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Meridional variations of temperature, C_2H_2 and C_2H_6 abundances in Saturn's stratosphere at southern summer solstice

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Abstract

Measurements of the vertical and latitudinal variations of temperature and C_2H_2 and C_2H_6 abundances in the stratosphere of Saturn can be used as stringent constraints on seasonal climate models, photochemical models, and dynamics. The summertime photochemical loss timescale for C_2H_6 in Saturn's middle and lower stratosphere (~40–10,000 years, depending on altitude and latitude) is much greater than the atmospheric transport timescale; ethane observations may therefore be used to trace stratospheric dynamics. The shorter chemical lifetime for C_2H_2 (~1–7 years depending on altitude and latitude) makes the acetylene abundance less sensitive to transport effects and more sensitive to insolation and seasonal effects. To obtain information on the temperature and hydrocarbon abundance distributions in Saturn's stratosphere, high-resolution spectral observations were obtained on September 13–14, 2002 UT at NASA's IRTF using the mid-infrared TEXES grating spectrograph. At the time of the observations, Saturn was at a $L_S \approx 270°$, corresponding to Saturn's southern summer solstice. The observed spectra exhibit a strong increase in the strength of methane emission at 1230 cm^{-1} with increasing southern latitude. Line-by-line radiative transfer calculations indicate that a temperature increase in the stratosphere of ≈10 K from the equator to the south pole between 10 and 0.01 mbar is implied. Similar observations of acetylene and ethane were also recorded. We find the 1.16 mbar mixing ratio of C_2H_2 at $-1°$ and $-83°$ planetocentric latitude to be $9.2^{+6.4}_{-3.8} \times 10^{-7}$ and $2.5^{+1.8}_{-1.0} \times 10^{-7}$, respectively. The C_2H_2 mixing ratio at 0.12 mbar is found to be $1.0^{+0.5}_{-0.3} \times 10^{-5}$ at $-1°$ planetocentric latitude and $2.6^{+1.3}_{-0.9} \times 10^{-6}$ at $-83°$ planetocentric latitude. The 2.3 mbar mixing ratio of C_2H_6 inferred from the data is $7.5^{+2.3}_{-1.7} \times 10^{-6}$ and $1.0^{+0.3}_{-0.2} \times 10^{-5}$ at $-1°$ and $-83°$ planetocentric latitude, respectively. Further observations, creating a time baseline, will be required to completely resolve the question of how much the latitudinal variations of C_2H_2 and C_2H_6 are affected by seasonal forcing and/or stratospheric circulation.

Keywords: Infrared observations; Saturn; Atmosphere; Abundances

1. Introduction

Saturn, like the Earth, undergoes seasonal variations due to an axial tilt of ≈27° to its orbital plane. Changes in insolation with latitude over a saturnian year cause latitudinal variations of temperature and photochemistry. Saturn's stratosphere is very similar to Jupiter's, where it has recently been shown that C_2H_2 and C_2H_6 are the dominant coolants

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(Yelle et al., 2001). These molecules are photochemical by-products of methane photolysis, so their abundance versus latitude may be tied to seasonally varying insolation. To understand how seasons affect the meridional temperature profile and photochemical production and loss rates requires knowledge of the temperature and abundances of these key photochemical molecules as a function of latitude and time.

In 1973, spatially resolved N/S scans of Saturn, taken at 12 µm in the ν_9 band of ethane, showed a gradual increase in emission from north to south and a substantial peak in emission over the south pole during Saturn's southern summer (Gillett and Orton, 1975; Rieke, 1975). Variations in ethane emission could be attributed to either temperature or abundance variations. Later, in 1975 and 1977, Tokunaga et al. (1978) made spatially resolved N/S scans at other wavelengths, including within the ν_4 band of methane at 7.9 µm. They observed a similar increase in emission with increasing southern latitude in the methane band as was seen earlier in the ethane-band observations. Because it is controlled by diffusion and transport rather than by photochemistry, the methane vertical distribution is not expected to exhibit noticeable variations in abundance with latitude. Therefore, the variable emission observed in the CH_4 ν_4 band provided evidence that the emission enhancement was caused by a temperature increase towards high-southern latitudes. Cess and Caldwell (1979) constructed a stratospheric seasonal model attempting to describe the physics behind the variable emission seen in these early observations. Their model successfully accounted for the emission trends observed by Tokunaga et al. (1978), with the predicted stratospheric temperature being higher at the south pole than at the equator. However, the model indicated the temperature at the south pole should be lower than that at the equator during the 1973 observations, whereas Gillett and Orton (1975) and Rieke (1975) observed enhanced 12-µm emission at the south pole. Cess and Caldwell (1979) therefore suggested that the observed south polar enhancement of 12-µm emission in 1973 could have been caused by enhanced ethane abundances rather than enhanced temperatures.

