Nearby Habitable Exoplanet Survey Program: Searching for the Next "Earth" Using Space Astrometry

Authors: Ji Jianghui, Li Haitao, Junbo Zhang, Li Dong, Fang Liang, WANG Su, Deng Lei, Chen Guo, Fei Li, Dong Yao, Li Baoquan, Gao Xiaodong, Xian Hao, Ji Jianghui

Date: 2024-06-02T00:00:00+00:00

Abstract

The Closeby Habitable Exoplanet Survey (CHES) employs space-based microarcsecond-level high-precision astrometric techniques to conduct a census of approximately 100 FGK-type stars in the solar neighborhood (within 10 pc), detecting habitable-zone Earth-like planets or super-Earths; it will conduct a detailed census of the number, true masses, and three-dimensional orbital parameters of habitable planets, marking the first international space mission to detect habitable-zone Earth-like planets in the nearby solar neighborhood. The CHES payload is a high-image-quality, low-distortion, high-stability optical telescope with an aperture of 1.2 m, a field of view of 0.44°$×0.44°, *andafocallengthof*36*m*, *employingacoaxialthree* − *mirroranastigmat*(*TMA*)*opticalimagingsystem*.*Toachievethedetectionofhabitable*− *zoneEarth*−*likeplanets*, *themeasurementprecisionoftheCHESmissionis*1*μas*, *representingthehighestmeas* *achievingasignificantbreakthroughinlarge* − *field* − *of* − *view*, *high* − *image* − *qualityspacetelescopeopticalsystemtechnologywithlowdistortion*; *breakingthroughthe*10^{-5}$ pixel-level star separation measurement technology; and realizing innovations in high-stability attitude control precision and thermal control precision for the satellite system. CHES is expected to discover 50 Earth-like planets, leading a leapfrog development in China' s space science exploration technology.

Full Text

Closeby Habitable Exoplanet Survey (CHES): an Astrometry Mission for Probing Nearby Habitable Planets

JI Jianghui[1],[2],[3], LI Haitao[4],[5], ZHANG Junbo[6],[7], LI Dong[8], FANG Liang[6], WANG Su[1],[2],[3], DENG Lei[8], CHEN Guo[1],[2],[3], LI Fei[8], DONG Yao[1],[3], LI Baoquan[4],[5], GAO Xiaodong[6], XIAN Hao[5],[6],[7]

[1]Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023
[2]School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026
[3]Key Laboratory of Planetary Sciences, Chinese Academy of Sciences, Nanjing 210023
[4]National Space Science Center, Chinese Academy of Sciences, Beijing 100190
[5]University of Chinese Academy of Sciences, Beijing 100049
[6]Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209
[7]National Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209
[8]Innovation Academy for Microsatellites, Chinese Academy of Sciences, Shanghai 201306

Abstract

The Closeby Habitable Exoplanet Survey (CHES) employs state-of-the-art, high-precision astrometry and positioning technology at the microarcsecond level in space. Its primary objective is to conduct a thorough survey of approximately 100 FGK-type stars within the Sun’ s proximity (within 10 parsecs), with the goal of detecting potentially habitable Earth-like planets or super-Earths. This pioneering mission involves a detailed census of habitable planets, providing intricate information on their numbers, true masses, and three-dimensional orbits. Notably, CHES marks a historic milestone as the inaugural international space exploration mission exclusively dedicated to the study of terrestrial planets within the nearby habitable zone.

CHES’ s payload features a cutting-edge optical telescope with a 1.2 m aperture, a field of view measuring 0.44°$×0.44°, *andafocallengthof*36*m.Thetelescopeutilizesacoaxialthree*−
mirrorTMAopticalimagingsystem.Impressively, CHESisdesignedwithapositioningmeasurementaccuracyo
advancingopticalsystemsforlargefieldofview, developinghigh−*qualityspacetelescopeswithminimaldistortio*
5}$ pixel level; and achieving high stability in satellite system attitude control and thermal control precision. CHES stands on the threshold of groundbreaking discoveries, with the exciting prospect of revealing 50 Earth-like planets. This announces a significant leap forward in China’ s space science exploration technology.

Key words: High-precision astrometry method, Exoplanets, Nearby Habitable Planets

---

Introduction

Since the discovery of the first exoplanet in 1995 [1], over 5,500 exoplanets have been discovered to date [2]. The search for extraterrestrial life and habitable exoplanets represents one of the frontiers of fundamental astronomical research, addressing major scientific questions such as "Is Earth unique?" and "How do planets become cradles of life?" The "2022-2031 Decadal Survey on Astronomy and Astrophysics" by the U.S. National Academies lists the search for habitable planets beyond Earth as one of three major scientific objectives for future exploration programs [3]. The European Space Science Programme (Voyage 2050, 2035-2050) identifies "nearby habitable planetary systems" as an important scientific goal [4]. The "China Astronomy 2035 Development Strategy" by the Chinese Academy of Sciences and the National Natural Science Foundation of China [5,6], the "14th Five-Year Plan Outline and 2035 Long-Range Objectives," and the "2021 China' s Aerospace" white paper [7] all identify habitable planet detection research as a major national strategic need. Therefore, exoplanet exploration and research directly address global scientific frontiers, will reveal the mysteries of cosmic structure and origin, and expand our understanding of extraterrestrial life and life' s origins.

Since 2000, multiple international projects have been initiated and implemented for space-based exoplanet detection, such as the Gaia satellite based on astrometry [8,9], and missions using the transit method including Kepler [10,11], TESS [12], CHEOPS [13], and JWST [14]. Recent or upcoming missions include the CSST coronagraph using direct imaging [15], Euclid [16] and ROMAN [17] using microlensing, and PLATO [18], ARIEL [19], and LUVOIR [20] using the transit method. These space missions reveal that international exoplanet detection has evolved from individual discoveries to statistical studies of large planetary samples, from broad understanding of planetary systems to detailed characterization of exoplanet properties, and the detection frontier has shifted from searching for various types of planets to focusing on finding habitable planets (see Figure 1 [Figure 1: see original paper]). However, current space missions have yet to discover Earth-like planets in the habitable zones of Sun-like stars, presenting China with an opportunity to proactively seize the technological high ground in exoplanet exploration.

Figure 2 [Figure 2: see original paper] illustrates the roadmap for habitable planet detection. In terms of detection methods, the trend moves from transit method to astrometry to direct imaging. From the perspective of detection targets, transit-based projects (e.g., Kepler, TESS, PLATO) focus on discovering habitable zone planets around red dwarfs, nearby red dwarfs, and Sun-like stars, respectively. Astrometry (CHES [21]) enables the discovery and characterization of habitable zone planets around nearby Sun-like stars, which can then be followed up with direct imaging (Habitable World Observatory, Miyin mission, ground-based E-ELT) for detailed atmospheric characterization of these planets. China' s proposed Closeby Habitable Exoplanet Survey (CHES [22]) adopts an original technical approach, using high-precision space astrometry to conduct in-depth detection of habitable planets around nearby Sun-like stars. Mission details are summarized in Table 1 [21]. Compared with the transit method, CHES offers unique advantages for detecting habitable zone Earth-like planets (see Figure 3 [Figure 3: see original paper]).

