Laboratory Measurements in Support of Millimeter-wavelength Observations of the Venus Atmosphere

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Introduction

- Recent observations of the Venus atmosphere have shown significant variability in the mm-wavelength continuum emission.
- This is related to variations in the abundance and distribution of sulfur-bearing constituents in the upper troposphere.
- While the millimeter-wave properties of gaseous SO_2 and of H_2SO_4 condensate are well understood, the millimeter-wavelength absorption from gaseous sulfuric acid $H_2SO_4(g)$ is largely unknown.

Background

- Our recent work measured the 2–4 mm opacity for SO_2 in a CO_2 atmosphere under simulated conditions for the upper troposphere of Venus (Bellotti and Steffes (2015) *Icarus* July 2015) .
- This work was applied to our Venus Radiative Transfer Model (GT-VRM)
- Using GT-VRM we were able to produce a residual map from recent CARMA observations that show a diurnal variation in the continuum emission of the Venus atmosphere.

Recent Observations

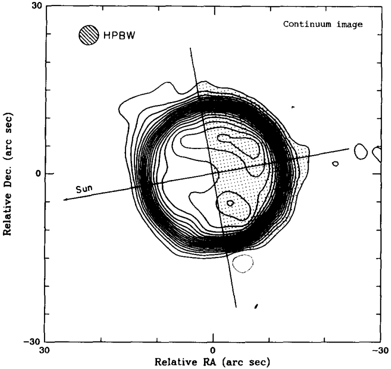

Figure: Radio image of Venus at 3-mm continuum wavelengths (112.4 GHz) taken by de Pater et al. (1991) *Icarus* 90, 282–298. This shows a diurnal variation in the atmosphere's brightness temperature.

Recent Observations

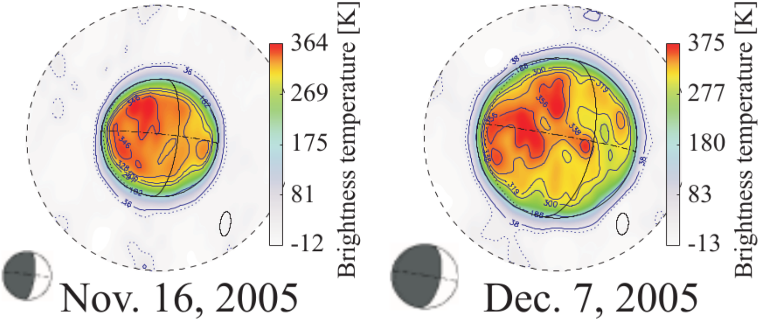

Figure: 103 GHz continuum map of Venus observed with the Nobeyama Millimeter Array taken by Sagawa (2008) *J. Nat. Inst. Of Inf. and Comm. Technology (Japan)*, 55, 149–157. This also shows the diurnal variation in the atmosphere.

Venus at 3-mm

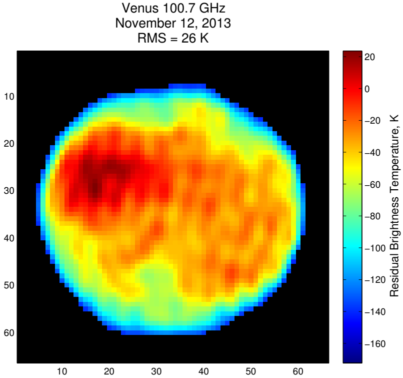

Figure: 3–mm Venus emission residual as measured using the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) (Private Communications, Devaraj, Luszcz Cook, DeBoer, de Pater, Steffes).

The terminator bisects the disk such that the night side is on the left.

