In search of water vapor on Jupiter: Laboratory measurements of the microwave properties of water vapor under simulated jovian conditions

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ABSTRACT

Detection and measurement of atmospheric water vapor in the deep jovian atmosphere using microwave radiometry has been discussed extensively by Janssen et al. (Janssen, M.A., Hofstadter, M.D., Gulkis, S., Ingersoll, A.P., Allison, M., Bolton, S.J., Levin, S.M., Kamp, L.W. [2005]. Icarus 173 (2), 447–453.) and de Pater et al. (de Pater, I., Deboer, D., Marley, M., Freedman, R., Young, R. [2005]. Icarus 173 (2), 425–447). The NASA Juno mission will include a six-channel microwave radiometer system (MWR) operating in the 1.3–50 cm wavelength range in order to retrieve water vapor abundances from the microwave signature of Jupiter (see, e.g., Matousek, S. [2005]. The Juno new frontiers mission. Tech. Rep. IAC-05-A3.2.A.04, California Institute of Technology). In order to accurately interpret data from such observations, nearly 2000 laboratory measurements of the microwave opacity of H_2O vapor in a H_2/He atmosphere have been conducted in the 5–21 cm wavelength range (1.4–6 GHz) at pressures from 30 mbars to 101 bars and at temperatures from 330 to 525 K. The mole fraction of H_2O (at maximum pressure) ranged from 0.19% to 3.6% with some additional measurements of pure H_2O. These results have enabled development of the first model for the opacity of gaseous H_2O in a H_2/He atmosphere under jovian conditions developed from actual laboratory data. The new model is based on a terrestrial model of Rosenkranz et al. (Rosenkranz, P.W. [1998]. Radio Science 33, 919–928), with substantial modifications to reflect the effects of jovian conditions. The new model for water vapor opacity dramatically outperforms previous models and will provide reliable results for temperatures from 300 to 525 K, at pressures up to 100 bars and at frequencies up to 6 GHz. These results will significantly reduce the uncertainties in the retrieval of jovian atmospheric water vapor abundances from the microwave radiometric measurements from the upcoming NASA Juno mission, as well as provide a clearer understanding of the role deep atmospheric water vapor may play in the decimeter-wavelength spectrum of Saturn.

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1. Introduction

Initial modeling studies have been performed which show that it is possible to retrieve water vapor abundance in Jupiter's deep atmosphere using a multi-channel radiometer as proposed for the NASA Juno mission (Janssen et al., 2005; Matousek, 2005), but there are a number of factors which limit the accuracy of this approach (de Pater et al., 2005). The most critical of these is the knowledge of the microwave absorption properties of water vapor under jovian conditions. Previous laboratory measurements of the microwave opacity of water vapor under pressures and temperatures representative of Jupiter have been conducted in a nitrogen atmosphere (Ho et al., 1966), but not in a hydrogen–helium atmo-

sphere. While models for water vapor absorption have been extrapolated to a hydrogen–helium atmosphere (Goodman (1969), and the DeBoer model, which appears in de Pater et al. (2005)), far more accurate measurements are necessary to accurately retrieve the jovian water vapor abundance (de Pater et al., 2005).

In this laboratory measurement campaign, nearly 2000 laboratory measurements of the microwave opacity of H_2O vapor in a H_2/He atmosphere have been conducted in the 5–21 cm wavelength range (1.4–6 GHz) at pressures from 30 mbars to 101 bars and at temperatures from 330 to 525 K. The mole fraction of H_2O (at maximum pressure) ranged from 0.19% to 3.6% with some additional measurements of pure H_2O. These results have enabled development of the first model for the opacity of gaseous H_2O in a H_2/He atmosphere under jovian conditions developed from laboratory data of H_2/He/H_2O mixtures. The new model is based on a terrestrial model of Rosenkranz (1998), with substantial modifications to reflect the effects of jovian conditions. The new model for water

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vapor opacity dramatically outperforms previous models and will provide reliable results for temperatures from 330 to 525 K, at pressures up to 100 bars and at frequencies between 1.4 and 6 GHz. The new formalism developed in this work outperforms jovian models such as the DeBoer model as it appears in de Pater et al. (2005), and the Goodman (1969) model, owing to the fact that neither model considers the well established existence of continuum water vapor absorption (see, e.g. Rosenkranz, 1998; Payne et al., 2008). By ignoring the continuum effect both the DeBoer and Goodman models over-estimate the opacity contribution from the foreign gas (H_2 and He), and not enough opacity is attributed to the amount of water vapor present. Also in both the DeBoer and Goodman (1969) models, the contributions from absorption lines are overestimated as each model attempts to attribute absorption from water vapor lines alone.

2. Measurement theory

The method used to measure the microwave absorptivity of a gas is based on the lessening in the quality factor (Q) of a resonant mode of a cylindrical cavity in the presence of a lossy gas. This technique involves monitoring the changes in Q of different resonances of a cavity resonator in order to determine the refractive index and the absorption coefficient of an introduced gas or gas mixture (at those resonant frequencies). Described at length by Hanley and Steffes (2007), it has been successfully utilized for over one half of a century (i.e., Bleaney and Loubser, 1950). The cavity resonator technique for measuring refractivity based on frequency shifts has had similar effectiveness, and is also described by Hanley and Steffes (2007). The cylindrical cavity resonator used in these experiments consists of a section of cylindrical waveguide capped at both ends, with resonant modes resulting from various standing-wave patterns. The quality factor of a resonance within a microwave resonator is defined by

$$Q_{resonance}^m = \frac{2\pi f_o \times \text{Energy stored}}{\text{Average power loss}}, \tag{1}$$

where f_o is the center frequency of a resonance characterized by a peak in the frequency response of the resonator (Matthaei et al., 1980). In practice the quality factor ($Q_{resonance}^m$) is measured by taking the center frequency and dividing it by its half-power bandwidth

$$Q_{resonance}^m = \frac{f_o}{\text{Bandwidth}}. \tag{2}$$

(Note that Eq. (2) only holds true where $Q_{resonance}^m \gg 1$.)

