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The Role of the James Webb Space Telescope in Exoplanet Studies and the Search for Life Beyond Earth

Introduction

Launched in late 2021, the James Webb Space Telescope (JWST) has had an arguably significant role in advancing our understanding of astronomy. High among these, and the focus of this essay, is on exoplanetary research. This essay will open on the technology and instrumentation on board the JWST, in particular the Near-Infrared Spectrograph (Birkmann, et al. 2022, p. 2), the Mid-Infrared Instrument (Wright et al., 2015, pp. 596,598) and its applications to exoplanetary research (Rieke et al., 2015, pp. 586-588). This will then lead to a discussion regarding current exoplanetary research based off data obtained by the JWST, including the analysis of the planetary atmospheres of WASP-39b, TRAPPIST-1b and TRAPPIST-1c. and the potential in highlighting conditions indicative of the potential for habitability, before concluding with an evaluation of both where the field is headed and the status of the ongoing search for potentially habitable exoplanets.

The Near-Infrared Spectrograph: Function and Applications to Exoplanet Research

Integral to the characterisation of exoplanetary atmospheres is the Near-Infrared Spectrograph, or NIRSpec. Birkmann and coauthors summarise NIRSpec as capable of making observations in the near-infrared, of wavelengths 0.6-5.3 μm (Birkmann, et al. 2022, p. 2). This requires an operating temperature of around 42.8K, as infrared observations are very sensitive, even to the heat signature of the JWST itself.

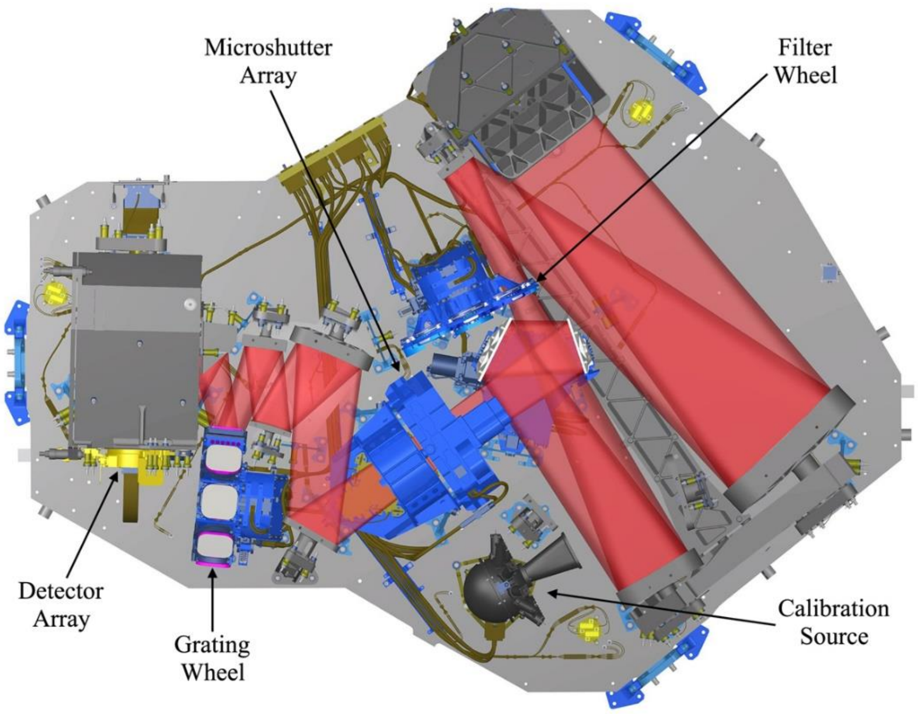

Figure 1: CAD rendering of NIRSpec with its three major mechanisms and the calibration source identified. (Source: Jakobsen et al., 2022, p. 3)

Figure 1 provides a visual overview of the structure and major components of NIRSpec. Birkmann and coauthors describe the Microshutter Array as an instrument capable of simultaneous spectroscopy of over 100 individual sources, allowing for efficient use of the JWST's time (Birkmann, et al. 2022, p. 2). NIRSpec also features an Integral Field Unit (not labelled in Figure 1), which has 3D-spectroscopy capabilities, and five apertures for high contrast precision spectroscopy of individual objects (not labelled in Figure 1). One of these apertures, a 1.6'' x 1.6'' wide aperture known as S1600A1 was specifically introduced for time-series observations of bright sources, for example the transit of a star by an orbiting exoplanet. This variety in instrumentation arguably makes NIRSpec well suited to a variety of interstellar observations, exoplanetary characterisation high among these.

To achieve the aforementioned low temperatures required for infrared observations with NIRSpec, two distinct measures were taken to ensure a low operating temperature. The first of these measures was the inclusion of a sun-shield in the design of the telescope (NASA, no date). Shaped like a kite, the sunshield separates the telescope into a warm side, facing the sun, and a cool side, which is where the infrared instrumentation is housed. The sunshield achieves this via radiating heat into outer space. The second measure taken was to position the JWST at the L2 point (NASA, no date). L2 is one of five Lagrange points, allowing for satellites placed in orbit there to maintain their position in line with the Earth. This is integral for the JWST, as this ensures that the Sun, Earth and Moon are on the warm side of the sunshield, protecting the telescope's infrared instrumentation from the heat of those three bodies.

