Temperature and area constraints of the South Volund Volcano on Io from the NIMS and SS1 instruments during the Galileo G1 orbit.

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Abstract. Analysis of data from darkside and eclipse observations of Io by the NIMS and SS1 instruments show that the South Volund hot spot is a manifestation of high temperature active silicate volcanism. The NIMS data are fitted with a two temperature model (developed from modelling terrestrial lavas) which yields a better fit to the data than a single temperature fit, The multispectral color temperatures obtained from NIMS are compared with the brightness temperatures obtained from the SS1 instrument, and show excellent agreement for the hotter of the two components fitted to the NIMS data. The two components might correspond to a cooled crust which has formed on the surface of an active flow or lava lake, at a temperature of approximately 450 K, and covering an area of about 50 km^2, and a hotter and much smaller component, at a temperature of approximately 1100 K and an area of less than 0.1 km^2. The hot component implies the existence of cracks in the surface crust of a flow or lake through which the hot interior radiates, a hot vent area, or breakouts of lava forming new flow lobes. The ratio of these areas is consistent with the crack-to-crust rat io of some lava flows and lava lakes on Earth.

Introduction

Io is the most volcanically active body known in the solar system. Volcanic hot spots were discovered on Io by the Voyager spacecraft in 1979 [*Pearl and Sinton,* 1982] with temperatures approaching 650 K, the detection limit of the Voyager Infrared Imaging Spectrometer (IRIS). These temperatures failed to resolve the on-going question of which form of volcanism was dominant on 10, silicate volcanism (with temperature from 900 K to greater than 1900 K) or sulfur volcanism (390-600 K, perhaps up to 1000 K if sulfides are involved). Since Voyager, Earth-based observations have yielded color temperatures indicative of silicate volcanism (e. g., 1550 K in 1986; 1225 K in 1990, *Veeder et al.,* 1994). During the early Galileo epoch, in the latter half of 1996, high temperature events were observed with ground based instruments with temperatures in excess of 1400 K [*Stansbury et al.,* 1997], while Galileo was observ-

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ing active volcanism from Jupiter orbit. This has greatly strengthened the case for silicate volcanism on Io [*Carr,* 1986; *Blaney et al.,* 1995; *Davies, 1996].*

Voyager and Galileo at Io

In 1979 Voyager detected a plume -75 km high emanating from the Volund vent, located at lat 23 N, 177 W. During the Voyager encounters a hot spot was observed in this region by Voyager IRIS with a temperature tit of 585 K over an area of 21 km^2 *[J. C. Pearl and A. S. McEwen,* personal communication].

One of the major mission objectives of the Galileo spacecraft is to observe Io's volcanic processes. As a Voyager plume site, the Volund region was a natural choice for close scrutiny during the Galileo mission. The Galileo spacecraft entered orbit around Jupiter on 7 December 1995 and since June 1996 has been observing Io. In sunlit images of Io the Galileo Solid State Imaging (SSI) experiment revealed surface color and albedo changes in the Volund region since Voyager observed it 17 years earlier [*McEwen et al.,* 1997a]. Centered at 18 N, 173 W, this feature (referred to hereafter as South Volund) is a new low-albedo linear feature (possibly fissure-fed flows) about 150 km long surrounded by more diffuse deposits (probably plume fall-out pyroclastic material). It appears to be a new volcanic center distinct from the Voyager-era Volund volcanic region. SS1 also detected an active plume at least 30 km high over South Volund during orbit G1 [*McEwen et al.,* 1997b]. Of the Vohrnd plume seen by Voyager, there was no sign. The South Volund plume site is about 200 km from the Volund plume site. If both are served by a common magma source then it must be deep-seated.

