

MODELING EUROPA'S SURFACE COMPOSITION WITH CRYOGENIC SULFATE HYDRATES J. B. Dalton¹, ¹Carl Sagan Center, SETI Institute, 515 N. Whisman Road, Mountain View CA 94043. dalton at carlsagancenter.org

Introduction: The surface of Europa has been found to consist predominantly of water ice along with hydrogen peroxide, sulfur dioxide, and carbon dioxide ices [1]. Irradiation by charged particles and communication with the interior may also have led to the creation of additional surface compounds [2,3]. Disrupted terrains on Europa reveal spectral evidence for such an additional component. Near-infrared reflectance spectroscopy from Galileo NIMS (Near-Infrared Mapping Spectrometer) indicates that this material is highly hydrated, as evidenced by strongly asymmetric absorption features attributed to waters of hydration at 1.5 and 2.0 microns [4].

Cryogenic Spectroscopy: Alone, no single material yet studied can account for the observed spectral character of the reddish, disrupted European terrain. Earlier work based on available room temperature spectra of terrestrial hydrated salts [5] suggested that mixtures of bloedite, hexahydrate, epsomite and mirabilite could approximate the Europa spectrum. However, several absorption band strengths and positions could not be reproduced using room temperature spectra. It has since been demonstrated that, at the cryogenic temperatures relevant to the surface of Europa (~100K), spectra of hydrates can be markedly different [6] from room temperature observations.

Linear Mixture Analysis: A linear mixture model has now been applied to the Galileo NIMS spectra of dark terrain, using only cryogenic laboratory spectra as

mixture endmembers. These included ordinary water ice Ih of varying grain sizes, Mg and Na sulfate brines, epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), hexahydrate ($\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$), magnesium sulfate dodecahydrate ($\text{MgSO}_4 \cdot 12\text{H}_2\text{O}$), mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), sulfuric acid hydrate ($\text{H}_2\text{SO}_4 \cdot 8\text{H}_2\text{O}$) and bloedite ($\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$). Taken individually, the cryogenic hydrated salts can still reproduce much of the observed spectral character; yet, they can not reproduce the Europa spectrum as well as their room temperature spectra could [6,7].

Modeled Abundances: When run using only hydrated salts and brines as spectral endmembers, the model selected bloedite, mirabilite, and hexahydrate as the most abundant species. This is in accord with predictions based on room temperature models [5]. Interestingly, the abundances of the other endmember materials, including brines and the dodecahydrate, were iteratively diminished to negligible levels. The inclusion of cryogenic sulfuric acid hydrate based upon earlier work [6,8,9] significantly improves the spectral match beyond what can be achieved using either sulfuric acid hydrate alone, or hydrated salts alone. The best fit achieved using the entire suite of cryogenic spectra (except for sulfuric acid) is shown in Figure 1. Many of the modeled band strengths, shapes and widths do not correspond to the Galileo observations. Several spectral absorption features arising from the salts (arrows) do not correspond to features observed in the Europa spectrum. Notably, the band center positions of

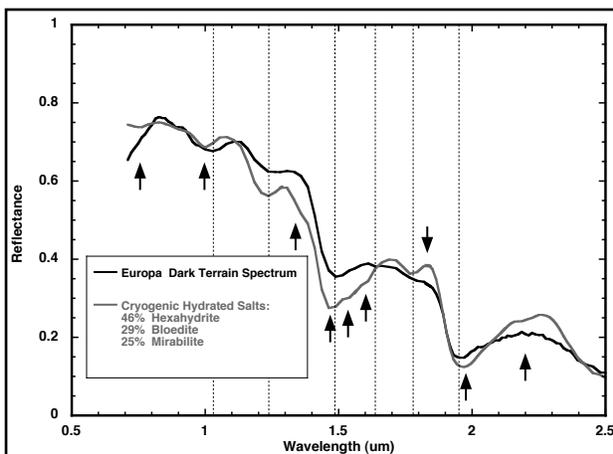


Figure 1. Europa spectrum modeled with linear mixture of cryogenic hydrated salts. Arrows indicate differences between modeled and observed spectral features.

