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Cloud clearing in the wake of Saturn's Great Storm of 2010–2011 and suggested new constraints on Saturn's He/H_2 ratio

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ABSTRACT

Saturn's Great Storm of 2010–2011 produced a planet-encircling wake that slowly transitioned from a region that was mainly dark at 5 µm in February 2011 to a region that was almost entirely bright and remarkably uniform by December of 2012. The uniformity and high emission levels suggested that the entire wake region had been cleared not only of the ammonia clouds that the storm had generated and exposed, but also of any other aerosols that might provide significant blocking of the thermal emission from Saturn's deeper and warmer atmospheric layers. Our analysis of VIMS wake spectra from December 2012 provides no evidence of ammonia ice absorption, but shows that at least one significant cloud layer remained behind: a non-absorbing layer of 3–4 optical depths (at 2 µm) extending from 150 to ~400 mbar. A second layer of absorbing and scattering particles, with less than 1 optical depth and located near 1 bar, is also suggested, but its existence as a model requirement depends on what value of the He/H_2 ratio is assumed. The observations can be fit well with just a single (upper) cloud layer for a He/H_2 ratio ≈ 0.064 in combination with a PH_3 deep volume mixing ratio of 5 ppm. At lower He/H_2 ratios, the observed spectra can be modeled without particles in this region. At higher ratios, in order to fit the brightest wake spectrum, models must include either significant cloud opacity in this region, or significantly increased absorption by PH_3, NH_3, and AsH_3. As the exceptional horizontal uniformity in the late wake is most easily understood as a complete removal of a deep cloud layer, and after considering independent constraints on trace gas mixing ratios, we conclude that the existence of this remarkable wake uniformity is most consistent with a He/H_2 mixing ratio of $0.055^{+0.010}_{-0.015}$, which is on the low side of the 0.038–0.135 range of previous estimates.

1. Introduction

Saturn's Great Storm of 2010–2011 was one of the most powerful convective events ever witnessed. Its rapid development, its huge horizontal scale, and the planet encircling wake it generated within ~6 months were accompanied by a prolific generation of lightning (Dyudina et al., 2013; Fischer et al., 2011) and an unusual spectral character consistent with the delivery of ammonia and water ices to the visible cloud deck (Sromovsky et al., 2013), which is ~200 km above the water vapor condensation level near 20 bar, where the lightning also appears to have originated. The dramatic growth of the storm after its initial formation in early December 2010 was documented by amateur and professional groundbased imaging (Sánchez-Lavega et al., 2012) and by Cassini imaging with the Imaging Science Subsystem (ISS) (Sayanagi et al., 2013).

The morphological characteristics of the storm during February and May of 2011 are illustrated in Fig. 1, where ISS images are displayed in comparison with infrared images obtained by the Visual and Infrared Mapping Spectrometer (VIMS). The first VIMS spectral imaging of the storm occurred in February 2011, after it was well developed and had a planet-encircling wake, though at the latitude of the storm head, the region upstream of the head was still undisturbed at that time. In these VIMS images, color assignments are 4.08 µm for red, 1.89 µm for green, and 3.05 µm for blue. The strong absorption at 3 µm in clouds that are bright at the other two wavelengths produce the orange color that indicates the presence of ammonia ice, which was mainly confined to a 10° band of latitude centered at 35°N planetocentric latitude, and much less evident in the secondary wake extending south of the storm, especially in the May 2011 images.

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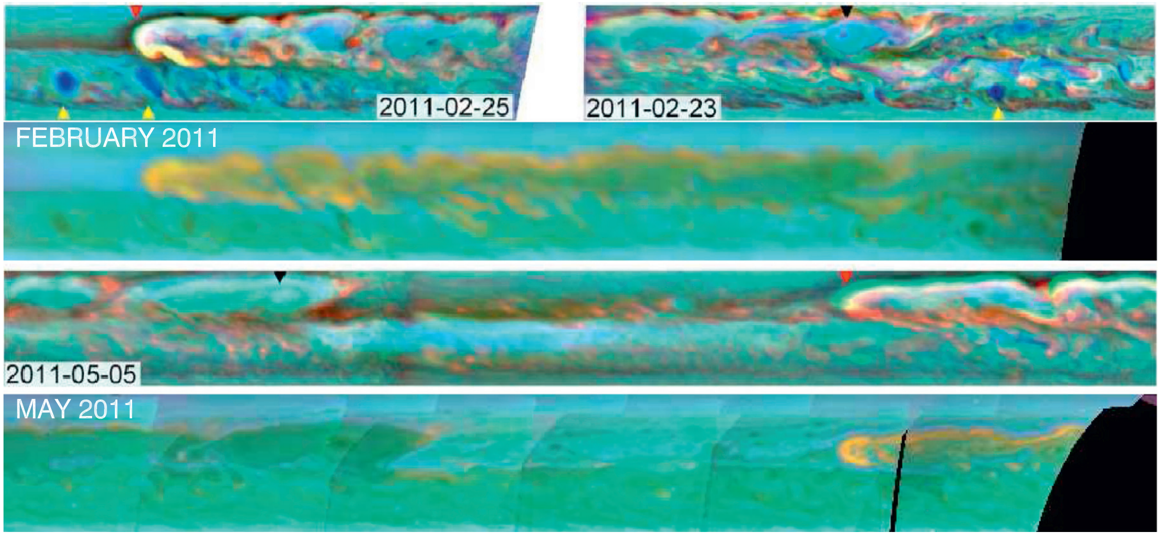

