FINAL REPORT
and
SUMMARY OF RESEARCH

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration

For Grant NNG06GF34G

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments, entry probe radio signal absorption measurements, and earth-based or spacecraft-based radio astronomical (emission) observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or the use of laboratory measurements of such properties taken under environmental conditions that are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. Additionally, even if laboratory measurements have previously been conducted, improvements in the sensitivity of new space-based and earth-based microwave sensors may require higher precision laboratory measurements to achieve their basic science goals.

As improved laboratory instrumentation has become available, it is possible to achieve the higher precisions necessary to support such sensors. For example, development of one of our new laboratory systems was completed recently by Hanley and Steffes (2007), and was used to conduct measurements of the 1-20 cm opacity of ammonia under simulated Jovian conditions with accuracies as precise as 2%. The over-2000 data points taken using this new system have led to development of a new model for ammonia microwave opacity under Jovian conditions (Hanley *et al*., 2009, jointly supported by the Juno mission). This model has been applied to data from the microwave opacity data from the Galileo entry probe and will be applied to microwave opacity data retrieved from the Cassini Radio Occultation and Cassini Radar experiments at Saturn. It will also impact planning of the Juno (Jupiter) mission and interpretation of a host of earth-based radio astronomical measurements of the microwave emission from all four of the Jovian planets.

The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by radio occultation experiments, entry probe radio link experiments, and radio astronomical observations, and over a range of frequencies which correspond to those used in both spacecraft experiments and in radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It is the goal of this investigation to conduct such measurements *and* to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

This project represents the latest stage of an ongoing activity begun in February 1984 to conduct laboratory measurements of the microwave and millimeter-wave properties of simulated planetary atmospheres, in support of NASA missions and ground-based microwave and millimeter-wave observations of planetary atmospheres. The project has also included application of the laboratory results to data from missions (such as Voyager, Pioneer-Venus, Magellan, Galileo, and Cassini) and earth-based observations (such as those from the NRAO/VLA), as well as direct involvement in mission-based microwave measurements and earth-based measurements.

From February 1984 through December 1996, this activity was supported by NASA Headquarters under Grant NAGW-533. From April 1, 1997 through December 31, 2001 this activity was supported by Grant NAG5-4190 from the NASA Goddard Space Flight Center. From May 1, 2002 through April 30, 2005, the project was supported by grant NAG5-12122 from the NASA Goddard Space Flight Center followed by a one-year, reduced-cost "extension" (NNG05GQ87G), through September 14, 2006. The current technical status of this project (NNG06GF34G, September 15, 2006-September 14, 2010) is described in Section III below, and was also highlighted in a new proposal (June 2010) to the NASA Planetary Atmospheres Program for a four-year successor project. The technical progress of this project has been described in three previous Progress Reports submitted in 2007, 2008, and 2009.

III. RECENTLY COMPLETED LABORATORY MEASUREMENTS

A. Centimeter-Wavelength Laboratory Measurements of Ammonia under Simulated Conditions for the Outer Planets

In the first year of this grant (2006-07), development of one of our new laboratory systems was completed by Hanley and Steffes (2007), and was used to conduct measurements of the 1-20 cm opacity of ammonia under simulated Jovian conditions (H_2/He atmosphere with 0.125-12 Bars total pressure, and 183-450K temperature), with accuracies as precise as 2%. The over-2000 data points taken using this new system have led to development of a new model for ammonia microwave opacity under Jovian conditions (Hanley *et al*., 2009, jointly supported by the Juno mission). Results of these measurements were also presented at the October 2007 and October 2008 AAS/DPS meetings in Orlando, FL and Ithaca, NY (Hanley and Steffes, AAS/DPS 2007 and Hanley *et al.,* AAS/DPS 2008) and at the January 2008 National Radio Science Meeting in Boulder, CO (Hanley and Steffes 2008). As shown in Figure 1, it appears as if none of the previously existing models best predicts the 4-20 cm opacity from NH_3 in an H_2/He atmosphere in the 8 Bar pressure range at 450K. The new model (Hanley and Steffes, shown as a "dotted" line) fits data well at all temperatures and pressures.

