Analysis and Comparison of Three Exoplanet Searching Schemes

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Abstract. In retrospect, from ancient times to the present, human beings have never stopped exploring the secrets of the universe. With this in mind, exploring the universe means the progress of human science and technology, promoting the exchange and integration of human civilization and avoiding unknown risks and continuing human civilization. In the 1990s, humans officially launched the challenge to detect exoplanets. Since then, research on exoplanet detection has developed rapidly. On this basis, this study introduces the research history, development status and research results of exoplanet detection, comprehensively introduces mainstream exoplanet detection methods and representative projects, and elaborates on the principles, instruments, and research results of the three most widely used methods. Finally, this study summarizes the current problems and difficulties that restrict the development of exoplanets, and look forward to the development trends and bright prospects of future planetary exploration. These results provide guiding insights of further exploration of exoplanet searching.

Keywords: Exoplanet searching; radial velocity; transit method; directly imaging.

1. Introduction

The universe is vast and infinite, and its trillions of galaxies attract people to continue to explore. Due to objective reasons such as the level of science and technology and observation distance, the earliest objects people began to observe and detect were the planets in the solar system. These studies help us analyze and reason about the composition, formation and evolution of the solar system, and understand the inseparable relationship between the solar system and the universe. With the development of technology and the continuous improvement of theory, scientists have begun to regard exoplanets as one of the important research targets. Exoplanets are planets orbiting stars located outside the solar system. The study of exoplanets can take the exploration of the universe to another level. First, through the detection data of the target planet, this study will analyze and deduce the connection between it and the star, and then explore the diversity and complexity of the universe. Secondly, one will search for the origin of life by comparing the differences between the environments of exoplanets and planets in the solar system; at the same time, this stuy will expand the database for certain types of planets, study the formation and evolution mechanisms of this type of planets, explore the theory of planetary evolution and planetary stability, and explore the environment of the Milky Way. The planetary motion reveals the origin and evolution of the Milky Way. Most importantly, the discovery of Earth-like planets can expand human living space and resources, and provide more opportunities and choices for humankind's future. However, due to the immaturity of astrometric methods, the accuracy of exoplanet detection has never reached people's ideal results.

In the 1990s, the advent of space telescopes greatly improved the accuracy of astronomical measurements. This was a huge turning point in the detection of exoplanets. In 1995, Mayor and Queloz observed 51 Pegasi b [1], which was the first exoplanet discovered by humans orbiting a sun-like star. This milestone officially kicked off the exploration of exoplanets. Since then, all countries have actively participated in the exploration of exoplanets. The Kepler mission proposed by NASA and the second Kepler mission, which achieved great success [2]. A famous discovery was the confirmation of the first rocky exoplanet. A total of 548 exoplanets were discovered during its service from 2009 to 2018. Its successor TESS, as the representative instrument of the transit method, is currently the most fruitful detection project. Discovering planets; the European Southern Observatory ESO's Very Large Telescope is currently the largest optical telescope in the world. Its equipped ESPRESSO breaks through the technical limits and improves the accuracy to 10cm/s, greatly improving detection accuracy [3]. In 2016, the "Red Dot Project" announced the discovery of Proxima Centauri b, a planet similar to the size of the Earth that orbits Proxima Centauri, the closest star to the sun, which is only 4.25 light-years away from the Earth. In 2017, researchers announced the discovery of the TRAPPIST-1 planetary system, which is only 39 light-years away from Earth and contains 7 Earth-like planets. This is the planetary system with the most planets discovered outside the solar system so far. As of September 10, 2023, humans have mastered more than ten exoplanet detection methods, and a total of 5,514 exoplanets have been discovered [4]. At present, the focus of planetary exploration has shifted from searching for planets to analyzing planetary structures and components, and specifically searching for Earth-like planets in the habitable zone.

