Ethylene Emission Following Saturn's 40-Degree N. Storm in 2010

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Introduction

Because Cassini had been in orbit since July 2004, mission operations were mature when the 40-degree N. storm erupted in December 2010 (Note: All coordinates are expressed as planetographic). Thus, the Composite Infrared Spectrometer (CIRS) was able to track ethylene at the millibar altitude level for the duration of the storm, from March 2011 to January 2012. The temperatures at the millibar level ranged from the pre-storm 140K to 220K in May 2011 and had relaxed back to 180K by April 2012. This ethylene emission data indicates abundance at the 1.3 mbar level ranging from 20 ppb to 100 ppb.

Previously, Encrenaz et al. (1975) and Be´zard et al., (2001) had difficulty detecting ethylene, but Shemansky and Liu (2012) had provided a pre-storm basis for comparison with this CIRS data. Using the Cassini Ultraviolet Imaging Spectrograph, they derived a vertical ethylene profile and retrieved a mole fraction of 1.6 x10-9 at 0.5 mbar in Saturn's atmosphere at 15.2 N latitude.

In May 2011, the high temperatures associated with two bright regions, known as the beacons, produced strong thermal emission at 10.5 µm (950 cm^{-1}) due to stratospheric ethylene. Ethylene is important because it is a short-lived tracer of photochemistry in

Observation Name	Day of Year	Date	Resolution (cm^{-1})	Average Latitude (degrees)	Average Longitude (degrees)	Average Emission Angle (degrees)	Number of Spectra
CIRS_137SA_COMPSIT004	254	11-Sep-10	0.53	37.5	164.7	72.9	4473
CIRS_145SA_COMPSIT007 (Beacon 2)	62	3-Mar-11	0.53	26.8	263.0	66.5	170
CIRS_145SA_COMPSIT007 (Beacon 1)	62	3-Mar-11	0.53	34.1	109.0	76.0	170
CIRS_146SA_COMPSIT003 (Beacon 2)	71	12-Mar-11	0.53	32.1	267.8	45.9	84
CIRS_146SA_COMPSIT004 & COMPSIT005 (Beacon 1)	72, 73	13/14-Mar-11	0.53	35.2	159.2	50.0	392
CIRS_148SA_MIRMAP001	124	4-May-11	2.50	37.6	289.1	38.0	304
CIRS_150SA_COMPSIT001	188	7-Jul-11	0.53	38.6	30.9	40.2	129
CIRS_151SA_MIRMAP001	207	26-Jul-11	2.50	40.9	71.9	41.4	688
CIRS_158SA_MIRMAP001	337	3-Dec-11	2.50	37.8	66.0	38.4	708
CIRS_159SA_COMPSIT004	13	13-Jan-12	0.53	38.5	170.1	65.9	126
CIRS_159SA_COMPSIT005	14	14-Jan-12	0.53	33.3	173.9	72.8	126
CIRS_161SA_COMPSIT001	47	16-Feb-12	0.53	33.8	269.1	68.7	129
CIRS_164SA_COMPSIT002	107	16-Apr-12	0.53	38.7	86.0	71.2	128

Saturn's stratosphere. Ethylene does not reach the deep atmosphere of Saturn; thus, the unexpected emission could not be the result of direct upwelling. Interpreting this data set poses a challenge.

Observations

Heated regions of Saturn's stratosphere at the latitude of the northern storm were first detected by Fletcher et al. (2011). These "beacon" features are thought to be produced by wave activity generated by a massive storm at 40_N latitude extending over a large altitude range from the water cloud near 10 bars to the upper troposphere around 100 mbars.