The Kepler and TESS missions first monitored extremely large stellar samples (10^7-10^9) for photometric variability, only detecting exoplanet candidates whose orbital planes align with the observer' s line of sight. Earth-like planet transits require extremely high photometric precision (60–80 ppm, with PLATO achieving better than 34 ppm) and ultimately rely on follow-up confirmation with high-precision radial velocity instruments on ground-based extremely large telescopes. In contrast, CHES employs high-precision astrometry, which is less affected by stellar activity, has minimal constraints on orbital configuration, and can obtain three-dimensional orbital information and true masses of planets. The probability of discovering habitable planets is high, with expectations of finding Earth 2.0 for the first time, including over 50 habitable zone Earth-like planets and super-Earths. Around 2030, China plans to launch additional habitable planet space missions including the ET program [23], Miyin mission [24], and Tianlin mission [25]. The ET program will use transit and microlensing methods for large-scale surveys of Earth-like planets in the Milky Way. The Miyin mission plans to launch a spatially distributed synthetic aperture array telescope to discover and confirm exoplanets and characterize their habitability through interferometric direct imaging. The Tianlin mission plans to launch a 6 m-class UV/optical/IR space telescope, primarily using coronagraphic direct imaging to discover and characterize rocky planets in nearby stellar habitable zones and search for potential biosignatures.

Why does CHES choose to detect nearby Sun-like stars? Currently, planets discovered within 32 light-years of the Solar System account for only 2% of all exoplanets, with only 16 being rocky planets in the habitable zone, all orbiting cooler M-dwarfs (see Figure 4 [Figure 4: see original paper]). These M-dwarfs typically have surface temperatures below 3,500 K, far lower than the Sun's 5,780 K, and their space environments are extremely harsh with strong flares that are detrimental to life survival. Therefore, finding "Earth 2.0" remains an unsolved mystery in astronomy. Theoretical inferences suggest that the probability of planets with radii 0.5–1.5 Earth radii existing in the conservative habitable zone around G and K main-sequence stars (Sun-like stars) in the Kepler sample is greater than 0.37 [29]. However, perplexingly, about 90% of Sun-like stars within 32 light-years have no detected planets. CHES' s original detection method is expected to fill this gap in nearby planet detection, making the discovery of true "Earth 2.0" seemingly within reach.

Why does CHES choose to detect habitable zone planets? The habitable zone refers to the region around a star where conditions are suitable for life, meaning planets within this zone can maintain stable liquid water on their surfaces [26], while stellar radiation and activity are not so intense as to destroy planetary atmospheres. In the Solar System, Earth' s orbit lies between Venus and Mars, precisely within the Sun's "habitable zone."To date, astronomers have discovered 69 habitable zone planets (see Figure 4), such as Proxima Centauri b [27] and TRAPPIST-1 e, f, g [28]. These habitable zone Earth-like planets are considered "new continents" in the universe and primary targets for humanity' s search for biosignatures. They hold promise as ideal second homes for humanity (

"Earth 2.0") because they may be comparable to Earth in mass and surface characteristics, potentially possessing suitable atmospheres and liquid water to sustain life stably.

How will CHES assess the habitability of terrestrial planets? Planetary atmospheric studies are crucial probes for revealing and characterizing habitability. In recent years, the CHES team has conducted systematic observational research on exoplanet atmospheres using ground-based telescopes [30–35]. With JWST' s launch, exoplanet atmospheric research has entered a new era. Through JWST, astronomers have successfully detected numerous molecules and atoms including water, carbon monoxide, carbon dioxide, sodium, and potassium in gas giant atmospheres with exceptional precision [36–40], first revealed photochemical processes through sulfur dioxide in hot Jupiter and warm Neptune atmospheres [41,42], first identified cloud types in exoplanet atmospheres [43], and first discovered methane-dominated atmospheres with potential biosignature spectral signals in a habitable zone sub-Neptune [44]. However, major breakthroughs in characterizing small planets, especially Earth-like planets, have not yet been achieved. For instance, the TRAPPIST-1 system, considered the most promising for transit spectroscopy observations, faces challenges: M-dwarf stellar activity greatly limits indirect detection methods like transit transmission spectroscopy [45], while thermal emission and phase curve measurements indicate that the two innermost Earth-like planets lack atmospheres [46,47]. Therefore, whether Earth 2.0 in M-dwarf habitable zones can maintain habitability faces enormous challenges. CHES will discover numerous nearby Sun-like star habitable zone Earth-like planets ideally suited for high-contrast direct imaging spectroscopy, pre-screening core observation targets for detailed atmospheric habitability characterization.

CHES will launch a 1.2 m-class high-precision astrometric space telescope to achieve microarcsecond-level star separation measurement precision, surveying approximately 100 Sun-like stars within 10 pc of the Solar System to find nearby habitable zone Earth-like planets or super-Earths, and comprehensively census nearby planetary numbers, true masses, and three-dimensional orbital information (see Table 2). Furthermore, CHES' s high-precision astrometric method can precisely determine stellar distances (see Figure 5 [Figure 5: see original paper]), enabling better study of stellar properties including size, mass, luminosity, and the Hubble constant, which directly impact key scientific questions in fields such as galaxy structure, cosmic expansion, and dark matter distribution [21].

This paper focuses on introducing CHES' s scientific objectives, payload configuration, overall mission design, key technologies, and latest progress.

1 Science Objectives

CHES' s core scientific objectives encompass the search for nearby habitable zone terrestrial planets (Core Science Objective 1) and a comprehensive census of planetary systems in the Solar System' s vicinity (Core Science Objective 2).

Extended objectives include cosmology, dark matter, and black hole research. By achieving these scientific objectives, CHES will answer key questions such as: What habitable zone terrestrial planetary systems exist around nearby stars? What are the orbital characteristics of terrestrial planets? What are the general patterns of their formation, evolution, and habitability? And what are the internal structures and distribution characteristics of planets?

1.1 Core Science Objective 1: Search for Habitable Zone Terrestrial Planets

1.1.1 Habitable Zone Terrestrial Planets As of January 2024, humanity has discovered 69 exoplanet candidates in the habitable zone, most located around M-dwarfs and detected primarily through transit photometry and radial velocity methods. However, the transit method only measures planetary size, not mass, while radial velocity only measures minimum mass (all substantially larger than Earth), preventing confirmation of whether these are truly habitable zone terrestrial planets. Kepler' s habitable zone planet candidates are generally distant (1,000–3,000 light-years) with large distance measurement errors, making verification and further screening difficult through other observational methods. Most habitable zone planets orbit M-dwarfs, whose strong UV radiation and uncertain atmospheric stability make habitability debatable. Due to observational limitations, some candidates lack critical information such as mass and size, leaving their status as terrestrial planets uncertain. Objectively speaking, no true "other Earth" has been discovered to date.

Habitable planet detection demands extreme precision. Ground-based instruments, even with active optics, struggle to break the 0.1 as precision limit due to atmospheric turbulence. Therefore, space telescopes represent the ideal choice for high-precision astronomical observations. Among current methods, radial velocity is severely affected by stellar activity, making effective detection of habitable planets around Sun-like stars difficult and preventing measurement of true masses. The transit method requires planetary orbital planes to align with the observer' s line of sight, resulting in low detection probability. Direct imaging, given current capabilities, more easily discovers more massive, more distant planets. Microlensing can obtain information about distant individual planets but cannot probe exoplanets in the Solar System' s vicinity. Currently, no international space project possesses the capability to detect habitable zone terrestrial planets around nearby Sun-like stars. CHES' s high-precision relative astrometry method can observe habitable planets around Sun-like stars and obtain their true masses and three-dimensional orbital information, giving CHES unique advantages for detecting habitable zone planets and characterizing their properties.

