Icarus 261 (2015) 149–168

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus

Evolution of stratospheric chemistry in the Saturn storm beacon region

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ARTICLE INFO

Article history:
Received 17 April 2015
Revised 26 June 2015
Accepted 8 August 2015
Available online 14 August 2015

Keywords:
Atmospheres, chemistry
Atmospheres, dynamics
Infrared observations
Photochemistry
Saturn, atmosphere

ABSTRACT

The giant northern-hemisphere storm that erupted on Saturn in December 2010 triggered significant changes in stratospheric temperatures and species abundances that persisted for more than a year after the original outburst. The stratospheric regions affected by the storm have been nicknamed "beacons" due to their prominent infrared-emission signatures (Fletcher, L.N. et al. [2011]. Science 332, 1413). The two beacon regions that were present initially merged in April 2011 to form a single, large, anticyclonic vortex (Fletcher, L.N. et al. [2012]. Icarus 221, 560). We model the expected photochemical evolution of the stratospheric constituents in the beacons from the initial storm onset through the merger and on out to March 2012. The results are compared with longitudinally resolved *Cassini*/CIRS spectra from May 2011. If we ignore potential changes due to vertical winds within the beacon, we find that C_2H_2, C_2H_6, and C_3H_8 remain unaffected by the increased stratospheric temperatures in the beacon, the abundance of the shorter-lived CH_3C_2H decreases, and the abundance of C_2H_4 increases significantly due to the elevated temperatures, the latter most notably in a secondary mixing-ratio peak located near mbar pressures. The C_4H_2 abundance in the model decreases by a factor of a few in the 0.01–10 mbar region but has a significant increase in the 10–30 mbar region due to evaporation of the previously condensed phase. The column abundances of C_6H_6 and H_2O above ~30 mbar also increase due to aerosol evaporation. Model-data comparisons show that models that consider temperature changes alone underpredict the abundance of C_2H_x species by a factor of 2–7 in the beacon core in May 2011, suggesting that other processes not considered by the models, such as downwelling winds in the vortex, are affecting the species profiles. Additional calculations indicate that downwelling winds of order $-10\ \mathrm{cm\ s^{-1}}$ near ~0.1 mbar need to be included in the photochemical models in order to explain the inferred C_2H_x abundances in the beacon core, indicating that both strong subsiding winds and chemistry at elevated temperatures are affecting the vertical profiles of atmospheric constituents in the beacon. We (i) discuss the general chemical behavior of stratospheric species in the beacon region, (ii) demonstrate how the evolving beacon environment affects the species vertical profiles and emission characteristics (both with and without the presence of vertical winds), (iii) make predictions with respect to compositional changes that can be tested against *Cassini* and *Herschel* data, and higher-spectral-resolution ground-based observations of the beacon region, and (iv) discuss future measurements and modeling that could further our understanding of the dynamical origin, evolution, and chemical processing within these unexpected stratospheric vortices that were generated after the 2010 convective event.

1. Introduction

The pristine, hazy appearance of Saturn, with its muted atmospheric banding, is known to be disturbed on rare occasions by enormous convective storms dubbed "Great White Spots" (e.g., Sanchez Lavega, 1982; Sanchez Lavega and Battaner, 1987). In December 2010, one such gigantic storm system erupted at northern mid-latitudes on Saturn (Sánchez-Lavega et al., 2011; Fischer et al., 2011; Fletcher et al., 2011). The "head" of the storm drifted westward with the prevailing zonal winds, leaving a turbulent wake of fresh cloud particles. Within a couple of months of the storm onset, the storm head had caught up with its wake "tail" to form a distinct planet-encircling band of clouds that persisted for more than a year after the storm's initial appearance

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http://dx.doi.org/10.1016/j.icarus.2015.08.012
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(e.g., Sánchez-Lavega et al., 2012; Sayanagi et al., 2013). Although the convective disturbance originated in the troposphere and had a notable effect on the cloud structure, lightning activity, atmospheric dynamics, thermal structure, and distribution of molecular species within the troposphere (Fischer et al., 2011; Sánchez-Lavega et al., 2011, 2012; Fletcher et al., 2011, 2012; Hurley et al., 2012; Sanz-Requena et al., 2012; Janssen et al., 2013; Laraia et al., 2013; Sayanagi et al., 2013; Dyudina et al., 2013; Sromovsky et al., 2013; Achterberg et al., 2014; Trammell et al., 2014), the storm also had some profound and unexpected consequences for higher-altitude regions. In particular, temperatures in the stratosphere were found to be greatly elevated in latitude regions associated with the storm, perhaps as a result of momentum and energy redistribution from vertically-propagating atmospheric waves generated from tropospheric convective plume activity and/or from dynamical compression within the resulting vortex region (Sayanagi and Showman, 2007; Fletcher et al., 2011, 2012). In addition, the gas-phase abundances of ethylene and water were inferred to have increased by roughly two orders of magnitude in these high-temperature stratospheric regions in the months after the storm onset (Hesman et al., 2012; Cavalié et al., 2012).

The strong stratospheric temperature increase was initially confined to two broad air masses nicknamed "beacons" due to their distinctive bright signatures at infrared wavelengths (Fletcher et al., 2011). These two initial air masses, centered at different longitudes/latitudes and associated with zonal winds of different relative velocities, encountered each other in April 2011, at which point the two beacons merged into a single, enormous, anticyclonic vortex (Fletcher et al., 2012). Temperatures within the initial two beacons rose rapidly in the months before the merger, intensified and reached a maximum in the combined beacon vortex after the merger, and then cooled slowly but steadily from May 2011 onward (Fletcher et al., 2012; see also Fletcher et al., 2011; Hesman et al., 2012).

