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# IUE's view of Callisto: Detection of an SO<sub>2</sub> absorption correlated to possible torus neutral wind alterations

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**Abstract.** Observations taken with the International Ultraviolet Explorer (IUE) detected a 0.28 $\mu$ m absorption feature on Callisto's leading and Jupiter-facing hemispheres. This feature is similar to Europa's 0.28 $\mu$ m feature, however it shows no correlation with magnetospheric ion bombardment. The strongest 0.28 $\mu$ m signature is seen in the region containing the Valhalla impact. This absorption feature also shows some spatial correlation to possible neutral wind interactions, suggestive of S implantation (rather than S<sub>x</sub>) into Callisto's water ice surface. Indications of possible temporal variations (on the 10% level) are seen at other wavelengths between the '84-'86 and the '96 observations.

## Introduction

Callisto displays a longitudinal albedo variation opposite to the hemispherical albedo dichotomy seen on Europa or Ganymede (Stebbins 1927, Stebbins and Jacobsen 1928, Millis and Thompson 1975, Morrison et al. 1974, Nelson et al. 1987). This hemispherical albedo dichotomy on Europa and Ganymede is attributed to the preferential interaction of the Jovian magnetosphere with their trailing side (Eviatar et al. 1981; Calvin et al. 1996; Johnson et al. 1984, 1988; Lane et al. 1981; Nelson et al. 1987; Noll et al. 1995; Pospieszalska and Johnson 1989). Micrometeoroid gardening of the leading side is hypothesized to be the mechanism for producing most of Callisto's hemispherical albedo differences (Calvin et al. 1995). Water ice grain size variations between leading and trailing sides are such that the leading side has a fine grained ( $\mu$ m) component in addition to the global coarse grained (mm to cm) ice component (Calvin and Clark 1993, Calvin et al. 1995). The spectral variations created by different grain sizes are modifications in the shape of existing water bands, not in the production of different absorption bands. This coupled with the hemispherical porosity variations found by Buratti (1991) are consistent with preferential micrometeoritic bombardment of the leading side.

Theoretical modeling studies of Callisto's spectra from 0.25 $\mu$ m to 4.3 $\mu$ m show the optical surface is 20-45 wt. % coarse grained water ice (Calvin and Clark 1991; Roush et al. 1990) with intimate mixtures of either magnetite and serpentine (Roush et al. 1990) or iron and magnesium rich serpentines (Calvin and Clark 1991). Model differences indicate the presence of additional phases and possibly opaque minerals (Calvin and Clark 1991). Near-UV studies by

Nelson et al. (1987) showed that Callisto's surface is dominated by a spectrally flat UV absorber asymmetrically distributed in longitude. The UV spectra examined by Nelson et al. (1987) were taken from '79 to '86 with IUE and within their S/N they detected no absorptions in this region. This is in contrast to the detection of an 0.28  $\mu$ m SO<sub>2</sub> absorption band on Europa whose strength is greatest on the trailing side (Lane et al. 1981; Nelson et al. 1987, Ockert et al. 1987; Noll et al. 1995) and with the 0.26 $\mu$ m O<sub>3</sub> absorption band on Ganymede whose strength and presence is correlated with the trailing side (Nelson et al. 1987; Noll et al. 1996).

We present the first detection of spatial and temporal variations in Callisto's UV spectrum which give evidence for an SO<sub>2</sub> absorption at 0.28 $\mu$ m. This feature has also been detected with HST on the leading side by Noll et al. (1997), this issue. Our observations were taken with IUE in '96 and are compared with reprocessed observations taken by Nelson et al. (1987). Variations between the '84-'86 (Post-Voyager era) and the '96 (Galileo era) observations show decade time scale temporal variability in Callisto's surface composition.

