A CO₂ Cycle on Ariel? Radiolytic Production and Migration to Low-latitude Cold Traps

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Abstract

CO₂ ice is present on the trailing hemisphere of Ariel but is mostly absent from its leading hemisphere. The leading/trailing hemispherical asymmetry in the distribution of CO₂ ice is consistent with radiolytic production of CO₂, formed by charged particle bombardment of H₂O ice and carbonaceous material in Ariel’s regolith. This longitudinal distribution of CO₂ on Ariel was previously characterized using 13 near-infrared reflectance spectra collected at “low” sub-observer latitudes between 30°S and 30°N. Here we investigated the distribution of CO₂ ice on Ariel using 18 new spectra: 2 collected over low sub-observer latitudes, 5 collected at “mid” sub-observer latitudes (31°N–44°N), and 11 collected over “high” sub-observer latitudes (45°N–51°N). Analysis of these data indicates that CO₂ ice is primarily concentrated on Ariel’s trailing hemisphere. However, CO₂ ice band strengths are diminished in the spectra collected over mid and high sub-observer latitudes. This sub-observer latitudinal trend may result from radiolytic production of CO₂ molecules at high latitudes and subsequent migration of this constituent to low-latitude cold traps. We detected a subtle feature near 2.13 μm in some low sub-observer latitude spectra, which might result from a “forbidden” transition mode of CO₂ ice that is substantially stronger in well-mixed substrates compared of CO₂ and H₂O ice, consistent with regolith-mixed CO₂ ice grains formed by radiolysis. Additionally, we detected a 2.35 μm feature in some low sub-observer latitude spectra, which likely include a carbon-rich component (Clark & Lucey 1984). CO₂ ice has also been detected on Ariel, Umbriel, Titania, and Oberon via three prominent absorption features centered near 1.966, 2.012, and 2.070 μm (Grundy et al. 2003, 2006; Cartwright et al. 2015). These bands are stronger on the trailing hemispheres of these moons (longitudes 181°–360°) compared to their leading hemispheres (longitudes 1°–180°). Furthermore, these CO₂ ice bands are strongest on Ariel and get progressively weaker with increasing orbital radius, with the weakest CO₂ bands detected on the outermost classical moon Oberon (e.g., Cartwright et al. 2015).

Previous studies have suggested that the observed longitudinal and radial trends in the distribution of CO₂ ice are consistent with a radiolytic origin (Grundy et al. 2006; Cartwright et al. 2015). In this scenario, charged particles from Uranus’s magnetosphere bombard native H₂O ice and carbonaceous material exposed on the surfaces of the classical moons, driving radiolytic production of CO₂ molecules. Because Uranus rotates faster (~17.2 hr) than the orbital periods of its classical moons (~1.4–13.5 days), charged particles trapped in its magnetosphere should preferentially interact with their trailing hemispheres as Uranus’s magnetic field lines sweep past these moons. Voyager 2 observed depletions in magnetospheric charged particle flux near the orbital location of some of the Uranian moons (including Ariel),

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hinting at extensive interactions between Uranus’s magnetosphere and the surfaces of its moons, possibly driving radiolytic chemistry (e.g., Paranicas et al. 1996). Alternatively, CO$_2$ ice could be a native constituent on the classical moons that is sourced from their interiors by geologic processes that expose and/or emplace material rich in CO$_2$, perhaps similar to Enceladus, where plume activity has likely deposited large amounts of CO$_2$ on its surface (e.g., Waite et al. 2006; Combe et al. 2019).

The spectral signatures of the detected CO$_2$ bands are remarkably consistent with “pure” CO$_2$ ice measured in the laboratory (i.e., segregated from other constituents in concentrated deposits with crystal structures dominated by CO$_2$ molecules; e.g., Hansen 1997; Gerakines et al. 2005). At the estimated peak surface temperatures of the Uranian moons (80–90 K; Hanel et al. 1986; Sori et al. 2017), CO$_2$ ice is thermodynamically unstable over geologic timescales (Grundy et al. 2006; Sori et al. 2017). Because of Uranus’s large obliquity (∼98°), the poles of the classical moons are bathed in continuous sunlight during the Uranian system’s long summers. As a result, long-term cold traps for CO$_2$ ice are likely concentrated at low latitudes, where the timescales of maximum solar heating are much shorter compared to high latitudes (Grundy et al. 2006; Sori et al. 2017). Additionally, CO$_2$ molecules should concentrate at similar longitudes to where they were formed or exposed (Sori et al. 2017), likely explaining why CO$_2$ ice remains concentrated on the trailing hemisphere of Ariel and the other Uranian moons. Thermodynamical models therefore predict that CO$_2$ molecules generated or exposed at polar latitudes should sublimate, migrate to equatorial latitudes, and condense in cold traps, primarily on Ariel’s trailing hemisphere.

Previously analyzed NIR spectra were collected during late southern summer and northern spring (subsol lar latitudes 30°S–25°N), when low-latitude regions that are likely rich in CO$_2$ (30°S–30°N) represented >50% of these moons’ observed disks. Consequently, modeling results that suggest that CO$_2$ could be generated/exposed at high latitudes and then migrate to low-latitude cold traps have not been tested using spectra collected at higher sub-observer latitudes that better sample polar regions. We present new results on the distribution of CO$_2$ ice on Ariel, the Uranian moon with the strongest CO$_2$ ice bands, using NIR spectra collected over “mid” sub-observer latitudes (31°N–44°N) and “high” sub-observer latitudes (45°N–51°N) latitudes, thereby expanding on the latitudinal coverage provided by previously collected spectra.

When possible, observations were made using slit orientations that matched or were similar to the parallactic angle to minimize atmospheric dispersion, which can introduce spectral slope changes to the continuum of spectra over visible and NIR wavelengths, in particular at wavelengths $\lesssim$1.2 μm. Some of the observations of Ariel were made using slit orientations that deviated notably from the parallactic angle to minimize scattered light from the bright disk of Uranus. Nevertheless, it is likely that atmospheric dispersion over the wavelength range of the CO$_2$ ice bands between 1.5 and 1.7 μm did not exceed 0′′05 and was typically <0′′02 (relative to 2.2 μm). Atmospheric dispersion over the wavelength range of the CO$_2$ ice bands between 1.9 and 2.1 μm did not exceed 0′′02 and was typically <0′′01 (relative to 2.2 μm). Consequently, the impact of atmospheric dispersion on our measurements and modeling of the spectral continuum proximal to these CO$_2$ ice bands is likely negligible.

IRTF/SpeX observations were made by placing Ariel in two different positions (“A” and “B”) separated by 7″5 on a 15″-long slit. The resulting exposures were separated into sequential “AB” pairs. We then subtracted the B exposures from the A exposures to provide a first-order correction for sky emission. The resulting A–B subtracted pairs were flat-fielded to account for variations across the detector. Flat frames were generated by illuminating SpeX’s internal integrating sphere with a quartz lamp. Wavelength calibration was performed using argon emission lines. We used the SpeXtool data reduction suite (Cushing et al. 2004), along with custom programs, to calibrate and extract all Ariel spectra. To remove the solar spectrum, perform additional atmospheric correction, and remove instrument artifacts, all Ariel spectra were divided by solar analog star spectra, which were observed on the same night and close in time and airmass to the observations of Ariel (within ±0.1 airmass). We observed HD 12124 (G0) and HD 16275 (G5) in 2020. To increase signal-to-noise (S/N), all star-divided frames from the same night were co-added, and the resulting uncertainties were calculated using the standard error (σ/$\sqrt{N}$) of each co-added pixel. The other 21 SpeX spectra we analyzed were collected by different teams between 2000 and 2019 (Grundy et al. 2003, 2006; Cartwright et al. 2015, 2018, 2020a).