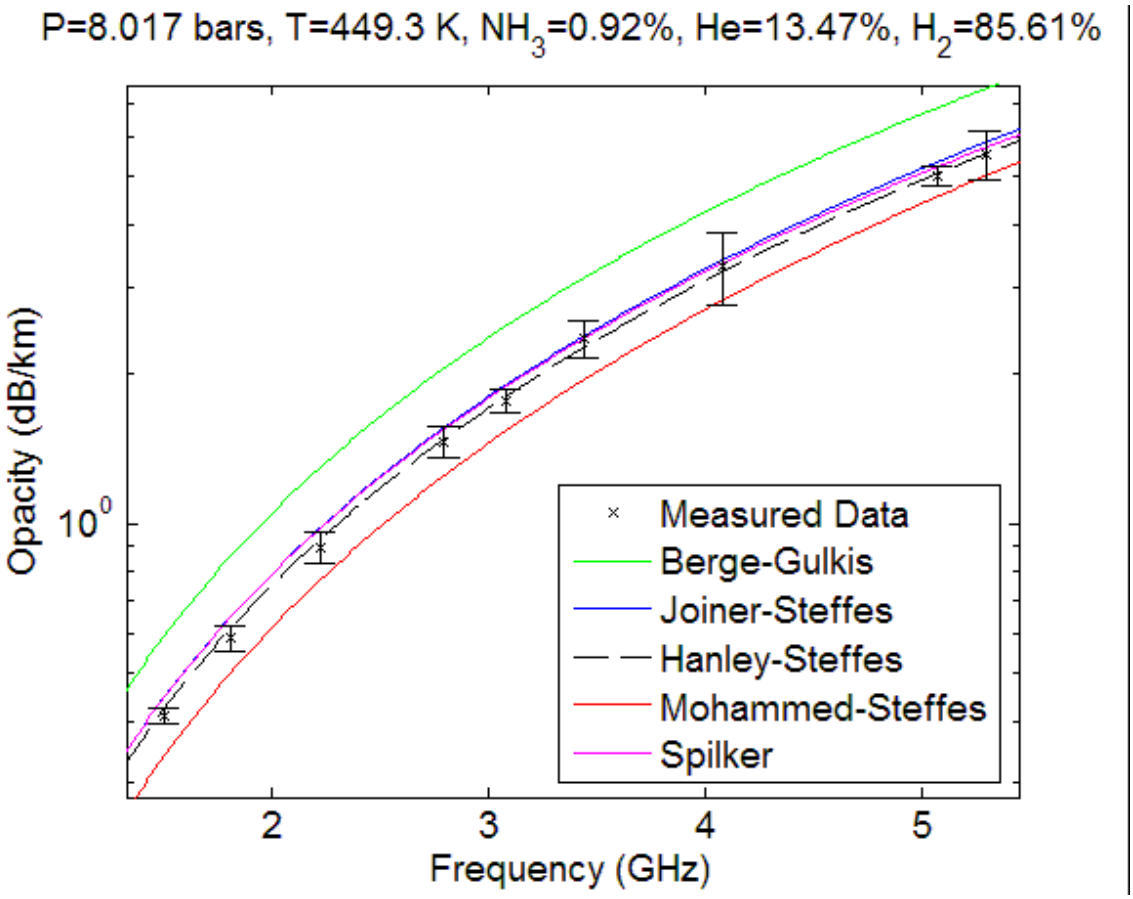

Figure 1: Measurement results for the opacity of ammonia under simulated Jovian conditions compared with existing models and the new model from Hanley et al. (2009).

