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The Effect of Magnetospheric Ion Bombardment on the Reflectance of Europa's Surface

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A series of laboratory experiments has been performed to investigate the role of sulfur ion implantation on the differences in the reflectivity of Europa's "leading" and "trailing" hemispheres in the UV and visible. The lower reflectivity of Europa's trailing hemisphere at around 0.28 μm can be attributed to a SO band which is caused by either the implantation of sulfur ions from Jupiter's magnetosphere into the water-ice surface of Europa's trailing hemisphere or by the preferential condensation of SO_2 from volcanism on the trailing side. Laboratory measurements of the strength of this absorption band allow an estimate of the column density of 2×10^{17} cm^{-2} SO bonds within the sampling depth of the photons reflected from Europa's trailing hemisphere. Under the conditions tested in the laboratory, sulfur implantation or SO_2 deposition cannot account for the general "reddening" in the UV of the trailing hemisphere relative to the leading hemisphere, a feature which we previously showed can be produced by fast penetrating ions. © 1992 Academic Press, Inc.

INTRODUCTION

Various satellites in the Jovian and Saturnian systems exhibit significant differences in the reflectivities of their "trailing" and "leading" hemispheres in the UV, visible, and IR wavelength regions (Johnson and Pilcher 1977, McFadden *et al.* 1980, Nelson and Lane 1987, Nelson *et al.* 1987). These differences have been attributed, at least in part, to the higher exposure of the trailing hemispheres to magnetospheric plasma ions. That is, since the satellites are phase locked, one side, the trailing side, is always more strongly bombarded by the more rapidly rotating magnetospheric plasma than is the leading side. Europa, one of Jupiter's satellites, has a surface consisting primarily of water ice (Pilcher *et al.* 1972, Clark and McCord 1980, Malin and Pieri 1986). Besides exhibiting variations in reflectance which are likely to be due to endogenic processes (bright planes and darker and redder areas) (McEwen 1986, Buratti and Golombek 1988), Europa also shows a characteristic difference in reflectance between its trailing and leading hemispheres (Johnson and Pilcher 1977, Nelson and Lane 1987) (Fig. 1). This has been attributed to two exogenic processes: a preferential bombardment of the trailing side by magnetospheric plasma ions (Pospieszalska and Johnson 1989), which results in sputtering and implantation of ions (Lane *et al.* 1981, Nelson *et al.* 1986, Johnson *et al.* 1981, 1988, 1990), and preferential impact of meteorites on the leading side, causing "gardening" and resurfacing (McEwen 1986). While the principal difference between the hemispherical reflectance spectra is that the trailing hemisphere is darker in the UV/VIS (Fig. 1), Lane *et al.* (1981) have seen, in addition, a clear absorption band at around 0.28 μm, which they suggested is caused by the implantation of sulfur ions from the Io torus. Since the enhanced absorption seen with the 0.32-μm filter on Voyager exhibits a longitudinal dependence which is independent of terrain type and is very close to that calculated from plasma bombardment, it is reasonable that a plasma effect may occur on this object (Johnson *et al.* 1988, Pospieszalska and Johnson 1989). However, the nature of this effect is not understood. For instance, Domingue *et al.* (1991) have analyzed the photometric function of Europa at various phase angles at 0.47 and 0.55 μm. Based on the observation of a uniform grain size distribution over Europa's surface and a more backscattering single particle scattering function on the leading hemisphere, and under the assumption that irradiation increases the number of internal scatterers, they came to the conclusion that ion bombardment cannot be the dominating factor determining the surface reflectance properties at these wavelengths.

In this paper we report new laboratory investigations that show that Europa's trailing/leading asymmetries in reflectance at around 0.28 μm can be explained by the differences between the flux of magnetospheric sulfur ions

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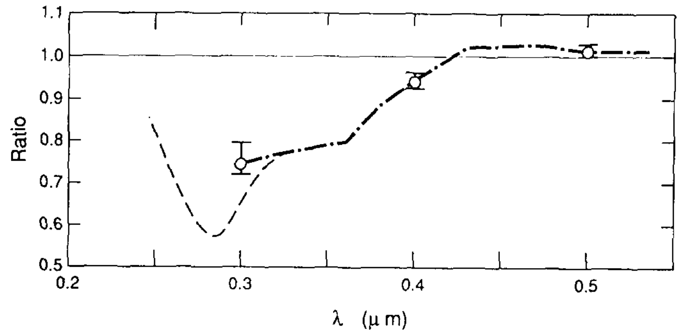

FIG. 1. Ratio in reflectance of Europa's trailing side to the leading side; dashed–dotted line after Johnson and Pilcher (1977), dashed line after Nelson and Lane (1987). It has been suggested that the minimum at around 0.28 μm is caused by preferential sulfur ion implantation on Europa's trailing hemisphere.

on the trailing side and that on the leading side of this satellite.