Spectra collected with ARC 3.5 m/TripleSpec were obtained in a similar manner. The A and B positions are separated by 21″ along a 1″1 × 43″ slit. The length of the TripleSpec slit sometimes allowed for opportunities to place multiple Uranian moons in the slit simultaneously. In these cases, the moons did not fall exactly on the nominal A and B positions, but the spectra were reduced and extracted using the same A–B procedure. Data reduction was performed using TripleSpecTool, a modified version of SpeXtool (Cushing et al. 2004). Flat frames were obtained with quartz lamps mounted on the telescope structure. We subtracted equivalent-length, unilluminated exposures from the lamp flats to remove intrinsic telescope thermal emission. Wavelength calibration was performed using OH airglow emission lines in our science frames. For our telluric correction, we observed the solar analog stars HD 16017 (G2V), BD+15 4915 (G2V), HD 19061 (G2V), and HD 224251 (G2V) in 2019 and 2020 and HD 16275 (G5) in 2021, usually within ±0.1 airmass of our observations of Ariel.

2. Data and Methods

2.1. Observations and Data Reduction

We analyzed 31 NIR reflectance spectra, 10 of which are reported here for the first time, with the other 21 spectra reported previously (observation details summarized in Table 1; Grundy et al. 2003, 2006; Cartwright et al. 2015, 2018, 2020a). Four of the new spectra and all 21 previously reported spectra were collected using the NIR SpeX spectrograph/imager at NASA’s Infrared Telescope Facility (IRTF), operating in moderate-resolution short cross-dispersed (SXD) mode (∼0.7–2.5 μm; e.g., Rayner et al. 2003). The other six new spectra were collected using the TripleSpec spectrograph (0.95–2.46 μm) on the Astrophysical Research Consortium (ARC) 3.5 m telescope at the Apache Point Observatory Wilson et al. (2004).
Table 1
IRTF/SpEX and ARC 3.5 m/TripleSpec Observations of Ariel

| Sub-observer Long. (deg) | Sub-observer Lat. (deg) | UT Date | UT Time (Mid-expos) | Integration Time (minutes) | Spectrograph | Slit Width (arcsec) | Average Resolving Power ($\lambda/\Delta\lambda$) | References |
|--------------------------|-------------------------|---------|---------------------|---------------------------|-------------|-------------------|-------------------------------------------|------------|
| 6.8                      | 44.8                    | 1/18/20 | 4:20               | 76                        | TripleSpec  | 1.1               | 3500                                      | This work |
| 15.3                     | 9/15/14                 | 3:55    | 11:35              | 88                        | SpeX       | 0.8               | 750                                      | Cartwright et al. (2018) |
| 26.7                     | 1/5/21                  | 3:55    | 50                 | 156                       | SpeX       | 0.3               | 2000                                      | This work |
| 53.6                     | 8/9/03                  | 12:15   | 55                 | 108                       | SpeX       | 0.5               | 750                                      | Grundy et al. (2006) |
| 79.8                     | 9/17/02                 | 13:25   | 55                 | 108                       | SpeX       | 0.8               | 2000                                      | Cartwright et al. (2015) |
| 87.8                     | 9/5/13                  | 11:10   | 92                 | 108                       | SpeX       | 0.3               | 750                                      | Grundy et al. (2006) |
| 93.5                     | 9/10/04                 | 5:45    | 108                | 96                        | TripleSpec | 1.1               | 3500                                      | This work |
| 100.3                    | 11/4/19                 | 5:10    | 10                  | 44                        | SpeX       | 0.8               | 750                                      | Cartwright et al. (2018) |
| 110.1                    | 9/11/15                 | 13:30   | 92                 | 108                       | SpeX       | 0.3               | 750                                      | Cartwright et al. (2018) |
| 132.2                    | 8/24/14                 | 14:05   | 40                 | 73                        | SpeX       | 0.5               | 1200                                     | Cartwright et al. (2018) |
| 144.8                    | 10/                    | 9:20    | 60                 | 92                        | SpeX       | 0.5               | 1200                                     | This work |
| 152.9                    | 11/18                  | 10/     | 9:20               | 60                        | SpeX       | 0.5               | 1200                                     | This work |
| 159.9                    | 7/15/04                 | 12:00   | 112                | 84                        | SpeX       | 0.3               | 2000                                     | Grundy et al. (2006) |
| 200.0                    | 8/5/03                  | 12:00   | 84                 | 84                        | SpeX       | 0.3               | 750                                      | Grundy et al. (2006) |
| 205.5                    | 11/4/20                 | 9:30    | 84                 | 84                        | SpeX       | 0.8               | 750                                      | This work |
| 205.8                    | 11/7/19                 | 11:20   | 60                 | 90                        | SpeX       | 0.3               | 2000                                     | Cartwright et al. (2018a) |
| 219.8                    | 9/7/03                  | 9:35    | 60                 | 80                        | SpeX       | 0.8               | 750                                      | Grundy et al. (2006) |
| 231.8                    | 10/                    | 11:00   | 60                 | 90                        | SpeX       | 0.8               | 750                                      | This work |
| 233.8                    | 20/20                  | 14:10   | 50                 | 92                        | SpeX       | 0.5               | 1200                                     | Grundy et al. (2003) |
| 235.9                    | 13/19                  | 11:30   | 32                 | 112                       | SpeX       | 0.3               | 2000                                     | This work |
| 257.6                    | 9/6/00                  | 7:35    | 76                 | 84                        | SpeX       | 0.8               | 750                                      | Cartwright et al. (2015) |
| 260.2                    | 10/                    | 5:05    | 36                 | 36                        | TripleSpec | 1.1               | 3500                                     | This work |
| 263.7                    | 21/19                  | 6:40    | 20                 | 36                        | SpeX       | 0.5               | 750                                      | Cartwright et al. (2015) |
| 268.3                    | 26/19                  | 8:00    | 40                 | 36                        | SpeX       | 1.1               | 3500                                     | This work |
| 273.2                    | 15/17                  | 12:00   | 42                 | 84                        | SpeX       | 0.5               | 1200                                     | Cartwright et al. (2018a) |
| 278.3                    | 8/7/13                 | 13:20   | 44                 | 84                        | SpeX       | 0.5               | 1200                                     | Cartwright et al. (2018a) |
| 292.8                    | 18/20                  | 8:50    | 84                 | 36                        | SpeX       | 0.5               | 1200                                     | This work |
| 294.8                    | 9/30/17                | 9:30    | 120                | 84                        | SpeX       | 0.5               | 1200                                     | Cartwright et al. (2018a) |
| 294.8                    | 7/16/02                | 13:10   | 140                | 84                        | SpeX       | 0.5               | 1200                                     | Grundy et al. (2003) |
| 304.8                    | 7/8/01                 | 14:40   | 48                 | 84                        | SpeX       | 0.5               | 1200                                     | Grundy et al. (2003) |
| 316.6                    | 10/8/03                | 7:55    | 132                | 84                        | SpeX       | 0.3               | 2000                                     | Grundy et al. (2006) |
which we hereafter refer to as CO₂ bands 1, 2, and 3, respectively. To assess the distribution of CO₂ ice on Ariel, we measured the areas of these three CO₂ bands in each spectrum, using a custom program (Cartwright et al. 2015). The program identified the continuum for each CO₂ band (example shown in Figure A1), divided each CO₂ band by its continuum, and used the trapezoidal rule to measure the areas of the resulting continuum-divided bands. To estimate band area errors, the program used Monte Carlo simulations to resample the 1σ uncertainties for the spectral channels covered by each CO₂ band (iterated 20,000 times). After measuring all three CO₂ bands in a spectrum, the program summed them into one total band area and propagated errors.

