

## Galileo NIMS Observations of Io

Ashley Gerard Davies

*Jet Propulsion Laboratory-California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109*

Sylvain Douté

*IGPP, University of California, Los Angeles, 405 Hilgard, Box 951567, Los Angeles, CA 90095*

**Abstract.** The Near Infrared Mapping Spectrometer (NIMS) on the Galileo spacecraft has been observing the volcanic Jovian satellite Io at regular intervals since June 1996. These infrared observations have allowed detailed mapping of the distribution and grain size of sulfur dioxide on Io's surface, identification of volcanic centers, mapping of the distribution of hot spots, and investigations into the style and evolution of individual volcanic eruptions.

### 1. Introduction

The Galileo spacecraft entered orbit around Jupiter in December 1995, and since June 1996 has been regularly observing Io, the most volcanically active body in the Solar System. On board the spacecraft is a suite of instruments capable of observing Io over a wide wavelength range. The Near Infrared Mapping Spectrometer (NIMS) is a moving grating spectrometer, sensitive at 408 wavelengths from 0.7 to 5.2  $\mu\text{m}$ . NIMS objectives at Io are to study surface composition, the thermal output from volcanoes, and map hot spot variability.

NIMS observations can be grouped into dayside (compositional) and night-side (thermal), and also by image scale. Between June 1996 and September 1999 115 global observations were obtained at low spatial resolutions (typically 100 to 300 km per pixel) but mostly with high spectral resolution. From the dayside observations  $\text{SO}_2$  distributions could be measured, on a broad scale. Regional observations were obtained during the close flybys of Io starting in October 1999 (orbit I24) with resolutions of typically 25 km/pixel, and local observations at high resolution (typically 0.5-2 km/pixel) were obtained of selected targets, including Loki, Prometheus, Chaac, and Pele (Lopes-Gautier et al. 2000). The regional and local observations obtained during the first three close flybys (32 observations in total) are at low spectral resolution (12 wavelengths across the wavelength range) as the grating in the NIMS instrument stuck, prior to the I24 close flyby. Attempts to restore movement have so far proved unsuccessful. This restricts spectroscopy, but still allows band-depth mapping and determination of temperatures.

## 2. Surface composition

The bright colors that give Io its distinctive appearance suggest an abundance of sulfur-bearing compounds such as SO<sub>2</sub>, native and short-chain sulfur, and sulfur oxides (Geissler et al. 1999). None of these compounds have been clearly identified, except SO<sub>2</sub>, due to its numerous and distinctive absorption bands in the NIR (Howell et al. 1984; Carlson et al. 1997), and sulfur, detected in the Pele plume (Spencer et al. 2000). Sulfur is probably a common volcanic gas given that red deposits, probably of red S<sub>2</sub> or S<sub>4</sub> molecules, are often seen at active volcanic sites (Geissler et al. 1999).

When carrying out spectral analysis of NIMS Io observations, it is difficult to escape the all-pervading influence of sulphur dioxide. Nevertheless, the form of the SO<sub>2</sub> deposits are revealing in themselves. Distribution and grain size maps of SO<sub>2</sub> frost deposits have been made from analyses of NIMS observations at the global scale, obtained during the G2 to E16 orbits and covering 75% of Io surface (Douté et al. 2001). These frost deposits can be used as tracers of the various parts of the SO<sub>2</sub> cycle. Global mosaics are produced that map SO<sub>2</sub> frost coverage and mean grain size. At the scale of the G2-E16 observations SO<sub>2</sub> deposits are omnipresent on Io's surface, but mainly concentrated in several large areas, centered at medium latitudes. These SO<sub>2</sub>-rich regions (with surface coverages higher than 60%) show a longitudinal correlation with volcanic plumes located lower in latitude suggesting that these plumes are the principal sources of SO<sub>2</sub> gas. This is more clearly seen in high-resolution NIMS images of Io's surface obtained during the close flybys (Lopes-Gautier et al. 2000). After a possible dynamic condensation around the plumes or at the equator, the gas is remobilized by solar or thermal (volcanic) flux and flows, for the most part, latitudinally towards the coldest and nearest regions devoid of hot spots. The correlation of the distribution and grain size mosaics distinguishes four different SO<sub>2</sub> physical units that indicate relative regional variations of condensation, metamorphism and sublimation. Finally, a comparison with Voyager ultraviolet (McEwen et al. 1988) and Galileo visible observations (Geissler et al. 1999) reveal some molecular contamination of SO<sub>2</sub> at medium and high latitudes, and that these SO<sub>2</sub> deposits may be optically thin (Douté et al. 2001).

