

Early Science Results for Transiting Exoplanets Observed by JWST

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JWST is ushering in a new epoch of exoplanet science that will rewrite textbooks. Progress will stem largely from the characterization of exoplanet atmospheres enabled by JWST technology. Herein, I will focus on the method of transmission spectroscopy. I note that coronagraphic observations from JWST will also provide significant contributions to our understanding of planet formation and evolution.

Background

To date, thousands of planets orbiting other stars in the Galaxy have been identified. Most were discovered using the Transit Method which involves precise monitoring of the brightness of stars to search for the dimming of light that occurs when a planet eclipses (or “transits” in front of) its star, blotting out a fraction of the light as seen from the telescope’s vantage point (Figure 1). The dimming repeats like clockwork, once every orbit. The amount of dimming tells us the radius of the star and the time between dimming events tells us the orbital period. Johannes Kepler taught us in the 1600’s that the orbital period is related to the distance between the star and the planet which is how we know if a planet is orbiting in the star’s Habitable Zone.

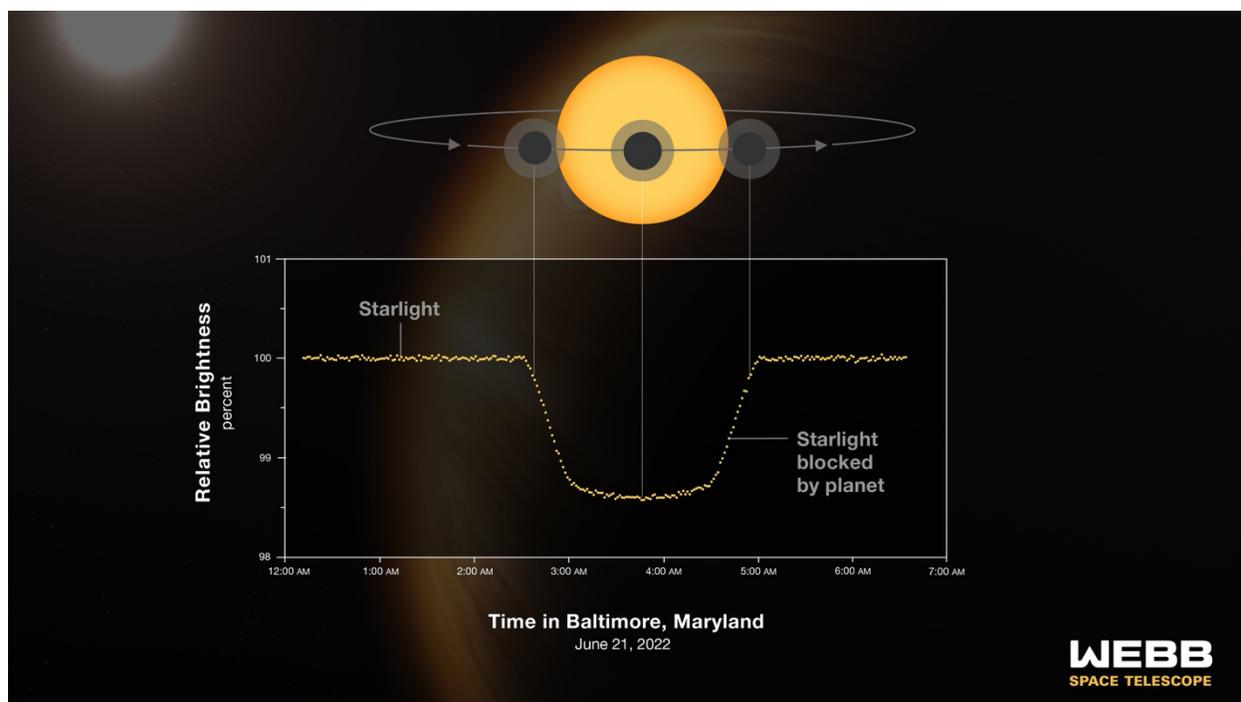


Figure 1. The Transit Method for detecting exoplanets is based on precise measurements of stellar brightness. Planets with edge-on orbits relative to our line of sight eclipse their star producing a dimming of the starlight that repeats once each orbit. During the planet’s transit across the face of the star, some light will pass through the planet’s atmosphere (here exaggerated by the gray annulus). Atoms and molecules in the atmosphere will imprint a chemical fingerprint on the light. (Credit: L. Hustak, STScI)

This is the method employed by NASA space missions like Kepler (2009 – 2017) and TESS (2018 – present). Kepler taught us that planets are common in the Galaxy. On average, every

sun-like star has at least one planet and more than 10 billion planets are terrestrial-sized and orbit in the Habitable Zone where liquid water could pool on the surface under the right conditions.

