

JWST Reveals Spectral Tracers of Recent Surface Modification on Europa

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ABSTRACT

Europa has been modified by a variety of geologic processes, exposing internally-derived materials that are heavily irradiated by charged particles trapped in Jupiter’s magnetosphere. Prior spectral analysis of H₂O ice on Europa relied on low signal-to-noise data at wavelengths $>2.5\ \mu\text{m}$, limiting assessment of a $3.1\ \mu\text{m}$ Fresnel peak that is diagnostic of exposed crystalline ice. We report new measurements of H₂O ice spectral features using high signal-to-noise data collected by the NIRSpec spectrograph ($1.48 - 5.35\ \mu\text{m}$) on the James Webb Space Telescope. These data reveal a narrow $3.1\ \mu\text{m}$ crystalline H₂O ice Fresnel peak, which is primarily located at southern latitudes in Tara and Powys Regiones. Our analysis indicates that crystalline ice exposed in these low-latitude regiones is likely sustained by ongoing thermal (re)crystallization outpacing charged particle amorphization of the top $\sim 10\ \mu\text{m}$ of Europa’s regolith over short timescales (<15 days). We also measured H₂O ice features centered near $1.5\ \mu\text{m}$, $1.65\ \mu\text{m}$, and $2.0\ \mu\text{m}$, and a broad $3.6\ \mu\text{m}$ H₂O continuum peak, which are all stronger at northern latitudes, in contrast to the $3.1\ \mu\text{m}$ Fresnel peak identified at southern latitudes. These results support the hypothesis that H₂O ice in Europa’s regolith is vertically stratified, with amorphous ice grains dominating its exposed surface, except in Tara and Powys Regiones. We also find that a previously detected $4.38\ \mu\text{m}$ ¹³CO₂ feature is present almost exclusively at southern latitudes in Tara and Powys Regiones, likely derived from an internal source of carbon-bearing material.

Keywords: Europa (2189); Galilean Satellites (627); James Webb Space Telescope (2291); Surface composition (2115); Surface processes (2116)

1. INTRODUCTION

Jupiter’s moon Europa exhibits widespread evidence for recent endogenic activity (Greeley et al. 1998, 2000, 2004; Pappalardo et al. 1999; Kattenhorn & Prockter 2014), primarily resulting from tidal heating of its interior, driven by shared orbital resonances with the neighboring moons Io and Ganymede (e.g., Sotin et al. 2009). This ongoing heating likely helps sustain an internal, global saline ocean, wedged between Europa’s silicate-rich mantle and exterior icy shell (e.g., Anderson et al. 1998; Petricca et al. 2025). Europa’s induced magnetic field, first detected by the Galileo spacecraft, likely originates from interactions between its internal saline ocean and Jupiter’s magnetosphere (Khurana et al. 1998; Kivelson et al. 2000; Zimmer et al. 2000; Schilling et al. 2007). Closer to the surface of Europa, pockets

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of saline meltwater could be perched in its icy shell, where collapse and refreezing may cause the formation of chaos terrains (e.g., Greeley et al. 2004; Schmidt et al. 2011). Europa chaos exhibits a spectrum of morphologies (Leonard et al. 2022) and a multitude of different mechanisms have been proposed to explain how they formed (summarized in Daubar et al. 2024). The aforementioned liquid H_2O lens collapse and refreezing mechanism (Schmidt et al. 2011) may result in saline solutions rich in sodium and other components reaching Europa’s surface and freezing in these chaos terrains, possibly exposing fresh, ocean-derived compounds (e.g., Vu et al. 2016; Thomas et al. 2017; Chivers et al. 2023). These ocean-derived materials are then chemically modified by Europa’s intense radiation environment, driving radiolytic production of hydrogen peroxide (H_2O_2) and possibly sulfates, formed in part by implantation of S^{n+} ions originating from volcanic venting at Io, as well as other compounds (e.g., Carlson et al. 1999, 2002; Brown & Hand 2013). Other sources of exogenic material, in particular dust grains originating on Jupiter’s irregular satellites (Bottke et al. 2013; Chen et al. 2024), potentially deliver ammoniated materials (NH-bearing), silicates, and carbon-rich species that overturn and mix with Europa’s irradiated regolith (Cartwright et al. 2024a; Sharkey et al. 2025), and perhaps also mix with native sources of ammoniated species (Tosi et al. 2024). Dust-mixed and irradiated salts and other components could then be delivered to Europa’s subsurface via geologic conduits and (re)mix with native meltwater (Kattenhorn & Prockter 2014; Hesse et al. 2022; Carnahan et al. 2022). The exposure and subsequent return of modified components could be a continuous cycle that diversifies Europa’s ocean chemistry (Zolotov & Kargel 2009). The evidence for recent geologic activity and ongoing subsurface-surface cycling of components makes chaos terrains potentially useful windows into Europa’s interior. Thus, measuring the spectral properties of chaos-dominated regions with remotely sensed data may provide insight into Europa’s ocean chemistry and potential habitability (e.g., Hand et al. 2007, 2009).

Reflectance spectra collected by ground-based telescopes, space telescopes, and spacecraft have revealed a wealth of information, linking Europa’s surface constituents to its internal ocean and tenuous atmosphere (Calvin et al. 1995; Brown & Hill 1996; Brown 2001; Carlson et al. 1996, 1999; McCord et al. 1998b; Filacchione et al. 2019; Trumbo et al. 2019a, 2022). Sodium chloride (NaCl) detected on Europa (Trumbo et al. 2022) likely originates in its interior, reaching the surface in chaos-dominated regions (e.g., Hand et al. 2009; Hesse et al. 2022), such as the large Tara and Powys Regiones that are located primarily over southern latitudes on Europa’s leading and anti-Jovian hemispheres, respectively (e.g., Leonard et al. 2024). Exposed NaCl is irradiated by charged particles, forming optically active defects called color centers (absorption band near $0.46\text{ }\mu\text{m}$; Hand & Carlson 2015; Trumbo et al. 2019a; Hibbitts et al. 2019). Continual irradiation gradually fragments and sputters NaCl molecules from Europa’s surface (Brown & Hand 2013), likely delivering Na to its exosphere (Brown & Hill 1996) and perhaps to its neutral torus as well (Smith et al. 2019). Similarly, the Cl^+ and Cl^- ions detected in a pick up cloud proximal to Europa (e.g., Volwerk et al. 2001) may originate from the destruction of NaCl on its surface. In contrast to the chaos-dominated regiones on Europa’s leading and anti-Jovian hemispheres, the spectral signature of NaCl is less apparent on Europa’s trailing hemisphere (Trumbo et al. 2019a, 2022), possibly because of greater interactions with Jupiter’s co-rotating plasma, which rapidly sputters and fragments NaCl , likely forming new salts via radiolysis, such as Na and Mg -bearing sulfates (MgSO_4), along with hydrated sulfuric acid ($\text{H}_2\text{SO}_4 \cdot \text{XH}_2\text{O}$) (Carlson et al. 2002; Brown & Hand 2013).

Along with salts, chaos terrains in Tara and Powys Regiones show spectral features indicative of other non-ice species, including a $3.51\text{ }\mu\text{m}$ H_2O_2 shoulder band, likely forming from irradiation of H_2O ice (Carlson et al. 1999; Hand & Brown 2013; Trumbo et al. 2019b; Wu et al. 2024; Raut et al. 2024). Observations of Europa’s leading and anti-Jovian hemispheres made by the Near-Infrared Spectrograph (NIRSpec) on the James Webb Space Telescope (JWST) revealed a double-lobed absorption feature, centered near $4.25\text{ }\mu\text{m}$ and $4.27\text{ }\mu\text{m}$, primarily concentrated in Tara and Powys Regiones, possibly representing ocean-derived CO_2 (Villanueva et al. 2023; Trumbo & Brown 2023). Alternatively, this double-lobed feature may result from charged particle bombardment of carbonaceous material exposed in chaos terrains, forming CO_2 molecules through radiolysis (e.g., Gomis & Strazzulla 2005; Raut et al. 2012; Strazzulla et al. 2023). A weak $4.38\text{ }\mu\text{m}$ absorption feature attributed to solid-state $^{13}\text{CO}_2$ was also detected in these JWST data (Villanueva et al. 2023). However, the spatial relationship between this $4.38\text{ }\mu\text{m}$ feature and the double-lobed $4.25\text{ }\mu\text{m}$ and $4.27\text{ }\mu\text{m}$ CO_2 band has yet to be determined, limiting our understanding of the origin and nature of CO_2 on Europa.

The surface composition of Europa is primarily defined by H_2O , as ice (Pilcher et al. 1972), as well as in hydrates (e.g., McCord et al. 1998a). The spectral signature of H_2O ice, in particular the fractional ratio between crystalline and amorphous ice, can be used to decipher the processes modifying icy regoliths and provide estimates for the rate of ice amorphization via charged particle bombardment. Prior analysis of data collected with Galileo’s Near

Infrared Mapping Spectrometer (NIMS; Carlson et al. 1992) found that a $1.65\ \mu\text{m}$ band, diagnostic of crystalline H_2O ice (Grundy & Schmitt 1998; Mastrapa et al. 2008), is present across Europa’s surface (Hansen & McCord 2004). However, a prominent $3.1\ \mu\text{m}$ Fresnel peak, also diagnostic of crystalline H_2O ice (Hagen et al. 1981; Mastrapa et al. 2009), is absent from Galileo/NIMS data of Europa, which instead exhibit a muted and somewhat neutral continuum in this wavelength range, more consistent with amorphous ice (Hansen & McCord 2004). H_2O ice absorption is very strong in the wavelength range of the $3.1\ \mu\text{m}$ Fresnel peak, causing photons to sample extremely shallow depths as they are effectively reflected off the surfaces of exposed ice grains (Hansen & McCord 2004). The apparent disparity between these prior NIMS measurements could therefore result from a stratified regolith, with efficient amorphization of exposed H_2O ice by heavy ions and protons, probed by the $3.1\ \mu\text{m}$ Fresnel peak ($<1\ \mu\text{m}$ depths; Mastrapa et al. 2009), whereas crystalline ice is preserved beneath this topmost layer and is probed by the $1.65\ \mu\text{m}$ band ($\sim 300 - 500\ \mu\text{m}$ depths; Mastrapa et al. 2008). Although analysis of Galileo/NIMS data advanced our understanding of H_2O ice on the Galilean moons, the generally low signal-to-noise (S/N) of these data, especially for Europa and other targets deep within the Jovian magnetosphere, has stymied follow-up work, in particular at wavelengths $>2.5\ \mu\text{m}$, where radiation-induced detector noise dominates and H_2O ice and hydrated salts absorb strongly, limiting the utility of older reflectance datasets.

Subsequent observations made by Juno’s Jovian Infrared Auroral Mapper (JIRAM; Adriani et al. 2017) did reveal a $3.1\ \mu\text{m}$ H_2O ice Fresnel peak, stronger at southern latitudes compared to northern latitudes on Europa’s leading hemisphere (Filacchione et al. 2019), hinting that crystalline ice might be present at its exposed surface in some regions. However, JIRAM does not have sufficient wavelength coverage ($\sim 2 - 5\ \mu\text{m}$) to detect Europa’s $1.65\ \mu\text{m}$ band and cannot be used to simultaneously compare these diagnostic crystalline ice features. Although ground-based observations have mapped the distribution of Europa’s $1.65\ \mu\text{m}$ band (e.g., Ligier et al. 2016), strong absorption by H_2O ice on Europa’s surface and persistent contamination by H_2O vapor and other gases in Earth’s atmosphere have prevented reliable characterization and spatial mapping of the $3.1\ \mu\text{m}$ Fresnel region. Thus, no single platform has been able to simultaneously measure and map Europa’s $1.65\ \mu\text{m}$ and $3.1\ \mu\text{m}$ features in disk-resolved data since the Galileo mission ended in 2003, limiting our understanding of H_2O ice on Europa and the fractional abundance of amorphous and crystalline ice.

NIRSpec on JWST is ideal for simultaneously measuring and mapping the spatial distribution of the $1.65\ \mu\text{m}$ and $3.1\ \mu\text{m}$ crystalline H_2O ice features, as well as the $4.38\ \mu\text{m}$ $^{13}\text{CO}_2$ feature. Here, we present new measurements and spectral maps for these three features, as well as H_2O ice features centered near 1.5 , 2.0 , and $3.6\ \mu\text{m}$ using JWST/NIRSpec reflectance spectra ($1.48 - 5.35\ \mu\text{m}$). We also present measurements and spectral maps of the $4.25\ \mu\text{m}$ and $4.27\ \mu\text{m}$ lobes of Europa’s prominent solid-state CO_2 feature, which were reported in prior work (Villanueva et al. 2023; Trumbo & Brown 2023). We use these measurements to investigate the processes modifying Europa’s surface, including possible geologic exposure and subsequent irradiation of ocean-derived components and thermal recrystallization of H_2O ice in lower albedo regions like Tara and Powys. This study provides useful precursor context for upcoming Europa observations that will be made by Clipper’s Mapping Imaging Spectrometer for Europa (MISE, $1 - 5\ \mu\text{m}$; Blaney et al. 2024), arriving at Jupiter in 2029 (e.g., Becker et al. 2024).