Venus at 3-mm

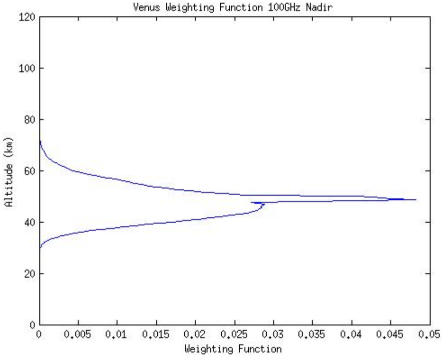

Figure: Weighting function from Georgia Tech Venus Radiative Transfer Model (GT-VRM).

- Sagawa attributes continuum brightness variations to spatial variations in the abundances of both H_2SO_4(g) and SO_2 in the range of 0.3 – 2 Bars
- This is consistent with the weighting functions calculated using our Venus radiative transfer model.

Venus at 3-mm

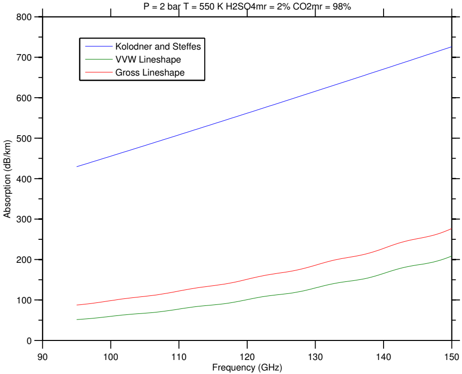

Figure: Comparison of different models for the 2–4 mm opacity of gaseous H_2SO_4 in a CO_2 atmosphere under simulated Venus conditions. Shown are the models from Kolodner and Steffes (1998) *Icarus*, 132, 151–169,and subsequent models developed using the latest line catalog assuming either Gross or Van Vleck-Wesskopf lineshapes.

Laboratory Measurement System

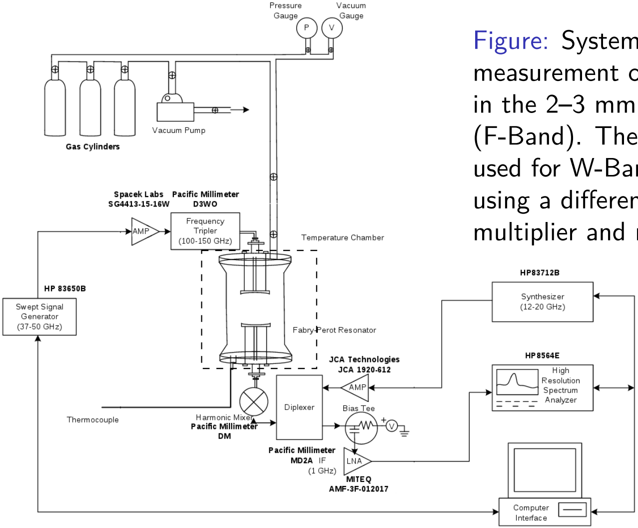

Figure: System used for measurement of SO_2/CO_2 mixture in the 2–3 mm wavelength range (F-Band). The same resonator was used for W-Band measurements using a different set of frequency multiplier and mixers.

Laboratory Measurement System

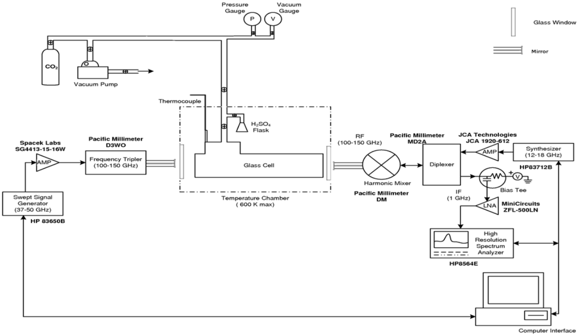

Figure: Proposed system to be used for $H_2SO_4(g)/CO_2$ mixtures in the 100–150 GHz range. The same resonator will be used for W-Band measurements along with a different set of frequency multipliers and mixers. Measurements in Ka-Band will be conducted using the same glass cell but different mirrors.