Kepler also taught us that the diversity of planets in the Galaxy far exceeds the diversity of planets in our Solar System. We know of worlds with lava oceans, two rising suns, lock-step orbits, and even comet-like tails. We also know of planets intermediate in size to the terrestrials and gas giants in our own Solar System. Dubbed “super-earths” or “mini-neptunes” (occasionally even “water worlds”), these are the most common types of planets known to us and yet we have no equal in our solar system. It behooves us to understand the physical processes that lead to such diversity in the Galaxy and how those processes impact planetary habitability.

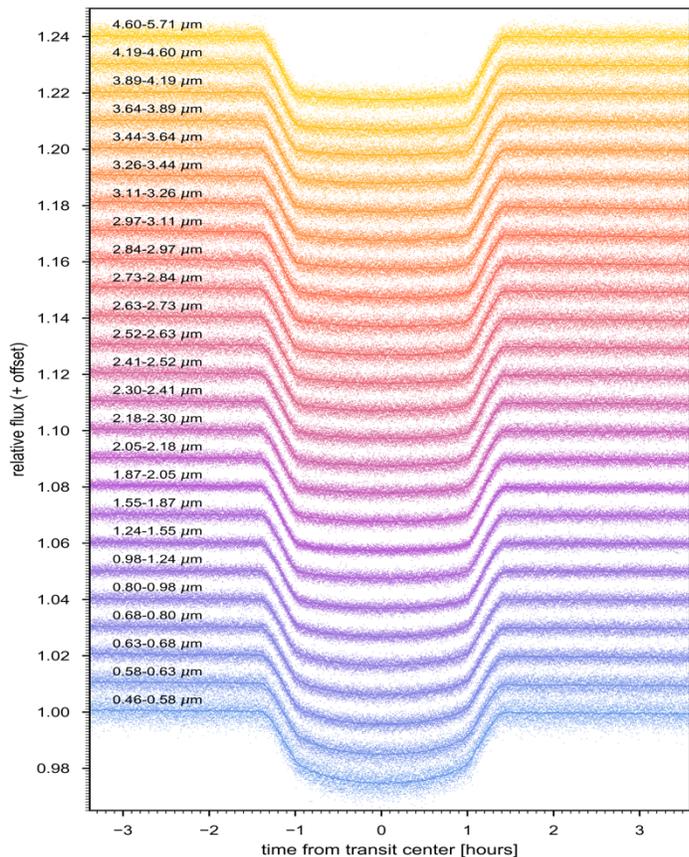
The study of demographics has been limited to the examination of bulk planet properties – properties like the total mass and radius gleaned from detection surveys. Applying the method of “transmission spectroscopy” to hundreds of exoplanets will yield a new lens on planetary diversity. JWST is uniquely suited to this task for nearby exoplanets (like those identified by NASA’s TESS Mission). From JWST data collected over the next decade, we will gain a much deeper understanding of how planets form and evolve, and we will be better equipped to identify the most likely abodes of life with future missions.

Transmission Spectroscopy

Transiting planets are especially valuable for scientific studies. Kepler and TESS observe transits in, effectively, “white light” whereby many colors are combined together. JWST is observing exoplanet transits too. But thanks to ultra-stable spectrometers, JWST observes transits in hundreds of infrared colors simultaneously (Figure 2).

Figure 2. JWST observes planetary transits in hundreds of infrared colors (wavelengths) simultaneously. Shown here are 25 transits, stacked vertically, each representing a different wavelength. The Carbon Dioxide (CO₂) molecule, for example, absorbs light preferentially at 4.3 μm (second transit from the top). A transiting planet with CO₂ molecules in its atmosphere will block out more starlight at 4.3 μm than at other colors. (Image Credit: Zafar Rustamkulov, JHU)

When planets eclipse their host star, some of the starlight passes through the planet’s thin atmosphere on its way to Earth’s telescopes. The atmosphere imprints a chemical fingerprint on the light since atoms and molecules absorb starlight at distinct colors. In effect, the planet blocks a slightly different fraction of light depending on the color and depending on which molecules



are present in the atmosphere. The spectrometers aboard JWST allow us to measure the amount of light blocked at each color thereby building up an atmospheric “spectrum.”

