Planetary Formation Theory Models and Planetary Classification Postprints

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Abstract

Classification is a commonly employed method in astronomy, which has been extensively applied in research on stars, galaxies, and other domains; however, a well-established classification system is currently lacking in the planetary field. This work reviews the developmental history of theoretical models of planet formation and their limitations; summarizes the detection results of exoplanets and the characteristics of their parameter distributions; introduces the current research background, progress, and constraints in planetary classification; proposes incorporating radio observations of protoplanetary disks to expand the sample size for theoretical research and classification framework construction, aiming to encompass a broader range of exoplanet populations; and finally, presents the observational capabilities and scientific objectives for exoplanet studies of the next-generation and planned large-scale observational facilities.

Full Text

Preamble

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Theoretical Models of Planet Formation and Classification of Planets

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Abstract

Classification is a commonly used method in astronomy that has been widely applied in research on stars, galaxies, and other fields. However, there is currently no complete classification system in the planetary domain. This paper reviews the construction history and shortcomings of theoretical models of planet formation; summarizes the search results for exoplanets and their parameter distribution characteristics; introduces the current research background, progress, and limitations in planetary classification; proposes combining radio observations of protoplanetary disks to expand the sample for theoretical research and classification framework construction in order to encompass more exoplanet populations; and finally describes the observational capabilities and scientific objectives of the latest generation and planned large-scale observational facilities regarding exoplanets.

Keywords: planetary theory; exoplanets; classification

1 Introduction

The Solar System is the planetary system we inhabit. On astronomical scales, the distances between Earth and other planets in the Solar System are negligible. Compared with other astronomical research objects, we have an unparalleled advantage in observing planetary samples: their proximity allows us to launch probes for direct, high-resolution, high signal-to-noise observations on planetary surfaces, such as the Cassini and New Horizons spacecraft, and the Spirit and Curiosity rovers. We can also directly obtain samples by sending landers to collect and return materials to Earth laboratories, as in the U.S. Apollo program, Japan's Hayabusa probe, and China's Chang'e project and planetary exploration program. We can not only observe but also acquire first-hand materials—advantages difficult to match in other areas of astronomy. These advantages have made the Solar System the primary sample for planetary science research.

Based on observations and understanding of the Solar System, previous researchers have constructed models for planetary origin and evolution, such as the vortex model, nebular hypothesis, Chamberlin-Moulton planetesimal hypothesis, gravitational instability model, and core accretion model. However, planets are also celestial bodies we know very little about. A planet's mass determines that it is difficult to undergo high-energy radiation processes and cannot produce sufficiently strong signals, making it hard for distant observers to detect their existence. It was not until 1995 that Mayor and Queloz [?] completed the first confirmation of planets around main-sequence stars outside the Solar System, which opened the era of large-sample planetary research. Subsequent ground-based surveys and space telescopes like Kepler have discovered large numbers of exoplanets, expanding the planetary sample from 8 to over 4,000 within 25 years, opening up a whole new world. Exoplanet observations have also overturned long-held human understanding and seriously challenged existing planetary formation theories.

2.1.1 Vortex Model

The earliest model for Solar System formation was proposed before Newton's law of universal gravitation. French philosopher and mathematician René Descartes proposed the vortex model in his 1632–1633 work *The World*. The model posited that the universe was filled with vortices composed of particles, from which the Sun and planets condensed. These vortices would contract through some mechanism, thereby explaining the circular motion of planets [**?**].

2.1.2 Nebular Hypothesis

Following the vortex model, the nebular hypothesis emerged. First proposed in 1743 by Swedish scientist, philosopher, and theologian Emanuel Swedenborg [**?**], it was later elaborated and expanded by German philosopher and central figure of the Enlightenment Immanuel Kant in 1755 [**?**]. Kant argued that the Solar System began as a dispersed cloud of particles. Gravitational forces caused mutual motion and collisions among particles, after which chemical forces bound them together. As some of these particle clusters grew larger than others and at faster rates, planets eventually formed.

Kant's theory had obvious observational flaws: it could not explain why planets orbit the Sun in the same direction and plane, nor did it account for the revolution of planetary satellites. In 1796, Pierre-Simon Laplace improved upon the nebular hypothesis [**?**]. He argued that planets formed after the Sun's formation. The Sun's atmosphere extended beyond the orbits of the outermost planets, and as the Sun gradually cooled through radiation, the gas pressure it could provide decreased, causing the Sun to contract. According to the law of angular momentum conservation, the Sun's shrinking would lead to faster rotation. Centrifugal forces caused material to drift outward while gravity pulled it inward, and under their combined action, multiple concentric rings formed. In subsequent evolution, material in each ring aggregated to form a planet.

Laplace used the same theoretical model to explain the formation of planetary satellites, arguing that planetary rings would eventually evolve into moons. Laplace's model could reasonably explain why Solar System planets orbit the Sun in the same plane and direction. Combining Kant's and Laplace's theories yields the Kant-Laplace planetary hypothesis, which was widely accepted for nearly a century. However, subsequent discoveries of high-eccentricity asteroids and exoplanets, as well as satellites with retrograde orbits, challenged this theory. Moreover, the Sun accounts for 99.9% of the total mass of the Solar System, yet the planets possess over 99% of the system's angular momentum. If the Solar System conformed to this theory, either the Sun should rotate faster or the planets should orbit more slowly.

2.1.3 Chamberlin-Moulton Planetesimal Hypothesis

In 1905, American geologist Thomas Chrowder Chamberlin and astronomer Forest Ray Moulton proposed an entirely new theory independent of the above hypotheses—the Chamberlin-Moulton planetesimal hypothesis [?]. The hypothesis suggested that in the Sun's early stage, a star passed extremely close to the Sun. Tidal forces produced bulges on the Sun's surface, which, combined with the Sun's internal mechanisms, extracted material from the Sun multiple times. Due to the gravitational influence of the passing star, the Sun would generate two spiral arms. Although most material would fall back to the Sun, some would remain in orbit. This orbiting material would condense into numerous asteroids and a few large protoplanets—planetesimals. These planetesimals would form planets and satellites through collisions, with the remaining planetesimals becoming the comets and asteroids observed later.

At the time, observed "spiral nebulae" were taken as observational evidence for this hypothesis, with spiral structures extending from a bright central region. Later, people realized that these so-called "spiral nebulae" were actually spiral galaxies, not evolving stars. By 1917, Jeans [?] argued that material could be ejected simply by a star passing very close to the Sun, without requiring bulges. However, the Chamberlin-Moulton planetesimal hypothesis still had fatal flaws. In 1935, Henry Norris Russell pointed out that the hypothesis struggled to explain the distribution of orbital angular momentum in the Solar System, because the velocity distribution of tidally stripped material should be concentrated mainly in the low-velocity region, with only a small fraction reaching high velocities. Correspondingly, the material should be distributed mainly in orbits close to the Sun, yet actual observations show that the vast majority of orbital angular momentum in the Solar System is distributed in regions far from the Sun [?].

