The Nature of Europa's Dark Non-Ice Surface Material: Spatially-Resolved High Spectral Resolution Spectroscopy from the Keck Telescope^{*}

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^{*} The data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation.

Submitted to Icarus, June 17th 2005

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Abstract

We present new $1.45 - 1.75 \,\mu\text{m}$ spectra of Europa's dark non-ice material with a spectral resolution $(\lambda/\delta\lambda)$ of 1200, obtained by using adaptive optics on the Keck telescope to spatially separate the spectrum of the non-ice material from that of the surrounding icerich regions. Despite the great increase in spectral resolution over the previous best spectra of the non-ice material, taken with Galileo's near-infrared mapping spectrometer (NIMS) with $\lambda/\delta\lambda = 66$, no new fine-scale spectral structure is revealed. The smoothness of the spectra is inconsistent with available laboratory spectra of crystalline hydrated salts at Europa temperatures, but is more consistent with various combinations of non-crystalline hydrated salts and/or hydrated sulfuric acid, as have been matched to the lower-resolution NIMS spectra.

Keywords:

Satellites of Jupiter; Europa; Surfaces, satellite; Spectroscopy

Introduction: Europa's Dark, Non-Ice Surface Component

Europa is the highest-density and most active icy body in the solar system (Greeley et al. 2004). It is particularly intriguing because of the possibility, based on both geological evidence (Pappalardo et al. 1999, Hoppa et al. 2000) and magnetic evidence (Kivelson et al. 2000, Zimmer et al. 2000) that it harbors an ocean beneath its surface. However, as yet we know little about the properties and chemistry of this ocean, if it exists.

One possible clue to the ocean chemistry comes from the dark reddish material that covers much of Europa's surface and co-exists with the almost pure ice that occupies the rest of Europa. The dark material is strongly concentrated in regions of recent surface disruption (Geissler et al. 1998, McCord et al. 1998, Fanale et al. 1999), particularly the "chaos" regions where the crust has been broken into iceberg-like plates, and the "lineae"- the long ridges that crisscross Europa's surface, though there are a few exceptions where bright lineae cut dark background material (Carlson et al. 2005). Association of the dark material with surface disruption strongly suggests that the dark material is derived from the subsurface, perhaps from the underlying ocean, and may thus provide clues to the ocean's composition.

However, exogenic processes are also important in controlling the distribution of the dark material. Dark material associated with resurfacing is darker and redder at visible wavelengths on Europa's trailing hemisphere, centered at 0 N, 270 W, where magnetospheric bombardment is maximized and micrometeorite bombardment is minimized, and is also more prominent at low latitudes (McEwen et al. 1986). Perhaps charged-particle sputtering alters or exposes the endogenic dark material on the trailing side (McEwen et al. 1986, Hendrix et al. 1998, Fanale et al. 1999) though it is also possible that the dark material is itself exogenic in origin (Carlson et al. 1999, 2005), and is concentrated in areas of resurfacing by thermal sublimation due to endogenic heat (Fagents et al. 2000).

Galileo Constraints on the Composition of the Dark Material

The Galileo Jupiter orbiter carried a Near-Infrared Mapping Spectrometer (NIMS), operating in the $0.7 - 5.2 \,\mu\text{m}$ range with a spectral resolution $\delta\lambda$ of $0.0243 \,\mu\text{m}$, or $R = \lambda/\delta\lambda$ of 66 at 1.6 μm , and spatial resolution varying from >100 km to 5 km, depending on range (Carlson et al. 1992). NIMS Europa observations have revealed that the dark material on the surface has a very distinctive spectrum. The 1.5 and 2.0 μm H₂O absorption bands, which are seen everywhere on Europa, are highly asymmetric in the dark regions, suggesting that the water there is not in the form of ice (McCord et al. 1998, 1999).

