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Europa's ridged plains and smooth low albedo plains: Distinctive compositions and compositional gradients at the leading side–trailing side boundary

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ABSTRACT

This investigation uses linear mixture modeling employing cryogenic laboratory reference spectra to estimate surface compositions and water ice grain sizes of Europa's ridged plains and smooth low albedo plains. Near-infrared spectra for 23 exposures of ridged plains materials are analyzed along with 11 spectra representing low albedo plains. Modeling indicates that these geologic units differ both in the relative abundance of non-ice hydrated species and in the abundance and grain sizes of water ice. The background ridged plains in our study area appear to consist predominantly of water ice (~46%) with approximately equal amounts (on average) of hydrated sulfuric acid (~27%) and hydrated salts (~27%). The solutions for the smooth low albedo plains are dominated by hydrated salts (~62%), with a relatively low mean abundance of water ice (~10%), and an abundance of hydrated sulfuric acid similar to that found in ridged plains (~27%). The model yields larger water ice grain sizes (100 μm versus 50–75 μm) in the ridged plains. The 1.5-μm water ice absorption band minimum is found at shorter wavelengths in the low albedo plains deposits than in the ridged plains (1.498 ± .003 μm versus 1.504 ± .001 μm). The 2.0-μm band minimum in the low albedo plains exhibits a somewhat larger blueshift (1.964 ± .006 μm versus 1.983 ± .006 μm for the ridged plains).

The study area spans longitudes from 168° to 185°W, which includes Europa's leading side–trailing side boundary. A well-defined spatial gradient of sulfuric acid hydrate abundance is found for both geologic units, with concentrations increasing in the direction of the trailing side apex. We associate this distribution with the exogenic effects of magnetospheric charged particle bombardment and associated chemical processing of surface materials (the radiolytic sulfur cycle). However, one family of low albedo plains exposures exhibits sulfuric acid hydrate abundances up to 33% lower than found for adjacent exposures, suggesting that these materials have undergone less processing, thus implying that these deposits may have been emplaced more recently.

Modeling identifies high abundances (to 30%) of magnesium sulfate brines in the low albedo plains exposures. Our investigation marks the first spectroscopic identification of $MgSO_4$ brine on Europa. We also find significantly higher abundances of sodium-bearing species (bloedite and mirabilite) in the low albedo plains. The results illuminate the role of radiolytic processes in modifying the surface composition of Europa, and may provide new constraints for models of the composition of Europa's putative subsurface ocean.

1. Introduction

The disciplines of imaging science, geologic mapping, and spectroscopic analysis have all made important contributions to our scientific knowledge of Europa. While the synergistic potential of combining the three approaches has long been recognized, remarkably few integrated studies have appeared in the literature. For this investigation, we have registered overlapping Galileo Solid State Imager (SSI) imaging and Galileo Near-Infrared Mapping Spectrometer (NIMS) spectroscopic datasets for a portion of Europa's anti-jovian "wedges" region (Argadnel Regio), and we have constructed a geologic map of the study area thus defined. Geologic mapping of the study area allows us to address questions of the relative ages and emplacement sequences of the terrains present. Precise registration of the datasets enables us to distinguish between terrain types at individual pixel scales. The NIMS data benefits from recently developed methods of radiation noise removal and data processing which facilitate the extraction of high quality region-of-interest (ROI) spectra for discrete individual exposures of particular geologic terrains. Our spectroscopic analysis employs

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cryogenic reference spectra of candidate surface materials for modeling the spectral contributions from multiple candidate materials (Dalton, 2007; Dalton et al., 2009).

We focus on two key stratigraphic units: (1) The background ridged plains, which have been exposed to Europa's surface radiation environment for the longest time; and (2) the low albedo plains, which are some of the youngest terrains present in our study area. The low albedo plains are distinguished from other visually dark units by their low topographic relief and by their embayment of pre-existing topography (Prockter et al., 1999; Prockter and Schenk, 2005). Some investigators have suggested that these deposits may have been produced by cryovolcanic flows of low-viscosity materials (Greeley et al., 1998, 2000, 2004; Fagents et al., 2000; Fagents, 2003; Miyamoto et al., 2005). However, mechanisms involving in situ modification of pre-existing terrain are also possible (Head and Pappalardo, 1999).

The linear mixture model solutions for water ice grain sizes and non-ice material compositions and abundances for the background ridged plains play an important role as a standard of comparison for the other geologic terrains present in the study area. The effects of radiation processing and micrometeoroid bombardment processes are presumably further advanced for the ridged plains exposures than for younger terrains. Compositional modifications due to exogenic processes are likely to have attained an equilibrium between creation and destruction of constituent molecules for these exposures (Johnson, 2001). The contrasts between the baseline composition of the ridged plains and the compositions found for other units in our study area may yield new insights into the composition of the subsurface, the radiolytic modification of the surface, and the composition of the putative ocean beneath (Carr et al., 1998; Pappalardo et al., 1999; Kivelson et al., 2000; Zolotov and Shock, 2001).

