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Saturn's latitudinal C_2H_2 and C_2H_6 abundance profiles from Cassini/CIRS and ground-based observations

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ABSTRACT

Hydrocarbons in the upper atmosphere of Saturn are known, from Voyager, ground-based, and early Cassini results, to vary in emission intensity with latitude. Of particular interest is the marked increase in hydrocarbon line intensity near the south pole during southern summer, as the increased line intensity cannot be simply explained by the increased temperatures observed in that region since the variations between C_2H_2 and C_2H_6 emission in the south pole region are different. In order to measure the latitudinal variations of hydrocarbons in Saturn's southern hemisphere we have used 3 cm^{-1} resolution Cassini CIRS data from 2006 and combined this with measurements from the ground in October 2006 at NASA's IRTF using Celeste, an infrared high-resolution cryogenic grating spectrometer. These two data sets have been used to infer the molecular abundances of C_2H_2 and C_2H_6 across the southern hemisphere in the 1–10 mbar altitude region. We find that the latitudinal acetylene profile follows the yearly average mean daily insolation except at the southern pole where it peaks in abundance. Near the equator (5° S) the C_2H_2 abundance at the 1.2 mbar level is $(1.6 \pm 0.19) \times 10^{-7}$ and it decreases by a factor of 2.7 from the equator toward the pole. However, at the pole (∼87° S) the C_2H_2 abundance jumps to $(1.8 \pm 0.3) \times 10^{-7}$, approximately the equatorial value. The C_2H_6 abundance near the equator at the 2 mbar level is $(0.7 \pm 0.1) \times 10^{-5}$ and stays approximately constant until mid-latitudes where it increases gradually toward the pole, attaining a value of $(1.4 \pm 0.4) \times 10^{-5}$ there. The increase in ethane toward the pole with the corresponding decrease in acetylene is consistent with southern hemisphere meridional winds [Greathouse, T.K., Lacy, J.H., Bézard, B., Moses, J.I., Griffith, C.A., Richter, M.J., 2005. Icarus 177, 18–31]. The localized increase in acetylene at the pole provides evidence that there is dynamical transport of hydrocarbons from the equator to the southern pole.

1. Introduction

Acetylene (C_2H_2) and ethane (C_2H_6) are important species in outer planet atmospheres as they are photochemical by-products of methane photolysis and the dominant stratospheric coolants at mid-infrared wavelengths. Their latitudinal abundance profiles may be tied to seasonally varying insolation (Moses and Greathouse, 2005) and possibly indicate the dynamical forces at work in the atmosphere. Therefore, latitudinal, temporal, and vertical variations of stratospheric hydrocarbons can provide constraints on dynamics, seasonal climate models, and photochemical models.

Observations of the south pole stratosphere, between Saturn's southern summer solstice and 3 saturnian weeks after solstice ($L_s = 270°$–$293°$, Apr 2002–Jan 2004), have shown that the pole is 10–15 K warmer than the equator regions (Flasar et al., 2005; Orton and Yanamandra-Fisher, 2005; Greathouse et al., 2005). An early radiative model by Bezard and Gautier (1985) and a radiative/dynamic model by Conrath et al. (1990) indicate that the radiative relaxation time is approximately 9 Earth years at the 1 mbar level on Saturn. Therefore, at the time of these observations a maximum difference of 5 K in stratospheric temperature should have been observed between the equator and the southern

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pole. This model-data mismatch is likely due to the assumption of uniform mole fraction profiles of C_2H_2 and C_2H_6 with latitude, altitude, and season. More accurate profiles of these species will greatly affect the outcome of radiative models and therefore the predicted seasonal behavior of the temperatures on Saturn.

Acetylene and ethane are formed at pressures less than 0.1 mbar by photolysis of methane. The complete chemical pathway by which these species are formed is given in Moses et al. (2000). Acetylene has a short lifetime because it has a large cross-section, relative to other species susceptible to photolysis, and is therefore not well shielded. It is however efficiently recycled which increases its lifetime above the vertical transport time; thereby, allowing its transport deeper into the atmosphere (e.g. at 2 mbar, 36° S, and $L_s = 273°$ its lifetime is ∼100 years; Moses and Greathouse, 2005). Ethane's lifetime is significantly longer as its photolysis cross-section is smaller than the more abundant species methane which effectively shields it and also allows its transport into the deeper atmosphere (e.g. at 2 mbar, 36° S, and $L_s = 273°$ its lifetime is ∼700 years; Moses and Greathouse, 2005). In addition, the long vertical diffusion timescales in Saturn's stratosphere should prevent any dramatic seasonal changes from propagating to the lower stratosphere. Models of the lower stratospheric latitudinal abundance profiles of acetylene and ethane, by Moses and Greathouse (2005), indicate that their shapes should resemble the yearly average mean daily insolation (see Fig. 4; Moses and Greathouse, 2005). Therefore, observations should show that the acetylene and ethane latitudinal profiles should decrease from the equator to the pole.

Investigation and monitoring of the latitudinal profiles of Saturn's hydrocarbons until recently was not possible and therefore only global averages were reported. The most recent measurements published which determined global averages were by Sada et al. (2005). Sada et al. used the cryogenic grating spectrometer, Celeste, at the McMath–Pierce telescope, in 1994 ($L_s = 178°$), to determine C_2H_2 and C_2H_6 abundances of 3.4×10^{-7} at 1.6 mbar and 6.7×10^{-6} respectively at 1.0 mbar. They also performed a re-analysis of Voyager IRIS data ($L_s = 8°–19°$) to find mid-latitude values of 1.6×10^{-7} at 2 mbar and 8.6×10^{-6} at 0.1–3 mbar for C_2H_2 and C_2H_6 respectively.