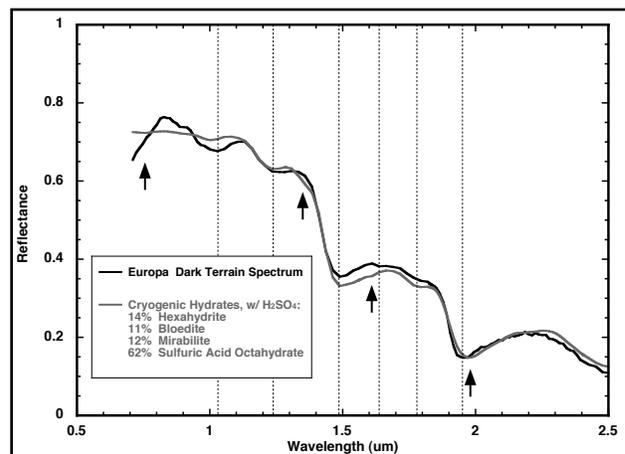


Figure 2. Europa spectrum modeled as linear mixture, including sulfuric acid hydrate. While improved, the spectral match still remains imperfect, suggesting an additional component or physical effect.

the Europa 1.5-micron and 2.0-micron asymmetric water absorptions (vertical lines) are not reproduced, while the band strengths vary from the observed band depths. A peak at 1.85 microns can be traced to the spectral character of bloedite at this wavelength. Three small absorption features within the 1.5-micron water absorption feature complex do not have counterparts in the Europa spectrum. The proportions of hydrated salts differ from those derived in previous work, with 45% hexahydrate, 29% bloedite and 25% mirabilite producing the best spectral match.

Figure 2 demonstrates the effect of adding sulfuric acid hydrate to the model. Although not perfect (arrows), the band positions and strengths more closely approximate the observed spectral character. The algorithm prefers a high (>50%) abundance of the sulfuric acid hydrate, but does not eliminate the hydrated salts entirely. Here the model selects 14% hexahydrate, 11% bloedite and 12% mirabilite along with 65% sulfuric acid hydrate to produce the best available match to the Europa observations.

While the spectral match is significantly improved over previous estimates, the modeled spectrum in Figure 2 still bears a number of discrepancies. The 2.0-micron feature still does not occur at exactly the correct frequency, and there is a subtle feature in the modeled spectrum just shortward of the 1.65-micron crystalline water ice feature which is not apparent in the Europa observations. A known cation-OH stretch at 1.35 microns, which is apparent in the hydrated salt spectra but not in the Galileo NIMS observations [6], persists in all model simulations. This could indicate structural effects on the crystal lattice, or the possibility that these materials are not appropriate analogues.

Dark Terrain Spectral Match: The dark terrains on Europa give rise to a spectrum resembling that of cryogenic mixtures of hydrates, suggesting that Europa contains these hydrates. However the spectral match remains imperfect, suggesting that the surface materials may exhibit radiation damage effects which have not yet been quantified experimentally. It is possible that the predicted mixtures, subjected to particle irradiation, could produce an even closer match. The spectral effects of such radiation damage are just now beginning to be understood. Alternatively, there may be additional components which have not yet been studied. Further, it must be remembered that there may be a physical reason to reject a material. The thermal and radiation stability of mirabilite, for example, are too low for it to have persisted over the geologic age of Europa's surface [10]. It is now clear that since the surface of Europa is not at room temperature, that room temperature materials cannot be present. Good spectral correlation between room temperature meas-

urements and spacecraft observations is not sufficient to claim an identification. Still, modeling of the surface composition with cryogenic laboratory spectroscopy of sulfate hydrates indicates that their structural, chemical, and physical properties make them useful analogues for the Europa surface material.

Conclusions: Linear spectral modeling of the European dark terrain using cryogenic endmember spectra lends credence to the idea that the surface may be comprised of a mixture of materials. The spectral characteristics of hydrated sulfate compounds provide strong analogs to the behavior observed in the Galileo NIMS measurements. Remaining discrepancies may be explained by additional components or as yet unquantified radiation damage to the crystalline structure of the surface materials. Additional laboratory work on the spectra of candidate compounds is needed to confirm or reject their possible presence. Further laboratory efforts to reproduce the observed spectral effects through irradiation of ices and hydrates has the potential to explain the enigmatic spectral character of Europa's surface. This knowledge will improve understanding of the parent materials and processes which gave rise to the present surface, with applications to understanding the interior and its composition.

References: [1] Carlson R.W. et al. (1999a) *Science* 283, 2062-2064. [2] Cooper J.F. et al. (2001) *Icarus* 149, 133-159. [3] Nimmo F. et al. (2005) *Icarus* 177, 293-296. [4] Dalton, J.B. (2003) *Astrobiology* 3, 771-784. [5] McCord T.B. et al., (1999) *J. Geophys. Res.* 104, 11824-11852. [6] Dalton J.B. et al. (2005) *Icarus* 177, 472-490. [7] McCord T.B. et al. (2002) *J. Geophys. Res.* 107, 4-1. [8] Carlson, R.W. et al. (1999b) *Science* 286, 5437-5440. [9] Carlson R.W. et al. (2002) *Icarus* 157, 456-463. [10] McCord T.B. et al. (2001) *J. Geophys. Res.* 106, 331-3320. [11] Carlson R.W. et al. (2005) *Icarus* 177, 461-471.