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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 SO2 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 SO2 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 SO2 absorption bands than expected from the average pattern of sulfur ion flux, suggesting a local source of SO2 in those regions, or diapiric heating that leads to a sulfur-rich lag deposit.

While the SO2 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 SO2 absorption, the near UV albedo also has local variations that depend on terrain type and age.
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Dear Icarus editors,  

Please consider this revised manuscript, “Europa’s Disk-Resolved Ultraviolet Spectra: Relationships with Plasma Flux and Surface Terrains,” for publication in Icarus. We have responded to the reviewers’ comments as indicated in the attached file.  

Thank you for your consideration.  

Best regards,  

Amanda R. Hendrix
MS#11608 (Hendrix et al.)
Responses to reviewer comments

Reviewer #1: The manuscript gives an analysis of Galileo UVS data as it pertains to the 280 nm SO2 band. Combined with this analysis are the results of a Monte Carlo simulation to account for sulfur ion implantation as a possible source of SO2. This reviewer finds the general details of the manuscript to be solid. The qualitative correlation between the spatial distribution of cold sulfur ions and SO2 band depth is not new, but the revised model includes updated parameters. What is particularly interesting however is that there are geologic variations within the trailing hemisphere that ties some portion of the 280 nm SO2 band depth with dark terrain. This implies a Europa-genic source of sulfur that then produces SO2 in a "sulfur cycle".

There are some issues that this reviewer feels should be addressed prior to publication. These are listed below.
1) Can the authors make an estimate of the relative amounts of SO2 produced from ion implantation (or in other words how much Europa-genic SO2 is required to account for the measurement)?

Sulfur ions have been impacting Europa’s surface for a long time. Some of them will eventually be carried away, some will be incorporated into the surface and some will be buried. These processes operate on many different timescales. Added to this Galileo EPD found that there is a varying rate of ion flux even between successive Europa encounters (Mauk et al. 2004). Therefore we don’t believe it is sensible at this time to attempt to establish a relative amount of endo- vs exo-genic sulfur.

2) If there is a Europa-genic sulfur source, what predictions can be made regarding other sulfur compounds and their regional distributions? If the model is correct it should be consistent for all sulfur containing molecules.

Our interpretation of the UVS data and the ion flux models is that sulfur may be distributed across the surface with a longitudinal variation as predicted, but that recently geologically active regions may be enhanced in sulfur-rich species. This is consistent with both the UVS-measured SO2 and the NIMS-measured hydrate. Depending on the chemical cycle, other sulfur species will be present, depending upon their stability.

3) If there is an ocean-based Europa-genic sulfur source, then sulfate salts are a potential candidate. I understand the authors' position in the hydrated sulfuric acid vs hydrated sulfate salts argument, but considering in the present work, the authors are claiming a geologic source of sulfur, then it would seem logical to include the possibility of sulfate salts as the origin, regardless of their position on the acid vs salt argument.

Our results do not require a sulfur source at Europa necessarily. Just one of the possibilities we discuss is an ocean-derived source of sulfur, the form of which is not defined but does not rule out hydrated sulfate salts. We have added statement about this to the text.
4) Have the authors considered that the Europa-genic sulfur source could possibly be the result of sulfur implantation from an earlier time when Io volcanic activity could possibly have been greater than present. Consequently, the implantation rate could have been much higher, and could have seeded the near surface with sulfur. Europan geologic activity could then produce the present distribution.

We cannot rule out variations in Io volcanic output altering the sulfur ion flux rates. Our model uses fluxes based on Galileo era measurements. This idea is actually not too different from what we have considered in our paper, where a possible source of the SO2 in the chaos regions derives from accumulated sulfur in the surface that is geologically recycled.

Minor typo: Pg 2 line "occrelations"
Fixed.

Reviewer #2:

This is a very interesting paper and I enjoyed reading it. I think this paper is suitable for publication but do have a few comments, which mostly pertains to the readability of the manuscript, although I do have a couple questions on the analysis, see comment 6 and 7:

1) I would strongly suggest combining the introduction and background section into one section, as currently it seems the authors jump from saying what they are going to do to giving some background. As it is right now, the first paragraph of the intro seems to be orphaned from the rest of the paper. After reading the paper, I can see why one would want to have a paragraph like this in there but I think this part could be put together more clearly.

This is a good suggestion. In response, we have merged the first two sections, calling the merged section “Introduction and Background.” What used to be the first paragraph is now the second paragraph and we think that it flows more smoothly this way.

2) 1st paragraph introduction: "Compositional variations associated with these geologic terrains are related to the presence of hydrated sulfuric acid"

I am not sure what this sentence implies. If there is hydrated sulfuric acid in one place and then not in another isn't that in itself a compositional variation? Please clarify.