2. DATA AND METHODS

2.1. JWST/NIRSpec Reflectance Spectra

Observation details. As part of Guaranteed Time Observations (GTO) Program 1250, JWST observed Europa’s leading hemisphere on November 23, 2022 (subobserver longitudes ranging between 91° and 95°W , subobserver latitude 2.70°N). These observations were conducted with NIRSpec’s Integral Field Unit (IFU) that has a $3'' \times 3''$ field of view and $0.1'' \times 0.1''$ spaxel dimensions across 30 image slices (Jakobsen et al. 2022; Böker et al. 2023). NIRSpec’s G140H/F100LP, G235H/F170LP, and G395H/F290LP grating/filter combinations were each utilized during these observations, providing an average resolving power, R , of ~ 2700 and nominal wavelength coverage between ~ 1.1 to $5.3\ \mu\text{m}$. Each of these H gratings record data across two detectors (short wavelength “NRS1” and long wavelength “NRS2”), with “unrecoverable” wavelength gaps in between them where data are not recorded. These gaps shift slightly in wavelength space in each of the image slices that comprise NIRSpec’s IFU. The Europa spectra exhibit wavelength gaps between 1.42 and $1.48\ \mu\text{m}$ (G140H), 2.38 and $2.48\ \mu\text{m}$ (G235H), and 4.02 and $4.18\ \mu\text{m}$ (G395H). Each observation consisted of two exposures taken in different sections of the IFU (i.e., two dithers) for a total on-target time of $\sim 859\ \text{s}$ with the G140H and $\sim 1074\ \text{s}$ with the G235H and G395H, using the NRSRAPID readout mode.

Saturation Mitigation. Due to Europa’s brightness at shorter wavelengths ($1 - 2.5 \mu\text{m}$), saturation occurred in nearly all the spaxels covering its disk in the G140H (NRS1 and NRS2) and G235H (NRS1) spectral cubes. To recover information in these spaxels, the *uncal* files were first trimmed from 4 groups down to 1 group, thereby eliminating the saturated groups in the G140H (NRS2) and most of the G235H (NRS1) spaxels. A modest range of wavelengths were additionally trimmed from the G235H (NRS1) data to remove residual saturation, creating a small wavelength gap ($1.890 - 1.898 \mu\text{m}$). No information was recovered from the G140H NRS1 data as saturation occurred within its first group, across all wavelengths ($1.1 - 1.42 \mu\text{m}$). In general, “edge” spaxels along the outer circumference of Europa’s disk have lower signal-to-noise (S/N) and are more likely to retain artifacts after data processing. Thus, we focused our measurements and analyses on spaxels interior to this outer ring.

Data Reduction. The data were downloaded from the Mikulski Archive for Space Telescopes (10.17909/ve8q-sq65). Data processing was conducted with the Science Calibration Pipeline v1.14.0 with CRDS context jwst.1241.pmap, processing raw *uncal* data into *s3d* spectral cubes for both dithers (Bushouse et al. 2023). The pipeline was run with default parameters and the $1/f$ pattern noise was removed using the NSClean routine (Rauscher 2023). The two dithers for each grating (NRS1 and NRS2) were georeferenced to Europa’s disk and median combined, resulting in six total spectral cubes. To remove the solar component, we then divided each spaxel in each cube by a solar model generated with the Planetary Spectrum Generator (PSG; Villanueva et al. 2018, 2022). This PSG-derived solar model includes Doppler shifts, uses the ACE solar spectrum (e.g., Hase et al. 2010) to integrate Fraunhofer lines, and utilizes a well established solar model (Kurucz 2005) to replicate the continuum intensity. Next, 1D spectra, and their associated georeferenced spatial information, were extracted from each spaxel on Europa’s disk for all six spectral cubes. The 1D spectra were stitched together into one spectrum and then recombined into a finalized spectral cube, spanning 1.48 to $5.35 \mu\text{m}$ in each spaxel. Uncertainties for this spectral cube were estimated with standard error propagation routines that utilized the underlying calibrated uncertainties for each spaxel (as reported by the pipeline).

Regional Reflectance Spectra. We generated representative spectra that highlight the spectral properties in three different regions on Europa’s leading hemisphere: Tara Regio, Powys Regio, and Europa’s ice-rich northern latitudes, normalized to 1 between 1.77 and $1.78 \mu\text{m}$. These spectra were generated by median combining 4 spaxels in each location (shown in Figure 1). These spaxels were chosen because they are representative of the distinct spectral properties of the three regions, while also being spatially contiguous and avoiding lower S/N edge spaxels.

Comparison to Synthetic Spectra. We compared the regional reflectance spectra to one-layer H_2O ice spectral models ($100 \mu\text{m}$ diameters), generated using the real, n , and imaginary, k , indices of refraction (i.e., “optical constants”) for crystalline H_2O ice (120 K) and amorphous ice (120 K) measured in the laboratory (Mastrapa et al. 2008, 2009). These models were derived from Mie scattering theory (Bohren & Huffman 2008) to calculate the single scattering albedo for each constituent, which were then passed to Hapke equations to calculate the geometric albedo (i.e., 0° phase angle) as a function of wavelength (Hapke 2012). These Hapke-Mie models do not account for Europa’s intrinsic photometric properties. Nevertheless, the models provide a useful approximation of H_2O ice measured in the laboratory that we can compare to H_2O ice features observed on Europa. Although Mie scattering can only approximate planetary regoliths, it has been widely applied to model the surfaces of icy bodies. Additional details and caveats on application of this Hybrid Hapke-Mie modeling approach for icy regoliths is provided in Cartwright et al. 2022, 2024b.

2.2. Band Parameter Measurements

We measured the areas and spectral contrast (i.e., band depths or peak heights) of all features using a measurement program that first defines and divides off a local linear or polynomial continuum for each feature (e.g., Cartwright et al. 2024a,b). Continuum-divided, spectral contrast measurements were made by averaging the reflectance values within ± 0.001 to $0.003 \mu\text{m}$ of the deepest/tallest point in each continuum-divided band (B_c) or peak (P_c) center, and uncertainties were computed using standard error propagation procedures (e.g., Taylor 1997). The quality of these central wavelength positions are assessed manually before measuring the spectral contrast for each absorption feature ($1 - B_d$) and scattering peak ($P_d - 1$). Using the trapezoidal rule, we measured each feature’s continuum-divided area, with error estimation conducted with Monte Carlo-based sampling of the 1σ errors for the spectral channels spanning each feature.

Band Measurement Caveats. Because the G140H NRS1 data are saturated, the short wavelength end and associated continuum for Europa’s $1.5 \mu\text{m}$ band are missing from these spectra, and we utilized a short wavelength cutoff of $1.48 \mu\text{m}$ for all measurements of this feature (Table 1). Consequently, the $1.5 \mu\text{m}$ band areas and spectral contrasts reported here are likely smaller than measurements made with other datasets that are able to sample the entire wavelength

range of the $1.5\ \mu\text{m}$ band. The $1.65\ \mu\text{m}$ band ($1.624 - 1.682\ \mu\text{m}$) is fully encapsulated within the broader $1.5\ \mu\text{m}$ band ($1.48 - 1.742\ \mu\text{m}$), and we therefore subtracted the $1.65\ \mu\text{m}$ band area from the $1.5\ \mu\text{m}$ band area to separate the contributions from each feature. Because of the long wavelength cutoff for the G395H NRS1 detector ($\sim 4\ \mu\text{m}$), the long wavelength end of the $3.6\ \mu\text{m}$ H_2O ice continuum peak was restricted to $4\ \mu\text{m}$ for all measurements. The short wavelength end of the $3.6\ \mu\text{m}$ H_2O ice continuum peak varies between ~ 3.3 and $3.55\ \mu\text{m}$, depending on its shape (Figure 2) and central wavelength (Table 1). The $4.25\ \mu\text{m}$ and $4.27\ \mu\text{m}$ lobes of Europa’s solid-state CO_2 feature are convolved, and we therefore report the same band area measurement for both lobes. Band minima for each lobe are readily discernible, and we are able to report separate band depths (Table 1).

Continuum-Divided Spectral Maps. We generated spaxel maps using the central wavelength for each feature and their associated continuum-divided band area and spectral contrast measurements (shown in Figures 3, 4, and 5). These maps are not projected and instead utilize the same grid of IFU spaxels that covered Europa’s disk during the NIRSpec observations. Because we used continuum-divided measurements to make the maps, albedo variations between spaxels are effectively removed, and we therefore did not perform photometric corrections.

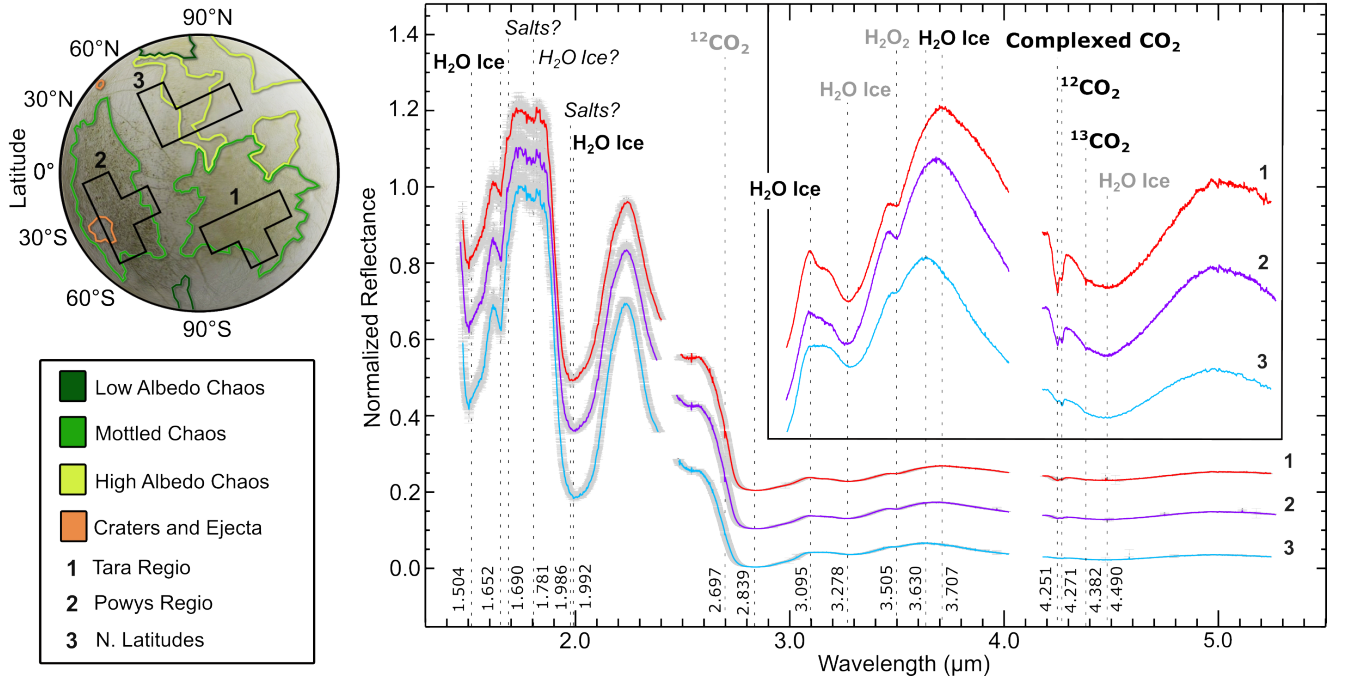


Figure 1. Left: Mosaic of Europa’s leading hemisphere, made with images collected by Galileo’s Solid State Imager, overlain by mapping of previously defined geologic features (Leonard et al. 2024). Black polygons show the locations of JWST/NIRSpec spaxels incorporated into the spectra shown on the right. Geologic units are defined in the legend below (utilizing a similar color scheme to Leonard et al. 2024). Right: JWST/NIRSpec spectra and 1σ uncertainties of Europa, representative of southern/central Tara Region (red, 1), southern Powys Region (purple, 2), and a northern low-latitude region dominated by ridges and bright terrains (cyan, 3). These spectra were generated by median-combining the four spaxels in each polygon shown in the map on the left, normalized to one between 1.77 and $1.78\ \mu\text{m}$ and offset vertically for clarity. The inset figure shows the same data, between 3 and $5.3\ \mu\text{m}$, normalized to one between 3.14 and $3.15\ \mu\text{m}$ and offset vertically. Confirmed absorption bands associated with H_2O ice, solid-state CO_2 , and H_2O_2 , and the $3.1\ \mu\text{m}$ H_2O ice Fresnel peak and $3.6\ \mu\text{m}$ H_2O ice continuum peak are labeled (bolded text). Spectral features that might include contributions from hydrated minerals, such as sulfates (De Angelis et al. 2021), chlorides (e.g., De Angelis et al. 2022), and carbonates (e.g., De Angelis et al. 2019), are labeled “salts?” (italicized text). Central wavelengths (μm) for these confirmed and possible features are listed vertically along each dotted line. Constituents labeled in gray font are shown here for completeness but were not measured by this study. Subtle spectral features between 4.7 and $5.1\ \mu\text{m}$ could be artifacts, and we did not analyze them in this study.

