Opportunities and Challenges for Exoplanet Atmospheric Research in the JWST Era: Postprint

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Abstract

To date, over 5,000 exoplanets have been detected, and the field of exoplanet research is transitioning from discovery surveys to detailed characterization. Over the past two decades, through atmospheric characterization of approximately 100 exoplanets, a preliminary framework has been established for atmospheric detection methods for transiting and directly imaged planets, as well as for a series of atmospheric spectral forward modeling, retrieval methods, and atmospheric theory. The James Webb Space Telescope (JWST) possesses unprecedented spectroscopic capabilities from near- to mid-infrared, and its high-quality data will drive transformative developments in atmospheric theory and models. Scientific results from the first cycle of observations have demonstrated JWST' s capabilities for atmospheric characterization of transiting and directly imaged planets, as well as its preliminary constraints on the atmospheres of habitable zone planets. Detailed studies of exoplanet atmospheres in the JWST era have already shown great promise, and combined with ARIEL—which will possess atmospheric survey capabilities—and large-aperture ground-based telescopes with adaptive optics, both to be commissioned within the next five years, will reveal the diversity of exoplanet atmospheres at a deeper level.

Full Text

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Opportunities and Challenges in the Study of Exoplanetary Atmospheres during the JWST Era

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Abstract

Currently, more than 5,000 exoplanets have been detected, and the field of exoplanetary science is transitioning from discovery and census to detailed characterization. Over the past two decades, atmospheric characterization of approximately 100 exoplanets has led to the preliminary establishment of detection methods for transiting and directly imaged planets, along with a foundational framework for atmospheric spectral forward modeling, retrieval methods, and atmospheric theory. The James Webb Space Telescope (JWST) possesses unprecedented near-to-mid-infrared spectroscopic capabilities, and its high-quality data will drive a transformative leap forward in atmospheric theory and models. Scientific results from the first cycle of observations have already demonstrated JWST' s capacity to characterize the atmospheres of both transiting and directly imaged planets, as well as its ability to place initial constraints on the atmospheres of potentially habitable planets. The era of refined exoplanet atmospheric study with JWST has begun, and when combined with upcoming missions such as ARIEL and large-aperture adaptive-optics ground-based telescopes within the next five years, it will reveal the diversity of exoplanetary atmospheres at an unprecedented depth.

Keywords: exoplanets; planetary atmosphere; space-based observation; spectroscopic observation
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Introduction

In 1995, Mayor and Queloz [1] discovered the first exoplanet orbiting a Sun-like star, 51 Pegasi b, ushering in a golden age of exoplanet exploration [2], for which they were awarded the 2019 Nobel Prize in Physics. As an increasing number of ground- and space-based exoplanet search programs have been initiated, over 5,000 exoplanets have been discovered as of April 2023, making exoplanetary science one of the most active fields in astronomy. However, since the first detection of an exoplanet atmosphere in 2002 [3], astronomers have conducted spectroscopic observations and atmospheric characterization for only about one hundred planets.

At this number, the existing sample of exoplanet atmospheres is incomplete, with biases arising from two aspects: the incompleteness of currently discovered planet types and the selectivity of atmospheric characterization methods. The latter fundamentally inherits the detection capability limitations of planet search methods, as exoplanet atmospheric detection methods are closely linked to the methods used to discover the planets. [Figure 1: see original paper] shows the distribution of orbital periods and planetary masses for exoplanets discovered by different methods, with dark purple circles marking planets that have undergone atmospheric characterization. Currently, characterized planets have been discovered primarily through the transit and direct imaging methods. Consequently, traditional exoplanet atmospheric detection techniques can be divided into two categories: observations of transiting systems and observations of directly imaged planets, which are also the two approaches JWST employs for exoplanet atmospheric research.

Transiting planets are characterized by orbital planes that are nearly aligned with the line of sight. When a planet passes between its host star and the observer, the resulting photometric depth of the transit is $D = (R_p/R_s)^2$, where R_p is the planetary radius and R_s is the stellar radius. Additionally, the transit probability P_{tr} is constrained by the orbital semi-major axis a, with $P_{tr} \approx R_s/a$. Therefore, the transit method tends to detect hot Jupiters with short periods and large radii.

Further study of the light curve during transit events reveals that transit depths at different wavelengths reflect possible atmospheric features. This is because planetary atmospheres are not completely transparent, and atmospheric constituents absorb stellar photons differently at various wavelengths, making the photometric depth a function of wavelength. By comparing the stellar spectrum outside of transit with that during transit, one can obtain the planetary atmosphere' s absorption of stellar radiation at different wavelengths, i.e., the transmission spectrum. Atmospheric thickness affects the signal strength in transmission spectra, typically measured by the atmospheric scale height $H = \frac{k_B T}{mg}$, where k_B is the Boltzmann constant, and T, m, and g are the planet' s equilibrium temperature, mean atmospheric molecular weight, and surface gravity, respectively. Consequently, transmission spectroscopy is more effective for characterizing hot Jupiters with high temperatures and lower mean molecular weights (H- or He-dominated). To date, transit transmission spectroscopy has been the most successful and effective method for atmospheric characterization, particularly for atmospheric chemical composition. Over one hundred planets have been observed with transit transmission spectroscopy, with more than 20 planets having high-precision, multi-band spectral data [4].

Transmission spectra provide absorption features, while emission information from the planetary surface can be obtained through secondary eclipse and phase curve observations for transiting systems. According to blackbody radiation laws, the planet-to-star contrast ratio is stronger in the infrared than in the ultraviolet and optical bands. The infrared thermal emission ratio at a specific observing frequency ν also depends on the brightness temperature ratio and radius ratio at that frequency, $F_p(\nu)/F_s(\nu) \approx (R_p/R_s)^2(T_p(\nu)/T_s(\nu))^4$. Massive hot Jupiters around cool, faint stars have relatively larger brightness temperature ratios and radius ratios, resulting in stronger signals in their secondary eclipse emission spectra and phase curves.

Similar to transits, when a planet passes behind its host star, the stellar light blocks the planet' s emitted and reflected light, causing a photometric dip in the light curve. This is distinguished from the primary transit (or primary eclipse) and is generally called a secondary eclipse or secondary occultation. Due to the high contrast between stellar and planetary emission spectra, typical secondary eclipse signals are 1–2 orders of magnitude smaller than transit signals. By comparing spectra before and after the star blocks the planet, one can obtain the emission spectrum of the planet' s dayside (the side facing the host star), providing temperature information and enabling detection of possible atmospheric chemical constituents.

Phase curves measure the variation in emission flux from the star-planet system over a longer temporal baseline as a function of orbital phase. This method provides important constraints on the temperature distribution of tidally locked hot Jupiter atmospheres.

