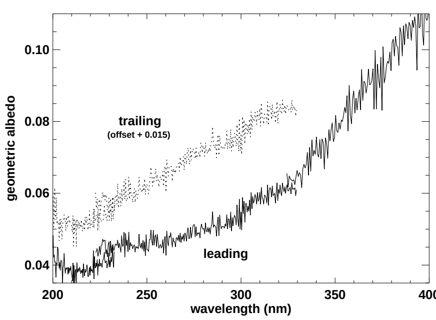
DETECTION OF SO_2 ON CALLISTO WITH THE HUBBLE SPACE TELESCOPE. K. S. Noll, *Space Telescope Science Institute, Baltimore, MD 21818, USA, noll@stsci.edu,* R. E. Johnson, *Engineering Physics, University of Virginia, Charlottesville, VA 22903, USA,* M. A. McGrath, *Space Telescope Science Institute, Baltimore, MD 21818, USA,* J. J. Caldwell, *York University, Dept. of Physics & Astronomy, North York, Ontario, M3J 1P3, Canada.*

We have detected SO_2 in ultraviolet spectra of Callisto obtained with the Hubble Space Telescope's Faint Object Spectrograph. An absorption band centered at 280 nm appears in the spectrum of Callisto's leading hemisphere, but is not apparent in the spectrum of the trailing hemisphere. The band is similar to the SO_2 band on Europa's trailing hemisphere. Callisto's leading hemisphere spectrum can be well fit with models that include SO_2 ice absorption with N(SO_2)$\geq 5 \times 10^{16}$ cm^{-2}. Callisto's leading hemisphere is modified by impacts with micrometeorites; this may directly or indirectly be a source of sulfur dioxide. This is the first identification of an ultraviolet absorber on Callisto.

Spectra of the leading hemisphere were recorded on 27 August 1996 and spectra of the trailing hemisphere were obtained on 5 September 1996 and are shown in Fig. 1. Measured count rates were converted to flux following standard STScI pipeline calibration procedures. The solar flux we used to create the albedo spectrum was measured by the SOLSTICE experiment (Woods et al. 1993). We applied a phase correction using a phase coefficient of p = 0.029 mags/degree (Nelson et al. 1987). The spectral resolution of the FOS for is 0.44, 0.63, and 0.92 nm for the three gratings we used.

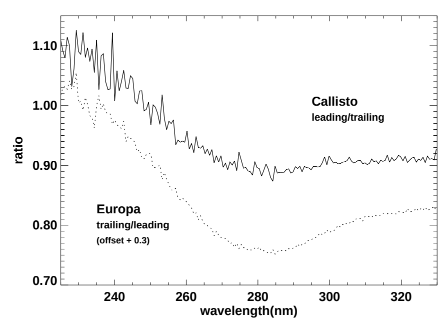


Observations of extended targets with the FOS show systematic differences in flux near the edge of the detector array where adjacent gratings overlap. The differences we observe are on the order of 10% or less. In the interval where they overlap, the FOS spectrum is 7% lower than a ground-based albedo spectrum of Callisto's leading hemisphere (Spencer et al. 1995). The gross shape of the albedo spectrum we measured is matched by broad band measurements of the albedo at 259, 307.5, 336, and 430 nm by the orbital astronomical observatory (OAO-2, Caldwell 1975). The OAO-2 albedos are lower than ours by approximately 20% .

Comparison with published IUE data is problematic because of inconsistencies in published broad band averages (Nelson et al. 1987). The ratio of the leading to trailing hemisphere albedo found by IUE is $\approx$ 0.6-0.8 in disagreement with the ratio of $\approx$ 0.90-0.95 that we find at comparable wavelengths. The ratio of leading to trailing hemisphere albedo for Callisto at visible and near-infrared wavelengths is also in the range 0.90-0.95 (Calvin et al. 1995).

Nelson et al. (1987) found no evidence for spectral features in ratios of coadded leading to trailing hemisphere spectra of Callisto. Given the relatively low S/N of the IUE spectra, this observation is consistent with our results. Lane et al. (1994) examined reprocessed IUE spectra of Callisto and claimed to identify several spectral features between 250 and 320 nm and a broad absorption feature on the *trailing* hemisphere from 240-330 nm. These results are not supported by the HST spectra in Fig. 1 that clearly show an absorption band on the *leading* hemisphere and little evidence for narrower features between 250 and 320 nm.

A ratio of the Callisto leading to trailing hemisphere spectra (Fig. 2) is strikingly similar to the ratio of Europa's trailing to leading hemisphere. SO_2 is thought to be responsible for the 280 nm band on Europa's trailing hemisphere. To identify the 280 nm absorber in Callisto, we assumed the Callisto spectrum can be described as a combination of a spectrally neutral component, a spectral component that has a constant slope from $\sim$ 220-320 nm, and a spectral absorber near 280 nm. We calculated and divided out a linear slope between 227.5 nm and 322.5 (Fig. 3). The modified trailing hemisphere spectrum was multiplied by the transmittance of SO_2 ice (Sack et al. 1992) for N(SO_2)$\approx 5 \times 10^{16}$ cm^{-2} producing an excellent fit to the modified leading hemisphere spectrum. The derived SO_2 column abundance is a lower limit because this method measures only the *additional* absorption on the leading hemisphere.