3. RESULTS AND ANALYSES

3.1. Detected Spectral Features

H₂O Ice and Hydrated Salts. The JWST/NIRSpec data display prominent 1.5 μm , 1.65 μm , and 2.0 μm absorption bands, and 3.1 μm scattering peaks and 3.6 μm continuum peaks, all of which primarily result from H₂O ice (e.g., Grundy & Schmitt 1998; Mastrapa et al. 2008, 2009). In some locations, the broader 3.1 μm scattering peak (hereon referred to as the “3.1 μm Fresnel region”) is overprinted by an additional narrow peak centered near 3.1 μm , primarily in spaxels co-located with Tara and Powys Regiones (Figure 1). We also identify a subtle feature centered near 1.69 μm on the shoulder of the 1.5 μm feature (1.67 – 1.71 μm) that appears to deviate from the spectral signature of “pure” H₂O ice (Figure 2), consistent with prior work that suggested non-ice species are contributing to the $\sim$ 1.7 μm wavelength range (Ligier et al. 2016). Although CH-bearing organic species can express absorption features near 1.7 μm (e.g., Quirico & Schmitt 1997; Clark et al. 2009), there are no obvious indicators for the stronger C-H stretching modes between $\sim$ 3.2 and 3.5 μm (Figures 1 and 2), hinting that salts might be more likely to contribute to this 1.69 μm shoulder feature. Another subtle feature near 1.78 μm might be consistent with crystalline H₂O ice or hydrated salts (Figure 2).

Aside from lower S/N edge spaxels, the 1.5 μm and 1.65 μm bands exhibit only minor variations in their band centers (1.502 – 1.505 μm and 1.652 – 1.653 μm , respectively, Figure 2). Ground-based and Galileo/NIMS data show similar trends for Europa’s 1.65 μm band, with widely varying band strengths but only small changes in its central wavelength position across Europa’s leading and trailing hemispheres (Cartwright et al. 2023). In contrast, the center of the 2.0 μm band exhibits wavelength shifts between the different regions of Europa’s leading hemisphere (1.994 ± 0.022 μm), with its central wavelength shifted to shorter wavelengths in spaxels associated with Tara Regio ($1.98 - 1.99$ μm), consistent with band measurements made by prior studies (e.g., McCord et al. 1998a; Ligier et al. 2016).

As defined in this study, Europa’s 3.1 μm region spans $\sim$ 2.9 to 3.3 μm with a flat, plateau-shaped top, consistent with global NIMS spectra and ground-based data collected over Europa’s leading hemisphere (Figure 2). The narrow 3.1 μm Fresnel peak that overprints the 3.1 μm region, primarily in spaxels spatially associated with Tara and Powys, exhibits minor variations in its central wavelength (3.096 ± 0.008 μm). Europa’s 3.6 μm continuum peak exhibits a large spread in central wavelengths (3.664 ± 0.06 μm ; Figure 2), primarily shifted to shorter wavelengths at northern latitudes ($\sim$ 3.63 μm), and longer wavelengths in Powys ($\sim$ 3.69 μm) and Tara ($\sim$ 3.71 μm), consistent with previous work that observed a 3.6 μm continuum peak shifted closer to 3.7 μm in Tara Regio (Fischer et al. 2016). The shape of the 3.6 μm continuum peak varies widely across Europa, primarily because of the variable band strength of the 3.505 μm H₂O₂ feature that forms a prominent shoulder band on its short wavelength side (Figure 1). We present continuum-divided band measurement maps for H₂O ice in Figures 3 and 4.

Solid-State CO₂. We identified absorption bands near 2.70 μm , 4.25 μm , 4.27 μm , and 4.38 μm that are all associated with solid-state CO₂, as described in prior work (Villanueva et al. 2023; Trumbo & Brown 2023). The 4.25 μm and 4.27 μm bands are two partially convolved lobes of Europa’s strongest CO₂ feature. The central wavelength of the 4.25 μm lobe exhibits only minor variation across Europa’s leading hemisphere (4.25 ± 0.002 μm), whereas the 4.27 μm lobe exhibits a slightly larger spread in its central wavelength (4.27 ± 0.005 μm). The central wavelength of the 4.38 μm band is essentially locked to 4.381 or 4.382 μm , and we detect no evidence for a double-lobed structure. Because we are primarily interested in understanding the relationship between Europa’s 4.38 μm band and its double-lobed 4.25 μm and 4.27 μm CO₂ feature, we did not analyze the 2.70 μm feature here and instead refer the reader to prior work that investigated this band (Villanueva et al. 2023; Trumbo & Brown 2023). We present continuum-divided band measurement maps for solid-state CO₂ in Figure 5.

3.2. Band Parameter Measurements

H₂O Ice and Hydrated Minerals. We report spectral maps showing continuum-divided band areas and spectral contrast measurements (i.e., band depths and peak heights) for Europa’s 1.5 μm , 1.65 μm , and 2.0 μm H₂O ice bands, and its 3.1 μm Fresnel region and peak and 3.6 μm H₂O peak (Figures 3 and 4). The 1.5 μm , 1.65 μm , and 2.0 μm bands and 3.6 μm continuum peak show similar spatial trends, with larger spectral contrasts and areas at northern latitudes, particularly in a wedge-shaped region, east of Powys and northwest of Tara (represented by spectrum 3 in Figure 1), which was previously identified as an ice-rich region on Europa (e.g., Ligier et al. 2016). The 3.1 μm Fresnel region exhibits larger spectral contrasts and areas in spaxels associated with Tara and Powys Regiones over Europa’s southern latitudes compared to its northern latitudes (Figures 4 and 6), consistent with prior analysis of Juno/JIRAM data (Filacchione et al. 2019). Furthermore, the 3.1 μm Fresnel peak is only reliably observed at southern latitudes ($>3\sigma$ detection), with the strongest peaks measured in spaxels covering Tara Regio. We also conducted band parameter

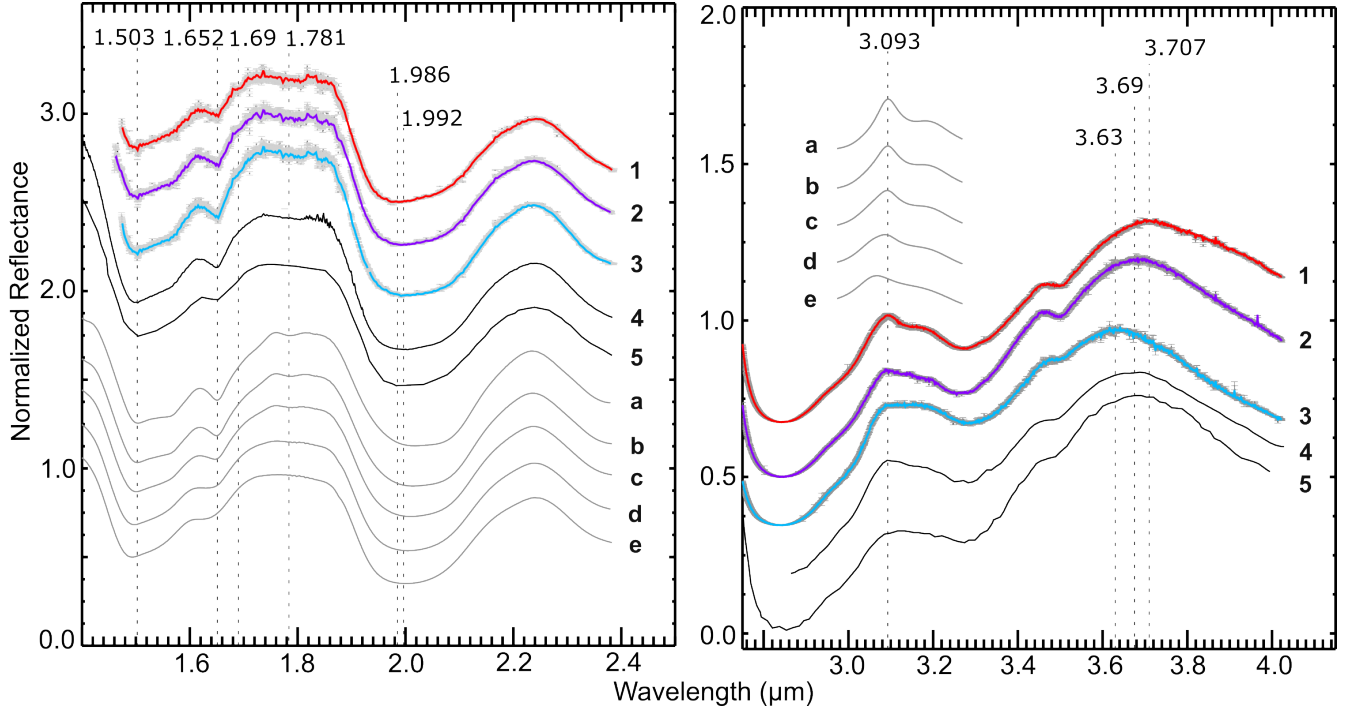


Figure 2. Left: Tara (red, 1), Powys (purple, 2), and northern low-latitude (cyan, 3) JWST/NIRSpec spectra and 1σ errors shown in Figure 1 compared to a ground-based, disk-integrated IRTF/SpEX spectrum of Europa’s leading hemisphere (black, 4, originally presented in [Cartwright et al. 2023](#)) and a global spectrum collected by Galileo/NIMS (black, 5, originally reported in [McCord et al. 1998a](#)). These empirical data are compared to spectral models (gray) that utilize linear mixtures of 100 μm diameter grains of H₂O ice measured at 120 K ([Mastrapa et al. 2008, 2009](#)) with the following fractional abundances: (a) 100% crystalline H₂O ice, (b) 75% crystalline H₂O ice and 25% amorphous H₂O ice, (c) 50% crystalline H₂O ice and 50% amorphous H₂O ice, (d) 25% crystalline H₂O ice and 75% amorphous H₂O ice, and (e) 100% amorphous H₂O ice (see Section 2.1 for more detail on our modeling procedures). All spectra are normalized to 1 at 1.77 μm and offset vertically for clarity. The dotted lines show the central wavelengths of Europa’s 1.5 μm and 1.65 μm H₂O ice bands, a weak 1.69 μm shoulder feature possibly resulting from salts, a potential hydrated salt or crystalline ice feature near 1.78 μm , and the varying central wavelength for Europa’s 2.0 μm H₂O ice band, shifting from 1.986 μm (Tara) to 1.992 μm (Powys and northern low-latitudes). Right: The same data and models, focused on longer wavelengths. The dotted lines show the central wavelengths of Europa’s 3.1 μm H₂O Fresnel peak and the large wavelength shift in its 3.6 μm H₂O ice continuum peak, ranging from 3.63 μm in the northern low-latitudes spectrum, 3.69 μm in the Powys spectrum, and 3.71 μm in the Tara spectrum.

analyses on the Tara, Powys, and northern low-latitudes regional spectra (Table 1), finding the same trends in band area and spectral contrast measurements. Thus, our band parameter measurements confirm a north/south latitudinal dichotomy in the strength of H₂O ice features on Europa’s leading hemisphere that was described in prior work ([Ligier et al. 2016](#); [Filacchione et al. 2019](#)).

Solid-state CO₂. We report band depth and area measurements for Europa’s double-lobed, solid-state CO₂ feature and its 4.38 μm ¹³CO₂ band, using spectral maps spanning Europa’s leading hemisphere (Figure 5). Our results indicate that the 4.25 μm and 4.27 μm lobes have stronger band depths at southern latitudes, primarily in spaxels associated with Tara and Powys, consistent with previously reported measurements ([Villanueva et al. 2023](#); [Trumbo & Brown 2023](#)). Additionally, the 4.25 μm lobe’s band depths weaken considerably at northern latitudes, whereas the 4.27 μm lobe’s band depths decrease more gradually at northern latitudes (Figure 7). The convolved band areas for these two lobes show similar trends, with larger area measurements at southern latitudes, in particular in spaxels spanning Tara Regio, and weaker measurements at northern latitudes. The band depth and area measurements for the 4.38 μm band indicate that this feature is primarily observed at southern latitudes, spatially associated with Tara and Powys ($>3\sigma$ detection), and is essentially undetected at northern latitudes (Figure 5).

