The 2-4 Millimeter-Wavelength Opacity of Ammonia

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Abstract

A millimeter-wavelength planetary atmospheric simulator and measurement system have been developed at the Georgia Tech Planetary Atmospheres Laboratory to accurately measure the propagation properties of gases under simulated planetary atmospheric conditions. The measurement system operates in the 2-4 millimeter-wavelength range and withstands up to 3 bars of pressure. Over 1000 laboratory measurements of the 2-4 millimeter-wavelength opacity of ammonia have been made under simulated Jovian atmospheric conditions using the new laboratory system. These laboratory measurements were made of various gas mixtures of hydrogen (≈77.5-85.5%), helium (≈12.5-13.5%), and ammonia (1-10%) at pressures between 1 bar and 3 bars and temperatures between 200 K and 300 K. Laboratory measurements were also made of the opacity of pure ammonia at pressures between 50 mbar and 1 bar and temperatures between 200K and 300K. Using these measurements, a new model is being developed to accurately characterize the absorption of ammonia in the 2-4 millimeter-wavelength region under Jovian conditions.

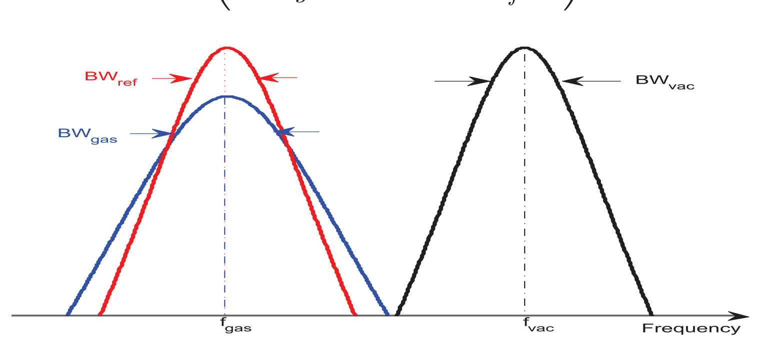
Measurement Theory

The reduction in the quality factor (Q) of a resonant mode of a resonator in the presence of a low-loss gas is used to measure the absorption of the gas (see, e.g., [1]). Q is defined as ([2])

$$Q = \frac{2\pi f_0 \times \text{Energy Stored}}{\text{Average Power Loss}},$$

where f_0 is the frequency of the resonance. The absorption at a particular frequency is computed as given below by measuring the Q of the resonator in the presence of the lossy gas (NH_3 with H_2 and He) and the reference gas (Ar), and the straight-through transmissivities at that frequency.

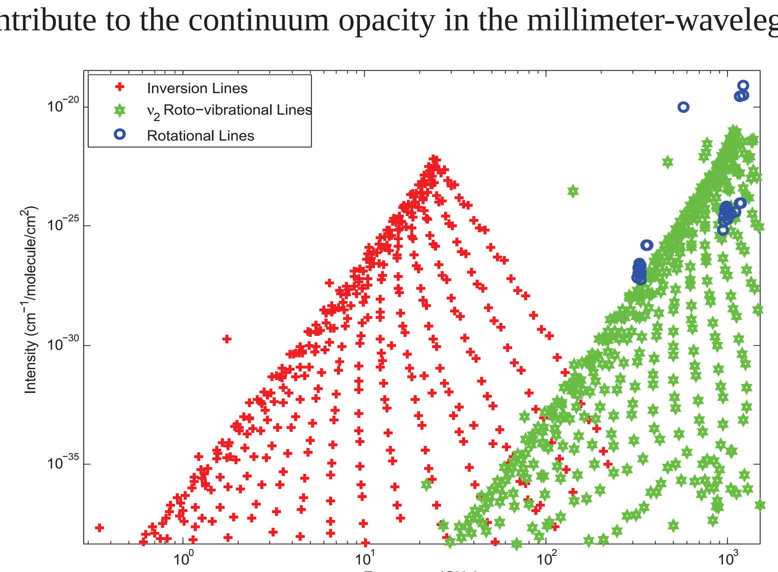
$$\alpha = 8.686\frac{\pi}{\lambda}\left(\frac{1-\sqrt{t_{gas}}}{Q_{gas}} - \frac{1-\sqrt{t_{ref}}}{Q_{ref}}\right) \quad dB/km.$$



Example of a resonance measured with gas, reference gas, and vacuum conditions

Ammonia Absorption in the Millimeter-Wavelength Region

Ammonia is one of the most predominant millimeter-wavelength absorbers in the Jovian planets, due to the presence of a series of inversion lines around 12.5 cm, several strong rotational lines in the submillimeter, and a strong roto-vibrational line at 2.16 mm. The opacity from gaseous ammonia in the Jovian planets should be accurately known before the potential effects of other absorbing constituents can be assessed. Ammonia absorption lines in the 0.3-1200 GHz range shown here strongly contribute to the 2-4 millimeter-wavelength absorption, although rotational lines at higher frequencies also contribute to the continuum opacity in the millimeter-wavelegnth.

