Laboratory Measurements of the 2-4 mm Opacity of Sulfuric Acid Vapor under Simulated Venus Conditions

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Introduction

For over 30 years, sulfuric acid vapor (H_2SO_4) has been recognized as a major source of the microwave absorption in the atmosphere of Venus [1]. Through radio occultation measurements from both the Pioneer-Venus and Magellan, it has been possible to retrieve abundance profiles of gaseous H2SO4 in the atmosphere of Venus [2,3]. Laboratory measurements of the *centimeter-wavelength* opacity of gaseous H_2SO_4 in a CO2 atmosphere [4] dramatically increased the precision of retrievals from both radio occultation experiments (conducted at 3.6 and 13 cm)and from radio emission measurements conducted at 1.3 and 2.0 cm [5].

Recently, observations of Venus with the Nobeyama millimeter-wave array conducted at 103 GHz (~3mm) showed substantial variation (~25%) in the millimeter-wave brightness with position on the disk [6]. While maps of the 1.3 and 2.0 cm emission from Venus have indicated dark (~3%) polar regions consistent with increased sulfuric acid vapor abundance due to vaporization of cloud condensate from the downwelling characteristic of Hadley cell circulation [5], the 3 mm maps show much stronger variations over a range of different locations, with some indication of diurnal variation. de Pater *et al.* [7] also reported significant variations (10%) in the 2.6 mm emission maps of Venus made with the Hat Creek Interferometer. Recent maps of Venus made by our group from 100-116 GHz (2.6-3.0mm) using the CARMA (Combined Array for Research in Millimeter- wave Astronomy) show the same types of variation.

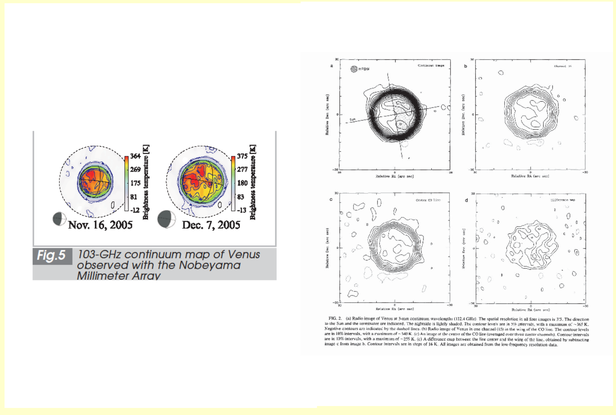
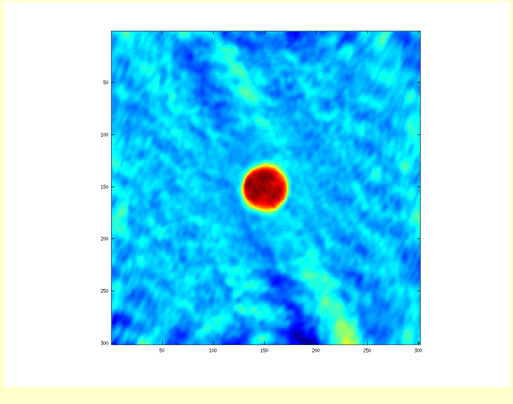


Figure 1 (above, from Sagawa[6], Figure 2 (above, from de Pater *et al.*[7]) and Figure 3 (below, from Devaraj, personal communication) all show variations in the 3-mm continuum emission from Venus.



Even higher resolution millimeter-wavelength images of Venus have been achieved with the Atacama Large Millimeter/Submillimeter Array (ALMA). (See, e.g., Moreno *et al.* [8])

Venus at 3-mm

Sagawa [6] attributes the Venus 3 millimeter-wavelength continuum brightness variations to spatial variations in the abundances of both gaseous H_2SO_4 and SO_2 in a range of altitudes from just below the lower cloud base to the top of the middle cloud (pressures 0.3-2 Bars). This is consistent with the weighting functions calculated using our(Georgia Tech) Venus radiative transfer model (below).

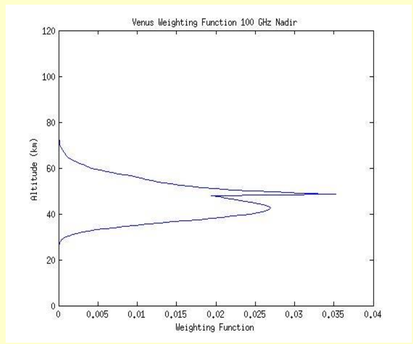


Figure 3: Altitude weighting functions for center of Venus disk at 3.0 mm computed with the Georgia Tech Venus Radiative Transfer Model (GT-VRM).