1.1.2 Detection of Terrestrial Planets Around Nearby Stars CHES will search for habitable zone terrestrial planets around approximately 100 F, G, and K-type stars within 10 pc of the Solar System, discovering nearby habitable zone terrestrial planets. Compared with other international exoplanet detection programs, CHES will focus on high-precision detection of terrestrial planets within the habitable zone. Primary scientific objectives include determining whether habitable zone planets exist around nearby stars and understanding their distribution and occurrence rates (see Figure 4). By searching for habitable zone planets in the Solar System' s vicinity, CHES will answer questions about their distribution around us—one of the most pressing questions for both the scientific community and the public, particularly regarding terrestrial planets within habitable zones.

1.1.3 Planetary Habitability Researchers have conducted occurrence rate studies of planets around different stellar types, analyzing Kepler Q1-Q17 data to estimate the probability of planets with radii 0.5-1.25 R existing in habitable zones. They found occurrence rates of 0.66 ± 0.14, 1.03 ± 0.10, and 0.75 ± 0.11 around F, G, and K-type stars, respectively [52]. Based on this, CHES expects to detect approximately 50 habitable planets. Additionally, CHES-detected nearby habitable zone terrestrial planets are exceptionally well-suited for follow-up high-contrast direct imaging observations [20,53-57]. Characterizing planetary atmospheric properties through reflected or thermal emission spectra can answer critical questions about habitability and potential biosignature spectral features [58]. Using the HD 219134 planetary system at 6.5 pc as an example (see Figure 6 [Figure 6: see original paper]), assuming an Earth twin exists in its habitable zone, a 6 m-class space telescope performing direct imaging spectroscopy could detect water vapor with ~13σ signal-to-noise ratio and oxygen with ~4σ signal-to-noise ratio in 100 hours of total exposure, given a coronagraph working angle suppression ratio of 10^{-10} and total telescope transmittance of 15%. Volume mixing ratio measurements for water and oxygen would achieve ~0.2 dex precision. Figure 7 [Figure 7: see original paper] shows this simulation applied to all CHES target stars. If Earth twins exist in their habitable zones, 100 hours of exposure would enable $>3\sigma$ detection of water vapor in 91% of nearby stars and oxygen in 25% of cases. Thus, CHES' s search for habitable planets will significantly enhance the efficiency of subsequent direct imaging spectroscopy missions (e.g., Miyin mission), allowing them to skip the search phase and focus precious observing resources on detailed atmospheric characterization and biosignature detection.

1.2 Core Science Objective 2: Census of Nearby Planetary Systems

1.2.1 Census of Nearby Planets Planetary formation theory suggests that planetary systems are ubiquitous around stars, with mass distributions similar to the Solar System's planets. However, most discovered exoplanets are substantially more massive than Earth, primarily due to observational selection effects: the transit method more easily discovers larger planets, while radial velocity more easily discovers more massive planets. Kepler data reveal a significant distribution gap in planetary radii between 1.5-2.0 R and poor completeness below 1.14 R [59-63], potentially indicating undiscovered patterns. CHES' s high-precision detection capability can not only discover habitable planets around nearby stars but also conduct comprehensive surveys of nearby planetary systems, providing more complete and systematic understanding of exoplanetary orbital characteristics, formation, and evolution history, ultimately addressing whether the Solar System is typical or unique.

1.2.2 True Masses, 3D Orbits, and Formation/Evolution Beyond orbital characteristics, planetary internal structure is crucial for habitability. As previously mentioned, habitability typically requires solid or liquid surfaces capable of maintaining liquid water, appropriate temperature ranges, and surface atmospheres. Obtaining true masses and three-dimensional orbital parameters provides critical information for accurately constraining planetary habitability from formation and evolution perspectives. Analysis of currently observed exoplanet mass-radius relationships reveals considerable uncertainties in atmospheric content ratios. Classical planet formation theory, such as core accretion analysis, shows that atmospheric content and internal structure directly affect evolutionary stages and whether planets undergo gas accretion—processes intimately related to planet formation and evolution. Therefore, CHES's acquisition of true planetary masses will powerfully support constraining planetary composition, inferring formation/evolutionary histories, and refining current planet formation theory.

Three-dimensional orbital information for multi-planet systems directly relates to their origin and evolution. The numerous exoplanet discoveries have revolutionized understanding of planetary system evolution, revealing complex and diverse characteristics. Multi-planet system 3D structures not only help understand system origins and evolution but provide statistical insights into migration processes that significantly affect long-term habitability [50,65,66]. CHES' s precise mass and 3D orbital information for planets in nearby multi-planet systems will provide invaluable observational evidence, greatly expanding human cognition and theoretical understanding of planetary systems. Given strong dependence on initial conditions, current planet formation theory cannot yet accurately predict formation physical images [50,67–73]. CHES observations of nearby multi-planet systems, covering not only habitable zone terrestrial planets but also super-Earths, warm Neptunes, and Jupiter-like planets, will provide powerful constraints on information needed to distinguish different formation theories (e.g., original nebula surface density)—a unique contribution compared with other missions.

1.2.3 Diversity of Planetary Systems Extensive observations reveal that exoplanetary systems exhibit dramatically different characteristics from the Solar System (e.g., discoveries of hot Jupiters and diamond planets) [74–82]. Known exoplanets can be classified into multiple types based on orbital properties and mass distributions, including hot Jupiters, warm Jupiters, cold Jupiters, warm Neptunes, and super-Earths [11,28,83,84] (see Figure 1). However, habitable zone exoplanets remain relatively rare, comprising only ~1% of the total

(69 planets), mostly super-Earths and Jupiter-like planets, with only 29 rocky habitable zone planets (see Figure 4). CHES will focus on finding rocky planets in habitable zones around nearby Sun-like stars, opening new possibilities for exoplanet exploration.

CHES' s unprecedented comprehensive and precise detection of planetary systems will yield discoveries and breakthroughs in planetary system and planetary science understanding.

1.3 Extended Science Objectives: Cosmology, Dark Matter, and Black Holes

Based on high-precision astrometry, CHES enables detection of X-ray binaries and black hole candidates, reveals Milky Way dark matter distribution, and helps understand black hole formation. Through cosmology, dark matter, and black hole research, CHES will address frontier questions about galaxy structure, cosmic expansion, and dark matter distribution. Precise masses of compact objects represent an important scientific question, and high-precision astrometry can more accurately characterize masses. Figure 8 [Figure 8: see original paper] compares CHES and Gaia mass measurements for compact objects (red and blue error bars represent Gaia and CHES uncertainties, respectively; vertical lines show Chandrasekhar/Oppenheimer limits). CHES can more accurately obtain compact object masses, determining whether they are white dwarfs, neutron stars, or black holes.

2 Payload Configuration

CHES' s payload is a high-imaging-quality, high-stability, low-distortion optical telescope using a coaxial three-mirror TMA optical imaging system, comprising the optical subsystem, focal plane subsystem, and on-orbit calibration subsystem. The telescope envelope measures 4.5 m × 2.6 m × 1.4 m, weighs approximately 765 kg, has a 1.2 m aperture, 0.44°\$×\$0.44° field of view, and 36 m focal length. The telescope operates in the 500–900 nm band, achieving near-diffraction-limited imaging across the full field of view. Figure 9 [Figure 9: see original paper] shows the optical system design [21], while Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show the structural design and 1/6-scale prototype [21].