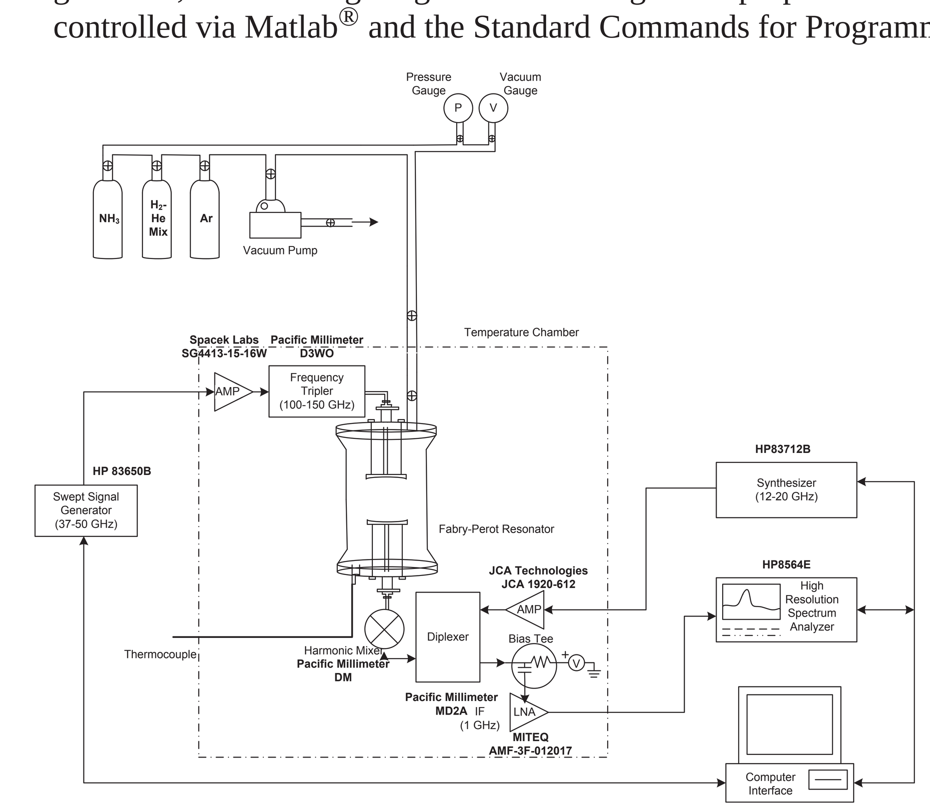


Ammonia line intensities in the 0.3-1200 GHz [3]

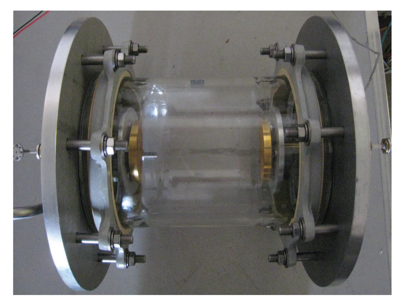
Measurement System

The measurement system consists of the following subsystems.

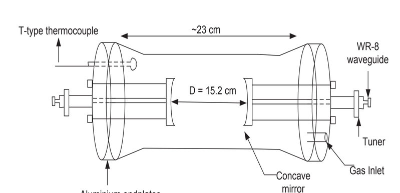
- The planetary atmospheric simulator controls and monitors the environment experienced by the measurement system. The temperature, pressure, and gas concentration are carefully controlled to simulate the desired planetary conditions. The simulator consists of
  - Glass pressure vessel enclosing the Fabry-Perot resonator capable of handling up to 3 bars
  - Pressure gauges, temperature gauge, vacuum pump, and various gas bottles
- Millimeter-wavelength measurement system consists of two subsystems: the W-band system operates in 3-4 mm-wavelength range and the F-band system operates in 2-3 mm-wavelength range.
  - Swept signal generator (HP 83650B) and frequency tripler/active multiplier chain
  - A near-confocal Fabry-Perot resonator with high Q and low losses
  - Harmonic mixers, local oscillator, and a spectrum analyzer (HP 8564E)
- Data handling subsystem consists of a computer connected to the spectrum analyzer, swept signal generator, and CW signal generator via a general purpose interface bus. The instruments are controlled via Matlab® and the Standard Commands for Programmable Instruments (SCPI).



