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The Application of the Transit Method in Exoplanet Detection

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Abstract： *Exoplanetary science stands as one of the most cutting-edge and promising research fields in modern astronomy, playing a pivotal role in unraveling fundamental scientific questions regarding planetary formation, evolution, and the origins of life. Among various detection methods, the transit method has emerged as one of the most successful techniques due to its high efficiency and reliability. This paper systematically elaborates on the fundamental principles of the transit method, which infers the existence of transiting exoplanets and their physical parameters (such as radius and orbital period) by detecting periodic dips in stellar brightness. This paper further presents current research developments of the transit method, while also examining the method's inherent limitations and prospective research directions. The high-precision detection capability of the transit method will continue to advance exoplanetary science, providing critical support in the search for habitable planets and potential biosignatures.*

***Keywords*：** *Transit method;exoplanetary systems;hot Jupiters;planetary habitability*

1 Introduction

Since ancient times, humanity has contemplated two profound philosophical questions while gazing at the stars: Are we alone in this vast universe? Is Earth life's only sanctuary? This fundamental quest to understand our cosmic existence traces back to the era of ancient Greek philosophers. During that era, philosophers such as Democritus proposed the groundbreaking conjecture of "countless worlds," suggesting that our Milky Way might harbor other inhabited planets. This revolutionary concept gained momentum in the 16th century when Copernicus' heliocentric theory fundamentally shattered the Earth-centered worldview. Building upon this foundation, Giordano Bruno later made his epochal proposition that "every star is a distant sun potentially orbited by planets." These remarkably prescient philosophical speculations, though constrained by the observational limitations of their era and lacking empirical support, nevertheless planted the conceptual seeds for future exoplanetary research, continuously driving humanity to push the boundaries of cosmic understanding. Modern astronomy has revealed an awe-inspiring cosmic panorama: hundreds of billions of observable galaxies populate the universe, each harboring countless stars. Confronted with this cosmic grandeur, we are compelled to ponder: Beyond our own planetary home, are planetary systems ubiquitous in the universe? Might there exist other oases in this boundless stellar ocean that could sustain life—or perhaps already nurture alien organisms? It is precisely such existential inquiries that have propelled revolutionary breakthroughs in observational technology - from the humble beginnings of naked-eye stargazing to the exquisitely precise measurements of modern telescopes; from the inherent limitations of ground-based observatories to the interstellar voyages of space probes. Each quantum leap in technological capability embodies humanity's unrelenting pursuit of cosmic understanding, bringing us incrementally closer to unraveling the enigma of extraterrestrial life.

However, detecting exoplanets presents extraordinary challenges. These celestial bodies are located at immense interstellar distances and, crucially, do not emit their own light - they are only observable through the faint reflection of their host star's radiation. It was not until the 1990s, with rapid advancements in scientific technology, that the field of exoplanet research achieved groundbreaking progress and truly gained momentum. In 1992, Wolszczan and Frail[1] made

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the first confirmed detection of an exoplanetary system, PSR1257+12, using the pulsar timing method. This system consists of a millisecond pulsar host star orbited by two planets with masses of 2.8 and 3.4 $M_\oplus$ respectively. Although the extreme environment surrounding pulsars is inherently inhospitable to life as we know it, this discovery nevertheless holds extraordinary significance for the field of exoplanet research. In 1995, Swiss astronomers Mayor and Queloz employed the radial velocity method to detect 51 Peg b—a hot Jupiter with a 4.2-day orbital period around a Sun-like star. This landmark discovery, which earned them the 2019 Nobel Prize in Physics, fundamentally transformed our understanding of planetary systems and ignited unprecedented enthusiasm for exoplanet exploration. It marked the dawn of a new era in exoplanetary research [2]. In 1999, Henry et al. achieved the first definitive detection of a transit event from exoplanet HD 209458 b, marking the transit method's emergence as the vanguard technique in exoplanet detection. The deployment of advanced space telescopes, notably the Kepler Space Telescope (launched in 2009) and the Transiting Exoplanet Survey Satellite (TESS, launched in 2018), has driven an exponential increase in exoplanet discoveries. To date, the transit method has detected over 75% of all confirmed exoplanets, surpassing the combined yield of all other detection techniques. Crucially, key physical parameters obtained through this method—including orbital inclination, mass, and radius—are essential for understanding planetary architecture, formation mechanisms, and dynamical evolution. The transit method precisely enables the determination of a planet's radius, orbital semi-major axis, and inclination through analysis of the observed light curve during transit events. This paper will subsequently provide a detailed examination of the transit method's applications in exoplanet detection.

