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Europa's disk-resolved ultraviolet spectra: Relationships with plasma flux and surface terrains

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ABSTRACT

The full set of high-resolution observations from the Galileo Ultraviolet Spectrometer (UVS) is analyzed to look for spectral trends across the surface of Europa. We provide the first disk-resolved map of the 280 nm SO_2 absorption feature and investigate its relationship with sulfur and electron flux distributions as well as with surface features and relative surface ages. Our results have implications for exogenic and endogenic sources. The large-scale pattern in SO_2 absorption band depth is again shown to be similar to the pattern of sulfur ion implantation, but with strong variations in band depth based on terrain. In particular, the young chaos units show stronger SO_2 absorption bands than expected from the average pattern of sulfur ion flux, suggesting a local source of SO_2 in those regions, or diapiric heating that leads to a sulfur-rich lag deposit.

While the SO_2 absorption feature is confined to the trailing hemisphere, the near UV albedo (300–310 nm) has a global pattern with a minimum at the center of the trailing hemisphere and a maximum at the center of the leading hemisphere. The global nature of the albedo pattern is suggestive of an exogenic source, and several possibilities are discussed. Like the SO_2 absorption, the near UV albedo also has local variations that depend on terrain type and age.

1. Introduction and background

We present results from Galileo Ultraviolet Spectrometer (UVS) observations of Europa. Extensive work was done in the Voyager era using results from the Voyager UV filter (~350 nm) with regard to the exogenically-derived UV "stain" on Europa's trailing hemisphere (e.g., Johnson et al., 1983; Nelson et al., 1986; McEwen, 1986). In this study, we extend deeper into the ultraviolet: the Galileo UVS data cover the 210–320 nm wavelength range. The nature of Europa's 280 nm absorption feature, which is consistent with and widely attributed to SO_2 (e.g., Lane et al., 1981; Noll et al., 1995), is investigated. We study the distribution and strength of this feature across the trailing hemisphere, and discuss the implications for exogenic and endogenic sources. We also present a model of the sulfur ions precipitating onto Europa, and explore correlations both between the 280 nm absorption and the sulfur flux and between the UV albedo and sulfur flux. We are concerned here primarily with the global nature of these patterns and the exogenic effects responsible for them, particularly the delivery of sulfur to the surface by plasma bombardment. Sulfur ions, ultimately derived from Io's volcanoes, bombard Europa's surface as Jupiter's magnetospheric plasma flows past Europa. This plasma bombardment peaks on the trailing hemisphere, the darker, redder hemisphere with the most abundant sulfur compounds (Carlson et al., 2009). Although the global patterns are emphasized, insight is obtained here by also considering correlations with the local surface terrain.

Europa is unique among icy satellites, in that it is one of the few that displays signs of recent or current surface activity. The surface of Europa has been disrupted in variety of ways (e.g. Greeley et al., 2004; Doggett et al., 2009), most commonly by the formation of ridges (and ridge complexes called bands), but more completely through the massive disruption that produces "chaos" terrain. A variety of smaller disruptions known as lenticulae pepper the surface. The origin of these features is unclear (e.g., Collins and Nimmo, 2009; Prockter and Patterson, 2009), but may be related to the presence of a subsurface ocean (Pappalardo et al., 1999) and may involve the delivery of ocean water (or other subsurface material) to the surface, including sulfur (Zolotov et al., 2009) or sodium (e.g., Leblanc et al., 2005) compounds. Hydrated sulfuric acid has been found to be associated with these geologic terrains (e.g., Carlson et al., 1999a), and SO_2 absorption has shown some correlation with the hydrate concentration (Hendrix et al., 2002) on the anti-jovian hemisphere.

Europa has long been known to exhibit a hemispheric variation in albedo, which was particularly evident in the Voyager camera

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UV filter, centered on 350 nm with a bandpass of 30 nm (Johnson et al., 1983; Nelson et al., 1986). Deeper into the UV, disk-integrated spectral UV observations of Europa from the International Ultraviolet Explorer (IUE) (Lane et al., 1981) and Hubble Space Telescope (HST) (Noll et al., 1995) showed an absorption feature centered at 280 nm on the trailing hemisphere; the trailing hemisphere is centered on 270°W while the center of the leading hemisphere is at 90°W. Low-resolution disk-resolved UV observations from the Galileo UVS (Hendrix et al., 1998) showed that the UV absorption feature decreases in strength with distance from the trailing hemisphere apex (270°W, 0°N). The Galileo UVS observations (Hendrix et al., 1998) also showed a large-scale variation in albedo, where the UV albedo increases with distance from the trailing hemisphere apex, similar to the longitudinal albedo pattern seen at longer wavelengths (e.g., Stebbins and Jacobsen, 1928; Johnson, 1971; Morrison et al., 1974; Johnson et al., 1983; Buratti and Veverka, 1983; McEwen, 1986).

On the basis of this hemispheric albedo and absorption asymmetry, Lane et al. (1981) proposed, along with Eviatar et al. (1981), that magnetospheric sulfur implantation was responsible. Noll et al. (1995) compared HST spectra of Europa's 280 nm feature with the laboratory measurements of Sack et al. (1992), who had measured the UV reflectance spectra of both S-bombarded H_2O ice and SO_2 deposited onto H_2O ice. Noll et al. concluded that the laboratory results for deposited SO_2 provided a better match than the simple implantation experiment, and suggested that a direct source of SO_2 might be required to explain their observations. Therefore, they suggested that the hemispheric dichotomy might be better explained by non-uniform ion erosion (sputtering) in which non-ice material containing SO_2 is uncovered, rather than simple implantation with no additional processing of the surface.

