

ETHANE, ACETYLENE AND PROPANE DISTRIBUTION IN SATURN'S STRATOSPHERE FROM CASSINI/CIRS LIMB OBSERVATIONS

Guerlet, S.¹, Fouchet, T.¹ and Bézard, B.¹

Abstract. We present an analysis of limb observations performed by the Composite InfraRed Spectrometer (CIRS) instrument onboard the Cassini spacecraft, in order to investigate the temperature and composition of Saturn's stratosphere. Spectra were acquired at twenty different latitudes between 80°S and 45°N from March 2005 to January 2008, which corresponds to mid-summer in the southern hemisphere. We used a line-by-line radiative transfer model, coupled to an iterative retrieval algorithm, to determine the vertical temperature profile of the stratosphere at each latitude. Then, we derived the volume mixing ratio vertical profiles of various hydrocarbons: ethane, acetylene and propane.

Our results show an equatorial maximum of the abundance of acetylene at 1 mbar, almost twice as high as expected from photochemical models, which can be explained by a descent of air at the equator. As already observed in 2002 and 2004 by Greathouse et al. (2005) and Howett et al. (2007) at 2 mbar, we note that the volume mixing ratio of ethane slightly increases towards the South pole, which is evidence for a meridional circulation. As for propane, its meridional distribution suggests that its chemical lifetime in Saturn's stratosphere may be shorter than predicted.

1 Introduction

In Saturn's upper atmosphere, methane photolysis by solar UV initiates a complex hydrocarbon chemistry, which by-products are transported downwards by eddy diffusion. Saturn's 29.5-years seasonal cycle modulates this photochemistry, as well as the stratospheric temperatures, through temporal and latitudinal changes in solar insolation. In addition, the meridional hydrocarbon distribution is also affected by atmospheric dynamics such as horizontal diffusion and advection, which are still poorly known.

In this study, we analyzed a set of limb data acquired by the Composite InfraRed Spectrometer (CIRS) onboard the Cassini spacecraft. We retrieved the acetylene (C₂H₂), ethane (C₂H₆) and propane (C₃H₈) vertical and meridional stratospheric distributions. In particular, we retrieved the propane distribution with a spatial coverage never achieved before. By taking advantage of the limb viewing geometry, where infrared radiation is emitted through a large optical path and a narrow altitude range, we also improved the vertical extent and resolution with respect to previous nadir observations. These three species, having various chemical lifetimes, are affected in different ways by atmospheric dynamics. Comparing their volume mixing ratios (*vmr*) inferred from observations to photochemical models thus provides a way of tracing dynamical phenomena.

2 Instrument and data

2.1 CIRS instrument

The Fourier-spectrometer CIRS comprises three focal planes covering the mid-infrared region, two being used in this study:

- Focal Plane 3 (FP3), covering the 600 - 1100 cm⁻¹ (9 μm to 16 μm) spectral range ;
- Focal Plane 4 (FP4), covering the 1100 - 1400 cm⁻¹ region (7 μm to 9 μm).

¹ LESIA - Observatoire de Paris

Both FP3 and FP4 consist in a linear array of 10 squared detectors, with an individual field of view (IFOV) of 0.273×0.273 mrad. Depending on the spacecraft distance to Saturn, the projected IFOV on the planet varied from 50×50 km to 100×100 km (one to two scale heights). During a limb observation, the two 10-detectors arrays of FP3 and FP4 were set perpendicular to the limb, so that each detector probed a different altitude.

2.2 Data selection

Spectra analyzed hereafter were acquired at 15 cm^{-1} spectral resolution during four dedicated fly-bys between March, 2005 and August, 2006, which corresponded to summer in the Southern hemisphere (since 2002, until equinox in 2009). The latitudinal coverage extended from 45°S to 45°N , every 5° , where most latitudes have been sampled two or three times. We also investigated a few data sets acquired at 1 and 3 cm^{-1} , including more southern latitudes at 70°S and 80°S .