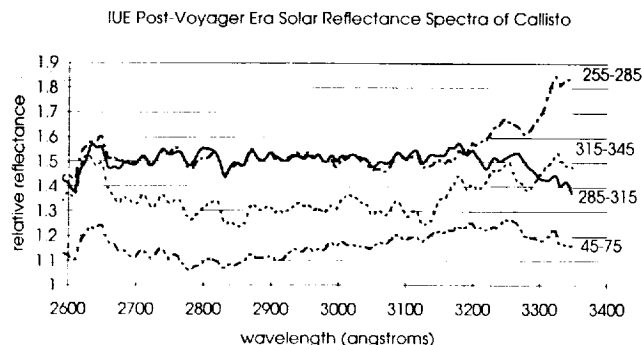
## Observations

All observations were taken with IUE's long wavelength prime camera (LWP) in the large aperture and calibrated using the NEWSIPS software; an updated software extraction and calibration process which reflects a better understanding of the IUE instruments. Corrections to an Earth and Sun distance of 5AU, and smoothing to the spectral response function of a 1-1.5 arcsecond object were applied. Solar phase angles range from 10°-11.5°, where viewing geometry variations are negligible. Double exposures (<4min. each) taken one at each end of the aperture slit were co-added to increase the S/N. Line-by-line examinations of the spectra insured that any scattered light from Jupiter was correctly subtracted and Callisto was fully contained within the slit.

The spectra were binned in 30° rotational phase angle increments centered on the leading and trailing sides. This longitudinal co-adding of spectra produced a higher S/N, yet preserved the large scale longitudinal variations. The binned spectra were ratioed to a SUSIM solar spectra (Wayne Pryor, private communication, VanHoosier et al. 1988) in order to remove the solar signature and smoothed with a 15 pixel boxcar function.

## Results

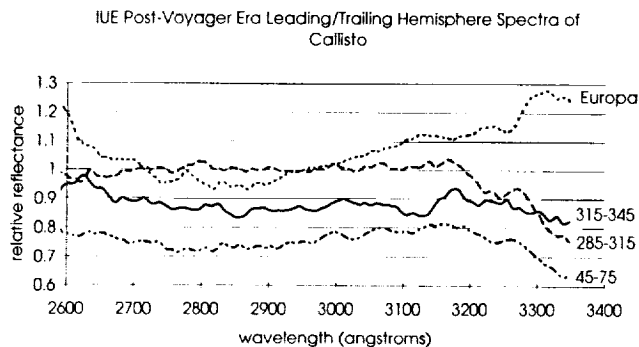
Figure 1 plots the Post-Voyager era binned spectra. Many longitudes are not represented since there are very few Post-Voyager era spectra which meet the solar phase angle criteria



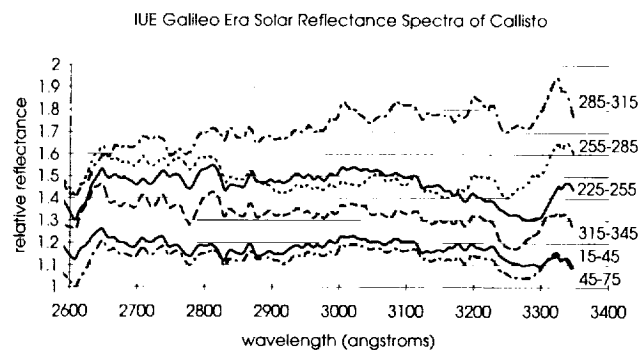
**Figure 1.** IUE reprocessed Post-Voyager era reflectance spectra of Callisto acquired from 1984-86. The dash-dot-dot line is the spectrum for the longitude region  $45^{\circ}$  to  $75^{\circ}$ , the dashed line covers  $255^{\circ}$  to  $285^{\circ}$  (central trailing side), the solid line represents  $285^{\circ}$  to  $315^{\circ}$ , and the dash-dot line represents longitudes  $315^{\circ}$  to  $345^{\circ}$ .