We have reworded this phrase to read “Hydrated sulfuric acid has been found to be associated with these geologic terrains (e.g., Carlson et al. 1999a)…”

3) "The nature of Europa's 280 nm absorption feature, which is widely attributed to SO2, is investigated."
Who attributes this to SO2? Can you add some references.

We have added references here (Lane et al. 1981, Noll et al. 1995).

4) Page 2: "The longitudinal albedo pattern measured by the Galileo UVS has also long been seen at longer wavelength"

Please clarify what the pattern is; the previous sentence refers to an absorption band and not the albedo.

Good point – we have added a sentence that reads “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.”

5) Page 3: "though its identification is not absolutely certain, we refer to it as the SO2 feature."

What are the other possibilities for this feature?

The primary other possibility is OH; however Johnson et al. (2004) have discussed that this species is not likely be stable in the Europa environment. Our absolute certainty about the identification is limited by a lack of lab measurements. We have rephrased the sentence to read “…though its identification is not absolutely certain, largely due to a lack of laboratory measurements, it is consistent with SO2 (Lane et al. 1981; Noll et al. 1995) and thus we refer to it as the “SO2” feature.”

6) Page 5: The reflectance is given by \( r = \frac{I}{4F} \). Is the reflectance the brightness \( (4\pi I) \) divided by the solar spectrum \( (\pi F) \)? This yields \( 4I/F \) not \( I/4F \). Please clarify.

The instrument measures brightness, \( B = 4\pi I \). Solstice measures \( \pi F \). \( r = I/F = (B/4\pi)/(\pi/F) \). Thus, we should have written \( r = B/4F \) and have changed the text accordingly.

7) Page 5: Quantifying the strength of the absorption band by scaling in reflectance units.

Is the absorption depth from this method going to be proportional to abundance, the light being absorbed attenuates exponentially, so does't one need to take a log or ln of the spectrum to get a more accurate linear relation?

For each spectrum, we divide out the red slope, which scales the spectrum to (close to) unity. Then, since we’re simply measuring the depth of the absorption band, we find the ratio of the value of the spectrum at the deepest part of the absorption to the continuum value. However, as shown in Fig. 9, the deepest absorption occurs in the darkest regions – which means that even more absorber must be present in those regions. Thus, we have added some text on the approximate abundances of SO2 given the albedo of the different regions, in the Discussion section, in which we do use the \( -\ln(\text{reflectance}) \) relationship,
after Carlson et al. (2009).

8) Page 5: "it is important to consider differences in brightness that are solely due to photometric variations"

How can one distinguish whether brightness is solely due to photometric variations?

Of course it’s difficult to interpret which brightness variation are due solely due photometric variations; what we meant here is that we are trying to determine whether brightness variations are largely due to photometric variations or not. We have replaced the word “solely” with “largely.”

9) Page 5: "the usual solar phase angle trend (increasing albedo with decreasing phase angle) is not significant"

Doesn't Fig 3 show the opposite trend? and How significant are the variations that are seen in the "usual" trend?

Our point here is that the “usual” phase angle trend is not seen and we interpret this as meaning that photometric variations are not playing a strong role in this dataset.

10) Page 6: last sentence 1st paragraph in 4.1 - what does it mean by both populations show substantial variability, i.e. variability across the surface or variability within the data (i.e. a lot of scatter). Please clarify.

We meant to imply temporal variability in the particle populations. We have clarified this in the text.

11) Page 7: tracing the ions motion backward: How many trajectories actually pass Europa? This comment does not to be included but is more of a curiosity for the reviewer.

Cheng and Paonessa (JGR, 1985) illustrated this problem for some of the Saturnian satellites. They asked, “what fraction of the protons that could hit the moon during their next bounce period actually do?” In general, the answer depends mainly on these 2 issues: the size of the gyroradius compared to the moon radius and most importantly for ions near Europa, the ratio of the ion half bounce time to the time the guiding-center field line of the particle takes to pass through the moon. For a 10 keV (100 keV) singly-charged sulfur ion, the gyroradius divided by the moon radius is 7% (30%), meaning that if the guiding center passes through Europa, the particle would likely hit the moon, based on this factor. However, more importantly, the half bounce time of the same ions is 4853 (1298) s. The guiding center field line of these ions passes through Europa in about 26 s (=2*1561/120). Therefore the vast majority of sulfur ions are at latitudes that are too north or too south to hit the moon as the guiding center field line passes through it.

12) Page 7: Are both Fig 5 and 6a and 6b similar to PJ89? It did not make sense how Fig
6b could be as it does not show anything on the flux.

The lines in Fig. 6b show the flux, as described in the caption.

13) Page 7 - Figure 4 is mentioned but 4a and 4b are never called out in the manuscript. What do the two cases that they represent. I get roughly the schematic but am not sure which figure the text refers to.

We have modified the text to clarify this and call out each figure. We have also updated the figure caption.