EXPERIMENTAL RESULTS

Water-ice films 100 μm thick were grown on a cold aluminum substrate at 60 K in a UHV chamber (background gas pressure $\approx 10^{-11}$ Torr). The water used for the preparation of the ice films was HPLC-grade H_2O (organic free; residue after evaporation, 0.9 ppm). The reflectance of these films between 0.24 and 0.54 μm was determined by measuring the light from a xenon lamp reflected from the film into a vacuum UV-visible spectrometer (incident angle, 55°; angle of detection, 35°; phase angle, 90°). Experimental details are described in Sack *et al.* (1991).

All of the following experiments involved 100 μm thick water-ice films grown at 60 K (growth rate: 1 μm/min). Although the absorption coefficients in the analyzed wavelength region are very low and do not show any characteristic bands (Warren 1984, Lebofsky and Fegley 1976, Hapke *et al.* 1981), we found vapor-deposited 100-μm water ice to be opaque to photons of wavelengths between 0.25 and 0.54 μm (Sack *et al.* 1991), which is in agreement with previous observations by Ghormley and Hochanadel (1971). This was determined by their optical appearance (in contrast to "normal" hexagonal ice the appearance is white and not transparent), by the angular distribution of the reflected light (no specular distribution, but diffuse reflectance), and by variation of the thickness. Up to about 10 μm, the bidirectional diffuse reflectance changed with increasing thickness, while for films more than 10 μm thick, it was constant within the experimental uncertainty. This behavior, which is different from that of hexagonal ice obtained by freezing liquid water, was attributed to an inhomogeneous microporous physical structure (Mayer and Pletzer 1984, 1986, Laufer *et al.* 1987, Kouchi *et al.* 1992, Sack and Baragiola 1992), which leads to strong scattering of the photons in the ice film.

In order to confirm earlier laboratory measurements of the S–O absorption band at around 0.28 μm, we grew layers of SO_2 of various thicknesses on top of a 100-μm water film at 60 K. The reflectance of these films was measured before and after condensation of SO_2. The ratio of the reflectance of this SO_2/H_2O film to the original H_2O film is depicted in Fig. 2. It can clearly be seen that the reflectance of SO_2 has a minimum at around 0.28 μm, which is caused by $A \leftrightarrow X$ transition in a SO bond (Herzberg 1966; for absorption coefficients of gaseous SO_2, see Thompson *et al.* 1963). These measurements agree with those of Nash *et al.* (1980) for a 1.5 mm thick sample of SO_2. Using pure SO_2, however, we do not see the slight minimum they observed at 0.35 μm. These SO_2 layers are thin compared to the mean distance between two light scattering events so that primarily absorption (not scattering) leads to the minimum at around 0.28 μm. If this were not the case, we would expect similar changes in reflectance versus thickness at all wavelengths in the spectrum as changes in the scattering properties affect a broad range of wavelengths. It should furthermore be mentioned that a 1-μm layer of a 1 : 9 mixture of SO_2/H_2O shows the same band depth and shape at 0.28 μm as a 0.1-μm SO_2 layer. This shows that the absorption feature of SO_2 at 0.28 μm is not very sensitive to the matrix in which SO_2 is embedded. When thicker samples are used, the band saturates, producing a "reddened" spectrum. Since a reddened spectrum is seen on Europa's trailing hemisphere and has been associated with the latitudinal dependence