South Volund in the dark

During Galileo's first (G 1) orbit of Jupiter the hemisphere of Io containing Volund was imaged, while it was in darkness, by both the Near Infrared Mapping Spectrometer (NIMS) and SS1. As described below, NIMS and SS1 identified South Volund as a thermal anomaly, part of which had a temperature in excess of 700 K [*McEwen et al.,* 1997c]. This was the only hot spot seen by both instruments in darkness during the G 1 encounter.

On June 291996, during the G 1 encounter, SS1 imaged 10 in eclipse, covering longitudes from 150 W to 330 W. The 2.13 second exposure through the clear filter (0.38 to 1.05 pm) revealed the presence of high-temperature hot spots (including one at South Volund) all of which corresponded to low albedo features on the surface of Io [*Belton et al.,* 1996). The image was taken at a range of 1,035,000 km, with a resolution of 10.5 km per pixel. The eclipse observation, however, had an effect ive resolution of about 50 km/pixel as the image was smeared clue to the long exposure. The operation of the SS1 instrument is described in Belton et al., [1992]. The derivation of the SS1 area-temperature relationship is discussed in McEwen *et al.,* [1997c]. To see a hot spot in eclipse requires a temperature of at least 700 K, if the hot spot fills an entire SS1 pixel.

Temperature is inversely proportional to area. The possible temperature/area combinations are shown in Figure 1, with the areas projected (corrected for oblique viewing) for comparison with the NIMS data.

Figure 1

On June 28 1996, ten hours before the SS1 observation, NIMS obtained one 408 wavelength observation of Io, ranging bet ween 0.7 and 5.2 μm. This observation encompassed all latitudes and the longitude range 54 W to 190 W, thus covering part of the leading hemisphere and most of the anti-jove hemisphere of Io. Longitudes between 95 W and 182 W were in darkness. The range to Io was 700,000 km, and the resolution of NIMS at this range was 350 km/pixel. South Volund was again identified as a hot spot.

Processing NIMS spectra

NIMS is an instrument particularly well suited to observing the thermal signature of volcanism. This signature is particularly easy to analyze in nightside observations where data are uncontaminated by reflected sunlight. Analysis of the NIMS data [*Carlson et al.,* 1996; *Lopes-Gautier et al., 1997*] revealed the presence of at least 16 hot spots in the nightside image, with the promise that with improving analysis techniques more will be revealed. Hot spots were initially identified by looking for NIMS pixels with characteristic thermal ramps towards the 5 micron end of the spectrum (see Figure 2). A hot spot typically occupies adjacent NIMS pixels in the direction of the instrument's mirror sweep. This is caused by the instrument's point spread function, described in Carlson *et al.,* [1992]. To obtain the true emittance from an individual hot spot, the spectra from the two adjacent NIMS pixels containing the hot spot are added. There is additional variat ion within the spectrum as the NIMS field of view moves across the spat ially small hot spot, caused by the instrument changing grating posit ions during the observation. This causes the slight patterning in the data in Figure 2 but which does not occur in the spectrum for each grating position, each of which consists of up to 17 wavelengths.

Figure 2

Fitting NIMS spectra: Single temperature fits

The South Volund NIMS spectrum was initially fitted with a single temperature black body Planck function, using a least-squares algorithm. Table 1 shows the temperature fits to the NIMS data for South Volund using a variety of methods. Fitting a temperature to all single grating positions for two added NIMS pixels produced a mean temperature of 537 K $\pm$17 K, (17 K being the standard deviation to the fit). Fitting a single grating spectrum (grating position 19) produced a best-fit temperature of 530 K $\pm$10 K. Fitting the combined spectrum of two NIMS pixels produced a best-fit temperature of 520 K $\pm$10 K (see Figure 2). It is apparent that the patterning does not produce significant errors in the analysis.

