Identifying Europa's surface features using water ice crystallinity and the abundances of non-ice materials.

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Introduction: Europa's surface composition and evidence for cryovolcanic activity can provide insight into the properties and composition of the subsurface ocean, allowing the evaluation of its potential habitability. One promising avenue for revealing the surface processing and subsurface activity is the relative fractions of crystalline and amorphous water ice observed on the surface, which are influenced by temperature, charged particle bombardment, vapor deposition from plumes, and cryovolcanic activity such as diapirs. The crystalline-to-amorphous water ice fraction ("crystallinity") observed on Europa's leading hemisphere cannot be reproduced by thermophysical and particle flux modeling alone [1], indicating there may be additional processes influencing the surface. This discrepancy may indicate that additional processes have existed in the past (or are currently active), which may be influencing Europa's surface and altering its crystallinity. In this study we aim to identify the spatial distribution of the crystallinity for two locations near the equator and south pole.

A combination of hydrated brines, hydrated sulfuric acid, and water ice have been proposed to be present on the surface and are likely to reproduce features in spectra of Europa's surface (e.g. [2-7]). The compositional interpretation of surface material using spectroscopy can be achieved through spectral mixture theory, the concept that a single observed spectrum is the combination of various pure material spectra, or endmembers, weighted by the respective fractional abundance that exists in that single observation.

This investigation uses a spectral mixture approach to identify the abundances of materials that are likely present across two Galileo Near-Infrared Mapping Spectrometer (NIMS) hyperspectral image cubes located near the equator (cube 15e015) and south pole (cube 17e009), both on the leading hemisphere. We build upon previous work by Dalton et al. [7] by (1) introducing amorphous water ice into the spectral mixture analysis process alongside crystalline water ice; (2) using updated optical constants for amorphous and crystalline water ice [8]; (3) including a more diverse cryogenic reference spectral library (e.g. [9]); and (4) analyzing the spatial variation of endmember abundances across each NIMS observation, rather than averaging multiple spectra together to represent a specific type of terrain/material within the cube.

Methodology: In order to investigate the context for the discrepancy between modeled and observed crystallinity, we perform a spectral mixture analysis on hyperspectral image cubes from Galileo NIMS to identify how surface crystallinity is influenced by physical processing at a high spatial resolution scale. We focus specifically on two image cubes, 15e015 (7.3° N, 114° W, 3.0 km/pixel) close to the equator, and 17e009 (63° S, 120° W, 1.5 km/pixel) close to the south pole, both on the leading hemisphere. We use synthetic amorphous and crystalline water ice spectra produced using Hapke theory for multiple grain sizes (25, 50, 75, 100, 150, 200, and 250 μm), and cryogenic laboratory reference spectra [9-12]. Since Europa's surface is not purely water ice and contains other materials such as hydrated sulfuric acid, and sodium and magnesium sulfates, chlorates, perchlorates, and chlorides (e.g. [7]), we include these materials in our analysis and perform a Non-Negative Least Squares spectral mixture analysis to identify abundances of endmember materials within each NIMS pixel separately (**Figure 1**) to reveal both the non-ice composition and the water ice crystallinity of the surface.

Equator Abundances: Near the equator, a minimal abundance of amorphous water ice is expected due to the thermal relaxation of water ice into the crystalline form within a few years at temperatures exceeding 115 K [13,14]. However, we find that amorphous water ice dominates at the equator, and we estimate a crystallinity of ~35%, which is consistent with the spectroscopically-derived crystallinities of ~30% found by Berdis et al. [1].

Furthermore, we identify a possible ridge or linea feature as traced by the magnesium sulfate abundance, however, the spatial resolution of the image is too low to discern a geological feature at this location.

South Pole Abundances: Amorphous water ice also dominates at the south pole, and we estimate a crystallinity of ~15%. A lower crystallinity near the south pole compared to the equator is expected due to (1) colder temperatures, which indicates a longer amount of time for the water ice to crystallize [13-15], and (2) migration of amorphous plume material [13,16].

We also identify several features in the amorphous water ice, magnesium chloride, and hydrated sulfuric acid abundances which appear to correlate with a double ridge feature, and may provide evidence for surface processing by upwelled subsurface material (**Figure 2**). If this feature is indeed correlated with a double ridge, this method could provide a way to determine which surface features are present in regions where the resolution of the imagery is too low to discern geological features, and can inform regions-of-interest observation selections for the Europa Clipper mission.

Conclusions: We estimate a mean crystallinity of ~35% within the 15e015 NIMS cube, and a mean crystallinity of ~15% within the 17e009 NIMS cube, which is consistent with ground-based spectroscopically-derived crystallinities (Berdis et al. 2020). We also identify a possible correlation of magnesium sulfate, magnesium chloride, and hydrated sulfuric acid with lineae and ridges, which may provide evidence for surface processing by upwelled subsurface material. Higher spectral resolution observations from Europa Clipper will also provide more accurate spectral mixture analysis results.

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Figure 1. Left: Spectral mixture analysis model result (red) from the spectra of a sample pixel (black) within the NIMS 15e015 cube. Right: Spectral mixture analysis model result (blue) from a selection of 20 IR Bright spectra (black) within the NIMS 15e015 cube (Figure 8 in Dalton et al. [7]).

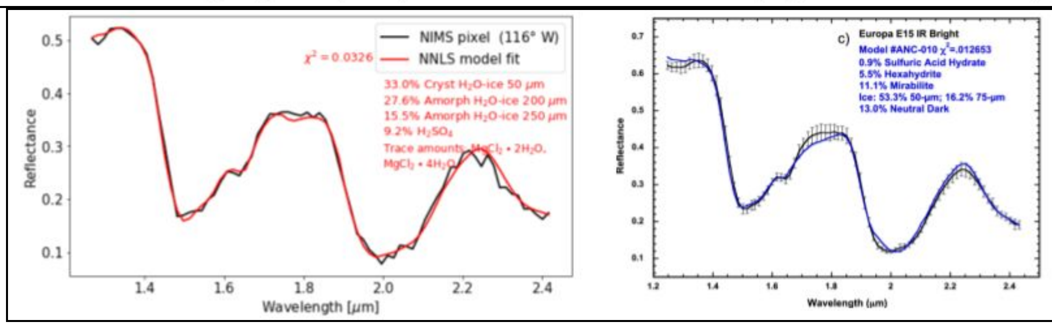

Figure 2. Abundance profiles across the 17e009 NIMS cube for magnesium chloride (top), hydrated sulfuric acid (middle), and amorphous water ice 250-micron (bottom).