JWST's eyes on an alien world

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Our galaxy is believed to have more than a hundred billion planets, with over 5,000 of them discovered so far. Of these, only around 50 have unveiled their composition beyond the most prevalent hydrogen and helium. Why is it so difficult? Unlike the exploration of planets within our Solar System where we can send probes to gather samples, studying exoplanets is more akin to wine tasting—we must rely on our sense of smell. Remote sensing is currently the only approach available for characterizing exoplanets. However, planets are usually small and faint compared with their big and bright host stars. Analyzing a firefly in the presence of a campfire is always challenging.

The molecules present in planetary atmospheres—the layer that is most easily accessible from the outside—absorb and emit light through their infrared vibrational-rotational bands. The infrared capability is essential for measuring the atmospheric structure, determining the atmospheric composition, and detecting potential signs of life on exoplanets. For over a decade, scientists have studied exoplanets utilizing ground-based and space-based telescopes with limited wavelengths. To fully characterize the exoplanet atmospheres, it is necessary to have a dedicated telescope with broad spectral coverage in the infrared.

Here comes the JWST. This 10 billion dollar space telescope was launched in 2021 and is now stationed at the Sun-Earth L2 Lagrangian point. As the largest space telescope in human history, JWST boasts unparalleled infrared sensitivity and resolution, equipped with multiple instruments and observational modes. All four instruments in the Integrated Science Instrument Module onboard the JWST are crucial for exoplanet research, including the near-infrared spectrograph (NIRSpec) (covering the wavelength range of 0.6–5 μm), the NIR camera (NIRCam) (0.6–5 μm), the fine guidance sensor/NIR imager and slitless spectrograph (NIRISS) (0.8–5 μm), and the mid-IR instrument (MIRI) (5–28 μm).

How effective is JWST in characterizing exoplanets? To address this question, NASA initiated the JWST Transiting Exoplanet Community Early Release Science (ERS) program to test various observational modes on the exoplanet WASP-39b. WASP-39b is a hot, Saturn-mass but Jupiter-sized planet, located around a G7-type star (our sun is G2-type) that is about 700 light years from us. Similar to 51-Pegasi b, the first exoplanet detected around a sun-like star, WASP-39b is a transiting planet that synchronously orbits its host star with a period of about 4 days. WASP-39b is approximately 1,200 K and is therefore not habitable.