This model has been applied to the microwave opacity data derived from monitoring the uplink signal from the Galileo entry probe (Folkner *et al.*, 1997) and will be applied to microwave opacity data retrieved from the Cassini Radio Occultation experiments and Cassini Radar (passive radiometric) experiments at Saturn. It will also impact planning of the Juno (Jupiter) mission and interpretation of a host of earth-based radio astronomical measurements of the microwave emission from all four of the Jovian planets, such as our recent observation of the July 2009 asteroidal impact with Jupiter (Devaraj et al., 2010).

Additionally, multiple measurements of the 1.3-20 cm opacity of water vapor in an H_2/He atmosphere were conducted at pressures from 1-12 Bars and at temperatures from 350-450 K. However, the opacity from water vapor is quite small under these conditions, and only limited insights into a proper model for the centimeter-wave opacity from water vapor under Jovian conditions was provided (Hanley and Steffes, 2008). As a result, a new, ultra-high pressure system capable of maintaining pressures up to 100 Bars in the 300-525 K temperature range has been built in our laboratory with support from the Juno mission. This system was recently used to complete measurements of the 5-21 cm (1.4-6 GHz) opacity from water vapor under pressures up to 100 Bars under simulated Jovian conditions. (These measurements were fully supported by the Juno mission.) Additionally, the new high-pressure system will be used to conduct measurements of the

1.4-6 GHz opacity of ammonia under conditions of the deep atmosphere of Jupiter, so as to verify the accuracy of the Hanley and Steffes (2009) model under more extreme conditions. (These measurements will also be fully supported by the Juno mission.)

B. Laboratory Measurements of Millimeter-Wavelength Continuum Absorption Spectrum of Ammonia under simulated Conditions for the Outer Planets

One of the major accomplishments of the work conducted under this grant (NNG06GF34G, 9/15/06-9/14/10) was the completion of an extensive measurement campaign of the 2-4 mm continuum absorption spectrum of ammonia in a hydrogen-helium atmosphere using a new millimeter-wavelength measurement system described in presentations at the 2007 and 2008 AAS-DPS Meetings in Orlando, FL and Ithaca, NY, at the 2008 National Radio Science Meeting in Boulder, CO, and in a new paper recently accepted by the journal, *Radio Science* (See Devaraj and Steffes, 2007, 2008a, 2008b, and 2010a.) This system is shown in Figure 2.

Results for the continuum opacity from ammonia in a hydrogen/helium atmosphere are shown in Figures 3 and 4. Most noteworthy is that these measurements provide coverage over an extensive wavelength range, rather than at just one or two wavelengths as in previous measurements. (See, e.g., Mohammed and Steffes, 2004 or Joiner and Steffes, 1991.) Additionally, the sensitivity of the systems used for these measurements have been dramatically improved. As a result, it is now possible to detect the contribution of the υ_2 vibrational line of ammonia (140 GHz) for both pure ammonia at low pressure and when pressure broadened by hydrogen and helium. The results indicate that none of the existing models for ammonia opacity correctly predict the 2-4 mm opacity from ammonia under simulated Jovian conditions. A new model has been developed (shown in black in Figures 3 and 4) to match the over-1000 millimeter-wave data points taken under the predecessor grant, using the latest, revised line catalog from the JPL/Spec database. This work was presented at the 2009 AAS/DPS meeting and at the May 2010 EGU Meeting, and is included in a new paper submitted to the journal, *ICARUS* (Devaraj and Steffes, 2009, 2010b, and 2010c). Note that Ph.D. student Kiruthika Devaraj was awarded the Young Scientist Outstanding Poster Paper Award for this work presented at the May 2010 EGU Meeting.