The color temperature of 520 K and the measured flux were used to determine that the surface area radiating at this temperature is about 23 km^2. From Figure 2 it is clear that a more sophisticated thermal model with more components is required as the SSI-detected hot spot in the same location has a temperature equal to or greater than 700 K [see *McEwen et al.*, 1997c]. *Close* examination of the NIMS South Volund spectrum (and some of the other hot spot spectra, including Prometheus) showed extra flux between 0.7 and 2.0 μm (see Figure 2), poorly fitted by the best single temperature fit. This is further evidence of the hotter component to the thermal anomaly. The hot component is very small relative to the much huger cooler component in the NIMS spectrum which tends to be dominated by larger radiances from the cooler component. A second, hotter component was therefore added to the fitting algorithm to see if the fit could be improved.

Two-temperature fits

With two areas at different temperatures, the resulting power spectrum is of the form

$$I_\lambda = f_h \frac{c_1}{\lambda^5 (e^{c_2/\lambda T_h}-1)} + f_w \frac{c_1}{\lambda^5 (e^{c_2/\lambda T_w}-1)}$$

where I_λ is the radiance at wavelength λ μm, c_1= 3.74185 x 10^8 W μm^4 m^{-2}; c_2= 1.4388 x 10^4pm K; f_w is the scale factor applied to the warm component which is at temperature T_w, and f_h *is* the scale factor applied to the hot component which is at temperature T_h. Emissivity for both units is taken to be 1.

The two-component least squares best fit was determined iteratively and the standard deviation and variance residuals checked to ensure that the fit was the best within computational limits (*10 K). Surface areas were determined from the best-fit temperature and scale factor, ratioed to the power output at a given wavelength at this temperature.

The best two temperature fit for the NIMS data was obtained using 450 K $\pm$10 K for the warm component, and 1100 K $\pm$10 K for the hot component. The resulting sped ra are shown in Figure 2. This two temperature fit reduced the standard deviation of the single temperature fit to the NIMS data by 40% (see Table 1). The 450 K component has an area of 40 km^2, and the 1100 K component has an area of 0.06 km^2.

Table 1

NIMS-SSI comparison

Using the SS1 clear filter flux and using the NIMS derived temperature of 1100 K, the SSI-implied area for a brightness temperature of 1100 K is 0.04 km'. The areas, corrected for the slightly different emittance angles (41 degrees for NIMS, 62.5 degrees for SSI) for the hot component are 0.080 $km^2 \pm 0.002$ km^2 from NIMS, and 0.087 km^2 for SS1 at 1100 K (see Figure 1), a remarkable degree of agreement. This good agreement between observations taken at significantly different viewing geometries suggests that there are no strong emission angle effects. From the NIMS data the projected area of the warm component is 53 km^2. If circular, the radius is just over 4 km.

Discussions

The source of this thermal anomaly could be a single flow or crusting-over lava lake, or a series of flows. The hot component comprises 0.15 % of the warm area. If this corresponds to a flow crack fraction, it is very close to those derived from the study of active Hawaiian (terrestrial) lava flows a few days after emplacement. These have been found to have crack fractions of 3.6% for very young (seconds to minutes) flow lobes, but this drops to about 0.4% for flow lobes tens of minutes older [*Flynn and Mouginis-Mark, 1992]*. As cooling proceeds over days the crack fraction decreases further, diminishing the contribution to thermal emission from the hottest lava. The crack fraction of the Kupaianaha (Kilauea, Hawaii) lava lake in a relatively quiescent state ranged from 1.43 % to 0.08% [Flynn, 1992]. The lack of observed emission angle effects implies the hot material is not hidden in deep vertical cracks observable only at low emission angles, and might be in the process of erupting on to the surface.

With terrestrial lava flows it has been shown that a good level of agreement to spectral data can be obtained with two temperature fits [e.g., *Crisp and Baloga, 1990; Flynn and-Mouginis-Mark, 1992; Flynn,* 1992]. *The* two temperatures generally correspond to a cooling crust on the surface of the lava flow (or crust forming on the surface of a lava lake) and cracks in the surface that reveal the hot material within. The temperature of the cracks remains remarkably constant, while the surface of the crust cools rapidly. With time, the proportion of the surface comprised of crack.., the crack fraction, tends to decrease.