Greathouse et al. (2005) published the first measurements of the latitudinal variations of C_2H_2 and C_2H_6. They used the mid-infrared TEXES grating spectrograph at the NASA Infrared Telescope Facility (IRTF) during Saturn's southern summer solstice (October 2002; $L_s = 270°$) to measure 12 latitude bins across the southern hemisphere. They found that C_2H_2 decreased in abundance from the equator to the south pole by a factor of ∼3.7 at 1 mbar and C_2H_6 stayed approximately constant from equator to the pole at 2 mbar.

Most recently, Howett et al. (2007) utilized the excellent spatial resolution available from the Composite Infrared Spectrometer (CIRS) onboard the Cassini spacecraft to determine the latitudinal abundance profiles of C_2H_2 and C_2H_6. Howett et al. used 0.5 cm^{-1}, low-emission angle CIRS data that ranged in latitude from ∼14°–66° S. The data were taken between June and November 2004 (centered on $L_s = 293°$). Howett et al.'s results indicate that the C_2H_2 latitudinal profile decreases by ∼1.7 from equator to the southern polar region whereas the C_2H_6 profile stays relatively constant until approximately 60° S and then increases toward the pole (both results stated for 2 mbar).

The results of Greathouse et al. (2005) and Howett et al. (2007) agree with the model results of Moses and Greathouse (2005) for C_2H_2; the latitudinal profiles decrease in abundance toward the south pole and approximately follows the yearly average mean daily insolation. However, the models of Moses and Greathouse indicate that C_2H_6 at the 2 mbar level should also have a profile that decreases from equator to pole; the observations indicate a constant or increasing abundance. The differences between the models and observations seem to indicate the presence of meridional transport, in the southern hemisphere, that has a timescale less than the ethane lifetime and longer than the acetylene lifetime. Moses and Greathouse concluded that the southern meridional winds should have a magnitude of ∼0.4–2 cm/s at 2 mbar.

Hydrocarbon monitoring is still required to confirm the above results and watch for changes in hydrocarbon latitudinal profiles as the seasons change on Saturn. In addition, CIRS observations have continued to add additional spectra at higher southern latitudes. The additional CIRS spectra enable us to determine an entire southern hemisphere latitudinal profile for C_2H_2 and C_2H_6, which includes observations performed within 3° of the southern pole. These observations have been combined here with ground-based C_2H_2 and C_2H_6 measurements that were performed in conjunction with south pole observations by CIRS on October 11, 2006 ($L_s = 317°$). The ground-based observations provide complementary measurements of individual C_2H_2 and C_2H_6 spectral features for the southern hemisphere.

2. Observations

The Cassini CIRS instrument in orbit around Saturn presents a unique opportunity to compare and contrast space-based observations with infrared ground-based observations, using a high-resolution (<0.1 cm^{-1}) cryogenic grating spectrometer (Celeste). The two methods complement each other as the CIRS observations provide excellent spatial resolution (∼0.5°) whereas Celeste provides higher spectral resolution and can produce a snapshot of all latitudes viewable from Earth at the time of the CIRS observations.

2.1. CIRS

The Composite Infrared Spectrometer (CIRS) on Cassini is a dual Fourier transform spectrometer covering the thermal infrared (Kunde et al., 1996). A Martin–Puplett polarizing interferometer covers the far-infrared from 10 to 600 cm^{-1} with a single 4 mrad field-of-view detector (FP1). A conventional Michelson interferometer covers the mid-infrared ranges 600–1100 cm^{-1} (FP3) and 1100–1500 cm^{-1} (FP4) with two 10-element detector arrays, each detector having a 0.3 mrad field-of-view. The apodized spectral resolution of CIRS can be chosen to be 0.5 to 15 cm^{-1}. The instrument operates at a temperature of 170 K, except for the mid-infrared detectors that operate near 80 K. CIRS is mounted on Cassini's remote sensing pallet and is bore-sighted with the other remote sensing ultraviolet, visible and infrared instruments. Pointing is achieved by positioning the spacecraft.

CIRS must build up planet-wide observations over many observing sessions and at higher spectral resolution more time is required at each latitude which results in there being less latitude coverage at 0.5 cm^{-1} spectral resolution. The 3 cm^{-1} spectral resolution observations provide relatively good spatial coverage and when this data is taken at high emission angle ($\theta > 70°$) it is possible to determine C_2H_2 and C_2H_6 abundances from the FP3 spectra. Fig. 1 shows the C_2H_2 and C_2H_6 contribution functions from model CIRS observations at 3 cm^{-1} with low- and high-emission angles. In the low-emission angle case (dash and dash–dot lines) there are two peaks: one in the stratospheric line forming region for these two hydrocarbons (∼1 mbar) and the other in the tropospheric continuum forming region (∼600 mbar). Using low-emission angle 3 cm^{-1} observations to retrieve hydrocarbon abundances can be difficult because any uncertainty in the tropospheric temperature can therefore affect the retrieved hydrocarbon abundance. Using high-emission angle data provides an excellent alternative as the contribution from the tropospheric continuum is significantly reduced which allows the hydrocarbon abundances to be retrieved