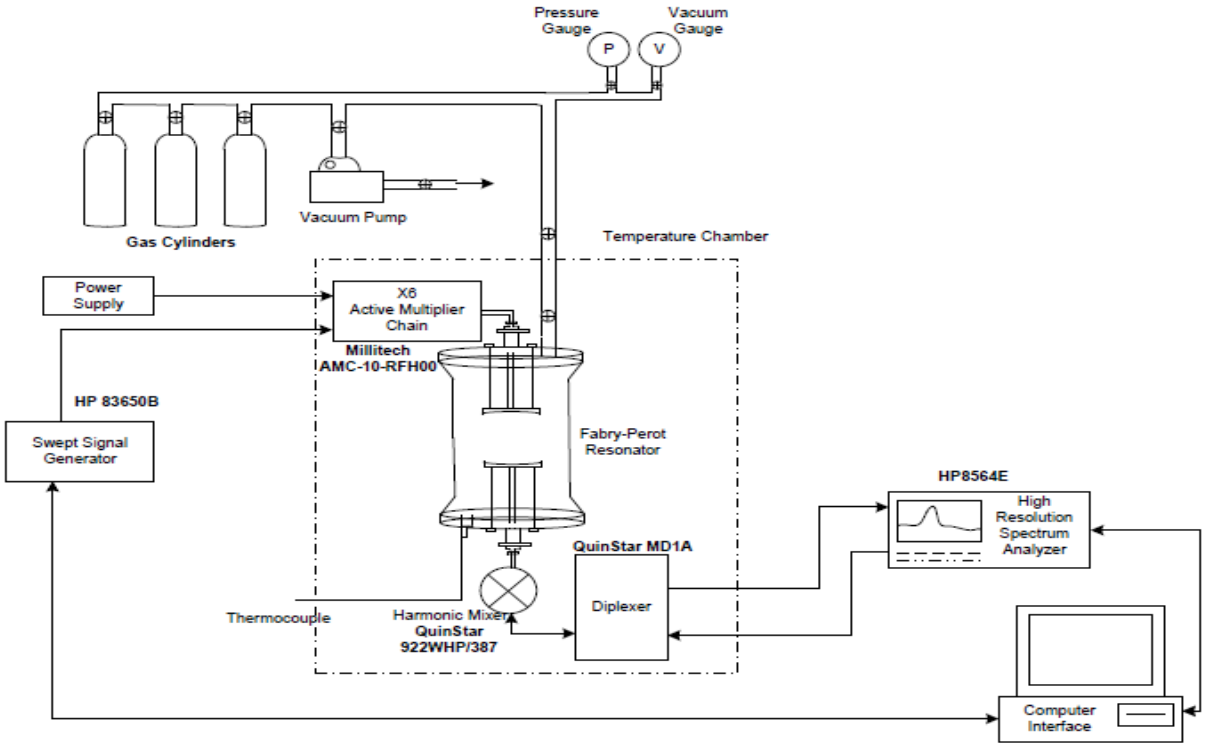

Figure 2: Millimeter-wavelength measurement system for studying gas properties under simulated planetary conditions.