Block diagram of the F-band ammonia measurement system



Glass pressure vessel enclosing the resonator



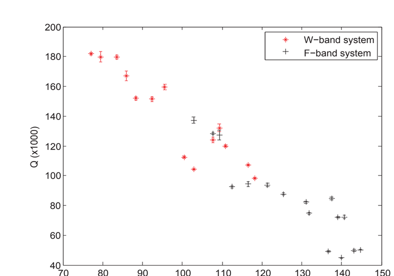
Block diagram of the pressure vessel and resonator

System Sensitivity

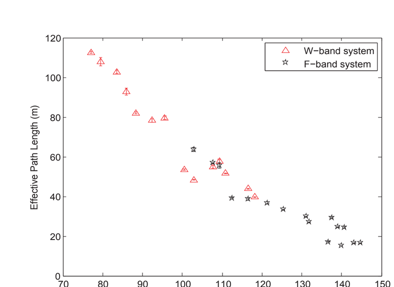
The sensitivity of the system directly depends on the Q of the resonator. The effective path length (EPL) is defined as [4]

$$\text{EPL} = \frac{Q\lambda}{2\pi}$$

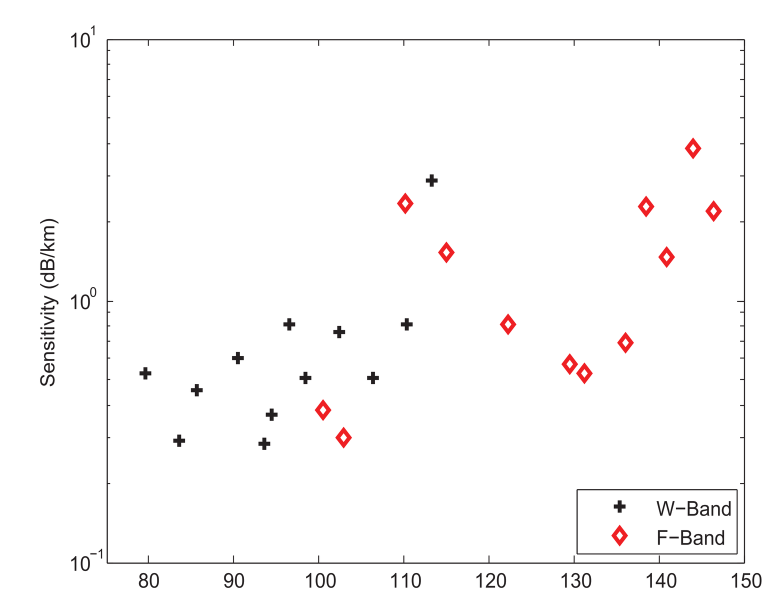
where λ is the wavelength of the resonance.