Of note, a 4.38 μm feature detected on Ganymede with JWST/NIRSpec (G395H grating) was attributed to a data calibration artifact ([Bockelée-Morvan et al. 2024](#)). Europa’s 4.38 μm feature is much narrower than the broad 4.38 μm feature detected on Ganymede, and it exhibits discernible band depth and area variations across Europa’s disk that

Table 1. Band measurements for the regional spectra of Tara and Powys Regiones and the Northern Low-Latitudes Zone

Region	Feature Name	Feature Center (μm)	Feature Wavelength Range (μm)	Spectral Contrast (%)	Band Area ($10^{-3} \mu\text{m}$)	$>3\sigma$ Spectral Contrast and Band Area?	Constituents (confirmed, bolded) (suggested, italicized)
1. Tara	^{a,b,c} 1.5 μm Band	1.504	1.480 – 1.742	39.62 ± 0.04	54.14 ± 0.56	Yes	Crystalline H₂O Ice , <i>Hydrated Salts</i>
2. Powys		1.502		46.93 ± 0.33	71.29 ± 0.04	Yes	
3. N. Lat.		1.504		56.93 ± 0.39	89.34 ± 0.06	Yes	
1. Tara	^b 1.65 μm Band	1.652	1.624 – 1.682	9.58 ± 0.57	2.84 ± 0.03	Yes	Crystalline H₂O Ice
2. Powys		1.653		13.00 ± 0.55	3.93 ± 0.02	Yes	
3. N. Lat.		1.652		17.24 ± 0.64	5.13 ± 0.04	Yes	
1. Tara	^c 2.0 μm Band	1.986	1.857 – 2.237	67.06 ± 0.19	150.50 ± 0.54	Yes	Crystalline H₂O Ice , <i>Amorphous H₂O Ice</i> , <i>Hydrated Salts</i>
2. Powys		1.992		70.03 ± 0.34	156.86 ± 0.13	Yes	
3. N. Lat.		1.992		78.31 ± 0.36	180.62 ± 0.07	Yes	
1. Tara	3.1 μm Region	3.095	3.034 – 3.280	37.87 ± 0.81	47.65 ± 0.30	Yes	Crystalline H₂O Ice , Amorphous H₂O Ice
2. Powys		3.091		24.85 ± 0.49	30.85 ± 0.17	Yes	
3. N. Lat.		3.104		15.26 ± 0.59	24.23 ± 0.18	Yes	
1. Tara	3.1 μm Peak	3.093	3.060 – 3.125	6.83 ± 0.96	2.08 ± 0.13	Yes	Crystalline H₂O Ice , Amorphous H₂O Ice
2. Powys		3.087		3.36 ± 0.69	0.88 ± 0.07	Yes	
3. N. Lat.		N/A		-0.08 ± 1.15	-0.06 ± 0.06	No	
1. Tara	^c 3.6 μm Peak	3.707	3.537 – 4.000	29.95 ± 0.12	479.98 ± 0.15	Yes	Crystalline H₂O Ice , <i>Hydrated Salts</i>
2. Powys		3.690		47.07 ± 0.17	657.93 ± 0.26	Yes	
3. N. Lat.		3.631		68.68 ± 0.21	814.46 ± 0.31	Yes	
1. Tara	^d 4.25 μm Lobe	4.251	4.203 – 4.292	25.38 ± 0.35	10.36 ± 0.03	Yes	Complexed CO₂
2. Powys		4.251		16.51 ± 0.34	7.01 ± 0.04	Yes	
3. N. Lat.		4.250		6.52 ± 0.28	2.99 ± 0.05	Yes	
1. Tara	^d 4.27 μm Lobe	4.269	4.203 – 4.292	16.70 ± 0.23	10.36 ± 0.03	Yes	¹² CO ₂
2. Powys		4.271		12.44 ± 0.30	7.01 ± 0.04	Yes	
3. N. Lat.		4.271		7.87 ± 0.83	2.99 ± 0.05	Yes	
1. Tara	4.38 μm Band	4.382	4.370 – 4.388	4.06 ± 0.68	0.25 ± 0.02	Yes	¹³ CO ₂
2. Powys		4.381		2.54 ± 0.33	0.17 ± 0.01	Yes	
3. N. Lat.		N/A		0.54 ± 0.39	0.09 ± 0.02	No	

^a The 1.50 μm band is bound by the short wavelength cutoff of the G140H grating (NRS2) and the values reported here are likely underestimates.

^b The 1.65 μm feature fully overlaps the 1.5 μm feature, and thus, its band area was subtracted off the 1.5 μm band area.

^c These features may include contributions from “hydrated salts,” a catchall designation that includes NaCl.

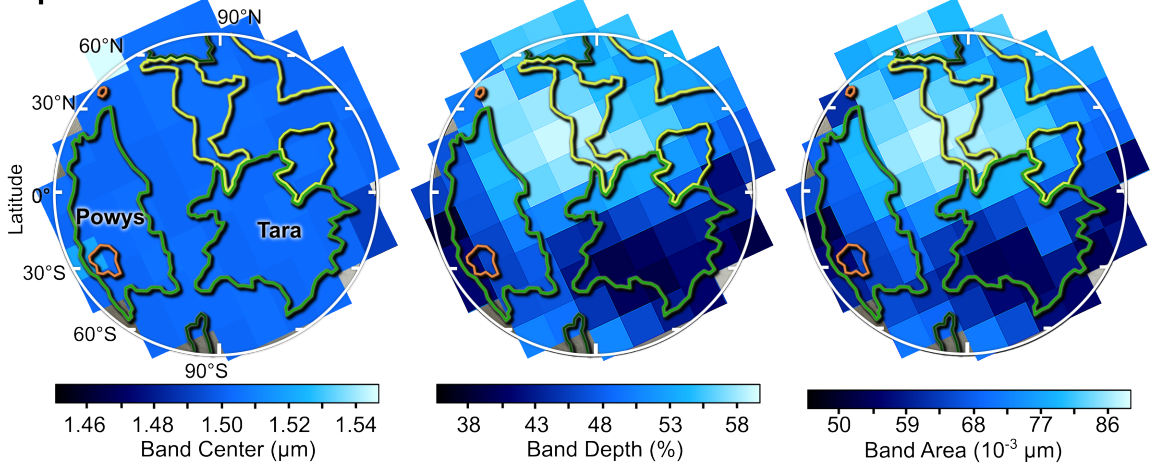
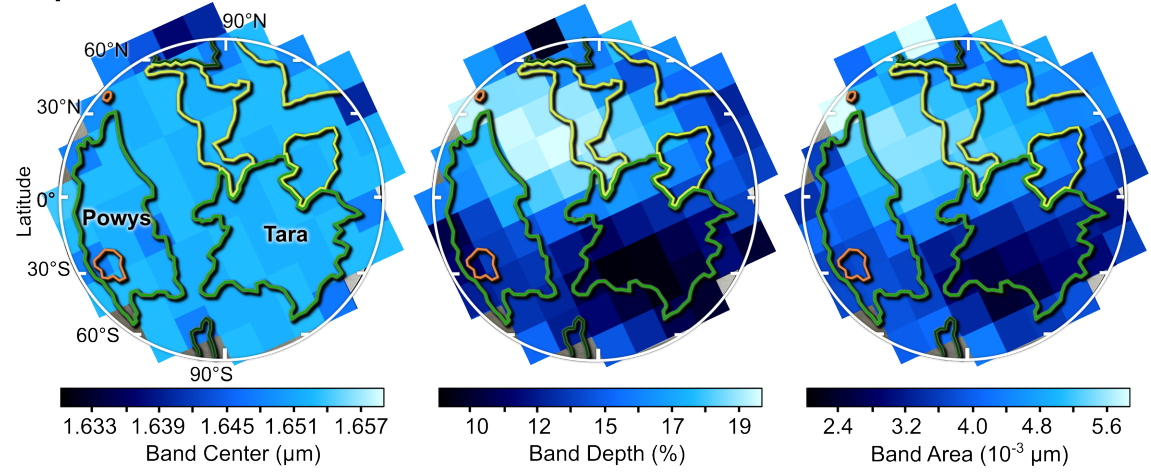
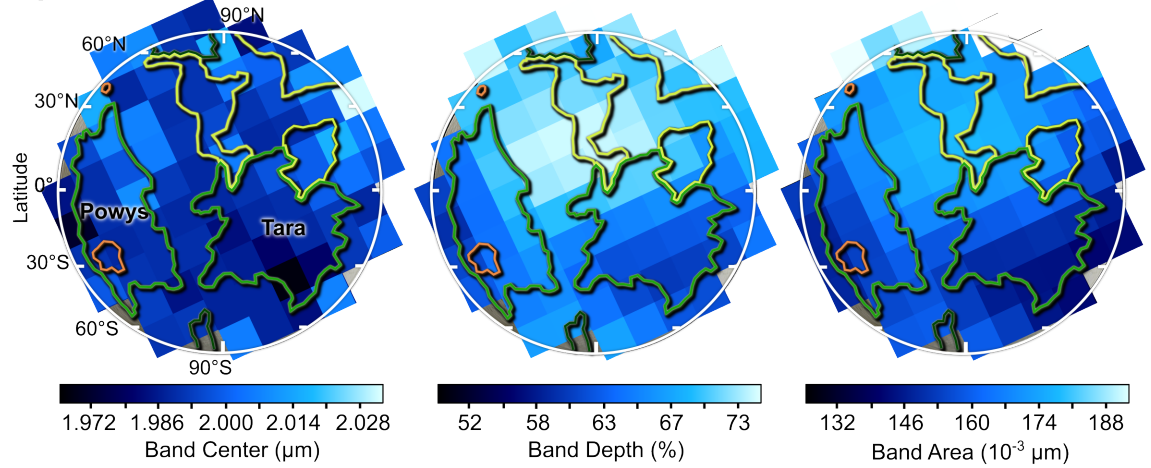
^d Band areas for the 4.25 and 4.27 μm lobes are convolved, and we report the same band area for both features.

appear to track the spatial distribution of its double-lobed CO₂ feature (Figures 5 and 7), unlike Ganymede’s 4.38 μm feature that exhibits a mostly uniform profile across its surface. Thus, the measurements we report here demonstrate that the 4.38 μm feature very likely results from solid-state ¹³CO₂ detected on Europa’s surface.

4. DISCUSSION

4.1. Spatial Distribution and Vertical Stratification of H₂O Ice

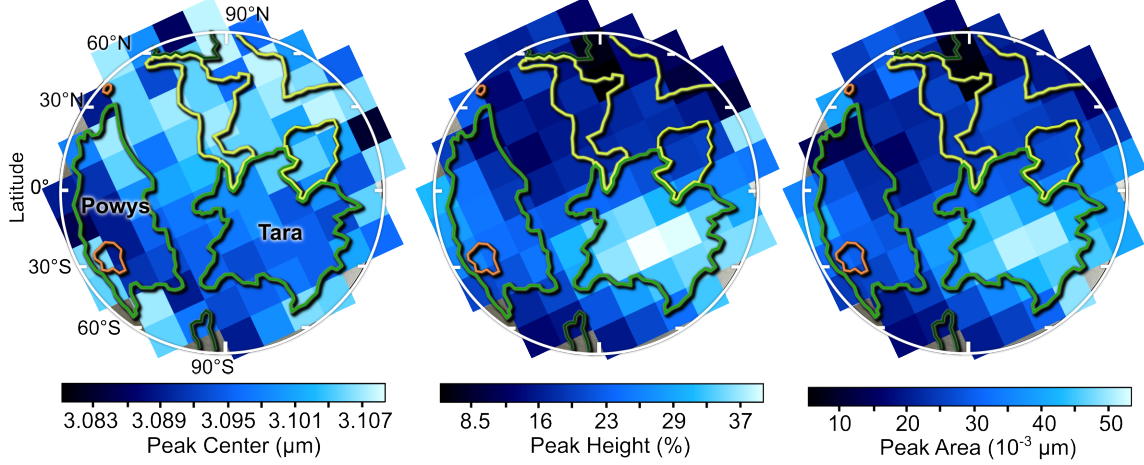
All of the H₂O features we measured are stronger at northern latitudes, except for the 3.1 μm H₂O ice Fresnel region and the narrow 3.1 μm Fresnel peak that are notably stronger at southern latitudes, in particular in spaxels spanning Tara and Powys Regiones (Figures 3 and 4). This latitudinal dichotomy in the strength of Europa’s H₂O ice features is particularly puzzling for the 1.65 μm band and the 3.1 μm Fresnel region (Figure 6), which are both diagnostic of crystalline ice (e.g. Mastrapa et al. 2008, 2009). One way to explain this discrepancy is if Europa’s icy regolith is vertically stratified, and these H₂O ice features are sampling different depths, as suggested by prior work (Hansen &

