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Analysis of Saturn's thermal emission at 2.2-cm wavelength: Spatial distribution of ammonia vapor

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ABSTRACT

This work focuses on determining the latitudinal structure of ammonia vapor in Saturn's cloud layer near 1.5 bars using the brightness temperature maps derived from the Cassini RADAR (Elachi et al. [2004], Space Sci. Rev. 115, 71–110) instrument, which works in a passive mode to measure thermal emission from Saturn at 2.2-cm wavelength. We perform an analysis of five brightness temperature maps that span epochs from 2005 to 2011, which are presented in a companion paper by Janssen et al. (Janssen, M.A., Ingersoll, A.P., Allison, M.D., Gulkis, S., Laraia, A.L., Baines, K., Edgington, S., Anderson, Y., Kelleher, K., Oyafuso, F. [2013]. Icarus, this issue). The brightness temperature maps are representative of the spatial distribution of ammonia vapor, since ammonia gas is the only effective opacity source in Saturn's atmosphere at 2.2-cm wavelength. Relatively high brightness temperatures indicate relatively low ammonia relative humidity (RH), and vice versa. We compare the observed brightness temperatures to brightness temperatures computed using the Juno atmospheric microwave radiative transfer (JAMRT) program which includes both the means to calculate a tropospheric atmosphere model for Saturn and the means to carry out radiative transfer calculations at microwave frequencies. The reference atmosphere to which we compare has a 3× solar deep mixing ratio of ammonia (we use 1.352×10^{-4} for the solar mixing ratio of ammonia vapor relative to H_2; see Atreya [2010]. In: Galileo's Medicean Moons – Their Impact on 400 years of Discovery. Cambridge University Press, pp. 130–140 (Chapter 16)) and is fully saturated above its cloud base. The maps are comprised of residual brightness temperatures—observed brightness temperature minus the model brightness temperature of the saturated atmosphere.

The most prominent feature throughout all five maps is the high brightness temperature of Saturn's subtropical latitudes near ±9° (planetographic). These latitudes bracket the equator, which has some of the lowest brightness temperatures observed on the planet. The observed high brightness temperatures indicate that the atmosphere is sub-saturated, locally, with respect to fully saturated ammonia in the cloud region. Saturn's northern hemisphere storm was also captured in the March 20, 2011 map, and is very bright, reaching brightness temperatures of 166 K compared to 148 K for the saturated atmosphere model. We find that both the subtropical bands and the 2010–2011 northern storm require very low ammonia RH below the ammonia cloud layer, which is located near 1.5 bars in the reference atmosphere, in order to achieve the high brightness temperatures observed. The disturbances in the southern hemisphere between −42° and −47° also require very low ammonia RH at levels below the ammonia cloud base. Aside from these local and regional anomalies, we find that Saturn's atmosphere has on average 70 ± 15% ammonia relative humidity in the cloud region. We present three options to explain the high 2.2-cm brightness temperatures. One is that the dryness, i.e., the low RH, is due to higher than average atmospheric temperatures with constant ammonia mixing ratios. The second is that the bright subtropical bands represent dry zones created by a meridionally overturning circulation, much like the Hadley circulation on Earth. The last is that the drying in both the southern hemisphere storms and 2010–2011 northern storm is an intrinsic property of convection in giant planet atmospheres. Some combination of the latter two options is argued as the likely explanation.

1. Introduction

The instruments on board the Cassini orbiter have provided the giant planets community with a plethora of data on Saturn's

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atmosphere for the past decade. Ideally, we would like to get a comprehensive picture of Saturn's atmosphere that reconciles the general circulation, the cloud and haze distributions and compositions, the zonal wind profile, and the storm locations and dynamics. One major observational roadblock is that the stratospheric and upper tropospheric clouds and hazes on Saturn block our view of the atmosphere beneath them.

The location and magnitude of the zonal jets at the cloud tops are well known from Voyager measurements (Sánchez-Lavega et al., 2000). The broad, strongly superrotating jet centered on the equator is a distinctive feature, with alternating eastward and westward jets to either side of the equator. Unlike Jupiter, convection on Saturn appears in both westward and eastward jets (Del Genio et al., 2009). Convective events on Saturn are intermittent, and the cause of the intermittency is uncertain. Saturn electrostatic discharges, or SEDs (Kaiser et al., 1983; Porco et al., 2005; Fischer et al., 2006, 2007), have been observed in convective storms and are indicative of lightning at depth. What causes these convective outbursts on Saturn, and how do they contribute to or maintain the general circulation? How does deep convection work on Saturn, and how does it fit together with the latitudinal belt-zone structure of the giant planets? Answers to these questions have been difficult to obtain. The 2.2-cm observations analyzed in this work provide new data on the distribution of ammonia vapor in and beneath the ammonia clouds, and will help diagnose the atmospheric dynamics at work inside the convective storms.