2 Fundamental Principles of the Transit Method

The transit method currently stands as the most widely utilized and efficient technique for detecting exoplanets. As of now, among the over 5,700 confirmed exoplanets discovered, more than 4,300 have been detected via the transit method - a figure that significantly surpasses the yield of all other detection techniques combined. When a planet passes in front of its host star, if its orbit is nearly in the same plane as Earth's line of sight, it will block part of the star's light, causing the star's brightness to show periodic decreases. On the light curve, this appears as a drop in the star's flux, with a depth of

$$\frac{\Delta F}{F_0} \approx \left(\frac{R_p}{R_*}\right)^2$$

Based on this phenomenon, exoplanets can be detected by measuring periodic decreases in stellar brightness. By combining observational data from the transit method with radial velocity measurements, we can determine an exoplanet's mass and radius, enabling the calculation of its density. These physical parameters are crucial for studying planetary system formation and internal structure. Figure 1 illustrates the process of a transit event [3]. As early as 1669, astronomer Giovanni Cassini observed shadows on Jupiter's surface, marking the first recorded documentation of a "transit" phenomenon. In 1999, astronomers Charbonneau, Henry, and colleagues successfully detected the transit of exoplanet HD 209458b [4][5]. This landmark achievement not only validated the feasibility of the transit method but also established its prominence, laying the foundation for subsequent research. The launch of the Kepler Space Telescope in 2009 marked the beginning of a systematic census phase in exoplanet research. The Kepler mission, through its four-year continuous observation campaign, identified thousands of exoplanet candidates, including several groundbreaking discoveries that redefined our understanding of planetary systems. Among its most significant findings were Kepler-452b [6], the first validated "Earth 2.0" candidate orbiting a Sun-like star, and Kepler-186f [7], the first confirmed Earth-sized planet residing within the habitable zone of an M-dwarf star. The launch of the Transiting Exoplanet Survey Satellite (TESS) in 2018 elevated exoplanet detection capabilities to unprecedented levels. TESS searches for exoplanets orbiting bright stars, with important discoveries including TOI-700d [8] in the habitable zone of

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an M-type dwarf. The planet's radius and incident radiation are similar to Earth's, and climate models suggest its surface could potentially sustain liquid water. The iterative development of these space telescope missions has significantly enhanced the detection efficiency and precision of the transit method. However, the transit method also has inherent limitations—it can only detect exoplanets whose orbital planes align with the observer's line of sight, which fundamentally constrains its detection probability.(see Table 1)

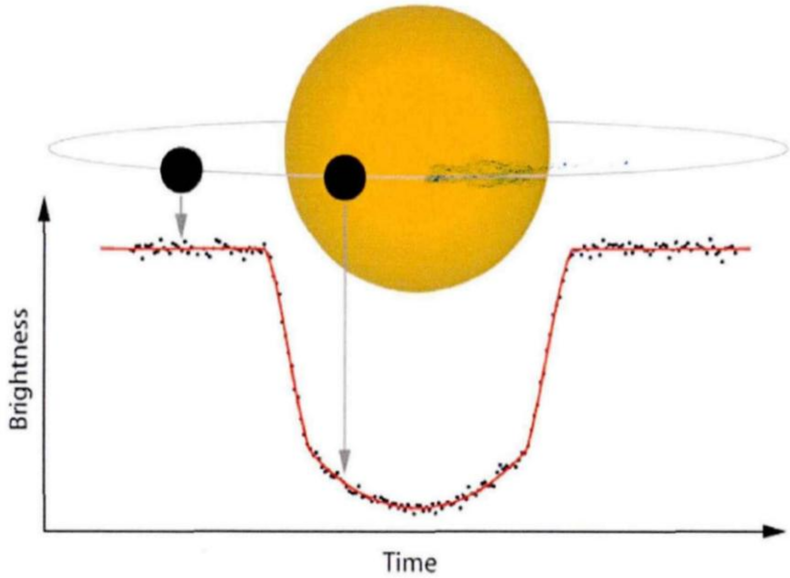

Figure 1. Schematic diagram of the transit method.

3 Current Research Status of the Transit Method

The transit method is one of the cornerstone techniques for exoplanet detection. Since its first successful observation of HD 209458 b [4][5] in 1999, the transit method has ushered exoplanet research into an era of large-scale discovery. In recent years, with the coordinated efforts of space telescopes and ground-based observation facilities, the transit method has achieved groundbreaking progress in detection efficiency, measurement precision, and the scope of applicable targets. Here we provide a concise overview of several major exoplanet detection programs utilizing the transit method:

In 2001, the Harvard-Smithsonian Center for Astrophysics initiated the HATNet survey project, which officially began operations in 2003. It aims to systematically search for extrasolar planets using the transit method. The project initially had only a single telescope. As it developed, six 11-cm aperture wide-field telescopes were deployed across the northern hemisphere—two at the Mauna Kea Observatory in Hawaii, USA, and four at the Fred Lawrence Whipple Observatory in Arizona, USA. Each telescope is equipped with a 2k×2k CCD, providing an 8°×8° field of view [9]. In 2009, the project expanded to the southern hemisphere with the addition of six new telescope arrays, each consisting of four 18-cm aperture telescopes. These arrays collectively covered a sky area of 269 square degrees and were deployed at observatories in Chile, Australia, and Namibia [10]. This enabled nearly 24-hour continuous monitoring, significantly improving the detection efficiency for long-period planets.