Vacuum testing of the 1/6-scale prototype demonstrated full-field wavefront error better than $\lambda/20$. Table 3 [21] details the payload optical telescope system technical requirements.

CHES employs heterodyne laser interferometry for on-orbit focal plane calibration, achieving micro-pixel-level star separation measurement precision of approximately 10^{-5} pixel (see Figure 12 [Figure 12: see original paper]).

2.1 Optical Subsystem

To meet requirements for large aperture, large field of view, high imaging quality, and extremely low distortion, CHES adopts a coaxial three-mirror TMA optical structure with three-fold mirror light path design. The telescope system includes primary mirror assembly, secondary mirror assembly, primary-secondary mirror truss, plane mirror assemblies (M4, M5, M6), detector assembly, focal plane calibration assembly, and support structure. The focal plane calibration assembly is located near plane mirror M6, generating calibration beams via lasers.

During ground processing, alignment, and testing, gravity offloading mechanisms are used for optical mirrors, structures, and detectors to minimize gravity-induced differences between ground and space environments. After launch, initial focusing uses the secondary mirror to reduce launch and orbit transfer impacts on the optical system, ensuring initial optical residuals remain within tolerance. Following this focusing, all optical elements maintain stable relative positions, and the telescope enters observation mode. During observations, differences in optical and structural materials, temperature variations, and external vibrations may cause changes in telescope interior orientation elements, leading to optical system stability errors. Two primary technical approaches address these factors: payload thermal control technology to manage thermal deformation, and on-orbit calibration technology to measure and correct errors.

2.2 Focal Plane Subsystem

The focal plane will use sCMOS detectors with 6.5 m pixel size. The focal plane detection subsystem comprises focal plane structure and electronic control systems. The focal plane structure is assembled through mosaic of multiple sCMOS detectors, while the electronic control system includes image sensor array electronics and control box electronics connected via cables. Data exchange between the telescope and satellite platform is primarily handled by the control box. With 36 m focal length and 0.44° field of view, the focal plane geometric size is approximately 276 mm × 276 mm. To meet this large format requirement, a MOSAIC-based image sensor mosaic scheme is proposed. Assuming single sCMOS chip pixel size of 6.5 m and 4000$×$4000 pixels, single chip size is about 32 mm × 32 mm (including package), requiring 9$×$9=81 sCMOS chips for full focal plane coverage.

2.3 On-orbit Calibration Subsystem

The on-orbit calibration subsystem includes a laser heterodyne interferometric calibration module for high-precision calibration of CMOS detector non-uniform response. Combined with a star centroid separation measurement algorithm based on real point spread functions (PSF), this achieves micro-pixel-level star separation measurement precision on the telescope focal plane, meeting CHES's 1 as target-reference star angular separation measurement requirement. Additionally, the on-orbit calibration subsystem utilizes microarcsecond-level inter-star angular measurement technology and distortion gradient inversion algorithms for high-precision on-orbit calibration of telescope optical distortion, correcting distortion distribution changes caused by satellite attitude adjustments or environmental temperature variations to ensure measurement precision.

3 Mission Design

3.1 Performance Requirements

3.1.1 Astrometric Precision Requirements When a planet orbits a star, the star' s astrometric signal due to gravitational perturbation is proportional to the planet-to-star mass ratio and the planet' s orbital radius, and inversely proportional to the distance from Earth. To detect habitable zone Earth-like planets at 10 pc (approximately 32.6 light-years), detection precision must reach 0.3 as. Determining 12 parameters for a planet and its host star (7 planetary and 5 stellar parameters) requires at least 12 observation sets over 5 years. In practice, each observation set consists of multiple exposures over 2 hours. Increasing observation sets improves signal-to-noise ratio or allows relaxed precision requirements. To detect habitable zone Earth-like planets at 10 pc with 200 observation sets, single-set measurement precision must be better than 1 as.

With CHES single-set precision of 1 as, detailed analysis of major error sources is required, including target star astrometric error, reference star astrometric error, telescope measurement error, detector calibration error, and other potential errors. Considering astrometric solution precision and current engineering capabilities, error allocations are: target star astrometric error 0.35 as, reference star astrometric error 0.58 as. Payload error sources include telescope wavefront error, post-calibration distortion residual, and detector calibration error. Simulation analysis shows that to meet these allocations, requirements are: telescope wavefront error $\leq \lambda/12$, maximum field-relative distortion residual $\leq$ 0.36 as, detector calibration residual $\leq$ 0.74 as, and other errors $\leq$ 0.24 as [21,85,86].

3.1.2 Aperture Requirements Telescope aperture depends on two factors. First, limiting detection magnitude: based on target and reference star selection, the faintest reference stars are about 13th magnitude, with CHES detector exposure time of 20 ms. With 6.5 m pixel size and F-number of 30 to meet Nyquist sampling requirements for micro-pixel star separation algorithms, a 1.2 m aperture enables detection of 13th magnitude stars, satisfying limiting magnitude requirements. Second, photon noise impact on star separation measurement: for 13th magnitude stars with 1.2 m aperture and 2 hour exposure, approximately 1.6$×10^{9}$ photons are collected. With 8 reference stars observed simultaneously for 2 hours, photon noise-induced error is about 1 as []. Through over 200 observations accumulated over 5 years, CHES can measure 0.3 as signals, meeting mission precision requirements.

Comprehensively balancing domestic mirror fabrication capabilities, cost, weight, and photon noise factors, a 1.2 m aperture is recommended for CHES.

3.1.3 Focal Length Requirements With 1.2 m aperture and F-number of 30, telescope focal length should be 36 m. At the shortest wavelength of 500 nm, PSF full width at half maximum (FWHM) is about 0.1 . With 36 m focal length, FWHM corresponds to 15 m on the sCMOS detector. With 6.5 m pixel size, this satisfies the Nyquist sampling theorem.

3.1.4 Field of View Requirements CHES achieves high-precision positioning by measuring relative positions between target and reference stars. At least 6–8 reference stars must enter the field of view. Statistical analysis of candidate targets shows that a field of view >0.44°$\times$0.44° ensures all target stars have at least 6–8 reference stars, meeting positioning requirements.

3.1.5 Inter-Star Separation Measurement Precision Requirements With 6.5 m pixel size and 36 m focal length, one pixel corresponds to 0.037 angular displacement. To achieve 1 as star separation precision, relative centroid positioning precision must reach 2.7×10^{-5} pixel.

3.2 Detection Principle

CHES employs space-based high-precision relative astrometry to accurately measure microarcsecond-level star separation variations between target stars and 6–8 standard reference stars. These minute variations allow calculation of stellar displacement due to planetary gravitational perturbations, enabling detection of habitable zone terrestrial planets with true masses around nearby stars (see Figure 13 [Figure 13: see original paper]). Figure 14 [Figure 14: see original paper] shows astrometric orbit retrieval simulations for terrestrial planets around Alpha Centauri A. Alpha Centauri A, located in the constellation Centaurus, forms a triple system with Alpha Centauri B and Proxima at 1.34 pc from Earth—our Solar System' s nearest neighbor and a CHES target star. As a G2V star with mass ~1.06 M and apparent magnitude 0.01, no planets have been detected around it. Assuming a 1 M planet at 1 AU (Alpha Centauri Ab), the astrometric signal would be 2.1 as. If CHES observes it 30 times over 5 years with 1 as precision, fitting the generated time-series astrometric data can recover the planet' s orbital parameters.