The temperature of the cool component of the thermal anomaly is a function of the age of the bulk of the coding material. At the t irne of emplacement, the temperature distribution along a lava flow is non-uniform, decreasing with distance (i.e., with age). Initially, heat loss from a flow surface by radiation is rapid, being a function of the fourth power of temperature. As temperature decreases with time, the rate of cooling decreases dramat ically. The result is that the warm component of a flow surface soon becomes near-isothermal. The thermal conductivity of the crust determines how fast heat is transferred to the surface of the flow (further buffered by latent heat release from a still-molten interior). It takes a few hours for a highly vesicular (bubble-rich) crust, to days for a less vesicular crust (close to Hawaiian cooling rates), to a few weeks for almost solid-(volatile-free) basaltic crests *[Davies,* 1996], for a flow to cool down to 450 K on the surface of Io. Assuming that the two temperature fit is representative of the actual temperature distribution, we may infer that the South Volund flow surface (or lava lake crust) was relatively young (less than a few weeks) during these observations.

The temperature of the hot component is considerably less than that expected if molten basalt (typically 1350 K to 1450 K) is the erupting material. However, the two-temperature component tit is somewhat insensitive to the highest temperature flow areas (areas close to the vent, or newly exposed lava at temperatures greater than -1300 K) as these areas are very small relative to the rest of the anomaly, emplaced days or weeks earlier. Additionally, the low signal to noise ratio in the NIMS data for thermal radiation at short wavelengths (< 2.0 μm) tends to mask the highest temperature components contributions at the shortest wavelengths. It has been found that two temperature fits often reduce the apparent temperature of the hot component by up to 250 K *[Flynn and Mouginis-Mark, 1992]*. This implies that part of the South Volund flow could be at a temperature in excess of 1350 K, in the range of molten basalt.

There also exists the possibility that 1100 K is indeed the temperature at which the material is erupted. Keszthelyi and McEwen [1996] postulate that the crust of Io should be dominated by alkali-rich, silica-rich compositions with melting points of < = 1400 K, the result of repeated partial melt ing and extensive different iat ion of the ionian mantle. Silica-rich rhyolites on Earth commonly have eruption temperatures from 1000 K to 1200 K and dacites can have eruption t emperatures as low as about 1100 K [e.g., *Francis, 1993]*, On Earth, the presence of water decreases melting temperatures, but it is not known if magmas on Io contain water or other volat iles which have similar effects on melting temperature. 1100 K is too high a temperature to be sulphur, which melts at 400 K and vaporizes at about 700 K at STP; sulfur boils vigorously at -500 K on Io [*Lunine and Stevenson*, 1985].

To summarize, NIMS and SS1 data collected during night and eclipse reveal the presence of thermal anomalies at sub-pixel resolution. For the South Volund hot spot there is excellent agreement between the area derived from NIMS data for the hot component of a two component thermal anomaly, and the area derived from SS1 'data using the NIMS hot component temperature. These measured temperatures are most likely a manifestation of silicate volcanism, possibly a flow or series of flows, or crusting-over lava lake, part of which was recently or currently active at the time of observation.

For the South Volund and other hot spot NIMS observations a multiple-component lava flow cooling model (such as used in *Davies*, 1996; *Howell*, 1997 and *Keszthelyi and McEwen*, 1997) may well be more appropriate than a two temperature model, providing better constraints on the high temperature components of the flow. The nature of the South Volund eruption (most likely involving both silicate lavas and sulphur compounds as volatiles) and other hot spots will be further constrained by analyzing NIMS and SS1 observations from subsequent orbits throughout the Galileo prime and Europa missions, to the year 2000.

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Figure 1. The curve is the SS1 South **Volund** area (corrected for **emittance** angle) as a function of temperature. Also shown is the best-fit NIMS hot component area **and** temperature, 0.08 **km^2** at 1100 K $\pm$ **10** K **(solid** circle). Change in area over the error temperatures is negligible.