Q of the resonator at vacuum and T=297K

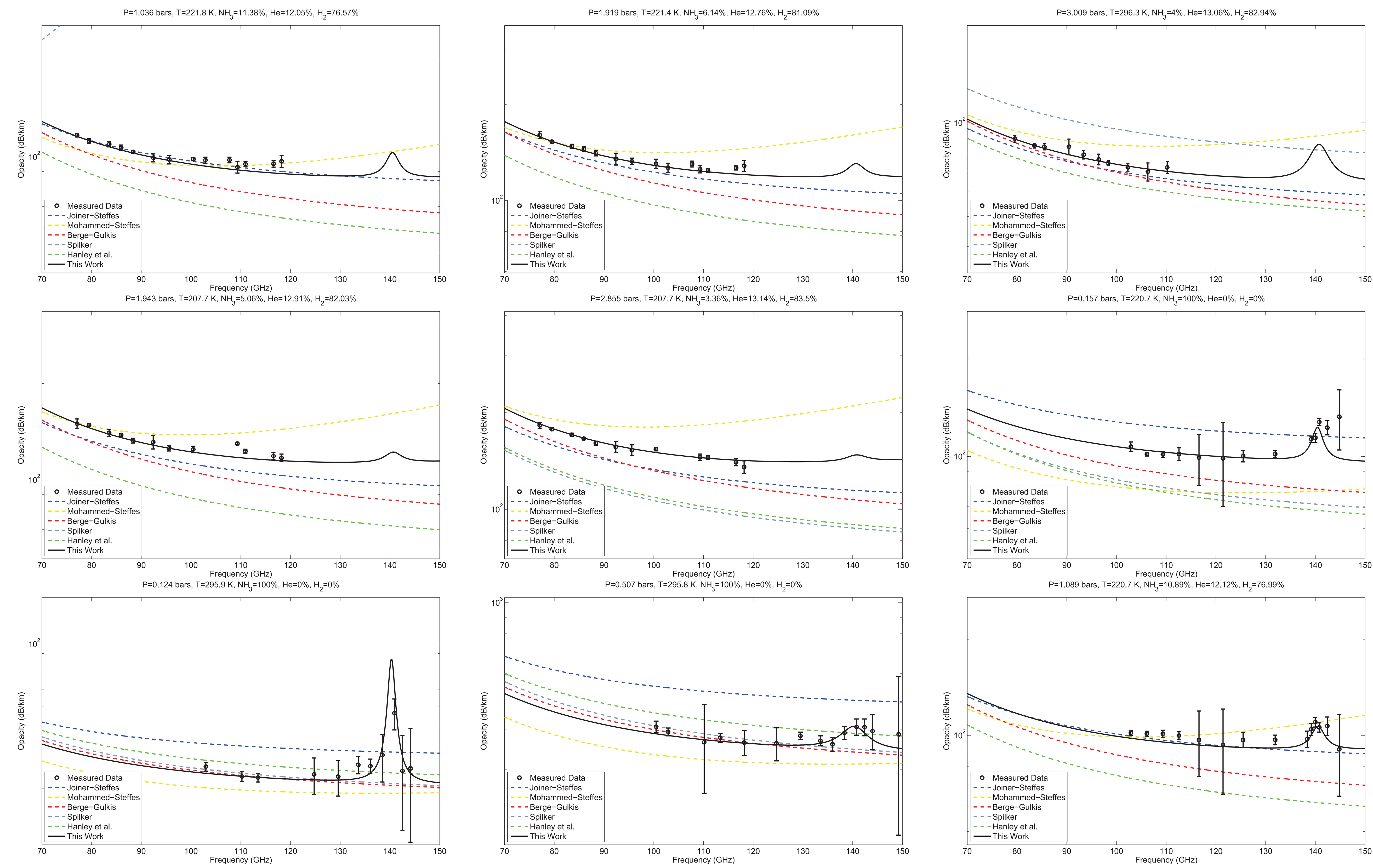


EPL of the resonator at vacuum and T=297K

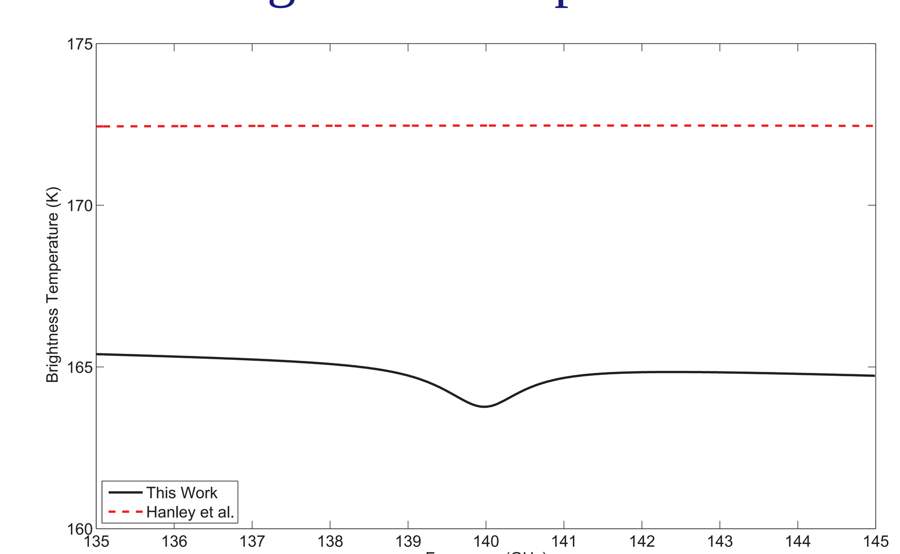


Measurement system sensitivity

Ammonia Opacity Measurements and Model



Jupiter Millimeter-Wavelength Brightness Temperature



Jupiter brightness temperature (NH_3 concentration = 800 ppm)

Conclusions

- The laboratory measurements have led to an accurate characterization of the 2-4 mm-wavelength opacity of ammonia under simulated Jovian conditions. The broadening parameters of the 140 GHz ν_2 roto-vibrational line of ammonia which has thus far only been theoretically predicted [5] has been measured for the first time in the laboratory.
- The preliminary millimeter-wavelength ammonia opacity model fits the laboratory measurements better than the existing opacity models [6; 7; 8; 9; 10]. The model uses a modified Ben-Reuven lineshape [11] to fit the inversion, rotation, and ν_2 roto-vibrational lines, and the old JPL line catalog [12]. Work is in progress to develop an opacity model incorporating the latest JPL line catalog [3] and different lineshapes that would yield a better fit to the laboratory measurements.
- The radiative transfer model shows that the 140 GHz line center is at least 1K darker than the continuum. Future work will involve searching for this line with IRAM.

References

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