The structure of Saturn's clouds and hazes is still being studied, although the general features are understood. The equatorial zone is a region of constant high clouds and thick haze, whereas the midlatitudes (generally between ±20° and ±60°) are regions of smaller, more variable clouds (West et al., 2009). The vertical structure and composition of these clouds and hazes is not well known, but Cassini observations made by the ISS (imaging science subsystem), VIMS (Visual and Infrared Mapping Spectrometer) and CIRS (Composite Infrared Spectrometer) instruments are closing our knowledge gaps in these areas. Tied to the distribution of clouds and hazes is the distribution of tropospheric gases, for example ammonia and phosphine. How does the latitudinal distribution of clouds, hazes, and tropospheric gases coincide with Saturn's belt-zone structure? Knowing the spatial distribution of these gases can help us determine the dynamical mechanisms that produce the spatial patterns themselves. For example, vertical motion, caused by either convection or large-scale meridional overturning, plays a key role in determining where clouds and hazes will or will not form.

This work focuses on determining the latitudinal structure of ammonia vapor in Saturn's ammonia cloud layer using the brightness temperature maps derived from the Cassini RADAR (Elachi et al., 2004) instrument, which works in a passive mode to measure thermal emission from Saturn at 2.2-cm wavelength. These maps are presented in a companion paper by Janssen et al. (2013, this issue), hereafter referred to as J13. The maps provide data on the spatial distribution of ammonia vapor in the pressure range 1–2 bars, in the vicinity of the ammonia ice cloud. We believe these maps provide information about Saturn's meridional circulation. The 2.2-cm data have better spatial resolution and sensitivity than any other microwave data on Saturn. The calibration of Cassini's RADAR instrument, described in detail in Janssen et al. (2009) and J13, is accurate and was validated using both Saturn and more recent Titan observations as described in J13.

Section 2 describes the 2.2-cm observations and the radiative transfer model used in our analysis. The brightness temperature maps are described in Section 3. Section 4 compares the observations to the output from the radiative transfer model. Discussion and implications for Saturn's atmospheric dynamics are given in Section 5, and conclusions are given in Section 6.

2. Observations and radiative transfer model

Cassini's RADAR radiometer was used to map Saturn during five equatorial periapsis passes occurring between 2005 and 2011. The maps were formed from continuous pole-to-pole scans taken through Saturn nadir during the periapsis passes, allowing the rotation of Saturn to sweep the scan westward in longitude. The observations and mapping are described in detail in J13 along with the calibration and error analysis. We refer the reader to Section 2 of J13 for a description of the observations and observational approach, and to Section 3.2 of J13 for a description of the map-generating process.

The reference model used to calculate the residual brightness temperature maps is also described in detail in Section 3.1 of J13. The model and radiative transfer calculations were made using the Juno atmospheric microwave radiative transfer (JAMRT, Janssen et al., 2005, in preparation) program, which is in development for the Juno Microwave Radiometer (MWR) experiment on Jupiter. To match the RADAR observations, radiative transfer calculations are carried out at 2.2-cm wavelength (13.78 GHz), and brightness temperatures are output for each observation. This model builds an atmosphere with user-prescribed physical parameters, such as the vertical mixing ratio profiles of ammonia, phosphine and water. Temperature and pressure profiles are calculated assuming hydrostatic equilibrium using both wet and dry adiabats. The reference model assumes a moist adiabatic temperature profile with 100% relative humidity (RH), with a dry adiabatic profile below cloud base, such that the temperature is monotonically decreasing from the bottom to the top layer of the model atmosphere. The adiabats include the contributions from the NH_4SH and H_2O clouds, although the weighting function drops to essentially zero before we reach the water cloud at great depth. A temperature of 134.8 K (Lindal et al., 1985) is specified at a pressure of 1 bar, and the model temperature profile is slaved to this reference value. We varied this value in order to test the sensitivity of the 2.2-cm brightness temperature to variations in the 1-bar temperature, and found the brightness temperature to be only minimally sensitive to this reference value (see Section 5.1). The topmost level of the model is the level at which the temperature reaches 110 K, which is 560 mb for the (134.8 K, 1 bar) reference point. The model assumes a completely transparent atmosphere above 110 K and therefore ignores this region of the atmosphere. The deepest level of the model atmosphere is 1000 bars, which is well below the pressure level sensed by the 2.2-cm observations, and the vertical layers are 100 m thick. The model also includes the emission angle dependence (limb darkening) of the brightness temperature.

Table 1 gives the atmospheric constituents and their respective abundances in the model atmosphere, including the values used for the solar abundances. H_2O, NH_3, PH_3, and H_2S are the condensable gases (Atreya, 2010). H_2S reacts with NH_3 to form an NH_4SH cloud with a base around 5 bars. An ammonia ice cloud forms above this, with a base around 1.5 bars. The water cloud is deeper (base ~10 bars) and out of the sensitivity range of the 2.2-cm

Table 1
Abundances of atmospheric constituents in the JAMRT program. Solar and enrichment values are from Atreya (2010), who calculated solar abundances from the photospheric values of Grevesse et al. (2005).

Constituent	Solar abundance (relative to H_2)	Enrichment relative to solar
He	0.195	0.6955
CH_4	5.50×10^{-4}	9.4
H_2O	1.026×10^{-3}	3.0
NH_3	1.352×10^{-4}	3.0
H_2S	3.10×10^{-5}	5.0
Ar	7.24×10^{-6}	1.0
PH_3	5.14×10^{-7}	7.5