CIRS is a dual Fourier transform spectrometer covering the thermal infrared with three focal planes. The far-infrared focal plane, FP1 is a single thermocouple detector spanning 10-600 cm^{-1}. The two mid-infrared focal planes, FP3 and FP4, are arrays of 10 HgCdTe detectors covering 600-1100 cm^{-1} and 1100-1500 cm^{-1} respectively (Flasar et al., 2005) and operating at 80 K. These were used to acquire this data. They have fields-of-view of 0.3 mrad and apodized selectable spectral resolution ranging from 0.5 to 15.0 cm^{-1}. These focal planes produce can produce broad-band, absolutely calibrated spectra at high spatial resolution and modest spectral resolution.

Seven CIRS data sets with sufficient spectral resolution and longitude coverage were identified. These observations characterize the changes in ethylene emission throughout 2011 and 2012.

There were two types of CIRS observations included in this data set:

1. COMPSIT observations with a spectral resolution of 0.5 cm^{-1} were taken in a sit-and-stare mode as the planet rotated beneath the spacecraft in order to study composition. These observations were either performed on the central meridian (low to moderate emission angle) or offset to one of the limbs (high emission angle) with the FP3/FP4 focal planes oriented north-south. COMPSIT observations at high emission angle have contribution functions for temperature and composition that peak near the 1.0 mbar level in Saturn's stratosphere.

2. MIRMAP observations with a spectral resolution of 3.0 cm^{-1} that sit-and-stare at the planet as it rotated beneath were used to map temperature and composition. These observations were obtained on the central meridian (low to moderate emission angle) in order to obtain temperatures throughout the stratosphere and in the upper troposphere.

All CIRS data sets were calibrated using a database that incorporates large amounts of deep space spectra. Table 1 contains the data that comprise this data set: The first entry is a pre-storm spectrum for comparison with the data obtained from the beacon region. Day 2011-199 is the date of the UKIRT ground-based data. We were unable to get temperature data from the ground so we used CIRS temperature profiles from that time-frame and averaged the CIRS spectra over the region that the ground-based instrument was viewing. Once we had this temperature profile from CIRS we used it to retrieve abundances from the UKIRT ground-based data.

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The data set can be divided into 4 periods:

1. The pre-storm period- before Dec 2010
2. Phase 1 - The interval when the beacons were growing in strength - Jan 2011 to May 2011.
3. Phase 2 - The interval when the beacons merged, yielding a maximum temperature enhancement of 140 deg. K - May 2011 to August 11.
4. Phase 3 - The time after the visible storm clouds dissipated in August 2011 but when infrared measurements were still showing changes from the pre-storm conditions.

By early 2012 the beacon temperature had dropped by about 50 deg K from its peak temperature in May 2011 (about 220 K), the span of the ethylene emission had shrunk from 25 deg. to less than 10 deg. in longitude. In addition the ethylene peak had shifted from 40_N to 35_N between 2011 and 2012.

Analysis of the Data

Ethylene Abundance Retrievals

Inspection of the spectra revealed that by January 2012 there was insufficient signal-to-noise (SNR) to readily distinguish the ethylene abundance over the beacon region. Therefore, all CIRS spectra in a 6-deg north-south by 20 deg east-west bin were averaged over the peak ethylene emission region in order to increase the SNR and create a single “hot-spot” spectrum for each of the data sets listed in Table 1. The average longitude, latitude, and emission angle of the binned data is also given in the table. Direct comparison of the spectra of these regions is not justified because their emission angles vary widely; however, the temperature and ethylene profiles retrieved from these data are comparable.

To obtain the abundance of ethylene from the CIRS data we used FP4 and FP3 spectra to obtain the temperature in the pressure range of 0.1-10 mbar for the spatial region of the averaged ethylene spectrum. Then using the optimal estimation retrieval method in the Non-Linear Optimal Estimator for Multivariate Spectral Analysis (NEMESIS) software we scaled a photochemical profile (produced by Paul Romani using his photochemistry code) of ethylene until the reduced chi-squared was minimized. The output was a scale factor on the photochemical profile. For the 0.5 cm^{-1} spectra we also allowed the abundance of ethylene to vary at each altitude level in the atmosphere around the 2mbar region to retrieve an absolute value for ethylene. This procedure was followed for higher resolution spectra in order to achieve an overall better fit (improved chi-squared) of the model to the data.