In 1939, Lyman Spitzer's research found that material extracted from the Sun would dissipate rather than condense into planets [?]. Moreover, applying this theory to the Milky Way reveals that the occurrence rate of such events would be extremely low, as it is very difficult for two stars to encounter each other at such close distances [?]. Additionally, with improved understanding of interstellar medium, it was discovered that substantial cloud-like material does exist, and stars form within these clouds. Planets must also be generated through some mechanism during the star formation period, thus supporting other theories. Current planetary formation theory has abandoned the Chamberlin-Moulton planetesimal hypothesis but retains the concept of planetesimals. The scientific community now views the origin of the Solar System as a case of star formation. With increasing observations, formation mechanisms have been gradually constrained. Inspired by the Kant-Laplace hypothesis, the main derived models are the gravitational instability model and core accretion model.

2.2.1 Gravitational Instability Model

The gravitational instability model was proposed by Kuiper in 1951 [?]. The model suggests that when a protoplanetary disk is perturbed, gravitational collapse tears it into multiple clumps, each of which further collapses to form planets. Cameron's 1978 calculations showed that the primordial Sun's accretion disk would be perturbed to form rings, which would collapse on their own to form gas giants [?]. In protoplanetary disks, temperature and pressure resist gravitational collapse and maintain stability. The stability of protoplanetary disks can be judged using the Safronov-Toomre criterion [?, ?]:

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \gtrsim Q_{\text{crit}} \sim 1,$$

where Q is the Toomre parameter, c_s is the sound speed (in $\text{cm} \cdot \text{s}^{-1}$), Ω is the orbital frequency (in $\text{rad} \cdot \text{s}^{-1}$), G is the gravitational constant (in $\text{cm}^3 \cdot \text{g}^{-1} \cdot \text{s}^{-2}$), and Σ is the protoplanetary disk surface density (in $\text{g} \cdot \text{cm}^{-2}$). This criterion is a necessary and sufficient condition for the disk to remain gravitationally stable. When this criterion is satisfied, the disk will remain stable and not fragment, but when it is not satisfied, it does not necessarily mean the disk will fragment.

For example: For a Sun-like star's protoplanetary disk at a distance of $r = 10$ AU from the center, taking $h/r \sim 0.05$, where h is the disk thickness at that location, we have $h/r \sim c_s/v_\phi$, where v_ϕ is the orbital velocity, giving $c_s \sim 0.5$ $\text{km} \cdot \text{s}^{-1}$. To achieve $Q \lesssim 1$, we require $\Sigma \gtrsim 1500$ $\text{g} \cdot \text{cm}^{-2}$, far exceeding the expected $\Sigma \sim 54$ $\text{g} \cdot \text{cm}^{-2}$ at 10 AU in the Minimum Mass Solar Nebula (MMSN). This indicates that the gravitational instability model can only be applied to very dense disks. The spatial scale most prone to collapse is:

$$\lambda_{\text{crit}} = \frac{2\pi^2 G \Sigma}{\Omega^2}.$$

The mass of the forming planet can be estimated as:

$$M_p \sim \Sigma \pi \lambda_{\text{crit}}^2 \sim \frac{4\pi^5 G^2 \Sigma^3}{\Omega^4} \sim 6 M_J.$$

Thus, the gravitational instability model would form massive planets and is more applicable to distant orbits.

2.2.2 Core Accretion Model

The currently most mainstream view is the core accretion model, first constructed by Safronov (1969) [?], Goldreich and Ward (1973) [?], and others. The core accretion model also holds that the Solar System originated from the gravitational collapse of a primordial nebula, which could be triggered by random density fluctuations in the cloud or by external perturbations, such as shock waves from supernova explosions. The cloud rapidly collapses into a spherical shape. Because it orbits the Galactic center, the near side moves slower than the far side. As the collapse progresses, the cloud begins to rotate. By angular momentum conservation, under the combined action of the central gravitational force and rotational centrifugal force, the cloud evolves into a disk shape, forming a protoplanetary disk.

As gas and dust accrete toward the center, gravitational potential energy is converted into kinetic energy, increasing pressure and temperature in the central region. When a certain threshold is reached, thermonuclear reactions begin, marking the formation of the Sun. Meanwhile, adjacent materials in the protoplanetary disk orbit at similar velocities, giving dust particles opportunities for gentle collisions that cause them to stick together and condense, eventually forming larger solid planetesimals. Solid planetesimals, as accretion cores, continuously accrete surrounding material to increase their mass and gravity. With greater mass, stronger gravity can expand the accretion range, positively promoting the accretion process until clearing material within its Hill radius. This process is the core idea of the core accretion model.

Based on the core accretion model, subsequent research has explained some observed phenomena, while observations have also constrained the model. Solar System observations reveal that rocky planets occupy close orbits while gas giants appear at distant orbits, indicating that during the evolutionary stage after the Sun's birth, solar radiation and heat influenced the environment in the protoplanetary disk. The core region had high temperatures, producing photoevaporation effects. As the radial distance from the Sun increased, environmental temperatures gradually decreased, allowing volatile substances to condense. For instance, in regions near the Sun, temperatures were too high to retain large amounts of volatile substances such as H_2O, CO_2, and NH_3, so inner-orbit planets are typically rocky: Mercury, Venus, Earth, and Mars. In outer orbits, the low environmental temperature makes it easier for celestial bodies to capture more volatile substances. When a body reaches about 10 $M_\oplus$, its gravitational field becomes sufficient to bind the lightest and most abundant molecules in the universe—H_2 and He.

The first substances to condense from gaseous material are silicates, which form the basic building blocks of rock, followed by water ice at greater distances. For example, the Moon in the inner Solar System has a density of 3.3 $\mathrm{g \cdot cm^{-3}}$ and is composed mainly of rock made of silicate minerals. In contrast, Saturn's moon Tethys in the outer Solar System has a density of about 0.97 $\mathrm{g \cdot cm^{-3}}$ and contains large amounts of water ice. Moons at even greater distances show slightly increased densities, incorporating denser solids such as CO_2. Therefore, very massive planets like Jupiter, Saturn, Uranus, and Neptune can form in outer orbits. Thus, the temperature gradient effect from solar radiation manifests as a gradual increase in the proportion of volatiles in solid bodies with increasing distance.

Although the Kant-Laplace solar nebula model still has some problems, its core ideas align with the core accretion model and have been verified by infrared and radio observations that discovered material disks around stars. Observations of star clusters can also verify that planet formation occurs on short timescales. Observationally, the proportion of stars showing near-infrared excess radiation due to optically thick gas disks decreases from nearly 100% (cluster age $\lesssim 1$ Myr) to $\lesssim 5\%$ (cluster age $\gtrsim 10$ Myr) [?, ?]. This indicates that from the beginning of cloud collapse to protoplanetary disk formation takes only about a million years. Whether through accretion, photoevaporation, or planet formation causing the decline in near-infrared radiation, giant planets must form their solid cores within a few Myr before gas in the disk dissipates. The same timescale constraints apply to planetesimal formation, as 80%–90% of rocky planets and ice giants need to condense from planetesimals, which must form within this time.