2.3. Radiative Transfer Modeling

To complement our CO₂ ice band area measurements and provide additional context on the spectral signature of CO₂ ice on Ariel, we utilized a Hapke–Mie spectral modeling program to generate synthetic spectra of the grand average low, mid, and high sub-observer latitude spectra collected over Ariel’s trailing hemisphere (shown in Figure 1). These synthetic spectra are one-layer models that provide an estimate of the fractional area of Ariel’s trailing hemisphere covered by CO₂ ice and the grain sizes of all included constituents. In order to focus our modeling efforts on the spectral signature of CO₂ ice, we generated synthetic spectra spanning 1.5 to 1.7 μm and from 1.9 to 2.1 μm.

Mie theory, which is used to model scattering and absorption by randomly spaced spherical particles, can simulate scattering off particles that are smaller than or similar in size to the incident wavelength of light (e.g., Bohren & Huffman 2008). Mie scattering theory is useful for simulating planetary regoliths that include small grains like the Uranian moons’ regoliths, which could include a large number of sub-micron- to micron-sized particles (e.g., Afanasiev et al. 2014; Cartwright et al. 2020b). In contrast, pure Hapke approaches provide less robust models for planetary regoliths that include grains comparable to, or smaller than, the wavelength of incident light (e.g., Emery et al. 2006). Our hybrid Hapke–Mie technique takes the complex indices of refraction (i.e., optical constants) for each constituent and calculates the single scattering albedo (\( \omega_0 \)) using Mie theory. The \( \omega_0 \) values, along with the bidirectional reflectance, opposition effect, and phase function, are utilized to calculate the geometric albedo of the synthetic spectrum (e.g., Hapke 2012). Small resonances can occur in scattering models that utilize Mie theory. To account for these resonances, our spectral modeling software incorporates a range of grain diameters (typically 10% spread in sizes) that are averaged together to match the desired grain size of each constituent in the simulated planetary regolith. This spectral modeling program was used previously to generate best-fit synthetic spectra for the CO₂ ice bands detected in Uranian moon reflectance spectra collected at low sub-observer latitudes (Cartwright et al. 2015). These synthetic spectra were generated using optical constants for crystalline H₂O ice (80 K) (Mastrapa et al. 2008), crystalline CO₂ ice (∼150 K) (Hansen 1997), and amorphous carbon (Rouleau & Martin 1991), which simulates the dark, spectrally neutral...
absorber that is present on the Uranian moons (e.g., Clark & Lucey 1984). Using the same approach as these previous modeling efforts, we generated particulate mixtures of H2O ice and amorphous carbon grains to simulate a well-mixed regolith dominated by “dirty” H2O ice, where CO2 molecules could form in situ via radiolysis. We then linearly combined these dirty H2O ice models with CO2 ice to simulate concentrated deposits of pure CO2 ice, where CO2 molecules that originated elsewhere might get cold trapped.

Prior spectral modeling efforts demonstrate that best-fit synthetic spectra for Ariel and the other Uranian moons include H2O ice grains with three different grain diameters: a small fraction (<1%) of sub-micron-sized grains (typically 0.2, 0.3, or 0.5 μm diameters) and larger fractions of two different moderately sized H2O ice grains, typically with 10 and 50 μm grain diameters (Cartwright et al. 2015, 2018, 2020b). The inclusion of multiple H2O ice grain sizes is required to simultaneously fit the 1.52 and 2.02 μm H2O ice bands, in particular small amounts of sub-micron H2O ice grains, which can substantially alter the relative strengths of these two H2O ice bands in the resulting synthetic spectrum. The synthetic spectra typically only require one amorphous C grain diameter (ranging between 5 and 15 μm) to simulate the low albedo absorber that weakens the H2O ice bands, effectively obscuring H2O ice features at wavelengths <1.4 μm, and “flattens” the spectral continuum between 1.4 and 2.4 μm. Of note, prior work has demonstrated that inclusion of amorphous “pyroxene” can also provide a suitable proxy for the dark, spectrally neutral absorber on the surfaces of the Uranian moons (Cartwright et al. 2018). Nevertheless, we only included amorphous C in the synthetic spectra presented here to more appropriately simulate a regolith where CO2 ice is generated by radiolysis of native H2O ice and carbonaceous species.

Prior spectral modeling work also demonstrates that a blend of two different CO2 ice grain diameters provides a good match to the band shape of the detected CO2 ice bands, with one smaller grain size (1 or 10 μm diameters) and another larger grain size (50, 100, or 200 μm diameters). Additional information on how grain size can modify synthetic spectra using this Hapke–Mie modeling program was reported in Appendix B of Cartwright et al. (2015). Because the CO2 ice bands between 1.5 and 1.7 μm require thick substrates to detect and measure in the laboratory (1.6–108 mm, Hansen 2005), and because CO2 ice on Ariel could be concentrated in large low-latitude cold traps, CO2 is assumed to be optically thick in our models (i.e., obscuring the spectral signature of Ariel’s regolith beneath it).

The quality of the fits provided by the synthetic spectra was assessed using reduced χ2 statistics: \( \chi^2_R = \frac{1}{a} \sum (O_i - M_i)^2 / \sigma^2_i \), where \( a \) is the degrees of freedom, \( O_i \) is the observed data, \( M_i \) is the modeled data, and \( \sigma^2_i \) is the variance (e.g., Bevington & Robinson 1969). Typically, \( \chi^2_R \approx 1 \) indicates that a given model is a good match to a set of observed data, whereas \( \chi^2_R > 1 \) indicates that a given model is likely a poor match to a set of observed data. A \( \chi^2_R \approx 1 \) can also indicate a good fit to the data and may result from underestimated measurement errors. Additionally, fitting models to data with large uncertainties, as well as uncertainty in the degrees of freedom (Andrae et al. 2010), can lower the accuracy of \( \chi^2_R \) statistics.

All of the synthetic spectra reported here provide nonunique solutions for estimating the fractional areal coverage and grain size of each constituent. Small adjustments in the grain sizes of different constituents can be accommodated by complementary adjustments in the amounts of each constituent. However, as demonstrated by prior work (Cartwright et al. 2015, 2018, 2020b), synthetic spectra that deviate substantially from the mixing regimes, constituents, areal coverages, and grain sizes described here typically do not provide suitable fits to spectra of the Uranian moons.

3. Results and Analyses

3.1. Near-infrared Spectra of Ariel

Ten new disk-integrated reflectance spectra of Ariel are shown in Figure A2. Nine of these spectra display evidence for CO2 bands 1, 2, and 3, including all seven spectra collected over Ariel’s trailing hemisphere (examples of CO2 bands 1, 2, and 3 are shown in Figure 1). We also observe the weak CO2 ice combination and overtone features between 1.5 and 1.7 μm, which were first reported in Grundy et al. (2006), in some of the spectra collected over Ariel’s trailing hemisphere. Additionally, we observe a subtle band near 2.13 μm in two of the new spectra, collected at similar sub-observer latitudes (47.3°N and 51.1°N) and longitudes (231.8° and 235.9°) (Figure 4). The detected 2.13 μm band may result from a “forbidden” overtone mode of CO2 ice, which is very weak in pure CO2 ice deposits and much stronger in substrates composed of CO2 intimately mixed with H2O ice or methanol (Bernstein et al. 2005). We also observe a subtle band centered near 2.35 μm in some of the spectra collected over Ariel’s trailing hemisphere (Figure 5). This feature might result from CO generated as part of a radiolytic production cycle of CO2 ice (e.g., Gerakines et al. 2001; Hand et al. 2007; Zheng & Kaiser 2007; Cassidy et al. 2010). We discuss the 2.13 and 2.35 μm absorption features in greater detail in Section 4.1.