and have been reprocessed with the NEWSIPS software. The spectrum for the longitude range  $285^{\circ}$  to  $315^{\circ}$  is relatively flat from  $0.255\mu\text{m}$  to  $0.335\mu\text{m}$  with a slightly diminished albedo around  $0.33\mu\text{m}$ . The spectrum for the longitude bin centered on the trailing side ( $255^{\circ}$ - $285^{\circ}$ ) is similar; however, it has an increased brightness from  $0.32\mu\text{m}$  longward. The spectra for longitude ranges  $45^{\circ}$ - $75^{\circ}$  and  $315^{\circ}$ - $345^{\circ}$  show a previously undetected absorption feature at  $0.28\mu\text{m}$  in addition to the overall lower near-UV albedo described by Nelson et al. (1987). The feature is strongest in the  $45^{\circ}$ - $75^{\circ}$  longitude region. In longitude regions between  $255^{\circ}$  and  $315^{\circ}$  the  $0.28\mu\text{m}$  absorption feature is not detected.

Ratios of each longitude bin versus the central trailing binned spectrum for the Post-Voyager era data are shown in Figure 2. The shallow  $0.28\mu\text{m}$  absorption feature seen in the Callisto data for longitude  $45^{\circ}$ - $75^{\circ}$  is still apparent in the ratio data, suggesting that the material responsible for this absorption has a greater concentration within this region relative to the central trailing region. The  $0.28\mu\text{m}$  feature is marginally discernible in the ratio spectrum of the  $315^{\circ}$ - $345^{\circ}$  longitude region. The ratio of the longitude region between  $285^{\circ}$ - $315^{\circ}$  and the central trailing side region, which is the



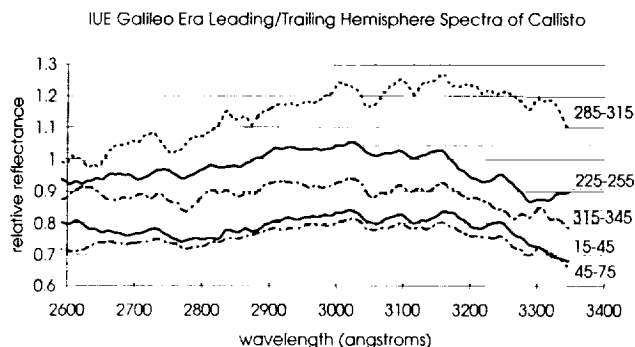
**Figure 2.** Ratio spectra of each available Post-Voyager era longitude spectrum versus the spectrum of the central trailing side of the Post-Voyager era data set. The dash-dot-dot line represents the ratio with the longitude region from  $45^{\circ}$ - $75^{\circ}$ , the dashed line represents the  $285^{\circ}$ - $315^{\circ}$  ratio, and the solid line gives the ratio for the longitude bin  $315^{\circ}$ - $345^{\circ}$ . For comparison, the trailing/leading side ratio spectrum for Europa (Domingue and Lane, unpublished data) is shown with a short dashed line.



**Figure 3.** IUE Galileo era reflectance spectra of Callisto taken in 1996. The dash-dot line represents the spectrum for the longitude region  $45^{\circ}$  to  $75^{\circ}$ , the solid lines represent regions  $15^{\circ}$  -  $45^{\circ}$  and  $225^{\circ}$ - $255^{\circ}$  as labeled in the figure. The short-dashed line covers the central trailing side  $255^{\circ}$ - $285^{\circ}$ , the dash-dot line represents  $285^{\circ}$ - $315^{\circ}$ , and the long-dashed line covers the longitude bin  $315^{\circ}$  -  $345^{\circ}$ .

adjacent bin, not only shows no evidence of the  $0.28\mu\text{m}$  absorption, but indicates the level to which two bins can be compared for the presence or absence of the  $0.28\mu\text{m}$  feature. This ratio displays a relative darkening longward of  $0.32\mu\text{m}$  (seen in all three available data bins), but examination of Figure 1 shows that the  $255^{\circ}$ - $285^{\circ}$  bin (central trailing region) has a noticeable brightening while the other bins do not. The apparent darkening in the ratio may only result from the increased reflectivity of the central trailing region. Comparison with the  $0.28\mu\text{m}$  absorption feature in Europa's trailing/leading side ratio spectrum shows that Callisto's absorption feature broader and shallower, however, the absorption maximum is at the same wavelength.