The quality factor of a resonator loaded with a test gas can be expressed as

$$\frac{1}{Q_{loaded}^m} = \frac{1}{Q_{gas}} + \frac{1}{Q_{vacuum}} + \frac{1}{Q_{probe1}} + \frac{1}{Q_{probe2}}. \tag{3}$$

Q_{gas} is the quality factor of the gas, which is related to the loss tangent and absorptivity of the gas by the relation

$$Q_{gas} = \frac{\epsilon'}{\epsilon''} = \frac{1}{\alpha}\frac{\pi}{\lambda}, \tag{4}$$

where ϵ' and ϵ'' are the real and imaginary parts of the permittivity of the gas mixture, α is the absorptivity (Nepers/km) and λ is the wavelength (km) (see, e.g. Pozar, 1998). Q_{vacuum} is the quality factor of the just the cavity under vacuum, and Q_{probe1} and Q_{probe2} represent the effects of coupling losses from the two probes on the quality factor of the resonator (Matthaei et al., 1980). Given that the resonator is symmetric, and the coupling probes are the same size and dimensions, it is assumed that $Q_{probe1} = Q_{probe2}$. This value is now referred to as $Q_{coupling}$ and is determined by measuring the

transmission losses in the system, or transmissivity of the system $t = 10^{-S/10}$ where S is the insertion loss of the resonator in decibels (dB) at the frequency of a resonance. Using the following relations, the value of $Q_{coupling}$ is found via

$$t = \left(2\frac{Q^m}{Q_{coupling}}\right)^2, \tag{5}$$

$$\frac{1}{Q_{coupling}} = \frac{\sqrt{t}}{2Q^m}, \tag{6}$$

where Q^m is a measured quality factor (Matthaei et al., 1980). The value for Q_{vacuum} is related to the measured quality factor under vacuum (Q_{vacuum}^m) conditions by

$$\frac{1}{Q_{vacuum}^m} = \frac{1}{Q_{vacuum}} + \frac{1}{Q_{probe1}} + \frac{1}{Q_{probe2}}. \tag{7}$$

After substitution of Eq. (6) into Eqs. (3) and (7), the value of Q_{gas} is given by

$$\frac{1}{Q_{gas}} = \frac{1 - \sqrt{t_{loaded}}}{Q_{loaded}^m} - \frac{1 - \sqrt{t_{vacuum}}}{Q_{vacuum}^m}, \tag{8}$$

where t_{loaded} and t_{vacuum} are the transmissivity values of the loaded and vacuum measurements. One could directly calculate Q_{gas} assuming that the center frequency of a resonance does not change with the addition of a test gas. It is known, however, that this is not the case. An effect known as dielectric loading which is related to the refractive index of a gas present will change the center frequency of the resonance. This effect can be compensated by using a tunable resonator (e.g., Ho et al., 1966; Morris and Parsons, 1970); However, in doing this the coupling properties of the resonator can change, resulting in a error prone measurement of Q_{gas}. In place of a measurement of Q under vacuum conditions (Q_{vacuum}^m), one can measure the Q in the presence of a microwave transparent gas with the same refractive index as the test gas. The amount of microwave transparent gas added can be used to tune the center frequency of the resonator. This allows for a "frequency matched" value replacing the "vacuum" terms in Eq. (8) with "matched" terms. After making the appropriate substitution from Nepers/km to dB/km (1 Neper/km = 2 optical depths km^{-1} = 2 × 10log$_{10}$(e) ≈ 8.686 dB/km) yields the expression used for calculating absorption

$$\alpha = 8.686\frac{\pi}{\lambda}\left(\frac{1 - \sqrt{t_{loaded}}}{Q_{loaded}^m} - \frac{1 - \sqrt{t_{matched}}}{Q_{matched}^m}\right)(\text{dB/km}), \tag{9}$$

where the wavelength λ has units of km (DeBoer and Steffes, 1996).

The dielectric loading of a resonance also gives information regarding the refractive index of a gas. For most gases the index of refraction (n) is usually close to unity. As a result the refractivity of a gas is given by multiplying the residual $n - 1$ by 10^6, or

$$N = 10^6(n - 1), \tag{10}$$

where N is the refractivity of a gas. The measurement of refractivity uses the dielectric loading principle discussed previously, and is calculated by a more direct method than absorption. The refractivity is measured using

$$N = 10^6\frac{f_{vacuum} - f_{gas}}{f_{gas}}, \tag{11}$$

where f_{vacuum} is the center frequency of a resonance measured under vacuum, and f_{gas} is the center frequency measured with a test gas (Tyler and Howard, 1969). Eq. (11) is only valid for values of refractive index (n) close to unity.

The center frequencies of a Transverse Electric (TE) or Transverse Magnetic (TM) mode resonance in a cylindrical cavity resonator are calculated using