3 Method

We used a line-by-line radiative transfer model to calculate synthetic spectra. It included opacity from CH_4 , CH_3D , C_2H_6 , C_2H_2 , C_3H_8 , C_3H_4 , C_4H_2 and collision-induced opacity from H_2 -He and H_2 - H_2 . The atmospheric grid consisted in 360 layers from 10 bar to 10^{-8} bar. It was coupled with an iterative inversion algorithm adapted from Conrath et al. (1998), in order to retrieve the atmospheric state (temperature, hydrocarbon vertical profiles) from the measured spectra.

As a molecular emission intensity depends on both its abundance and temperature, we proceeded in two steps. First, we retrieved the temperature vertical profile from the methane ν_4 emission band at 1305 cm^{-1} (assuming it is uniformly mixed with a *vmr* of 4.5×10^{-3} (Flasar et al. 2005)), providing information in the 1 mbar - 2 μbar region. In order to retrieve the temperature between 20 mbar and 1 mbar, we simultaneously inverted the $600\text{-}660 \text{ cm}^{-1}$ continuum emission induced by H_2 -He and H_2 - H_2 collisions. Then, this temperature profile was incorporated in the model, so that we could retrieve the C_2H_6 *vmr* profile from its ν_9 emission band (centered at 822 cm^{-1}), the C_2H_2 profile from its ν_5 emission band (730 cm^{-1}) and the C_3H_8 profile from its ν_{21} band (748 cm^{-1}).

The two latter molecules had to be inverted simultaneously, as the propane ν_{21} Q-branch is located in the same region as the C_2H_2 ν_5 R-branch. The calculated kernels (which represent how the intensity at a wavenumber i is a function of a state parameter at a level z) showed that CIRS observations were sensitive in the range 5 mbar-10 μbar for C_2H_2 and C_2H_6 , and in the range 5 mbar to 0.5 mbar for C_3H_8 .

Figure 1 shows an example of a comparison between synthetic and observed emission bands of ethane, acetylene and propane at two given pressure levels (all the different pressure levels probed by CIRS have not been plotted for the sake of clarity) and Fig. 3 the corresponding retrieved profiles.

4 Results and discussion

4.1 Stratospheric temperature

The temperature structure is discussed in details in Fouchet et al. 2008. The main feature is an equatorial oscillation, analogous to the Earth's quasi-biennial oscillation (QBO), resulting from interactions between vertically propagating waves and the mean zonal flow. Regarding the seasonal response, we find a larger north to south temperature gradient at ~ 1 mbar than at ~ 0.01 mbar. The thermal inertia being larger at low altitudes, this is not expected from the thermal response of the atmosphere.

4.2 Hydrocarbon distribution

Results about the meridional distribution of the C_2H_6 , C_2H_2 and C_3H_8 volume mixing ratio at 1 and 0.1 mbar are displayed in Fig. 3.

We first note that all three hydrocarbon meridional distributions exhibit a maximum at the equator at 1 mbar. This is in good agreement with photochemical models which predict that mean insolation being greater at the equator, it should coincide with a larger hydrocarbon production and thus a larger abundance. However, especially for C_2H_2 , our derived maximum at the equator is larger than predicted: at 1 mbar, we note a 80°S -to-equator enhancement of about 4, in contrast to the expected factor of 2 (Moses et al., 2005). This enhancement