14) Page 8 - 2nd paragraph - were any experimental results used for the sputtering yield calculations?

We don't discuss this; it is in the references cited earlier, but, yes, the sputtering yields are calculated using fits derived from laboratory data.

15) Page 8 - "that sputtering at Europa is dominated by the hot sulfur ions" - compared to oxygen? Cold sulfur ions? Both?

Both, as mentioned on the top of page 7. The combination of high energy and high mass means that the energetic sulfur ion population dominates the sputtering rate.

16) Page 8 and in Figures - could the authors define the longitudinal degrees which are referred to as leading and trailing. There is a reference to the trailing on Page 10 but it should probably be given early in the manuscript or possibly on the figures.

We have added the following phrase on page 2 as well as in the caption for Figure 1: "...the trailing hemisphere is centered on 270°W while the center of the leading hemisphere is at 90°W." We have also annotated the leading and trailing hemispheres in Figs. 4a and 4b.

17) Page 10, last sentence first full paragraph: "The shape of the hot sulfur flux pattern is somewhat more similar to the IUE curve than the sputtering model"

Really? They look pretty similar to me. Is the error in the model that low.

This is something about which there is uncertainty, both in the data and the models, and we tried to express this in the originally submitted version. We have removed this sentence entirely in the resubmitted manuscript.

18) Page 14: "This is reinforced by the fact that there are chaos regions on the leading hemisphere that do not exhibit the SO2 absorption."

I understand this from reading the results section but I think you should expand on this so it is clear, as it is not mentioned here in the discussion.
We have added the following sentence to clarify this point: “The E15 sucomp03 observation (the purple points on Figs. 1 and 6b) overlaps the region near 105°W, which in the geologic map of Fig 8 is designated as a chaos region (Doggett et al. 2010) but exhibits low SO2 abundance in Fig 6b.”

19) Page 13-14: The paragraph that starts on 13 and continues to 14 needs some clarification. I think I get what the authors are saying: the SO2 probably comes from a combination of ion bombardment and sulfurous material coming from the putative ocean, which is decomposed into the sulfur cycle by the ions. I think the presentation of these ideas could have been significantly improved.

We have expanded and altered this paragraph in response to other comments and think it is more clear now. We leave our summarizing ideas to the conclusion section.

20) Page 15: last paragraph, 4th line - "low flux" - how low, over long times couldn't it be significant

Low is relative, in this case. Since we don't have a good physical model, we cannot quantify what is "low" and "high" other than to observe the correlations described in our paper.

21) Page 16: "accumulated implanted sulfur being geologically recycled to the surface in these regions.."

This is interesting, I do not recall this being in the main part of the paper and appears as an afterthought. Could the authors mention this in the discussion as well?

We have added mention of this to the discussion (as was our original intent!).

22) Figure 6b - it is really hard to see the flux numbers on the plot, could the authors darken the font or make it bigger.

We’re guessing the reviewer is referring to Figure 6a (not Fig 6b). We have made the font and lines thicker/darker.

Typos:

2nd paragraph abstract, first line, "the near near UV albedo"
Fixed.

Page 2, next to last sentence before background: "ocrrelations" should be "correlations"
Fixed.
Europa’s Disk-Resolved Ultraviolet Spectra: Relationships with Plasma Flux and Surface Terrains

Amanda R. Hendrix, Timothy A. Cassidy, Robert E. Johnson, Chris Paranicas, Robert W. Carlson

- We analyze Galileo UVS data of Europa to look for spectral trends
- We model the cold and hot sulfur fluxes to the surface of Europa
- A significant increase in SO2 amounts in the dark young chaos regions is found
- A Europa-genic source of sulfur or modification mechanism is suggested
Europa’s Disk-Resolved Ultraviolet Spectra: Relationships with Plasma Flux and Surface Terrains

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Manuscript pages: 27
Figures: 9
Tables: 0
Proposed Running head: Europa’s UV Signature

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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 SO₂ 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 SO₂ 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 SO₂ absorption bands than expected from the average pattern of sulfur ion flux, suggesting a local source of SO₂ in those regions, or diapiric heating that leads to a sulfur-rich lag deposit.

While the SO₂ 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 SO₂ absorption, the near UV albedo also has local variations that depend on terrain type and age.

Keywords: Europa; ices, UV spectroscopy; Jupiter, satellites; ultraviolet observations; satellites, composition
1.0 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 SO₂ (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. 2010). 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 and Kargel 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 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$_2$O ice and SO$_2$ deposited onto H$_2$O 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$_2$O has not yet been observed in the laboratory (Strazzulla et al. 2007). Moore et al. (2007), however, found that the irradiation of an H$_2$O/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. 1999; Carlson et al. 2005).

2.0 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 sec, with 0.006 sec integration time at each channel. The UVS instantaneous field-of-view (IFOV) was 0.1°x0.4°, 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.

[Figure 1 goes here.]

