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The temperature and width of an active fissure on Enceladus measured with *Cassini* VIMS during the 14 April 2012 South Pole flyover

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ABSTRACT

The width and temperature of the active fissures on Saturn's satellite Enceladus provide key observable constraints on physical models of these geyser-like eruptions. We analyze a sequence of high spatial resolution near-infrared spectra acquired with VIMS at 0.025 s intervals during a 74 km altitude flyover of the South Pole of Enceladus by the Cassini spacecraft on 14 April 2012 UTC. A thermal-emission spectrum covering 3- to 5-μm wavelengths was detected as the field of view crossed one of the four major fissures, Baghdad Sulcus, within 1 km of 82.36S latitude and 28.24W longitude. We interpret this spectrum as thermal emission from a linear fissure with temperature 197 ± 20 K and width 9 m. At the above wavelengths, the spectrum is dominated by the warmest temperature component. Looking downward into the fissure at only 13° from the vertical, we conclude that our results measure the temperature of the interior fissure walls (and the H_2O vapor) at depths within 40 m of the surface.

1. Introduction

One of the most exciting discoveries from the NASA/ESA Cassini spacecraft orbiting Saturn is the unexpected activity from the South Pole region of Enceladus, a small 250-km-radius inner icy Moon (Dougherty et al., 2006). Four prominent fissures, dubbed the tiger stripes, are the source of active plumes: high-velocity jets comprised mostly of H_2O molecules and ice grains, some of which escape the satellite's gravity and populate Saturn's faint E-ring (Hansen et al., 2006; Porco et al., 2006; Postberg et al., 2009; Ingersoll and Ewald, 2011). The Composite Infrared Spectrometer (CIRS) measured strong thermal emission from Enceladus' South Pole region with the warmest emission concentrated along these linear fissures (Spencer et al., 2006). The mechanism for the subsurface heating is poorly understood and a topic of intense interest (Hurford et al., 2007; Spencer et al., 2009). Although there may be a liquid water reservoir beneath the South Pole with the H_2O-dominated plume generated by exposure of the liquid to the vacuum of space through cracks (Matson et al., 2012; Postberg et al., 2011), alternative hypotheses that do not require H_2O liquid have been proposed (Kieffer et al., 2006, 2009). The high spatial resolution near-infrared measurements reported here provide important new constraints on such models of the physics of the heat transfer to the surface.

The Visual Infrared Mapping Spectrometer (VIMS) covers the critical 3–5 μm wavelength range that includes the short wavelength rising edge of the Planck blackbody emission spectrum for the relevant ∼200 K fissure temperatures and measures the warmest temperature component of the emission. In this regard, VIMS provides an ideal complement to the spectra from Cassini's CIRS instrument which covers wavelengths from 6.7 to several hundred μm, where extended areas that include cooler temperatures also contribute significantly to the emission spectrum.

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2. Enceladus plume fly-through on 14 April 2012 UTC

VIMS observed one of the fissures, Baghdad Sulcus, at exceptionally high resolution during a spectacularly low 74-km-altitude pass by the Cassini spacecraft over Enceladus' South Pole at a velocity of 7.5 km s^{-1}. The trajectory was designed to enable *in situ* sampling of the plume composition with the Ion and Neutral Mass Spectrometer (INMS) and Cosmic Dust Analyzer (CDA). The orientation of the spacecraft was chosen to point the VIMS and CIRS instruments towards Enceladus' surface so that their fields of view were 'dragged' across the fissure region at the spacecraft velocity in a ride-along mode with no independent control of their pointing. At this speed, the entire diameter of Enceladus was traversed in 67 s. During this observation, much of Enceladus' South Pole region was not illuminated by the Sun providing optimum conditions for detecting endogenic thermal emission against an otherwise cold and dark background.

VIMS spectra were acquired in the 'occultation mode' designed for rapid sampling of the signal from a star as it is occulted by Saturn's rings or Titan's atmosphere (Brown et al., 2004). VIMS acquired a continuous series of 0.025-s integration time spectra covering the 3- to 5-μm wavelength range for a single hi-resolution pixel (0.25 × 0.50 mrad, scan mirror stationary). The pixel footprint on Enceladus' surface is 38 m in the across-track direction and 214 m in the along-track direction parallel to the spacecraft velocity. The along-track footprint length is determined mainly by the 7.5 km s^{-1}spacecraft velocity during the integration.

3. Results

A 25.6 s section within the series of spectra acquired as the spacecraft traversed the South Pole region at closest approach is shown in Fig. 1. We detected a bright source of thermal emission contained within a single integration when the field of view crossed Baghdad Sulcus, one of the four major fissures. There is no comparable emission detected in any of the other 1023 spectra obtained during this interval. It is noteworthy that there is no measurable thermal emission in either the spectrum acquired just 0.025 s before or 0.025 s after the detection. The adjacent-sample non-detections are only separated by 214 m from the detection location and set an upper limit on the size of the emission source and the temperature gradient. The CIRS instrument simultaneously detected a strong thermal source (Spencer et al., 2012).

