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Stratospheric benzene and hydrocarbon aerosols observed in Saturn's upper atmosphere

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Abstract

Saturn's polar upper atmosphere undergoes significant auroral activity, which could impact Saturn's stratospheric chemistry and in return its radiative budget. Photochemical models including ion chemistry developed for Jupiter predict that benzene is enhanced in the auroral regions due to the precipitation of high-energy electrons and is a precursor for the formation of heavier ring polycyclic aromatic hydrocarbons. Here we review recent observations of benzene in Saturn's middle and upper atmosphere by Cassini/CIRS and Cassini/UVIS that advocate for a strong influence of solar-driven and auroral-driven ion chemistry on Saturn as well. Hydrocarbon aerosols are detected in Saturn's auroral regions by both instruments, supporting a similar aerosol formation scenario than in Jupiter's stratosphere. We then evaluate their radiative impact on Saturn's stratospheric temperatures.

1. Introduction

Saturn's polar regions are characterized by permanent dark polar caps in the ultraviolet, whose latitudinal extent coincides with that of auroral emissions [3]. These dark regions are generally attributed to the presence of polar stratospheric hazes [13, 7], possibly produced by the precipitation of energetic auroral electrons [11]. In the case of Jupiter's polar atmosphere, benzene (C_6H_6) has been proposed as a precursor to the formation of more complex hydrocarbons, such as polyacetylenes and multi-ring compounds, which could condense to form polar aerosols [2, 14]. This formation scenario, in which ion chemistry plays a key role, could also apply to Saturn, but such model has not been applied to Saturn yet. In addition, until recently, only the disk-average benzene column density had been measured from ISO [1]. Such measurements could not shed light on the influence of ion chemistry or aerosol formation in Saturn's atmosphere.

Here we review two recent observational studies that support the importance of ion chemistry in producing benzene and aerosols in Saturn's atmosphere. We then study the radiative impact of stratospheric aerosols on the temperature profile and will present comparisons with seasonal temperature changes observed by Cassini.

2. Benzene observations

The benzene emission band at 673 cm^{-1} has been detected in two sets of spectra acquired by the Composite Infrared Spectrometer (CIRS) in limb viewing geometry: at 80S in 2007 (mid-summer) and at 77N in 2015 (late spring). These measurements probes the neutral, middle stratosphere (3–0.01 mbar). Using a radiative transfer model coupled to an inversion algorithm, its partial column abundance has been retrieved. Upper limits on its column abundance have been derived from other CIRS limb spectra acquired at 40N, 35S and the equator. The partial column of C_6H_6 derived at 80S, of $4.1 \pm 1 \times 10^{13}$ cm^{-1}, is of the same order of magnitude that the upper limits derived at mid and low latitudes [5]. However, photochemical (neutral) models predict 50 times less benzene at 80S than at the equator [10]. Furthermore, at 77N in 2015, we find that the benzene mixing ratio profile must increase with altitude up to at least the 0.01 mbar pressure level to match the radiances measured by CIRS at different tangent altitudes [6], which is also at odds with the neutral photochemical model prediction of a peak abundance at $\sim$0.5 mbar.

In parallel, absorption by benzene has been detected in 18 Cassini/UVIS stellar occultations, including three pronounced absorptions at latitudes of 48.9S in April 2005, 74.3N in September 2012, and 72.7S in January 2015 [9]. UVIS data uniquely probe the photochemical production region at the 1 μbar pressure level. Hydrocarbon number densities are retrieved as a function of radial distance from Saturn's center and are then converted to volume mixing ratios as a function of pressure. The resulting peak mixing ratios of benzene at 0.1–10 μbar range from about 2×10^{-8} (72.7S) to 5×10^{-7} (74.3N), which is much larger than predictions based on solar UV-driven neutral photochemistry that produces a peak benzene mixing ratio of 2×10^{-10} at 0.4 mbar [10]. The detection of benzene at lower latitudes and near the equator could be explained by solar-driven ion chemistry, with enhanced production from the aurora at high latitudes.

Altogether, these two studies advocate for the inclusion of both solar-driven ion chemistry and auroral-driven ion chemistry in current Saturn photochemical models to explain the observed benzene abundances.

3. Aerosol observations

Three Cassini/CIRS limb spectra, acquired at 80S in 2007, 77S and 77N in 2015 also exhibited residual signatures that were attributed to aerosol signatures. We retrieved their opacity profiles in the range 3–0.1 mbar in distinct spectral bands centered at 700, 750, 780, 1390 and 1450 cm^{-1} [5]. Interestingly, similar spectral features are also observed in Titan's stratosphere [12] which have been assigned to vibration modes of aliphatic and aromatic hydrocarbons. We find that the aerosol scale height is about twice the pressure scale height, which suggests that these aerosols are produced at high altitudes and sediment in the lower stratosphere, where they accumulate. We also estimate the aerosol mass loading in Saturn's polar stratosphere, which is found to be one order of magnitude lower than on Jupiter, consistent with their respective auroral intensities.

Absorption by haze is also detected in one UVIS occultation, at 72.7S in January 2015 [9]. This absorption feature in the 180–190 nm wavelength window is also similar to extinction by haze on Titan [8]. This unique detection occurs during the polar night where the mesospheric temperatures are low (125K, as derived from CIRS limb measurements) and favor the condensation of benzene and hydrocarbon aerosols.

In summary, haze signatures are detected at high latitudes both in CIRS and UVIS datasets. This supports the link between the precipitation of energetic electrons and the production of benzene and aerosols, as suggested by previous Voyager and HST observations and by photochemical models including ion chemistry developed for Jupiter.

4. Radiative impact

We evaluate the radiative impact of this polar haze on the thermal structure using a seasonal radiative-convective model of Saturn's atmosphere [4]. We assume that aerosols are spherical aggregates with a radius of 0.1 μm and use Mie scattering theory to compute their extinction coefficient. We find that the polar haze induces a net stratospheric heating during summer reaching +6 K at the 10-mbar pressure level, and a net stratospheric cooling during winter reaching -5 K at and above the 0.1-mbar pressure level [5]. We will discuss the possibility that Saturn's warm polar hood observed in the middle stratosphere during summer could be partly due to radiative heating by aerosols.

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