Theoretical studies on the subsequent evolution of Solar System planets suggest that in addition to the currently observed major planets, there should have existed several Moon- or Mars-sized bodies in the Solar System. These giant planetesimals (or planetary embryos) could have dramatic effects when colliding with planets, explaining some observed anomalies. For example, in research on the Moon's origin, Hartmann et al. (1986) [?] proposed that Earth-like protoplanets may have suffered impacts from bodies of comparable mass during the final stages of formation, with the Moon possibly originating from a collision between a Mars-sized body and Earth, where fragmented material re-aggregated to form the Moon.

In studies of Mercury, observations reveal that Mercury's uncompressed density is unusually high. Mercury's density is 5.43 $\mathrm{g \cdot cm^{-3}}$, comparable to Earth's 5.52 $\mathrm{g \cdot cm^{-3}}$. However, considering uncompressed (i.e., zero-pressure) conditions, the uncompressed densities of terrestrial planets Mercury, Venus, Earth, and Mars are 5.3, 4.4, 4.4, and 3.8 $\mathrm{g \cdot cm^{-3}}$, respectively, making Mercury's density exceptionally high by comparison. Urey realized that Mercury must have a higher Fe-Si ratio than other terrestrial planets [?], meaning Mercury's silicate mantle lost some material through some mechanism. Hartmann's theory for the Moon's origin can also explain Mercury's high density [?]. Based on this theory, Benz et al. (1988) [?] calculated that pre-impact Mercury had about 2.25 times its current mass, and a subsequent high-speed collision with a body about 1/6 the mass of pre-impact Mercury stripped most of the mantle, leaving behind an iron-dominated solid core.

Observations also reveal that Venus's rotation rate is extremely slow, with a rotation period of 243 Earth days, and its rotation direction is opposite to that of other planets in the Solar System. To explain this anomaly, astronomers have proposed explanations such as core-mantle friction combined with atmospheric tides [?, ?, ?], and more intuitive viewpoints that a few large bodies or numerous small bodies that once existed in the Solar System collided with primordial Venus, dramatically altering its rotational angular momentum [?].

The Solar System we observe is equivalent to a time slice in the evolution of planetary systems, while the various exoplanet systems we observe are likely at different stages of evolution, allowing us to piece together the entire process of planetary system evolution and constrain theoretical models of planet formation. As the currently most mainstream view, the core accretion model has also been applied to discussions of exoplanets. Mordasini et al. [?, ?] conducted computational analyses of planetary populations within the framework of the core accretion model, finding that variations in the initial conditions of planetary systems could lead to the formation of diverse planets. Due to the limitations of observational selection effects, currently detected exoplanets represent only the tip of the iceberg of all planets. As detection capabilities improve, more planetary populations can be discovered [?].

Building on Mordasini et al.'s work, Emsenhuber et al. [?] recently proposed a new generation of planetary population synthesis models (NGPPS). This model predicts necessary planetary observables as comprehensively as possible, including radius, luminosity, and evaporation rate; expands the range of planetary masses and orbital distances applicable to the model; and finds that for Earth-like planets, introducing a sufficient number of embryonic planets (about 100) in the initial stage would produce a violent impact phase. For giant planets, they found that Jupiter-mass planets must form their solid cores within a very short time before the protoplanetary disk dissipates; otherwise, they would migrate significantly to the inner edge of the protoplanetary disk.

3.1.1 Mysteries of the Core Accretion Model

Although the astronomical community widely accepts the core accretion model, and we already understand the process of dust growing from micron-scale to centimeter-scale particles, mysteries still remain regarding growth at larger scales. Numerical simulations show that when dust particles grow to centimeter size, their coupling with gas weakens, and particle growth may stall at the centimeter scale. Experimental and numerical simulation results indicate that when bodies grow to centimeter size, the effectiveness of adhesion and sticking decreases significantly, while average collision velocities increase. Overly large particles collide at excessively high speeds, preventing surface chemical processes from functioning and even shattering the particles, thereby halting their growth. This is known as the "bouncing barrier" [?].

Bodies undergo radial migration in the disk, but excessively fast migration speeds can cause planets to be swallowed by their host stars. Due to gas pressure, the orbital velocity of gas in the protoplanetary disk is lower than Keplerian velocity. Gas molecules moving at sub-Keplerian velocities extract angular momentum from formed bodies, pulling them toward the central star. Radial drift velocity is approximately proportional to planet size. As planets grow larger, their inward drift velocity increases. Numerical simulations show that meter-scale bodies have the fastest inward drift velocities. Radial drift increases relative velocities between bodies, causing them to collide at higher speeds. Since the stickiness of bodies decreases with increasing volume, collisions can be expected to shatter many bodies. This process is called the "meter-size barrier," preventing bodies from growing further [?]. Even if these fragments re-accumulate, they would repeat the above process and eventually drift to the central star, leaving only gas behind and thus lacking the key solids needed to form planetesimals.

Regarding protoplanetary disk lifetimes, theoretical requirements are difficult to match with observational results. According to the core accretion model, the process of Jupiter's internal solid core growing and accreting surrounding gas requires a continuous supply of nebular gas for about 10 Myr. However, observations indicate that the lifetime of protoplanetary disks around young stars is about 0.1–10 Myr, and for half of the systems with planetary disks, the disk lifetime is only 3 Myr [?].

3.1.2 Missing Ring Formation Theory

There is still no consensus on the theory of planetary ring formation. Currently, it is generally understood through the Roche limit: when the mutual attraction between two small celestial bodies near a planet is less than the difference in the planet's gravitational pull on them, they cannot aggregate to form a larger body. For Solar System bodies, the ring systems of Jupiter, Saturn, Uranus, and Neptune all lie within the Roche limit range. The current challenge is determining when and through what mechanism the ring-forming material arrived within the Roche limit and reached its current position, and how to constrain the radial extent of rings for different ring systems.

Theories may differ dramatically for different planetary ring systems. Jupiter's rings exist in a steady state of creation and destruction, with new particles supplied by geological activity from moons. For Saturn, there is still much debate. In 1849, Edouard Roche proposed that Saturn's ring system formed from a moon whose orbit reached Saturn's Roche limit and was tidally disrupted. Subsequently, new variants of the tidal disruption theory emerged, suggesting that a Saturn moon was impacted by a large comet or asteroid and disintegrated to form Saturn's rings. Another viewpoint holds that Saturn's rings did not originate from Saturn's moons but from residual material of the primordial nebula that formed Saturn [?].

3.2 Observational Contradictions

The Galileo probe discovered that Jupiter's atmosphere is rich in volatile substances such as Ar and He. For these gases to condense and participate in Jupiter's core formation, temperatures of 30 K or lower are required, corresponding to orbital distances that contradict traditional views of Jupiter's formation orbit. However, some subsequent models indicate that the midplane temperature of the protoplanetary disk was lower than previously estimated, reaching down to 25 K.

Studies of meteorites reveal that the oldest meteorites show no significant chemical differences and are almost identical in composition to the solar photosphere, except for volatile elements. These meteorites also provide clues about the size of primordial particles: 90% of meteorite volume is filled with grain structures about 0.1 mm to centimeter scale. Research shows they were heated above their melting point for several minutes, but the specific mechanism for this heating remains unclear. Some researchers propose it was due to nebular shocks, but the origin of these shocks is also controversial [**?**].