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 sec 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 $10^6 \text{ph/cm}^2\text{-sec-4}\pi\text{-str-Å}$. The calibrated measurements are brightness $B = 4\pi I$. Because the SOLSTICE-measured solar spectrum is $\pi F$, 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.

[Figure 2 goes here.]

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 et al. 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.
3.0 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 Monte Carlo approach, they began by generating a representative population of ions with the appropriate properties (temperature, density), and traced the motion of these ions until they either hit Europa’s surface or passed by Europa without hitting the surface. Our approach also involved the tracing of ion motion, but with the computational expedient of tracing the ion motion backwards in time from Europa’s surface (e.g., Smart and Shea, 2009), which allows us to avoid calculating the many trajectories that pass by Europa.

As in PJ89, the ion motion was modeled as a superposition of three motions: gyration about Jupiter’s magnetic field, unconstrained motion parallel to the field, and a “guiding center drift,” the guiding center being the axis about which the ion gyrates (parallel to the magnetic field). For sufficiently low energy ions, this drift is simply the co-rotation velocity (Fig. 4a). With increasing ion energy, positive ions drift faster than co-rotation speed (Fig. 4b) (Thomsen and Van Allen, 1981), an effect not implemented in PJ89. Another difference from PJ89 is that our model includes the tilt of Jupiter's magnetic dipole, which results in a (slightly) time-varying field at Europa's orbit. As in PJ89, we assumed that Europa is electromagnetically inert; we did not include the relatively small electric and magnetic fields produced by Europa's interaction with Jupiter's magnetosphere.

[Figures 4a and 4b go here.]

Our results (Figs. 5 and 6) are qualitatively similar to PJ89, though we found an
order of magnitude larger asymmetry in sulfur flux between the leading and trailing hemispheres. As in PJ89, the "cold" sulfur ions do not reach the leading hemisphere; their flux is confined to the trailing hemisphere. The hot ions, in contrast, hit both the leading and trailing hemispheres. They have access to the leading hemisphere for two reasons: their relatively large gyroradii and, more importantly, their tremendous speed parallel to the magnetic field lines. Their average motion perpendicular to the magnetic field is limited to the guiding-center drift speed (~100 km s\(^{-1}\)), but the ions are free to move parallel to the magnetic field. When the ion speed parallel to the field line exceeds the drift speed, the ions have access to the leading hemisphere (Fig. 4).

[Figures 5, 6a and 6b go here.]

In addition to calculating the total sulfur ion flux, we also calculated the sputtering rate. Each ion that impacts Europa’s surface ejects a number of water molecules. The sputtering yield, the number of H\(_2\)O molecules ejected per incident ion, depends on ion energy and type (H, O or S at Europa). The energy dependence is described by Johnson et al. (2009) and Cassidy et al. (2010). We found, as in previous studies (e.g., Paranicas et al., 2009), that the sputtering at Europa is dominated by the hot sulfur ions.

As mentioned above, Noll et al. (1995) hypothesized that SO\(_2\) rich deposits might be uncovered by sputtering erosion, rather than being derived from implanted S ions. We consider this unlikely because regolith gardening mixes the near surface at rates much faster than ions erode the surface (Cooper et al., 2001). Furthermore, since SO\(_2\) is more volatile, in a mixed ice it would be removed faster.
3.2 Spatial pattern in UV absorption

We compare the measured SO\textsubscript{2} band strengths across the surface with the sulfur flux model in Fig. 6. Figure 6a displays the 2-D sulfur model output (the total flux of sulfur ions) and the SO\textsubscript{2} band strength for each observation location. Fig. 6b shows the measured band strength vs. longitude compared with the sulfur plasma flux model; we have chosen to scale the model to the cyan data points near 210-220°W, which appear to exhibit a trend with longitude. We find that absorption strengths are greater on the trailing hemisphere; this is as expected from previous disk-integrated observations of the UV absorption band itself (Lane et al., 1981; Noll et al., 1995) and from Voyager-era disk-resolved measurements of large-scale UV darkening in the broad-band UV filter (Johnson et al. 1983; Nelson et al. 1986; McEwen 1986).

The SO\textsubscript{2} absorption distribution generally correlates with the sulfur ion flux to the surface, particularly the cold ion flux (the hot flux is much smaller in comparison, as shown in Fig. 5). Deviations from the overall trend are due to specific terrain units and are discussed in section 3.4. Paranicas et al. (2001) also pointed out that the same region, the low-latitude trailing hemisphere, receives the largest dosage of ionizing radiation due to the flux of high energy electrons there. It is our hypothesis that both the sulfur ions and electrons act in concert to increase the SO\textsubscript{2} production above levels seen at other longitudes on Europa.