Because our study area spans the 180° meridian, which represents the boundary between the orbital leading and trailing sides of Europa, we are able to search for compositional variations associated with the asymmetric trailing-side bombardment of Europa by magnetospheric charged particles (Paranicas et al., 2001; Johnson and Quickenden, 1997; Carlson et al., 1999a, 2002, 2005, 2009; Johnson, 2001; Cooper et al., 2001; Johnson et al., 2004). The solutions obtained illuminate questions of the relative contributions of endogenic and exogenic processes in producing the observed surface characteristics of Europa. The ability to separate the effects of endogenic and exogenic processes in producing the observed surface characteristics opens the way for improved understanding not only of radiation chemistry but also of the geochemical processes operating within Europa's crust and subsurface ocean.

2. Prior visible and near-infrared spectral investigations and compositional mapping

Telescopic observations revealed Europa's hemispheric leading versus trailing side brightness asymmetry early in the last century. Though subject to severe limitations of spatial resolution, a succession of later investigations (Moroz, 1966; Pilcher et al., 1972; Clark and McCord, 1980; see also Calvin et al., 1995) resulted in the identification of water ice as a principal constituent of Europa's surface. These early observations also allowed the recognition of the presence of non-ice materials, and in some constraints with respect to surface particle sizes (Clark et al., 1983, 1986).

Following the Voyager encounters of the late 1970s, the geologic mapping by Lucchitta and Soderblom (1982) was employed as a basis for spectral investigations and spectral mapping by a number of investigators, notably Johnson et al. (1983), Nelson et al. (1986), Buratti and Golombek (1988), and Domingue and Hapke (1992). Although the spatial resolution of the Voyager images was as good as 1.8 km/line pair, data from only four spectral channels were available for analysis. Analysis of these data did not lead to an unambiguous identification of the non-ice surface materials, or even to consensus regarding the number of distinctive compositional units present on Europa's surface.

Color imagery obtained by the Solid State Imager (SSI) system on board the Galileo spacecraft was likewise limited to a small number of spectral channels. Nonetheless the unprecedented spatial resolution of the SSI image data has led to the confident identification of a wide variety of geologic terrains (Greeley et al., 1998, 2000, 2004; Clark et al., 1998; Fanale et al., 1999; Prockter et al., 1999).

Observations by Galileo's Near-Infrared Mapping Spectrometer (NIMS; Carlson et al., 1992) opened a new window on Europa's surface composition. With 408 channels spanning the range from 0.7 to 5.2 μm, NIMS obtained spectra revealing variations in the shapes and positions of the principal water ice absorption bands. The distortions of the water ice bands are due to vibrational modes associated with water in a bound state; they are characteristic of hydrated materials. The asymmetric absorption features have been employed to characterize the abundance and nature of the icy components and the non-ice materials (Carlson et al., 1996, 1999a,b, 2005; McCord et al., 1998, 1999a,b, 2008, 2009; Fanale et al., 1999, 2000; Orlando et al., 2005; Dalton et al., 2005, 2009; Dalton, 2007; Hansen and McCord, 2008). The spectra of the visibly dark, least icy surface materials were found to be similar for several different locations on Europa, leading to the working hypothesis of a single "dark end member" (or, non-ice end member) composition. A simple two-component continuum model, ranging from pure ice at one extreme, to 100% non-ice end member materials at the other, has been employed in a number of spectral mapping studies (cf. McCord et al., 1998, 1999a,b, 2009; Fanale et al., 2000; Hansen and McCord, 2008). McCord et al. (1999a,b) described a method of assigning non-ice material percent concentration levels to individual NIMS spectra. Fanale et al. (2000) later employed a similar approach to produce maps of the non-ice material abundance for the impact craters Pwyll and Tyre Macula.

Carlson et al. (2005) developed a radiative transfer algorithm to model the non-ice fractional content (f), the ice particle size (r_I), and the non-ice material particle size (r_A) for NIMS spectra within standard data cubes. The hydrated non-ice material assumed for this modeling effort was sulfuric acid hydrate ($H_2SO_4{\cdot}8H_2O$). Carlson et al. (2005) demonstrated excellent agreement between the derived model spectra and the NIMS spectra, and provided maps of the fractional hydrate content f for a large portion of Europa's surface.

The laboratory-based approach of Orlando et al. (2005) differs from prior investigations in important ways. These authors prepared solutions of magnesium and sodium sulfate brines with sulfuric acid in various proportions, and obtained spectra for the flash-frozen brines following multiple cycles of thermal cycling. They found that several of their spectra were quite similar to the NIMS non-ice end member spectrum. They placed upper limits on the permissible magnesium and sodium sulfate fractions, but found equally good agreement for several mixtures with percent abundance differences of >20%.

More recent compositional investigations by McCord et al. (2009) have adapted the spectral mixing analysis method of Combe et al. (2008), using as input the most icy and least icy spectra extracted from a particular NIMS observation. While this approach does not identify specific molecules, the authors did find that two non-ice end member components were needed to adequately model their spectra.

There have been a few attempts to relate the ice versus non-ice end member distributions obtained in this way to morphological features of Europa's surface (McCord et al., 1999b, plates 3 and 4;