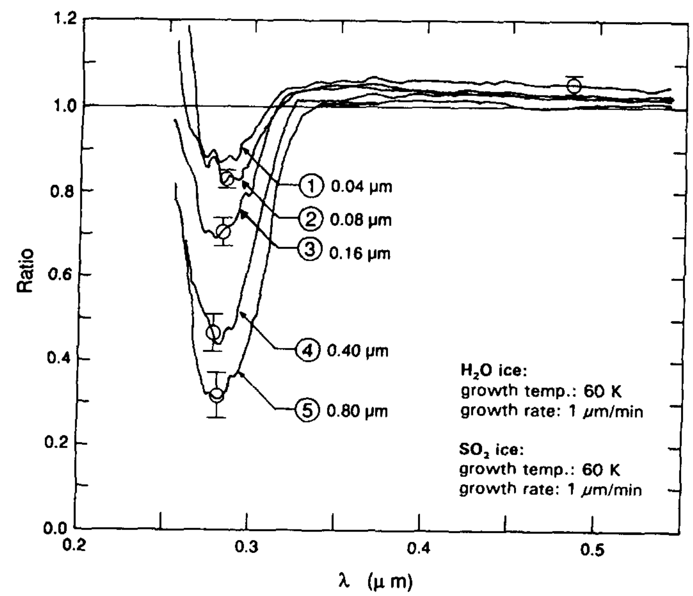

FIG. 2. Ratio of the reflectance of SO_2 layers on top of 100 μm H_2O to the reflectance of a 100 μm thick H_2O film grown at 60 K.

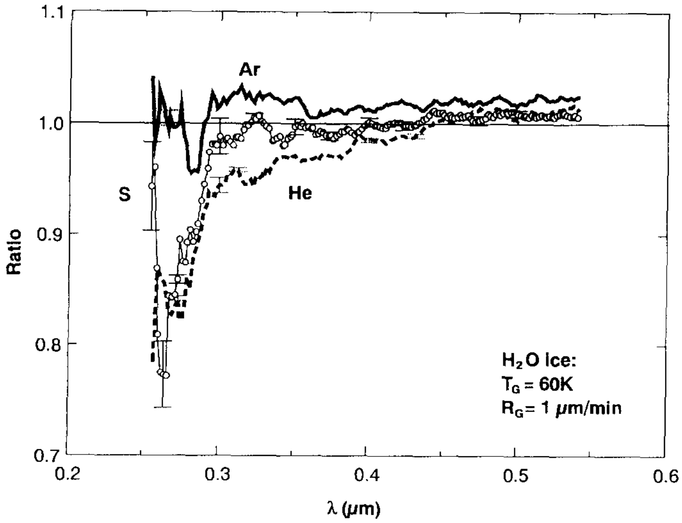

FIG. 3. Ratio of the reflectance of a H_2O film bombarded at 60 K with 3.2×10^{16} ions/cm^2 of various 33 keV ions to the reflectance of the unbombarded 100 μm H_2O film; the error bars are statistical counting errors.

seen in the 0.34-μm filter on Voyager (Nelson *et al.* 1986, Johnson 1990), the SO absorption has been evoked to explain this. However, as seen in Figs. 1 and 2 when the band does not saturate, absorption by SO does not contribute significantly at 0.34 μm.

Figure 3 shows the ratio of the reflectance of 60 K H_2O films (100 μm thick) bombarded with various ions to the reflectance of the original H_2O film. The keV ions were provided by an ion accelerator. (For these relatively thick samples the visual appearance of the sample did not change significantly upon irradiation.) All spectra were obtained by averaging four spectra taken one immediately after the other, each of which showed the features to be discussed. Then the spectrum of the bombarded sample was divided by that of the unbombarded sample and afterward averaged over as many channels as correspond to the resolution of the spectrometer. Therefore the error bars in Fig. 3 represent statistical counting errors, which are lower limits to the experimental error; small structures, such as those between 0.3 and 0.4 μm for the He^+ or S^+ data, were not reproducible.

Two effects can be seen in the spectra: the spectra are reddened (i.e., reflectance decreases with decreasing wavelength) and absorption bands are seen. Bombardment with a dose of 3.2×10^{16} ions/cm^2 by all ions leads to a slight brightening in the visible (Johnson *et al.* 1985), in agreement with the measurements of Strazzulla *et al.* (1988). This effect is stronger for heavier ions (Ar^+: range, 0.068 μm) than for lighter ions with a higher penetration range (He^+: range, 0.54 μm) (Johnson 1990). It is also seen in Fig. 3 that He^+ irradiation leads to a decrease in reflectivity in the UV referred to as a reddening of the ice spectrum. This has been reported before (Sack *et al.* 1991); it was also observed for Ar^+ bombardment of H_2O ice films formed *under different growth conditions*. This effect is absent from the data on Ar^+ bombardment for the growth conditions used here. Since similar effects have also been observed to occur when changing the temperature of the film, they have been attributed to a change in the physical structure of the outermost layer of the film by the bombarding ions (Sack *et al.* 1991, Johnson *et al.* 1985). Changes in the microstructure of the sample affect the scattering of the photons in a manner which depends on wavelength and grain size, and, therefore, on the reflectance of the film (Clark *et al.* 1983, Hapke 1981, 1984, Kortüm 1969, Egan and Hilgeman 1976).