This article aims to summarize the current mainstream exoplanet detection methods and reveal their method principles and related instruments. By analyzing the results of the detection project, one can provide directions and new ideas for the subsequent exoplanet detection. In the second section of this article, the mainstream planet detection methods and detection results will be introduced. In the third section of this article, this study will focus on the measurement method of radial velocity method, related instruments, application projects and results. In the fourth section of this article, the method principle, related instruments, reasons for widespread application and detection results of the transit method will be analyzed in detail. In the fifth section of this article, the measurement principle, instrument application and important progress of the microgravitational lens method will be clearly explained. The Section 6 will systematically review the current problems that limit the development of exoplanet detection and the opportunities and challenges for future detection. Section 7 will summarize the contents of this article and look forward to the bright future of exoplanet exploration.

2. Basic Description

As analysis technology continues to mature and instrument accuracy continues to improve, humans have now mastered many planetary detection methods. These methods can be divided into two major categories, the first category is indirect detection methods, and the second category is direct detection methods. Indirect detection methods include astrometry, timing, microlensing， radial velocity, transit, orbital brightness adjustment, planetary disk motion, etc. In the following sections, the three currently most widely used methods, the radial velocity method, the transit method and the direct detection method, will be introduced in detail and will not be described in detail in this chapter. As one of the oldest detection methods, astrometry detects exoplanets by monitoring the gravitational effects of exoplanets on the position of their host stars. The advantage of astrometry is the ability to measure the mass of binary stars [5]. According to data, a total of 12 planets have been discovered through astrometry by 2020.

The core principle of the timing method is to monitor the impact of the revolution of exoplanets on the host star to find the existence of exoplanets. The mainstream timing methods are divided into pulsar timing method, eclipsing binary timing method, transit timing method and pulsation period timing method. The principles of these four methods are that exoplanets cause "swaying" periodic changes in the pulsation center of the main star, planetary gravity affects the eclipse phenomenon of binary star systems, planetary gravitational interactions influence each other, and planetary tidal forces cause changes in the pulsation period of the main star. The essence of the microgravitational lensing method is based on Einstein's general theory of relativity. It uses the gravitational lensing method to detect exoplanets. The current main detection projects include MOA, OGLE, WISE, and KETNET [6]. An exoplanet may experience a Doppler brightening effect as it rotates around its host star, that is, the observed frequency is inconsistent with the actual frequency, and the brightness of the host star increases or decreases due to the radial velocity of the planet. This method is called the orbital brightness adjustment method, and the James Webb Space Telescope is a typical representative. The planetary disk motion method is to detect the substructure of the planetary disk through submillimeter light wave arrays based on existing theories and observation results, and determine the formation and existence of exoplanets through changes in the substructure of the protoplanetary disk. ALMA detection is a direct application of this method. Although only one exoplanet has been confirmed using this method so far, the application scope of this method continues to expand and the prospects are promising.

3. Radial Velocity

For a basic two-body system, while the planet orbits the star under the influence of gravity, the planet's gravity will cause the star to produce slight fluctuations, that is, the star makes an elliptical motion around the center of mass of the system composed of the two. The radial velocity method uses the Doppler effect to confirm the periodic changes in the motion of stars to infer the existence of exoplanets, so it is also called the Doppler effect method. The Doppler effect means that the wavelength of an object's radiation changes due to the relative motion of the wave source and observer. The spectral lines in a star's spectrum will be blue-shifted when the star moves toward the Earth in the line-of-sight direction, and the spectral lines will be red-shifted when the star moves away from the Earth. Based on the degree of red (or blue) shift of the wave, the speed of the wave source moving in the direction of observation can be calculated. One can determine the existence of exoplanets by monitoring changes in spectral lines, that is, changes in star RV or position over time, through a spectrum analyzer equipped on a telescope. Calculating the half-amplitude of the stellar RV based on Kepler's law shows that the half-amplitude and high-precision RV detection capabilities are mainly related to the planet's mass, orbital period and orbital inclination. Therefore, the exoplanets discovered by the RV method are mainly short-period and large-mass.