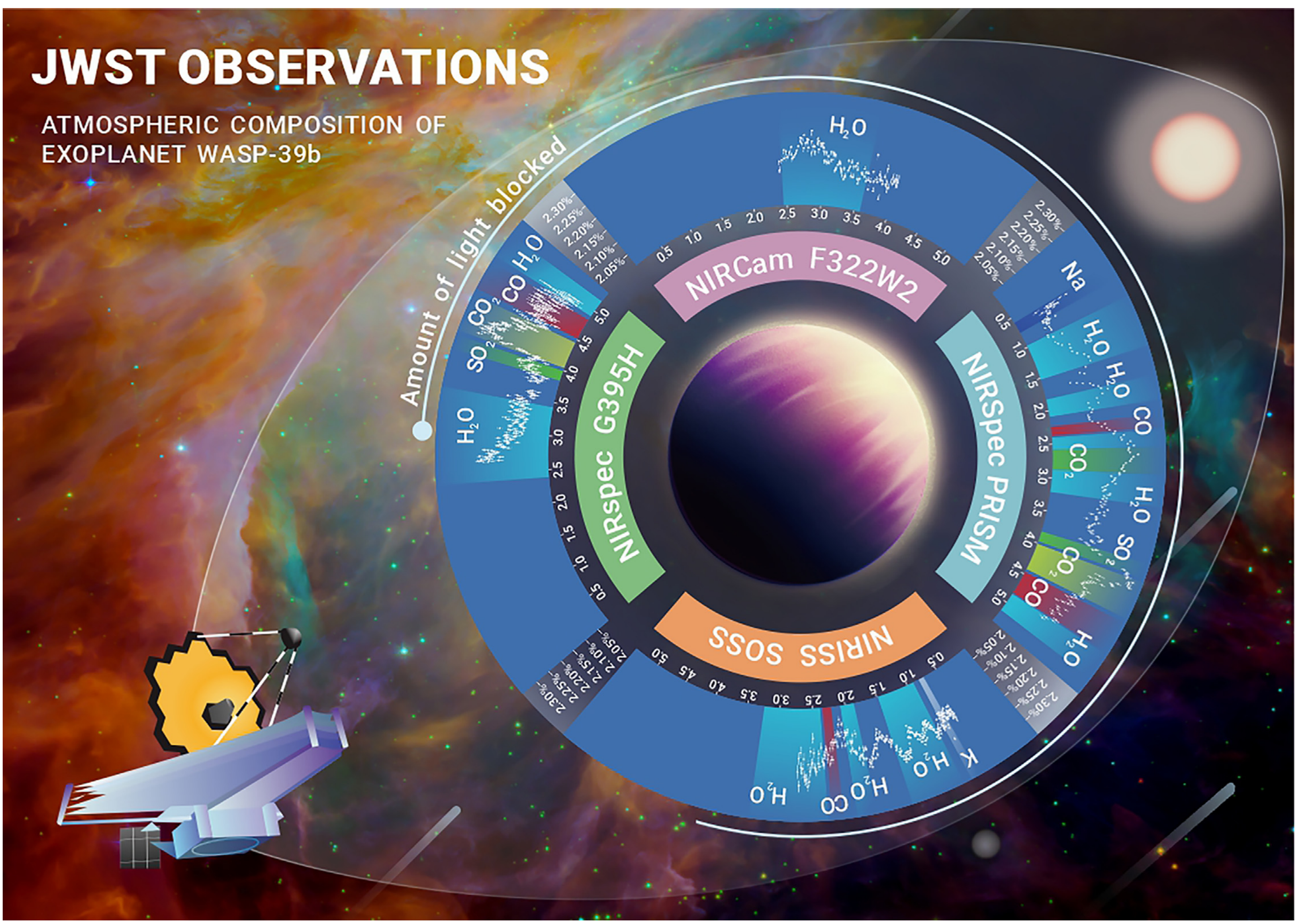

Figure 1. A compilation of the transmission spectra of WASP-39b from four observational modes of JWST in the Transiting Exoplanet Community ERS program. Important chemical species are identified. The horizontal axis is in units of microns.

But its puffy size makes it an ideal target for testing transmission spectroscopy during transits in front of its star, much like an eclipse. The atmosphere at the limb of the planet will filter part of the stellar light that reaches JWST. As different chemicals absorb photons at different wavelengths, a spectrum obtained by JWST contains valuable information about the planets.

In a series of papers,[1–5] the ERS team published an initial set of data on WASP-39b captured by JWST's NIRSpec PRISM mode, NIRSpec's G395H mode, NIRCam, and NIRISS' SOSS mode. The data quality obtained from JWST's spectrophotometry exceeded expectations and was significantly better than previous data collected by the Hubble space telescope and the Spitzer telescope. For the first time, a continuous spectrum of an exoplanet from 0.5 to 5.5 μm was obtained, providing stringent constraints on the temperature and chemical composition of WASP-39b (Figure 1). In addition to previously detected sodium, potassium, and water, JWST has detected carbon monoxide, carbon dioxide, and sulfur dioxide, and evidence of high-temperature clouds. It also put an upper limit on the abundance of methane. The ERS program demonstrates JWST's exquisite sensitivity to chemical signatures in exoplanet atmospheres. The scientific return from WASP-39b is also substantial, demonstrating that JWST will greatly enhance our understanding of the planetary structure, origin and evolution, and habitability—three fundamental themes in planetary characterization.

JWST is not just a standard telescope; it is a powerful microscope that can shed light on the subtle details of planetary structure. Synchronously rotating planets with a permanent day and night side should have strong variations across the planet. The ingress and egress of the primary eclipse can provide information about the differences in the atmospheric composition at the planet's leading and trailing hemispheres. Previous telescopes lacked the sensitivity to resolve these details, but JWST can successfully accomplish this task. This achievement puts crucial constraints on the distributions of temperature and chemicals, providing insights into the dynamic circulation and mixing in the atmosphere. The ERS team is continually working toward a comprehensive understanding of the three-dimensional structure of the atmosphere.