Two main explanations of the asymmetric water bands have been proposed. McCord et al. (1998, 1999) suggest hydrated salts as likely candidates- their best match was obtained with highly-hydrated sodium and magnesium salts such as epsomite (MgSO₄·7H₂O) and natron (Na₂CO₃ · 10H₂O). Most candidate salt species in crystalline form at low temperatures show fine spectral structure in the $1.5 - 1.8 \mu m$ region that is not seen in the NIMS spectra, though NIMS spectral resolution is barely adequate to resolve this structure (McCord et al. 2001, Dalton 2003). The amplitude of the fine structure is

reduced at higher hydration states, and in flash-frozen brine spectra (McCord et al. 2002), providing a better match to the NIMS spectra.

An alternative explanation is that the asymmetric water bands are due to hydrated sulfuric acid (e.g., $H_2SO_4 \cdot 8H_2O$), which could form as part of a radiolytic cycle also involving endogenic or exogenic sulfur or SO₂, both of which are probably present on Europa's surface (Carlson et al. 1999, 2002). In this case, the sulfur could be the coloring agent producing the visible-wavelength reddish color of the non-ice component (Spencer et al. 1995).

The truth may lie somewhere in between these extremes: flash-frozen combinations of hydrated $MgSO_4$, Na_2SO_4 , and H_2SO_4 provide a close spectral match to the NIMS spectra of the non-ice material (Orlando et al. 2005).

Combining High Spectral and Spatial Resolution

While the possible non-ice components on Europa's surface are not easily distinguishable at NIMS spectral resolution, higher spectral resolution offers the chance to distinguish some of the candidates, in particular the crystalline salts which show fine structure barely resolvable by NIMS. While high-quality groundbased R=700 spectra of Europa have been published (e.g. Grundy et al. 1999), these are disk-integrated and thus cannot cleanly separate the ice and non-ice components on Europa, neither of which occupies a full hemisphere. To obtain a diagnostic spectrum of the non-ice material, we need both spatial resolution of Europa's disk and substantially higher spectral resolution than NIMS. On Europa's trailing hemisphere the ice-rich and darker non-ice-rich regions are spatially segregated on 500-km scales. From the Earth's distance of 4.2 AU at opposition, 500 km subtends 0.16 arcsec, easily resolved by AO systems on modern telescopes. We therefore used the Keck AO system with the NIRSPEC IR camera/spectrometer to obtain spectra of Europa's dark regions at high spatial and spectral resolution

Observations

We observed Europa with the AO system on the Keck 2 telescope (Wizinowich et al. 2000) in conjunction with the Keck Near Infrared Spectrometer, NIRSPEC (McLean et al. 1998) in December 2001. NIRSPEC is an all-reflective, high-resolution near-IR spectrograph with an 1024^2 InSb array, operating from 0.95 to 5.4µm. We used the low resolution grating and the "NIRSPEC-5" order-sorting filter, providing coverage of the wavelength range $1.45 - 1.75\mu$ m, the probable location of the most diagnostic non-ice absorption features, in a single integration with a spectral resolution of 2000. With the AO system, the slit dimensions were $0.036'' \times 3.93''$. The spatial scale on the spectroscopic array was 14 mas/pixel, and dispersion was $2.75 \times 10^{-4} \mu$ m/pixel. NIRSPEC also includes a guide camera (SCAM) which provides images of the slit and the surrounding sky, with a scale of 0.017''/pixel, as a check on pointing and image quality, using the same filter as the spectroscopic mode.

Though we obtained image cubes of Europa on both the 8th and 9th of December UT, only the results from December 9th, which covered the trailing hemisphere where the dark non-ice material is concentrated, are discussed here (Table 1). Range to Europa on

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2001/12/09 Observations of Europa and Io							
Target	UT Time	Airmass	Spatial Offset	# Spectra	Slit Orient- ation	Central Longitude	Radial Velocity,* km/sec
Europa	09:27 - 10:55	1.25 – 1.05	0.055"	20	E/W	230 - 237	+10.4 - +12.4
Io	11:37	1.01	_	2	E/W	337	+1.5
Europa	13:46 - 14:40	1.09 – 1.23	0.073"	15	N/S	249 - 253	+15.2 - +16.0
*Sum of heliocentric and geocentric velocities							

Table 1

December 9th was 4.26 AU, and solar phase angle was 4.8°. Conditions were generally photometric but thin cirrus was present occasionally.