With upgrades to high-stability, high-resolution spectrographs on ground-based telescopes, high-resolution Doppler spectroscopy has emerged as a promising new technique for atmospheric studies [6]. This method is conceptually related to the radial velocity method used for planet detection. The radial velocity method measures the Doppler effect caused by the star' s motion around the barycenter due to gravitational interaction with the planet. The stellar radial velocity amplitude is $K_\star = v_\star \sin i$. However, during this orbital motion, a typical hot Jupiter' s radial velocity is about 1×10^3 times faster than the star' s, causing the planetary spectrum to exhibit large periodic Doppler shifts within the combined spectrum. By leveraging high-resolution spectrographs on large ground-based telescopes, one can extract the planet' s intrinsic emission line signals. Moreover, while the radial velocity amplitude is modulated by the orbital inclination $\sin i$, it does not require the strict alignment of the orbital plane with the line of sight as transit methods do. Thus, high-resolution Doppler spectroscopy can also study the atmospheres of non-transiting systems, further expanding the sample of exoplanet atmospheres available for research.

Direct imaging searches for exoplanets occupy a unique niche in the current exoplanet landscape, providing a distinct sample of wide-orbital-separation planets. Approximately 20 planets have been detected through direct imaging to date. For directly imaged exoplanets, the greatest challenges are the inner working angle limitation and the need for high-contrast imaging. Consequently, this method more easily detects systems with faint host stars, planets at large separations, and young planets.

In terms of sample distribution by planet type, exoplanet atmospheric detection shares similarities with exoplanet searches. Transiting hot Jupiters have been studied most extensively, while the directly imaged planet population remains relatively distinct. As detection capabilities improve, the target objects have gradually expanded to smaller, cooler Neptune-like planets and super-Earths, ultimately enabling atmospheric detection of Earth-like planets. Studies of representative hot Jupiters have confirmed that the synergistic use of multiple detection methods, multi-wavelength observations, and multi-phase observations enables more refined and accurate characterization of distant exoplanet atmospheres, from one-dimensional to three-dimensional atmospheric structures, from qualitative measurements of major atmospheric constituents or single characteristic molecules to quantitative constraints on elemental abundances, and from time-averaged descriptions to characterizations with temporal variability and phase differences.

Launched on December 25, 2021, the James Webb Space Telescope (JWST) is the largest space telescope ever built. As a revolutionary space telescope, one of its six scientific objectives is planetary systems and the origins of life. With a 6.5-meter diameter aperture and operating temperature as low as 35 K at the Sun-Earth L2 Lagrange point for long-term stable observations, JWST has the capability to study exoplanet atmospheres across a much larger parameter space while also enabling more precise atmospheric characterization of known planets. For instance, with its unprecedented high-resolution, high signal-to-noise infrared spectroscopic capabilities, JWST will "see" the atmospheres of planets as small as Earth mass and richer molecular absorption features in the near- to mid-infrared bands, telling us more about atmospheres beyond the Solar System and perhaps even finding the building blocks of life beyond our solar system.

[Figure 2: see original paper] shows a schematic diagram of exoplanet atmospheric detection methods. Section 2 of this paper primarily introduces the history and progress of exoplanet atmospheric research before JWST' s launch; Section 3 describes JWST' s detection capabilities for exoplanet atmospheres; Section 4 discusses the challenges and innovations in theory, models, and methods during the JWST era; Section 5 presents the scientific results released from the first cycle (Cycle 1) of observations since JWST' s launch; and finally, we summarize and look forward to future detection programs.

2.1 History of Atmospheric Detection

Exoplanet atmospheric detection before JWST can be divided into two phases based on the capabilities and characteristics of the instruments used for exoplanet research. The Hubble Space Telescope (HST) and the Spitzer Space Telescope were the two major space-based instruments for exoplanet atmospheric detection prior to JWST.

In the first decade of the 21st century, early photometric and sparse data came from HST' s NICMOS (Near Infrared Camera and Multi-Object Spectrometer), STIS (Space Telescope Imaging Spectrograph), and Spitzer photometric instruments. Due to observational selection effects, atmospheric research focused on transiting planets, with many breakthrough studies centered on two typical hot Jupiters: HD 189733 b and HD 209458 b [7–9]. The first detections of exoplanet atmospheres were achieved during planetary transits. In 2002, HST/STIS with visible-band spectroscopic capability detected sodium atomic features in the transmission spectrum of HD 209458 b [3], marking the first empirical evidence for an atmosphere beyond our Solar System. During the same period, astronomers used STIS to detect (15 ± 4)% absorption of the stellar Lyman-α line in the UV band during HD 209458 b' s transit [10]. The planet-to-star contrast ratio is greater in the infrared than in the visible and UV bands, but still requires about 10^{-4} precision for typical hot Jupiters. The first infrared transit measurements of exoplanet atmospheres were achieved through Spitzer and HST' s NICMOS instrument [7, 8]. Since the detection instruments in this phase were not specifically designed for exoplanet research, photometric precision limited atmospheric detection levels to about 1σ. For transiting systems, the geometric relationship during secondary eclipse also provided an effective pathway for atmospheric detection under limited instrumental constraints. As mentioned earlier, secondary eclipse signals are weaker than transit signals and require infrared observations, with Spitzer' s broadband photometry being the primary tool [11]. Spitzer' s Infrared Spectrograph (IRS) observed a significant secondary eclipse signal (32σ) for HD 189733 b at 16 μm [12]. Knutson et al. [13] used Spitzer' s Infrared Array Camera (IRAC) 8 μm channel to measure photometric variations between primary transit and secondary eclipse at different orbital phases, producing the first two-dimensional temperature distribution map of an exoplanet atmosphere. During this decade, exoplanet atmospheric researchers conducted many pioneering observational and theoretical studies on the two typical transiting hot Jupiters HD 189733 b and HD 209458 b, pushing space-based detectors to their limits to achieve preliminary detection of molecular spectral features, day-night temperature gradients, and vertical atmospheric structure constraints for transiting hot Jupiters [14].

Direct imaging detection of exoplanets with ground-based telescopes also began during this period. In 2004, the European Very Large Telescope (VLT) achieved the first direct imaging of an exoplanet, obtaining infrared imaging and spectroscopic observations of 2M1207 b [15]. In 2008, the Keck Observatory discovered a multi-planet system around the main-sequence star HR 8799 through high-contrast observations [16].

In the second decade, dedicated space missions for exoplanet science emerged, such as the Kepler Space Mission [17] and its follow-up missions K2 [18], TESS [19], and CHEOPS [20]. However, these missions focused more on discovering more exoplanets (candidates) using the transit method or more precisely determining planetary orbital and physical parameters, and thus were not equipped with spectrometers for exoplanet atmospheric research.

In 2009, Spitzer' s coolant was exhausted, transitioning to a "warm" mission phase with only the 3.6 μm and 4.5 μm detector arrays of the Infrared Array Camera remaining operational. Fortunately, HST' s WFC3 (Wide Field Camera 3) was commissioned that same year, and together with Spitzer's two broadband photometric channels, they supported exoplanet atmospheric detection from space.