All 10 new spectra display the 1.52 and 2.02 μm H2O ice bands and the 1.65 μm crystalline H2O ice feature detected previously on Ariel (e.g., Grundy et al. 2006; Cartwright et al. 2018). We also observe an absorption band centered near 2.2 μm in several of the new Ariel spectra, which has been detected previously and attributed to NH3- and NH4-bearing species (Cartwright et al. 2018, 2020a; Cook et al. 2018). Analysis of these H2O ice bands and possible NH3- and NH4-bearing constituents is beyond the scope of this paper and will be included in future work.

3.2. CO2 Ice Band Parameter Analyses

We measured the areas of CO2 bands 1, 2, and 3 in the 10 new Ariel spectra, as well as eight previously reported Ariel spectra (Cartwright et al. 2018, 2020a) that do not have published CO2 band area measurements. We report these 18 sets of CO2 band areas and their 1σ uncertainties in Table 2, along with CO2 ice band areas for another 13 Ariel spectra that were measured previously (Grundy et al. 2003, 2006; Cartwright et al. 2015). All 31 of the Ariel spectra were analyzed using the same CO2 ice band measurement procedure, originally presented in Cartwright et al. (2015). To investigate possible latitudinal trends in the distribution of CO2 ice, we calculated mean CO2 ice band areas using spectra collected at low (30°S–30°N), mid (31°N–44°N), and high (45°N–51°N) sub-observer latitudes (final column in Table 2).
Leading hemisphere

The analysis of those 13 previously analyzed Ariel spectra, we determined that CO$_2$ bands are much stronger in the spectra collected over Ariel’s leading hemisphere compared to its trailing hemisphere (Grundy et al. 2006; Cartwright et al. 2015). Utilizing the same measurement procedure presented in Cartwright et al. (2015) for the analysis of those 13 previously analyzed Ariel spectra, we assessed the distribution of CO$_2$ ice in the 18 previously unanalyzed Ariel spectra (Figure 2(a)). The measurements show similar trends in the longitudinal distribution of CO$_2$ ice in the spectra collected over low, mid, and high sub-observer latitudes. However, the previously determined leading/trailing hemispherical dichotomy in the distribution of CO$_2$ ice appears to be weaker for the spectra collected at mid and high sub-observer latitudes compared to low sub-observer latitudes (Table 2, Figure 2(a)).

We then calculated the percentage of Ariel’s observed disk that was composed of low-latitude regions (30°S – 30°N) for all of the spectra collected over its trailing hemisphere (see Holler et al. 2016 for disk-area calculation details). We found that for spectra where the disk of Ariel was composed of >55% low-latitude regions, the total band areas for detected CO$_2$ ice features range from (13.02 ± 1.14) × 10$^{-4}$ μm to (15.37 ± 1.45) × 10$^{-4}$ μm. When Ariel’s disk was composed of 45%–55% low-latitude regions, the measured CO$_2$ band areas decreased to (10.74 ± 2.06) × 10$^{-4}$ μm to (14.30 ± 0.71) × 10$^{-4}$ μm. When low-latitude regions composed <45% of Ariel’s observed disk, CO$_2$ band areas decreased further to (7.76 ± 0.49) × 10$^{-4}$ μm to (12.42 ± 1.04) × 10$^{-4}$ μm. Thus, CO$_2$ ice band areas are gradually decreasing as the sub-observer latitude moves further north and away from Ariel’s low latitudes.

To further investigate latitudinal trends in the distribution of CO$_2$ ice, we compared the mean CO$_2$ ice total band areas of each sub-observer latitude zone (final column of Table 2, Figure 2(b)). This comparison shows that the low sub-observer latitude zone has the largest mean CO$_2$ total band area. The mid sub-observer latitude zone has a smaller mean CO$_2$ total band area, and the high sub-observer latitude zone has the smallest mean CO$_2$ total band area (>1σ difference between CO$_2$ band areas for the low and high sub-observer latitude zones). On Ariel’s leading hemisphere, these mean measurements show negligible differences between the three sub-observer latitude zones (<1σ difference).

We also calculated the mean areas for each of the three CO$_2$ bands (Figure 2(c)). CO$_2$ band 1 shows <1σ difference between the
different sub-observer latitude zones, whereas CO2 bands 2 and 3 show >2σ differences between the high and low sub-observer latitude zones (>1σ difference between the high and mid sub-observer latitude zones). Of note, CO2 band 1 is located on the long-wavelength end of a strong telluric band resulting from H2O vapor, possibly explaining the inconclusive results for this band compared to CO2 bands 2 and 3, which are less contaminated by species in Earth’s atmosphere. Thus, our measurements demonstrate that CO2 ice bands are stronger in spectra collected at low and mid sub-observer latitudes compared to spectra collected at high sub-observer latitudes over Ariel’s trailing hemisphere. Spectra collected over Ariel’s leading hemisphere do not display discernible differences in CO2 band areas at different sub-observer latitudes.

3.4. Radiative Transfer Modeling of CO2 Ice Bands

In Figure 3, we present 10 spectral models that fit the CO2 ice bands detected on Ariel’s trailing hemisphere between 1.5 and 1.7 μm (synthetic spectra 1–7) and between 1.9 and 2.1 μm (synthetic spectra 8–10). The areal coverage and grain sizes of all included components are summarized in Table 3 (CO2 ice bands centered near 1.543, 1.578, and 1.609 μm) and Table 4 (CO2 bands 1, 2, and 3). The previously reported spectral models for CO2 bands 1, 2, and 3 in Ariel’s low sub-observer latitude, grand average spectrum (Cartwright et al. 2015) are included here (synthetic spectrum 10), along with new models of the mid and high sub-observer latitude, grand average spectra (synthetic spectra 9 and 10, respectively). The low sub-observer latitude data points (gold dashed line) highlight the clear longitudinal trend in the distribution of CO2 ice on Ariel in this latitude zone. Similarly, the sinusoidal fit to the mid and high sub-observer latitude data points (black dashed line) highlights the reduction in CO2 ice band areas on Ariel’s trailing hemisphere at sub-observer latitudes >30° N. Repeat longitudes (gray-toned zones) are shown to highlight the periodicity in the distribution of CO2 on Ariel. (b) Mean CO2 ice total band areas and 1σ uncertainties (vertical error bars) for the low, mid, and high sub-observer latitude zones (gold, green, and blue symbols, respectively) over Ariel’s leading (diamonds) and trailing (circles) hemispheres. The horizontal error bars represent the range of latitudes we use to define each sub-observer latitude zone. Numerical values for these data points are shown in the “Mean CO2 Total Areas” column in Table 2. (c) Mean CO2 band 1, 2, and 3 areas and 1σ uncertainties for the low, mid, and high sub-observer latitude zones (gold, green, and blue circles, respectively) on Ariel’s trailing hemisphere.
observer latitude synthetic spectrum includes 27% CO₂ ice, the mid sub-observer latitude model includes 23% CO₂ ice, and the high sub-observer latitude model includes 16% CO₂ ice (model components are summarized in Table 4).

The low sub-observer latitude, grand average spectrum shows the strongest evidence for the 1.543, 1.578, and 1.609 μm CO₂ bands, which we fit with three different models (synthetic spectra 5–7) spanning from 1.5 to 1.7 μm. The amount of CO₂ ice included in synthetic spectra 5–7 ranges between 35.5% and 38.5%, which is substantially higher than the amount of CO₂ included in synthetic spectrum 10 (27%), spanning from 1.9 to 2.1 μm. Furthermore, synthetic spectra 5–7 include greater amounts of larger CO₂ ice grains, including grains with diameters of 100 and 200 μm, which are not included in any of the models spanning from 1.9 to 2.1 μm (synthetic spectra 8–10).