Currently, a total of 1,063 exoplanets have been discovered using the radial velocity method, among which the most successful representative detection projects are HARPS and ESPRESSO. HARPS was born out of a program at the European Southern Observatory in 1998 to design a high-precision instrument capable of detecting exoplanets using the radial velocity method. In January 2003, HARPS made its first run on the 3.6 m telescope at La Silla Observation in Chile with the expected results, maintaining an apparent velocity accuracy of 1 m/s, making it the most successful discoverer of low-mass exoplanets to date. On the basis of HARPS, ESO configured the spectrometer HARPS-N with the same parameters on the TNG telescope (Telescope Nazionale Galileo) and performed the initial light on March 27, 2012. The instrument distinguishes gaseous exoplanets in search of "super-Earths" by combining transit photometry and Doppler spectroscopic measurements to distinguish rocky terrestrial planets.

With the advancement of science and technology, the spectrometer ESPRESSO (Echelle Spectrograph) with higher resolution and accuracy has appeared. ESPRESSO is installed on the Combined-Coude´ Laboratory of the VLT telescope (very large telescope array) [7]. The VLT telescope has four 8.2m-diameter telescope units, which makes ESPRESSO's working characteristics both independent and joint. That is, ESPRESSO can process any light waves received by the four UTs individually, or it can process the light waves from the four UTs at the same time. A schematic view of the different observing modes is shown in Fig.1. Combined light waves. As a light-feeding, cross-dispersion, high-resolution spectrometer, ESPRESSO is a device specially used to find and study rocky Earth-like planets. It achieved first light in November 2017. In terms of performance, ESPRESSO has higher detection efficiency, spectral accuracy and stability than HARPS. ESPRESSO's radial accuracy reaches 10cm/s, which means that the accuracy of radial velocity monitoring of possible exoplanets has been greatly improved. ESPRESSO has three observation modes: high-resolution spectroscopic observation (HR) with a single telescope, ultra-high-resolution spectroscopic observation (UHR) with a single telescope, and medium-resolution spectroscopic observation (MR) with multiple telescopes. (ESPRESSO focuses its observations on inactive, non-rotating dwarf stars with spectral types G to M), and due to its high accuracy, it is possible to detect lower-mass, rocky Earth-like planets. Due to the wide observation range of VLT, the joint application of ESPRESSO and other equipment will greatly improve detection efficiency, such as follow-up observations of candidate objects discovered by the Kepler telescope. In addition, in the future, ESPRESSO will combine with VLT's high-contrast imager SPHERE to carry out more in-depth observations of exoplanets [8, 9], such as detecting planet reflected light, planetary disk scattered light, and searching for planets with conditions suitable for life. In addition to the above, ESPRESSO can also measure changes in physical constants. The basic constants of nature are usually considered to be fixed. However, as the universe gradually evolves, these constants will also undergo slight changes. Observing these small changes requires the collection of larger areas of data and more accurate wavelength accuracy measurements [10], ESPRESSO's high-resolution features are expected to fulfill this need (seen from Fig. 1).