This method of studying planetary atmospheres is called “transmission spectroscopy,” and it has been employed by the Hubble Space Telescope and large ground-based telescopes on a small number of (mostly giant) planets. JWST is extending the capability and increasing sensitivity by collecting more photons in a stable environment across a broader range of infrared wavelengths where a variety of molecules generate strong absorption features.

Pre-launch simulations predicted that JWST data will enable atomic and molecular abundance measurements, atmospheric temperature and pressure determinations, an understanding of heavy element enrichment in planetary systems, investigation of cloud dynamics and haze production, and studies of photoevaporation and photochemistry for hundreds of planets down to super-earth and sub-neptune sizes. Pre-launch simulations also predicted that JWST will be able to detect the presence of atmospheres on terrestrial-size planets orbiting M-type stars, including a number of planets that orbit in the Habitable Zone (e.g. those orbiting TRAPPIST-1).

Early Science with JWST

In 2016, the exoplanet science community started an open-science initiative to discuss strategies for the first exoplanet observations with JWST. This effort resulted in Early Release Science Program ERS-1366. It has grown to include over 300 scientists working collaboratively. The program aims to test all of the JWST observing modes capable of performing transmission spectroscopy by observing three giant planets in short-period orbits (i.e. “hot jupiters”): WASP-39b, WASP-18b, and WASP-43b. Each planet had previously been observed by the Hubble Space Telescope, and each showed some evidence of atmospheric absorption. The goal of the program is to provide representative data to the community together with analysis tools and best practices.

Herein, I report on early science results for WASP-39b. WASP-39 is a sun-like star approximately 700 light-years away toward the constellation Virgo. The transiting exoplanet is 30% larger than Jupiter with a mass comparable to that of Saturn. It orbits the star once every four days at a distance that’s 8 times closer than Mercury is to our Sun. Four transits of the exoplanet have been observed, each with a different instrument mode.

A transmission spectrum is constructed by measuring the amount of light blocked during eclipse at each infrared color. Figure 3 shows the spectrum from NIRSpec PRISM. The most prominent feature near 4.3 microns is due to the absorption of starlight by Carbon Dioxide (CO₂) molecules – the first robust detection of CO₂ in an exoplanet atmosphere [1]. CO₂ is present in all solar system planets that have atmospheres. It’s also the primary background gas that we expect to detect in terrestrial-size exoplanets. Moreover, it’s a very sensitive tracer of the overall heavy element enrichment in a planetary atmosphere.

Other science discoveries gleaned from the transmission spectra of WASP-39 b include:

- The identification of multiple chemical species in the atmosphere, including sodium (Na), potassium (K), four independent water (H₂O) features, carbon dioxide (CO₂), and carbon monoxide (CO).
- Evidence of clouds. The data suggest that the cloud deck is not one uniform blanket. To fit the spectral features, higher complexity in the cloud deck is required as seen on solar system giant planets.
- The first detection of sulfur dioxide (SO₂), a molecule produced from chemical reactions triggered by high-energy light from the planet's parent star. On Earth, the protective ozone layer in the upper atmosphere is created in a similar way (Figure 4).

More than a dozen scientific studies using these data are in progress. We will be able to quantify chemical abundances, study disequilibrium processes, vertical mixing and photochemistry, search for additional molecules, and constrain the temperature and pressure structure of the atmosphere.

