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Endogenic heat from Enceladus' south polar fractures: New observations, and models of conductive surface heating

Oleg Abramov *, John R. Spencer

Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA

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ABSTRACT

Linear features dubbed "tiger stripes" in the south polar region of Enceladus have anomalously high heat fluxes and are the apparent source of the observed plume. Several explanations for the observed activity have been proposed, including venting from a subsurface reservoir of liquid water, sublimation of surface ice, dissociation of clathrates, and shear heating. Thermal modeling presented in this work, coupled with observations from the Cassini Composite Infrared Spectrometer (CIRS) instrument, seeks to elucidate the underlying physical mechanism by constraining vent temperatures and thermal emission sources, using a model in which the observed thermal signature results primarily from conductive heating of the surface by warm subsurface fractures. The fractures feed surface vents, which may themselves contribute to the observed thermal emission. Model variables include vent temperature, presence of a surface insulating layer, vent width, time-variable heat input, and heat sources other than the central vent. Results indicate that CIRS spectra are best fitted with a model in which the surface is heated by narrow vents at temperatures as high as 223 K. Although equally good fits can be obtained for vent temperatures in the range of 130 to 155 K if the vents are wider (180 m and 22 m respectively) and dominate the emission spectrum, these models are probably less realistic because vents with these temperatures and widths cannot supply the observed H_2O vapor flux. The lack of emission angle dependence of the thermal emission when July 2005 and November 2006 CIRS observations are compared also argues against thermal emission being dominated by the vents themselves. Thus, results favor high-temperature models, possibly venting from a subsurface liquid water reservoir. However, a fracture filled with liquid water near the surface would produce significantly higher radiances than were detected unless masked by a thermally insulating surface layer. Models that best match the CIRS data are characterized by small fractions of the surface at high temperatures, which strengthens the case for the vents and/or their conductively-heated margins being the primary heat source. Models where the thermal emission is dominated by conductive heating of the surface from below by a laterally-extensive buried heat source cannot reproduce the observed spectrum. Models with a 10 cm thick upper insulating layer produce a poor match to the CIRS spectra, suggesting high thermal inertias near the tiger stripes. Finally, tiger stripe thermal emission measured by CIRS varied by less than 15% over the 16 month period from July 2005 to November 2006.

1. Introduction

The south polar region of Enceladus, a small icy satellite of Saturn, consists of young, tectonically deformed terrain dominated by roughly parallel, 2-km wide linear depressions dubbed "tiger stripes" (e.g., Porco et al., 2006). Recent observations by multiple instruments on the Cassini spacecraft describe an anomalously high heat flux associated with these tiger stripes, along with active plumes of water vapor and ice particles that originate from them (Porco et al., 2006; Spencer et al., 2006; Hansen et al., 2006; Waite et al., 2006; Spahn et al., 2006; Spitale and Porco, 2007).

Several explanations for the observed elevated temperatures and the resulting plume have been proposed, including venting from a subsurface reservoir of liquid water (Porco et al., 2006; Schmidt et al., 2008), sublimation of surface ice (Spencer et al., 2006), decompression and dissociation of clathrates (Kieffer et al., 2006), and shear heating (Nimmo et al., 2007). These mechanisms predict a range of vent temperatures: ~140 K for clathrate decompression (Kieffer et al., 2006), >180 K for sublimation of H_2O (Spencer et al., 2006), and up to 273 K for the shallow reservoir of liquid water (Porco et al., 2006). The elevated vent temperatures would conductively heat the nearby surface, contributing to the thermal signature observed by Cassini. The thermal modeling presented in this work, coupled with observations from the Cassini CIRS instrument, seeks to constrain the vent temperatures

* Corresponding author. Fax: +1 303 492 2606.
E-mail address: oleg.abramov@Colorado.edu (O. Abramov).