3.3 Longitudinal pattern in UV albedo
The longitudinal variation in the disk-resolved UV albedo (at 300-310 nm) is shown in Fig. 7. When compared with the longitudinal variation in SO$_2$ band strength (Fig. 6b), it becomes clear that different processes drive these two spatial trends. Whereas the SO$_2$ absorption is confined to the trailing hemisphere (longitudes $\geq 180^\circ$W), the albedo is seen to increase steadily from the trailing hemisphere apex at 270$^\circ$W to the leading hemisphere apex at 90$^\circ$W. The longitudinal disk-resolved albedo trend is shown to be consistent with the familiar orbital lightcurves of Europa (e.g., McEwen 1986) also shown in this figure. That is, we also show the Voyager filter data and the disk-integrated UV orbital phase curve as measured by IUE (Hendrix et al. 2005). The IUE curve is similar to that measured by Galileo, but is more subdued, as the data are disk-integrated and therefore not as sensitive to variations in brightness driven by the individual terrains targeted in the Galileo disk-resolved data set.

In Fig. 7, we compare the UV data with our models of hot sulfur flux and sputtering rate, by scaling both models to the disk-integrated IUE data, under the assumption that these large-scale processes could be responsible for the large-scale disk-integrated hemispheric variation in brightness. Both models provide satisfactory fits to the data, suggesting that one or both of these contributes to the longitudinal darkening pattern.

In Fig. 7, we also show the Voyager UV-filter (350 nm) disk-integrated longitudinal trend (McEwen 1986), which has often been invoked to suggest the
importance of magnetosphere-surface interactions. The longitudinal trend exhibits a smaller excursion than the IUE and Galileo curves which are at the shorter wavelengths (300-310 nm), as discussed later.

### 3.4 Relationship between UV absorption and surface features

In Figs. 6 and 7, we have compared models with UVS-measured data, for both the UV albedo (300-310 nm) and the SO$_2$ band depth. Though there is broad agreement between the model curves and data in Figs. 6 and 7, there is considerable scatter in these disk-resolved observations. In this section we consider how the geology of each observation could affect the patterns described above. Figure 8 shows the UVS observations on a geologic map (Doggett et al. 2009). Below we discuss the trailing hemisphere observations.

[Figure 8 goes here.]

**Red points (E14 iceraft):** These observations are in the equatorial region of the center of the trailing hemisphere, near the Conamara Chaos region. From the geologic map, much of this region is the younger “chaos terrain” (bright green regions in Fig. 8), namely Annwn Regio. In terms of SO$_2$ absorption (Fig. 6b), there is great variety in the band depth measured in this region – but all points exhibit dramatically stronger band depths than in the other terrains. The region also has a low UV albedo (Fig. 7), as well as visible albedo.
Black points (E6 sucomp01). This observation is focused on the Pwyll crater, one of the freshest features present on Europa; Pwyll is notable in particular for having bright rays in the midst of the relatively dark trailing hemisphere. The observation swath covers the bright ejecta and extends into the neighboring (darker) chaos terrain to the east (the southernmost part of Dyfed Regio). There is significant variation in SO\textsubscript{2} band depth (Fig. 6b) measured during this observation, but overall the band strength is lower than expected from the sulfur flux model; generally the band depth appears to increase away from the center of the crater, toward the chaos terrain.

Light blue/cyan points (E11 Drklit). This dataset observed the anti-Jovian-trailing quadrant, along the equator. The primary difference between this region and the region observed during the E11 Cyclod sequence (blue points discussed below) is that this observation captured some of the banded terrain (Fig. 8), in the Argadnel Regio. We expect that the two regions experience roughly the same amounts of sulfur and electron fluxes. In the UVS data, this region has a significantly higher SO\textsubscript{2} band depth, and approximately the same albedo, as the Cyclod data points. The SO\textsubscript{2} band depth measured in the Drklit sequence is consistent with the sulfur flux model; as noted, we have chosen to scale our sulfur model in Fig. 6b to these data points. The geologic episode that created the Argadnel Regio is considered to have occurred earlier than the episode that created the chaos region on the trailing hemisphere, Annwn Regio, and occurred after the initial emplacement of the ridged plains.

Blue/violet points (E11 Cyclod). This observation is on the anti-Jovian-trailing quadrant, at ~15°N latitude, largely on the older ridged plains within Falgo Regio. The region exhibits weaker SO\textsubscript{2} band depths than expected from the sulfur flux model; the
band depths are also mostly weaker than measured in the Argadnel Regio (discussed above), at similar longitude but lower latitude (light blue points). This suggests that the SO$_2$ band depths are linked not only with sulfur flux, but also with surface age. This is our single observation of the ridged plains terrain, the oldest terrain on Europa, and it exhibits weak SO$_2$ absorption, despite experiencing relatively high amounts of sulfur flux.