Absorption bands can also be seen for all ions. The weak band at 0.28 μm for Ar^+ bombardment might be a reaction product of H_2O, like an O_2 band ($A \leftrightarrow X$, called the Herzberg band; Herzberg 1966). It can also be seen in the shoulder of the 0.27-μm band for S^+, which will be discussed later, and it can be seen at 0.275 for He^+, where it is slightly shifted toward a lower wavelength due to its position in the shoulder of the decrease toward 0.25 μm. The existence of O_2 produced by ion bombardment in the water matrix at 60 K has been reported earlier (Boring *et al.* 1983; Johnson 1990). The positive identification of this band will be the goal of future research. O_3, which might be produced through hydrogen loss and subsequent oxidation of O, shows a gas phase absorption band at 0.26 μm and might be partially responsible for the decreasing reflectance ratio for He^+ bombardment (Fig. 3) toward 0.25 μm. The wings of this band may play a role in the reddening produced by ion bombardment. We will also examine this point in future work. Here, our goal is to test if S^+/HS^+ irradiation can cause a specific band that is close to that of Europa's trailing/leading ratio spectrum.

Since S ions have mass similar to that of Ar ions, radiation damage and the production of species, such as O_2, should be similar at the same energy. However, the ratio spectrum for the S^+ bombardment shows a strong absorption band at 0.27 μm, compared to the Ar^+ bombardment. When S^+/HS^+ are implanted into the outer layer of the solid (about 0.075 μm), they can react with target molecules or fragments at the end of their path to form new molecular species. It is not unreasonable to assume that, for the density of implanted S^+, molecules containing S–O bonds are preferentially formed, since oxidized molecules are favored at high radiation doses at low temperatures (e.g., Rössler 1985) and since the H_2 is formed and lost easily (Johnson *et al.* 1985, Strazzulla *et al.* 1988). This is also consistent with the binding energies: S–O bonds have higher binding energies than S–H bonds. As discussed above, the SO_2 molecule shows an S–O absorption band at around 0.28 μm, while this occurs at around 0.27 μm for the SO molecule (Herzberg 1966). This band can be seen in Fig. 3 for S^+/HS^+ bombardment, together with the possible weak band at 0.28 μm discussed earlier. The principle band seen for S^+ implantation is not as broad as the one in Fig. 2 and is shifted toward lower wavelengths. A reason for this is that implantation of sulfur ions into water at 60 K does not lead initially to the formation of SO_2 but rather to SO. As this is a diatomic molecule, the absorption band is expected to be sharper and shifted slightly toward lower wavelengths (Herzberg 1966).

We confirmed that the band at 0.27 μm cannot be caused by H_2S formed in radiation-induced chemical processes. In a separate experiment, we observed that H_2S grown on top of H_2O lacks any absorption features at around 0.28 μm. This is in agreement with the data in Herzberg (1966), which shows the main absorption bands of H_2S to be at around 0.23 μm.

Our new results differ somewhat from those obtained earlier. O'Shaughnessy *et al.* (1988) observed a minimum in the ratio curve at around 0.42 μm for both Ar^+ and SO^+ bombardment. However, the interpretation in that paper is based on only one data point below 0.4 μm. Systematic error in this low wavelength region (for instance, a zero offset, which influences the UV region more apparently affected this data point. The rest of the data in that paper is in agreement with the new data obtained here, using a better light source and better spectrometer, when we increase the fluences to the level used earlier.

We have shown here that in addition to the brightening of the reflectance of ice in the visible, the reddening in the UV, and the existence of some absorption bands attributed to O_2 and O_3, a bombarding plasma containing sulfur, at a moderate dose, can lead to an absorption band near 0.27 μm. We attribute this to a S–O band caused by S implantation forming a SO containing molecule as initially suggested by Lane *et al.* (1981). In the following we will use these results to interpret the ratio curve of Europa (Fig. 1) under the assumption that this is the effect seen, and then we will estimate the concentration of SO bonds in the H_2O matrix within the sampling depth of the photons on the surface of Europa's trailing hemisphere.

IMPLICATIONS FOR EUROPA

The ion bombardment contribution to Europa's trailing to leading reflectance ratio spectrum between 0.25 and 0.54 μm can be explained by two principal effects: (i) the stronger ion bombardment on the trailing side causes a slight reddening below 0.45 μm, a feature also seen on other icy satellites (Sack *et al.* 1991), and (ii) the implantation of sulfur ions under our experimental conditions leads to the formation of S–O bonds and is responsible for the minimum observed around 0.28 μm.