Figure 3 plots Galileo era spectra of Callisto. Similar to the Post-Voyager data set, the central trailing bin has the highest overall near-UV albedo, with a weak indication of enhanced brightening around  $0.33\mu\text{m}$ . The shallow  $0.28\mu\text{m}$  absorption feature is seen in the Galileo era spectra for longitude bins  $15^{\circ}$ - $45^{\circ}$  and  $45^{\circ}$ - $75^{\circ}$ , but it is not as deep as the feature in the Post-Voyager era spectra. IUE's photometric sensitivity was measured every month using several standard stars; hence temporal instrument sensitivity variations are well understood and were removed in the NEWSIPS processing. IUE camera



**Figure 4.** Ratio spectra of each available Galileo era longitude spectrum versus the spectrum of the central trailing side from the Galileo era data set. The dash-dot lines represent the ratio with the longitude regions  $45^{\circ}$ - $75^{\circ}$ , and  $315^{\circ}$ - $345^{\circ}$  as labeled in the figure. The solid lines represent the  $15^{\circ}$ - $45^{\circ}$  ratio and the  $225^{\circ}$ - $255^{\circ}$  bin ratio as also labeled in the figure. The short-dashed line shows the  $285^{\circ}$ - $315^{\circ}$  region.

repeatability analyses by Garhart and Nichols (1994) show that repeatability and rms errors for the wavelength region between 0.26 $\mu$ m and 0.30 $\mu$ m are  $\sim 2\%$  for two or more co-added spectra. For longitude region 45 $^{\circ}$ -75 $^{\circ}$  the Post-Voyager era and Galileo era spectra vary by 4%, resulting in an  $\sim 50\%$  band depth difference well above the 1 sigma level.

Figure 4 shows the ratio spectra of each Galileo era longitude bin to the central trailing side spectrum. The 0.28 $\mu$ m feature is only seen in the ratio of the longitude regions between 15 $^{\circ}$ -45 $^{\circ}$  and 45 $^{\circ}$ -75 $^{\circ}$  to the central trailing side; suggesting that the material responsible for this absorption is more abundant in the 15 $^{\circ}$ -45 $^{\circ}$  and 45 $^{\circ}$ -75 $^{\circ}$  longitude regions than the central trailing region and its adjacent longitude bins. From 0.26 $\mu$ m to 0.325 $\mu$ m the ratio spectra for longitude regions 225 $^{\circ}$ -255 $^{\circ}$ , 285 $^{\circ}$ -315 $^{\circ}$  and 315 $^{\circ}$ -345 $^{\circ}$  to the central trailing side are flat to within the noise bandwidth of the ratio data. The ratio spectrum for the region from 225 $^{\circ}$  to 255 $^{\circ}$  to the central trailing side is flat between 0.26 $\mu$ m and 0.32 $\mu$ m and is very close to unity (adjacent longitude bins). Above 0.305 $\mu$ m this ratio spectrum displays a decreasing slope with increasing wavelength, which, as in the case of the Post-Voyager data set, may be the result of enhanced reflectivity of the central trailing longitude region.