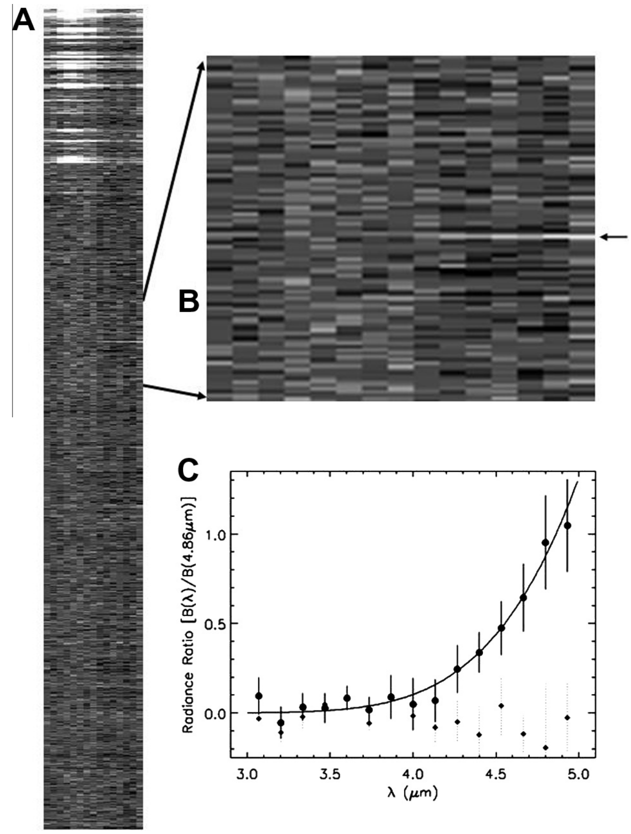

Fig. 1. (A) 1024 spectra, acquired during 25.6 s as Cassini passed over Enceladus' nighttime South Pole, shown as an image with each image line displaying a single 0.025 s integration. Time increases from bottom to top and wavelength increases from 3.0 μm at left to 5.0 μm at right. Strong signals at top are reflected sunlight after terminator crossing. (B) Magnified section of A showing the thermal emission spectrum that is apparent in only a single integration indicated by the arrow. (C) The wavelength variation of the emission identified by the arrow in B and normalized at 4.86 μm (circles) compared to the average of the preceding and following integrations (diamonds) when VIMS measured no emission. The solid line shows the spectrum for the best fit color temperature of 197 ± 20 K. The area sampled during an integration is 214 by 38 m.

Table 1
Summary of results.[a]

Latitude	Longitude	Error	Temperature	Error	Width[b]
82.36S	28.24W	±1 km	197 K	±20 K	9 m

[a] Cassini VIMS measurements acquired during sequence S73, Parameter Set ID VIMS_164EN_ENCEL18001, start times 2012-105T14:01:54.762Z and 2012-105T14:00:02.671Z.
[b] Fill factor 12%; for a discussion of the limits on widths and temperatures, see Section 4.1 and Table 2.

3.1. Location

The surface track of the VIMS field of view across Enceladus' South Pole region is shown in Fig. 2. To provide context for the VIMS measurements, the locations of the spectra are plotted over the best image (18 m/pixel) of this region acquired in November 2009 by the Imaging Science Subsystem (ISS) when the South Pole was still illuminated by sunlight. The location of the thermal source on the background image is uncertain by ±1 km due to the combination of uncertainties in the precise shape and orientation of Enceladus, spacecraft position, local topography, and instrument pointing at the two epochs of the background image and the VIMS measurement. It is likely that the actual thermal source lies on the linear Baghdad Sulcus fissure at its closest point to the location shown in Fig. 2C and Table 1.

The remainder of this section provides some detailed supporting information on determination of the latitude and longitude of the source of the thermal emission and its location relative to the Imaging Sub-System (ISS) Narrow Angle Camera image (NASA Planetary Data System image N1637462854_1) in Fig. 2. The coordinates (Table 1) are planetocentric latitude and West longitude on the tri-axial ellipsoid with $(a, b, c) = (256.6, 251.4, 248.3)$ km (Thomas et al., 2007) and the IAU 2009 updated prime meridian (Archinal et al., 2010). The NAIF toolkit software package (Acton, 1996) with the reconstructed Cassini kernels was used to determine the coordinates of each VIMS sample. As a check on the absolute pointing, the time when the field of view crossed the bright limb of Enceladus was calculated and compared to the observed time of the bright limb crossing which occurred 0.050 s after the calculated time. The coordinates in Table 1 include this small correction (∼375 m along track) to match the measured limb crossing time.

To overlay the calculated VIMS sample positions on the ISS image, we used the USGS ISIS version 3 software (Anderson et al., 2004), which uses the same NAIF geometry routines and data