Currently, using WFC3 to detect H_2O absorption bands in exoplanet atmospheres has become routine, and astronomers have discovered that water is not scarce in exoplanet atmospheres. However, WFC3' s low resolution and relatively narrow wavelength coverage (1.1-1.4 μm) prevent stable detection of atmospheric molecules other than H_2O. In some planets, alkali metal lines Na and K have been detected at low resolution from space [21].

Thanks to ground-based telescopes' pursuit of high-precision radial velocities, spectral detection resolution has improved dramatically. Early instruments included HARPS on the ESO 3.6 m telescope, UVES (Ultraviolet and Visual Echelle Spectrograph) and CRIRES (Cryogenic High-resolution Infrared Echelle Spectrograph) on the VLT, HDS (High Dispersion Spectrograph) on Subaru, HIRES (High Resolution Echelle Spectrometer) on Keck, and HARPS-N on the Galileo National Telescope (TNG). Recent upgrades include ESPRESSO (Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) and CRIRES+ on the VLT, and MAROON-X on Gemini-North, all providing high-resolution spectral data.

With improved instrumental resolution, high-resolution spectroscopy (R = 25,000–100,000) has gradually become prominent in exoplanet atmospheric studies. Snellen et al. [22] used CRIRES to observe the hot Jupiter HD 209458 b, separating the planet' s Doppler shift in high-resolution time-series spectra and achieving the first reliable detection of a molecule (CO) in an exoplanet atmosphere. High-resolution spectroscopy is now commonly used to study the atmospheric compositions of transiting and non-transiting hot gas giants and can provide constraints on sub-Neptunes [23] and super-Earths [24].

Additionally, for directly imaged planets, with further development of high-contrast imaging technology, approximately 20 wide-orbital-separation (10–100 AU) massive planets (or planet-mass objects) have been characterized through direct imaging. H_2O and CO_2 are relatively common in these planetary atmospheres, and some planets may also contain CH_4. [Figure 3: see original paper] summarizes the detection results of atmospheric chemical composition in different types of planets.

Note: Green indicates that the signal has been measured by at least two instruments, yellow marks atmospheric components whose characteristic absorption has been measured multiple times by one instrument, and red indicates that detection results for that component on the planet remain controversial.

In this context, space-based exoplanet atmospheric detection capabilities urgently need improvement, and JWST' s launch is undoubtedly a critical piece in the current exoplanet detection landscape.

2.2 Development of Research Methods and Models

Over the past two decades, the planetary atmospheric community has largely established a theoretical framework and research methodology based on detection capabilities [4], with comprehensive reviews available in the literature.

One-dimensional forward self-consistent models generally assume atmospheric elemental composition and equilibrium conditions (thermochemical equilibrium and radiative-convective equilibrium) in a plane-parallel geometry. The thermochemical equilibrium assumption allows calculation of chemical abundances (i.e., atomic or molecular abundances) from elemental abundances, while the radiative-convective equilibrium assumption enables calculation of self-consistent temperature-pressure (P–T) profiles with chemical abundances. The radiative-convective equilibrium assumption is crucial for exoplanet thermal emission spectra because atmospheric temperature gradients play a key role in shaping spectral features. The obtained chemical composition and P–T structure can be used to calculate radiative transfer through the atmosphere, ultimately producing a spectrum. Three-dimensional atmospheric circulation models calculate the complete three-dimensional atmospheric structure given planetary parameters and radiation fields. General circulation models (GCMs) encompass atmospheric chemistry, thermal properties, dynamics, and radiation characteristics [26–28]. Classical retrieval methods couple parameterized forward models with parameter estimation algorithms to estimate model parameters for a given spectral dataset. Free parameters in the model include chemical composition with significant features in the observed spectral bandpass, temperature distribution, macroscopic cloud parameters (location in the atmosphere, spatial extent, and opacity), and any other free parameters related to the observed spectrum [29, 30]. Currently, theoretical model development focuses more on atmospheres deviating from equilibrium, such as chemical disequilibrium [31] and atmospheric escape [32, 33].

3 JWST’ s Exoplanet Atmospheric Detection Capabilities

Ground-based high-resolution instruments have achieved exciting results in exoplanet atmospheric detection, but space-based instruments with high signal-to-noise ratio remain irreplaceable due to strong absorption by Earth’ s atmosphere in the infrared. JWST will dramatically expand the wavelength coverage of existing space-based atmospheric detection and improve spectral resolution.

Among JWST’ s four scientific instruments, the Near-Infrared Camera (NIRCam), Near-Infrared Spectrograph (NIRSpec), and Near-Infrared Imager and Slitless Spectrograph (NIRISS) cover the near-infrared band (0.6–5.3 μm), fully covering and bridging the wavelength ranges of HST/WFC3 and Spitzer/IRAC, with partial overlap with HST/STIS in the visible band, encompassing alkali metal Na and K absorption lines. The Mid-Infrared Instrument (MIRI) extends wavelength coverage from 5 μm to 28 μm, unveiling for the first time the mid-infrared spectral details of exoplanet atmospheres. [Figure 4: see original paper] compares the spectral capabilities of JWST’ s NIRSpec instrument with HST/STIS, WFC3, and Spitzer/IRAC. In [Figure 4: see original paper]a, colored data points represent observational data from pre-JWST space-based instruments for hot Jupiter atmospheres, with colored curves showing the corresponding best-fit spectra. Gray data points simulate JWST/NIRSpec observations of WASP-17b. JWST observations will densely fill the gap between WFC3 and Spitzer/IRAC, precisely capturing atmospheric features from near- to mid-infrared. [Figure 4: see original paper]b shows that compared to WFC3, JWST will improve constraints on important parameters for atmospheric research, such as atmospheric metallicity and C/O ratio, by at least an order of magnitude [34].

Transit science is a major JWST science topic, placing high demands on spectrographs for transmission spectroscopy, secondary eclipse spectroscopy (or emission spectroscopy). As shown in [Figure 5: see original paper], all four JWST scientific instruments have spectroscopic capabilities. summarizes the spectrometer parameters of each instrument. Selecting different instrument modes and filters based on target system characteristics can maximize JWST' s powerful light-gathering capability and platform stability. Below we introduce the characteristics and detection capabilities of each instrument.

JWST' s Near-Infrared Camera (NIRCam) uses a dichroic beam splitter to observe the same field of view in both short-wave (0.6–2.3 μm) and long-wave (2.4–5.0 μm) channels, as shown in [Figure 5: see original paper]. Grisms in the long-wave channel work with two broadband filters to obtain slitless spectra with resolution $R \approx 1,600$ in the range $\lambda = 2.4$–4.0 μm or $\lambda = 3.8$–5.0 μm. Fast readout subarrays enable NIRCam to conduct spectroscopic observations of stars with $K \approx 4$ mag or brighter. Meanwhile, the short-wave channel can perform photometric measurements of targets as bright as $K \approx 6$ mag using a defocusing lens. In the absence of HST' s rapid scanning mode, NIRCam can achieve photometric precision similar to WFC3 G141 (about 3.5×10^{-5}) [36].