Since the 1990s, large numbers of exoplanets have been discovered, many of which seriously challenge the above planetary theories. Among exoplanets, there are numerous giant planets very close to their host stars, called hot Jupiters. Hot Jupiters have masses and radii comparable to Jupiter, but their orbital periods are extremely short (less than 10 days), with orbital distances of only a few hundredths of an AU—there are no corresponding planets in the Solar System. Moreover, such close orbits experience intense radiation from the host star, and the ability to retain abundant gas at high temperatures also challenges previous theories.

Theoretical models predict that when planetary orbits are relatively distant, the disk's orbital velocity is slower, and relative velocities between planetesimals in the disk are also slower, making collision processes more likely to result in aggregation. Additionally, at greater distances, the ambient temperature in the disk is low, and planetesimals are composed mainly of ice, giving them greater stickiness during collisions. Therefore, planetesimals at greater distances can easily grow into Earth-mass bodies in a short time. Furthermore, gas in close orbits is prone to volatilization by heat and can only be accreted by planetary embryos after escaping to distant orbits and cooling. Theoretical calculations thus conclude that gas giant planets should appear at more distant orbits.

Starting from accretion disks, we would expect material on the disk plane to orbit in the same direction and share the same direction as stellar rotation, naturally resulting in consistent planetary orbital directions. However, observations have discovered retrograde exoplanets [**?**] and planets with high orbital inclinations, such as HAT-P-7 b, whose orbital plane can be inclined up to 86° relative to its host star's equatorial plane [**?**].

According to orbital tidal dissipation theory, planets orbiting host stars dissipate orbital energy and eccentricity through tidal interactions. Planets with higher masses, higher orbital eccentricities, and larger radii dissipate eccentricity at higher rates, leading to orbital circularization [**?**, **?**]. However, observations have found examples that violate tidal dissipation theory, such as HD 80606 b. HD 80606 b is a planet with mass 3.94 M_J, radius 0.9214 R_J, and semi-major axis 0.449 AU, but its orbital eccentricity is surprisingly high at 0.93. Its host star has mass 0.98 $M_\odot$ and age 7.63 Gyr. In contrast, the planet's mass is already very large. After billions of years of evolution, maintaining such high orbital eccentricity does not conform to tidal circularization theory's expectation that massive planets' orbital eccentricities should decrease over time, eventually resulting in nearly circular orbits.

Densities of planets in the Solar System typically range from 1–5 $\mathrm{g \cdot cm^{-3}}$, with the most extreme case, Saturn, at 0.7 $\mathrm{g \cdot cm^{-3}}$. Among exoplanets, however, a batch of extremely low-density planets has been discovered, dubbed "super-puffs" due to their low-density characteristics. The most extreme examples are Kepler-51 b and Kepler-51 c, with masses of 4.4 $M_\oplus$ and 5.7 $M_\oplus$, radii as large as 8.98 $R_\oplus$ and 9.46 $R_\oplus$, and corresponding densities of only 0.03 $\mathrm{g \cdot cm^{-3}}$ and 0.04 $\mathrm{g \cdot cm^{-3}}$, far lower than any celestial bodies seen in the Solar System. Hot Jupiters are inflated due to high equilibrium temperatures, but "super-puffs" with significantly lower temperatures cannot be explained by thermal inflation. Current viewpoints include: "super-puffs" may be young systems still in the collapse process and have not reached stable density values; other explanations include dust outflows [?], photochemical hazes [?], tidal heating-induced inflation [?], or inherently having particularly thick atmospheres [?]. A recent theory proposes that "super-puffs" might be ringed planets, where the presence of rings increases transit depth, leading us to overestimate their radii [?]. Due to current observational data scarcity, various explanations remain possible, and no consensus has been reached.

3.3 The Distant Prospect of Extraterrestrial Life

Humans instinctively ponder our place in the universe, whether other intelligent beings exist, and whether Earth is the only planet with life. Extraterrestrial life is currently the hottest topic in planetary science, and the question "Are we alone?" has been a long-standing issue that astronomers have made prolonged efforts to address. As early as 1896, Nikola Tesla proposed that an extreme version of his radio transmission system could communicate with beings on Mars [?]. In 1960, Cornell University radio astronomer Frank Drake first used radio methods to search for extraterrestrial life in Project Ozma, using a 26 m radio telescope to observe stars Tau Ceti and Epsilon Eridani at 1.420 GHz, but detected no valuable signals.

The most famous radio search for extraterrestrial life is the SETI program, whose SETI@home component is well-known to the public, utilizing volunteer computer idle time to analyze observational data for possible extraterrestrial life signals, though no reliable signals have been identified to date. On March 31, 2020, the project stopped sending new tasks to users, and work has been suspended indefinitely. The SETI team stated they would provide new ways for the public to contribute to SETI.

Based on current human understanding of life, the concept of the habitable zone has been proposed—the range around a star suitable for life. The habitable zone is determined by the range where water can exist in liquid form. The basic idea is that a star radiates energy outward through blackbody radiation $F \propto T^4$. A planet at orbital distance r receives radiation flux $F_p \propto \frac{F}{r^2} \propto \frac{T^4}{r^2}$, while the heated planet also spontaneously radiates energy outward with flux $F_p \propto T_p^4$. When the two radiation values are equal ($F_{p,\mathrm{in}} = F_{p,\mathrm{out}}$), the planet reaches equilibrium temperature T_{pb}. The orbital positions d_0 and d_{100} corresponding to equilibrium temperatures of 0°C and 100°C define the outer and inner boundaries of the habitable zone.

In 1993, Jim Kasting et al. used a one-dimensional climate model to estimate the habitable zone range for main-sequence stars. They defined the inner boundary of the habitable zone as the critical position where water would be photolyzed into H_2 and O_2 by sunlight, and the outer boundary as the critical point where even at maximum greenhouse gas concentrations, temperatures cannot remain high enough to maintain water in liquid form, obtaining a Solar System habitable zone range of 0.95–1.67 AU [**?**]. By 2003, Kasting et al. [**?**] improved the one-dimensional climate model for estimating habitable zone range, performing more precise calculations of energy absorption by water vapor and CO_2, as well as light scattering by water vapor, adjusting the habitable zone range to 0.99–1.70 AU. The above calculations of habitable zone range all used one-dimensional climate models. Kasting et al. [**?**] used more reliable three-dimensional models to re-estimate the habitable zone, readjusting the inner boundary of the Solar System habitable zone to 0.95 AU.

The Planetary Habitability Laboratory (PHL) at the University of Puerto Rico has made numerous efforts in this regard. Its list of potentially habitable planets (HEC) already contains 60 planets (as of December 2020, see Figure 1 [Figure 1: see original paper]). The planets' masses are concentrated between 0.5 $M_\oplus$ and 10 $M_\oplus$, with orbital periods typically shorter than 100 days, not yet covering the positions of terrestrial planets in the Solar System. The HEC selection criteria for habitable planets require: (1) host stars with spectral types F, G, K, M; (2) planetary orbits within the habitable zone given by Kopparapu et al. [**?**] and corrected for orbital eccentricity by Méndez and Rivera-Valentín [**?**]; (3) planetary radii between 0.5 $R_\oplus$ and 2.5 $R_\oplus$ or minimum masses between 0.1 $M_\oplus$ and 10 $M_\oplus$.