Purple points (E6 Sucomp02). This swath traversed a visibly dark lineament on the anti-Jovian hemisphere, at ~20°N latitude (Fig. 1). The average albedo is somewhat lower than expected from the sputtering and hot sulfur flux model (Fig. 7). There is variation in the amount of SO$_2$ measured along the swath, but the SO$_2$ band depths are generally as expected from the sulfur flux model (i.e., lower than the cyan values to which we’ve scaled the model).

4.0 Discussion

The Galileo UVS data exhibit two different effects: a global-scale darkening, where the albedo smoothly decreases from the leading hemisphere to the trailing, and the SO$_2$ absorption band, which is primarily confined to the trailing hemisphere. The albedo pattern (300-310 nm) is similar to the flux of high energy sulfur ions, while the SO$_2$ pattern is similar to the total flux of sulfur ions (including the dominant "cold" ions in addition to the high energy ions). Both the SO$_2$ absorption and UV albedo (300-310 nm) are also influenced by local geology. Younger terrains, in particular, tend to have larger SO$_2$ absorptions.
Figure 9 exhibits the relationship between UV albedo and SO$_2$ band strength, demonstrating that the SO$_2$ absorption is strongest in the UV-dark regions. In the chaos region on the trailing hemisphere apex (E14 iceraft), the SO$_2$ band depths correspond roughly with an SO$_2$ column density of $\sim 1.18 \text{ cm}^{-2}$, which, considering the lower albedo (shorter path length) corresponds to $\sim 2.5\%$ molar density of SO$_2$ (after Carlson et al., 2009). Toward the anti-Jovian hemisphere, SO$_2$ abundances vary between $\sim 4.17 \text{ cm}^{-2}$ (E11 drklit) to $< 1.17 \text{ cm}^{-2}$ (E11 cyclod); considering the albedo of this region, these abundances correspond to between approximately $\sim 0.5\%$ and $< 0.1\%$, respectively.

The correlation of the 280 nm SO$_2$ band depth with dark terrains on Europa’s trailing hemisphere suggests that sulfur ions implanted into the surface are not the sole cause of the UV feature. That being said, the fact that the 280 nm band appears mainly on the trailing hemisphere implies a strong relationship with cold plasma bombardment. This is reinforced by the fact that there are chaos regions on the leading hemisphere (Fig. 8) that do not exhibit the SO$_2$ absorption: The E15 sucomp03 observation (the purple points on Figs. 1 and 6b) overlaps the region near 105°W, which in the geologic map of Fig 8 is designated as a chaos region (Doggett et al. 2010) but exhibits low SO$_2$ abundance in Fig 6b. (Carlson et al. (2009) pointed out that the ice shell on the leading hemisphere could be thicker than on the trailing hemisphere, which may explain the hemispherical difference in the chemical variations between chaos regions.)

The measured SO$_2$ densities are roughly correlated with NIMS-measured hydrate abundances. NIMS measured the highest concentrations of hydrate at the trailing hemisphere apex (Carlson et al., 2005), where the UVS also measures the highest abundances of SO$_2$. In observed leading hemisphere regions, both the hydrate and the SO$_2$
abundances are roughly zero. Elsewhere, detectable amounts of SO$_2$ are present in regions where there is at least $\sim$50% hydrate. The correlation between the SO$_2$, the hydrate and the dark material is consistent with the sulfur cycle proposed by Carlson et al. (1999a, 2002), where a dynamic equilibrium exists between continuous production and destruction of sulfur polymers $S_x$, SO$_2$, and H$_2$SO$_4$$^*$$n$H$_2$O. The sulfur cycle involves an initial (unknown) sulfurous material on the surface of Europa, which is exposed to ionizing radiation. Higher SO$_2$ abundances in the geologically young regions (red dots in Fig. 6b) suggest that sulfur-rich species from the ocean are a candidate source. Another possibility is that diapiric heating leads to sublimation of water ice, leaving a sulfur-rich lag deposit in isolated regions. Irradiation of the sulfur-rich material from either of these sources would lead to enhanced concentrations of SO$_2$. Alternately, implanted sulfur that has accumulated in the surface and been buried due to gardening over time could be geologically recycled to the surface in these regions (Carlson et al., 1999a). Carlson et al. (2009) pointed out that irradiation of sulfate salts can also produce SO$_2$, but the general relationship between the SO$_2$ abundance and the cold sulfur flux makes sulfur implantation a greater likelihood; however, irradiation of sulfate salts in the dark chaos regions is a distinct possibility.

[Figure 9 goes here.]
confined to the trailing hemisphere, as is the high-energy electron bombardment (Paranicas et al. 2009). Thus, the cold ion interaction cannot be the source of the global-scale albedo variation in this synchronously rotating model.

The correlation between the sputtering rate and 300 nm albedo, as suggested by the data and model in Fig. 7, could be due to an increase in the average grain size (Clark et al. 1983). Small grains are preferentially destroyed by sputtering and larger grains tend to be more absorbing due to longer path length. Calvin et al. (1995) point out that Europa’s trailing hemisphere has larger grains than the leading hemisphere.