In 2003, the University of Cambridge in the UK led the launch of the SuperWASP survey project in collaboration with seven international research institutions. It was one of the most influential wide-field exoplanet search programs in the early 21st century, designed to detect short-period exoplanets through wide-field photometric observations. The project adopted a coordinated northern and southern hemisphere observation strategy, deploying identical telescope

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array systems at the Roque de los Muchachos Observatory in La Palma, Spain (SuperWASP-North) and the South African Astronomical Observatory (SuperWASP-South). Each observation site was equipped with eight 200mm Canon lenses, each paired with a 2k×2k CCD, collectively covering a total field of view of 482 square degrees. Meanwhile, the project achieved a photometric precision of 0.01 magnitudes in the V-band for target sources with magnitudes between 7.5 and 11.5[11] . The CCD cameras provided a spatial resolution of 13.7" per pixel, fully meeting the requirements for detecting typical hot Jupiter transit signals.

Also in 2003, the XO Survey Project was officially launched under the leadership of astronomer Peter McCullough. It was an exoplanet search program led by the Space Telescope Science Institute in the United States, designed to detect transiting hot Jupiters around bright stars using a specially designed telescope system. The project deployed two identical telescopes at a 3,000-meter-altitude observatory site on Maui, Hawaii. Each telescope featured a 0.11-meter aperture, a 200mm f/1.8 lens, and a 1024×1024-pixel CCD, providing a 7°×7° field of view [12]. This setup enabled continuous monitoring of brightness variations in approximately 10,000 bright stars.

Launched in December 2006 by the French National Center for Space Studies in collaboration with the European Space Agency (ESA) and the Brazilian Space Agency (AEB), CoRoT was the first space telescope dedicated to exoplanet detection and asteroseismology research. It employed a 27-cm aperture telescope system, achieving photometric precision as high as 100 ppm within a 2.7°×2.7° field of view [13]. During observations, it could simultaneously and continuously monitor up to 12,000 stars over a 150-day observing period. During its operational period from 2007 to 2012, the CoRoT mission achieved several groundbreaking scientific discoveries, including the detection of the transiting Earth-like planet CoRoT-7b[14].

Launched in 2009 by NASA, the Kepler Space Telescope was a revolutionary exoplanet detection mission and a pivotal milestone in humanity's search for habitable worlds beyond our solar system. The project was named after the renowned astronomer Johannes Kepler, with its primary scientific objective being the systematic search for Earth-like planets within the habitable zones of Sun-like stars [11]. The telescope featured a 0.95-meter primary mirror and a focal plane array composed of 42 2k×1k CCDs, providing a 115-square-degree field of view. With photometric precision reaching several tens of ppm (parts per million) [15], it was capable of detecting the faint transit signals caused by Earth-sized planets. During its four-year primary mission, the Kepler telescope amassed an unprecedented collection of continuous light curve data and achieved numerous groundbreaking scientific discoveries.

In April 2018, NASA launched the next-generation space telescope TESS (Transiting Exoplanet Survey Satellite). Designed primarily to detect planets around nearby stars using the transit method, it specifically targets Earth-like planets and those within habitable zones. This marked the dawn of a new era in exoplanet research. As the successor to the Kepler mission, TESS adopted a revolutionary all-sky survey strategy. The spacecraft was equipped with four 10-cm aperture wide-field telescopes, each covering a 24°×24° sky area. With a combined field of view of 2,300 square degrees, the system enabled a systematic survey of 85% of the celestial sphere. Among its discoveries, TOI-700 d [16] was identified as a planet orbiting within the habitable zone of an M-type dwarf star. The planet has a radius of 1.14 $R_{\oplus}$, closely matching Earth's size, and receives approximately 86\% of the stellar radiation that Earth gets from the Sun. These conditions suggest a high probability of liquid water existing on its surface.

These programs have not only dramatically expanded the exoplanet census, but also provided a wealth of data for studying the diversity and complexity of planetary systems. Furthermore, the accumulated high-precision, long-baseline observational data from these surveys have opened new avenues for understanding the dynamical characteristics of exoplanetary systems.