JWST' s Near-Infrared Imager and Slitless Spectrograph (NIRISS) includes a Single-Object Slitless Spectroscopy (SOSS) mode specifically designed for transit spectroscopy and optimized for time-series observations. This mode uses a cross-dispersed grating to achieve wavelength coverage of 0.6–2.5 μm with resolution $R \approx 700$. Cylindrical lenses broaden the spectrum to 20–25 pixels in the spatial direction, allowing longer integration times and reducing the impact of pixel-to-pixel variations in detector response, ultimately enabling observations of targets as bright as $J \approx 7$ mag. Additionally, NIRISS can use a subset of NIRCam filters and can in principle be used for direct imaging from 0.8–5.0 μm [36].

JWST' s Near-Infrared Spectrograph (NIRSpec) is a powerful tool for obtaining exoplanet spectra, designed as a versatile spectrograph for multi-object spectroscopy and high-contrast, high-throughput single-object spectroscopy. Exoplanet transit science primarily uses NIRSpec' s Fixed Slit Spectroscopy (FSS) mode for high-contrast single-object spectroscopy and the Bright Object Time-Series (BOTS) mode for high-throughput observations. Notably, the $1.6'' \times 1.6''$ wide aperture in this instrument is specifically designed for transit spectroscopy in BOTS mode and is the only slit supporting time-series observations with exposure times exceeding 1×10^4 s. Therefore, measuring transit spectra, secondary eclipse spectra, and phase curves of bright stars is a major task for NIRSpec. It can obtain medium-resolution ($R = 1,000$) or high-resolution ($R = 2,700$)

spectra in four slightly narrower wavelength regions (0.7-1.2; 1.0-1.8; 1.7-3.1; 2.9-5.2 µm). For fainter sources ($J < 10$ mag), the low-resolution ($R = 100$) prism mode can be used to directly obtain spectra from $\lambda = 0.6$-5.0 µm.

JWST' s Mid-Infrared Instrument (MIRI) provides valuable mid-infrared spectroscopic capabilities. The low-resolution spectrometer (LRS, $R = 100$) obtains slitless spectra from $\lambda = 5.0$-12 µm using a compound prism. The medium-resolution spectrometer (MRS, $R = 1,300$-$3,700$) obtains integral field spectroscopy through four integral field units covering (5.0-7.7; 7.7-11.9; 11.9-18.4; 18.4-28.3 µm). MIRI' s imaging module (MIRIM) provides photometric measurements with ten selectable broadband filters covering central wavelengths from 5.6-25.5 µm with bandwidth ranges of $\Delta\lambda = 0.7$-4.0 µm.

JWST' s instrumental capabilities give scientists great confidence in placing further constraints on the atmospheric compositions of giant exoplanets. As shown in [Figure 6: see original paper], black double-arrowed lines mark the wavelength coverage of all JWST spectroscopic instrument modes, while colored curves show the absorption cross-sections of important atmospheric molecules in the visible-to-infrared band [4].

In JWST' s first cycle of scientific observations (ERS, GTO, GO), transit science observations will be completed for 68 planets in 54 systems. [Figure 7: see original paper] shows the distribution of these systems in terms of distance and host star type. Host star types include A, F, G, K, M dwarfs, and white dwarfs (WD 1856+543). The number of JWST-observed planetary systems decreases with increasing host star effective temperature. In the first cycle, 27 planets orbit M dwarfs, while 39 orbit F, G, and K stars. The distance to target systems increases with host star effective temperature, meaning JWST focuses on observing transits in M dwarf systems within 20 pc of the Solar System (see).

[Figure 8: see original paper] shows the distribution of these planets by type in the orbital radius-equilibrium temperature parameter space. Planet types are classified based on planetary radius and equilibrium temperature. JWST' s target planets concentrate in two regions– "small" planets with sizes of 0.7-3 $R_\oplus$ and warm temperatures, and hot Jupiters. Using Solar System planets as references, JWST can already observe planets similar to Earth in radius and equilibrium temperature, with a considerable fraction within 20 pc of the Solar System. However, [Figure 7: see original paper] shows that most of these planets orbit M dwarfs rather than Sun-like stars. M dwarf activity significantly affects the evolution and atmospheric conditions of these planets, potentially making them distinct from terrestrial planets in the Solar System. JWST observations of these planets are expected to deepen our understanding of the formation and evolution of Earth-like planets in M dwarf systems. Additionally, JWST will observe 23 super-Earths ($1.2R_\oplus < R_p < 2R_\oplus$) and sub-Neptunes ($2R_\oplus < R_p < 3R_\oplus$)–two types of planets that do not exist in the Solar System. In the current sample of detected exoplanets, planetary radii show a bimodal distribution with fewer planets in the (1.5-2) $R_\oplus$ range [37, 38]. Photoevaporation theory predicts the existence of this distribution valley [39], and core-powered mass loss theory [40, 41] can also explain this phenomenon. Using JWST to probe the atmospheres of planets in this range will enable more in-depth studies to complement our understanding of planetary formation and evolution. In the parameter space of planetary radius-equilibrium temperature for JWST' s planned observations, Jupiter in the Solar System remains unique; the only cold Jupiter target is WD 1856+534 b orbiting a white dwarf, followed by Kepler-51 d at 381 K located 783 pc away.

JWST' s exoplanet atmospheric detection targets are not limited to transiting systems; directly imaged planets and protoplanetary disks are another important topic in exoplanet science. Because Earth' s atmosphere absorbs mid-infrared radiation, all previous direct observations were obtained in the near-infrared. MIRI' s spectroscopic capability beyond 5 μm makes JWST a potential game-changer for characterizing directly imaged exoplanet atmospheres [42]. MIRI' s wavelength range corresponds to where planets emit most of their radiative flux, and the star-to-planet brightness ratio is smaller, enabling clear atmospheric features to be revealed. As mentioned in the introduction, the greatest challenges in detecting directly imaged planets and their atmospheres are high-contrast imaging and inner working angle limitations. Currently, JWST employs two methods to achieve high-contrast imaging: coronagraphic imaging with NIRCam and MIRI, and Aperture Masking Interferometry (AMI) with NIRISS. Notably, MIRI' s four-quadrant phase-mask coronagraph (4QPM) is the debut of such an instrument in space. Compared to traditional Lyot masks, it has a smaller inner working angle (IWA $\approx \lambda/D$). MIRI' s three 4QPMs have central wavelengths at $\lambda = 10.575$, 11.3, and 15.5 μm. The MASK1065 mask ($\lambda = 10.575$ μm) corresponds to a characteristic absorption band of NH_3, and when combined with the adjacent MASK1140 mask ($\lambda = 11.3$ μm), it will provide powerful constraints on NH_3 abundance in directly imaged planetary atmospheres, distinguishing between chemical equilibrium and non-equilibrium states in the atmosphere.