In fact, the production of SO_2 from the sulfur ion irradiation of H_2O has not yet been observed in the laboratory (Strazzulla et al., 2007). Moore et al. (2007), however, found that the irradiation of an H_2O/SO_2 compound mixture by energetic protons which do not sputter efficiently results in a steady-state abundance of SO_2 in which SO_2 is created and destroyed at equal rates. This is consistent with a "radiolytic sulfur cycle" in which sulfur, from any source, is continually cycled through several compounds by incident ionizing radiation (e.g., Carlson et al., 1999a, 2005).

2. Observations and analysis

The Galileo UVS was built at the University of Colorado's Laboratory for Atmospheric and Space Physics and is described by Hord et al. (1992). The observations discussed in this paper were performed using the F-channel of the UVS, which covers the 161.6–321.3 nm wavelength range. The calibration is described by Hendrix (1996). The observations were performed in "full-scan" mode, where the grating was stepped over the 528 channels covering the wavelength range in 4.33 s, with 0.006 s integration time at each channel. The UVS instantaneous field-of-view (IFOV) was $0.1^\circ \times 0.4^\circ$, and measurements described here were made from distances of ~10,000 km. During the Galileo mission (1996–2000), the UVS performed observations covering much of the surface of Europa, particularly at low latitudes, focusing on the anti-jovian hemisphere. A map indicating the coverage of Europa obtained by the Galileo UVS is shown in Fig. 1; each observation set is shown in a different color with the observation name shown below. Plots of results shown later in this report display data from each observation using the same color scheme.

For every observation in the UVS database, we applied the same reduction and analysis technique, as follows. Each spectrum, a total of 14 grating scans (60.67 s total integration), was converted to a reflectance spectrum by subtracting background, applying calibration and dividing by the solar spectrum. The solar spectrum was measured by the Solar–Stellar Irradiance Comparison Experiment (SOLSTICE) (Rottman et al., 1993) and was double boxcar smoothed to match the UVS resolution. The background signal primarily includes system radiation signal and is wavelength-independent. The background level is determined by averaging the signal at the shortest wavelengths, where reflected sunlight does not contribute to the measured signal.

The Galileo UVS instrument was calibrated in terms of what would be observed from an extended source, in units of 10^6 ph/cm^2 s-4π–str Å. The calibrated measurements are brightness $B = 4\pi I$. Because the SOLSTICE-measured solar spectrum is πF, the reflectance ($r = I/F$) is given as $r = B/4F$, where the solar spectrum is corrected for the Sun–Jupiter distance. Sample reflectance spectra are shown in Fig. 2.

In an effort to map out the SO_2 absorption feature strength, we quantify the strength of the absorption in each reflectance spectrum by fitting the data with a straight line and dividing the spectrum by that straight line fit (to remove the overall red slope); an example is shown in Fig. 2. The strength of the band is then the ratio of the signal strength at ~310 nm to the signal strength at ~280 nm.

We also investigate the variation in UV albedo (300–310 nm) across the surface of Europa. In this aspect of the study, it is important to consider differences in brightness that are largely due to photometric variations; Europa's disk-integrated UV solar phase curve is well understood (Nelson and Lane, 1987; Hendrix et al., 2005). However, we find in the present study of high spatial resolution observations, that the usual solar phase angle trend (increasing albedo with decreasing phase angle) is not significant (Fig. 3). It appears that, with these disk-resolved observations, variations in albedo across the surface are driven by factors other than solar phase angle. We investigate sulfur flux and surface features as the important factors driving the UV albedo.

3. Results

3.1. Sulfur flux model

Pospieszalska and Johnson (1989), hereafter PJ89, created a map of sulfur ion precipitation onto Europa's surface. They estimated the sulfur ion flux using parameters (ion density and temperature) derived from Voyager observations of Jupiter's magnetosphere. In this study, we updated their calculation with the latest estimates of plasma parameters near Europa. There are two ion populations that bombard Europa: the "cold" ions, which have a temperature of about 100 eV (for sulfur and oxygen, Paterson et al., 1999), and the energetic tail above tens of keV (see, e.g., Paranicas et al., 2009), which we refer to as the "hot" ion population. We used parameters from Paranicas et al. (2009) to describe the hot ion population and the latest detailed description of the cold ion population by Bagenal (1994), which was based on Voyager data. We caution that both populations show substantial time variability, particularly the cold ions (Kivelson et al., 2004). Further, the parameters used here are based upon a small number of in situ plasma observations whereas the reflectance data presented here reflects the cumulative effects of space weathering over Europa's surface age, and it is unknown if plasma conditions were similar tens of millions of years ago. We assume that Europa is and has been in synchronous rotation and ignore longitudinal and latitudinal differences in gardening and burial rates, so the resulting surface concentrations will be proportional to the local influx.

PJ89 followed the motion of many individual ions in Jupiter's magnetosphere and recorded which hit Europa's surface, and where, and which passed by without hitting the surface. In this