3.3 Simulation Platform

Leveraging expertise in planetary dynamics and extensive experience processing light curve data [75,82,87-89], the CHES team developed Nii, a Bayesian planetary orbit parameter retrieval code implementing APT-MCMC algorithms for orbit retrieval from CHES simulated relative astrometry data using multiple reference stars [90]. For single and double planet systems, this algorithm effectively converges posterior probability distributions when combined with radial velocity data, accurately retrieving planetary orbital parameters and masses.

Further systematic studies investigated target star activity effects on high-precision astrometry. Results show that astrometric errors due to stellar activity cause photocenter jitter below 1 as for over 90% of stars. Stellar activity impacts on habitable planet detection are minimal for most targets, satisfying error allocation constraints for target star astrometric precision. Additionally, simulations show that CHES can detect habitable zone terrestrial planets around ~95% of Sun-like stars [93].

Assuming a Solar System analog (Sun, Earth, and Jupiter) at 10 pc, CHES conducting 200 observations over 5 years can retrieve Earth' s orbital period and mass within 10% of true values even with strong Jupiter interference, demonstrating CHES' s capability to detect terrestrial planets in multi-planet systems. If mission duration exceeds 5 years, detection capabilities for long-period cold Jupiters will further improve.

The CHES team rewrote the International Astronomical Union' s SOFA (Standards of Fundamental Astronomy Service) software, creating PyMsOfa—a Python package consistent with IAU resolutions. Integrated into the CHES simulation platform, it enables field-of-view simulations for target and reference stars (see Figure 5) and generates astrometric data for retrieval.

3.4 Satellite Platform

The CHES satellite consists of platform and payload, divided into service module, propulsion module, and payload module (see Figure 16 [Figure 16: see original paper] [21]). The platform comprises structure, thermal control, power, TT&C, attitude/orbit control, and data management subsystems, providing power, communications, and thermal environment for the payload. The payload is a high-imaging-quality, high-stability, low-distortion optical telescope including optics, focal plane, temperature controller, frequency-stabilized laser, and data processing system. Addressing key technical challenges, CHES achieves high-stability attitude control and high-precision thermal control. System-level feasibility analysis provides a solid foundation for subsequent CHES project development. Table 4 [21] details satellite technical specifications.

CHES uses three-axis stabilized attitude control with inertial pointing and maneuvering capabilities. Twelve µN-level cold gas micro-thrusters provide high-stability attitude control during observations, twelve 20 mN cold gas thrusters handle orbit insertion and momentum unloading, reaction wheels perform attitude maneuvers and routine control, and two 40 mN Hall thrusters maintain orbit. Power uses solar arrays and Li-ion batteries: fixed solar panels on the -x and ±y faces with total area $ 11.8m^{2}$ provide 1,493 W end-of-life power, with 120 Ah batteries meeting requirements. X-band integrated TT&C and data transmission with phased-array antenna provides 20 Mbit/s data rate and 1 Tbit solid-state storage.

Thermal design uses active and passive control tailored to payload requirements and the special thermal environment at Sun-Earth L2. The satellite operates in L2 Halo orbit for 5 years. The launch vehicle injects the satellite into a parking orbit (200 km × 35,958 km) at 28.5° inclination, then orbital maneuvers place it into the transfer orbit. After ~117 days, small maneuvers insert it into the mission orbit (see Figure 17 [Figure 17: see original paper] [21]).

To ensure effective data reception, data transmission rates are designed with multiple levels: 20, 10, 5 Mbit/s and 800 kbit/s. Adding 10, 5 Mbit/s and 800 kbit/s levels enables compatibility with 25 m Urumqi, 18 m Qingdao/Kashgar, and 12 m Chinese Academy of Sciences remote sensing antennas, reducing ground station requirements and improving data reception stability and reliability.

4 Key Technologies

Three key technologies are critical: micropixel star separation measurement, low-distortion large-field telescope optical system, and high-stability attitude control with high-precision thermal control.

4.1 Micropixel Star Separation Measurement Technology

This technology is key for detecting nearby habitable zone terrestrial planets using space astrometry. Based on external laser interferometry for detector pixel characterization calibration, it achieves ~10^{-5} pixel-level star separation measurement precision.

High-frequency-stability lasers produce coherent light via heterodyne methods. Fiber output creates interference fringes; different baseline directions produce different fringe orientations, enabling pixel characterization retrieval from fringes for star image separation measurement. Fiber-coupled LED white light sources reflected by spherical mirrors simulate star images for micropixel separation measurement experiments. CMOS cameras collect fringe and star image data for detector calibration and separation calculations.

The experimental apparatus comprises six subsystems: high-stability differential frequency laser interferometry, pseudo-star source simulation, image acquisition and analysis, precision vibration isolation support, vacuum test chamber, and stray light suppression. System design is shown in Figure 18 [Figure 18: see original paper] and technical flow in Figure 19 [Figure 19: see original paper].

The micropixel star separation measurement apparatus is China' s first such system, providing technical assurance for nearby habitable planet detection and other space missions. Innovations include high-stability multi-modal dynamic interference fringe generation and global pixel characterization calibration of large-area scientific CMOS sensors via fast Fourier transform-based iterative optimization phase retrieval algorithms.

4.2 Low-Distortion Large-Field Telescope Optical System Technology

Since CHES uses narrow-angle astrometry measuring relative position changes between target and reference stars, optical system stability is paramount. Differences in optical and structural materials, temperature variations, and external vibrations cause changes in telescope interior orientation elements, creating stability errors. The telescope employs on-orbit distortion calibration technology to measure and calibrate stability, with requirements for temperature and pointing stability implemented through satellite platform key technology development. This technology includes mirror grinding, low-stress mounting, structural stability design, lightweighting, assembly, and testing.

To address small optical distortion changes from attitude adjustments or temperature variations, a distortion gradient-based on-orbit calibration method reconstructs distortion distribution (see Figure 20 [Figure 20: see original paper]). This method doesn’ t use reference star positions from existing catalogs but exploits the fact that reference and target stars remain essentially fixed (angular displacement <0.1 as) during single observations (~2 hours). By comparing image motion between central and edge fields using telescope pointing instability, distortion gradients at star positions are obtained, then used to reconstruct full-field distortion distribution, enabling high-precision measurement of telescope optical distortion [95].

Notably, structural stability design, lightweighting, and low-stress control correlate strongly with telescope aperture. Larger aperture and architecture demand higher structural stability than scaled models. Simulation analysis shows scaled model stability requirements (e.g., temperature, vibration) scale proportionally, allowing experimental parameters to be scaled accordingly for validation. The research team has extensive experience in low-stress mounting and surface deformation control for large telescope mirrors, having successfully developed multiple meter-class ground- and space-based telescopes with excellent in-orbit performance, enabling direct technology inheritance for the full-aperture telescope.