JWST' s coronagraphs do not yet have spectroscopic capabilities; a space-based coronagraph with spectroscopic capability is expected to be implemented on the next-generation Roman Space Telescope. However, the integral field units on NIRSpec and MIRI can obtain spectra of star-planet (or substellar object) pairs at appropriate separations (greater than 1). [Figure 9: see original paper] shows MIRI' s observational capability for directly imaged planets, with the vertical axis showing the distance from the peak of the normalized point spread function (PSF). The black curve shows simulated MIRI observation results, and dots represent current directly imaged planets colored by planetary surface temperature. Targets above the black curve have stellar PSF contributions much smaller than planetary contributions at their angular separations from the host star, meaning these four targets do not require coronagraphic observations. Simulation work by Malin et al. [44] shows that for such planets, MIRI' s signal-to-noise ratio for emission spectroscopy is not sensitive to host star spectral type. Molecular detection achieves the highest signal-to-noise ratio for planets with temperatures between 750–1,750 K. For most planets with temperatures below 1,500 K, MIRI can detect molecules such as H_2O, CO, NH_3, CH_4, HCN, PH_3, and CO_2 through molecular mapping. Important parameters for directly imaged planets (or substellar objects) are listed in [43]; currently, all planets detected through direct imaging fall within the temperature range indicated by this high signal-to-noise molecular detection.

With JWST' s widespread use, how broad and deep will exoplanet atmospheric science expand? First, for planets already characterized (strongly irradiated hot gas giants and wide-orbit directly imaged giant planets), atmospheric characterization will reach longer spectral bands, more spectral features, more detailed line descriptions, and the capture of time-varying signals. Descriptions of atmospheric structure will become more comprehensive, and constraints on atmospheric chemical abundances and elemental abundances will be more precise, aiding further understanding of giant planet formation processes. Second, for smaller planets with weaker spectral signals, such as super-Earths and Neptune-like planets, more definitive atmospheric features or cloud signatures may be found at longer wavelengths, breaking the degeneracy between featureless spectra and assumptions of no atmosphere or cloudy atmospheres. Although detecting biosignatures on Earth-like planets remains a distant goal, we are unprecedentedly close to observing silicates in the volatile atmospheres of super-Earths and sub-Neptunes [45]. The vast parameter space of exoplanets will truly open before JWST. With JWST, astronomers will begin to more deeply investigate what the diversity of planetary atmospheres—or planets themselves—really means.

4 Model and Theoretical Challenges

Over the past 20 years, a basic framework for describing exoplanet atmospheres has been established. In particular, the characteristics of hot Jupiter atmospheres are preliminarily understood, with extensive research on atmospheric theory itself, self-consistent modeling of atmospheric spectra, and retrieval methods for inferring atmospheric parameters from observed spectra. JWST' s enhanced instrumental capabilities bring high-quality data, opening new exploration space and requiring improvements in atmospheric theory, models, and methods.

The foremost challenge concerns retrieval methods most closely related to observed spectra. Opacity describes the interaction between light and matter, and opacity models simulate this process as a function of material properties. Current state-of-the-art opacity models have performed well in decoding spectra from HST and other instruments. However, as data enters a new era of precision with JWST, biases in opacity models may hinder or mislead our capture of subtle details, such as clues to habitability. Niraula et al. [46] simulated the impact of opacity model perturbations on transmission spectra. As shown in [Figure 10: see original paper], different colored curves represent transmission spectra generated by different absorption cross-section models (perturbations) (top panel) and their deviations from the standard model (bottom panel). CS-DFLT is the nominal cross-section used in the study, while other models investigate uncertainties in line parameters (CS-1SUP, CS-1SDN), line broadening mechanisms (CS-SELF, CS-MAXB, and CS-MINB), far-wing line profile mechanisms (CS-500W), and different databases (CS-EXML: ExoMol and CS-HTMP: HITEMP2010). The results show that the sensitivity of atmospheric retrieval outputs, combined with current opacity model limitations, will lead to a precision wall of 0.5–1 dex (i.e., 3–10 times) when interpreting next-generation exoplanet spectra—an order of magnitude lower than the precision goals of JWST' s first phase.

Therefore, in this new phase, careful consideration must be given to error sources in opacity models (line lists, absorption cross-sections, thermodynamic data) and establishing necessary descriptions of deviations from model perturbations. This process can also be viewed as data-driven corrections to physics models from theory to practical application. Even for hot Jupiters and ultra-hot Jupiters, the most maturely modeled objects in exoplanet atmospheric science, accelerated remodeling is needed. (1) From equilibrium to non-equilibrium: atmospheric processes deviating from equilibrium must be incorporated into retrieval processes. (2) From one-dimensional to two- and three-dimensional modeling: previous self-consistent models for transmission and emission spectra and retrieval models were based on one-dimensional radiative-convective transfer models. Three-dimensional atmospheric circulation models were initially used to explain hot Jupiter thermal phase curve observations and day-night temperature differences, but one-dimensional retrieval methods may lead to biased parameter estimates for (ultra-)hot Jupiter atmospheres when equilibrium temperatures exceed 1,400 K, requiring correction by incorporating three-dimensional atmospheric circulation effects into retrieval models [47]. (3) From steady-state to time-varying: the offset of hot spots in hot Jupiter atmospheres is one of the most successful predictions of atmospheric dynamics simulations, which further indicate that hot spot offsets vary with time. JWST has the opportunity to capture such variations, urgently requiring theoretical explanations and descriptions of the mechanisms producing these offsets.

Regarding retrieval methods themselves, there is a tension between the accuracy of parameterized forward models in describing real situations and the computational simplicity required for statistical inference. Adopting more efficient sampling methods to explore parameter space may be one solution. Currently, state-of-the-art codes use extensive parameter estimation methods, including Markov Chain Monte Carlo methods, optimal estimation gradient descent algorithms, and nested sampling algorithms. The potential of machine learning algorithms for atmospheric retrieval remains to be explored in the future.

Additionally, as JWST conducts atmospheric studies of colder, smaller planet types, previous research experience on hot Jupiters does not fully apply, and the Solar System may not provide corresponding prototypes for comparative study. Atmospheric theory needs to be adjusted according to planet type. The atmospheres of more distant, smaller Neptune-like planets and super-Earths are expected to be more complex than those of hot Jupiters. On one hand, they receive less stellar radiation and have lower surface gravity, making processes such as atmospheric escape, photochemistry, and even interaction with the surface more significant for atmospheric evolution. Studies of secondary and mixed atmospheres on super-Earths and sub-Neptunes are limited by chemical theory, but future JWST data has great potential to place preliminary constraints on mantle oxygen fugacity through abundance ratios of CO_2 to CO for such planets. Therefore, future work must consider photochemical processes and clarify the general role of atmospheric escape, quantifying the relationship between mass and oxygen fugacity for super-Earth and sub-Neptune samples [48]. On the other hand, the orbital parameter space of these planets may make atmospheric processes more complex (more common orbital eccentricities, axial tilts), introducing more asymmetry and time-varying features into observations.