We also obtained spectra of Io, which has an almost featureless spectrum in this wavelength range, as a local extinction and solar-type standard, as well as solar-type star BS 2569 (G0V, V=5.76). We also imaged the star HD 262645 (F0, V=9.48) as a point-spread function (PSF) reference due to its proximity to Jupiter.

Typical spectroscopic integration times on Europa were 100 - 200 seconds. All targets were bright and small enough that AO lock could be achieved on them, though some star spectra were taken without AO in order to produce an image that would fill the slit in a way comparable to the ~ 1 arcsec AO images of Io and Europa. AO performance gave near diffraction-limited point-spread function (PSF) cores, with typical FWHM on the comparison stars of 0.05", but broad wings so that typical Strehl ratios were about 0.1 (Fig. 1). We used



Figure 1 PSF of the comparison star HD 262645 with adaptive optics engaged (green), compared to a theoretical diffractionlimited 1.6 μ m PSF for a 10-meter telescope (black), both scaled to the same peak intensity. The AO PSF consists of an essentially diffraction-limited core and broad wings. The broad wings resulted in contamination of our spectra of any given point on Europa's surface with light from adjacent parts of the disk. The orange line shows the estimated PSF for the Europa AO spectra modified from the star PSF to match the off-limb flux in

a macro to step the spectrograph slit across Europa's disk, using step sizes ranging from $0.05^{\prime\prime}$ to $0.1^{\prime\prime}$, with periodic interspersed sky integrations, to build up an image cube. 2 full image cubes of Europa were obtained on December 9th, with the slit oriented both parallel to and perpendicular to Europa's rotational axis. Flux levels for a few spectra in the first cube taken on December 9th, covering parts of Europa's southern hemisphere, were reduced by intermittent clouds.

We periodically obtained calibration spectra using internal calibration lamps, particularly after shifts in instrument settings. A continuum lamp and corresponding dark frame were obtained for flat fields, and Argon lamp spectra for wavelength calibration.



Figure 2 Images derived from our AO image cubes of Europa, compared to a Galileo NIMS observation of the same region. The red and green boxes show the locations of the representative high-latitude ice rich and low-latitude ice-poor regions from each image cube, whose spectra are compared in Fig. 5. The 1.65 μ m band depth image is generated by ratioing the mean 1.630 – 1.659 μ m reflectance to the mean 1.597 – 1.630 μ m and 1.6359 – 1.684 μ m reflectance. Noise in the Keck Cube 1 1.65 micron band depth image in the southern hemisphere results from cloud obscuration during acquisition of those parts of that image cube.

Data Reduction

Generation of Image Cubes

We used the spectroscopic reduction package "redspec", developed by S.S. Kim, L. Prato, and I. McLean, written in the IDL language for use with NIRSPEC data (www2.keck.hawaii.edu/inst/nirspec/redspec/), for sky subtraction, flat-fielding, spatial rectification, and wavelength calibration. We removed OH emission lines and any continuum background from each object spectrum by subtracting a sky spectrum obtained close in time and with the same exposure time. We divided the resulting difference spectrum by a flat field, obtained from the difference between a continuum lamp spectrum and an adjacent dark exposure, to correct for pixel-to-pixel sensitivity differences. Because NIRSPEC produces spectra with both spatial and spectral distortion, we then used "redspec" to rectify the spectra, using information from point source and argon lamp spectra to determine the necessary geometric corrections. The rectified spectra had a wavelength scale of 0.00028 μ m / pixel and spatial scale of 0.011 arcsec/pixel. The brightness of Io and Europa required short enough exposures that OH airglow lines in the satellite spectra were too faint to be useful for wavelength calibration.