1.5- μm Band**1.65- μm Band****2.0- μm Band**

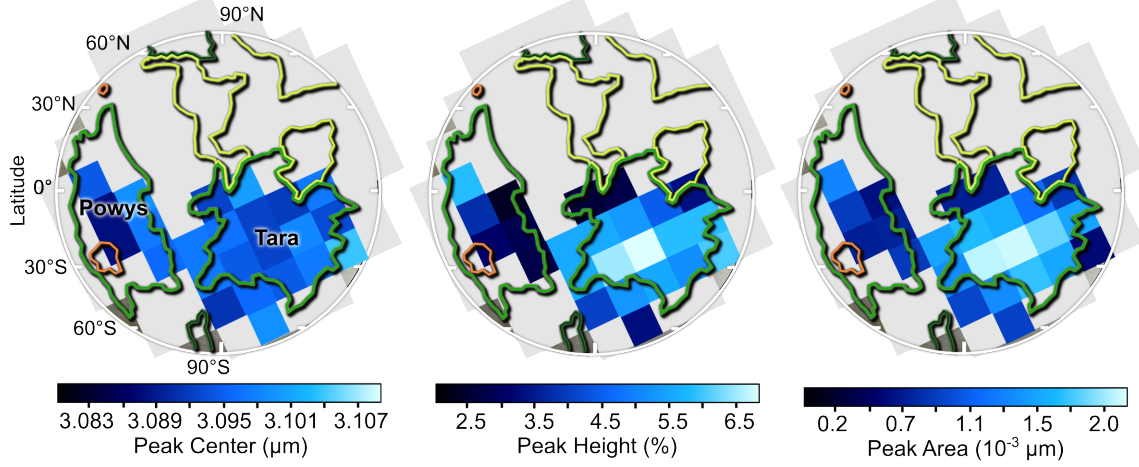
Low Albedo Chaos
 Mottled Chaos (Tara and Powys)
 High Albedo Chaos
 Craters and Ejecta

Figure 3. Spectral maps illustrating the distribution in the band centers, depths, and areas for (top) Europa's 1.5 μm band (1.48 – 1.74 μm), (middle) its 1.65 μm band (1.62 – 1.68 μm), and (bottom) its 2.0 μm band (1.86 – 2.24 μm), each primarily attributed to H_2O ice. The 1σ uncertainties for the spectral contrast measurements range between: 0.37 – 0.57%, 0.75 – 1.11%, and 0.10 – 1.00%, for the 1.5 μm , 1.65 μm , and 2.0 μm bands, respectively. The 1σ uncertainties for the area measurements are 0.12 – 0.32 μm , 0.11 – 0.21 μm , and 0.08 – 0.88 μm for the 1.5 μm , 1.65 μm , and 2.0 μm bands, respectively. The spatial extents of large-scale geologic units on Europa's leading and anti-Jovian sides, including Tara (10° S, 75° W) and Powys (0°, 145° W) Regions are indicated and described in the included legend (see [Leonard et al. 2024](#)).

3.1- μm Fresnel Region



3.1- μm Fresnel Peak



3.6- μm Continuum Peak

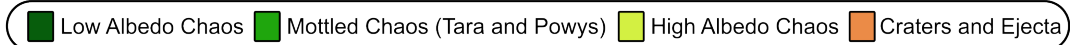
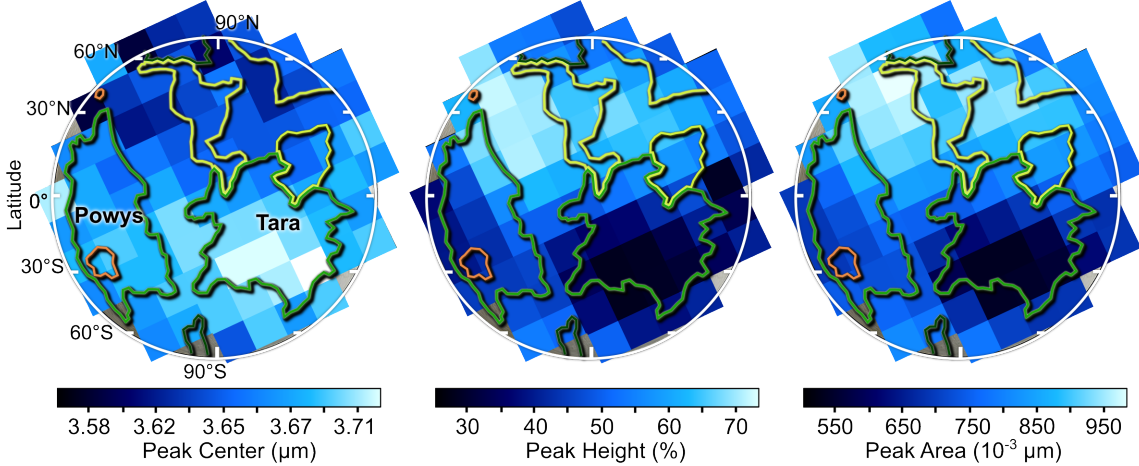
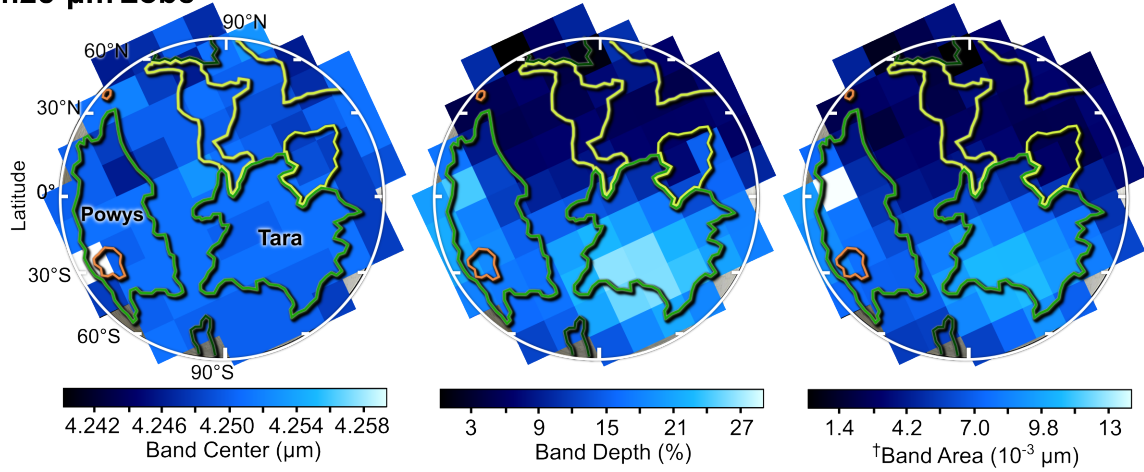
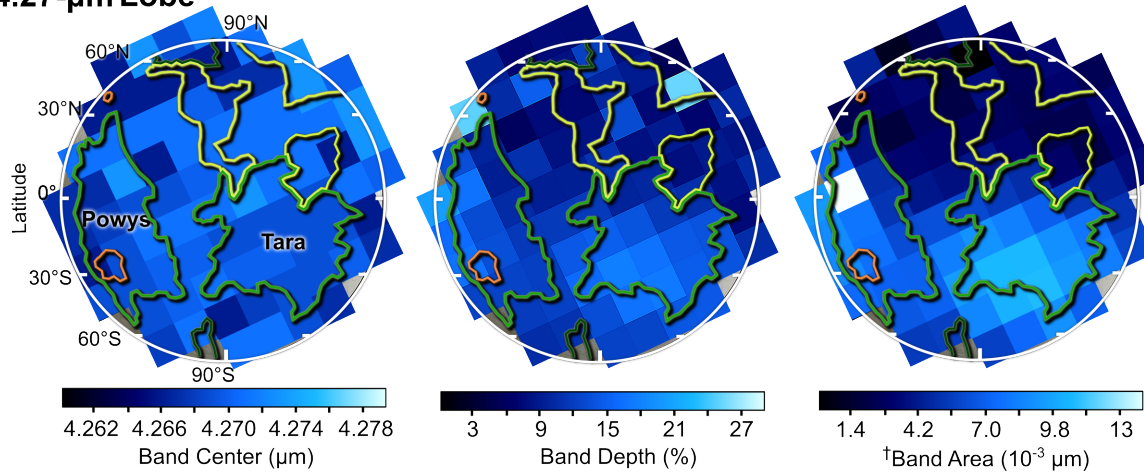


Figure 4. Spectral maps illustrating the distribution in the centers, heights, and areas for (top) Europa's 3.1 μm H_2O ice Fresnel region (2.9 – 3.3 μm), (middle) its 3.1 μm H_2O ice Fresnel peak (3.05 – 3.15 μm), and (bottom) its 3.6 μm H_2O ice continuum peak (3.3 – 4.0 μm). The 1σ uncertainties for the spectral contrast measurements range between: 0.58 – 1.78%, 0.70 – 1.00%, and 0.011 – 0.79%, for the 3.1 μm Fresnel region, 3.1 μm Fresnel peak, and 3.6 μm continuum peak, respectively. The 1σ uncertainties for the area measurements are 0.080 – 0.094 μm , 0.08 – 0.26 μm , and 0.08 – 0.14 μm for Europa's Fresnel region, 3.1 μm Fresnel peak, and the 3.6 μm continuum peak, respectively. Spazels where the 3.1 μm Fresnel peak was not detected ($>3\sigma$) are shown in light gray. The spatial extents of large-scale geologic units on Europa's leading and anti-Jovian sides, including Tara (10° S, 75° W) and Powys (0°, 145° W) Regions are indicated and described in the included legend (see Leonard et al. 2024).

4.25- μm Lobe



4.27- μm Lobe



4.38- μm Band

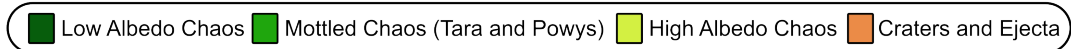
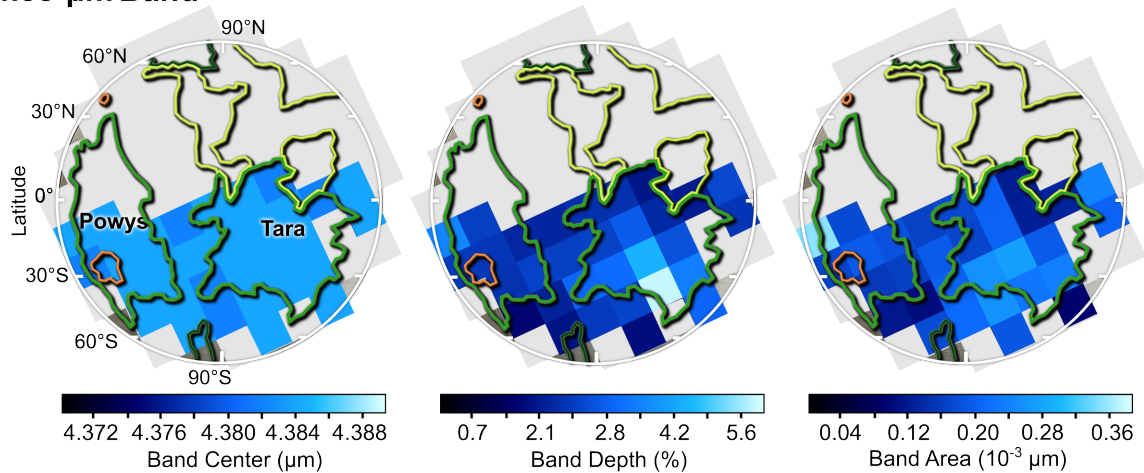


Figure 5. Spectral maps illustrating the distribution in the band centers, depths, and areas for (top) Europa’s 4.25 μm lobe (4.2 – 4.3 μm), (middle) 4.27 μm lobe (4.2 – 4.3 μm), and (bottom) 4.38 μm band (4.37 – 4.39 μm), each attributed to solid-state CO_2 . [†] The band areas of the 4.25 μm and 4.27 μm lobes are convolved, and we therefore report the same area measurements for both features. The 1σ uncertainties for the spectral contrast measurements range between: 0.10 – 0.90%, 0.38 – 1.90%, and 0.40 – 1.36%, for the 4.25 μm region, 4.27 μm band, and 4.38 μm band, respectively. The 1σ uncertainties for the area measurements are 0.03 – 0.07 μm and 0.01 – 0.03 μm for the convolved 4.25 μm and 4.27 μm lobes and the 4.38 μm band, respectively. Spazels where the 4.38 μm band was not detected ($>3\sigma$) are shown in light gray. The spatial extents of large-scale geologic units on Europa’s leading and anti-Jovian sides, including Tara (10°S, 75°W) and Powys (0°, 145°W) Regions are indicated and described in the included legend (see [Leonard et al. 2024](#)).