The grand vision of exoplanet science is to find another Earth beyond the Solar System, with the current driving goal being to characterize the atmospheres of terrestrial exoplanets and search for atmospheric biosignatures (also called life fingerprints). JWST can significantly advance the field of exoplanet science, but finding definitive signs of life on Earth-like planets around Sun-like stars is unrealistic with current capabilities. Present detection limitations restrict such studies to planets around nearby cool dwarfs. Whether JWST can effectively characterize the atmospheres of potentially habitable Earth-like planets orbiting cool dwarfs remains controversial, with the main challenge being the balance between biosignature effectiveness and observing time. In this regard, the three habitable-zone planets e, f, and g in the TRAPPIST-1 system are key research targets. For many common biosignature candidate molecules such as O_2 and CH_4, there are potential false positives from non-biological planetary processes. Two solutions exist: (1) Constrain the relative abundances of these molecules with higher signal-to-noise ratios. For example, Krissansen-Totton et al. [49] proposed that atmospheric $CH_4+CO_2 \rightarrow CO$ disequilibrium could serve as a future atmospheric biosignature. Simulation results show that JWST can conduct effective anaerobic biosignature detection with 10 transit observations of TRAPPIST-1 e. The simulated data can also detect CO_2, constrain CH_4 abundance to exclude non-biological sources, and provide a rough upper limit on CO in TRAPPIST-1 e' s atmosphere. (2) Search for molecules with lower false-positive probabilities, such as methylated halogens CH_3Br, CH_3Cl, and CH_3I [50].

While JWST's capabilities are outstanding, it is not alone in the JWST era. The advantages of this period also include 20 years of accumulated observational data and high-quality contemporaneous ground-based telescope data. Therefore, to maximize JWST' s research capabilities and current resources, data integration studies from multiple instruments and sources deserve attention. Combining multi-epoch, multi-wavelength, multi-telescope transit data can improve the precision of planetary ephemerides and eclipse depths, and even enable further studies of stellar variability or planetary atmospheric temporal variations [51].

Future PLATO mission measurements of stellar ages combined with JWST’ s atmospheric chemical measurements can improve understanding of planetary evolution processes [52]. Thus, multi-instrument, multi-source data integration for individual planets or systems can maximize observational resources in the JWST era and promote refined characterization of planetary structures.

5 Scientific Output

JWST has completed its commissioning and first-cycle observations, with second-cycle observation plans recently reviewed and announced. The earliest released observational data were the atmospheric transmission spectrum of WASP-96b obtained using NIRISS SOSS mode (PID: 2734). This observation was part of JWST’ s commissioning program, aimed at demonstrating JWST’ s unprecedented detection capabilities in the infrared band to the public. The six images, including WASP-96b’ s atmospheric transmission spectrum, generated 26,000 news articles and 120 billion impressions within days, becoming one of the largest public science events in history [53]. However, even in this simple 6.4-hour observation, JWST updated previous understanding of WASP-96b. Earlier observations with HST/WFC3, Spitzer/IRAC, and ground-based VLT/FORS2 and Magellan/IMACS showed atmospheric features in the optical-to-near-infrared transmission spectrum that were not obscured by aerosols (Na I), with retrieval analysis supporting a cloud-free conclusion for this planet’ s atmosphere [54]. However, JWST’ s observations from 0.6–2.8 µm revealed clear but weaker-than-expected H_2O signals, suggesting the presence of clouds. Samra et al. [55] combined 3D GCM atmospheric simulations with kinetic non-equilibrium formation models for mixed-composition cloud particles, demonstrating that mineral cloud particles composed of mixed metal oxides and silicates can explain how cloud presence in WASP-96b’ s atmosphere matches current spectral features.

More scientifically valuable are two large Early Release Science (ERS) programs: (1) JWST Transiting Exoplanet Community Early Release Science Program (ERS-TRANS, ERS PID 1366); (2) JWST Director’ s Discretionary Early Release Science Program for Direct Imaging and Spectroscopy of Exoplanet Systems (ERS PID 1386).

ERS-TRANS focuses on transiting exoplanet science including transit, secondary eclipse, and phase curve observations [34]. The program plans to use three exoplanet characterization modes (see [Figure 11: see original paper]): (1) transit observations of WASP-39 b with overlapping wavelength coverage using four independent modes across all three near-infrared instruments; (2) single-phase curve observations of WASP-43 b using MIRI/LRS; (3) secondary eclipse observations of WASP-18 b with a bright host star using NIRISS/SOSS.

Note: The right panel shows wavelength coverage for the instrument modes to be used, with color coding on the left text corresponding to instrument mode labels on the right.

WASP-39 b has physical parameters: mass $M_p = 0.28M_{Jup}$, radius $R_p = 1.27R_{Jup}$, equilibrium temperature $T_{eq} \approx 1,100$ K, orbiting a G-type star with a period of 4.055 days. Before JWST, only Na, K, and H_2O had been detected in WASP-39 b’ s atmosphere. JWST immediately detected previously undetected CO_2 and SO_2. The CO_2 signal shows high consistency across four observation modes in the near-infrared (NIRSpec PRISM [53], NIRSpec G395H [56], NIRISS [57], NIRCam [58]). The SO_2 feature at 4.05 µm, as the first evidence of photochemical processes in an exoplanet atmosphere, has attracted significant attention from astronomers.

Program 2783 proposed using MIRI LRS during discretionary time (DDT) in the first cycle to conduct follow-up observations of WASP-39 b to further investigate SO_2 detection and atmospheric chemical processes. By observing WASP-39 b’s transit with MIRI’s low-resolution spectrometer, the 7.5 µm SO_2 feature can be directly detected, with an expected amplitude three times that of the 4.05 µm feature. The approved MIRI follow-up observation will definitively confirm SO_2’ s presence in WASP-39 b’ s atmosphere, place stringent constraints on atmospheric metallicity, and strongly demonstrate that active photochemical processes are occurring in exoplanet atmospheres. This detection will also impose unprecedented constraints on sulfur inventory and overall metallicity in exoplanet atmospheres, further constraining the relationship between atmospheric composition and exoplanet formation history. In addition to atmospheric composition detection, JWST also provides new information about clouds in WASP-39 b’ s atmosphere. Previous HST and Spitzer detections of pressure-broadened wings of Na and K lines corresponded to relatively cloud-free atmospheric conditions. However, current JWST observations favor a cloudy atmosphere for WASP-39 b. The discrepancy may arise from overly simplistic cloud models that fail to capture the complex nature of mixed condensation clouds in exoplanet atmospheres. Clouds in WASP-39 b’ s observable upper atmosphere are mixtures of different silicates and metal oxides. Using cloud particles with constant particle sizes or single compositions may be insufficient to capture the full complexity of JWST observations [59].