We then assembled the long-slit spectra from each scan into image cubes. In image cube 1, several spectra had lower flux levels due to obscuration by cirrus, and we multiplied these spectra by a constant value to match the brightness of neighboring spectra. We used bicubic interpolation in the spatial direction perpendicular to the slit to produce cubes with the same spatial scale in both dimensions, and determined the latitude and longitude of each spatial point by a visual fit to the limb (Fig. 2).

Conversion to Reflectance: Io's Spectrum

We divided the Europa spectra by spectra of Io to eliminate solar Fraunhofer lines and telluric features. However, because the wavelengths of solar Fraunhofer lines differed by up to 0.27 pixels between the two satellites, due to their differing heliocentric and geocentric radial velocities, while telluric features had no relative Doppler shift, it was not possible to perfectly eliminate telluric and Fraunhofer features simultaneously. We therefore applied a first-order correction for extinction to the Io and Europa spectra separately, by dividing by the ratio of a standard star taken at two different airmasses, before shift and then dividing Europa by Io to remove the Fraunhofer features along with residual telluric features. The removal of telluric features by this technique is not perfect, and results in some spectral artifacts shortward of 1.5 μ m.

To convert the Europa/Io ratios into Europa albedo spectra requires knowledge of Io's reflectance spectrum in this wavelength range. Fig 3 shows the average of a limb-to-limb long-slit spectrum of Io taken along the equator, at central longitude 337 W, ratioed to two different spectrum of the solar-type star BS 2569. The ratios are featureless to a precision of a few percent, and the numerous shallower features can probably be attributed to imperfect cancellation of telluric and Fraunhofer lines, as seen by the fact that these features are also seen in the unratioed star spectrum. No narrow spectral



Figure 3 Spectrum of Io's equatorial region, averaged along the slit, ratioed to our solar-type comparison star, BS 2569, after each spectrum has been corrected for telluric extinction as described in the text, and the stellar spectrum has been shifted by 0.00017 μ m to provide the best cancellation of Fraunhofer lines. Remaining "noise" in the spectrum probably results primarily from differences between the Fraunhofer lines in BS 2569 and the Sun, and (below 1.50 μ m) imperfect cancellation of residual telluric features, as can be seen by comparison to the unratioed BS 2569 spectrum. A Galileo NIMS spectrum of Io's anti-Jupiter hemisphere (Carlson et al. 1997) is shown for comparison.

features have been reported on Io in this spectral range: the shortest-wavelength SO_2 frost bands appear at 2.13 and 1.98 µm (Schmitt et al. 1994).

Fig. 3 shows that the Io spectra differ by a few percent in overall slope across the bandpass, depending on which spectrum of BS 2569 was used in the ratio. Ratios of different Io spectra to each other also show linear slopes of a few percent across the bandpass. The much lower spectral resolution Galileo NIMS albedo spectrum of the opposite hemisphere of Io has a slight red slope, amounting to an increase in reflectance of 4% over the Keck bandpass, which is different from either of the Io/BS 2569 ratios.

We have therefore generated scaled Europa reflectance spectra by dividing our Io/Europa ratios by a linear spectrum with a 4% red slope across the bandpass, to correct for the slight red slope seen in the NIMS Io spectra. However the few percent variation in slope of our Io/star ratios, and ratios between different Io spectra, suggests that the overall slopes of the Keck spectra across the bandpass are unreliable to within a few percent, something that should be kept in mind when interpreting the derived Europa spectra.

No correction to absolute reflectance is possible, due to unknown and variable slit losses, so all spectra show relative reflectance only unless scaled to other spectra with known absolute calibration.