Grain size cannot, however, explain the variation in orbital phase curve with wavelength (as shown clearly in McEwen (1986) Fig 6 and here in Fig 7) – which is likely evidence for an unidentified red absorber. We have shown a good longitudinal correlation between the UV albedo and sputtering rate and also with hot sulfur flux. It is not clear, however, whether such energetic ions, with their relatively low flux, can be the source of a substance that would darken the surface with the distinct wavelength variation that is measured at Europa. Hydrogen peroxide, though present on Europa and detected by the Galileo UVS (Carlson et al. 1999b), does not absorb at 300 nm so should not play a role in the longitudinal variation in 300 nm albedo. Clearly, the longitudinal phase curve becomes steeper with decreasing wavelength, especially considering the Voyager blue, violet and UV filters (McEwen 1986) and the Galileo UVS data studied here. This suggests some sort of red absorber in the surface, perhaps consistent with some type of sulfur. Sulfur in various polymorphs has long been suggested as Europa’s chromophore (see Carlson et al., 2009). Spencer et al. (1995) suggested cyclo-octal S₈ as a component on the leading side. The concentration of sulfur, and the fraction of polymeric sulfur, may
increase onto the trailing side, resulting in the observed higher ultraviolet absorption (Carlson et al. 2009).

One possibility is that the wavelength dependence in the orbital phase curve is related to hot sulfur implantation and the creation of sulfur-rich grain rims. Ultraviolet wavelengths, probing the shallow rims, would be more sensitive to the composition of the rims than longer wavelength observations. Such a scenario would mean that interaction between hot sulfur ions and icy grains on Europa’s surface create sulfur-rich rims on the grains, which, though present on the leading hemisphere, are thinner or less abundant on there due to lower hot sulfur ion fluxes. Longer wavelengths, probing deeper into the grains, sense less of the sulfur-rich rims and more of the ice-rich grain interiors, resulting in a less dramatic orbital phase curve.

5.0 Conclusions

In conclusion, high-resolution UV observations of the surface of Europa show that the 280 nm SO$_2$ absorption band increases in strength toward the trailing hemisphere apex, consistent with a sulfur ion implantation source as has been suggested earlier. However, here we find a significant increase in absorption in the dark young chaos regions on the trailing hemisphere. This suggests that there is either a local source, or diapiric heating leading to a sulfur-rich lag deposit, in addition to the magnetospheric plasma source; accumulated implanted sulfur being geologically recycled to the surface in these regions is another possibility. We thus find that the commonly-stated idea that the UV absorption is due to logenic sulfur implantation is not sufficient. Although there is a broad correlation with this flux, strong local variations exist. We therefore conclude,
considering the sulfur flux to the surface, that implantation of Iogenic sulfur ions is responsible for some of the UV absorption on Europa’s trailing hemisphere, but that a Europa-genic source or modification mechanism is also required, particularly in the visibly dark, recently active regions of the trailing hemisphere. The UVS spectra support the model of H$_2$SO$_4$-SO$_2$-S cycle occurring in regions of high particle bombardment (trailing hemisphere) and geologic activity (dark linea). Furthermore, the UV hemispheric albedo dichotomy decreases with increasing wavelength, suggestive of chemical contributions. One possibility is the presence of sulfur-rich rims on surface grains, which could be due to interactions with hot sulfur ions.

Though we cannot say with certainty, due to a lack of complete Galileo coverage on the trailing hemisphere, these results suggest that the early disk-integrated measurements of the 280 nm absorption on the trailing hemisphere (Lane et al. 1981; Noll et al. 1995) were primarily due to the enhanced concentration of SO$_2$ in the dark, young regions. Ultraviolet observations of the region west of Pwyll (i.e., close to the apex of the trailing hemisphere but not in a chaos region) would be a test of this. Future observations using instrumentation on the Jupiter Europa Orbiter will no doubt prove invaluable in understanding from both endogenic and exogenic sources contributing to Europa’s surface composition.

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References


Calvin, W. M., Clark, R. N., Brown, R. H., & Spencer, J. R. 1995. Spectra of the icy Galilean satellites from 0.2 to 5 μm: A compilation, new observations, and a recent summary. *J. Geophys. Res.* **100**: 19041-19048.


Williams, S. M. Krimigis, and A. Lagg 2004. Energetic ion characteristics and neutral gas
interactions in Jupiter's magnetosphere, *J. Geophys. Res.* 109, A09S12,

W. D. Smythe, J. K. Crowley, P. D. Martin, A. Ocampo, C. A. Hibbitts, J. C. Granahan,
NIMS Team 1999. Hydrated minerals on Europa’s surface from the Galileo NIMS


Moore, M. H., Hudson, R. L., Carlson, R. W. 2007. The radiolysis of SO\textsubscript{2} and H\textsubscript{2}S in
water ice: Implications for the icy jovian satellites. *Icarus* 189: 409-423.