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4 Scientific Achievements of the Transit Method

4.1 Detection of Hot Jupiters

We define as hot Jupiters those exoplanets with masses greater than 0.3 Jupiter masses and orbital periods shorter than 10 days. These gas giants exhibit several distinctive characteristics that facilitate their detection via transit observations: their substantial masses and radii, close proximity to host stars, and short orbital periods collectively enhance the probability of observable transit events. Consequently, hot Jupiters constitute a statistically robust sample population for exoplanetary research. The first confirmed hot Jupiter, 51 Pegasi b, was discovered in 1995 orbiting a solar-type main-sequence star. This massive, short-period planet posed a fundamental challenge to the core accretion model of planet formation, as the in-situ formation theory could not adequately explain the stable existence of a gas giant at such close orbital distances. The discovery of 51 Pegasi b compelled the astrophysical community to revise planetary migration theories, fundamentally establishing orbital migration mechanisms as essential for explaining the present-day orbital architectures of hot Jupiters. To explain the origin of hot Jupiters, the planetary migration theory was proposed and subsequently refined. This theoretical framework posits that gas giants initially formed in distant orbits beyond the system's ice line and subsequently underwent progressive inward orbital migration, ultimately reaching their current short-period configurations [17]. Looking ahead, as observational precision improves and theoretical models are refined, hot Jupiters will remain crucial testbeds for validating planet formation and evolution theories, while continuing to provide vital clues for understanding the diversity of exoplanetary systems. Their intrinsic value as "natural laboratories" will continue to drive advancements in exoplanetary physics.

4.2 Earth-like planets in the habitable zone

It is well known that Earth is currently humanity's only home, but whether extraterrestrial life exists elsewhere remains one of the most profound scientific questions of our time. The search for habitable planets may very well hold the key to answering this fundamental question. Habitable-zone terrestrial planets refer to rocky planets with Earth-like sizes whose orbital distances from their host stars allow for the potential existence of liquid water on their surfaces. The habitable zone is the region around a star where a planet with sufficient atmospheric pressure could maintain liquid water on its surface, given appropriate orbital distances. For example, Kepler-186f, discovered by the Kepler Space Telescope in 2014, was the first exoplanet confirmed to be both Earth-sized and orbiting within its star's habitable zone[7]. Orbiting the host star Kepler-186, its discovery provided a crucial case study for identifying potentially habitable exoplanets. Additionally, the TRAPPIST-1 system has multiple planets located within the star's habitable zone [18], which may have rocky surfaces and liquid water. Particularly, TRAPPIST-1e is not only located within the star's habitable zone, but its mass is also similar to Earth's, making it a potential habitat for life. And the outermost planet TOI-700d [16], located within the habitable zone of the M-type dwarf star. The planet has a radius and insolation level similar to Earth's, and orbits the host star TOI-700 which exhibits low stellar activity - characteristics that make it particularly favorable for further studies of atmospheric escape. In summary, the search for and study of habitable exoplanets currently represents one of the most active research frontiers in astronomy and the broader scientific community, as well as a topic of great public interest. However, it should be noted that simply being located within the habitable zone does not guarantee a planet's habitability. The potential for hosting life or suitability for human habitation depends on multiple factors, including stellar activity levels, planetary atmospheric characteristics, and the evolutionary history of the planetary system.

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5 Conclusion and Prospect

The transit method holds landmark significance in the detection of exoplanets. By monitoring periodic minute dips in a star's brightness, it indirectly reveals the presence of planets, greatly expanding humanity's understanding of worlds beyond our solar system. The most notable advantage of this method lies in its highly efficient detection capability, particularly for identifying planets orbiting close to their host stars. Compared to other detection methods, the transit technique can simultaneously monitor tens of thousands of stars, enabling large-scale survey missions like the Kepler Space Telescope and TESS to discover thousands of exoplanets. More significantly, the transit method not only confirms planetary existence but also provides critical parameters including planetary radii and orbital periods. The determination of physical parameters in exoplanetary systems proves crucial for investigating the formation and evolution of planetary systems. Moreover, the discovery and study of exoplanets can profoundly expand humanity's understanding of the formation and evolutionary mechanisms of planetary systems. While traditional planet formation theories were primarily based on observations of our Solar System, the remarkable diversity of exoplanets—including hot Jupiters, super-Earths, and mini-Neptunes—demonstrates that planetary system formation processes are far more complex than previously envisioned. This compelling evidence underscores the critical need for additional exoplanetary observations to provide essential data for advancing our understanding. Furthermore, exoplanetary research provides critical scientific foundations for the exploration of extraterrestrial life and habitable environments.

Finally, with the deployment of numerous next-generation observational facilities, our exoplanet detection capabilities will be significantly enhanced, providing unprecedented precision in data collection to search for potential biosignatures. Concurrently, exoplanet research has become a major driving force behind innovations and advancements in astronomical observation technologies. A suite of high-precision observational instruments and cutting-edge technologies has emerged, including high-resolution spectrographs, adaptive optics systems, and space telescopes. The advancement of these technologies has not only propelled astronomical progress but also yielded extensive applications across diverse scientific disciplines.

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