A difference between the laboratory simulation and the processes on Europa may be that on Europa we assume that water ice is deposited constantly (by sublimation, sputtering, and redeposition from other surfaces or by volcanic activity) and simultaneously bombarded by plasma torus ions leading to implanted sulfur ions over the full photon penetration depth. In the laboratory experiment, the film is first deposited and then irradiated, eventually reaching equilibrium between implantation of ions and sputtering of both target molecules and those species formed from implanted ions. This would be the situation if, for instance, volcanic activity deposited a fresh layer rapidly and if this deposit was exposed to the plasma. A second difference is that the plasma exhibits a distribution of ion energies, up to MeV energies (Lanzerotti *et al.* 1982), which have larger penetration depths (Johnson 1990).

Using values for the penetration depth of the 33 keV ions used in our experiment and the measured sputtering yield (Chrisey *et al.* 1986, Johnson 1990), we calculated the equilibrium column density achieved to be 1.5×10^{16} implanted ions/cm^2. This would correspond to a SO_2 layer of about 10 nm on top of H_2O. A comparison of Figs. 2 and 3 shows that the maximum absorption which can be achieved in our laboratory ion implantation experiment is small. Nevertheless, we identify the feature in Fig. 3 with the absorption feature due to SO bonds because it is very close in wavelength to the minimum in Fig. 2. Also, the area of the peak of the minimum at 0.27 μm in Fig. 3 is roughly consistent with the measurements in Fig. 2.

Our conclusion, that preferential ion bombardment of Europa's trailing hemisphere might explain certain aspects in Europa's reflectance spectra, is consistent with Domingue *et al.*'s (1991) analysis. By examining the wavelengths 0.47 and 0.55 μm, they found (i) that the grain size distribution of Europa's surface is uniform and (ii) there are more internal scatterers on the leading than on the trailing side; i.e., the trailing hemisphere is "darker" in the UV. Under the reasonable assumption that ion bombardment creates new internal scatterers, they concluded from (ii) that their analysis cannot be consistent with a model of a stronger ion bombardment of the trailing side. Their analysis, however, does not contradict the conclusion given here. First, the flux of energetic sulfur ions on Europa's surface is relatively low. Since the resurfacing rate on Europa is known to be relatively high (Eviatar *et al.* 1985), the size distribution of grains larger than 1 μm as analyzed in Domingue *et al.* (1991) is probably not affected significantly by the magnetospheric ion sputtering. Furthermore, we showed in Sack *et al.* (1991) that, quite surprisingly, a vapor-deposited layer of water ice was in fact darkened in the UV by ion bombardment while brightening in the visible. This is due to local "annealing" of an ice sample which was initially highly scattering in the UV, although the formation of a new absorbing species

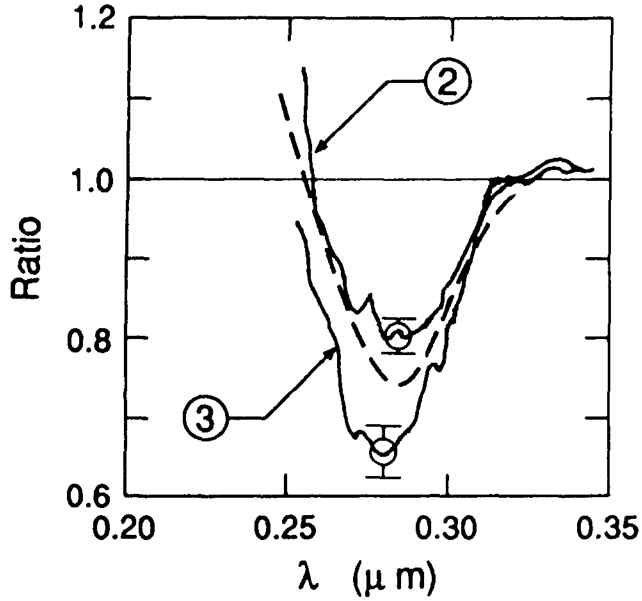

FIG. 4. Fit of the minimum at around 0.28 μm in Europa's ratio curve (dashed line; from Fig. 1) to the ratio of (2) 0.08 or (3) 0.16 μm SO_2 on top of 100-μm H_2O to the original 100-μm H_2O film (from Fig. 2).

(e.g., O_2, O_3) cannot be excluded. We have shown that the size of this effect depends on the grain microstructure (determined by the growth conditions (Sack and Baragiola 1992)) and the ion penetration depth (Johnson 1990). Hence (ii) of Domingue *et al.*'s (1991) analysis is in agreement with our ion bombardment results if the surface layer deposition on Europa's surface occurs by a process similar to the laboratory process.