4.3 High-Stability Attitude Control and High-Precision Thermal Control

4.3.1 High-Stability Attitude Control Payload observation requirements demand pointing precision better than 0.07 and stability of 0.0036 /0.02 s, imposing stringent attitude control requirements. High-stability attitude control technology development includes high-precision guide star sensor attitude determination and high-precision thruster attitude stabilization. The system comprises guide star sensors, high-precision fiber optic gyros, µN-level attitude control thrusters, high-precision attitude determination software, and high-precision micro-thrust phase plane control technology (see Figure 21 [Figure 21: see original paper]).

Building on µN-level thruster development and high-stability control algorithms for Taiji satellite, simulations show that based on CHES telescope measurement precision, final stability control precision exceeds 3$\times10^{-5}$ (°) $\cdot$ s^{-1}, with 0.0022 drift over 20 ms and 0.0108 drift over 100 s at 10 Hz control frequency. Technology development completed algorithm development and simulation verification meeting requirements. A ground FGS image simulator was developed for high-precision attitude control hardware-in-the-loop testing, achieving technology readiness level 5.

4.3.2 High-Precision Thermal Control CHES' s star separation measurement algorithm requires optical imaging quality across the full field better than $\lambda/12$. In space, primary error sources affecting imaging quality are thermal and vibrational. Temperature fluctuations cause optical and structural material expansion/contraction, leading to mirror deformation and relative position changes that degrade imaging quality. The payload optical system temperature must be maintained within A$\pm$0.045°C during each 2-hour observation (where A ranges 15–25°C), requiring specialized thermal control design with 45 mK stability.

High-precision thermal control characteristics include: extremely high stability requirements, large aperture entrance heat loss compensation, and interference from high-power detectors. The 100 W focal plane heat dissipation from mosaic CMOS detectors, mounted on the telescope main structure, creates significant thermal control challenges.

The thermal control approach leverages the Sun-Earth L2 orbit (1.5$\times10^{6}$ km from Earth), where only solar heat flux is significant, with negligible Earth infrared and albedo effects. The telescope uses anti-Sun pointing, with sunshades and satellite platform blocking most solar radiation to provide a stable thermal environment (see Figure 22 [Figure 22: see original paper]). Telescope optical system temperature simulations show 15–21°C range. Detailed thermal control design and simulation analysis verified feasibility, meeting requirements. Technology readiness levels for sunshield, high-precision temperature measurement, control algorithms, and high-stability thermal control subsystems have reached level 5 or higher.

Conclusion

Supported by the Chinese Academy of Sciences Strategic Priority Program on Space Science (Phase II) background model project, CHES has achieved significant results: refined scientific objectives; breakthroughs in low-distortion, large-field, high-quality space telescope optical systems; 10^{-5} pixel-level star separation measurement; and high-stability attitude control and thermal control solutions. These key technologies have reached readiness level 5, providing important support for subsequent CHES project approval.

CHES is expected to achieve the first discovery of habitable zone terrestrial planets around nearby Sun-like stars—a major breakthrough from zero to one—and discover ~50 Earth-like planets or super-Earths while precisely characterizing masses of compact objects like black holes. As China' s first high-precision astrometry space science mission, CHES will improve international astrometric precision by an order of magnitude, greatly enhancing China's influence in fundamental astronomy and planetary science, and promoting leapfrog development in space science exploration technology.

References

[1] MAYOR M, QUELOZ D. A Jupiter-mass companion to a solar-type star[J]. Nature, 1995, 378(6555): 355-359

[2] Exoplanet Team. The Extrasolar Planets Encyclopaedia [OL]. [1995-02]. http://www.exoplanet.eu/

[3] National Academies of Sciences・Engineering・Medicine, Division on Engineering and Physical Sciences, Space Studies Board, et al. Pathways to Discovery in Astronomy and Astrophysics for the 2020s[R]. Washington: The National Academies Press, 2023

[4] European Space Agency (ESA). Voyage 2050 Long-Term Planning of the ESA Science Programme White Papers[OL] (2023-02-07). https://www.cosmos.esa.int/web/voyage-2050/white-papers

[5] Project team of Research on the Development Strategy of Chinese Disciplines and Frontier Fields (2021-2035). Chinese Astronomy 2035 Development Strategy[M]. Beijing: Science Press, 2023: 8

[6] WU Ji, WANG Chi, FAN Quanlin. Review on 11 years of implementation of Strategic Priority Program (SPP) on space science and its prospect[J]. Bulletin of Chinese Academy of Sciences, 2022, 37(8): 1019-1030

[7] The State Council Information Office of the People's Republic of China. 2021 China's aerospace white paper[OL]. [2022-01]. https://www.gov.cn/zhengce/2022-01/28/content_{5670920}.htm

[8] LINDEGREN L, PERRYMAN M A C. GAIA: global astrometric interferometer for astrophysics[J]. Astronomy and Astrophysics Supplement Series, 1996, 116(3): 579-595

[9] CLEMENTINI G, RIPEPI V, LECCIA S, et al. Gaia Data Release 1. The Cepheid and RR Lyrae star pipeline and its application to the south ecliptic pole region[J]. Astronomy & Astrophysics, 2016, 595: A133

[10] KOCH D G, BORUCKI W J, WEBSTER L, et al. Kepler: a space mission to detect Earth-class exoplanets[C]//Proceedings of SPIE 3356, Space Telescopes and Instruments V. Kona: SPIE, 1998: 599-607

[11] BORUCKI W J, KOCH D G, BASRI G, et al. Characteristics of planetary candidates observed by Kepler. II. Analysis of the first four months of data[J]. The Astrophysical Journal, 2011, 736(1): 19

[12] RICKER G R, WINN J N, VANDERSPEK R, et al. Transiting exoplanet survey satellite[J]. Journal of Astronomical Telescopes, Instruments, and Systems, 2015, 1(1): 014003

[13] BROEG C, FORTIER A, EHRENREICH D, et al. CHEOPS: A transit photometry mission for ESA' s small mission programme[J]. EPJ Web of Conferences, 2013, 47: 03005