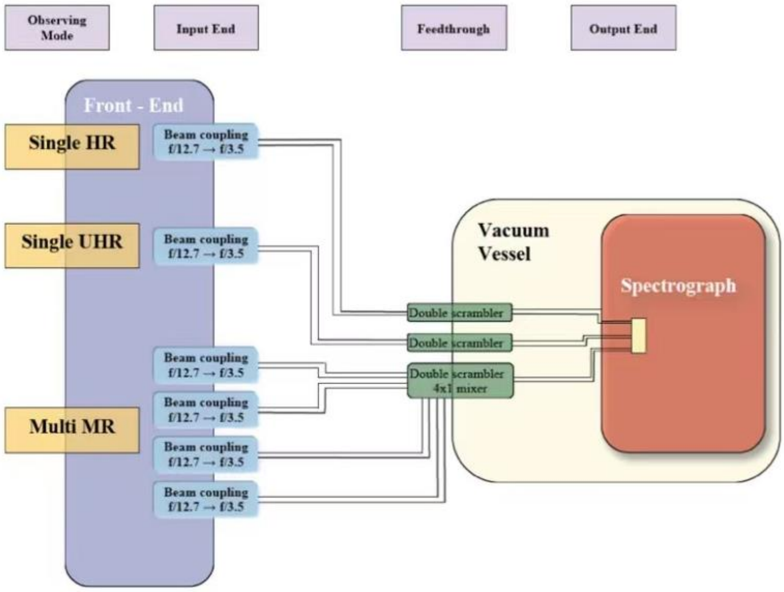

Fig. 1 A schematic view of the different observing modes

4. Transit

The transit method is currently the most fruitful and widely used method, with a total of 4,115 exoplanets discovered. This is due to the successful development of detection projects such as Kepler, K2, CoRoT and TESS. The basic principle of the transit method is to use the eclipse phenomenon when the planet rotates around the main star, and use satellites to observe the decrease in the brightness of the main star to determine the existence of exoplanets. Scholars usually call it a primary eclipse when a planet moves between the observer and the star, and it is called a secondary eclipse when the planet moves behind the main star or is blocked by the main star. The degree of decrease in brightness of the primary star is also called the occultation depth. Since the brightness of the secondary eclipse primary star decreases less, current detection methods mainly focus on monitoring the primary eclipse. The biggest feature of the transit method is that it can use changes in the brightness of the star to calculate the radius of the target planet. In addition, the transit method combined with spectroscopic analysis technology can analyze the properties of planets. Compared with other methods, the advantage of the transit method is that space observation can avoid the impact of changes in the earth's atmosphere on photometry accuracy, greatly improving detection efficiency and accuracy. The limitation of the transit method is that the probability of a planet's eclipse decreases with the extension of its orbit. Therefore, the planets currently discovered by the transit method are mainly short-period planets. The photometry accuracy of ground-based telescopes is extremely high; therefore, the minimum volume of detected planets is limited.

The "Kepler" probe is the first probe launched by NASA on March 6, 2009, Eastern Time, to use the transit method to detect Earth-like planets. The main goal of the Kepler probe is to search for

Earth-like planets within the range of 0.5-2 times the size of Earth in or near the habitable zone of the Milky Way. Until the reaction wheel was lost in May 2013, Kepler had discovered a total of 2,778 exoplanets. K2, Kepler's second mission, was officially put into operation in May 2014 to continue the Kepler mission [11]. Until the end of operation in 2018, K2 independently discovered 548 planets.

In 2018, NASA launched the new-generation exoplanet exploration project TESS [12]. TESS was launched on April 18, 2018 aboard the Space times the sky area, surveying 200,000 "nearest and brightest" stars outside the solar system. TESS targets 30 to 100 times more stars than the Kepler mission and K2 follow-up observations, enriching data on known exoplanets while greatly reducing the difficulty of subsequent ground and space telescope observations. Using the known size, orbit and mass of the planet, TESS and ground-based instruments working together can determine the planet's composition. Therefore, it will be very easy for scientists to classify target planets, and it will also be conducive to the exploration and discovery of rocky Earth-like planets. TESS will survey the entire sky within two years, dividing it into 26 different areas, each area is 24 degrees x 96 degrees wide, and the target star observation period is 27 days, so the TESS project is more sensitive to short-period planets. Within an observation period, the greater the mass and volume of a star, the easier it is for planets orbiting it to be detected, so 75% of the asteroids detected by TESS are expected to orbit M dwarfs. The number of M-like dwarfs and their system structures can be analyzed through TESS. Its advantages are mainly reflected in the following aspects [13]. A result is shown in Fig. 2. First, Tess will detect more planets around M dwarfs than previously predicted, and the number of planets that can be detected is approximately 2.5 times that previously predicted; Second, in terms of compact multi-master star detection, Kepler can only detect 45±10% of the total number of planets it has discovered, while TESS is predicted to detect 68±12% of its total number of planets.