PHL provides a list of potentially habitable planets divided into conservative and optimistic samples. The conservative sample requires planetary radii less than 1.5 $R_\oplus$ or minimum masses less than 5 $M_\oplus$, likely to be habitable planets. The optimistic sample expands the radius constraint to 1.5–2.5 $R_\oplus$ or masses to 5–10 $M_\oplus$. Compared with the conservative sample, planets in the optimistic sample have lower probabilities of being habitable. Additionally, the Earth Similarity Index (ESI) is suitable for selecting planets most similar to Earth among those with similar radii and masses. Planets in the sample are required to have ESI values above 0.5. The ESI expression is:

$$\mathrm{ESI}(S, R) = 1 - \sqrt{\left(\frac{S - S_\oplus}{S + S_\oplus}\right)^2 + \left(\frac{R - R_\oplus}{R + R_\oplus}\right)^2},$$

where S and R are the radiation flux received by the planet from its host star and the planetary radius, respectively, and $S_{\oplus}$ and $R_{\oplus}$ are the solar radiation flux received by Earth and Earth's radius.

Despite previous efforts, we still cannot determine which planets harbor extraterrestrial life. We must conduct in-depth research on the forms, conditions, and signals that life would present, as well as the evolutionary history of the planets themselves. With advances in observational technology, we will obtain exoplanet parameters in more direct ways.

4 Large Sample: Exoplanets

As discussed above, current planetary formation theories are incomplete, and theories based on a single planetary system have yet to be tested for universality. Exoplanets provide our path to new breakthroughs. They help answer whether the Solar System is a special system and whether other planetary systems evolve according to Solar System planetary theories, effectively testing or constraining universal planetary formation theories. To seek a complete and universal theory, astronomers have continuously searched for and observed exoplanets over the past two decades, accumulating a large sample of exoplanets for deepening theoretical research.

4.1 Search Results

As of December 2020, the NASA Exoplanet Archive [?] has cataloged 4,307 confirmed exoplanets, of which 3,275 (76%) were discovered through the transit method and 821 (19%) through radial velocity measurements. Radius data have been measured for 3,300 planets, mass data for 998 planets, and minimum mass data for another 833 planets.

The annual discovery count has gradually increased over time (see Figure 2a [Figure 2: see original paper]), while the upper mass limit of discoveries has remained stable near $10^4 M_{\oplus}$ (related to NASA Exoplanet Archive's inclusion criterion requiring object masses or minimum masses $\leq 30 M_J$, corresponding to $10^4 M_{\oplus}$). The lower mass limit of detected planets has also gradually decreased, from 264 $M_{\oplus}$ (55 Cnc b) in 1995 to 0.06 $M_{\oplus}$ (Kepler-138 b) around 2015, with a few Mercury-mass exoplanets now discovered (see Figure 2c).

In the planet (minimum) mass versus orbital period diagram (see Figure 2b), these planets differ significantly from Solar System planets in orbital period and mass, with numerous short-period, high-mass planets. Extreme orbital periods are only a few hours, with few long-period planets like those in the Solar System. This phenomenon may be caused by selection effects in exoplanet searches. Currently, the most mainstream detection methods are the transit method and radial velocity method.

The transit method's principle is that a planet blocks part of its host star's light, causing the observer to detect a brief dimming of the star's brightness that recovers, with the light curve showing a fixed period and specific shape.

The transit method requires multiple transits to confirm a planet's existence, with the time interval between two transits corresponding to the planet's orbital period. Therefore, the transit method strongly favors large-sized planets on short-period orbits. When a planet orbits its host star, both actually revolve around their common center of mass (focus). When the host star revolves, its light exhibits a Doppler effect from the observer's perspective, allowing exoplanet searches through radial velocity measurements. When the star moves toward the observer, spectral lines shift blueward; when moving away, they shift redward. The frequency shift relates to the star's radial velocity relative to the observer, satisfying $f_0 - f \propto v/c$, where c is the speed of light and v is radial velocity. The amplitude of radial velocity v satisfies [**?**]:

$$v = 28.43\,\mathrm{m\cdot s^{-1}}\frac{M_p \sin i}{M_\star + M_p}\frac{1}{\sqrt{1-e^2}}\left(\frac{P}{1\,\mathrm{yr}}\right)^{-1/3},$$

where e is orbital eccentricity, M_p is planet mass, $M_\star$ is stellar mass, i is orbital inclination, and P is orbital period. This shows that massive planets on short-period, high-eccentricity orbits have large radial velocity amplitudes and are easier to detect. Short-period planets have higher detection rates, and with the Kepler space telescope's observation duration of only 9 years, it is difficult to certify longer-period planets, causing detection results to strongly favor short-period planets.

In Figure 2b, compared with the radial velocity method, exoplanets discovered by the transit method are more concentrated on short-period orbits, while the radial velocity method has detected planets on longer-period orbits that are difficult for the transit method to find. The concentrated region of exoplanets shows three distinct clusters. Since current observations are relatively complete for short-period planets, the distribution valleys appearing between clusters should be real. This result is also confirmed by models such as NGPPS [**?**]. Orbital period reflects distance from the host star and can characterize planetary temperature. Therefore, it is customary to call the upper-left cluster "hot Jupiters," the lower-left "hot Neptunes" or "hot super-Earths," and the upper-right "ice giants." From the perspective of planet formation and evolution theory, the differences between these three types of planets should correspond to different physical processes, providing breakthrough points for studying planet formation and evolution mechanisms.

Currently, confirmed planets can be clearly divided into two categories in mass (radius), mainly concentrated between Earth and Neptune masses (radii) and near Jupiter mass (radius) (see Figures 2c and 2d). Planetary masses or minimum masses are measured through radial velocity, while planetary radii are measured through transits. The selection effects of the two methods do not completely match, so the peak heights in the histograms also do not match. However, it is certain that there are indeed two types of celestial bodies in terms of mass or radius. According to the core accretion model, planets form from micron-scale dust grains that adsorb and aggregate, then accrete gas—a process from small to large. Smaller planets better reflect the properties of early planet formation. We also look forward to discovering smaller celestial clusters in more complete future exoplanet searches, leading to deeper understanding of early-stage planets and the early processes of planet formation.

5.1 Background on Planetary Classification

Classification is crucial for deeply understanding celestial bodies. Currently, the astronomical community has constructed comprehensive and reliable classification systems for stars and galaxies, such as the Hertzsprung-Russell diagram for stars and Hubble's tuning fork for galaxies. The HR diagram and Hubble tuning fork play pivotal roles in stellar physics and galactic astronomy, reflecting the entire evolutionary process of celestial bodies through simple diagrams and facilitating understanding and dissemination of formation and evolution theories.

A complete classification system should fully reflect the formation and evolution theory of celestial bodies, presenting the characteristics and properties of various stages of formation and evolution in the classification system for graphical representation of theories, predicting new types of celestial bodies, and promoting theoretical model development in reverse. For planets, over 4,000 exoplanets have been discovered. Through statistical classification of exoplanet properties, we hope to discover more unknown planets and promote theoretical development. However, there is currently no complete classification system to describe planetary formation theory. For a long time, our understanding of planets has been limited to observations of the Solar System. Based on the characteristics of the eight major planets' composition or size, we distinguish between terrestrial and Jovian planets. According to orbital distances, Mercury, Venus, Earth, and Mars are classified as inner planets, and Jupiter, Saturn, Uranus, and Neptune as outer planets.