The CIRS C_2H_4 observations that were used were obtained using the nadir mode rather than the limb mode. The C_2H_4 abundance profile retrievals were performed using the NEMESIS code (See Irwin et al. (2008)). Absorption of the contributing species was calculated using the correlated-k method (Lacis and Oinas, 1991). The k-tables for C_2H_4 were calculated using line parameters based on data from the GEISA 2003 line atlas (Jacquinet-Husson et al., 2005) with modifications to the temperature exponent (set to 0.73), which is used in the relation of the temperature dependence of the pressure-broadening coefficient, modified to use H_2 pressure broadening rather than N_2 (Bruno Be´zard, private communication). Inputs into the model were the temperature profiles and an assumed ethylene mole fraction profile. A one-dimensional photochemical model was used along with a temperature profile from the beacon region to generate an ethylene mole fraction profile. The model takes into account the photolysis and chemical reactions that interlink the hydrocarbons with each other and atomic hydrogen. It solves their coupled continuity equations assuming steady state conditions. The net flux of the species includes terms for both transport (eddy mixing) and molecular diffusion (See Romani et al. (2008)). The photochemical profile was allowed to vary with altitude to produce a continuously variable profile that best fit the data.

Temperature Retrievals

The temperature profiles were retrieved using spectral bands free of ethylene emission in both the FP3 and FP4 focal planes.

The same averaging used to produce the ethylene spectrum in the beacon region was used to create the spectra used for temperature retrievals. Separate retrievals for upper tropospheric and stratospheric temperatures were performed using the constrained linear inversion algorithm described by Conrath et al.

(1998), with the profiles from the stratospheric retrievals used at the a priori for the tropospheric retrieval.

The FP4 data was used to derive the stratospheric temperatures. Methane transmittances were calculated for the γ4 band of CH_4 between 1250 and 1311 cm^{-1} using the correlated-k method (Lacis and Oinas, 1991), the line data from the GEISA 2003 line atlas (Jacquinet-Husson et al., 2005) with H_2/He broadening (Linda Brown, private communication).

For tropospheric retrievals in the FP3 data (600-620 and 640-660 cm-1), where the major source of opacity is from the collision-induced S(1) line of hydrogen, an equilibrium hydrogen ortho-to-para ratio, a He/H_2 ratio of 0.135 (Conrath and Gautier, 2000), a pressure dependent CH_4 mole fraction profile based on the photochemical profile in Moses et al. (2000) scaled to a tropospheric value of $4{:}5 \times 10^{-3}$ as given in Flasar et al. (2005) was assumed, opacity from H_2-H_2, H_2-He and H_2-CH_4 pairs was included, using algorithms from Borysow et al. (1985, 1988) and Borysow and Frommhold (1986).

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This method for temperature retrieval yields uncertainty limits in the retrieved temperature profile that are approximately 1 K over the 0.5 to 10 mbar range in the stratosphere and over the 50 to 200 mbar range in the troposphere. Between these pressure regions, the inversion algorithm smoothly interpolates temperatures. (Note: Although the temperature inversion algorithm uses the P and Q branches of the ν4 band, the observation that the strongest part of the Q branch is in absorption suggests that the upper stratosphere is cooler than the lower regions).

Structure of the Data

The data spans the time period from 2011-03-03 to 2012-04-16 and consists of a PDS4 label and a table of ethylene abundances and the conjoined error table and the supporting table and label containing the corresponding temperature profiles. The tables contain mole fraction and temperatures as a function of pressure (mbar). Retrievals were accomplished for March 2, 2011, July 7, 2011, July 18, 2011, Jan 13, 2012, Jan 14,2012, Feb 16, 2012 and Apr 16, 2012.

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