In contrast, Ariel’s grand average mid and high sub-observer latitude, grand average spectra display weaker 1.578 and 1.609 μm CO₂ bands compared to the low sub-observer latitude spectrum, and the weak 1.543 μm band is not visibly identifiable in either spectrum (Figure 3). The spectral models for Ariel’s mid sub-observer latitude spectrum that we present here (synthetic spectra 3 and 4) include 23% and 24% CO₂ to fit the 1.578 and 1.609 μm bands, respectively. These two synthetic spectra include greater amounts of larger grains (10, 50, and 200 μm diameters) compared to synthetic spectrum 9 that spans 1.9–2.1 μm of the mid sub-observer latitude, grand average spectrum (1 and 50 μm diameters). Similarly, the spectral models for Ariel’s high sub-observer latitude, grand average spectrum (synthetic spectra 1 and 2) include 15% and 16% CO₂ to fit the 1.578 and 1.609 μm bands, respectively. Synthetic spectra 1 and 2 also include greater amounts of larger grains (10, 50, and 100 μm diameters) compared to synthetic spectrum 8 spanning from 1.9 to 2.1 μm (1 and 50 μm diameters). Therefore, all of the synthetic spectra spanning from 1.5 to 2.1 μm include more CO₂ ice, and larger CO₂ ice grains, than the corresponding synthetic spectra that span from 1.9 to 2.1 μm.

Along with visual assessment, we utilized χ² tests to assess the quality of the fits provided by the synthetic spectra. The χ² statistics for the 1.543 μm CO₂ ice band (synthetic spectra 5–7) and the 1.578 and 1.609 μm CO₂ bands (synthetic spectra 1–7) demonstrate that the generated models are suitable fits to the observed spectra (Table 5). Similarly, the χ² values for CO₂ ice bands 1, 2, and 3 (synthetic spectra 8–10) demonstrate that the generated models are suitable fits to the observed spectra. The χ² values for the synthetic spectra spanning the 1.5–1.7 μm and 1.9–2.1 μm continua also appear to provide reasonable fits, although some of the χ² values for the synthetic spectra spanning from 1.5 to 1.7 μm are quite low (<0.1) and may result from overestimated errors. Comparison of the χ² statistics for synthetic spectra 1–7 suggests that the small differences in the grain size ranges and the amount of CO₂ ice included in each of these...
spectral models are not sufficient to cause significant variations in their goodness of fit for each of the CO₂ ice bands between 1.5 and 1.7 μm (Table 5). More sophisticated and computationally intensive model assessment techniques may be necessary to better delineate between the fits provided by synthetic spectra 1–7. Nevertheless, the small differences between each of these synthetic spectra may reflect subtle spectral variations resulting from differences in photon penetration depths at different wavelengths (see Section 4.2).

In summary, the synthetic spectra we generated for CO₂ ice bands between 1.5 and 1.7 μm and between 1.9 and 2.1 μm suggest that the areal coverage of CO₂ ice is highest at low sub-observer latitudes, decreases at mid sub-observer latitudes, and decreases further at high sub-observer latitudes. These spectral modeling results are consistent with our CO₂ band area measurements, indicating that CO₂ ice is likely concentrated at low latitudes on Ariel.

4. Discussion

4.1. Distribution and Nature of CO₂ Ice on Ariel

Thermodynamical models predict that CO₂ molecules generated and/or exposed at polar latitudes on the surfaces of the

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### Table 3
Model Parameters for Synthetic Spectra: CO₂ Ice Bands between 1.5 and 1.7 μm

| Synthetic Spectrum | CO₂ Ice Band | H₂O Ice: Grain Size, Areal Coverage | H₂O Ice: Grain Size, Areal Coverage | H₂O Ice: Grain Size, Areal Coverage | Amorphous C: Grain Size, Areal Coverage | CO₂ Ice: Grain Size, Areal Coverage | CO₂ Ice: Grain Size, Areal Coverage |
|--------------------|--------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| High sub-obs. lat. |              |                                   |                                   |                                   |                                   |                                   |                                   |
| 1                  | 1.578 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 10 μm,                            |
|                    |              | 26.8%                             | 57.0%                             | 0.3%                              | 0.9%                             | 9.5%                             | 7.5%                             |
| 2                  | 1.609 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 100 μm,                           | 50 μm,                            |
|                    |              | 26.5%                             | 56.5%                             | 0.3%                              | 0.9%                             | 8.8%                             | 7.2%                             |
| Mid sub-obs. lat.  |              |                                   |                                   |                                   |                                   |                                   |                                   |
| 3                  | 1.578 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 10 μm,                            |
|                    |              | 55.1%                             | 20.8%                             | 0.3%                              | 0.8%                             | 13.8%                            | 9.2%                             |
| 4                  | 1.609 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 200 μm,                           | 50 μm,                            |
|                    |              | 54.3%                             | 20.6%                             | 0.3%                              | 0.8%                             | 21.6%                            | 2.4%                             |
| Low sub-obs. lat.  |              |                                   |                                   |                                   |                                   |                                   |                                   |
| 5                  | 1.543 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 10 μm,                            |
|                    |              | 51.6%                             | 11.9%                             | 0.3%                              | 0.7%                             | 8.9%                             | 26.6%                            |
| 6                  | 1.578 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 200 μm,                           | 50 μm,                            |
|                    |              | 50.8%                             | 11.7%                             | 0.3%                              | 0.7%                             | 7.3%                             | 29.2%                            |
| 7                  | 1.609 μm     | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 100 μm,                           | 10 μm,                            |
|                    |              | 49.2%                             | 11.4%                             | 0.2%                              | 0.7%                             | 21.2%                            | 17.3%                            |

Note. Synthetic spectra shown graphically in Figure 3.

### Table 4
Model Parameters for Synthetic Spectra: CO₂ Bands 1, 2, and 3

| Synthetic Spectrum | H₂O Ice: Grain Size, Areal Coverage | H₂O Ice: Grain Size, Areal Coverage | H₂O Ice: Grain Size, Areal Coverage | Amorphous C: Grain Size, Areal Coverage | CO₂ Ice: Grain Size, Areal Coverage | CO₂ Ice: Grain Size, Areal Coverage |
|--------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| High sub-obs. lat. |                                   |                                   |                                   |                                   |                                   |                                   |
| 8                  | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 1 μm,                            |
|                    | 25.2%                             | 56.3%                             | 0.7%                              | 1.8%                             | 9.6%                             | 6.4%                             |
| Mid sub-obs. lat.  |                                   |                                   |                                   |                                   |                                   |                                   |
| 9                  | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 1 μm,                            |
|                    | 54.6%                             | 21.1%                             | 0.6%                              | 1.7%                             | 7.7%                             | 14.3%                            |
| Low sub-obs. lat.  |                                   |                                   |                                   |                                   |                                   |                                   |
| b10                | 50 μm,                            | 10 μm,                            | 0.3 μm,                            | 12.5 μm,                          | 50 μm,                            | 10 μm,                            |
|                    | 36.5%                             | 34.3%                             | 0.6%                              | 1.6%                             | 22.5%                            | 4.5%                             |

Notes. Synthetic spectra shown graphically in Figure 3. Previously reported in Cartwright et al. (2015).
Uranian moons should readily sublimate during summer, when the pole is continuously exposed to direct sunlight (Grundy et al. 2006; Sori et al. 2017). In the high-obliquity Uranian system, equatorial regions experience less net sublimation than polar regions over the course of a Uranian year. Consequently, CO₂ should migrate over geologically short timescales from these moons’ poles to their equators, thereby enriching their low latitudes with CO₂ ice. If CO₂ molecules are distributed uniformly across the surfaces of the Uranian moons, then CO₂ could migrate to cold traps at latitudes between 50°S and 50°N, with the removal of CO₂ increasing steadily with latitude, peaking near their poles (see Figure 9 in Sori et al. 2017). Conversely, if CO₂ is already depleted from latitudes >50°S or N, then the zone of CO₂ accumulation may be smaller, spanning only 30°S to 30°N, with peak CO₂ removal concentrated near 45°S and 45°N. In both model scenarios, CO₂ molecules get cold trapped at similar latitudes to where they were initially generated and/or exposed. Thus, the apparent concentration of CO₂ ice on the trailing hemispheres of Ariel and the other Uranian moons suggests that CO₂ molecules originate on their trailing sides (Sori et al. 2017).