WASP-18 b is an ultra-hot Jupiter orbiting an F6V star with an orbital period of only 0.94 days and mass $M_p = (10.4 \pm 0.4)M_{Jup}$. ERS-TRANS selected this target to test JWST’ s NIRISS/SOSS mode for observing exoplanet atmospheres around bright stars [60]. The results show that for planets like WASP-18 b with high transit signal-to-noise ratios, three-dimensional mapping of their atmospheres can be performed, enabling retrieval of variations in dayside temperature structure and molecular abundances [61]. JWST will be able to measure these physical properties for most bright transiting exoplanets, potentially enabling direct study of various exoplanets’ dynamical and chemical properties from secondary eclipse observations.

The successful MIRI/LRS observation of WASP-43 b demonstrated JWST’ s capability to measure thermal phase curves of exoplanets [62]. Over a time span exceeding 24 hours, photometric precision was within 25% of the photon limit.

Some instrumental systematic ramp effects were present in the light curves, with the ramp shape changing dramatically in the 10.6–11.8 µm wavelength range, corresponding to the detector’ s “shadow” region. Further testing of the systematic stability of the ramp is needed to determine whether partial phase curves are feasible.

The JWST Director’ s Discretionary Early Release Science Program for Direct Imaging and Spectroscopy of Exoplanet Systems (ERS PID 1386) is the only ERS program testing JWST’ s high-contrast exoplanet imaging modes. The program uses all four JWST instruments to extend characterization of directly imaged planets (or planet-mass companions) to the 15 µm band and to image circumstellar disks with unprecedented sensitivity in the mid-infrared. The program also tests JWST’ s performance in key modes typically used for exoplanet direct imaging and spectroscopy, optimizes data calibration and processing, and generates representative datasets to enable the broad user community to effectively plan future General Observer (GO) programs. Planned observations include: (1) imaging the newly discovered exoplanet HIP 65426 b using NIRCam and MIRI coronagraphs; (2) performing aperture masking interferometry (AMI) observations of the HIP 65426 system with NIRISS; (3) coronagraphic imaging of the young debris disk around HD 121569 A with NIRCam and MIRI; (4) obtaining NIRSpec/IFU and MIRI/MRS spectra and NIRCam imaging of the wide-orbit planet-mass companion VHS 1256-1257 b. The program’ s results show the first-ever images of exoplanets taken directly by JWST and the first exoplanet images at wavelengths exceeding 5 µm. The ERS-1836 project has published direct imaging results for HIP 65426 b [63] and the brown dwarf companion VHS 1256-1257 b [64]. Observations of HIP 65426 b obtained precise fluxes from near- to mid-infrared, enabling accurate constraints on the planet’ s total emitted energy or luminosity. Observations of VHS 1256-1257 b detected CH_4, CO, CO_2, H_2O, K, and Na, and discovered silicate clouds for the first time in a planet-mass companion. ERS-1836 results show that JWST’ s sensitivity is at least 10 times better than expected [65], and the project has provided detailed guidance for second-cycle exoplanet direct imaging observations [66].

Fu et al. [67] (ERO-2734) used NIRISS/SOSS to obtain the transmission spectrum (0.6–2.8 µm) of the inflated giant HAT-P-18 b, revealing for the first time infrared spectral features beyond 1.6 µm: excess He absorption and comet-like tail structures. Previous ground-based observations of HAT-P-18 b did not see tail features due to lower signal-to-noise ratios in excess absorption. This result highlights JWST’ s clear advantage in photometric precision over typical ground-based observatories. Although JWST NIRSpec/G140H’ s spectral resolution ($R \approx 2,700$) is lower than ground-based high-resolution spectrographs ($R > 10,000$), this instrument mode has enormous potential for He observations due to its excellent stability and precision.

The first cycle also includes tracking real-time CH_4-CO conversion in the atmosphere of the high-eccentricity gas giant HD 80606 b and calculating its chemical timescale. Additionally, sulfur components triggered by sudden heating and photochemical forcing exhibit short- and long-term cycles, opening an interesting avenue for sulfur detection on exoplanets. Programs GO-2008 and GO-2488 will use NIRSpec and MIRI to obtain time-series spectra of HD 80606 b to reveal in detail how this planet responds to flash heating near periastron [68].

The key to detecting life on exoplanets in the next decade is studying whether rocky planets around M dwarfs have atmospheres and how these atmospheres evolve. In the first cycle, JWST demonstrated powerful capabilities for detecting and characterizing Earth-sized planetary atmospheres. In transmission spectroscopy, program GO-1981 confirmed JWST’ s first exoplanet, LHS 475 b (GJ-4102 b) [69], a warm (586 K) planet almost exactly Earth-sized ($R_p = (0.99 \pm 0.05)R_\oplus$) within its system’ s habitable zone. Previous TESS observations hinted at this planet’ s existence. The project used JWST/NIRSpec BOTS mode at $R \approx 2,700$ resolution in the 2.87–5.27 μm band for a 2.9-hour observation, achieving independent confirmation and obtaining LHS 475 b’ s transmission spectrum. The featureless transmission spectrum is consistent with a planet having high-altitude clouds (Venus-like), a thin atmosphere (Mars-like), or no significant atmosphere at all (Mercury-like). Current detections rule out a primordial H-dominated atmosphere or cloudless pure methane atmosphere for LHS 475 b. The results also show that JWST has sufficient sensitivity to constrain secondary atmospheres on Earth-like exoplanets with absorption features smaller than 5×10^{-5}; the current atmospheric constraints reflect the planet’ s nature rather than instrumental limitations [70, 71]. The degeneracy between featureless transmission spectra and high mean molecular weight atmospheres or high-altitude cloud coverage for terrestrial planets existed already in the HST and Spitzer era. An effective way to break this degeneracy is to measure the planet’ s dayside temperature. Previous space- and ground-based transit observations of TRAPPIST-1 terrestrial planets could only rule out cloudless H-dominated envelopes for the inner six planets. Spitzer attempted to detect secondary eclipse of TRAPPIST-1 b, as this is the innermost and hottest planet in the system where secondary eclipse signals should be most easily detected, but Spitzer’ s photometry at 4.5 μm failed to detect a credible secondary eclipse signal [72]. Program GTO-1177 successfully detected TRAPPIST-1 b’ s secondary eclipse using MIRI at longer wavelengths with higher photometric precision, achieving the first measurement of emission from an exoplanet terrestrial planet’ s dayside [73]. The dayside temperature of 503 K is significantly higher than the planetary equilibrium temperature calculated from stellar irradiation, consistent with tidally locked atmosphereless planet dayside temperature models (508 K) [74].