Spatial Purity of AO Spectra

As discussed above, the Keck AO delivers a PSF that has a diffraction-limited core, but also includes significant power in a broader region of size comparable to the uncorrected seeing disk. The spectrum of a small region of an extended object will thus be contaminated by light from the PSF wings of all surrounding regions- a significant concern when, as in this study, we wish to isolate the spectrum of one geologic unit on Europa's disk. We have not attempted spatial deconvolution of the image cubes to correct for this contamination, because of variations in the PSF during the acquisition of the spectra, but have simply characterized the degree of contamination. We define the spatial purity of a spectrum extracted from a region of the image cube as the fraction of the flux within that region, after convolution by the observed PSF, that originates within that region.

Determination of spatial purity is complicated by the fact that while the PSF for a point source is readily determined from stellar images, the AO system may respond differently to extended sources such as Europa, so that the PSF determined from a star image may differ from the PSF in the spectra comprising a Europa image cube. To compare a typical star PSF to the Europa PSF, we convolved a uniform model disk with the image



Figure 4 The effect of the AO PSF on the spatial content of the Europa spectra. 4A shows (black solid lines), the diametric profile across a featureless Europa-sized model disk, before and after 2-D convolution with the assumed PSF for the Europa spectra (Fig. 1). The orange line shows the along-slit spatial profile of one of the observed Europa spectra, with the slit along the equator: the good match to the convolved model shows that our assumed PSF is realistic. 4B1- 4B3 show the spatial distribution of light from a variable-sized square box centered on the model disk (orange) and from regions outside that box (green), before and after convolution with the assumed PSF. 4C shows the spatial purity, as defined in the text, as a function of box size.

of the star HD 262645 taken with the SCAM guide camera, and compared the observed profile across Europa's disk. We found that raising the stellar PSF to the power 0.9, which slightly enhances the PSF wings relative to the core, provided an excellent match to the along-slit profile of most of the Europa spectra (Fig. 1, Fig 4A). We determined the spatial purity of various-sized subsets of the Europa image cubes by constructing a Europa-sized model disk, setting a variable-sized square box centered in the disk to zero, convolving the disk by the modified PSF, and determining how much light was scattered into the central box from surrounding areas by the convolution. We similarly set the part of the disk outside of the box to zero before the convolution, to determine the amount of light within the box which remained in the box after convolution (Figs. 4B). Spatial purity is plotted as a function of box size in Fig. 4C. It is clear that spectra of small areas are heavily contaminated by light from surrounding regions.

Results

Fig. 2 shows images derived from our two Keck image cubes of Europa's trailing hemisphere, compared to comparable images from a Galileo NIMS cube of the same part of Europa, G1ENNHILAT01, which was obtained on Galileo's first orbit of Europa with a sub-spacecraft point location of 219 W, 23 N and phase angle of 31 degrees. There is a qualitative agreement in the appearance of the Keck and NIMS reflectance and banddepth images, though the NIMS image has much higher spatial resolution. The non-ice regions can be identified by their low visible albedo, high 1.5 µm albedo (because of their relatively shallow 1.5 µm water band), and weak 1.65 µm band depth, because the feature is not present in the non-ice material). To represent the ice-rich and non-ice components, we chose two regions that were well seen in both NIMS and Keck data sets: an ice-rich region in the northern hemisphere (200 - 230 W, 30 - 60 N), shown in red, and an nonice-rich equatorial region of dark chaotic terrain (245 - 260 W, 15 S - 15 N), shown in green. The angular size of these regions in the Keck images is about 0.2 arcsec, so their spatial purity is only 25 - 30% (Fig 4C). However because each of these regions is surrounded by terrain of similar composition, contamination of the non-ice spectrum with light from icy regions, and vice versa, is less severe than the spatial purity would suggest.

Fig 5 shows spectra of these two regions extracted from each of the Keck cubes, compared to corresponding spectra from the NIMS cubes. The spectra obtained directly form the Keck image cubes (upper panels), do not match the NIMS spectra of the same areas very closely. The non-ice-rich spectrum shows a distinct 1.65 μ m H₂O ice feature that is absent or much weaker in the NIMS spectrum, and the slope of the Keck ice-rich spectrum is much less red than the NIMS version.