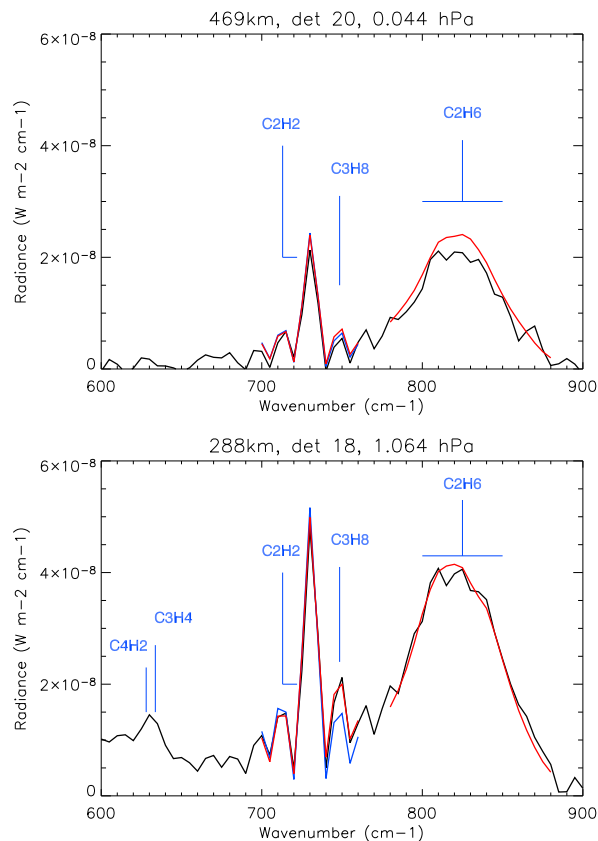


Fig. 1. Synthetic spectra (in red and blue) plotted over observed spectra (in black) at $20^\circ S$ from two different detectors, thus two different altitudes. The model that do not account for propane opacity (in blue) fails to reproduce the acetylene R-branch intensity around the 1-mbar pressure level

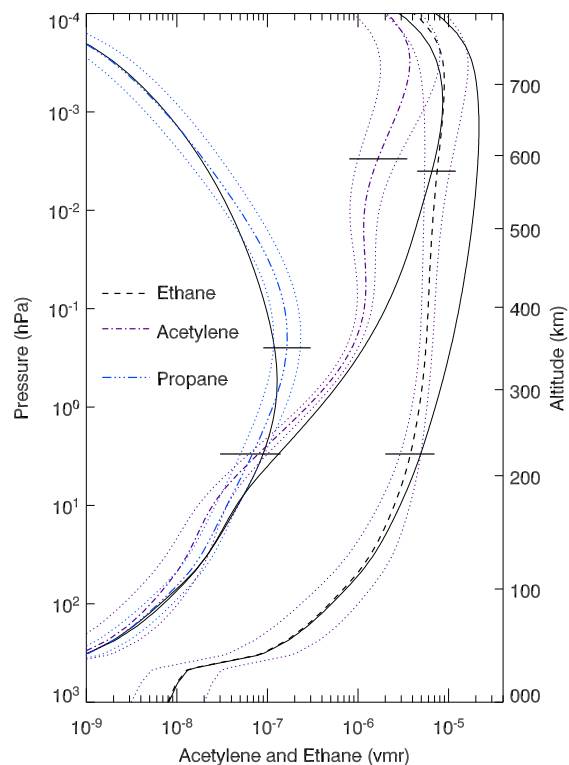


Fig. 2. The corresponding retrieved profiles of C_2H_6 , C_2H_2 and C_3H_8 in dashed and dotted-dashed lines. The a priori profiles are in solid lines, the error bars in dotted lines and the horizontal bars represent the vertical limits in sensitivity.

can be explained by a descent of rich-hydrocarbon air at the equator, initiated by the equatorial oscillation, and would affect preferentially C_2H_2 because its vertical profile has a steeper gradient than compared to C_2H_6 .

Another unexpected feature is the region of strong hydrocarbon abundance around $25^\circ N$, observed at the 0.1-mbar pressure level and above for both C_2H_2 and C_2H_6 . It seems to be correlated with the area undergoing ring shadowing at this season. It may be associated with a downwelling branch of the meridional circulation.

The global meridional distribution of the three hydrocarbons can be analyzed in terms of their net photochemical lifetimes. Below the 0.1-mbar level, these lifetimes are supposed to be longer than Saturn's year, so that their distributions should reproduce the yearly averaged solar insolation (decreasing towards both poles). At 1 mbar, apart from the equatorial region, C_2H_2 distribution agrees very well, qualitatively, with this prediction (cf Fig 3) whereas C_2H_6 is found to slightly increase towards the South Pole. This trend for C_2H_6 has already been observed by Greathouse et al. (2005) and Howett et al. (2007) at 1 and 2 mbar and interpreted as caused by meridional circulation from equator to South Pole. It can be explained by the fact that C_2H_6 have a much longer lifetime (about 600 years at 1 mbar) than C_2H_2 (~ 100 years at 1 mbar): as the two molecules are transported towards the South Pole, C_2H_2 is more rapidly chemically destroyed than C_2H_6 , which explains why we only observe an enhancement for C_2H_6 and constrains the dynamical timescale to lie between 100 and 600 years at 1 mbar.