Several observed characteristics of Callisto's leading hemisphere may be related to the presence of SO_2 there and may provide clues to its origin. Callisto's leading hemisphere is darker and redder at visible wavelengths (Morrison et al. 1974, Buratti 1991) despite the fact that it may contain a higher proportion of water ice (Roush et al. 1990). On Europa, where it is the trailing hemisphere that is darker and more red, elemental sulfur and sulfur compounds have been suggested (Spencer et al. 1995). SO_2 is present on Europa's trailing hemisphere

(Lane et al. 1981, Noll et al. 1995) so it may not be coincidental that we find SO_2 on Callisto's darker, redder leading hemisphere.

At Europa, the source of sulfur and SO_2 is closely connected to the enhanced bombardment of the trailing hemisphere by the sulfur-rich plasma co-rotating with Jupiter's magnetic field. At Callisto, the plasma density is lower by a factor of 80 compared to Europa (Johnson 1990) and the fraction of sulfur relative to helium in the plasma is reduced by a factor of 10 or more (Hamilton et al. 1981) making the plasma a less likely source of sulfur at Callisto. In addition to the low density of sulfur, the question of how co-rotating plasma could result in enhanced sulfur on the *leading* hemisphere of Callisto is an additional strike against this source.

Noll et al. (1995) suggested pre-existing, endogenic sulfur in Europa as an alternative source for the observed SO_2 and reddening. In this scenario the additional plasma flux on the trailing hemisphere produces the observed hemispheric dichotomy by acting primarily as an energy source that enriches sulfur in the surface ice through the selective sputtering and loss of H_2O. For this mechanism to operate at Callisto, a source of energy on the leading hemisphere is required, eliminating co-rotating ions as a possibility. Micrometeorite impacts, on the other hand, could provide this source of energy as described below.

Callisto's leading hemisphere is marked by several microphysical distinctions. It is less compacted and has smaller grained particles than the trailing hemisphere (Buratti 1991, Calvin and Clark 1993). Bell et al. (1984) and Buratti (1991) have suggested that an enhanced impact flux from a population of small particles released from Jupiter's outer four retrograde satellites could explain the smaller grain size, polarization, and photometric anomalies observed on the leading hemisphere.

Micrometeorites could be a direct source of sulfur or could enhance pre-existing sulfur in the surface layers through volatilization of H_2O and enhanced gardening (though this is difficult to reconcile with the suggestion of more H_2O on the leading hemisphere). It is possible that micrometeoritic sulfur is preferentially deposited on Callisto's leading hemisphere while magnetospheric sulfur is swept up by Europa's trailing hemisphere. However, we note that the most economical hypothesis is that sulfur is indigenous to the ice of Europa and Callisto with enrichment occurring via two qualitatively different, but functionally similar energy sources. However, the apparent absence of SO_2 on Ganymede (Noll et al. 1996) remains as a challenge to this hypothesis.

Analysis of these observations was supported by grant GO-6817 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy under NASA contract NAS5-26555.

Bell, J. F., D. P. Cruikshank, and M. J. Gaffey, Icarus *61*, 192-207, 1985.

Buratti, B. J., Icarus *92*, 312-323, 1991.

Caldwell, J., Icarus *25*, 384-396, 1975.

Calvin, W. M. and R. N. Clark, Icarus *104*, 69-78, 1993.

Calvin, W. M., R. N. Clark, R. H. Brown, and J. R. Spencer, JGR *100*, 19,041-19,048, 1995.

Hamilton, D. C., G. Gloeckler, S. M. Krimigis, and L. J. Lanzerotti, JGR *86*, 8301-8318, 1981.

Johnson, R. E. *Enegetic Charged Particle Interactions with Atmospheres and Surfaces* 230 pp., Springer-Verlag, New York, NY 1990).

Lane, A. L., R. M. Nelson, D. L. Matson, Nature *292*, 38-39 1981.

Lane, A. L., D. L. Domingue, S. K. Price, and M. Lankton, (Abstract) Bull. Amer. Astron. Soc. *26*, 1159, 1994.

Morrison, D., N. D. Morrison, and A. R. Lazarewicz, Icarus *23*, 399-416, 1974.

Nelson, R. M., A. L. Lane D. L. Matson, G. J. Veeder, B. J. Buratti, and E. F. Tedesco, Icarus *72*, 358-380, 1987.

Noll, K. S., H. A. Weaver, A. M. Gonnella, JGR *100*, 19,057-19,059 1995.

Noll, K. S., R. E. Johnson, A. L. Lane, D. L. Domingue, and H. A. Weaver, Science *273*, 341-343, 1996.

Roush, T. L., J. B. Pollack, F. C. Witteborn, and J. D. Bregman, Icarus *86*, 355-382, 1990.

Sack, N. J., R. E. Johnson, J. Q. Boring, R. A. Baragiola, Icarus *100*, 534-540 1992.

Spencer, J. R., W. M. Calvin, and M. J. Person, JGR *100*, 19,049-19,056, 1995.

Woods, T. N., G. J. Rottman, and G. J. Ucker, JGR *98*, 10679-10694, 1993.