Spatial Decontamination

The Keck/NIMS spectrum discrepancies can be attributed to the lack of spatial purity of the Keck spectra, discussed above. For instance, the non-ice-rich spectrum contains a strong 1.65 μ m band due to light scattered into that region from the surrounding ice-rich regions, where that band is strong. We corrected for these effects by assuming that Europa's surface consists of an areal mixture of just two surface components, ice and non-ice, which are present in differing amounts in the spectra of the two regions. The ice-rich spectrum can then be used as a model for the light that is being scattered into the



Figure 5 Spectra of representative ice-rich and non-ice-rich regions on Europa, from Fig. 2, compared to Galileo NIMS spectra of the same regions. The NIMS spectra are scaled to approximate geometric albedo by reference to other calibrated Europa spectra (Spencer et al. 2004), and the Keck spectra are scaled to match the NIMS spectra, with small variations in scaling to separate the lines. Keck spectra are smoothed to a spectral resolution R of 1200 to reduce noise. The upper panels show the spectra extracted directly from the image cubes, while the Keck spectra in the lower panels have been corrected for spatial contamination as described in the text, and are approximations to pure spectra of each surface component. The smooth continuous lines show the corrected Keck spectra after smoothing to NIMS resolution.

non-ice-rich region, and vice versa. We then corrected for the spatial impurity of the non-ice-rich spectrum by subtracting a fraction of the ice-rich spectrum from the non-ice-rich spectrum, adjusting the subtracted fraction until the shape of the difference spectrum, after rescaling and convolving with the NIMS line spread function (taken to be triangular with a FWHM of 0.0243 μ m, Carlson et al. 1992) was as close as possible to the shape of the NIMS spectrum of the same area. We applied the corresponding correction to the ice-rich spectrum. The subtracted fractions needed to match the NIMS spectra indicated that about 65% of the light from the non-ice-rich region of the Keck image cube originated from that region or from neighboring regions with similar non-ice-rich spectra, and similarly about 65% of the light from the ice-rich region originated from surfaces with ice-rich spectra. These percentages are higher than the expected 25 – 30% spatial



Figure 6 Comparison of the two Keck spectra of the non-ice-rich region, after spatial decontamination (Fig. 5), with the NIMS spectrum of the same region, and several candidate surface materials at Europa temperatures. Salt and flash-frozen brine matches are shown in the top panel, acid and flash frozen acid/brine matches in the bottom panel. The Keck spectra have been smoothed to a spectral resolution R of 640.

purity discussed above, because each of our chosen regions was surrounded by terrain with similar spectra.

Results are shown in the lower panels of Fig. 5. We obtained excellent matches to the shapes of the NIMS spectra, but at far higher spectral resolution: R = 1200 (after smoothing to reduce noise and residual artifacts) compared to R = 66 for NIMS.

Discussion

Fig. 6 compares the two decontaminated spectra of the non-ice-rich region to the NIMS spectrum of the same region, and some low-temperature laboratory spectra of candidate surface materials. The Keck spectra are very smooth even at this high spectral resolution, and the only discrete features that reproduce between the two spectra are the convex-upwards curvature between 1.5 and 1.75 μ m, the turnup at the shortest wavelengths, and the residual 1.65 μ m band which may result from a small areal coverage of H₂O ice within the "non-ice-rich" region. Other very subtle undulations do not reproduce between the two independent Keck spectra and are probably not real.