[14] GARDNER J P, MATHER J C, CLAMPIN M, et al. The James Webb space telescope[J]. Space Science Reviews, 2006, 123(4): 485-606
[15] GAO Ming, ZHAO Guangheng, GU Yidong. Space science and application mission in China' s space station[J]. Bulletin of Chinese Academy of Sciences, 2015, 30(6): 721-732
[16] LAUREIJS R, AMIAUX J, ARDUINI S, et al. Euclid definition study report[OL]. arXiv preprint arXiv: 1110.3193, 2011
[17] GREEN J, SCHECHTER P, BALTAY C, et al. Wide-Field InfraRed Survey Telescope (WFIRST) final report[OL]. arXiv preprint arXiv: 1208.4012, 2012
[18] RAGAZZONI R, MAGRIN D, RAUER H, et al. PLATO: a multiple telescope spacecraft for exo-planets hunting[C]//Proceedings of SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave. Edinburgh: SPIE, 2016: 990428
[19] TINETTI G, DROSSART P, ECCLESTON P, et al. The science of ARIEL (atmospheric remote-sensing infrared exoplanet large-survey)[C]//Proceedings of SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave. Edinburgh: SPIE, 2016: 99041X
[20] The LUVOIR Team. The LUVOIR mission concept study final report[OL]. arXiv preprint arXiv: 1912.06219, 2019
[21] JI J H, LI H T, ZHANG J B, et al. CHES: a space-borne astrometric mission for the detection of habitable planets of the nearby solar-type stars[J]. Research in Astronomy and Astrophysics, 2022, 22(7): 072003
[22] Closeby habitable exoplanet survey[OL]. [2023-04]. http://www.ps.pmo.cas.cn/CHES/
[23] GE J, ZHANG H, ZANG W C, et al. ET white paper: to find the first Earth 2.0[OL]. arXiv preprint arXiv: 2206.06693, 2022
[24] ZHOU Jilin, XIE Jiwei, GE Jian, et al. Progress on exoplanet detection and research in space[J]. Chinese Journal of Space Science, 2024, 44(1): 5-18
[25] WANG W, ZHAI M, ZHAO G, et al. The Tianlin mission: A 6-m space telescope to probe into habitable worlds and the universe[J]. Research in Astronomy and Astrophysics, 2023, 23(9): 095028
[26] KASTING J F, WHITMIRE D P, REYNOLDS R T. Habitable zones around main sequence stars[J]. Icarus, 1993, 101(1): 108-128
[27] ANGLADA-ESCUDÉ G, AMADO P J, BARNES J, et al. A terrestrial planet candidate in a temperate orbit around Proxima Centauri[J]. Nature, 2016, 536(7617): 437-440
[28] GILLON M, TRIAUD A H M J, DEMORY B O, et al. Seven temperate terrestrial planets around the nearby ultracool dwarf TRAPPIST-1[J]. Nature, 2017, 542(7642): 456-460
[29] BRYSON S, COUGHLIN J, BATALHA N M, et al. A probabilistic approach to kepler completeness and reliability for exoplanet occurrence rates[J]. The Astronomical Journal, 2020, 159(6): 279
[30] CHEN G, PALLÉ E, WELBANKS L, et al. The GTC exoplanet transit spectroscopy survey. IX. Detection of haze, Na, K, and Li in the super-Neptune WASP-127b[J]. Astronomy & Astrophysics, 2018, 616: A145
[31] YAN F, HENNING T. An extended hydrogen envelope of the extremely

hot giant exoplanet KELT-9b[J]. Nature Astronomy, 2018, 2(9): 714-718
[32] YAN F, CASASAYAS-BARRIS N, MOLAVERDIKHANI K, et al. Ionized calcium in the atmospheres of two ultra-hot exoplanets WASP-33b and KELT-9b[J]. Astronomy & Astrophysics, 2019, 632: A69
[33] CHEN G, CASASAYAS-BARRIS N, PALLÉ E, et al. Detection of Na, K, and Hα absorption in the atmosphere of WASP-52b using ESPRESSO[J]. Astronomy & Astrophysics, 2020, 635: A171
[34] JIANG C, CHEN G, MURGAS F, et al. Confirmation of TiO absorption and tentative detection of MgH and CrH in the atmosphere of HAT-P-41b[OL]. arXiv preprint arXiv: 2311.13840, 2023
[35] YANG Y H, CHEN G, WANG S H, et al. High-resolution Transmission Spectroscopy of Ultrahot Jupiter WASP-33b with NEID[J]. The Astronomical Journal, 2024, 167(1): 36
[36] JWST Transiting Exoplanet Community Early Release Science Team. Identification of carbon dioxide in an exoplanet atmosphere[J]. Nature, 2023, 614(7949): 649-652
[37] FEINSTEIN A D, RADICA M, WELBANKS L, et al. Early release science of the exoplanet WASP-39b with JWST NIRISS[J]. Nature, 2023, 614(7949): 670-675
[38] ALDERSON L, WAKEFORD H R, ALAM M K, et al. Early release science of the exoplanet WASP-39b with JWST NIRSpec G395H[J]. Nature, 2023, 614(7949): 664-669
[39] RUSTAMKULOV Z, SING D K, MUKHERJEE S, et al. Early release science of the exoplanet WASP-39b with JWST NIRSpec PRISM[J]. Nature, 2023, 614(7949): 659-663
[40] AHRER E M, STEVENSON K B, MANSFIELD M, et al. Early release science of the exoplanet WASP-39b with JWST NIRCam[J]. Nature, 2023, 614(7949): 653-658
[41] TSAI S M, LEE E K H, POWELL D, et al. Photochemically produced SO_2 in the atmosphere of WASP-39b[J]. Nature, 2023, 617(7961): 483-487
[42] DYREK A, MIN M, DECIN L, et al. SO_2, silicate clouds, but no CH_4 detected in a warm neptune[J]. Nature, 2024, 625(7993): 51-54
[43] GRANT D, LEWIS N K, WAKEFORD H R, et al. JWST-TST DREAMS: quartz clouds in the atmosphere of WASP-17b[J]. The Astrophysical Journal Letters, 2023, 956(2): L34
[44] MADHUSUDHAN N, SARKAR S, CONSTANTINOU S, et al. Carbon-bearing molecules in a possible Hycean atmosphere[J]. The Astrophysical Journal Letters, 2023, 956(1): L13
[45] LIM O, BENNEKE B, DOYON R, et al. Atmospheric reconnaissance of TRAPPIST-1 b with JWST/NIRISS: Evidence for strong stellar contamination in the transmission spectra[J]. The Astrophysical Journal Letters, 2023, 955(1): L22
[46] GREENE T P, BELL T J, DUCROT E, et al. Thermal emission from the Earth-sized exoplanet TRAPPIST-1 b using JWST[J]. Nature, 2023, 618(7963): 39-42
[47] ZIEBA S, KREIDBERG L, DUCROT E, et al. No thick carbon dioxide

atmosphere on the rocky exoplanet TRAPPIST-1 c[J]. Nature, 2023, 620(7975): 746-749
[48] ZAIN P S, DE ELÍA G C, RONCO M P, et al. Planetary formation and water delivery in the habitable zone around solar-type stars in different dynamical environments[J]. Astronomy & Astrophysics, 2018, 609: A76
[49] ZHANG X. Atmospheric regimes and trends on exoplanets and brown dwarfs[J]. Research in Astronomy and Astrophysics, 2020, 20(7): 99
[50] HUANG P H, ISELLA A, LI H, et al. Identifying anticyclonic vortex features produced by the rossby wave instability in protoplanetary disks[J]. The Astrophysical Journal, 2018, 867(1): 3
[51] HUANG P H, DONG R B, LI H, et al. The observability of vortex-driven spiral arms in protoplanetary disks: basic spiral properties[J]. The Astrophysical Journal Letters, 2019, 883(2): L39
[52] HUANG P H, LI H, ISELLA A, et al. Meso-scale instability triggered by dust feedback in dusty rings: origin and observational implications[J]. The Astrophysical Journal, 2020, 893(2): 89
[53] SNELLEN I, DE KOK R, BIRKBY J L, et al. Combining high-dispersion spectroscopy with high contrast imaging: probing rocky planets around our nearest neighbors[J]. Astronomy & Astrophysics, 2015, 576: A59
[54] WANG J, MAWET D, RUANE G, et al. Observing exoplanets with high dispersion coronagraphy. I. The scientific potential of current and next-generation large ground and space telescopes[J]. The Astronomical Journal, 2017, 153(4): 183
[55] SKIDMORE W, TMT International Science Development Teams, TNT Science Advisory Committee. Thirty meter telescope detailed science case: 2015[J]. Research in Astronomy and Astrophysics, 2015, 15(12): 1945-2140
[56] KASPER M, CERPA URRA N, PATHAK P, et al. PCS –A Roadmap for Exoearth Imaging with the ELT[J]. The Messenger, 2021, 182: 38-43
[57] KALTENEGGER L. How to characterize habitable worlds and signs of life[J]. Annual Review of Astronomy and Astrophysics, 2017, 55: 433-485
[58] OWEN J E, WU Y Q. Kepler planets: a tale of evaporation[J]. The Astrophysical Journal, 2013, 775(2): 105
[59] FULTON B J, PETIGURA E A, HOWARD A W, et al. The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets[J]. The Astronomical Journal, 2017, 154(3): 109
[60] JIN S, MORDASINI C. Compositional imprints in density-distance-time: a rocky composition for close-in low-mass exoplanets from the location of the valley of evaporation[J]. The Astrophysical Journal, 2018, 853(2): 163
[61] PAN M R, WANG S, JI J H. Near mean motion resonance of terrestrial planet pair induced by giant planet: application to Kepler-68 system[J]. Monthly Notices of the Royal Astronomical Society, 2020, 496(4): 4688-4699
[62] WANG S, JI J H. Near mean-motion resonances in the system observed by Kepler: affected by mass accretion and type I migration[J]. The Astronomical Journal, 2017, 154(6): 236
[63] WANG S, LIN D N C, ZHENG X C, et al. Departure from the exact location of mean motion resonances induced by the gas disk in systems observed