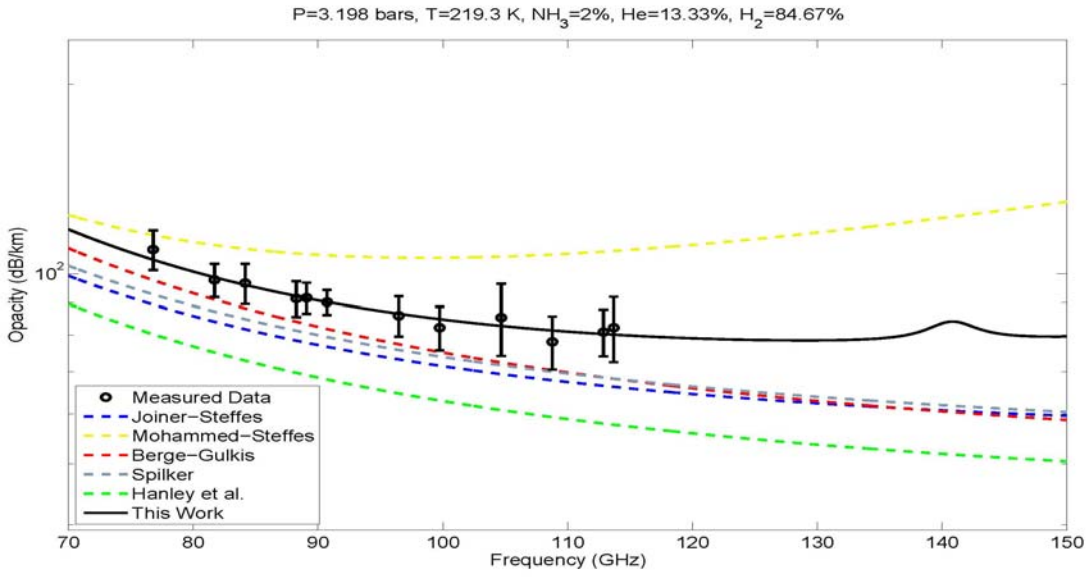

Figure 3: Laboratory measurements of the 75-115 GHz opacity of ammonia in an H_2/He atmosphere under simulated Jovian conditions. (Devaraj and Steffes, 2010b)

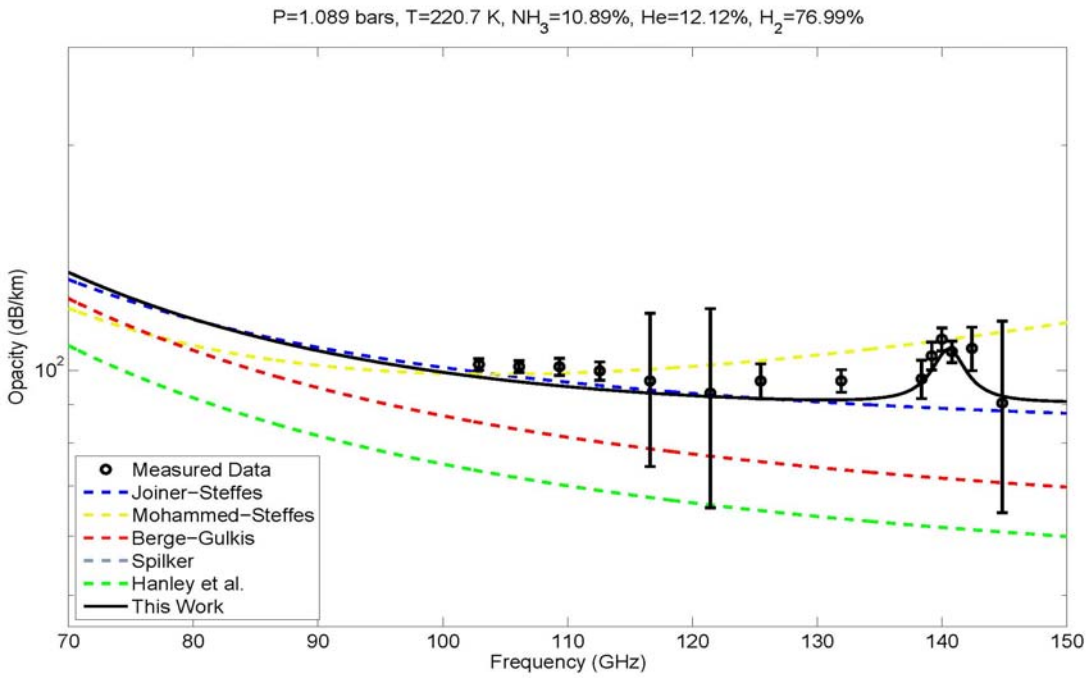

Figure 4: Laboratory measurements of the 105-145 GHz opacity of ammonia in an H_2/He atmosphere under simulated Jovian conditions. (Devaraj and Steffes, 2010b)

The results of these measurements are significant, in that they provide insight into interpreting the millimeter-wave emission spectra of the outer planets. Interpretive studies of observations of the millimeter-wave spectra of the outer planets (see, e.g., Van der Tak *et al.*, 1999, Orton *et al.*, 1986, Hesman *et al.*, 2007) are currently ongoing, and will benefit directly from these measurements. Moreover, our measurement of the 140 GHz vibrational line has motivated observers at Observatoire de Paris (Moreno et al.) to observe Jupiter in August 2010 with the IRAM 30-meter millimeter-wave telescope (the largest single aperture millimeter-wave telescope in the world) so as to detect this resonance and allow our use of the new data in modeling variabilities in upper tropospheric ammonia.