The composition of a wine drop reflects the chemicals present in the grapes and the soil they are grown in. Similarly, the atmosphere of a planet can reveal its bulk composition and birthplace in a protoplanetary disk. The existence of synchronously rotating gas giants such as WASP-39b, which are not found in our Solar System, remains a mystery. Some theories suggest that these planets formed far away where water ice could condense and later migrate close to their host star. However, extraordinary claims require extraordinary evidence. The enrichment of elements heavier than hydrogen and helium and the elemental ratios provide important clues about the planet's origin. The initial analysis of JWST spectra reveals the abundance of chemical species to support these findings. As a late G-type star, WASP-39 has a similar composition to our Sun. However, WASP-39b was found to have 10 to 30 times solar metallicity, a sub-solar carbon-to-oxygen ratio, and a solar-to-super-solar potassium-to-oxygen ratio. These results suggest that WASP-39b may have formed outside the water ice line, but with significant contamination by solids during formation and migration. For over a decade, the carbon-to-oxygen ratio has been used as the primary method to infer planetary origins. With access to species like sodium, potassium, carbon, oxygen, and sulfur, we now have the ability to study the history of exoplanets in a more comprehensive and nuanced manner.

WASP-39b is too hot to be habitable. However, the JWST ERS program has found compelling evidence of photochemistry, a crucial process that impacts planetary habitability, atmospheric composition, and stability. For the first time in an exoplanet atmosphere, sulfur dioxide was unambiguously detected at 4.05 μm, providing strong evidence of photochemistry. In a hydrogen-dominated atmosphere, sulfur forms hydrogen sulfide, but high-energy stellar photons destroy it in the upper atmosphere. This process liberates sulfur radicals, which are then oxidized to produce sulfur dioxide. These chemical pathways were first established in Earth and Solar System science, demonstrating the potential for collaboration between exoplanet science and Solar System science in the JWST era. The sulfur feature is highly sensitive to atmospheric processes and bulk sulfur abundance, making it a new tool for understanding exoplanet atmospheres and formation. The team also predicted that sulfur dioxide may produce the largest feature in the mid-infrared spectra. Future JWST observations using the MIRI could validate their hypothesis.

JWST is a revolutionary game changer. The triumph of the ERS program is not only due to the advancements in infrared technology but also a result of successful international collaboration. Since receiving the first JWST data in July 2022, over 300 exoplanet scientists from around the world worked tirelessly for 6 months. Their expertise will continue to benefit the JWST science returns for years to come. Working with JWST data and collaborations will be an invaluable asset to their future careers, making it a mutually beneficial opportunity.

What's next? WASP-39b is just one of the hundred billion exoplanets in our galaxy. If it is a drop in a wine glass, there is a full house of wine bottles waiting to be uncorked. JWST is currently observing many other targets, including Neptune-size planets and Earth-sized planets in habitable zones. In addition to the transiting planet ERS program, NASA has also launched the High-Contrast Imaging of Exoplanets and Exoplanetary Systems ERS program, targeting self-luminous planets to minimize contamination from their distant host stars. This program has also seen great success, further solidifying the notion that JWST has ushered in a new era of exoplanet characterization. For over a century, astronomers have been using spectroscopy to characterize and classify stars in the galaxy. Now it is time to do the same for planets. To characterize 1 hundred billion exoplanets, a deep spectroscopic survey of the entire sky will be needed to map out the statistical properties of planetary systems in our neighborhood.

The Spitzer telescope retired in 2020, and the Hubble space telescope is set to come to an end in the near future. But for exoplanetary characterization, this is not the end, but rather just the beginning of a new chapter. JWST has inherited the legacy of its predecessors and embarked on a new journey to uncover the deepest mysteries of nature. It will shed light on the numerous alien worlds lurking in the deep universe, and perhaps one day it may even bring us a message from our kin in a nearby stellar system.

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DECLARATION OF INTERESTS

The authors declare no competing interests.