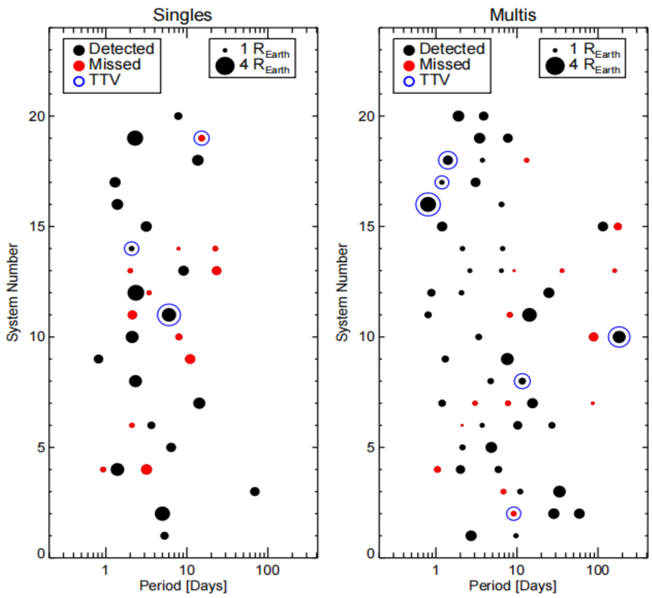

Fig. 2 A representative sample of M dwarf planetary systems in which TESS detected a single transiting planet (left) and simple sample for systems in which TESS detected two or more transiting planets (right).

5. Direct Imaging

The direct detection method requires higher instrument accuracy, so the direct detection method can describe the characteristics of exoplanets more comprehensively and specifically. The instruments currently in use include the Keck telescope and the Gemini South telescope equipped with a GPI terminal and a Lyot coronagraph. 51 exoplanets have been confirmed through direct detection methods. The direct imaging method can directly image and observe exoplanets to obtain a series of information such as the planet's orbit and spectrum. It is very important for studying the formation and evolution of planets and astrolabes. Direct observation and imaging of exoplanets is critical to the resolution of the instrument. There are very high requirements for the efficiency, and it is necessary to separate the planet's light signal from the scattered light of the host star, which is achieved through high-resolution imaging technologies such as adaptive optics and coronagraphs. Adaptive optics technology has low latency and extremely high imaging contrast. It is mainly used to correct the effects of atmospheric turbulence and other effects on ground-based telescopes when receiving optical signals, and to minimize or eliminate the distortion of incident light. Although space-based telescopes can avoid the influence of the Earth's atmospheric environment, it is still meaningful to install a coronagraph on a space-based telescope, which can reduce the aperture requirements of the telescope without affecting the imaging of exoplanets. The first image of a multi-planet system in human history came from the direct observation of the exoplanet system HR8799 by the ground-based telescope Keck in 2008. Direct imaging methods can provide strong evidence for planetary systems detected by other detection methods.

The Hubble Space Telescope (HST) was officially named after astronomer Edwin Powell Hubble in 1983. After more than 40 years of preparation, it was launched from the Kennedy Space Center in the United States on April 24, 1990. A space telescope orbiting the Earth in Earth orbit. It is located above the Earth's atmosphere and is not interfered by atmospheric turbulence. The spectra and images it obtain are extremely stable and reproducible, and it can also observe ultraviolet light absorbed by the ozone layer. Since its launch, the images and data observed by the Hubble Space Telescope have changed the view of the universe and helped us understand the universe. In 2001, astronomers reported that the Hubble Space Telescope's Imaging Spectroradiometer (STIS) successfully measured the atmospheric composition of the exoplanet HD [14]. In 2002, the Hubble Space Telescope helped astronomers accurately measure the true mass of the exoplanet Gliese 876b. In 2008, Hubble measured the organic molecules methane and carbon dioxide on two different exoplanets. In 2008, it took the first visible light snapshot of an exoplanet. In 2017, Hubble studied seven components of the TRAPPIST-1 system. In the atmosphere of an exoplanet about the same size as the Earth, liquid water was found to accumulate on its surface. In 2018, a possible exoplanet was discovered. In 2019, water vapor was detected for the first time in the atmosphere of the exoplanet K2-18b. The Hubble Space Telescope was repaired five times during its service. The last repair was in 2009. The James Webb Space Telescope was launched on December 25, 2021. It will gradually take over the work of the Hubble Space Telescope.