Our band area measurements and synthetic spectra are consistent with a reduction in the abundance of CO₂ ice at higher latitudes on Ariel. However, the disk-integrated nature of the data analyzed here limits our ability to develop more detailed maps of the latitudinal distribution of CO₂ ice. Our analyses are therefore unable to discern whether the abundance of CO₂ ice is steadily decreasing with increasing sub-observer latitude, or whether CO₂ ice is mostly concentrated in one or perhaps a few large cold traps at low latitudes and essentially absent at latitudes ≥30°N.

Large, high albedo regions that act as cold traps for volatile ices are well documented on other planetary bodies. For example, the Martian poles are dominated by thick deposits of H₂O ice and CO₂ ice (e.g., Farmer et al. 1976; Kieffer 1979; Kieffer et al. 2000), and Sputnik Planitia at low northern latitudes on Pluto is a large volatile sink for N₂ ice and CO ice (e.g., Bertrand & Forget 2016; Hamilton et al. 2016; Earle et al. 2017). Furthermore, the available photogeologic evidence (e.g., Smith et al. 1986) and photometric measurements made with the Voyager 2 Imaging Science System (e.g., Buratti & Mosher 1991) indicate that a large and bright annulus of material is mantling the floor of Wunda crater on Umbriel’s trailing hemisphere, which has been interpreted to be a cold trap for CO₂ ice (Sori et al. 2017). Ariel, on the other hand, does not appear to display large and bright regions on its trailing hemisphere that might serve as volatile sinks for CO₂ ice. Nevertheless, large CO₂ ice cold traps could be present at low northern latitudes, which were shrouded by winter darkness at the time of the Voyager 2 flyby and were not imaged. Continued observations of Ariel as the Uranian system migrates into northern summer in 2030 February, reaching a maximum subsolar latitude of ~82°N, might help discern between the two different modeling predictions for the latitudinal distribution of CO₂ ice presented in Sori et al. (2017).

### Possible radiolytic production of CO₂ molecules

Charged particle bombardment of H₂O ice mixed with C-rich material in Ariel’s regolith could drive radiolytic production of oxidized carbon-based species such as CO₂. Radiolytically generated CO₂ molecules should not be thermodynamically stable in Ariel’s dark regolith, in particular at high latitudes, where the timescales of maximum solar heating are considerably longer than at low latitudes (Grundy et al. 2006; Sori et al. 2017). Consequently, CO₂ molecules radiolytically generated in Ariel’s summer polar region should diffuse out of its regolith, hop along its surface, and get cold trapped in its equatorial region over seasonal timescales. Assuming that the source(s) of CO₂ molecules operate over long timescales, low-latitude cold traps should gradually expand as they accumulate more CO₂, forming an optically thick layer of CO₂ ice, with a crystalline structure dominated by CO₂ molecules (i.e., a “pure” CO₂ ice deposit). The detection of the weak CO₂ ice bands between 1.5 and 1.7 μm, which are a factor of 60–200 weaker than CO₂ ice bands 1, 2, and 3 and require substrates as thick as 107.5 mm to detect them in the laboratory (Hansen 1997, 2005), supports the hypothesis that thick deposits of CO₂ ice are present on Ariel. Once assimilated into cold traps, CO₂ molecules should be fairly stable and resistant to sublimation due to the deposit’s higher albedo and thermal inertia compared to the surrounding regolith (Sori et al. 2017).

| Wavelength range (μm) | 1.540–1.545 | 1.574–1.581 | 1.609–1.613 | 1.5–1.7 | 1.962–1.969 | 2.008–2.015 | 2.068–2.072 | 1.9–2.1 |
|----------------------|--------------|--------------|--------------|---------|--------------|--------------|--------------|---------|
| Ice Band             | 1.543 μm CO₂ | 1.578 μm CO₂ | 1.609 μm CO₂ | Continuum | 1.966 μm CO₂ | 2.012 μm CO₂ | 2.070 μm CO₂ | Continuum |
| Synthetic spectra    |              |              |              |         |              |              |              |         |
| 1                    | ...          | ...          | ...          | 0.789   | 0.993        | 0.029        | ...          | ...      |
| 2                    | ...          | ...          | ...          | 0.849   | 1.004        | 0.029        | ...          | ...      |
| 3                    | ...          | ...          | ...          | 0.894   | 0.876        | 0.163        | ...          | ...      |
| 4                    | ...          | ...          | ...          | 1.600   | 0.847        | 0.182        | ...          | ...      |
| 5                    | 0.958        | 0.709        | 1.365        | 0.065   | ...          | ...          | ...          | ...      |
| 6                    | 1.117        | 0.836        | 1.512        | 0.064   | ...          | ...          | ...          | ...      |
| 7                    | 6.927        | 0.717        | 0.386        | 0.111   | ...          | ...          | ...          | ...      |
| 8                    | ...          | ...          | ...          | 0.227   | 0.225        | 1.028        | 0.126        | ...      |
| 9                    | ...          | ...          | ...          | 0.434   | 0.677        | 0.567        | 0.348        | ...      |
| 10                   | ...          | ...          | ...          | 0.366   | 1.286        | 0.667        | 0.688        | ...      |

**Note.** Boldface values highlight the primary CO₂ ice band fit by each of the synthetic spectra spanning from 1.5 to 1.7 μm.
surface, forming CO:

\[
e^{-} + \text{CO}_2 \rightarrow \text{CO} + \text{O}
\]

\[
p^+ + \text{CO}_2 \rightarrow \text{CO} + \text{O}
\]

CO and O are likely transient at Ariel’s estimated peak surface temperature (84 ± 1 K; Hanel et al. 1986) and should back-react with surrounding species to form new radiolytic products (e.g., Gerakines et al. 2001; Hand et al. 2007; Zheng & Kaiser 2007; Cassidy et al. 2010). As a result, CO and O fragments generated by irradiation of pure CO2 ice deposits should primarily recombine into CO2. Some spectra collected over Ariel’s trailing hemisphere exhibit a subtle band centered near 2.35 μm, in particular spectra collected over low sub-observer latitudes, where CO2 ice bands are strongest (Figure 4). This 2.35 μm band could result from the 2ν overtone of 12CO ice, centered near 2.352 μm (e.g., Gerakines et al. 2005). Supporting this scenario, the 2.35 μm band does not appear to be present in spectra collected over Ariel’s leading hemisphere (Figure 4), where CO2 ice is essentially absent. CO and O fragments should be rapidly removed if exposed on Ariel’s surface. Fragments of CO2 molecules dissociated at depth within CO2 ice deposits, however, might be retained long enough for some of the newly formed CO to back-react and re-form CO2, possibly enhancing the persistence of CO2 ice deposits on Ariel and the other Uranian moons. Additionally, perhaps some CO and O fragments get trapped in void spaces and defects within the crystalline structure of the surrounding CO2 ice instead of back-reacting or escaping. In this scenario, O fragments would likely combine into more stable O2 molecules before getting trapped. A possibly analogous process is suspected to occur on the icy Galilean moons, which display a 0.577 μm absorption band attributed to trapped O2 formed by radiolysis of H2O ice on their surfaces, which is subsequently trapped in defects and voids in the surrounding ice (e.g., Spencer et al. 1995; Spencer & Calvin 2002).