Morrison, D., Morrison, N.D., Lazarewicz, A.R. 1974. Four-color photometry of the

A. Soderblom 1986. Europa: Characterization and interpretation of global spectral surface
units. *Icarus* 65: 129-151.


Figure Captions.

Figure 1. Map of UVS coverage on Europa, shown on a USGS basemap. Rectangles indicate the size of the UVS IFOV during each observation. Different colors correspond to different observation sequences and correlate with color of data points in Figs 6b and 7. The trailing hemisphere is centered on 270°W while the center of the leading hemisphere is at 90°W.

Figure 2. (a) A sample UVS spectrum (from the E11 DRKLIT set) with fit to slope overplotted in red. The reflectance spectrum is normalized at ~310nm. (b) The sample spectrum with the fitted slope divided out. Overplotted in red is a best-fit polynomial, to demonstrate a broad absorption band centered near 280 nm. The band depth shown here is consistent with an SO$_2$ vapor column density of ~6e17 cm$^{-2}$.

Figure 3. UV reflectance vs. phase angle. Phase angle does not appear to play an important role in determining reflectance for these regions; if it did, we would expect the lower phase angle observations to exhibit higher I/F values than observations at high phase angles.

Figure 4. Schematic of ion motion near Europa, from two perspectives. (a) Particles exhibit circular gyration motion about the field lines, superimposed on linear motion in the corotation direction. (b) In addition to the gyration about field lines, the ions also travel parallel to the magnetic field. For higher-energy ions, the combination of large gyroradius and rapid motion parallel to the field lines allows access to the leading
hemisphere.

**Figure 5.** Sulfur flux model results, averaged over all latitudes. The cold ions dominate the flux and are concentrated on the trailing hemisphere. The hot, or nonthermal, ions are more broadly distributed with longitude. The nonthermal flux is shown both at its absolute values and scaled to the maximum value of the cold flux to demonstrate both the difference in scale between the two fluxes and the longitudinal variation in the hot flux.

**Figure 6a.** Map of SO$_2$ absorption strength compared with hot + cold sulfur flux. The footprint colors symbolize SO$_2$ absorption band strength (as shown in Fig. 6b): red, >2; orange, 1-2; yellow, 0.5-1; green, 0.4-0.5; cyan, 0.3-0.4; blue, 0.2-0.3; purple, 0.1-0.2; black, <0.1.

**Figure 6b.** UVS-measured 280 nm (SO$_2$) band strength vs. longitude on Europa. Symbol colors correspond with map locations in Fig 1. Overplotted are models of total sulfur flux (red: averaged over all latitudes; blue: averaged over ±30° latitude). The models have been scaled so that they approximately follow the trend of the cyan points. The band strength increases toward the trailing hemisphere, and significant absorption is confined to the trailing hemisphere, consistent with the sulfur flux. However, the SO$_2$ band strength in specific regions is driven by the surface terrain.

**Figure 7.** Galileo-measured UV reflectance vs longitude at 300 nm. Also shown is the disk-integrated orbital phase curve measured by IUE at 300 nm (orange line), scaled to
The Galileo data exhibit excursions from the disk-integrated IUE curve, which we presume are due to surface features of varying brightnesses. Also shown is the disk-integrated Voyager-measured orbital phase curve in the UV filter (350 nm), scaled at 180°W, to show that the hemispheric variation in brightness is not as great at 350 nm as at 300 nm. Our model flux of hot sulfur ions is shown, inverted (blue dashed line), as is the model sputtering rate, inverted (red dashed line). We have scaled these models to the IUE data, under the assumption that these large-scale processes could be responsible for the large-scale disk-integrated hemispheric variation in brightness. Note that the sputtering process and the hot sulfur flux extend onto the leading hemisphere, unlike the cold sulfur flux (Fig. 6), suggesting that one or both of these processes contributes to the longitudinal darkening pattern. The shape of the hot sulfur flux model is more similar to the IUE curve than the sputtering model.

**Figure 8.** Galileo UVS footprints on a Europa geologic map (after Doggett et al., 2010). Bright green regions represent chaos terrain, while teal regions criss-crossed with orange regions represent older ridged plains. UVS observations are colored according to observation sequence as in Fig. 1.

**Fig. 9.** UV band strength vs UV reflectance. Since the band strengths increase in dark regions, this means there must be a lot of absorber. There is very little absorber where R>.04, but for R<0.04, there is a wide variety in absorption band strengths (not linear).
Figure 2b
Figure 6b
Figure 7

Reflectance factor (300 nm)

- Sputtering rate
- Non-thermal sulfur flux
- IUE disk-integrated 300 nm
- Voyager disk-integrated UV filter

West longitude