The acquisition of high-resolution NIMS images have been particularly valuable for mapping SO<sub>2</sub>. For example, in regional observations the distribution of SO<sub>2</sub> in the deposition ring around Prometheus is seen to be larger than the visible white counterpart: this suggests that Prometheus emits several different compounds (such as S<sub>8</sub>) in the gas phase, that condense at a distance from the vent inversely proportional to volatility (Lopes-Gautier et al. 2000). The high-resolution NIMS observations show that the red deposits in the vicinity of volcanic centers (e.g., Culann) were also rich in SO<sub>2</sub>.

## 3. Monitoring volcanic thermal emission

Silicate volcanic activity appears to be ubiquitous on Io (McEwen et al. 1997, 1998) and NIMS is an excellent instrument for measuring volcanic thermal emission. Various models of volcanic thermal emission have been applied to NIMS data.

NIMS determined that silicate temperature volcanism was taking place on Io at Zamama, from a two-temperature fit to data obtained during a night-side observation during Galileo's first orbit (Davies et al. 1997). This yielded a liquidus temperature of at least 1100 K, beyond the range of sulfur volcanism. The high temperature and area (less than 0.1 km<sup>2</sup>) well-matched the temperature and area derived from a SSI eclipse image obtained during the same orbit. Using two-temperature fits, other NIMS hot spots have been found to have areas at silicate liquidus temperatures (Davies, 2000; Davies et al. 2000a). Multiple-temperature fits using silicate cooling models (e.g., Davies 1996) yield ages of eruptions and rates of areal coverage. Most of the volcanoes on Io exhibit relatively quiescent eruption styles, indicative of relatively low viscosity magmas. Volumes of eruption are typically tens of m<sup>3</sup> per second, with flow thicknesses of order 1 m (Davies et al. 2000b). With a characteristic slope towards longer wavelengths, the thermal spectra of these eruptions indicate a laminar flow emplacement regime. SSI high-resolution images show that flows at Prometheus and Amirani are akin to terrestrial pahoehoe flow fields (McEwen et al. 2000).

Not all volcanoes behave in this low-key manner. Eruptions in other locations exhibit a more vigorous emplacement mechanism. Galileo observed a large eruption at Pillan in September 1997 (orbit C9). Fortuitously, both NIMS and SSI observed this eruption in darkness during orbit C9. A dual-filter SSI observation yielded a magma temperature in excess of 1700 K (McEwen et al. 1998). This was the first indication of the presence of high temperature, ultrabasic magmas on Io. Detailed modelling of the combined NIMS and SSI dataset has yielded a better-constrained minimum temperature of 1870 K, a melting temperature comparable to the terrestrial Comondale komatiites (Davies et al. 2000a). This eruption type has not been seen on Earth since the Archean. Post-C9 observations revealed new 8-10 m thick flows covering 5600 km<sup>2</sup> (Williams et al. 2000). Modeling of the eruption yielded average mass eruption rates in excess of 10<sup>3</sup> m<sup>3</sup> s<sup>-1</sup>, implying peak mass eruption rates an order of magnitude greater (Davies et al. 2000a). Subsequently, NIMS watched as the thermal emission from Pillan decayed as the emplaced flows cooled.

Pele is an equally fascinating volcano, the site of a large plume and red and black plume deposits. Pele consistently emits a preponderance of thermal energy at short NIMS wavelengths over long periods of time. The volume of new, hot material that has to be constantly erupted in order to produce this short IR thermal flux would normally be expected to produce extensive flows, except that with time, there is no evidence of an expected large cooling flow unit. In some way the activity at Pele is strongly confined areally. The most likely explanation is that Pele is an active lava lake, on a scale much larger than those currently active on Earth (Davies et al. 2000a). This analysis was only possible due to good temporal coverage of Io's volcanic activity.

Loki remains enigmatic. Periodic huge eruptions resurface the caldera floor, but the exact nature of the resurfacing mechanism has not yet been identified.

#### 4. Distribution of hot spots and future observations

To date, Galileo has observed 97 main volcanic centers on Io: there may be considerably more smaller sites (Blaney et al. 2000; Lopes-Gautier et al. 2000).

The distribution of active volcanic centers generally shows no obvious correlation with latitude or longitude, with the exception of a lack of volcanoes at very high latitudes. The distribution of active volcanic centers is not well correlated with predictions of surface heat flow patterns derived from the aesthenosphere and deep mantle dissipation models, although the apparent deficit of active centers at high latitudes are consistent with the aesthenosphere model (Lopes-Gautier et al. 1999). High resolution images have been obtained with NIMS in 1999 and 2000. Future observations include, at high resolutions, observations of the Jupiter facing hemisphere and night-side maps of volcanic centers, including Loki and Pele.

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