The spectral signature of CO2 on the Uranian moons is consistent with crystalline CO2 ice, segregated from other constituents in concentrated deposits. However, if CO2 molecules are being actively generated by charged particle bombardment of H2O ice and C-rich material in Ariel’s regolith, then the spectral signature of these radiolytic production sites might be consistent with CO2 well mixed with H2O and other constituents. Laboratory experiments that investigated the spectral signature of CO2 “intimately” mixed with H2O ice and methanol ice (CH3OH) detected a broad band centered near 2.134 μm (Bernstein et al. 2005), which is a factor of ~10^4 weaker in pure CO2 ice isolated in Ar (Sandford et al. 1991) or N2 (Quirico & Schmitt 1997) matrices and is absent from pure H2O ice. This band could result from the 2ν “forbidden” first overtone of the asymmetric stretching mode of CO2 ice, centered near 2.134 μm (Bernstein et al. 2005), and may be a useful indicator of the presence of well-mixed CO2 ice grains in planetary regoliths.

Two spectra collected at similar mid-observation, sub-observer longitudes and latitudes on Ariel’s trailing hemisphere exhibit subtle absorption features centered at 2.129 and 2.130 μm (Figure 5), hereafter referred to as the “2.13 μm” feature. These two spectra were collected by different teams using different telescopes (IRTF and ARC 3.5 m), lending additional confidence to the detection of this feature. The 2.13 μm bands we detected span from 2.123 to 2.137 μm (0.014 μm wide) along the long-wavelength shoulder of the 2.02 μm H2O ice band. The CO2 2ν band presented in Figure 3 of Bernstein et al. (2005) is centered between 2.133 and 2.138 μm and is ~0.016–0.041 μm wide, with the band becoming narrower and shifting to shorter wavelengths as the amount of CO2 ice relative to H2O ice is decreased. The closest match to the 2.13 μm band we detected on Ariel is a laboratory spectrum of an H2O:CO2:CH3OH substrate (100:2.5:1 abundance ratio), displaying a band centered near 2.133 μm that is ~0.016 μm wide (Bernstein et al. 2005).

Using the results of these laboratory experiments as a guide, if the 2.13 μm band we detected is caused by CO2 grains well mixed with H2O grains, then it is likely only a minor component of Ariel’s regolith. Nevertheless, if present, regolith-mixed CO2 grains could be a tracer of a radiolytic production cycle, where CO2 molecules and other oxidized carbon compounds are produced by charged particle bombardment of dirty H2O ice in Ariel’s regolith. In this scenario, the charged particles would break apart H2O molecules, forming OH radicals that interact with...
nearby C-rich grains to form CO₂ molecules:

\[
\begin{align*}
\text{OH} + \text{C(s)} & \rightarrow \text{CO} + \text{H}, \\
\text{OH} + \text{CO} & \rightarrow \text{CO}_2 + \text{H},
\end{align*}
\]

where H efficiently diffuses out of Ariel’s regolith and is preferentially removed via Jean’s escape. Laboratory experiments (e.g., Raut et al. 2012) have demonstrated that OH is an efficient catalyst for the production of CO₂ molecules in substrates composed of H₂O ice and C-rich material that are irradiated at cryogenic temperatures (<100 K) relevant to the Uranian moons. Supporting the possible presence of OH on the Uranian moons, a 280 nm absorption band, attributed to trapped OH, has been detected at high southern latitudes on Ariel (~45°S) using the Faint Object Spectrograph on the Hubble Space Telescope (Roush et al. 1998).

Other laboratory experiments have demonstrated that irradiation of hydrogenated carbon grains capped by a layer of H₂O ice can also lead to radiolytic generation of CO₂ molecules (e.g., Mennella et al. 2004, 2006). Consequently, perhaps “intramixtures” of individual carbon grains coated by a layer of H₂O ice, or perhaps a thin layer of H₂O ice with numerous embedded carbon grains, could represent other useful analogs for understanding the spectral signature of radiolytic chemistry in Ariel’s regolith.

In summary, a subtle 2.35 μm band we detected in NIR reflectance spectra collected over Ariel’s trailing hemisphere hints at the presence of CO₂, which, if present, is probably a transient species. The presence of a 2.13 μm band in two spectra collected at similar sub-observer latitudes and longitudes suggests that CO₂ molecules might be well mixed with H₂O ice in some high-latitude locations. Such a mixture could be a tracer of radiolytic production sites where CO₂ molecules are being generated by irradiation of H₂O and C-rich material in Ariel’s regolith. Particulate mixtures of CO₂ ice, H₂O ice, and C-rich material, or alternatively intramixtures where CO₂ molecules are formed at the boundary between C grains embedded in H₂O ice, could both represent suitable analogs for radiolytic production sites in Ariel’s regolith. Our results and analyses therefore support the presence of a sustained CO₂ “life cycle” on Ariel, with radiolytic production of CO₂ molecules and migration to low-latitude cold traps, as predicted by thermodynamical models (Grundy et al. 2006; Sori et al. 2017).

It is also possible that CO₂ ice originates in Ariel’s interior and has been exposed by geologic processes, perhaps concentrated in deposits that are also rich in carbonates and/or NH₃-bearing species that could be contributing to Ariel’s 2.2 μm band (Cartwright et al. 2020a). However, the 2.2 μm band has been identified across Ariel’s surface, hinting that the species contributing to it are concentrated in local geologic landforms or regional provinces, whereas CO₂ ice is present primarily on Ariel’s trailing hemisphere and is essentially absent from its leading hemisphere. It is therefore difficult to explain the strong leading/trailing hemispherical asymmetries in the distribution of CO₂ ice on Ariel and the other Uranian moons if this constituent primarily originates from geologic processes.

4.2 Compositional Stratification of Ariel’s Regolith?

Analysis of synthetic spectra generated by prior spectral modeling efforts suggests that Ariel’s surface could be compositionally stratified, with a thin layer of small H₂O ice grains capping concentrated deposits of CO₂ ice grains underneath (Cartwright et al. 2015, 2018, 2020b). These spectral modeling conclusions were based on the premise that NIR photons at different wavelengths travel different distances into planetary surfaces, depending on the composition of the grains within the regolith (e.g., Clark & Roush 1984). Comparison of a planetary body’s spectral properties in different wavelength regions might therefore yield insight into the vertical structure of its regolith. One technique that can be used to gain such insight is the mean optical path length (MOPL), which provides an estimate for the average travel distance of photons into a particulate-dominated regolith before they are absorbed, accounting for intergrain boundary scattering (for calculation details, see Clark & Roush 1984).