McCord 2004). Laboratory experiments have demonstrated that photon penetration depths into H_2O ice are a steep function of wavelength, with photons spanning the $1.5\ \mu\text{m}$, $1.65\ \mu\text{m}$, and $2\ \mu\text{m}$ bands traversing ~ 100 to $500\ \mu\text{m}$ depths into icy surfaces (e.g., Mastrapa et al. 2008, 2009). In contrast, across the wavelength range of the H_2O ice Fresnel region ($\sim 2.9 - 3.3\ \mu\text{m}$), photons are largely absorbed within the very top surface of icy regoliths ($< 10\ \mu\text{m}$ depths), and in the narrower wavelength range of the $3.1\ \mu\text{m}$ Fresnel peak ($\sim 3.05 - 3.15\ \mu\text{m}$), photons essentially only interact with the surfaces of exposed H_2O ice grains ($< 1\ \mu\text{m}$ depths; Becker et al. 2024). H_2O ice features at shorter near-infrared wavelengths ($< 2.5\ \mu\text{m}$) therefore probe greater depths than H_2O ice features in the Fresnel region, and comparing spectral features in these two wavelength ranges can provide key clues on the vertical stratification of H_2O -dominated regoliths (e.g., Hansen & McCord 2004; Cartwright et al. 2015, 2020; Protopapa et al. 2024).

Prior work that investigated vertical stratification of Europa’s icy regolith determined that its exposed surface is dominated by amorphous ice due to the non-detection of a narrow $3.1\ \mu\text{m}$ Fresnel peak (Hansen & McCord 2004). Our results show that the narrow $3.1\ \mu\text{m}$ Fresnel peak is present on Europa’s leading hemisphere, but only at southern latitudes, primarily in spaxels spanning Tara and Powys Regiones (discussed at greater length in Section 4.4). The much lower S/N of Galileo/NIMS data compared to JWST/NIRSpec data at wavelengths $> 2.5\ \mu\text{m}$ might explain the prior non-detection of this weak feature.

4.2. Spectral Properties and Inferred Temperature Ranges for H_2O Ice

To investigate the state of H_2O ice on Europa’s surface, we compared the JWST/NIRSpec spectra to a disk-averaged, ground-based spectrum collected with the SpeX spectrograph on NASA’s Infrared Telescope Facility (Rayner et al. 2003) and a global Europa spectrum collected with Galileo/NIMS (Figure 2). We compared the $1.5\ \mu\text{m}$ and $1.65\ \mu\text{m}$ bands and $3.1\ \mu\text{m}$ Fresnel region in all of these empirical data to synthetic spectra of crystalline and amorphous ice (Figure 2).

H_2O ice at wavelengths $< 2.5\ \mu\text{m}$. Comparison between the telescope and spacecraft reflectance spectra highlights the essentially unchanging central wavelengths of Europa’s $1.5\ \mu\text{m}$ and $1.65\ \mu\text{m}$ band across its leading hemisphere (spectra 1-5 in Figure 2), which are most consistent with high concentrations of crystalline ice (model spectra a and b in Figure 2). The central wavelength of Europa’s $1.65\ \mu\text{m}$ band ($1.652 - 1.653\ \mu\text{m}$) suggests a crystalline H_2O ice temperature range of 100 to $110\ \text{K}$, which falls within existing estimates of Europa’s equatorial surface temperature, ranging from a nightside minimum of $\sim 80\ \text{K}$ to a dayside maximum of $\sim 130\ \text{K}$ (e.g., Spencer et al. 1999; Teolis et al. 2017). The central wavelength of Europa’s $1.5\ \mu\text{m}$ band ($1.502 - 1.505\ \mu\text{m}$) suggests a crystalline H_2O ice temperature range of 90 to $150\ \text{K}$ (Mastrapa et al. 2008). Because the G140H NRS1 data are saturated between 1.1 and $1.42\ \mu\text{m}$, we are unable to measure the entirety of this feature, which may impact the accuracy of the $1.5\ \mu\text{m}$ band’s central wavelength range reported here.

The central wavelength of Europa’s $2.0\ \mu\text{m}$ band exhibits notable shifts, from about $1.986\ \mu\text{m}$ in Tara Regio to $1.992\ \mu\text{m}$ in other regions, and closer to $2.0\ \mu\text{m}$ in disk-integrated datasets (Figure 2). At first glance, this range in central wavelengths ($1.986 - 2.000\ \mu\text{m}$) is broadly consistent with the presence of large concentrations of amorphous ice (Mastrapa et al. 2008), in particular in Tara Regio (model spectra d and e in Figure 2). Laboratory measurements indicate that the $2.0\ \mu\text{m}$ H_2O ice band samples shallower regolith depths ($\lesssim 100\ \mu\text{m}$) compared to the $1.5\ \mu\text{m}$ and $1.65\ \mu\text{m}$ bands ($\lesssim 200\ \mu\text{m}$ and $\lesssim 500\ \mu\text{m}$, respectively; Mastrapa et al. 2008), and perhaps Europa’s $2.0\ \mu\text{m}$ band is sampling larger concentrations of amorphous ice closer to Europa’s exposed surface. However, the presence of a prominent $3.1\ \mu\text{m}$ H_2O Fresnel peak in Tara Regio, and the ubiquitous presence of a $1.65\ \mu\text{m}$ band, clearly indicates crystalline ice is exposed in this region and present at depth across Europa. Furthermore, comparison to laboratory measurements suggests the central wavelength of the $2.0\ \mu\text{m}$ band in Tara Regio is best matched by cryogenic amorphous ice ($< 70\ \text{K}$; Mastrapa et al. 2008), which is incompatible with Europa’s estimated surface temperature range ($80 - 130\ \text{K}$). Instead, it seems more likely that hydrated minerals are shifting Europa’s $2.0\ \mu\text{m}$ band to shorter wavelengths, as demonstrated in a variety of different laboratory experiments that examined chloride salts (e.g., Hanley et al. 2014; Thomas et al. 2017; De Angelis et al. 2022), especially in Tara and Powys Regiones where irradiated NaCl has been identified (e.g., Trumbo et al. 2022).

H_2O ice at wavelengths $> 2.5\ \mu\text{m}$. The IRTF/SpeX and Galileo/NIMS data (spectra 4 and 5 in Figure 2) have similar spectral properties between 3 and $4\ \mu\text{m}$, with $3.6\ \mu\text{m}$ continuum peaks centered near $3.67\ \mu\text{m}$, albeit with minor evidence for a narrow $3.1\ \mu\text{m}$ Fresnel peak in the IRTF/SpeX spectrum, but not in the Galileo/NIMS spectrum. The $3.1\ \mu\text{m}$ Fresnel regions in these two spectra are most consistent with high concentrations of amorphous ice ($120\ \text{K}$) at Europa’s exposed surface (model spectra d and e in Figure 2), as noted in prior work (Hansen & McCord 2004).

In contrast, the three regional spectra collected with JWST/NIRSpec reveal notable spectral differences in H₂O ice across Europa. The northern low-latitude spectrum shows no evidence for a narrow 3.1 μm Fresnel peak, consistent with exposed amorphous ice (model spectra d and e). The 3.6 μm continuum peak in this spectrum is centered near 3.63 μm , consistent with crystalline H₂O ice that is relatively free of contaminants (Filacchione et al. 2019), with an ice temperature of ~ 120 K. The Powys spectrum shows a subtle 3.1 μm Fresnel peak, consistent with a regolith comprised of mostly amorphous H₂O mixed with minor amounts of crystalline ice (model spectra c and d), and a 3.6 μm continuum peak shifted to 3.69 μm , consistent with warmer crystalline ice (~ 170 K; Filacchione et al. 2019) and/or mixing with non-ice contaminants. The Tara spectrum shows a prominent 3.1 μm Fresnel peak, consistent with high concentrations of crystalline ice mixed with a minor fraction of amorphous ice (model spectra b and c), and a 3.6 μm continuum peak shifted to 3.71 μm , hinting at a crystalline ice temperature above 200 K (Clark et al. 2012) and/or substantial mixing with non-ice contaminants.

The temperatures inferred from the wavelength shift of the 3.6 μm continuum peak in spaxels spanning Powys and Tara Regiones (>170 K) are significantly higher than existing estimates of Europa’s peak surface temperature (~ 130 K). Additionally, there is no evidence for thermal emission at wavelengths >4.5 μm that should be observed at such elevated surface temperatures, as seen in JWST/NIRSpec data of Callisto (see Figure A5 in Cartwright et al. 2024a). Given the documented challenges with using the 3.6 μm continuum peak as a surface ice thermometer for regoliths that include well-mixed impurities (e.g., Filacchione et al. 2012), it seems more likely that the shifted central position of this feature results primarily from the presence of contaminants mixed with H₂O (e.g., frozen salts, CO₂) as opposed to large regional variations in the surface temperature of ice. Nonetheless, if warmer ice is indeed present in Powys and Tara Regiones, it may be an indicator of recent exposure of liquid meltwater that rapidly froze once exposed at Europa’s surface.

The 3.1 μm H₂O ice Fresnel peak samples extremely shallow depths (<1 μm), where near-infrared photons are essentially reflected off ice grains, making it a sensitive indicator of “pure” H₂O ice (i.e., without volume scattering contributions from non-ice impurities in the underlying regolith). In Tara and Powys Regiones, the 3.1 μm Fresnel peak is centered near 3.09 μm , implying a temperature between 120 to 150 K for ice grains exposed on Europa’s surface (Mastrapa et al. 2008; Stephan et al. 2021). Laboratory experiments demonstrate that pure crystalline ice can shift the central wavelength of the H₂O ice Fresnel peak to 3.09 μm when warmed to 150 K (Stephan et al. 2021). Thus, the slightly shifted central wavelength of the 3.1 μm Fresnel peak in Tara and Powys (~ 3.09 μm) may result from interactions between near-infrared photons and a thin mantle of warm crystalline ice grains, with negligible or no interactions with amorphous ice grains.

The intensity of the 3.6 μm continuum peak can be used to infer the prevailing size range for H₂O ice grains in a regolith (e.g. Filacchione et al. 2012), with larger, more absorbing grains ($\gtrsim 100$ μm diameters) suppressing the peak height relative to smaller grains (~ 1 to few 10’s μm diameters; Mastrapa et al. 2009). The regional spectrum of Tara exhibits a suppressed 3.6 μm continuum peak relative to the regional spectrum of Powys, which is in turn suppressed relative to the ice-rich northern low-latitudes regional spectrum (Figure 2, Table 1), suggesting that Tara’s regolith may be dominated by larger grains than elsewhere on Europa’s leading hemisphere. However, the lower intensity of the 3.6 μm continuum peak may also result from higher concentrations of impurities, and thus, less exposed H₂O ice. Supporting this interpretation, the 1.5 μm , 1.65 μm , and 2.0 μm bands in the regional spectrum of Tara are notably weaker than the regional spectra of Powys or Europa’s northern low-latitudes (Table 1), consistent with less ice and/or a regolith dominated by smaller grains.

The 3.6 μm continuum peak samples over an order of magnitude greater regolith depths (~ 50 μm deep) compared to the 3.1 μm Fresnel peak (<1 μm deep). Consequently, these two features likely probe distinct regolith layers, with the 3.1 μm Fresnel peak sensitive to a thin layer of small ice grains exposed at the surface, whereas the 3.6 μm continuum peak, and the other H₂O ice features examined here, sensitive to a layer (or multiple layers) of larger grains at depth. Follow-up laboratory experiments that measure reflectance spectra of samples composed of H₂O ice mixed with salts and other non-ice impurities are needed to better understand how grain size and temperature influence the spectral properties of Europa’s 3.6 μm H₂O ice continuum peak. Future measurements made by the Europa Thermal Emission Imaging System (E-THEMIS; (Christensen et al. 2024)) on Europa Clipper will provide invaluable insight on the temperature and porosity of Europa’s regolith.