The James Webb Space Telescope (JWST) was launched into space on December 25, 2021 [15]. It is the successor of the Hubble Telescope. Compared with the Hubble Telescope, the JWST is larger and more sophisticated, but its mass is only three times that of the HST. one, and can survey farther into space. JWST has extremely high sensitivity and angular resolution. The data collected through JWST helps study the diversity of exoplanets, understand their history, geological and climatic interactions, and thus search for the conditions that support life. On September 1, 2022 (local time), NASA announced the first direct photo of the exoplanet HIP 65426b taken by JWST. It was found that there are three dust rings surrounding this star, two of which were discovered for the first time. On July 24, 2023, JWST detected water vapor in the rocky planet formation area. On September 11, 2013, JWST discovered methane and carbon dioxide in the atmosphere of K2-18b. Between January and June 2022, 6 micrometeorites hit the main mirror of JWST. Because JWST is too far away from the earth, astronauts cannot be sent for maintenance, but fortunately these damages will not affect JWST's photography. In the future, it can still help astronomers better study and understand the evolution of the universe, the formation and composition of planetary systems, and investigate the possibility of life in these systems.

6. Limitations and Prospects

Exoplanet exploration is an important research content in the field of astronomy and cosmology. However, because these exoplanets are so far from Earth, there are many technical and scientific difficulties in detecting them. At present, there are "three limitations" and "three difficulties" in planetary exploration. The three limitations are as follows. Firstly, due to the characteristics of exoplanets themselves, they are often difficult to be directly observed, especially at distant interstellar distances. At present, the main methods for detecting exoplanets include transit method, direct imaging method and Doppler velocimetry, but these methods have certain limitations. For example, transit can only detect brief changes in light as a planet passes in front of its parent star, and cannot obtain images or spectral information about the planet itself. Direct imaging requires extremely high telescope resolution and advanced image processing to separate planets from the light of their parent stars. Doppler velocimetry requires years of continuous observations to accurately determine the orbit and mass of a planet. Inaddition, detecting exoplanets requires the use of advanced telescopes and instruments. For example, direct imaging requires extremely high-performance telescopes and specialized instrumentation to obtain high-resolution and high-sensitivity images in low-light conditions. Doppler velocimetry requires the use of precise optometric instruments and high-performance computers to accurately determine the orbital parameters and masses of planets. Moreover, exploring exoplanets requires a lot of capital investment. In addition to instrument development and maintenance costs, it is also necessary to pay the salaries of scientific researchers, the cost of experimental materials, and labor costs for data processing and analysis. Due to the long-term and high cost of such research, many scientific institutions and companies cannot afford these costs, thus limiting the development of exoplanet exploration.

The three difficulties are as follow. Initially, since exoplanets are so far from Earth, it is almost impossible to visit them in the field. Even with the most advanced space technology available, it will not be possible to send astronauts on field expeditions to these planets in the foreseeable future. In addition, because the environmental conditions of these planets may be very different from those of Earth, even if astronauts are sent, they may not be able to adapt to the environment there. Therefore, the study of exoplanets mainly relies on long-range observations and simulations. Therefore, exoplanet detection requires long-term observation and tracking of distant objects, so it requires a lot of data analysis and processing. During this process, data errors or anomalies may occur, such as errors in planetary orbital parameters, instrument failures, etc. Besides, determining the physics of exoplanets is a challenge. In general, these properties can only be inferred from the interaction of parent stars and planets. For example, some information can be obtained by measuring changes in the radial velocity of the parent star or by observing planetary transits. However, these methods have limitations in that they cannot determine all the physical properties of planets. In addition, further research is needed to develop more advanced identification techniques. Moreover, because exoplanets are far from the solar system, studying their physical properties and chemical composition is very difficult. Although some techniques have been developed to study the atmospheric and surface properties of these planets, they are still limited. In addition, because these planets are far from their parent stars, it is difficult to obtain sufficient spectral resolution for detailed studies even with state-of-the-art telescopes.