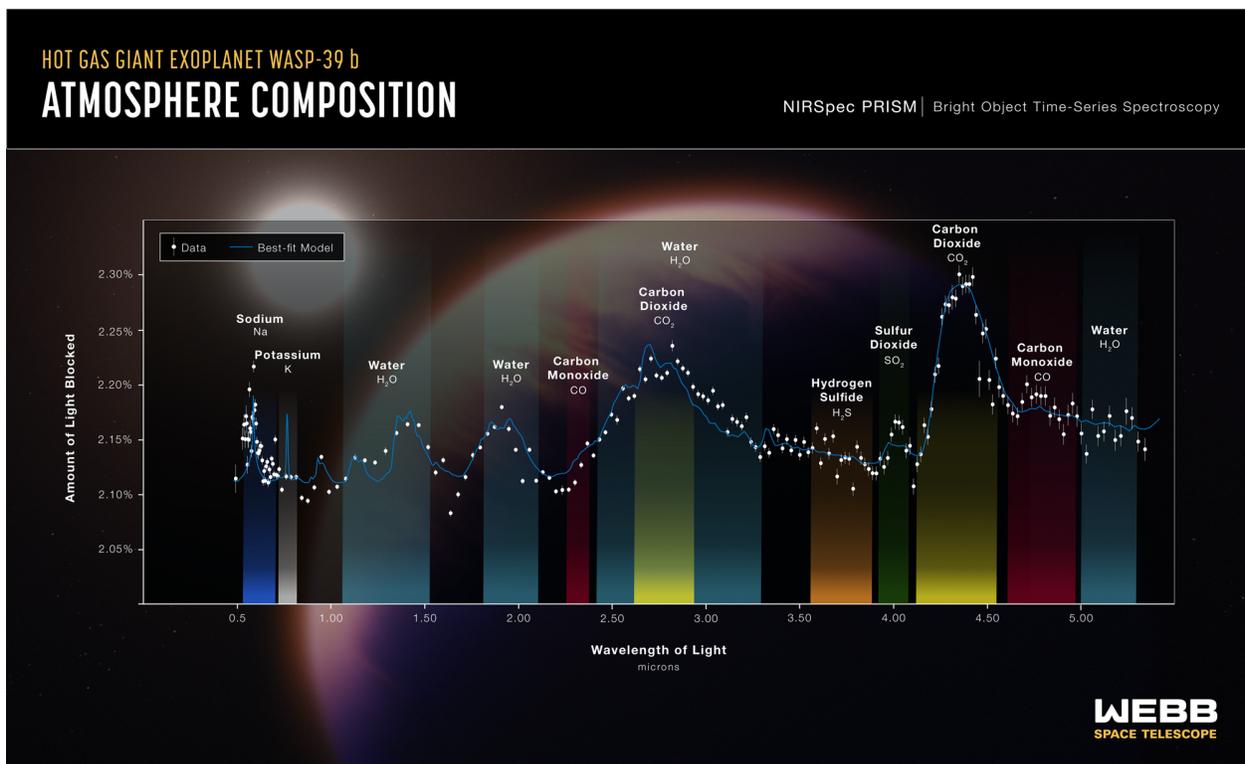


Figure 3. The atmospheric spectrum of the exoplanet WASP-39b from JWST's NIRSpec PRISM instrument is generated by measuring the amount of starlight blocked by the planet (y-axis) at each wavelength (x-axis). The measurements are shown here as white circles. The shaded regions in the background mark wavelengths impacted by a variety of atoms and molecules. The rise and fall of the data points align with these regions. JWST data reveal the presence of Sodium, Potassium, Water, Carbon Dioxide, Sulfur Dioxide, and Carbon Monoxide in the atmosphere of WASP-39b. (Image Credit: STScI)

Instrument Performance:

The WASP-39 b observations allow us to independently investigate the performance of the JWST instruments. The open-science nature of the Transiting Exoplanet Early Release Science Team allows us to apply independent analysis pipelines to the data for robust intercomparison of

performance benchmarks. Observing the same exoplanet with multiple instruments at overlapping wavelengths allows us to perform consistency checks. We find:

- The telescope and its instruments are performing at or better than pre-launch expectations. This finding is in agreement with the commissioning test on the exoplanet HAT-P-14 b. [2]
- JWST yields unprecedented precision and stability in spectroscopic timeseries data.
- There are no obvious and/or unexpected systematic errors that limit the interpretation of the data. We have not yet identified a noise floor for JWST timeseries data. As we average more data together, the precision continues to improve.
- Data from different instruments are consistent in the overlap regions.