4.3. Spectral Properties and Spatial Distribution of CO₂

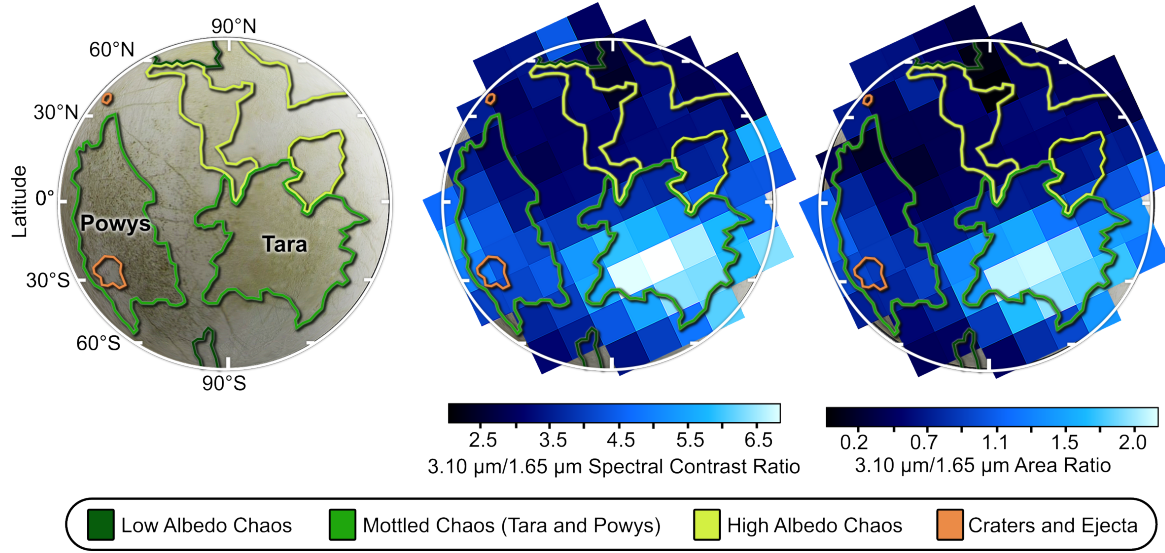


Figure 6. Spaxel maps displaying the ratios between Europa’s 3.1 μm Fresnel region and its 1.65 μm band (3.1 μm Region/1.65 μm band), generated with the spectral contrast and area measurements shown in Figures 3 and 4. These ratio maps highlight the dissimilar trends in the distribution of crystalline H_2O ice on Europa, with the 1.65 μm band stronger at northern latitudes and the 3.1 μm Fresnel region stronger at southern latitudes, particularly in Tara and Powys Regions. This dissimilarity points to vertical stratification of H_2O ice in Europa’s regolith, with more exposed crystalline H_2O ice at southern latitudes. The spatial extents of large-scale geologic units on Europa’s leading and anti-Jovian sides, including Tara (10°S , 75°W) and Powys (0° , 145°W) Regions are indicated and described in the included legend (see Leonard et al. 2024).

Solid-state CO_2 is present across Europa’s leading and anti-Jovian hemispheres, primarily identified by a prominent, doubled-lobed feature centered near 4.25 μm and 4.27 μm (Figure 5). Prior analysis of Galileo/NIMS data shows that CO_2 is also present across Europa’s trailing and sub-Jovian hemispheres (e.g. Hansen & McCord 2008), demonstrating the global presence of this molecule. The formation of the 4.25 μm lobe has been attributed to irradiation of H_2O in an organic-rich environment, as well as CO_2 deposited onto a frozen saline mixture (Villanueva et al. 2023). The 4.27 μm lobe could form from irradiation of a substrate composed of $^{12}\text{CO}_2$ and H_2O ice (Protopapa et al. 2024).

Unlike the convolved 4.25 μm and 4.27 μm CO_2 feature, the 4.38 μm band displays no evidence for band splitting, with a band center locked to 4.381 or 4.382 μm (Table 1 and Figures 5 and 7). At first glance, the lack of band splitting suggests $^{13}\text{CO}_2$ is primarily associated with either the 4.25 μm or 4.27 μm lobe, but not both. Irradiated samples composed of CO_2 deposited onto frozen salts exhibit 4.25 μm lobes and $^{13}\text{CO}_2$ bands near 4.386 μm (Villanueva et al. 2023), representing a 0.004 to 0.005 μm wavelength shift from the center of Europa’s 4.38 μm band, which should be detectable with the G395H grating ($R \sim 3000$ near 4.4 μm). Thin and thick films composed of crystalline CO_2 ice (e.g., Quirico & Schmitt 1997) exhibit 4.27 μm $^{12}\text{CO}_2$ and 4.38 μm $^{13}\text{CO}_2$ absorption bands consistent with the features detected on Europa, but crystalline CO_2 ice should sublime rapidly at its estimated dayside surface temperatures (e.g. Fray & Schmitt 2009) and seems unlikely to contribute. CO_2 molecules isolated in a crystalline H_2O ice matrix (4.257 μm ; Eric Quirico, private communication) or CO_2 clathrates (4.261 and 4.277 μm ; Oancea et al. 2012) could persist on Europa’s surface at peak dayside temperatures, albeit the central wavelengths of these CO_2 features are not ideal matches to Europa’s 4.27 μm lobe (centered between 4.268 and 4.272 μm). Alternatively, CO_2 trapped in amorphous H_2O ice ($\sim 4.273 \mu\text{m}$; e.g., Ehrenfreund et al. 1999) can provide a closer match to the central wavelength of Europa’s 4.27 μm lobe. CO_2 trapped in amorphous ice was proposed to explain Ganymede’s 4.270 μm CO_2 feature detected at high northern latitudes on its leading hemisphere (Bockelée-Morvan et al. 2024). Amorphous ice is likely more prevalent on Europa than Ganymede due to its colder surface temperatures and its lack of an intrinsic magnetic field, which helps to shield ice at low latitudes on Ganymede from amorphization via charged particle bombardment. On the other hand, peak dayside temperatures at Europa’s low latitudes are more than sufficient to remove exposed amorphous ice on short timescales (see “thermal recrystallization” subsection below), hinting that trapping of CO_2 in crystalline ice may be more prevalent.

The 4.38 μm band is primarily detected over southern latitudes and is essentially absent from the northern latitudes of Europa’s leading hemisphere (Figure 7). Consequently, the 4.38 μm band is present where the 4.25 μm and 4.27 μm lobes are strongest (Figure 5). The central wavelength of the 4.38 μm band suggests it might be primarily spatially associated with the 4.27 μm lobe (i.e., CO_2 trapped in amorphous or crystalline ice). In contrast, the spatial distribution of the 4.38 μm band appears to more closely track the 4.25 μm lobe (Figure 5), and the 4.38 μm band is only present ($>3\sigma$ detection) in spaxels where the band depth of the 4.25 μm lobe is greater than the band depth of the 4.27 μm lobe. Unraveling this discrepancy between the spectral properties and spatial distributions of Europa’s solid-state CO_2 features will benefit from ongoing and future laboratory experiments that investigate the spectral properties of CO_2 trapped in amorphous and crystalline ice, with and without hydrated salts, under conditions relevant to Europa. Furthermore, future close flybys by Clipper/MISE will be able to more precisely map the distribution of CO_2 and determine whether $^{13}\text{CO}_2$ is present at northern latitudes, beyond Tara and Powys Regiones.

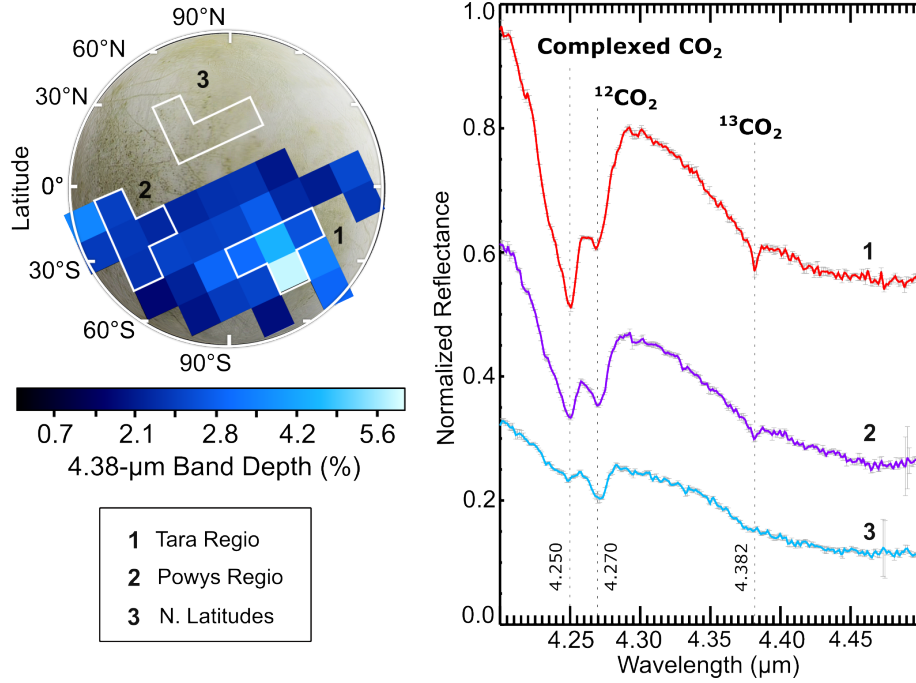


Figure 7. Left: Band depth measurements for the 4.38 μm band ($>3\sigma$ detection, also shown in Figure 5 above). White polygons show the locations of JWST/NIRSpec spaxels incorporated into the representative regional spectra shown on the right: 1. Tara Regio (red), 2. Powys Regio (purple), 3. northern low-latitudes (blue), and their 1σ uncertainties (gray error bars). These data are normalized to 1 at 4.0 μm and offset vertically for clarity. The central wavelengths (μm) for detected solid-state CO_2 features are listed vertically along each dotted line.

4.4. Refreshing Surface Constituents in Tara and Powys Regiones

The results reported here for H_2O ice and $^{13}\text{CO}_2$, along with prior observations that characterized H_2O ice (e.g., Ligier et al. 2016), irradiated NaCl (e.g., Trumbo et al. 2022), solid-state CO_2 (Villanueva et al. 2023; Trumbo & Brown 2023), and H_2O_2 (e.g., Wu et al. 2024; Raut et al. 2024), demonstrate that Tara and Powys Regiones are spectrally distinct from the surrounding terrains, in particular when compared to H_2O ice-rich regions at northern low-latitudes (Figure 2). The presence of a 3.1 μm Fresnel peak, diagnostic of crystalline H_2O ice, indicates that the exposed surfaces of Tara and Powys ($<1 \mu\text{m}$ depths) are refreshed over timescales short enough to outpace the irradiation processes that are able to effectively amorphize ice-rich regions at northern low-latitudes and elsewhere on Europa’s leading hemisphere. Refreshment of crystalline ice could be driven by thermal recrystallization of exposed ice grains outpacing amorphization in these relatively dark and warm low-latitude regions. Geologic exposure of saline meltwater in the chaos terrains that dominate Tara and Powys may help replenish crystalline ice and solid-state CO_2 over longer timescales.

Thermal recrystallization. The surface of Europa is subjected to a substantial flux of co-rotating magnetospheric plasma and energetic charged particles, with surface bombardment patterns that are non-uniform and significantly affected by draping of the Jovian magnetic field due to Europa’s atmosphere (e.g., Addison et al. 2021; Nordheim et al. 2022). The previously noted absence of a 3.1 μm H_2O ice Fresnel peak is generally assumed to result from intense sputtering and charged particle weathering disrupting the long-range order of crystalline ice (e.g., Hansen & McCord 2004). However, thermal recrystallization rates for H_2O ice at low latitudes ($30^\circ\text{S} - 30^\circ\text{N}$) could be competitive with amorphization rates, perhaps occurring over timescales as short as ~ 0.15 to 2 days, for a more porous regolith (43% pore space), or ~ 3.5 to 41 days for a more compacted regolith (9% pore space) (Mitchell et al. 2017). Consequently, thermal recrystallization should be operating efficiently at latitudes corresponding to Tara and Powys Regiones ($0 - 30^\circ\text{S}$), where exposed crystalline ice is present, *as well as* the northern low-latitude zone identified in this study ($0 - 30^\circ\text{N}$), where exposed ice is dominantly amorphous.

To investigate whether thermal recrystallization may be operating over different timescales in Tara versus the northern low-latitude zone, we estimated the timescales for effective amorphization of ice by charged particle irradiation in these two locations. We utilized the calculated surface fluxes for 1 keV to 100 MeV protons, O^{n+} , and S^{n+} ions (Nordheim et al. 2022), finding that the total surface energy flux (F) from magnetospheric ions in these two locations is almost identical ($\sim 1.5 \times 10^8 \text{ MeV cm}^{-2} \text{ s}^{-1}$). Using the approach described in Famá et al. (2010), we estimated the fraction of amorphous ice, $\phi_A = \phi_{Amax} (1 - \exp(-kFt/N))$ [Equation 1], where the maximum fraction of amorphous ice on the surface (ϕ_{Amax}) was set to 1 (Dalle Ore et al. 2015). The experimentally determined amorphization coefficient, k , given in molecules eV^{-1} (Baragiola et al. 2013; Famá et al. 2010; Loeffler et al. 2020) was set to 0.2 molecules eV^{-1} , based on experimental results for ion bombardment of H_2O ice at $\sim 100 \text{ K}$ (see Figure 16.3 in Baragiola et al. 2013), a reasonable approximation of the *mean* surface temperatures in these two regions. The number of H_2O molecules, N , represents an icy regolith volume of 1 cm^2 by $10 \mu\text{m}$ deep, covering the range of depths over which protons (100’s of keV to MeV) deposit most of their energy (e.g., Berger et al. 1999). The amorphization rate, t , is the timescale to amorphize volume N , and represents an upper limit for this process.