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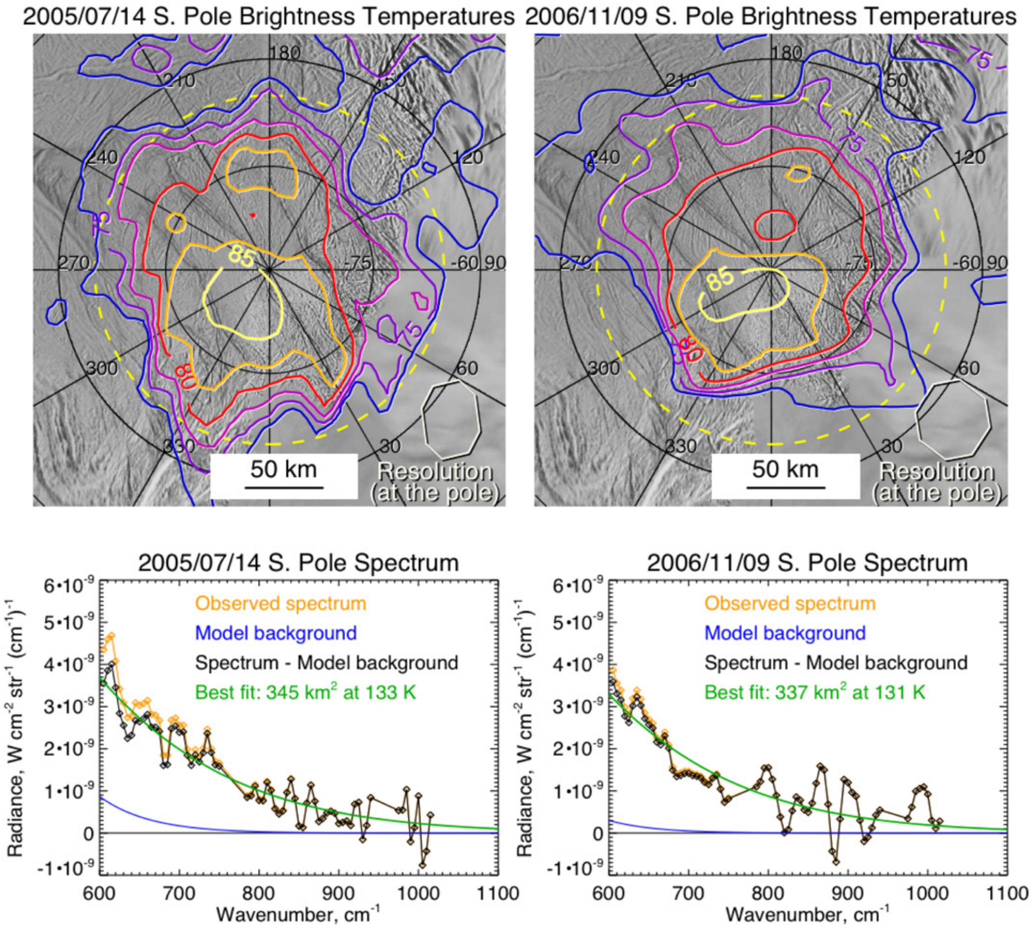

Fig. 1. Top: Maps of the Enceladus south polar 9–16 µm brightness temperature distribution from the July 2005 and November 2006 flybys. For July 2005 flyby, the subsolar latitude is 23° S, the subspacecraft latitude is 46° S, south polar emission angle is 44°, range to Enceladus is ~80,000 km, and spatial resolution is 23 × 32 km. For November 2006 flyby, the subsolar latitude is 16° S, south polar emission angle is 22°, the subspacecraft latitude is 68° S, range to Enceladus is ~110,000 km, and spatial resolution is 32 × 35 km. The temperature distribution is probably consistent, within the noise, between the two maps, though overall temperatures are somewhat lower in 2006 due to cooling of the passive (solar-heated) background as southern winter approaches. Bottom: Average spectrum south of 65° S (yellow dashed line on the maps) for the two flybys, before and after correction for emission from a model passive background (blue line). The best-fit graybody curve to the two background-corrected spectra (green line) is very similar, indicating little dependence of thermal emission on emission angle.

and thermal emission source, and thus potentially elucidate the underlying physical mechanism.

2. Summary of observations

Observations of Enceladus' south polar thermal emission were conducted using Cassini's Composite Infrared Spectrometer (CIRS) (Flasar et al., 2004) instrument. Although optimized for atmospheric spectroscopy, CIRS is also used to investigate thermal radiation from the surfaces of icy satellites to constrain physical properties and detect possible endogenic activity. CIRS consists of two Fourier transform spectrometers, one using a 16–1000 micron detector with low spatial resolution (4 mrad field of view), and the other using two 1 × 10 arrays of 7–9 and 9–16 micron detectors with much higher spatial resolution (0.3 mrad field of view). Most of the endogenic heat measurements have been made using the 9–16 micron detectors.

2.1. July 2005 flyby

On July 14, 2005, the Cassini spacecraft flew by Enceladus with a closest approach of 168 km at a subspacecraft point of 24° S 326° N, and an approach trajectory that provided an excellent view of the south polar region. CIRS global mapping at 25 km resolution resulted in the discovery of a large region of elevated temperatures near the south pole (Spencer et al., 2006, and Fig. 1), which correlates closely with the location of the tiger stripes. Scattered "ridealong" CIRS observations at 0.6–20 km resolution confirmed localization of warm material along the tiger stripes. The most powerful spectrum obtained corresponds to a maximum temperature of 145 ± 14 K in a two-temperature fit, and the average south polar spectrum south of 65° S can be fit with a blackbody at 133 ± 12 K occupying ~345 km^2. The total non-solar radiated power for the south polar region is estimated as 5.8 ± 1.9 GW.

2.2. November 2006 flyby

This more distant flyby, on November 8–9, 2006, provided views of the south pole from a minimum range of 90,000 km. CIRS obtained a map of the south polar region from 00:09 to 00:54 UT on November 9th from an average sub-spacecraft direction of 239 W, 68 S, giving an emission angle of 22° at the south pole, compared to 44° for the July 2005 flyby, where the sub-spacecraft point was at 176 W, 45 S. The view direction was just 14° from the orientation of the tiger stripes (which averages ~225 W), compared to 49 degrees in July 2005. Both these geometric factors allowed a more direct view into the interior of the tiger stripe fractures in November 2006 than in July 2005. However, the two data sets yielded very similar spectra and temperature estimates (Fig. 1). After subtraction of the passive background, the average south polar spectrum south of 65°