These findings have profound implications. For example, several pre-launch studies were conducted to predict JWST capabilities for transiting exoplanet science. Among those were studies of the seven terrestrial-size planets orbiting the nearby M-type star, TRAPPIST-1. Three of its planets orbit in the Habitable Zone. Those studies predicted that JWST would be capable of detecting the presence of an atmosphere should one exist and identify the dominant background gas assuming enough transits are observed. Pre-launch predictions were based on models of how we thought the telescope would perform. Now we have ground-truth observations that confirm the models and confirm that we can achieve our science goals with JWST even for these challenging exoplanets.

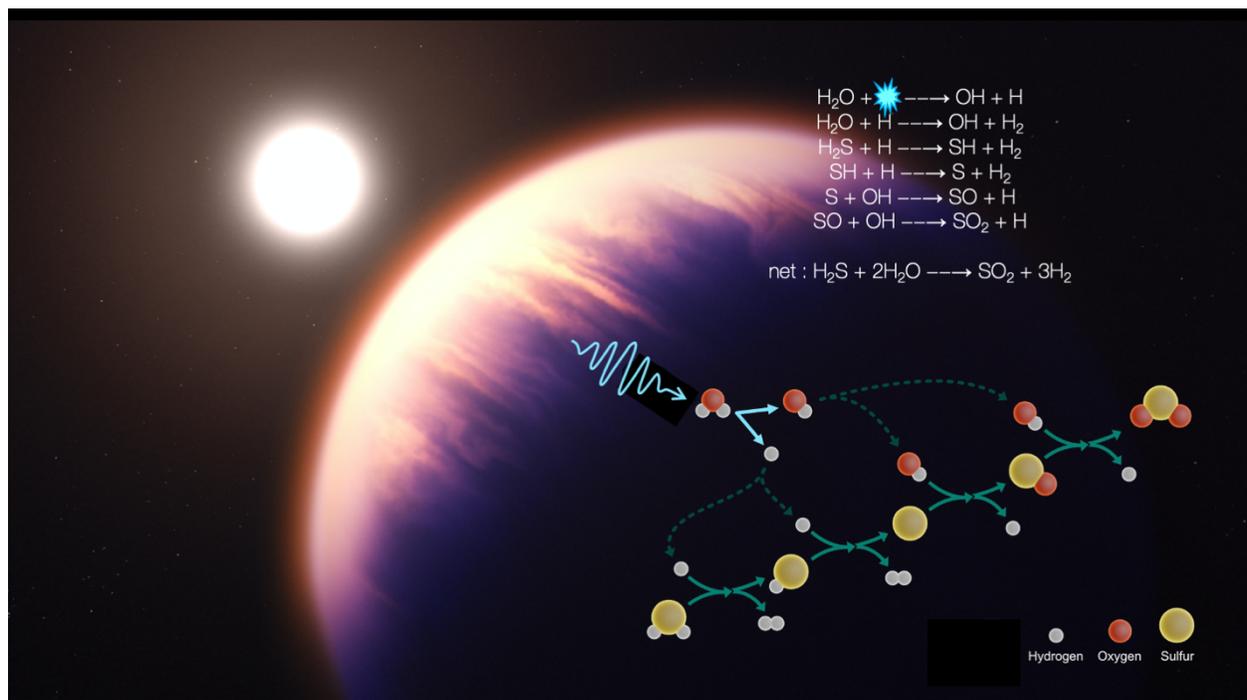


Figure 4. Detailed modeling reveals that SO_2 in the WASP-39b atmosphere is produced by photochemistry – chemical reactions catalyzed by high-energy starlight (light blue symbols). Photochemistry is fundamental for life on Earth to thrive, from the production of ozone in the upper atmosphere to photosynthesis in plants and algae to the production of Vitamin D in our skin. (Credit: R. Hurt, JPL)

Looking Forward:

With its unprecedented precision, stability, and infrared wavelength coverage, JWST will catalyze a new epoch of exoplanet exploration characterized by atmospheric studies. Over 70 transiting exoplanets will be observed by JWST in Cycle 1 alone. Over its lifetime, hundreds could be studied providing a new lens on exoplanet diversity and a new survey data for demographic studies. From these data, we gain deep insights into planet formation and evolution processes. We will learn about the nature of the mysterious but common super-earths/mini-neptunes. We will know if terrestrial-size planets orbiting M dwarfs have atmospheres, and we will lay the groundwork for identifying habitable environments and living worlds in the future.