## Discussion

Trailing/leading side ratios of Europa show an enhanced absorption feature at 0.28 $\mu$ m associated with the preferential bombardment of the trailing side by corotating sulfur ions trapped in the Jovian magnetosphere (Eviatar et al. 1981; Calvin et al. 1996; Johnson et al. 1984, 1988 Lane et al. 1981; Nelson et al. 1987; Noll et al. 1995; Pospieszalska and Johnson 1989; Sack et al. 1992). The 0.28 $\mu$ m feature seen in the Callisto spectra shows a similar shape to Europa's trailing side 0.28 $\mu$ m feature. Figure 5 plots the Callisto spectra with the strongest 0.28 $\mu$ m feature along with an IUE trailing side Europa spectrum (Domingue and Lane, unpublished data), an S $^{+}$  irradiated ice spectrum, and a transmittance spectrum of a 0.16 $\mu$ m thick SO $_2$  frost layer grown on a 100 $\mu$ m thick layer of H $_2$ O ice. (Sack et al. 1992, Noll et al. 1995). On Europa the 0.28 $\mu$ m feature is attributed to an SO $_2$  absorption band (Lane

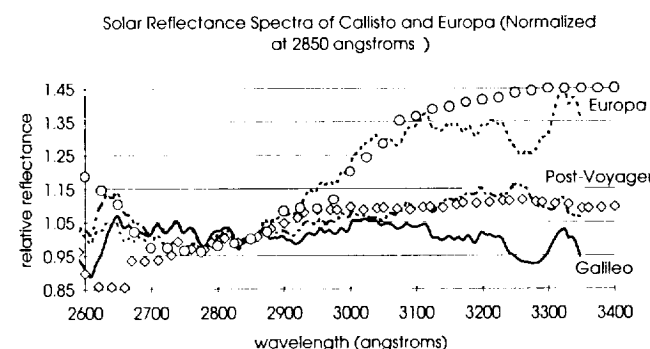
et al. 1981, Noll et al. 1995). Comparisons of our Callisto and Europa spectra suggests SO $_2$  is present on Callisto's leading and Jupiter-facing hemispheres. The formation of OH in water ice during the radiolysis of H $_2$ O ice also produces an 0.28 $\mu$ m absorption feature (Johnson and Quickenden 1997). However at temperatures greater than 100K (well below Callisto's average surface temperature) irradiation produced OH is lost (Johnson and Quickenden 1997, Noll et al. 1997). We attribute the 0.28 $\mu$ m feature to an SO $_2$  absorption.

Band depth differences between Post-Voyager and Galileo era spectra show temporal variability in SO $_2$  abundance, implying a greater detectable abundance during the Post-Voyager epoch. The presence of the SO $_2$  on the leading side instead of the trailing side argues against direct ion implantation via magnetospheric-surface interactions being the dominate process, unlike the situation at Europa.

Callisto's visible rotational light curves (Morrison et al. 1974, Nelson and Hapke 1978) are not commensurate with a darkening or spectral coloration process of magnetospheric origin. Their measurements do not indicate a smooth sinusoidal albedo variation with longitude as seen on Europa and Ganymede. Callisto's hemispherical albedo dichotomy is opposite that of Europa and Ganymede and the darker leading side does not display a smooth sine function with a minimum visual albedo at 90 $^{\circ}$  longitude. A local minimum in the visible rotation curve at 60 $^{\circ}$  longitude correlates with Valhalla Basin. The region with the strongest detected 0.28 $\mu$ m absorption in our IUE data also correlates with Valhalla, implying a possible impact or excavation origin for the SO $_2$  feature. There are longitude regions not observed in the IUE data set and the detection of a stronger 0.28 $\mu$ m absorption in some of these areas would invalidate the correlation with Valhalla and the impact/excavation hypothesis for the SO $_2$  feature source. Noll et al. (1997, this issue) have detected this feature at  $\sim 91^{\circ}$  longitude which also includes the Valhalla basin. Comparisons between the HST and IUE observations may help map the change in SO $_2$  across this impact basin.

