EPSC Abstracts
Vol. 18, EPSC-DPS2025-182, 2025, updated on 12 May 2026
https://doi.org/10.5194/epsc-dps2025-182
EPSC-DPS Joint Meeting 2025

JWST Observes the CO2-rich Surfaces of Uranus' Large Moons

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Over the past 20+ years, ground-based observations have determined that the surfaces of the large Uranian moons Ariel, Umbriel, Titania, and Oberon are enriched in CO_2 ice via the detection of a CO_2 "triplet band" between 1.9 and 2.1 µm [1,2]. The spectral properties of the detected CO_2 is strikingly similar to crystalline CO_2 ice measured in the laboratory. The origin of CO_2 on these moons and across the Uranus system, however, remains uncertain. CO_2 ice is unstable at the estimated peak surface temperatures of these moons (80-90 K), and it must be replenished [3]. It has been suggested that CO_2 could be formed radiolytically via irradiation of H_2O ice mixed with carbon-bearing compounds, possibly explaining the stronger CO_2 features detected on the trailing hemispheres of these satellites [1,2]. Alternatively, the large moons of Uranus are candidate ocean worlds that may host subsurface saline oceans, possibly enriched in carbonate (CO_3^{2-}) species and CO_2. These carbon-bearing compounds could be outgassed or exposed through geologic processes [4]. Understanding the origin of CO_2 and other carbon oxides in the Uranus system is one of the key science questions driving the rationale for future measurements made by a near-infrared (NIR) mapping spectrometer onboard a Uranus orbiter [5].

More recent observations made with the NIRSpec spectrograph (G395M, 2.9 – 5.1 µm, R ~ 1000) on the James Webb Space Telescope (program 1786, [4]) were able to identify the strong CO_2 asymmetric stretch fundamental mode (v_3), roughly spanning 4.2 to 4.4 µm, a wavelength range inaccessible from the ground due to telluric CO_2 absorption. The CO_2 v_3 mode is a factor of ~1000 stronger than the CO_2 triplet band measured in prior ground-based observations, and therefore, we predicted that the Uranian moons would exhibit strong and possibly saturated CO_2 ice absorption features across the 4.2 to 4.4 µm wavelength range, similar to NIRSpec data of Neptune's moon Triton [6]. However, the $^{12}CO_2$ ice bands detected by NIRSpec on the trailing hemispheres of these moons are surprisingly weak, and instead, are convolved with scattering peaks that obscure these absorption features (***Figure 1***). NIRSpec also revealed $^{12}CO_2$ on the leading hemispheres of these moons and hyper-volatile CO ice on their trailing sides. Furthermore, $^{13}CO_2$ is present, primarily on the inner moons Ariel and Umbriel, and CO_3-bearing species, carbon chain oxides (C_XO_2), and CN-bearing organics (nitriles) may also be present on Ariel and Umbriel (***Figure 1***). Thus, the surfaces of the large Uranian moons are enriched in carbon oxides, especially Ariel [4].