The Mid-Infrared Instrument: Function and Applications to Exoplanetary Research

Unlike the other instruments aboard the JWST, the Mid Infrared Instrument (MIRI) observes in the mid-infrared section of the electromagnetic spectrum in the range 5-28.5μm (Wright et al., 2015, p. 596). As a result, the instrument is far more sensitive to heat, requiring an operating temperature of less than 6.7K, of which the passive cooling provided by the aforementioned sunshield isn't sufficient. As such, a cooler system was implemented to ensure the low operating temperatures required for MIRI's operation (Wright et al., 2015, p. 598).

Rieke and coauthors describe two key applications of MIRI (Rieke et al., 2015 pp. 586-588). The first is its imaging potential of exoplanets up to 0.1-0.2 Jupiter masses, particularly those a distance in excess of 10 AU from their host stars. However, the second of these, transit and eclipse spectroscopy, has potential to enable detailed characterisation of the chemical composition of exoplanetary atmospheres and how said atmospheres redistribute heat. As elaborated upon later in this essay regarding TRAPPIST-1b and TRAPPIST-1c, there is potential to determine whether a planet has significant atmosphere, a key prerequisite for any possibility of habitability.

Case studies of exoplanetary atmospheric analysis via the James Webb Space Telescope

WASP-39b

WASP-39b is a roughly Saturn-mass exoplanet located relatively close to its star, having an orbital period of around four days (Faedi et al., 2011, p. 1). As part of the JWST Transiting Exoplanet Community Early Release Science Program, WASP-39b was selected for observation by NIRSpec's PRISM (Rustamkulov et al., 2023, pp. 659-

663) and G395H (Alderson et al., 2023, pp. 664-669) modes in July 2022. Siedel and coauthors summarise the key findings from both papers, in which it was found that elements greater in atomic mass than helium were more common in the atmosphere of WASP-39b than that of the Sun (Seidel et al., 2023). Additionally, the carbon to oxygen ratio measured for WASP-39b, often used in deducing where an exoplanet formed, is indicative of the planet forming beyond the water ice line, the region beyond which water typically exists as solid ice. This suggests that the planet migrated to its current position later in its lifetime, potentially owing an explanation as to how gas giants like WASP-39b can exist so close to their parent stars. However, Alderson and coauthors rule out the formation of WASP-39b beyond the carbon dioxide ice line indicative of a C/O ratio greater than one, instead suggesting that the planet formed at a distance where the accretion of gas was still a possibility, but that the accretion of oxygen-rich solids enriched its atmosphere early in formation (Alderson et al., 2023, p. 667).