On the other hand, the propane abundance is found to gradually increase from $45^\circ N$ to $80^\circ S$ at 1 mbar (cf Fig. 3) by a factor of 2.5. Although its chemical lifetime is not well constrained because of the lack of laboratory data, it is supposed to be intermediate between C_2H_6 and C_2H_2 lifetimes at 1 mbar. We thus expect

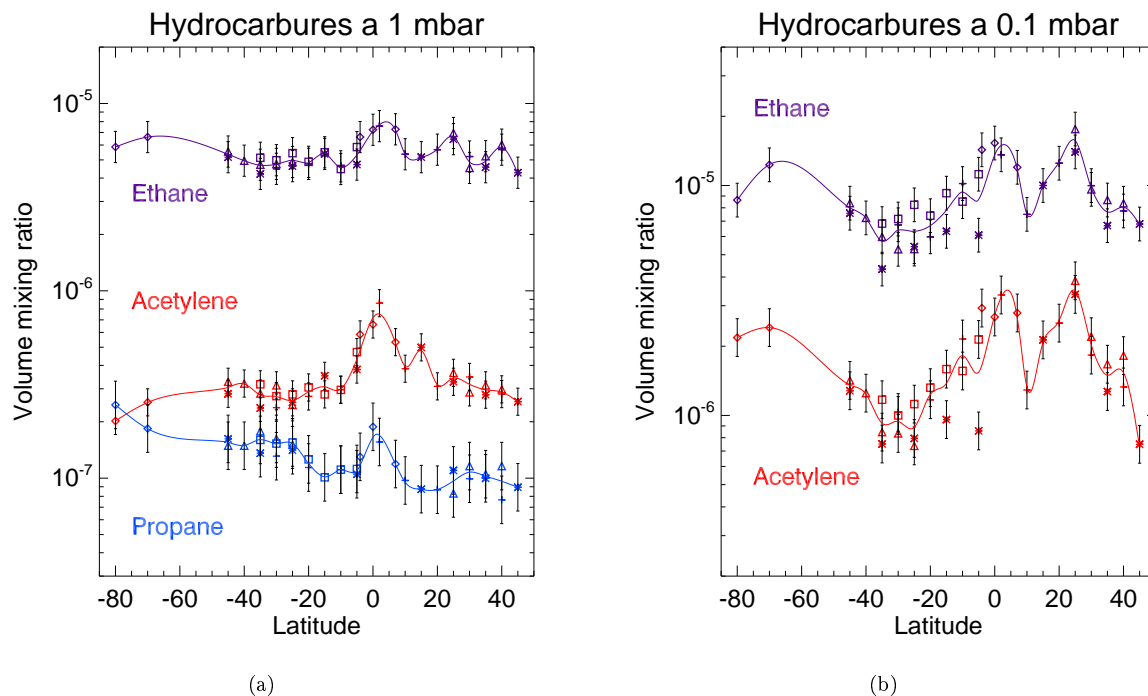


Fig. 3. Meridional hydrocarbon variations at the 1-mbar (left) and the 0.1-mbar (right) pressure levels.

the propane distribution to be less affected by meridional transport than C_2H_6 . However, the North-to-South gradient is found greater for propane than for ethane. This anomaly can be explained if the C_3H_8 lifetime at 1 mbar is shorter than or similar to Saturn's season, leading to an increase of C_3H_8 towards southern latitudes due to the increasing solar insolation, at odds with predictions from photochemical models.

Eventually, at 0.1 mbar, we find that the two molecules display very similar distributions, meaning that the two molecules are transported, chemically produced and destroyed on same timescales. This is consistent with photochemical models that predict they have similar chemical lifetimes at this pressure level (Moses & Greathouse, 2005).

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