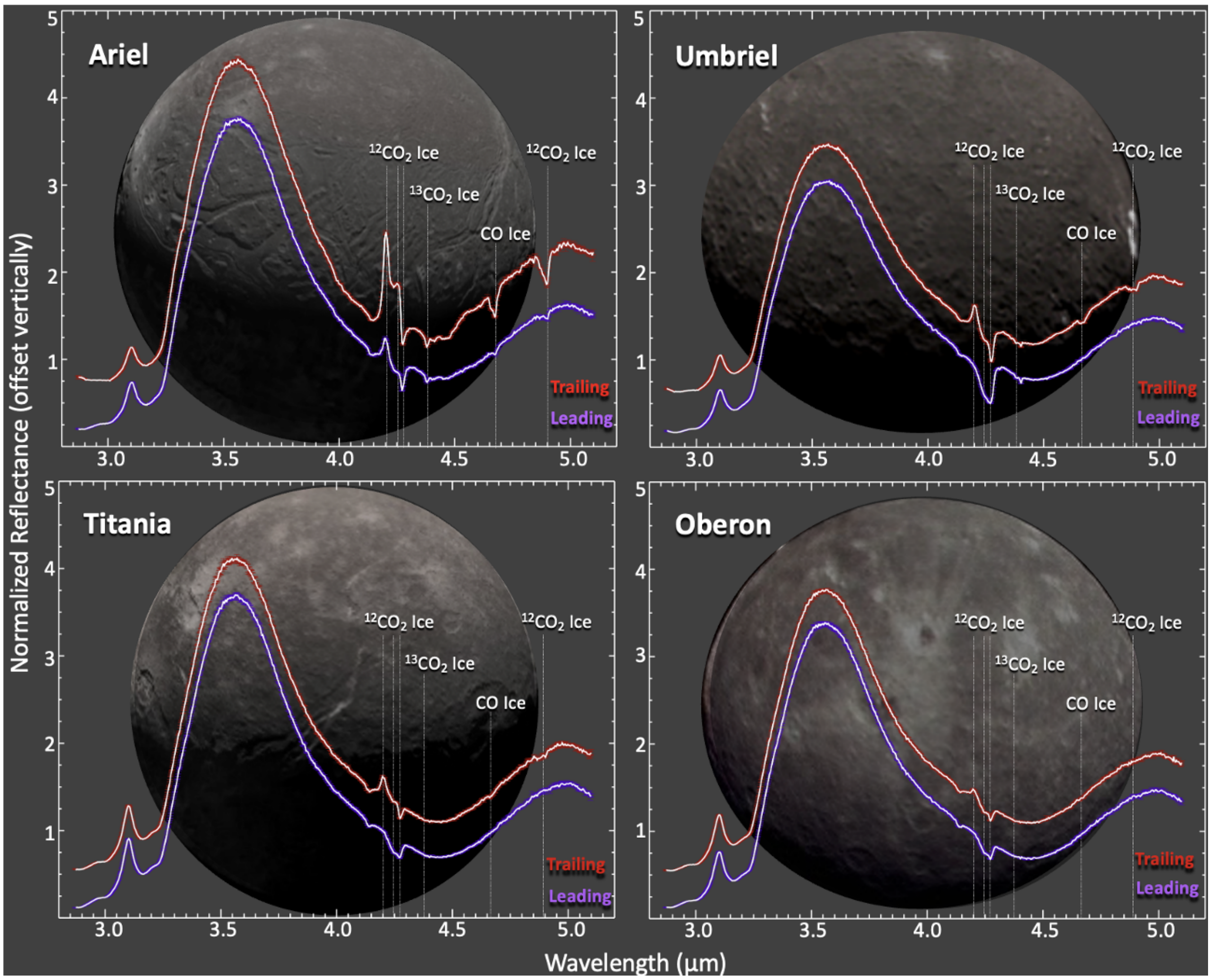

Figure 1: *JWST/NIRSpec data (G395M) of the large Uranian moons, normalized to 1 at 4.14 µm*

and offset vertically for clarity.

At first glance, the detected species and their hemispherical distributions are broadly consistent with prior ground-based observations, supporting radiolytic production of CO_2 and other carbon oxides via charged particles trapped in Uranus' magnetosphere. However, none of the data display notable hydrogen peroxide (H_2O_2) combination modes near 3.51 μm, features that laboratory experiments have shown to emerge in irradiated H_2O ice substrates (< 100 K), in particular when mixed with small amounts of CO_2 [7], representing conditions relevant to the surfaces of Uranus' moons. Furthermore, icy satellites at Jupiter and Saturn tend to display darker and redder trailing hemispheres over UV/VIS wavelengths due to irradiation by corotating plasma, but observations made with Hubble's Space Telescope Imaging Spectrograph (~200 – 550 nm) indicate no such hemispherical asymmetry in albedo for the large moons of Uranus [8]. Because Uranus' magnetosphere is notably offset from the orbital plane of its satellites (~59°) and seemingly devoid of heavy ions (i.e., C^{n+}, O^{n+}), it is possible that moon-magnetosphere interactions may be somewhat limited at Uranus. Instead, perhaps CO_2 is primarily native to the large moons and exposed by geologic processes, such as cratering, tectonism, cryovolcanism, and outgassing.

Other observations by JWST (program 4645) have revealed that CO_2 is present across the Uranian system, including in its rings, ring moons, and irregular satellites [9,10]. The origin(s) of CO_2 on these smaller bodies and rings is presumably varied, but almost certainly includes native sources of CO_2, especially on the far-flung irregular satellites that orbit well beyond the influence of Uranus' magnetosphere and exhibit strong 4.27 μm and 2.7 μm features, consistent with native CO_2. Similar to the large moons, CO_2 ice is unstable on these small bodies and rings and must be replenished and trapped in more refractory compounds.

To gain a more complete understanding of the origin and nature of these species will require a Uranus orbiter equipped with a NIR mapping spectrometer and a charged particle suite making measurements during close passes [11]. We will present NIRSpec results and analyses for carbon oxides on the large moons Ariel, Umbriel, Titania, and Oberon and provide an update on the developing picture of the origin of carbon oxides in the Uranus system in the JWST era.

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