Conclusion

- It is possible to extract abundance profiles for both SO_2 and H_2SO_4 from observations done at two different frequencies.
- This requires knowledge of the frequency dependence of the absorption from both gasses.
- These measurements are critical for interpreting the millimeter-wave continuum spectrum from Venus.

BACKUP: Measurement System W-band

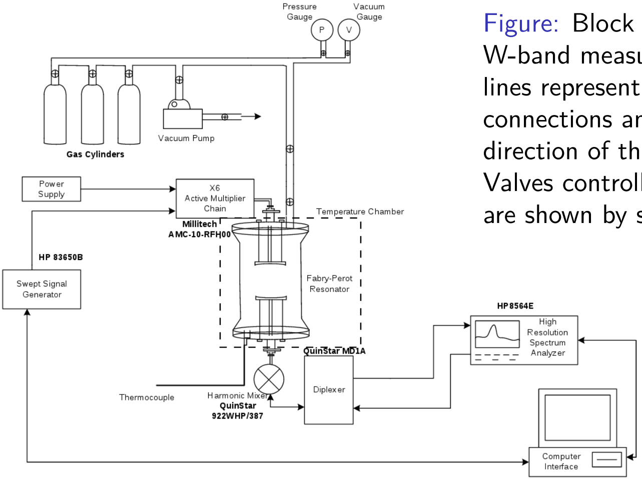

Figure: Block diagram of the W-band measurement system. Solid lines represent the electrical connections and the arrows show the direction of the signal propagation. Valves controlling the flow of gasses are shown by small crossed circles.

BACKUP: Correction for Equivalent Path Length

- In our "traditional" Fabry-Perot resonator measurements where the entiree resonator is exposed to the test gas mixture the relationship between quality factor and absorptivity is given by:

$$\alpha = 8.68\frac{\pi}{\lambda}\left(\frac{1-\sqrt{t_{loaded}}}{Q^{m}_{loaded}} - \frac{1-\sqrt{t_{matched}}}{Q^{m}_{matched}}\right)$$

- Effective Path Length (in km) through the test gas in the resonator is given by

$$EPL = Q^{m}_{loaded}\lambda/2\pi$$

- It's possible to relate the path length to the change in insertion loss and the measured absorptivity at the resonant frequency:

$$EPL = 10\log_{10}(t_{matched}/t_{loaded})/\alpha$$

BACKUP: Correction for Equivalent Path Length

- While the results from the previous two equations are normally identical, they will deivate in the new system.
- To derive an accurate extinction coefficient we can scale the results from the traditional Fabry-Perot by the ratio of the ideal effective pathlength and the modified effective path length

$$\alpha_{corrected} = \alpha^2 Q^m_{loaded} \lambda / \left[20\pi \log_{10} \left(t_{matched} / t_{loaded} \right) \right]$$

BACKUP: Atmospheric Parameters of GT-VRM

- The principal component of the Venus atmosphere is gaseous CO_2 which comprises 96.5% of the atmosphere.
- Gaseous N_2 constitutes about 3.5%
- Gaseous SO_2 is implemented using a uniform mixing ratio of 75 ppm at altitudes below the main cloud layer (48 km), Above the cloud layer the SO_2 abundance profile is assumed to decay exponentially with a scale height of 3.3 km.

BACKUP: Atmospheric Parameters of GT-VRM

- H_2SO_4 Clouds are located at altitudes between 48–50 km with an assumed bulk density of 50 mg/m^3
- Gaseous H_2SO_4 is modeled using a saturation vapor pressure model based on Mariner 10 radio occultation. Below 48 km the H_2SO_4 mixing ratio is zero. Above it is

$$
\begin{aligned}
P_{H_2SO_4} &= 1.01325 \exp\left(10156\left[-\frac{1}{T} + \frac{0.38}{T_c - T_o}\left(1 + \ln\frac{T_o}{T} - \frac{T_o}{T}\right)\right]\right. \\
&\qquad \left. - \frac{\Delta F}{RT} + 16.259\right)
\end{aligned}
$$