None of the candidate materials shown here provide a perfect match to the Keck spectra, though some come close. The differences in absolute reflectance seen in Fig. 6 are of relatively minor concern, as the laboratory spectra are not calibrated in terms of geometric albedo, unlike the Europa spectra, and minor contaminants can easily change absolute reflectance levels, so we are mostly concerned with the shapes of the spectra. The MgSO₄, $6H_2O$ and MgSO₄, $7H_2O$ spectra, like other crystalline salts with similar or lower hydration, show fine spectral structure that is not seen in Europa's non-ice component, and can be rejected as candidates in their unaltered form (McCord et al. 2001). The flash-frozen brine (McCord et al. 2002), which is more H_2O -rich, shows much less fine structure and is more consistent with the Europa spectra, though it shows a stronger 1.65 µm band than is seen in Europa's non-ice material. The crystalline $H_2SO_4.8H_2O$ spectrum, like the Europa spectrum, shows no significant fine structure and thus matches the Keck spectrum better than the crystalline salts. Combination with a small amount of water ice improves the fit further (Carlson et al. 2005). However, the reflectance increase below about 1.5 µm begins at longer wavelengths in the crystalline H₂SO₄ spectra than the Europa spectra. This mismatch could be due to crystal lattice disorder resulting from radiation damage to the acid on Europa, producing a liquid-like spectrum: the spectrum of liquid H_2SO_4 also turns up at shorter wavelengths than the crystalline phase (Carlson et al. 1999, 2005). Flash-frozen combinations of MgSO₄, Na₂SO₄, H₂SO₄, and H₂O provide a good match to both the NIMS spectrum and the higher-resolution Keck spectra (Orlando et al. 2005).

In summary, while the chemical nature of Europa's dark, non-ice material has not yet been definitively established, these new high-resolution spectra of this material, and in particular the result that there is no fine spectral structure in the $1.5 - 1.75 \mu m$ region, provide an important new constraint on the chemistry of Europa's surface and perhaps that of the underlying ocean. Unfortunately, the lack of fine spectral structure in the non-ice component spectrum, at least over the several 100 km sized regions resolvable by adaptive optics, reduces the prospects for definitive identification of this material by high spatial and spectral resolution observations from future space missions (Dalton 2003). However, it is certainly possible that higher spatial resolution will reveal local concentrations of crystalline species with distinctive and identifiable spectra.

Acknowledgements

We thank Bob Goodrich, Jim Lyke, and the Keck telescope operators for assistance with planning and execution of the observing program, and interpretation of the results. We

also thank Roger Clark for useful discussions. This work was funded by NASA grant NAG5-13350. These data were obtained at the W.M. Keck Observatory from telescope time allocated to the National Aeronautics and Space Administration through the agency's scientific partnership with the California Institute of Technology and the University of California. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

References

- Carlson, R.W., P.R. Weissman, W.D. Smythe, J.C. Mahoney, and the NIMS science and engineering team 1992. Near-infrared mapping spectrometer experiment on Galileo. Space Sci. Rev. 60, 457-502.
- Carlson, R. W., and 10 colleagues 1997. Distribution of sulfur dioxide and other infrared absorbers on the surface of Io. Geophysical Research Letters 24, 2479.
- Carlson, R.W., R.E. Johnson, and M.S. Anderson 1999. Sulfuric acid on Europa and the radiolytic sulfur cycle. Science 286, 97-99.
- Carlson, R. W., Anderson, M. S., Johnson, R. E., Schulman, M. B., Yavrouian, A. H. 2002. Sulfuric Acid Production on Europa: The Radiolysis of Sulfur in Water Ice. Icarus 157, 456-463.
- Carlson, R.W., M.S. Anderson, R. Mehlman, and R.E. Johnson 2005. Distribution of hydrate on Europa: Further evidence for sulfuric acid hydrate. Icarus, in press.
- Dalton, J. B., 2003. Spectral behavior of hydrated sulfate salts: Implications for Europa mission spectrometer design. Astrobiology 3, 771 784.
- Fagents, S. A., Greeley, R., Sullivan, R. J., Pappalardo, R. T., Prockter, L. M., The Galileo SSI Team, 2000. Cryomagmatic Mechanisms for the Formation of Rhadamanthys Linea, Triple Band Margins, and Other Low-Albedo Features on Europa. Icarus 144, 54-88.
- Fanale, F. P., and 23 colleagues 1999. Galileo's Multiinstrument Spectral View of Europa's Surface Composition. Icarus 139, 179-188.
- Geissler, P. E., and 16 colleagues 1998. Evolution of Lineaments on Europa: Clues from Galileo Multispectral Imaging Observations. Icarus 135, 107-126.
- Greeley, R., Chyba, C. F., Head, J. W., McCord, T. B., McKinnon, W. B., Pappalardo, R. T., Figueredo, P. H. 2004. Geology of Europa. Jupiter. The Planet, Satellites and Magnetosphere 329-362.
- Grundy, W.M., M.W. Buie, J.A. Stansberry, and J.R. Spencer 1999. Near-infrared spectra of icy outer solar system surfaces: Remote determination of H₂O ice temperatures. Icarus 142, 536-549.
- Hendrix, A. R., Barth, C. A., Hord, C. W., Lane, A. L. 1998. Europa: Disk-Resolved Ultraviolet Measurements Using the Galileo Ultraviolet Spectrometer. Icarus 135, 79-94.
- Hoppa, G., B.R. Tufts, R. Greenberg, and P. Geissler 1999. Formation of cycloid ridges on Europa. Science 285, 1899-1902.
- Kivelson, M. G., Khurana, K. K., Russell, C. T., Volwerk, M., Walker, R. J., Zimmer, C. 2000. Galileo Magnetometer Measurements: A Stronger Case for a Subsurface Ocean at Europa. Science 289, 1340-1343.