Even the definition of a planet was only established in 2006 through an International Astronomical Union resolution [?], though this resolution remains controversial. The latest exoplanet definition was expanded from the Solar System planet definition by the IAU in 2018 [?], adding a maximum mass limit ($M_p \leq 13M_J$) and requiring that planets orbit stellar-mass bodies with mass ratios below the L4/L5 instability condition ($M/M_{\mathrm{planet}} \leq 1/25$). A higher-level planetary classification system is even more distant, with no recognized classification system to date, and most classification methods exist only in science fiction works.

5.2 Progress in Planetary Classification

Current classification efforts for all planets include:

(1) Single-parameter classification

1) The easiest way to classify planets is by mass. In mass classification, Michael's approach divides planets into categories for each order of magnitude from 1.90×10^{24} kg to 1.90×10^{30} kg.

2) Meghar's classification method is similar, dividing planets into categories for each order of magnitude from 0.000005 to 50,000 $M_\oplus$.

3) Different materials show significant differences in density, as do gas planets and rocky planets. Fischer et al. [?] classified detected exoplanets by considering mass-density relationships for planets composed of pure hydrogen-helium, pure water, pure silicate, and pure iron, each with density compressed by its own gravity (see Figure 3 [Figure 3: see original paper]).

4) Chen and Kipping [?] analyzed planetary mass-radius relationships (see Figure 4 [Figure 4: see original paper]), finding turning points in density relationships at 2.0 $M_\oplus$, 0.41 M_J, and 0.080 $M_\odot$, corresponding to the physical processes of beginning to form a volatile envelope, beginning self-gravitational compression, and hydrogen ignition, respectively.

5) By density alone, extremely low-density planets are directly called "superpuffs," with the criterion $\rho \leq 0.3 \text{ g} \cdot \text{cm}^{-3}$.

6) In their study of exoplanet giant atmospheres, Marley et al. [?] proposed a classification method by composition: ammonia clouds, water vapor clouds, cloudless, carbon monoxide and alkali metal clouds, and silicate clouds. This order also corresponds to orbital distances from far to near, i.e., the spatial positions of corresponding material boiling points.

(2) Multi-parameter classification

1) In 2002, Stern and Levison proposed a classification method based on mass and composition [?]. By mass: sub-dwarf planets ($< 0.03M_\oplus$), dwarf planets ($< 10M_\oplus$), sub-giant planets ($< 10^2M_\oplus$), giant planets ($< 10^3M_\oplus$), and super-giant planets ($< 10^{4.5}M_\oplus$). By composition: rock-dominated, ice-dominated, and hydrogen-dominated categories. Mass and composition combine to determine the final planetary type. They also stated that such classification methods are incomplete and proposed requirements that a classification framework should satisfy: Classification should be physics-based; Types should be determined by easily observable characteristics to facilitate classification of the entire sample and minimize observational selection effects; Object parameters and characteristics should be expressed numerically; Each object should have a uniquely determined type and should not appear in multiple types; Characteristics used for classification should remain constant; The system should be robust to new types, reserving space for unknown categories (e.g., binary or triple planets escaping host stars); Classification criteria should be as simple as possible, not complicated.

2) Russell [?] introduced a classification method considering planetary composition, mass, and orbital properties. In composition, considering mass ratios of metal, silicate, water ice, and atmosphere, it is divided into 19 categories. Based on planetary mass, it is divided into 5 categories, each corresponding to brown dwarf mass, Jupiter mass, Neptune mass, Earth mass, and Ganymede mass bodies. Additionally, planetary orbits are considered: typical planets (Earth), belt planets (dwarf planets), satellites, rogue planets, typical binary planets, belt binary planets, and rogue binary planets. The combination of these three aspects constitutes the final classification.

3) In FANDOM's introduction to planetary classification [?], the classification framework considers planetary mass, orbit, surface state, and composition. Planetary mass ranges from 0.01 $M_\oplus$ to 13 M_J, divided into three major categories: Earth-like (E), Neptune-like (N), and Jupiter-like (J), each with a, b, c subcategories. Orbital distances from less than 0.1 AU to greater than 100 AU are divided into 12 categories in a quasi-geometric sequence, i.e., as distance increases, type intervals also become larger. Surface classification is based on human imagination of planetary characteristics: gas, lava, volcanic, desert, arid, mountainous, ice, ocean, forest, and urban. Finally, composition is considered: planets dominated by H, He, Fe, C, H_2O, silicate, and other components.

(3) Habitability classification

1) PHL's habitability classification, based on habitability, further divides habitable planets into sub-Earth-size, Earth-size, and super-Earth-size types.

2) Saha et al. [?] used neural networks for exoplanet habitability classification, dividing planets into three categories: non-habitable, Mesoplanet, and Psychroplanet. Mesoplanets are habitable planets with temperature ranges of 0°C–50°C, while Psychroplanets range from -50°C to 0°C, typically uninhabitable but potentially habitable under specific conditions.

3) Charles and José believe that to find habitable Earth-like planets, Earth-like planets need to be classified, as tiny variations in key element (C, O, Mg, Si, S, and radioactive isotopes) abundances can severely affect habitability [?]. They propose: Starting analysis from the Sun's composition to determine the depletion pattern of element ratios forming Earth-like planets; Using stellar spectroscopic surveys to measure the abundance range of stellar elements and compare them with the Sun; Based on depletion pattern and stellar element abundances , estimate the chemical composition of Earth-like planets around nearby stars; Earth-like planets will have different main element abundances and should be classified based on estimated chemical composition; Through Earth studies, establish closer connections between composition and habitability.

5.3 Defects in Planetary Classification

Existing planetary classification methods have many defects. Most numerical criteria are set arbitrarily, lacking physically meaningful boundaries, and cannot reflect the essential physical differences between various types of planets. The main problems are as follows:

(1) Classification systems constructed based on different backgrounds and purposes have their own biases, often focusing on specific topics such as habitability or whether they are "super-puffs." They cannot effectively distinguish objects they do not focus on and lack universality.

(2) There are too few classification parameters, often targeting one parameter or characteristic rather than classifying planets as a whole. We need to find a set of parameters that can completely describe all planets and classify based on this set.

(3) Various classification systems generally have Solar System-based problems. Using Solar System characteristics to describe all planetary systems is inappropriate because the Solar System is a relatively special system that cannot comprehensively present the full picture of planetary celestial bodies. Exoplanet survey results tell us that there are too many unknown celestial bodies in the universe. We do not know what other states and modes planetary systems have or how many parameters are needed to completely describe various planetary systems. More comprehensive observations of exoplanets are necessary.