During the Voyager missions in 1980 and 1981, shortly after Saturn's northern spring equinox, $L_S \approx 0°$, the infrared spectrometer IRIS provided spatially and spectrally resolved measurements of thermal emission (e.g., Hanel et al., 1981, 1982). Using temperatures retrieved from the inversion of Voyager infrared spectra, Conrath and Pirraglia (1983) showed that Saturn's tropospheric temperature at the 150-mbar level exhibited a warming trend from north to south, but this trend was not present at the 290- or 730-mbar levels. They explained that this difference was caused by the variation in thermal inertia with altitude producing a phase lag in the thermal response. Due to observational limitations (see Hanel et al., 1981, 1982), stratospheric temperature maps have never been derived from the Voyager IRIS data. Similarly, although latitudinal variations in hydrocarbon emissions were observed by IRIS, no analysis of the abundance variations has ever been published, perhaps because of the difficulty in separating the individual roles of temperature and abundance in contributing to the emission (see Courtin et al., 1984; Bjoraker et al., 1985). Using the Voyager IRIS data as a constraint, Bézard and Gautier (1985) improved upon previous seasonal models by incorporating a radiative transfer treatment and including ring shadowing effects on the insolation of Saturn. By calculating latitudinally dependent heating and cooling rates modulated by the saturnian season, they showed that at 5-mbar seasonal variations of insolation could produce peak temperature variations from pole to pole of 30 K, three to five years following the solstices.

Ground-based infrared images obtained by Gezari et al. (1989) have revealed a latitudinal gradient in 7.8-µm methane emission increasing from the equator to the north pole. This reversal of the emission gradient from the early 1973 and 1975 observations was successfully predicted by the seasonal climate models of Bézard and Gautier (1985), Bézard et al. (1984), and Cess and Caldwell (1979). More recent observations of seasonal effects on Saturn were attempted by Ollivier et al. (2000). The observations, taken in 1992 during Saturn's northern summer, exhibited brightness variations in their mid-infrared circular-variable-filter (CVF) images similar to those observed by Gezari et al. (1989). Ollivier et al. (2000) attempted retrievals of temperature and abundances of C_2H_2 and C_2H_6. However, their observations could not constrain the temperature at the 2-mbar level independently from the abundance of C_2H_2 or C_2H_6.

In this paper we attempt to derive the stratospheric temperature using independent information from that used to derive the abundances of C_2H_2 and C_2H_6 in Saturn's stratosphere. We use high-resolution spectra of the ν_4 band of methane to derive stratospheric temperatures. Methane is the most abundant trace molecule in Saturn's atmosphere; however, its mixing ratio is still uncertain due to the derivations being somewhat model dependent. Using recent Cassini CIRS observations of CH_4 pure rotational lines, Flasar et al. (2004) determined the methane tropospheric mixing ratio to be $4.5 \pm 0.9 \times 10^{-3}$. This result is in excellent agreement with that of Courtin et al. (1984) who derived a constant mixing ratio of $4.5^{+2.4}_{-1.9} \times 10^{-3}$ for the lower stratosphere using Voyager IRIS observations. Other determinations have ranged from $\sim 1.7 \times 10^{-3}$ to $\sim 4.2 \times 10^{-3}$ (Tomasko and Doose, 1984; Trafton, 1985; Killen, 1988; Karkoschka and Tomasko, 1992; Kerola et al., 1997; Lellouch et al., 2001). The CH_4 mixing ratio is expected to remain roughly constant in the lower stratosphere until it declines due to diffusive separation above the methane homopause (e.g., Festou and Atreya, 1982; Smith et al., 1983). In addition, the methane abundance is affected primarily by diffusion and not by chemistry in the middle and lower stratosphere. The methane distribution is therefore expected to be homogeneous with latitude and longitude throughout much of the stratosphere, and variations in the strength of its emission lines must then be due to thermal variations. This assumed uniformity, along with the fact that CH_4 emits on