The general reddening of Europa's trailing hemisphere in the UV is not necessarily due to the SO implantation feature or SO_2 deposition. In Sack *et al.* (1991) and again here, we showed that reddening is caused by morphological changes in the ice by ion bombardment effect. The strong latitudinal correlation (Pospieszalska and Johnson 1989) shown between the plasma bombardment and the reflectance seen in the 0.34-μm filter on Voyager may also be associated with this plasma-induced reddening in the UV.

In Fig. 4 we show a comparison of the minimum at around 0.28 μm in Europa's ratio curve (from Fig. 1) to our results of SO_2 films grown on water ice (from Fig. 2). We scaled the curves such that the shoulder of the band in Fig. 2 (ratio 1.2) and that of the band in Fig. 1 (ratio 0.8) coincide and then scaled the ratios. The shape of the curves is in good agreement with Europa's band and seems to be fitted best with a SO_2 overlayer of about 0.12 μm; therefore, we estimate the presence of a column density of S–O bonds, N_{SO}, of about 2×10^{17} cm^{-2} within the sampling depth of the photons. In this estimate, we have paid attention to the fact that in the SO_2 molecule the sulfur is attached to two oxygen atoms forming two bonds that absorb light at around 0.28 μm. This value of N_{SO} is a factor of 10 higher than the one estimated by Lane *et al.* (1981).

The sampling depth of photons on Europa's surface is needed to estimate a resurfacing rate of H_2O ice assuming constant redeposition with a constant ion bombardment flux (known from Voyager measurements) and assuming that all S^+ ions will form SO_2 bonds (Eviatar *et al.* 1985, Sieveka and Johnson 1982). Squyres *et al.* (1983) and Lane *et al.* (1981) assumed a sampling depth of 0.5 μm. Our laboratory experience with ice films prepared by vapor deposition of H_2O on a cold substrate indicates larger sampling depths. However, this quantity depends strongly on the microstructure of the ice, which is determined by the deposition conditions and any subsequent annealing (Sack *et al.* 1991, Sack and Baragiola 1992). The microstructure strongly affects the scattering behavior of the ice and therefore the UV photon penetration depth. Hence, any laboratory penetration depth may be very different from the photon sampling depth for Europa's surface, making further estimates uncertain.

CONCLUSIONS

Ion bombardment of water ice with inert ions leads, in general, to a slight brightening in the visible which we explain as the alteration of the morphology of the surface. Irradiation with fast, penetrating ions, like He^+, also leads to a decrease in reflectivity in the UV, which was also attributed to structural effects, and, possibly, the formation of new absorbing species. This may account for the reddening of the trailing hemisphere relative to the leading hemisphere in Europa and other icy satellites exposed to plasma bombardment. Comparing the results in Sack *et al.* (1991) to those presented here shows that this reddening is sensitive to growth conditions and ion penetration depth.

The principal result of this paper is that bombardment of water ice with sulfur ions leads to an *additional* absorption band near 0.27 μm. A similar band is also seen for SO_2 layers condensed on top of a water-ice sample indicating that this is the SO band. The small shift between these features is consistent with expectations based on gas phase data for SO and SO_2. Using our measurements and the reflectance measurements on Europa we were able to derive the concentration of SO bonds within the sampling depth of the photons to be about 2×10^{17} cm^{-2} on the trailing hemisphere. Since this absorption band can be produced by either ion implantation in H_2O ice or by coadsorbing SO_2 with H_2O, both a preferential S^+ bombardment and preferential SO_2 volcanism on Europa's trailing hemisphere can explain the absorption feature seen by IUE.

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REFERENCES

BORING, J. W., R. E. JOHNSON, C. T. REIMANN, J. W. GARRET, W. L. BROWN, AND K. J. MARCANTONIO 1983. Ion-induced chemistry in condensed gas solids. *Nucl. Instr. Meth. Phys. Res.* **218,** 707–711.

BURATTI, B., AND M. GOLOMBEK 1988. Geological implications of spectrophotometric measurements of Europa. *Icarus* **75,** 437–449.

CHRISEY, D. B., J. W. BORING, J. A. PHIPPS, R. E. JOHNSON, AND W. L. BROWN 1986. Sputtering of molecular gas solids by keV ions. *Nucl. Instr. Methods. Phys. Res. B* **13,** 360–364.

CLARK, R. N., AND T. B. MCCORD 1980. The Galilean satellites: New near-infrared spectral reflectance measurements (0.65–2.5 μm) and a 0.325–5 μm summary. *Icarus* **41,** 323–339.

