R M. Instrumentation for the detection and characterization of exoplanets. Nature, 2014, 513(7518): 358-366.

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

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

[5] Howell S B. The grand challenges of exoplanets. Frontiers in Astronomy and Space Sciences, 2020, 7: 10.

[6] Batalha N M. Exploring exoplanet populations with NASA's Kepler Mission. Proceedings of the National Academy of Sciences, 2014, 111(35): 12647-12654.

[7] Lammer H, Blanc M, Benz W, et al. The science of exoplanets and their systems. Astrobiology, 2013: 793-813.

[8] Lee C H. Exoplanets: past, present, and future. Galaxies, 2018, 6(2): 51

[9] NASA. Exoplanets. Retrieved from: https://science.nasa.gov/exoplanets/

[10] NASA. https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/?intent=021#/5

[11] Dumusque X, Cretignier M, Sosnowska D, et al. Three years of HARPS-N high-resolution spectroscopy and precise radial velocity data for the Sun. Astronomy & Astrophysics, 2021, 648: A103.

[12] Petersburg R R, Ong J M J, Zhao L L, et al. An extreme-precision radial-velocity pipeline: first radial velocities from EXPRES. The Astronomical Journal, 2020, 159(5): 187.

[13] ESO organization. Retrieved from: https://www.eso.org/public/images/eso0305c/

[14] Tsapras Y. Microlensing searches for exoplanets. Geosciences, 2018, 8(10): 365.