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Current position:

2018- Professor of Astronomy & Director of Astrobiology, University of California, Santa Cruz

Previous positions:

2012-2018 Research Astrophysicist, NASA Ames Research Center, Moffett Field, California
2008-2012 Associate Professor of Physics and Astronomy, San Jose State University, California
2002-2008 Assistant Professor of Physics and Astronomy, San Jose State University, California
2000-2002 National Research Council Post-doctoral Fellow, NASA Ames Research Center
1998-2000 Postdoctoral Fellow, Observatório Nacional, Rio de Janeiro, Brazil

Education and degrees:

1997 PhD, Astrophysics, University of California, Santa Cruz, CA
1992 MSc, Astrophysics, Observatório Nacional, Rio de Janeiro, Brazil
1989 B.S., Physics and Astronomy, University of California, Berkeley, CA

Synergistic Activities:

NASA's Kepler Mission

2016-2017: Kepler Project Scientist, Mission Closeout Phase, NASA Ames Research Center
Duties include advocating for decisions that ensure the mission meets its science goals, advising the project manager on science matters, participating in scientific analyses, reviewing technical documents, interfacing with NASA headquarters and the Exoplanet Program Office, communicating science results to the public and the scientific community.

2012- 2016: Kepler Mission Scientist, Extended Mission Phase, NASA Ames Research Center
Lead scientist for exoplanet occurrence rates; responsible for ensuring that the Kepler mission meets its science goals; interface between external science community and Kepler project office; member of Kepler's Science Leadership team; science liaison to Kepler Public Affairs;.

2010-2012: Kepler Science Team Lead, Prime Mission Phase, NASA Ames Research Center
Responsible for coordinating a 50+ member science team, devising strategies to achieve the science goals of the mission, organizing working groups to accomplish scientific goals. allocating resources, constructing budgets, interfacing with Kepler Education and Public Outreach team, working closely with NASA Public Affairs, and serving as chairperson of the Science Council.

NASA's Nexus for Exoplanet System Science

2014-2018: co-Lead for NASA's Nexus for Exoplanet Systems Science (NExSS)
NExSS is a cross divisional (Astrophysics, Planetary Sciences & Astrobiology, Earth Sciences, Heliophysics) research coordination network (17 teams, ~250 scientists) working to advance the field of planetary habitability and the search for life on exoplanets.

James Webb Space Telescope

2017 - 2021: James Webb Space Telescope Users Committee (JSTUC)
Committee serves as a conduit of information between STScI and the science community

2015-2017: James Webb Space Telescope Advisory Committee (JSTAC)
Advises the STScI on the Institute's readiness to support science operations with JWST, the implementation of NASA's science policies, and matters related to the general observer program.

Selected Recent Grants & Contracts:

NASA Interdisciplinary Consortia for Astrobiology Research (ICAR), PI
Follow the Volatiles, 2021 - 2026
Multi-Institutional, UCSC lead, \$5M

NASA Keck Key Strategic Mission Support FY20 - FY22, co-PI
The TESS-Keck Survey, FY20 - FY22
Space Telescope Science Institute, Early Release Science Program for JWST, PI
78.1 hours awarded, ~\$400k (FY21-22) + ~\$500k (FY22-23)
NASA Keck Key Strategic Mission Support 2018 A&B, co-I
A Spectroscopic Catalog of Kepler Planets Orbiting Cool Stars: Probing the Physics of
Photo-Evaporation, 10 nights awarded
NASA's Nexus for Exoplanet System Science, PI, 2015-2020
Management contract, NASA Astrobiology, ~\$100k per year

Individual Awards & Honors:

2020 Legacy Fellow of the American Astronomical Society
2019 Elected to American Academy of Arts & Sciences
2018 Honorary Doctorate, University of Uppsala, Sweden
2018 Alumni Achievement Award, UCSC
2017 Smithsonian Ingenuity Award in Physical Sciences
For scientific leadership of NASA's Kepler Mission.
2017 Time Magazine's List of the 100 Most Influential People of the World for 2017
2017 Lecar Prize, Harvard-Smithsonian Center for Astrophysics
For exceptional contributions to the study of extrasolar planets
2011 NASA Exceptional Public Service Medal
For outstanding leadership of the Kepler Science Team

Selected Recent Publications:

TESS-Keck Survey. V. Twin Sub-Neptunes Transiting the Nearby G Star HD 63935
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