CLARK, R. N., F. P. FANALE, AND A. P. ZENT 1983. Frost grain size metamorphism: Implications for remote sensing of planetary surfaces. *Icarus* **56,** 233–245.

DOMINGUE, D. L., B. W. HAPKE, G. W. LOCKWOOD, AND D. T. THOMPSON 1991. Europa's phase curve: Implications for surface structure. *Icarus* **90,** 30–42.

EGAN, W. G., AND T. HILGEMAN 1976. Retroreflectance measurements of photometric standards and coatings. *Appl. Opt.* **15**(7), 1845–1849.

EVIATAR, A., A. BAR-NUN, AND M. PODOLAK 1985. Europan surface phenomena. *Icarus* **61,** 185–191.

GHORMLEY, J. A., AND C. J. HOCHANADEL 1971. Amorphous ice; Density and reflectivity. *Science* **171,** 62–64.

HAPKE, B. 1981. Bidirectional reflectance spectroscopy. I. Theory. *J. Geophys. Res. B* **86**(4), 3039–3054.

HAPKE, B. 1984. Bidirectional reflectance spectroscopy. 3. Correction for macroscopic roughness. *Icarus* **59,** 41–59.

HAPKE, B., E. WELLS, AND J. WAGNER 1981. Far-UV, visible, and near-IR reflectance spectra of frosts of H_2O, CO_2, NH_3, and SO_2. *Icarus* **47,** 361–367.

HERZBERG, G. 1966. *Molecular Spectra and Molecular Structure.* Van Nostrand Reinhold, New York.

JOHNSON, R. E. 1990. *Energetic Charged-Particle Interactions with Atmospheres and Surfaces.* Springer-Verlag, Berlin.

JOHNSON, R. E., L. J. LANZEROTTI, W. L. BROWN, AND T. P. ARMSTRONG 1981. Erosion of Galilean satellite surfaces by Jovian magnetosphere particles. *Science* **212,** 1027–1030.

JOHNSON, R. E., L. A. BARTON, J. W. BORING, W. A. JESSER, W. L. BROWN, AND L. J. LANZEROTTI 1985. Charged particle modification of ices in the Saturnian and Jovian systems. In *Ices in the Solar System* (J. Klinger, Ed.), pp. 301–315. Reidel, Dordrecht.

JOHNSON, R. E., M. L. NELSON, T. B. MCCORD, AND J. C. GRADIE 1988. Analysis of Voyager images of Europa: Plasma bombardment. *Icarus* **75,** 423–436.

JOHNSON, T. V., AND C. B. PILCHER 1977. Satellite spectrophotometry and surface compositions. In *Planetary Satellites* (J. A. Burns, Ed.), pp. 232–268. Univ. of Arizona Press, Tucson.

KORTÜM, G. 1969. *Reflectance Spectroscopy.* Springer, New York.

KOUCHI, A., J. M. GREENBERG, T. YAMAMOTO, AND T. MUKAI 1992. Extremely low thermal conductivity of amorphous ice: Relevance to comet evolution. *Astrophys. J.* **388,** L73–L76.

LANZEROTTI, L. J., W. L. BROWN, W. M. AUGUSTYNIAK, R. E. JOHNSON, AND T. P. ARMSTRONG 1982. Laboratory studies of SO_2 ice and applications to the frosts of Io. *Astrophys. J.* **259,** 920–929.

LANE, A. L., R. M. NELSON, AND D. L. MATSON 1981. Evidence for sulphur implantation in Europa's UV absorption band. *Nature* **292,** 38–39.

LAUFER, D., E. JOCHAVI, AND A. BAR-NUN 1987. Structure and dynamics of amorphous water ice. *Phys. Rev. B* **36**(17), 9219–9227.

LEBOFSKY, L. A., AND M. B. FEGLEY 1976. Laboratory reflection spectra for the determination of chemical composition of icy bodies. *Icarus* **28,** 379–387.

MALIN, M. C., AND D. C. PIERI 1986. Europa. In *Satellites* (J. A. Burns and M. S. Matthews, Eds.), pp. 689–717. Univ. of Arizona Press, Tucson.

MAYER, E., AND R. PLETZER 1984. Polymorphism in vapor deposited amorphous solid water. *J. Chem. Phys.* **80**(6), 2939–2952.

MAYER, E., AND R. PLETZER 1986. Astrophysical implications of amorphous ice—a microporous solid. *Nature* **319,** 198–301.