6 Outlook

This paper has introduced the transformative significance of JWST for exoplanet atmospheric research, including the field’ s development before JWST’ s launch, JWST’ s instrumental capabilities for exoplanet atmospheric science, challenges and opportunities brought by advanced detection capabilities and high-quality data, and current first-cycle scientific output. JWST will conduct detailed atmospheric characterization of exoplanets in both transiting science (including transmission spectroscopy, secondary eclipse spectroscopy, and phase curves) and direct imaging, enabling initial exploration of potentially habitable terrestrial planet atmospheres around cool dwarfs. Faced with JWST' s broad-band, high signal-to-noise data, models for interpreting the data require deeper understanding of non-equilibrium processes, multi-dimensional thermal structures, and dynamical processes such as atmospheric winds. More efficient parameter estimation and machine learning algorithms will help consider more details in data retrieval. Research on atmospheric biosignatures and habitability requires interdisciplinary collaboration. Current efforts can focus on finding more atmospheric features that can exclude non-biological processes and conducting theoretical and experimental studies of existing atmospheric life signals. JWST' s first-cycle scientific results are being released, with this paper highlighting the two major ERS programs in transiting science and direct imaging. Multi-instrument, multi-mode spectral observations of WASP-39 b discovered significant CO_2 signals and detected SO_2, the first product of photochemical processes. The direct imaging planet program also demonstrated JWST's better-than-expected sensitivity. We also introduced JWST' s first confirmed planet, LHS 475 b, and the possibility of an atmosphere on this terrestrial planet.

Finally, we reiterate the importance of combining multi-epoch, multi-wavelength, multi-telescope transit data in the JWST era. During JWST' s 10-year operational lifetime, a series of space telescopes and large-aperture ground-based instruments will come online, jointly advancing exoplanet atmospheric science (see and [Figure 12: see original paper]). Below we briefly introduce the detection capabilities and scientific goals of these instruments.

The Nancy Grace Roman Space Telescope, formerly the Wide Field Infrared Survey Telescope (WFIRST), is a NASA infrared space telescope planned for launch before 2027 that will conduct broad explorations of the universe including exoplanets and dark energy. WFIRST features an ultra-wide field of view (effective area of 0.281 square degrees) with a telescope aperture comparable to HST (2.4 m), equivalent to 100 HSTs working simultaneously to cover larger sky areas. In exoplanet atmospheric science, WFIRST will discover and study exoplanets through direct imaging. WFIRST' s Coronagraph Instrument (CGI) will be the first space-based coronagraph capable of exoplanet imaging and spectroscopy. CGI' s expected contrast approaches 10^{-9}, two to three orders of magnitude better than existing facilities, and is expected to enable direct imaging and spectroscopic analysis of hot and cold Jupiters, potentially even imaging super-Earths and Neptune-like planets around Sun-like stars within 10 pc, laying the foundation for future direct imaging and characterization of nearby habitable Earth-like planets.

Next-generation ground-based extremely large telescopes include the Thirty Meter Telescope (TMT), Extremely Large Telescope (ELT), and Giant Magellan

Telescope (GMT), expected to see first light in 2027 or later. With the help of adaptive optics systems, high-contrast coronagraphic imagers may come online around 2035, aiding characterization of warm giant planets at contrasts of 10^{-8}.

The ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) mission [75], ESA’ s fourth medium-class mission planned for launch in 2029, will conduct a census of approximately 1,000 exoplanet atmospheres in visible and infrared wavelengths. Due to its smaller collecting area, ARIEL will focus primarily on gaseous and rocky planets with temperatures above 500 K and may not be able to study atmospheres of habitable Earth-like planets around G and K stars. ARIEL’ s goal is to measure the chemical composition and thermal structure of exoplanet atmospheres to reveal their formation and evolution processes and their relationship with the host star environment. ARIEL will provide a unique opportunity to explore atmospheres of different types, sizes, and temperatures of exoplanets, searching for signs of possible present or past life.

Before telescopes with true spectroscopic capabilities can target the ultimate goal of exoplanet research—Earth-like planets in the habitable zones of Sun-like stars—dedicated survey observations are necessary to obtain required planetary physical parameters for assessing atmospheric observability. ESA’ s PLATO mission [76] (PLAnetary Transits and Oscillations of stars) aims to monitor millions of bright stars (4–11 mag), detecting Earth-sized planets through transit photometry and determining planetary masses through follow-up ground-based radial velocity observations, ultimately providing the first large sample catalog of planets with precise radius, mass, mean density, and age parameters. Chinese scientists have proposed the Closeby Habitable Exoplanet Survey (CHES) [77], which will conduct high-precision astrometric measurements of approximately 100 F, G, and K stars in the solar neighborhood, enabling comprehensive and precise observations of possible planets and Earth-like planets in habitable zones. Astrometric methods can reconstruct valuable three-dimensional planetary orbital motion information, depicting more realistic planetary physical pictures.

In the future, NASA’ s next-generation flagship mission succeeding Roman may truly delve into the world of habitable Earth-like planets, conducting direct imaging or more detailed habitability characterization of Earth-like planets in the habitable zones of Sun-like stars. Since 2016, NASA has been considering four different space telescopes, among which the Habitable Exoplanet Observatory (HabEx) [78] and the Large UV/Optical/IR Surveyor (LUVOIR) [79] both focus on exoplanet atmospheric research. The former’ s primary goal is to directly image Earth-sized rocky exoplanets and characterize their atmospheric compositions. By measuring these planets’ spectra, HabEx will search for habitability indicators such as water and potential life fingerprint gases. The latter’ s multi-wavelength capability from UV to infrared can detect many key atmospheric biosignatures and further understand how host star UV radiation regulates photochemistry in habitable planetary atmospheres. In 2021, the U.S. National Academies released the decadal survey “Pathways to Discovery in

Astronomy and Astrophysics for the 2020s" [80], recommending that NASA consider a new 6 m aperture telescope combining design elements from LUVOIR and HabEx. The new telescope will be called the Habitable Worlds Observatory (HWO), with a preliminary launch date set for 2040. Before that, China' s Tianlin program space telescope is expected to begin a 10-year observation program in 2035, with its main mission being the detection of extraterrestrial life and habitable exoplanets [81]. Tianlin will employ a 6 m monolithic primary mirror, operating in a Halo orbit at the Sun-Earth L2 point. The Tianlin program' s main technologies include coronagraphic direct spectroscopy and low-to-high-resolution transit spectroscopy, potentially covering wavelengths from UV to near-infrared (0.25-2.5 μm). Since JWST lacks UV capability and HST' s service life is nearing its end, Tianlin' s UV capability may fill the gap after HST' s retirement for studying upper atmospheres of exoplanets around Sun-like stars.

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