However this attribution involves use of models for the millimeter-wavelength opacities of these constituents which were extrapolated from previous centimeter-wavelength measurements. Additionally, it has been suggested [6] that the effects of the two constituents could be distinguished based on differences in frequency (wavelength) dependencies of the millimeter-wave absorption from both constituents, but those wavelength dependencies were uncertain. We recently completed measurements of the 2-4 mm absorption from SO_2 at these pressures under simulated Venus conditions (CO_2 atmosphere with temperatures from 307-343 K [9]) employing a Fabry-Perot resonator (shown below) and its accompanying glass pressure envelope placed within the temperature chamber (oven) into which was added the gas mixture under test. All components within the resonator pressure envelope were exposed to the gas mixture under test and were maintained at the temperature under test.

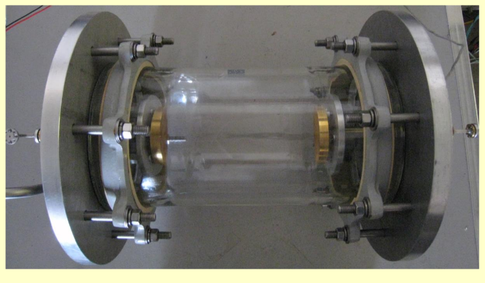


Figure 4: Fabry-Perot resonator and glass envelope used within oven for measurement of SO_2/CO_2 mixtures.

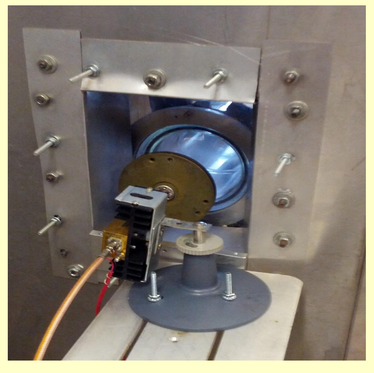
While this was appropriate for measurements of **SO_2/CO_2** mixtures at temperatures below 400 K, significant damage would occur if a mixture of highly corrosive gaseous H_2SO_4 in a CO_2 atmosphere were introduced at temperatures above 450 K. (Note that because of its low vapor pressure, sulfuric acid measurements must be conducted at temperatures above 450 K so that enough vapor will be present in the test mixture so as to be measurable with such a resonator system.)

As an alternative, we are developing a Fabry Perot resonator system wherein the gas mixture under test is located in a glass cylinder within the temperature chamber, but the mirrors and all electronics are located external to the oven.

Laboratory Measurement System

As shown below, high-temperature glass windows are mounted in the oven walls allowing the microwave signals to propagate through the windows and to the mirrors. As with the previous system used for measurements of SO_2/CO_2 mixtures, the absorptivity and refractivity of the test mixtures are measured based on changes to the center frequency and quality factor (or Q) of the individual resonances [9]. However, because there will be portions of the resonator system not containing the test gas, a correction for "equivalent path length through the gas mixture under test" must be used.

Figure 5: Glass cell mounted within temperature chamber (oven), with glass widow (rear) providing access to the externally mounted resonator mirror.



Figures 6 : Glass cell mounted within temperature chamber (oven), with glass widow (rear) providing access to the externally mounted resonator mirror and signal source.

References

[1] Steffes P.G. and Eshleman V.R. (1982) *Icarus*, *51*, 322–333. [2] Jenkins, J.M. and Steffes P.G. (1991) *Icarus*, *90*, 129–138. [3] Jenkins,J.M. *et al.* (1994) *Icarus*, *90*, 129–138. [4] Kolodner,M.A. and Steffes P.G. (1998) *Icarus*, *132*, 151–169. [5] Jenkins, J.M. *et al.* (2002) *Icarus*, *158*, 312–328. [6] Sagawa, H. (2008) *J. Nat. Inst. Of Inf. and Comm. Technology (Japan)*, *55*, 149-157. [7] de Pater, I. *et al.* (1991) *Icarus*, *90*, 282-298. [8] Moreno, R., et al., *Journees de l'Action Specifique ALMA (ASA) 2013*, Grenoble, November 12 and 13, 2013. [9] Bellotti A. and Steffes P.G. (2015) *Icarus*, in press.

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