By setting the fraction of amorphous ice to 63% ($\phi_A = 0.63$), and solving for t in Equation 1, we estimate that exposed crystalline ice ($\leq 10 \mu\text{m}$ depths) should be amorphized by magnetospheric ion bombardment on timescales of ~ 15 days at low latitudes on Europa’s leading hemisphere. Because Tara and the northern low-latitude zone receive similar input from magnetospheric ion bombardment, our calculation indicates that some other important difference exists between the properties of the exposed regoliths in these two locations. We suggest that Tara, and by extension Powys, are mantled by porous layers of ice grains that rapidly recrystallize, thereby outpacing amorphization over timescales < 15 days, which is more consistent with the ~ 0.15 to 2 days recrystallization estimates for the high porosity case presented in Mitchell et al. (2017). In contrast, the northern low-latitude zone is mantled by a more compacted layer of ice grains, where recrystallization operates over timescales > 15 days and amorphization processes dominate, which is more consistent with the ~ 3.5 to 41 days recrystallization estimates for the low porosity case presented in Mitchell et al. (2017).

Supporting this interpretation, Tara and Powys Regiones exhibit lower bond albedos ($B = 0.4 - 0.6$) than the northern low-latitude zone ($B = 0.7 - 0.8$; Mergny et al. 2025), consistent with warmer temperatures and faster rates of recrystallization in these regions. Tara and Powys also have lower estimated thermal inertias and higher brightness temperatures ($\sim 100 \text{ K}$) compared to the northern low-latitude zone ($\sim 80 \text{ K}$), based on the analysis of Band 7 (0.87 mm) Atacama Large Millimeter/submillimeter Array (ALMA) observations, which probe ~ 10 to 20 cm depths (Cordiner et al. 2024). Furthermore, analysis of Band 3 (3.05 mm) ALMA data suggests the porosity of regolith material on Europa’s leading hemisphere ranges between 40 to 70% at depths of ~ 500 to $1000 \mu\text{m}$, with Tara and Powys likely being more porous than the ice-rich, northern low-latitude zone (Thelen et al. 2024). A different study that analyzed ALMA data (Trumbo et al. 2018) also derived higher thermal inertia, or lower emissivity, estimates for an anomalous region co-located with the northern low-latitude zone, suggesting larger particle sizes or higher transparency to sunlight in this region (Trumbo et al. 2018).

Thus, prior studies support our interpretation that a colder, brighter, and lower porosity regolith, possibly dominated by larger ice grains, mantles Europa’s northern low-latitude zone, where amorphization outpaces recrystallization. Similarly, these studies support our interpretation that a warmer, darker, and higher porosity regolith, possibly dominated by smaller ice grains, mantles Tara and Powys Regiones, where recrystallization outpaces amorphization. Below, we consider a few different processes that could help explain these disparate regolith properties and the prevalence of exposed crystalline ice and solid-state CO_2 in Tara and Powys Regiones.

Exposed during chaos formation? Fresh crystalline ice and hydrated salts could result from the exposure and subsequent freezing of meltwater due to chaos formation. Of the currently hypothesized chaos formation mechanisms (see Daubar et al. 2024), our results are more consistent with the rapid freezing of saline meltwater, perhaps resulting from collapsing and refreezing of liquid H₂O lenses (e.g., Collins et al. 2000; Schmidt et al. 2011; Michaut & Manga 2014). This chaos formation mechanism is favored by detailed morphological studies of chaos terrains (Leonard et al. 2018), although other mechanisms involving exposure of saline liquid H₂O could hypothetically reproduce the spectral results reported here. In our preferred scenario, saline liquid H₂O containing dissolved CO₂ or other carbon-bearing compounds resides in melt-pockets. This saline liquid mixture begins to freeze and expand in the ice shell, eventually causing the mixture to breach Europa’s surface where it then rapidly freezes, locking in entrained CO₂ molecules, or organic content that is radiolytically-modified into CO₂ post-emplacement. This mixture could explain the presence of Europa’s 4.25 μm lobe, which results from CO₂ complexed with salts (Villanueva et al. 2023). Molecular interactions between CO₂ and refractory salts on Europa are presumably consistent with prior detection of a prominent 4.257 μm feature by Galileo/NIMS that was attributed to CO₂ complexed with refractory dark material (e.g., Carlson et al. 1996; McCord et al. 1997, 1998b; Hibbitts et al. 2000). In this scenario, a thin layer of H₂O frost might also condense, possibly capturing CO₂ molecules in the rapidly forming crystalline structure. Alternatively, trapped organics are irradiated, reacting with surrounding H₂O molecules to form ¹²CO₂ and ¹³CO₂, thereby explaining the origin of the 4.27 μm lobe and the 4.38 μm band, respectively. Thus, chaos formation mechanisms that result in exposure of internally-derived saline meltwater might be an important source of crystalline H₂O ice and CO₂ in Tara and Powys Regiones, albeit subsequent amorphization and recrystallization cycles would quickly obscure the spectral signature of internally-derived ice.

Plume deposits? Crystalline ice in Tara and Powys may result from sporadic, CO₂ gas-driven south polar plume activity (Roth et al. 2014), or hitherto undetected localized geysers in Tara Regio. In either scenario, ice grains are rained onto Europa’s surface, primarily over its southern latitudes. Plume activity could be complemented by lower level outgassing of H₂O vapor that condenses once exposed at the surface. Plume grains that rain onto Europa’s surface could be initially crystalline, or they could be crystallized by subsolar heating, especially if they land on darker and warmer surfaces, such as Tara and Powys Regiones. Deposition of plume material might explain the stronger 3.1 μm Fresnel region at southern latitudes reported here and previously observed by Juno/JIRAM (Filacchione et al. 2019). However, it is uncertain whether a south polar plume would be sufficiently energetic to mantle the entirety of Europa’s southern latitudes with ice grains, which is required to explain the spatial distribution of crystalline ice reported here.

Whether this mechanism can explain the spatial association between Tara and Powys and solid-state CO₂ is also uncertain. Although outgassed CO₂ molecules could hypothetically co-condense with H₂O on chaos terrains, it is doubtful that CO₂ could persist at Europa’s peak dayside surface temperatures (~ 130 K). Deposition of plume material that includes CO₂ complexed with frozen salts, or organic material subsequently irradiated and oxidized to CO₂, should be more stable on Europa’s surface and could account for Europa’s 4.25 μm lobe. However, if complexed CO₂ primarily originates from plume fallout, it is uncertain why it is concentrated in Tara, unless sourced by undetected localized geysers.

Volatile migration and condensation? Perhaps sublimated H₂O vapor and CO₂ gas, migrating from Europa’s warmer and darker trailing hemisphere, condense on the nightside leading hemisphere, contributing to a transient frost layer. Subsequent dayside heating then preferentially recrystallizes condensed H₂O frost on the darker and warmer surfaces of Tara and Powys Regiones compared to the brighter and colder, ice-rich northern low-latitudes. This scenario cannot readily account for the concentration of CO₂ in Tara and Powys, as this volatile should display a strong preference for condensation at high latitudes and in colder and brighter icy terrains, counter to the observed spatial distribution, and an internal origin for CO₂ therefore seems more likely.

Impact exposure? Collisions with micrometeorite grains and large-scale impactors overturn regolith materials on icy moons over geologic timescales, exposing fresh crystalline H₂O ice, CO₂, and other compounds that have been shielded at depth from irradiation (e.g., Zahnle et al. 2003; Costello et al. 2021). On tidally-locked objects like Europa, impact gardening is hypothesized to operate more efficiently on their leading hemispheres, especially near their apexes (0° latitude, 90°W). Our results show that exposed crystalline H₂O ice and CO₂ are not concentrated at Europa’s apex, and instead are found at southern low-latitudes, near the center of Tara Regio ($\sim 10 - 30^\circ\text{S}$ and 75°W). In contrast, the northern low-latitude zone ($\sim 10 - 30^\circ\text{N}$ and 105°W) shows negligible evidence for exposed crystalline ice or ¹³CO₂ (spectrum 3 in Figure 2). If impact gardening is the primary driver of regolith refreshment in Tara, then

some other, currently unknown, mechanism is needed to explain why dust grains preferentially strike Europa’s southern hemisphere and do not equally refresh H₂O ice at northern low-latitudes. Furthermore, micrometeorite exposure of fresh crystalline ice likely operates at considerably slower rates than the ~ 15 day estimate for amorphization reported here, and it seems unlikely that impact gardening would play an equally prominent role in shaping Europa’s exposed regolith. A large impact that exposed fresh ice or meltwater in the very recent past may explain the presence of crystalline H₂O ice in Tara. However, the geographic scale of the $3.1\ \mu\text{m}$ Fresnel peak detected by JWST/NIRSpec (Figure 4) suggests that the resulting impact crater would be spatially extensive and presumably visible in Galileo images ($\gtrsim 1\ \text{km/pixel}$), but there is no evidence for an impact feature or a large ejecta blanket in Tara or Powys.

5. SUMMARY AND CONCLUSIONS

We analyzed JWST/NIRSpec observations of Europa ($\sim 1.48 - 5.35\ \mu\text{m}$) to investigate the origin of crystalline H₂O ice and solid-state CO₂. For H₂O ice, we made continuum-divided measurements of Europa’s $1.5\ \mu\text{m}$, $1.65\ \mu\text{m}$, and $2.0\ \mu\text{m}$ H₂O absorption bands (Figure 3) as well as of its $3.1\ \mu\text{m}$ H₂O Fresnel peak and its $3.6\ \mu\text{m}$ H₂O continuum peak (Figure 4). For CO₂, we made band measurements of the $4.25\ \mu\text{m}$ and $4.27\ \mu\text{m}$ lobes of Europa’s strongest solid-state CO₂ feature and its $4.38\ \mu\text{m}$ ¹³CO₂ absorption band (Figure 5). We also generated and compared the properties of three regional spectra, representative of Tara Regio, Powys Regio, and Europa’s northern low-latitudes (Figures 1, 2). The resulting measurements and spectral maps for the $1.65\ \mu\text{m}$ band demonstrate that crystalline H₂O ice is present beneath the exposed surface ($\gtrsim 300\ \mu\text{m}$ depths) across Europa, with the strongest signature at northern low-latitudes, consistent with prior observations (e.g., Hansen & McCord 2004; Ligier et al. 2016). Our measurements of the $3.1\ \mu\text{m}$ H₂O ice Fresnel peak demonstrate that crystalline H₂O ice is largely absent from the exposed surface of Europa’s northern hemisphere ($< 1\ \mu\text{m}$ depths), but it is present at the exposed surface of its southern hemisphere, especially in Tara and Powys Regiones. The disparity between these measurements supports the hypothesis that Europa’s regolith is vertically stratified (Hansen & McCord 2004), with crystalline ice dominating at depth and amorphous ice dominating at the exposed surface of Europa’s leading hemisphere, except in Tara and Powys Regiones, where crystalline ice dominates both at depth and at the exposed surface (Figures 2 and 4).

We estimate that charged particle-driven amorphization effectively removes the signature of exposed crystalline ice from low latitudes on Europa’s leading hemisphere in ~ 15 days, and the presence of crystalline ice at the topmost surface of Tara and Powys Regiones indicates ongoing refreshment over shorter timescales (perhaps $\ll 15$ days). Because the $3.1\ \mu\text{m}$ Fresnel peak is sensitive to extremely shallow depths, it only samples exposed ice grains that may form a porous H₂O frost layer, mantling the relatively darker and warmer surfaces of Tara and Powys Regiones. Thermal recrystallization of amorphous ice contained within such a porous layer should outpace amorphization rates, in particular for low latitude regions near the subsolar point. Our results therefore suggest that the $3.1\ \mu\text{m}$ crystalline H₂O ice Fresnel peak is a spectral tracer of recent (and presumably ongoing) surface modification.

The origin of such a porous H₂O frost layer is uncertain, and it could arise from a variety of processes including exposure of saline meltwater, sporadic plume activity, outgassing of H₂O vapor, sublimation and migration of H₂O vapor from Europa’s dayside trailing hemisphere, or recent regolith overturn by impacts. Exposure of saline meltwater in chaos terrains may be the most likely process given the presence of other, likely internally-derived species in Tara and Powys Regiones, such as NaCl and CO₂. Indeed, our analysis of Europa’s double-lobed CO₂ feature and its $4.38\ \mu\text{m}$ ¹³CO₂ band favors an endogenic origin for CO₂, consistent with prior work (Villanueva et al. 2023; Trumbo & Brown 2023). However, the physical state of CO₂ on Europa’s surface is less certain, and it is likely complexed with more refractory components, such as frozen salts, and trapped in crystalline or amorphous H₂O ice. Finally, the results reported here provide high signal-to-noise context for the upcoming Europa Clipper mission that will make many close passes of Europa, collecting high spatial resolution footprints with its NIR spectrometer, MISE ($1 - 5\ \mu\text{m}$).

6. ACKNOWLEDGMENTS

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