by Kepler[J]. The Astronomical Journal, 2021, 161(2): 77
[64] PAN M R, WANG S, JI J H. The terrestrial planet formation around M dwarfs: in situ, inward migration, or reversed migration[J]. Monthly Notices of the Royal Astronomical Society, 2022, 510(3): 4134-4145
[65] HUANG X M, JI J H. Extremely inclined orbit of the S-type planet γ Cep Ab induced by the eccentric Kozai-Lidov mechanism[J]. The Astronomical Journal, 2022, 164(5): 177
[66] HUANG X M, JI J H, LIU S F, et al. Evolution of planetary obliquity: the eccentric Kozai-Lidov mechanism coupled with tide[J]. The Astrophysical Journal, 2023, 956(1): 45
[67] BORUCKI W J, KOCH D, BASRI G, et al. Kepler planet-detection mission: introduction and first results[J]. Science, 2010, 327(5968): 977-980
[68] BATALHA N M, ROWE J F, BRYSON S T, et al. Planetary candidates observed by Kepler. III. Analysis of the first 16 months of data[J]. The Astrophysical Journal Supplement Series, 2013, 204(2): 24
[69] TRAUB W A. Kepler exoplanets: a new method of population analysis[OL]. arXiv preprint arXiv: 1605.02255, 2016
[70] GAUDI B S, SEAGER S, MENNESSON B, et al. The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Final Report[OL]. arXiv preprint arXiv: 2001.06683, 2020
[71] CHIANG E, LAUGHLIN G. The minimum-mass extrasolar nebula: in situ formation of close-in super-Earths[J]. Monthly Notices of the Royal Astronomical Society, 2013, 431(4): 3444-3455
[72] HUANG P H, ISELLA A, LI H, et al. Identifying anticyclonic vortex features produced by the rossby wave instability in protoplanetary disks[J]. The Astrophysical Journal, 2018, 867(1): 3
[73] JIN S, LI S T, ISELLA A, et al. Modeling dust emission of HL TAU disk based on planet-disk interactions[J]. The Astrophysical Journal, 2016, 818(1): 76
[74] JI J H, KINOSHITA H, LIU L, et al. Could the 55 Cancri planetary system really Be in the 3:1 mean motion resonance[J]. The Astrophysical Journal, 2003, 585(2): L139-L142
[75] JI J H, LI G Y, LIU L. The dynamical simulations of the planets orbiting GJ 876[J]. The Astrophysical Journal, 2002, 572(2): 1041-1047
[76] JI J H, KINOSHITA H, LIU L, et al. The secular evolution and dynamical architecture of the Neptunian triplet planetary system HD 69830[J]. The Astrophysical Journal, 2007, 657(2): 1092-1097
[77] WANG S, JI J H, ZHOU J L. Predicting the configuration of a planetary system: KOI-152 observed by Kepler[J]. The Astrophysical Journal, 2012, 753(2): 170
[78] WANG S, JI J H. Near 3:2 and 2:1 mean motion resonance formation in the systems observed by Kepler[J]. The Astrophysical Journal, 2014, 795(1): 85
[79] WANG S, LIN D N C, ZHENG X C, et al. Departure from the exact location of mean motion resonances induced by the gas disk in systems observed by Kepler[J]. The Astronomical Journal, 2021, 161(2): 77
[80] PAN M R, WANG S, JI J H. The terrestrial planet formation around M

dwarfs: in situ, inward migration, or reversed migration[J]. Monthly Notices of the Royal Astronomical Society, 2022, 510(3): 4134-4145
[81] HUANG X M, JI J H. Extremely inclined orbit of the S-type planet γ Cep Ab induced by the eccentric Kozai-Lidov mechanism[J]. The Astronomical Journal, 2022, 164(5): 177
[82] HUANG X M, JI J H, LIU S F, et al. Evolution of planetary obliquity: the eccentric Kozai-Lidov mechanism coupled with tide[J]. The Astrophysical Journal, 2023, 956(1): 45
[83] BORUCKI W J, KOCH D, BASRI G, et al. Kepler planet-detection mission: introduction and first results[J]. Science, 2010, 327(5968): 977-980
[84] BATALHA N M, ROWE J F, BRYSON S T, et al. Planetary candidates observed by Kepler. III. Analysis of the first 16 months of data[J]. The Astrophysical Journal Supplement Series, 2013, 204(2): 24
[85] The Theia Collaboration. Theia: faint objects in motion or the new astrometry frontier[OL]. arXiv preprint arXiv: 1707.01348, 2017
[86] NEMATI B, SHAO M, GONZALEZ G, et al. The Micro-Arcsecond astrometry small satellite: MASS[C]//Proceedings of SPIE 11443, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave. SPIE, 2020: 114430O
[87] BAO Chunhui, JI Jianghui, TAN Dongjie, et al. Simulation observation and orbital retrieval based on CHES satellite[J]. Acta Astronomica Sinica, 2023, accepted
[88] JI J H, TAN D J, BAO C H, et al. PyMsOfa: A python package for the Standards of Fundamental Astronomy (SOFA) service[J]. Research in Astronomy and Astrophysics, 2023, 23(12): 125015
[89] BAO C H, JI J H, TAN D J, et al. Closeby Habitable Exoplanet Survey (CHES). I. Astrometric noise and planetary detection efficiency due to stellar spots and faculae[J]. The Astronomical Journal, 2024, accepted
[90] TAN D J, JI J H, BAO C H, et al. Closeby Habitable Exoplanet Survey (CHES). II. An observation strategy for the target stars[J]. The Astronomical Journal, 2024, submitted
[91] SUN Y H, FANG L, ZHANG H. On-orbit calibration method based on distortion gradient reconstruction distortion[J]. Semiconductor Optoelectronics, 2022, 43(4): 802-807

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

Source: ChinaXiv —Machine translation. Verify with original.