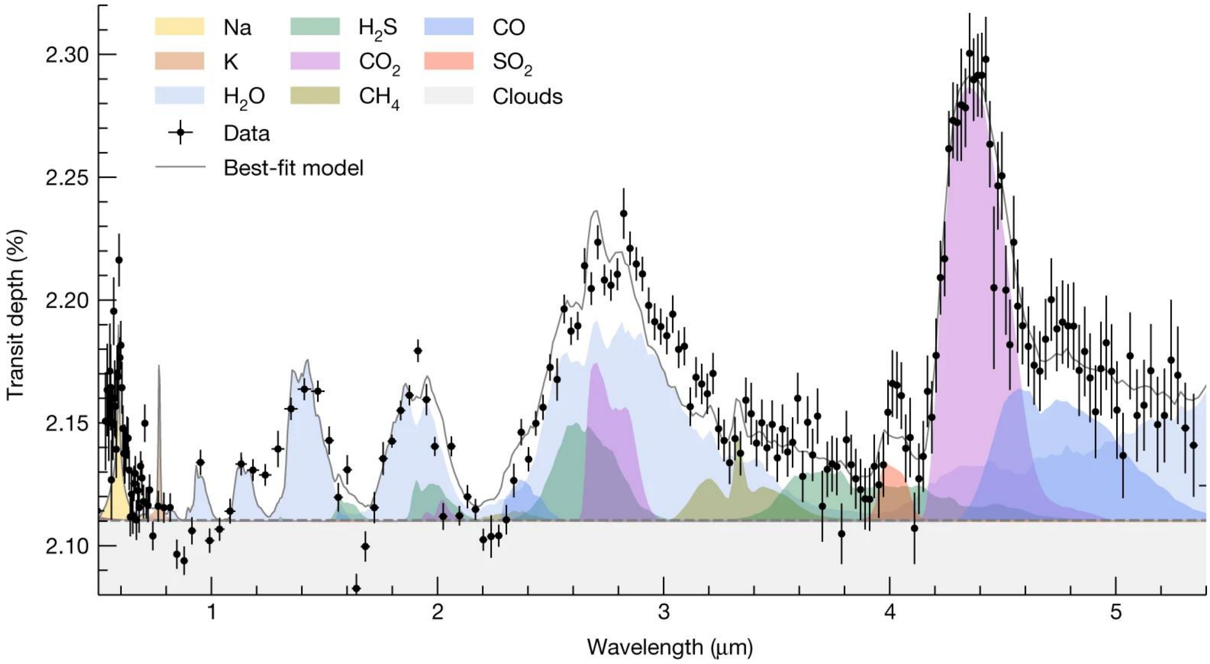

Figure 2: The transmission spectrum of WASP-39b via NIRSpec PRISM, with chemicals offering key contributions to the spectrum highlighted. (Source: Rustamkulov et al., 2023, p. 662).

One detection of particular interest as shown in Figure 2 is that of SO_2, detected at a wavelength of 4μm. Rustamkulov and coauthors discuss this detection to be indicative of an unusually high abundance of SO_2, and suggests that photochemical reactions, where due to the action of UV radiation (Seidel et al., 2023) compounds containing sulfur are broken apart and recombine into SO_2 in concentrations significantly greater than what would otherwise be expected (Rustamkulov et al., 2023, p. 662). This detection thus serves as the first evidence for photochemical reactions in exoplanetary atmospheres. This is significant in the search for planets with potential to harbour life, in part due to the protection of planetary surfaces from high-energy irradiation as a result of photochemical reactions.

TRAPPIST-1b

TRAPPIST-1 is a system consisting of seven terrestrial planets of a similar order of magnitude in both mass and size to the Earth, which orbit a cool red dwarf star of 0.09 solar masses (Greene et al., 2023, p. 39). The JWST's MIRI was involved in attempting to detect the atmospheric features of TRAPPIST-1b, the closest planet to the system's host star via measurement of thermal emission during secondary eclipses. Via this approach, a dayside blackbody brightness temperature of 503K, with uncertainty +26/-27 K, was calculated. These observations are likely to be indicative of no heat redistribution to the nightside of TRAPPIST-1b, which if occurring would have presented a lower dayside blackbody brightness temperature than what was compatible with the observations documented in Greene and coauthor's paper (Greene et al., 2023, pp. 40-41). Further incompatibilities with models suggesting an atmospheric composition of either CO_2 or a combination of CO_2 and O_2 suggests TRAPPIST-1b likely possessing negligible atmosphere of any kind. With red dwarf stars such as TRAPPIST-1 well characterised by energetic stellar activity enough to strip away the atmospheres of their planets, especially in the first billion years after formation, these observations have consistency with models of TRAPPIST-1b gradually losing its atmosphere over time.

TRAPPIST-1c

The second closest planet to its host star, TRAPPIST-1c was also a focus for thermal emission measurements via secondary eclipse observations. Olson summarises the end result of having been similar to that of TRAPPIST-1b, in that TRAPPIST-1c either possesses very little to no atmosphere whatsoever (Olson, 2023). Zieba and coauthors elaborate further on the particular lack of thick CO_2 and O_2 based atmospheres for TRAPPIST-1c, highlighting that the planet formed with little volatile substances such as water, with the planet possessing anywhere from 9.5 Earth ocean masses of water, to less than 4.0 Earth ocean masses for assumed CO_2 concentrations of greater than 10 ppm (Zieba et al., 2023, [Preprint], pp. 3-4). If the scarcity of volatiles is consistent with the TRAPPIST-1 planets within the host star's habitable zone, such lack of volatile abundance may be a common outcome for planets orbiting red dwarf stars and a potential roadblock in their potential to host life, a suggestion that will without a doubt prompt further follow-up study.

Conclusion

Throughout the past year, the JWST has played an arguably significant role in characterising the atmospheric properties of exoplanets, an area key to determining the possibility of extraterrestrial life, which is a prospect simultaneously supported, through the evidence of photochemical reactions on WASP-39b (Rustamkulov et al., 2023 p. 662), and possibly doubted, by the presence of little to no atmosphere for both TRAPPIST-1b (Greene et al., 2023, pp. 39-41). and TRAPPIST-1c (Zieba et al., 2023, [Preprint], pp. 3-4), a possibility with potential to be common among many terrestrial planets orbiting red dwarf stars and that follow-up observations of other similar exoplanets via the JWST have the potential to confirm.

Furthermore, it is evident that both NIRSpec and MIRI, the two of four instruments focused upon in this essay, are well adapted to their function in regards to exoplanet characterisation, as proven by the aforementioned discoveries in the last year. This is clearly aided by the sunshield design and positioning of the JWST at L2 (NASA, no date), ensuring the very low operating temperatures required for said instruments to function, conditions that cannot be replicated by ground-based observatories here on Earth. With JWST still in the beginning era of its mission, without a doubt our understanding of exoplanets will enhance, with their potential for hosting life facing both additional hope and likely challenge as the field progresses in the next decade.

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