The Galilean satellites are imbedded within the inner Jovian magnetosphere, albeit the densities of O and S ions are down by at least a factor of 30 at Callisto's orbit (Cheng 1986, Bagenal et al. 1992). Nonetheless, over long time scales the accumulation of energetic impacts should produce a near-UV coloration such as that observed on Europa and Ganymede, where the trailing side has been darkened by ion impacts leading to the formation of UV absorbing molecules. The recent discovery by the Galileo magnetometer team (Khurana et al. submitted to *Nature*) that Callisto has no measurable internal magnetic field indicates that the  $>100$ km/sec ions should reach and impact within the trailing side surface. The molecules are seen more easily on Europa and Ganymede because they are present in a strongly UV-reflecting, relatively clean, water-ice surface. Callisto is far darker in its mean visible reflectivity (Nelson and Hapke 1978), making it more difficult to detect weak absorptions. Thus, there could be a magnetospheric absorption signature not yet detected at or near the central trailing longitudes, buried within the gray, very broadband darkening material found all over the Callisto surface. This, does not explain the preferential detection of SO $_2$  in the regions of the leading and Jupiter-facing hemispheres.

The visible light curves give evidence for at least one and possibly two additional processes leading to spatially inhomogeneous absorptions. Our detection of small quantities of S-O or SO $_2$  (0.28 $\mu$ m band) around the Jupiter-facing



**Figure 5.** Callisto ratio spectra which show the strongest evidence for the 0.28 $\mu$ m absorption, the longitude region 45 $^{\circ}$ -75 $^{\circ}$  for the Post-Voyager (dash-dot-dot line) and Galileo (solid line) eras. The Europa comparison (short dashed line) is provided to illustrate the weakness of the Callisto absorption. The diamonds represent the sulfur irradiated ice spectrum of Sack et al. 1992. The circles represent the transmittance of SO $_2$  frost grown on H $_2$ O ice (Sack et al. 1992, Noll et al. 1995). All spectra have been normalized to unity at 0.285 $\mu$ m to facilitate the data comparisons.

hemisphere (most easily detected around 60° longitude) match the visible light curve darkening seen by Nelson and Hapke (1978) in that longitude region. But SO<sub>2</sub>, as a frost in bulk, is bright in the visible down to 0.32 μm. The brown, red, and black forms of S<sub>x</sub> are dark in the visible. Given that the SO<sub>2</sub> signature we detected is not that of a bulk frost, we believe that the principal species responsible for the observations are either the in situ products formed from high velocity S or S<sub>x</sub> flowing outward from the Io torus as high-speed neutral electron-recombination products formed near 6R<sub>J</sub> and colliding with Callisto's water ice surface (Smyth 1992), or formed and excavated by modest to large size meteor impacts on Callisto's surface. Depending upon an ion's magnetospheric radial location at the time of neutralization, outward velocities could range from 50 to 150+km/s (Cheng 1986, Bagenal et al. 1992), producing a low density, high speed 'neutral wind' outflowing from the torus, resembling a radial arm garden sprinkler. The direction of this 'wind' when vectorially combined with Callisto's ~8km/s orbital velocity, produces an impingement zone that is biased towards the Jupiter-facing hemisphere. As has been postulated to occur at Europa, the high speed S<sub>x</sub> impacts disrupt the surface water ice lattice, and when the incoming neutral has lost its translational energy, the S or S<sub>x</sub> sits in a disturbed lattice. Atomic S can form weak bonds with the nearby O atoms, whereas S<sub>x</sub> would have a far lesser interaction (electron covalency shells filled), and thereby keep its own spectral signature (mostly visible absorption in the blue-green wavelength region with no UV features). The spatial co-existence of these material would explain both the near-UV signature and Callisto's visible albedo behavior in the 310° to 90° longitude region.

S<sub>x</sub> is stable (not reactive) in water ice at 120K. If a meteor impact were to occur shock heating of the Callisto's outer surface would probably produce temperature impulses of >1sec well in excess of 500K leading to reactions of S<sub>x</sub> with hot volatilized water. One product would be SO<sub>2</sub>. IUE's spatial resolution is insufficient to discern individual craters, therefore the detection of impact produced SO<sub>2</sub> by IUE requires either a very large impact, such as Valhalla, or a number of very strong, localized impact-produced concentrations. UV measurements from the Galileo orbiter should resolve this enigma.

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