Utilizing prior estimates of the MOPL for the Uranian moons’ regoliths (Cartwright et al. 2018), we find that photons penetrate to depths of ~0.1 mm over the wavelength range of CO₂ bands 1, 2, and 3 (1.9–2.1 μm). In contrast, photons penetrate to depths of ~0.2 mm over the wavelength range of the 1.543 and 1.578 μm CO₂ bands and ~0.4 mm over the wavelength range of the 1.609 μm CO₂ band. The CO₂ ice grains included in synthetic spectra 1–7, which fit the CO₂ bands between 1.5 and 1.7 μm, are larger than the CO₂ grains included in synthetic spectra 8–10, which fit CO₂ bands 1, 2, and 3 between 1.9 and 2.1 μm. The larger CO₂ grains included in synthetic spectra 1–7 could be simulating the factor of 2–4 longer path lengths that photons achieve through Ariel’s regolith between 1.5 and 1.7 μm. Relatively stronger
absorption by H₂O ice between 1.9 and 2.1 μm reduces photon path lengths, thereby possibly explaining the smaller CO₂ grains included in the synthetic spectra that fit CO₂ bands 1, 2, and 3. Thus, our spectral modeling results are consistent with prior studies that suggest that the Uranian moons’ regoliths are compositionally stratified, with larger grains of CO₂ ice retained at greater depths (Cartwright et al. 2015, 2018, 2020b).

The spectral modeling results presented here might instead hint at a different regolith structure, where CO₂ ice is formed beneath a thin H₂O ice cap, at the boundary between carbon grains embedded into a dominantly H₂O ice matrix or individual C grains coated by a layer of H₂O ice (i.e., intramixtures). However, visible polarimetric observations of the Uranian moons are consistent with crumbly regoliths that include sub-micron- and micron-sized grains (Afanasyev et al. 2014), supporting the interpretation that particulate mixtures are good analogs for Ariel’s regolith. Determining whether particulate mixtures or intramixtures are better analogs for the structure of Ariel’s regolith is beyond the scope of this work and should be considered by future studies. As described in Section 3.4, minor variations in grain size and areal coverage between synthetic spectra 1 and 7 do not cause significant changes in the goodness of fit to the CO₂ bands between 1.5 and 1.7 μm (Table 5). Consequently, these synthetic spectra may not be entirely sensitive to variations in photon penetration depths between the 1.543 and 1.578 μm bands and the 1.609 μm band described above.

5. Conclusions and Future Work

We measured the distribution and spectral signature of CO₂ ice as a function of sub-observer latitude and longitude to investigate whether a radiolytic production cycle, as well as associated transport of CO₂ molecules to low-latitude cold traps, is occurring on Ariel. We measured the integrated areas of three CO₂ ice bands between 1.9 and 2.1 μm in 31 reflectance spectra collected over a wide range of sub-observer longitudes and latitudes (30°S–51°N). Our results and analyses indicate that CO₂ ice band areas are decreasing with increasing sub-observer latitude on Ariel’s trailing hemisphere but do not vary on its leading hemisphere. These results suggest that the amount of CO₂ ice on Ariel’s surface is higher at low latitudes, as predicted by thermodynamical models. Furthermore, two spectra collected at high northern sub-observer latitudes (47°N and 51°N) display subtle 2.13 μm bands, hinting at the presence of CO₂ ice grains well mixed with H₂O ice and carbonaceous material, possibly representing a spectral tracer of radiolytic production sites for CO₂ molecules in Ariel’s regolith. Similarly, a subtle 2.35 μm band detected in low sub-observer latitude spectra of Ariel hints at the presence of CO₂, which could be a transient product generated by irradiation and fragmentation of CO₂ molecules in low-latitude cold traps. The work presented here is therefore consistent with radiolytic production of CO₂ molecules and subsequent migration and cold trapping of this constituent in concentrated deposits of CO₂ ice at low latitudes on Ariel.

Continued observations of Ariel over the next decade as the Uranian system approaches northern summer solstice, when the subsolar latitude will reach 82°N, will provide key measurements of the changing distribution and spectral signature of CO₂ ice. These future measurements could be compared to the results presented here to further test whether CO₂ ice is a radiolytic product that migrates to low-latitude cold traps. Furthermore, follow-up observations are needed to confirm the presence of the 2.13 μm band reported here and to determine whether this feature is present in other locations. Similar to Ariel, CO₂ ice has been detected in reflectance spectra collected over low sub-observer latitudes on the trailing hemispheres of Umbriel, Titania, and Oberon (Grundy et al. 2006; Cartwright et al. 2015), but the nature of CO₂ ice at high sub-observer latitudes on these moons has yet to be investigated. If CO₂ ice originates as part of a radiolytic production cycle on Umbriel, Titania, and Oberon, then CO₂ ice band areas should decrease in spectra collected at higher sub-observer latitudes on these moons, similar to the observed trends on Ariel. Furthermore, determining whether subtle 2.13 μm bands are present in spectra collected over high sub-observer latitudes of these three moons could provide insight into whether this feature is a tracer of radiolytic production sites in the Uranian satellites’ regoliths. Follow-up near-UV observations are also needed to confirm whether a 280 nm band attributed to trapped OH, a key catalyst for the radiolytic production of CO₂ molecules, is present at high northern latitudes on Ariel and the other Uranian moons.

To fully characterize the life cycle of CO₂ ice on the classical Uranian satellites, a spacecraft equipped with a visible wavelength camera and NIR mapping spectrometer, making multiple close flybys of these moons, is needed to reveal their previously unimaged northern hemispheres, measure the localized distribution and spectral signature of CO₂ ice, and characterize any possible associations between CO₂ ice and geologic landforms like craters and chasmata that might serve as cold traps (e.g., Cartwright et al. 2021; Leonard et al. 2021). Similarly, a Uranus orbiter equipped with a plasma spectrometer and an energetic particle detector could measure Uranus’s magnetosphere proximal to Ariel and the other moons, thereby providing critical context on moon–magnetosphere interactions that could be driving CO₂ production and volatile cycling on these moons (e.g., Kollmann et al. 2020). New measurements made by a thermal camera on board a Uranus orbiter are also needed to measure local and regional variations in the surface temperatures of these moons, which would provide important information on the location and longevity of CO₂ ice cold traps and the source regions where CO₂ molecules are being generated by radiolysis or exposed by geologic processes.

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Appendix

A.1. Methods: Band Parameter Measurements

In this appendix, we show the wavelength ranges of CO₂ ice bands 1, 2, and 3 and their associated continua (Figure A1).

A.2. Results: IRTF/SpeX and ARC 3.5 m/TripleSpec Spectra

Here we show 10 NIR reflectance spectra of the Uranian satellite Ariel at their native spectral resolutions (Figure A2).
Figure A1. A graphical demonstration of the wavelength ranges of CO$_2$ ice bands 1, 2, and 3, and their associated continua, using the grand average low-latitude spectrum of Ariel (1σ uncertainties shown as gold error bars). The data points used to calculate the areas of CO$_2$ bands 1, 2, and 3 (spanning 1.962–1.969 μm, 2.008–2.015 μm, and 2.068–2.072 μm, respectively) are shown as red data points. The data points utilized for the continua of these three CO$_2$ bands are shown as white data points that are connected by black lines.
Figure A2. Four new IRTF/Spex spectra (longitudes 153°, 205°, 232°, and 293°) and six new ARC 3.5 m/TripleSpec spectra (longitudes 07°, 27°, 100°, 236°, 260°, and 264°) of Ariel and their 1σ uncertainties, collected in 2019 and 2020. The mid-observation, sub-observer longitude for each spectrum is included in the lower left corner of each plot (see Table 1 for observation details). All spectra have been normalized to 1 between 2.24 and 2.25 μm. The sensitivities of Spex (SXD mode) and TripleSpec are lower at wavelengths <1.4 μm and >2.3 μm, resulting in lower S/N compared to wavelengths between 1.4 and 2.3 μm. Scattered light from Uranus contributes additional structure to some of these spectra at wavelengths <1.3 μm.
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