MCEWEN, A. S. 1986. Exogenic and endogenic albedo and color patterns on Europa. *J. Geophys. Res. B* **91,** 8077–8097.

MCEWEN, A. S., AND L. A. SODERBLOM 1983. Two classes of volcanic plumes on Io. *Icarus* **55,** 191–217.

MCFADDEN, L. A., J. F. BELL, AND T. B. MCCORD 1980. Visible spectral reflectance measurements (0.33–1.1 μm) of the Galilean satellites at many orbital phase angle. *Icarus* **44,** 410–430.

MOSES, J. I., AND D. B. NASH 1991. Phase transformations and the spectral reflectance of solid sulfur: Can metastable sulfur exist on Io? *Icarus* **89,** 277–304.

NASH, D. B., F. P. FANALE, AND R. M. NELSON 1980. SO_2 frost: UV-visible reflectivity and Io surface coverage. *Geophys. Res. Letters* **7/9,** 665–668.

NASH, D. B., M. H. CARR, J. GRADIE, D. M. HUNTEN, AND C. F. YODER 1986. Io. In *Satellites* (J. A. Burns and M. S. Matthews, Eds.), pp. 629–688. Univ. of Arizona Press, Tucson.

NASH, D. B., AND R. R. HOWELL 1989. Hydrogen sulfide on Io: Evidence from telescopic and laboratory infrared spectra. *Science* **244,** 454–457.

NELSON, M. L., T. B. MCCORD, R. N. CLARK, T. V. JOHNSON, D. L. MATSON, J. A. MOSHER, AND L. A. SODERBLOM 1986. Europa: Characterization and interpretation of global spectral surface units. *Icarus* **65,** 129–151.

NELSON, R. M., AND A. L. LANE 1987. Planetary satellites. In *Scientific Accomplishments of IUE* (Y. Kondo, Ed.), pp. 67–99. Reidel, Dordrecht.

NELSON, R. M., A. L. LANE, D. L. MATSON, G. J. VEEDER, B. J. BURATTI, AND E. F. TEDESCO 1987. Spectral geometric albedos of the Galilean satellites from 0.24–0.34 micrometers: Observations with the International Ultraviolet Explorer. *Icarus* **72,** 358–380.

O'SHAUGHNESSY, D. J., J. W. BORING, AND R. E. JOHNSON 1988. Measurements of reflectance spectra of ion-bombarded ice and application to surfaces in the outer solar system. *Nature* **333,** 240–241.

PILCHER, C. B., S. T. RIDGWAY, T. B. MCCORD 1972. Galilean satellites: Identification of water frost. *Science* **178,** 1087–1089.

POSPIESZALSKA, M. K., AND R. E. JOHNSON 1989. Magnetospheric ion bombardment profiles of satellites: Europa and Dione. *Icarus* **78,** 1–13.

RÖSSLER, K. 1985. Hot atom chemistry and radiolysis of gaseous and solid components of planetary atmospheres. In *The Atmospheres of*

Saturn and Titan, Proc. Int. Workshop, Alpach, Austria, 16–19 September 1985, ESA SP-241 (December 1985), pp. 175–188.

SACK, N. J., J. W. BORING, R. E. JOHNSON, R. A. BARAGIOLA, AND M. SHI 1991. Alteration of the UV-visible reflectance spectra of H_2O ice by ion bombardment. *J. Geophys. Res. Planets E* **96**(2), 17535–17539.

SACK, N. J., AND R. A. BARAGIOLA 1992. Sublimation and thermal conductivity of vapor deposited water ice below 170 K and their dependence on growth conditions. Submitted for publication.

SIEVEKA, E. M., AND R. E. JOHNSON 1982. Thermal- and plasma-induced molecular redistribution on the icy satellites. *Icarus* **51**, 528–548.

SQUYRES, S. W., R. T. REYNOLDS, AND P. M. CASSEN 1983. Liquid water and active resurfacing on Europa. *Nature* **301**, 225–226.

STRAZZULLA, G., L. TORRISI, AND G. FOTI 1988. Light scattering from ion-irradiated frozen gases. *Europhys. Lett.* **7**(5), 431–434.

THOMPSON, B. A., P. HARTECK, AND R. R. REEVES, JR. 1963. Ultraviolet absorption coefficients of CO_2, CO, O_2, H_2O, N_2O, NH_3, NO, SO_2, and CH_4 between 1850 and 4000 Å. *J. Geophys. Res.* **68**(24), 6431–6436.

WARREN, S. G. 1984. Optical constants of ice from the ultraviolet to the microwave. *Appl. Opt.* **23**(8), 1206–1225.