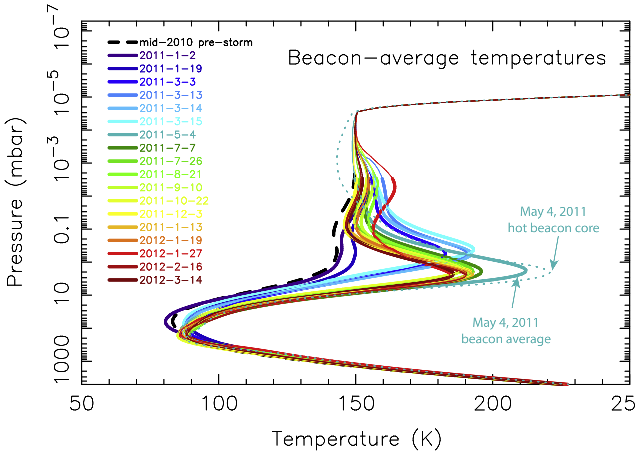

Fig. 1. Evolution of the vertical temperature profiles within one of the initial beacons ('B1') and the merged beacon ('B0') as a function of time after the storm onset, as retrieved by Fletcher et al. (2012) from *Cassini* CIRS spectra coadded from regions within ±5° latitude and ±10° longitude of the beacon centers. Dates of the observations are color-coded, as labeled. The actual retrievals are shown by the thicker lines, while the thinner lines at high altitude show model profiles artificially expanded beyond the pressure range of CIRS sensitivity (i.e., the actual published CIRS retrievals extend to $\sim 10^{-3}$ mbar, although note that the nadir temperature retrievals lose their sensitivity beyond the ~0.5–230 mbar range). Although our photochemical models require extensions to higher altitudes, no simultaneous temperature data exist for the beacon regions at such high altitudes. The dotted line represents the retrieved thermal profile from the hottest region of the beacon on May 4, 2011. Figure is adapted from Fletcher et al. (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The *Cassini* spacecraft was in a prime position to track the evolution of the storm and its associated beacon features. Fig. 1 shows the vertical temperature profiles derived by Fletcher et al. (2012) from spectra acquired with the Composite Infrared Spectrometer (CIRS) instrument aboard *Cassini*. These temperature retrievals were obtained from spectra coadded over broad areas of the beacons (i.e., within ±10° longitude, ±5° latitude of the beacon center)—temperatures within the hottest regions at the beacon centers were even higher. For example, on May 4, 2011, after the merger, 2-mbar temperatures at the central "core" of the beacon reached ~220 K, about 80 K greater than the pre-storm temperature (Fletcher et al., 2012; see also Hesman et al., 2012), whereas the broader-scale averages indicated temperatures of ~210 K at 2 mbar.

The higher temperatures resulted in increased infrared emission, making molecular bands from trace stratospheric constituents easier to identify. One such example is ethylene (C_2H_4), which was not identified in CIRS spectra before the storm at northern mid-latitudes, but which was detected by Hesman et al. (2012) in the post-storm beacon region in May 2011, from both *Cassini* CIRS data and ground-based infrared observations. Hesman et al. (2012) derived stratospheric temperatures at ~0.5–5 mbar using the ν_4 band of methane (CH_4) in the 1250–1311 cm^{-1} wavenumber region, which then allowed them to retrieve the C_2H_4 abundance from the observed ethylene emission band near 950 cm^{-1}. The retrievals of the ethylene abundance profile are complicated by the possibility that the C_2H_4 emission may not originate from the 0.5–5-mbar pressure levels where the temperatures are best constrained; however, the Hesman et al. (2012) analysis clearly indicates that the ethylene abundance in May 2011 was significantly increased in the beacon region at $\sim 10–10^{-2}$ mbar in comparison with pre-storm observations and expectations (Fig. 2). In fact, Hesman et al. (2012) found that their pre-storm photochemical-model profile for C_2H_4 would need to be increased uniformly by almost two orders of magnitude in order to reproduce the observed ethylene emission from the beacon, whereas their photochemical models predicted only a factor of ~2 increase in the C_2H_4 mixing ratio due to the elevated temperatures in the beacon. Hesman et al. (2012) explored several ideas as to the mechanisms that could be the cause of the C_2H_4 enhancement, but they did not come up with a definitive conclusion. Fig. 2 shows

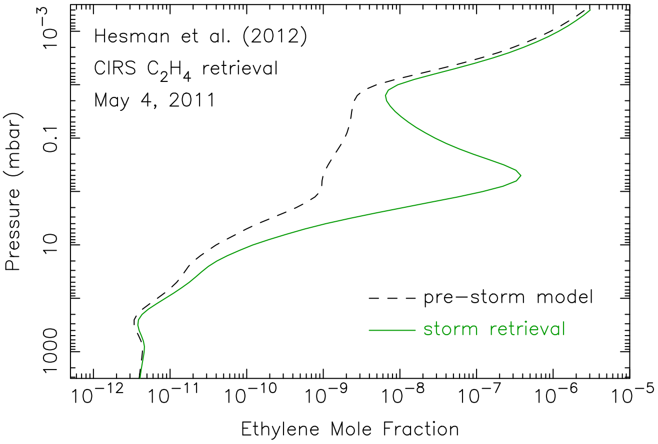

Fig. 2. The ethylene mole fraction predicted from the photochemical model presented in Hesman et al. (2012) (dashed line), compared with the Hesman et al. (2012) retrieval from 2.5 cm^{-1}-resolution CIRS beacon spectra from May 2011 (green solid line). Note the strongly peaked behavior between 0.1 and 1 mbar and the very large increase in the retrieved C_2H_4 mole fraction compared with pre-storm predictions. Figure is adapted from Hesman et al. (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)