(4) Existing classification systems often directly classify observables without considering processes expected in planetary formation and evolution theories. Throughout a planet's life, parameters are unlikely to remain constant. In addition to parallel relationships between types, there may also be evolutionary sequence relationships, i.e., evolving from type A to the next type B, where A is the basis for B, and B is the result of A. If we plot scattered points of various celestial types on a diagram, the same type of celestial bodies should cluster in the same region; the density of scattered points in transition zones between types can also reflect evolutionary timescales. The positional distribution of various planetary types in the diagram will reflect the evolutionary relationships of various planets.

If we can construct a complete classification system applicable to all planets, it will help us understand planetary formation and evolution theories, facilitate planetary discussions and knowledge dissemination, and promote theoretical development.

6 New Window for Planetary Theory and Classification: Protoplanetary Disks

To construct a comprehensive planetary formation theory and classification system, it is necessary to study planets at various stages, including those in the birth stage from protoplanetary disks to old planets around elderly stars. These samples covering a planet's entire life help us understand the complete process from birth to death. Since the planet formation timescale is far shorter than the evolution timescale, the planets we directly observe are often in their late formation stages, having reached stable states. Protoplanetary disks provide our window into the early formation environment and processes. Protoplanetary disks are the form of matter during star-planet system formation. Initially, their existence was perceived through excess infrared radiation beyond the stellar blackbody spectrum, but with mature synthesis aperture radio observation technology and greatly improved angular resolution, we can now directly conduct morphological observations of protoplanetary disks in radio bands.

Protoplanetary disk mass measurements are divided into solid mass and gas mass measurements. Solid mass measurements are usually based on millimeter-wave continuum luminosity, while gas mass measurements utilize CO molecular lines, with a future preference for HD molecular lines. The Very Large Array (VLA) and the Atacama Large Millimeter/submillimeter Array (ALMA) have conducted protoplanetary disk survey observations, obtaining large amounts of observational data for studying early planetary formation environments.

6.1 VLA+ALMA: VANDAM Survey

The VLA/ALMA Nascent Disk and Multiplicity Survey (VANDAM) [?] has scientific objectives to characterize the frequency of multiplicity in the protostar stage, determine the spatial separation distribution of protostellar companions, resolve disk structures around protostars, measure dust radiation spectral indices, and measure protostellar jet radiation in centimeter bands. The survey consists of Perseus and Orion components.

The Perseus survey uses the VLA for multi-band radio observations of all known protostars in the Perseus molecular cloud at about 230 pc, covering 8 mm, 1 cm, 4 cm, and 6.4 cm bands. Observations are conducted in A and B array configurations: Array A for highest image resolution and Array B for greater sensitivity to compact extended sources, with best resolutions of $0.065''$ (15 AU) and $0.22''$ (46 AU), respectively.

The Orion survey, as an extension, adds observations of protostars in the Orion molecular cloud. ALMA observed 328 protostars from the Herschel Orion Protostar Survey (HOPS) at 0.87 mm for 9.1 hours, including continuum, ^{12}CO J=3-2, and ^{13}CO J=3-2 lines, with about $0.12''$ resolution for all sources. Additionally, VLA observed 100 youngest Orion protostars for 350 hours in A and C arrays, with about $0.082''$ resolution at 8 mm and 1 cm bands. Subsequent observations of 40 multiple systems are planned in ALMA Cycle 6.

6.2 ALMA: DSHARP Survey

The Disk Substructures at High Angular Resolution Project (DSHARP) [?] is a large ALMA program in Cycle 4. DSHARP conducted deep radio observations at 240 GHz (1.25 mm) continuum and ^{12}CO J=2-1 emission lines for 20 nearby, bright, large protoplanetary disks, achieving $0.035''$ resolution, corresponding to 5 AU spatial resolution. Scientific objectives include studying disk universal properties, positions, sizes, small-scale substructure fluctuations, and disk material distribution and its participation in star formation.

DSHARP found that protoplanetary disks are basically centrally symmetric structures, with each disk having its own subtle structures on this basis (see Figure 5 [Figure 5: see original paper]). Fifteen disks show bright rings and dark gaps. Protoplanetary disks IM Lup, Elias 27, and WaOph 6 show spiral arm structures similar to galaxies, and these spiral structures can superimpose with rings to form more complex morphologies. In multiple star systems such as HT Lup and AS 205, clear signs of dynamical interaction appear, such as two distinct spiral arm structures and complex CO distributions [?].

In addition to radio observations, instruments such as VLT/SPHERE, Gemini/GPI, and Subaru/HiCIAO have observed protoplanetary disk detail features similar to radio observations in near-infrared bands. Based on these protoplanetary disk observations and using numerical simulation methods, planets of specific masses can be introduced to reproduce observed details in protoplanetary disks. Teams such as Rosotti et al. [?], Dong and Fung [?], and Hallam and Paardekooper [?] have inverted planetary masses from protoplanetary disk observational data, with mass ranges of 0.02 M_J to 10 M_J. These inverted planetary data can serve as parameters for early-stage planets, complementing actually detected exoplanets and providing more references and constraints for early planet formation theoretical research.

7.1 Next-Generation Telescopes

Due to limitations in observational equipment performance and ground-based observations, current observations of planetary bodies are incomplete. Obtained parameters are often limited to summary descriptors such as mass, radius, and orbital parameters, failing to capture complete planetary information. This makes it difficult to truly distinguish various types of planets from these physical quantities, let alone conduct more reliable certification or construct a complete planetary classification system, further limiting the development of planetary formation and evolution theories. Space telescopes already used for exoplanet observations, Kepler and TESS, both detect through the transit method with the sole purpose of searching for exoplanets as celestial bodies, lacking deeper observational capabilities. Therefore, new-generation observational equipment is urgently needed to deepen our understanding of planets. New-generation singlemirror radio telescopes can enhance our search for extraterrestrial civilization signals, while radio telescope arrays with extremely high angular resolution can conduct more detailed observations of protoplanetary disks and search for exoplanets still in the formation stage. Next-generation space telescope designs have already considered exoplanet coronal spectroscopy observations, expecting to understand planets from more comprehensive dimensions.

7.1.1 FAST

The Five-hundred-meter Aperture Spherical Radio Telescope (FAST) located in Pingtang, Guizhou, is currently the world's largest telescope. Its huge receiving area gives it extremely high sensitivity for searching for exoplanets and extraterrestrial civilization signals. The Solar System contains six magnetized planets (Mercury, Earth, Jupiter, Saturn, Uranus, Neptune) with planetary-scale magnetic fields. In their magnetospheres, various mechanisms accelerate electrons to keV to MeV levels, producing radio radiation at high latitudes. Radiation frequency depends on local cyclotron frequency, proportional to magnetic field strength, typically below tens of MHz. Due to galactic background noise interference, at decimeter wavelengths, only Jupiter-magnitude radio radiation within 0.2 pc can be resolved. However, studies of stellar wind-planet magnetosphere interactions indicate that hot Jupiter radio radiation can reach 10^3 to 10^5 times that of Jupiter, thus expanding the search range for exoplanets.

Although radio imaging may not directly resolve star-planet systems, signals from stars and planets can be distinguished through radio radiation polarization and periodicity, thereby detecting planetary existence [**?**]. Additionally, FAST's scientific objectives include pulsar surveys, which can search for exoplanets near pulsars through pulsar timing methods [**?**].