With the continuous development of science and technology, exoplanet research will usher in more opportunities and challenges. In the future, more advanced instruments and observation methods will be put into use. These new observational devices and methods will allow us to gain a deeper understanding of the properties and evolution of exoplanets. At the same time, as data processing and analysis techniques improve, one will be able to extract more valuable information from these observations. In addition, with the continuous strengthening of international cooperation and exchanges, the future direction of exoplanet research includes the following major projects: First, the search for habitable exoplanets: this project will look for planets with suitable conditions for life by observing hundreds of star systems. Hundreds of habitable exoplanets are expected to be discovered in the next 10 years. Second, study the atmospheric composition and climate of exoplanets: by observing the atmospheric composition, temperature, and climate change of many exoplanets, study their ecological environment and evolution. This will help to understand the origin and evolution of life in different planetary systems. Explore the physical characteristics of exoplanets: study the physical characteristics of exoplanets such as surface structure, atmosphere, mass and size through direct imaging or spectroscopic observation. This will provide insight into the evolution and formation of planets. Establish an exoplanet database: Establish a database containing thousands of exoplanets by integrating and analyzing various observation data. This will provide important data support for studying the distribution, properties, and evolution of exoplanets. Fifth, the application of artificial intelligence in the field of exoplanet detection is very exciting, the development of artificial intelligence to identify exoplanet algorithms, the use of big data classification and reduce observation errors to improve accuracy.

Conclusion

To sum up, with the advancement of science and technology and researchers' continuous deepening of interstellar space, the space technology has also made great progress. Although human beings still have many difficulties and challenges to overcome, the technologies and methods are constantly evolving and evolving. Future interstellar exploration is of great significance to us humans, because it will bring more knowledge and enlightenment, let us better understand the world and the universe, and will also profoundly affect and change the future.

References

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

[2] Borucki W J, Koch D, Basri G, et al. Kepler planet-detection mission: introduction and first results. Science, 2010, 327(5968): 977-98

[3] Pepe F, Molaro P, Cristiani S, et al. ESPRESSO: The next European exoplanet hunter. Astronomische Nachrichten, 2014, 335(1): 8-20.

[4] Exoplanet. Caltech. Retrieved from:https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html.

[5] Sahlmann J, Fekel F C. Astrometric mass ratios for three spectroscopic binaries. Astronomy & Astrophysics, 2013, 556: A145.

[6] Yock P, Muraki Y. Microlensing Surveys for ExoplanetResearch (MOA). Handbook of Exoplanets, 2018: 122.

[7] Baldini V, Calderone G, Cirami R, et al. The instrument control electronics of the ESPRESSO spectrograph. VLT, 2015.

[8] Beuzit J L, Vigan A, Mouillet D, et al. SPHERE: the exoplanet imager for the Very Large Telescope. Astronomy & Astrophysics, 2019, 631: A155.

[9] Lovis C, Snellen I, Mouillet D, et al. Atmospheric characterization of Proxima b by coupling the SPHERE high-contrast imager to the ESPRESSO spectrograph. Astronomy & Astrophysics, 2017, 599: A16.

[10] Fischer D A, Anglada-Escude G, Arriagada P, et al. State of the field: extreme precision radial velocities. Publications of the Astronomical Society of the Pacific, 2016, 128(964): 066001.

[11] Seader S, Jenkins J M, Tenenbaum P, et al. Detection of potential transit signals in 17 quarters of Kepler mission data. The Astrophysical Journal Supplement Series, 2015, 217(1): 18.

[12] Barclay T, Pepper J, Quintana E V. A revised exoplanet yield from the transiting exoplanet survey satellite (TESS). The Astrophysical Journal Supplement Series, 2018, 239(1): 2.

[13] Ballard S. Predicted number, multiplicity, and orbital dynamics of TESS M-dwarf exoplanets. The Astronomical Journal, 2019, 157(3): 113.

[14] Debes J H, Ren B, Schneider G. Pushing the limits of the coronagraphic occulters on Hubble space telescope/space telescope imaging spectrograph. Journal of Astronomical Telescopes, Instruments, and Systems, 2019, 5(3): 035003.

[15] Kalirai J. Scientific discovery with the James Webb space telescope. Contemporary Physics, 2018, 59(3): 251-290.