Figure 2. Single (long-dash) **and** two-temperature (solid) fits to the S. **Volund NIMS** data (stars). The standard deviation of the fit of the two temperature model (1100 K, 0.08 **km^2,** dot-dash line; **and** 450 K, 53 km^2, shortdash line) is 40% less than that obtained from the single temperature (520 K, 23 **km^2)** fit.

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Table 1, Temperature Fits to South Volund Data

Best fit with single temperature

	Temperature K	Area km^2	stand dev. of data fit
Individual grating positions: mean temperature[a]	537 ± 34	17 * 1	0.0728
Two NIMS pixels combined spectrum	520 ± 10[b]	23	0.0698
Grating position 19	530 ± 10[b]	20	0.0653

Best fit with two temperatures

	Temp 1 K	Area1 km^2	Temp2 K	Area2 km^2	atand. dev. of data fit
Two NIMS pixels spectrum.	11OW	0.080	450[b]	53	0.0457
Grating pos. 19	1100[b]	0.078	450[b]	49	0.0395

(a) Using added grating positions for the two NIMS pixels for S. Volund. The temperature for each grating position is determined, and the mean calculated.

(b) Fitting algorithm temperature increment = 10 K.

DAVIES ET AL.: TEMPERATURE AND AREA OF SOUTH VOLUND
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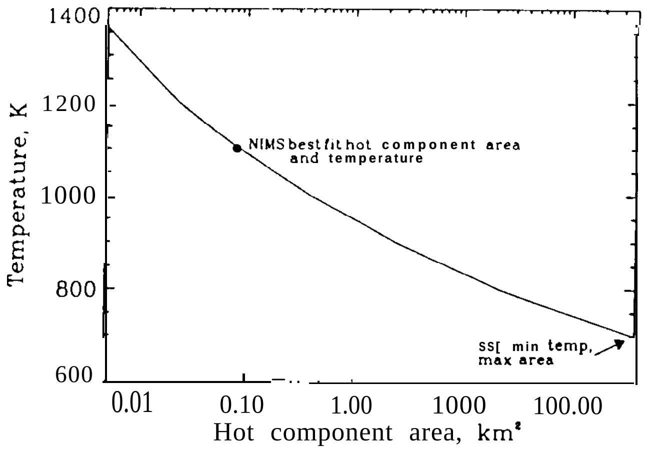
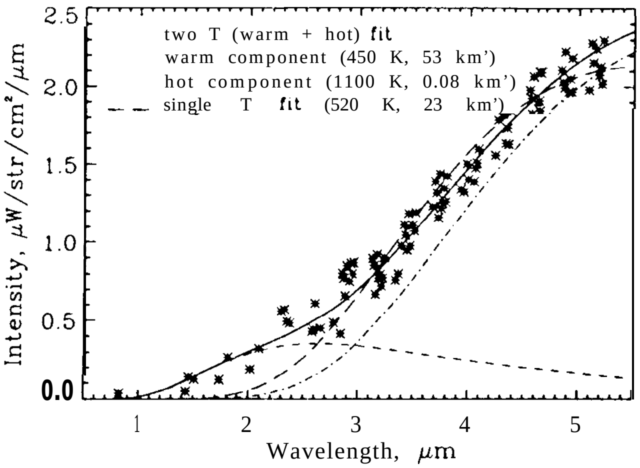

1400
1200
1000
800
600
Temperature, K
NIMS best fit hot component area
and temperature
min temp,
max area
0.01
0.10
1.00
1000
100.00
Hot component area, km²

Figure 1



two T (warm + hot) fit
warm component (450 K, 53 km')
hot component (1100 K, 0.08 km')
single T fit (520 K, 23 km')
Intensity, μW/str/cm²/μm
Wavelength, μm

Figure 2