7.1.2 CSST

The Chinese Space Station Telescope (CSST) serves China's space station optical sky survey project [**?**]. With a 2 m aperture, it will conduct optical imaging and prism spectroscopy observations covering near-ultraviolet to near-infrared bands (255–1000 nm). Scheduled for launch around 2024 into a ~400 km Earth orbit, it will fly in formation with the Chinese space station with an expected lifetime of 10 years. CSST carries a Cool Planet Imaging Coronagraph (CPIC) for direct imaging observations of planets in distant orbits in star-planet systems, achieving a contrast of 10^{-9}. Complementing ground-based detection of hot planets through transit and radial velocity methods, CPIC will build a more complete exoplanet sample for us. Using more direct observation methods, it can obtain richer and more important information about exoplanets (such as color and composition), aligning with future trends in space astronomy development.

7.1.3 SKA

The Square Kilometre Array (SKA) [?] is a large radio telescope array being built in South Africa and Australia, named for its total receiving area of 1 km^2, with scientific observations expected to begin after 2027. China, as a founding and full member of SKA, participates in research and development of six international work package alliances: antennas, low-frequency aperture arrays, mid-frequency aperture arrays, signal and data transmission, scientific data processing, and broadband single-pixel feeds [?]. In SKA Phase 1, observations near the 2 cm band can achieve 4 AU spatial resolution for the nearest systems, allowing detection of centimeter-scale particle distributions near the snow line. This band can be used to deeply search for molecules related to life's origin, such as amino acids.

Similar to FAST, SKA can use low-frequency observations to study magnetic fields originating from exoplanets, gaining insight into their internal information from planetary auroral radio radiation, and can also be used to search for exoplanet moons. Since SKA's inception, SETI has been part of its core science, and due to SKA's huge receiving area and extreme sensitivity, SETI should become one of its core scientific objectives, detecting radio signals produced by extraterrestrial life activities [?].

7.1.4 JWST

The James Webb Space Telescope (JWST) [?] is a 6.5 m aperture telescope that succeeded the Hubble Space Telescope (HST), launched on December 25, 2021, from the Guiana Space Centre to the Earth-Sun L2 point. Although it is HST's successor, its observation band differs; JWST is actually an infrared telescope covering wavelengths of 0.6–30 μm. Since molecular spectral lines have rich features in the infrared band, infrared telescopes are of great significance for exoplanet observations. Scientific objectives regarding exoplanets include the birth of stars and protoplanetary systems and the origins of planetary systems and life.

7.1.5 PLATO

The PLAnetary Transits and Oscillations of stars (PLATO) telescope [?], developed by the European Space Agency, is planned for launch to the Earth-Sun L2 point in 2026. PLATO will detect exoplanets by monitoring stellar brightness variations, with the main objective of searching for transit events among over 1 million stars and confirming rocky planets around Sun-like stars, subgiants, and red dwarfs. To find liquid water, the mission focuses on searching for Earth-scale planets in the habitable zones of Sun-like stars. PLATO carries 26 cameras, including 24 "normal" cameras and two "fast" cameras, each consisting of 4 CCDs mosaicked together. Normal cameras monitor stars fainter than 8 mag with 25 s long exposures, while fast cameras monitor bright stars of 4–8 mag with 2.5 s short exposures. Normal cameras will be divided into four telescope groups, each consisting of six 120 mm aperture lenses, with a combined total field of view of about 2,232 square degrees.

7.2 Future Large Space Projects

NASA has proposed four large strategic science missions for future large space missions: the Habitable Exoplanet Observatory, the Large UV/Optical/IR Surveyor, the Origins Space Telescope, and the Lynx X-ray Observatory. The first three are closely related to exoplanets. These projects were submitted to NASA and the U.S. National Academy of Sciences in 2019 and will be reviewed by its independent Decadal Survey Committee for priority ranking. The highest-priority project will be implemented and receive funding, with launch to the Earth-Sun L2 point expected between 2035 and 2040.

7.2.1 HabEx

The Habitable Exoplanet Observatory (HabEx) [**?**] is a 4 m off-axis telescope with a designed lifetime of 5–10 years. Its most distinctive feature is using a 52 m diameter starshade placed 76,600 km in front of the telescope to block starlight for observing faint planets near stars. Scientific objectives include finding nearby planets and detecting their habitability; detecting nearby planetary systems to understand planetary composition diversity; and enabling new astrophysical system studies from Solar System to galaxy and cosmic scales through extended UV and near-infrared observations.

7.2.2 LUVOIR

The Large UV/Optical/IR Surveyor (LUVOIR) [**?**] covers 100–2,500 nm, with a structure similar to JWST. It has two design options, A and B, with apertures of 15 m and 8 m, using primary and off-axis designs, respectively. The initial mission duration is 5 years, with consumables for 10 years and component lifetimes set at 25 years. Scientific objectives include determining atmospheric compositions of large numbers of exoplanets and measuring atmospheric escape rates of transiting planets; studying the evolution of C, H, O molecular carriers in protoplanetary disks and tracking disk winds; observing spatial distributions of planetesimals in late-stage planet formation; and surveying planetary system structures around late-type main-sequence stars. For Solar System studies, it can determine sizes, colors, and orbits of small bodies in the outer Solar System.

7.2.3 OST

The Origins Space Telescope (OST) [**?**] has a 5.9 m aperture covering 2.8–588 μm, effectively bridging the observation bands of JWST and ALMA. Scientific objectives include how stars and metals form in galaxies, how supermassive black holes at galaxy centers grow, how habitability conditions evolve during planetary evolution, and whether planets orbiting M-type dwarfs can sustain life.

7.3 Summary

Planets are familiar yet unfamiliar celestial bodies that humans have studied for hundreds of years, establishing numerous models for Solar System planets. Currently, the gravitational instability model struggles to explain the formation of close-orbit, low-mass planets in low-density disks, and observations of protoplanetary disks have yet to find clumpy structures supporting the gravitational instability model. For the widely accepted core accretion model, although observed details in protoplanetary disks support the view that planets grow gradually by accreting material in disks, many problems in the gradual growth process of planetesimals remain unsolved with reliable solutions, and many details remain incomplete.

Theoretical models still have their own application limitations and defects, and progress on planetary classification systems is even more unreliable. We long for a universal and unified planetary formation and evolution theoretical model and classification system to depict planetary formation and evolution, guiding our understanding of this class of celestial bodies and life itself.

Successful detection of exoplanets has opened a new window for studying planets. The TESS satellite has succeeded the retired Kepler satellite, and we continue to discover new exoplanets. New next-generation equipment brings revolutionary leaps in observational capabilities, enabling us to study the diversity and complexity of exoplanets across various wavelengths, providing clues and foundations for modifying or completely rebuilding theoretical models. Based on further improving or overturning theoretical models such as gravitational instability and core accretion, we also look forward to higher-level development of planetary classification systems. We hope to clearly and thoroughly present planetary theoretical models in graphical form, make reliable predictions for discovering completely new types of planets, piece together the complete puzzle of all planetary features and properties, facilitate our in-depth understanding of planets, and express the conditions for life's birth, evolution, and survival, deepening our understanding of life itself.

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Note: Figure translations are in progress. See original paper for figures.