Fig. 1. Early stages of the Great Storm in February 2011 (top 2 panels). The first and third panels from the top, from Sayanagi et al. (2013), are mosaics of ISS observations displayed using CB2, MT2, and MT3 filters for R, G, and B channels, in which red triangles indicate the location of the storm head, black triangles the location of the large bright blue anticyclonic oval vortex, which Sayanagi et al. referred to as the AV, and yellow triangles the locations of dark ovals. The storm head disappeared after it caught up to the anticyclone in June 2011. The second and fourth panels are from VIMS, covering 200° of longitude and latitudes 20°N to 44°N. The VIMS color maps used R = 4.08 μm, G = 1.89 μm, and B = 3.05 μm, for which yellow/orange regions indicate large particles, optically thick clouds, and strong 3-μm absorption characteristic of ammonia ice. Note that features may appear at slightly different longitudes in pairs of maps from the same month due to time differences. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The sample VIMS data set provided in Fig. 2 emphasizes the most striking spectral characteristic of the storm: its remarkably low reflectivity at wavelengths near 3 μm. (Here brightness is expressed in units of I/F, given by radiance/(solar irradiance/π), which can exceed unity near 5 μm because there Saturn's thermal emission can exceed the amount of reflected sunlight.) Clearly, the materials convected upward from deeper levels are very different from the surrounding clouds that usually dominate Saturn, which have no trace of 3-μm absorption. From a spectral analysis of the storm head Sromovsky et al. (2013) showed that it contained a mixture of primarily ammonia ice, with likely contributions of water ice, and a third component that might be either NH_4SH or the unknown material that dominates the upper haze over most of Saturn. As evident in Fig. 1, the ammonia absorption was widespread in the main wake region when the storm head was in a highly active state. We can also see that at 4.08 μm, a pseudo continuum wavelength, the storm clouds are brighter than surrounding clouds, indicating relatively larger particles. Where they are bright at 4 μm, they are also optically thick enough and absorbing enough at 5 μm to block thermal emission from deeper layers of Saturn's atmosphere. The wake region in February 2011 also had regions where 5-μm emission was greater than regions upstream of the storm, one of which (near 150° east) is near the long-lived anticyclonic vortex (AV) described by Sayanagi et al. (2013) and Momary and Baines (2014) and may be an effect produced by that circulation feature.

Fig. 2 also shows that a remarkable transition of the wake region occurred during the two years following its beginning in early December 2010. By December 2012, in the latitude band from 30°N to 39°N there was no evidence of bright large-particle cloud features at 4.08μm and no evidence of 3-μm absorption by ammonia ice (or anything else). Most surprising, and a unique outer planet feature as far as we know, the primary wake region turned from being mainly very dark at 5 μm to being entirely bright and remarkably uniform. This indicates a dramatic decrease in the opacity of aerosols that normally attenuate thermal radiation emanating from the 5 to 6 bar level in Saturn's atmosphere. I/F values at 5 μm increased from pre-storm values of 0.6–0.8, and even lower deep storm values of 0.2–0.3, to a remarkably high I/F averaging ~2.7. The spatial uniformity and high emission levels reached by December 2012 suggested that the entire wake region had been cleared not only of the ammonia clouds that the storm had generated, but also of any other deep aerosols that might provide significant blocking of Saturn's 5-μm thermal emission.

In the following, we use VIMS imaging at 5 μm to define the morphological evolution of the wake's "cleared" regions. We then use VIMS spectral observations to constrain the cloud structure of those regions, finding that they were not completely cleared of all aerosols, but instead retained an upper level cloud similar to surrounding regions. We show that a deep layer of aerosols that blocks part of the thermal emission declined dramatically to less than one optical depth, and is only needed if the He/H_2 mixing ratio is at the higher end of the range of values previously published, but find that complete deep clearing could explain the remarkable uniformity of the late wake region if the He/H_2 mixing ratio is in the lower part of that range.

2. Overview of wake evolution

2.1. Evolution of apparent wake "clearing"

The morphological evolution of the wake is illustrated by the 5-μm mosaics displayed in Fig. 3. After the anticyclone was overtaken by the head of the storm in mid June 2011 (Sayanagi et al., 2013), no evidence of the storm head was subsequently seen. But even before that event, the wake was already beginning to develop regions of high emission at 5 μm, evident from the 11 May 2011 mosaic in Fig. 3. It may also be significant that the region around the anticyclone (near 320°E in that mosaic) is marked by excess emission. The widespread clearing seemed to begin in local regions distributed near the mid line of the storm's main wake, and over time became more widely distributed within the wake. By August 2011, the regions of excess 5-μm emission grew significantly in number and both in longitudinal coverage and in latitudinal extent. By December 2012 the 5-μm bright wake region spanned latitudes from 30°N to 39°N (planetocentric), extended over all longitudes,