- McCord, T. B., and 11 colleagues 1998. Salts on Europa's Surface Detected by Galileo's Near Infrared Mapping Spectrometer. Science 280, 1242.
- McCord, T.B. et al. 1999. Hydrated salt minerals on Europa's surface from the Galileo Near-Infrared Mapping Spectrometer (NIMS) investigation. J. Geophys. Res. 104, 11827.
- McCord, T. B., Teeter, G., Hansen, G. B., Sieger, M. T., Orlando, T. M. 2002. Brines exposed to Europa surface conditions. Journal of Geophysical Research (Planets) 4-1.
- McEwen, A. S. 1986. Exogenic and endogenic albedo and color patterns on Europa. Journal of Geophysical Research 91, 8077-8097.
- McLean, I. S., and 14 colleagues 1998. Design and development of NIRSPEC: a nearinfrared echelle spectrograph for the Keck II telescope. Proc. SPIE Vol. 3354, p. 566-578, Infrared Astronomical Instrumentation, Albert M. Fowler; Ed. 3354, 566-578.
- Orlando, T.M., T.B. McCord, and G.A. Grieves 2005. The chemical nature of Europa surface material and the relation to a sub-surface ocean. Icarus, submitted.
- Pappalardo, R. et al. 1999. Does Europa have a subsurface ocean? Evaluation of the geological evidence. J. Geophys. Res. 104, 24015-24056.
- Schmitt, B., de Bergh, C., Lellouch, E., Maillard, J., Barbe, A., Doute, S. 1994. Identification of three absorption bands in the 2-um spectrum of Io. Icarus 111, 79-105.
- Spencer, J.R., W.M. Calvin, and M.J. Person 1995. CCD spectra of the Galilean satellites: Molecular oxygen on Ganymede. J. Geophys. Res. 100, 19049-19056.
- Spencer, J. R., Carlson, R. W., Becker, T. L., Blue, J. S. 2004. Appendix 1: Maps and spectra of Jupiter and the Galilean satellites. Jupiter. The Planet, Satellites and Magnetosphere 689-698.
- Wizinowich, P. L., Acton, D. S., Lai, O., Gathright, J., Lupton, W., Stomski, P. J. 2000. Performance of the W.M. Keck Observatory Natural Guide Star Adaptive Optic Facility: the first year at the telescope. Proc. SPIE Vol. 4007, p. 2-13, Adaptive Optical Systems Technology, Peter L. Wizinowich; Ed. 4007, 2-13.
- Zimmer, C., K. Khurana, and M. Kivelson 2000. Subsurface Oceans on Europa and Callisto: Constraints from Galileo Magnetometer Observations. Icarus 147, 329-347.