In future research, we hope to use our updated millimeter-wavelength radiative transfer program (using these new laboratory results) to retrieve magnitudes and variations of upper tropospheric ammonia abundances in the Jovian atmosphere. Initial development of this radiative transfer model was conducted by Karpowicz (2010). The ability to demonstrate this capability will be of high value to the upcoming Juno mission, since earth-based observations will be used to set the context for the mission's microwave observations.

IV. STUDENTS SUPPORTED

Over the course of this grant, three different Ph.D. students have received support (at least partially) as graduate research assistants. (Dr. Thomas J. Hanley, Dr. Bryan M. Karpowicz and Ms. Kiruthika Devaraj). In addition, two M.S. students conducted research in the area of this grant. Nearly every graduate student was involved in the publication of papers in either refereed journals or at conferences, such as AAS/DPS. (See Section V.) One of the three Ph.D. students supported by this grant, Dr.Karpowicz, has gone on to a permanent positions in planetary and earth sciences.

TABLE I

Students supported by or conducting projects in the area of Grant NNG06GF34G

Ph.D.
Thomas J. Hanley
Bryan M. Karpowicz
Kiruthika Devaraj

M.S.
Abishek Chhikara
Peter J. Speirs

V. PUBLICATIONS

The following theses, journal publications, and conference presentations were supported (or partially supported) by Grant NNG06GF34G.

Ph.D. Dissertations/Theses

Thomas R. Hanley (Ph.D. June 2008)

Thesis Title: The microwave opacity of ammonia and water vapor: application to remote sensing of the atmosphere of Jupiter (partial support from PATM)
Available on-line: http://smartech.gatech.edu/handle/1853/24673

Bryan M. Karpowicz (Ph.D. January 2010)

Thesis Title: In search of water vapor on jupiter: laboratory measurements of the microwave properties of water vapor and simulations of jupiter's microwave emission in support of the Juno mission. (partial support from PATM)
Available on-line: http://smartech.gatech.edu/handle/1853/33947

Kiruthika Devaraj (Ph.D. expected May 2010)

Thesis Title: Reconciling the Centimeter and Millimeter-Wavelength Amonoia Absorption Spectra under Jovian Conditions: Extensive Laboratory Measurements and a Consistent Model. (primary support from PATM)

Journal Publications

T. R. Hanley and P.G. Steffes, "A High-Sensitivity Laboratory System for Measuring the Microwave Properties of Gases under Simulated Conditions for Planetary Atmospheres," Radio Science, vol 42, no. RS6010, pp.1-12, November-December 2007. (Reprint sent with 2008 Progress Report.)

T. R. Hanley, P.G. Steffes, and B.M. Karpowicz, "A New Model of the Hydrogen and Helium-Broadened Microwave Opacity of Ammonia Based on Extensive Laboratory Measurements," Icarus, vol. 202, pp. 316-335, July 2009. (Reprint sent with 2009 progress report.)

K. Devaraj and P.G. Steffes, "The Georgia Tech Millimeter-Wavelength Measurement System and Some Applications to the Study of Planetary Atmospheres" Radio Science, in press, 2010. (Preprint attached.)

K. Devaraj, P.G. Steffes, and B.M. Karpowicz, "Reconciling the Centimeter and Millimeter-Wavelength Ammonia Absorption Spectra Under Jovian Conditions: Extensive Millimeter-Wavelength Measurements and a Consistent Model," submitted to Icarus, July 2010. (Preprint attached.)

Conference Presentations with Published Proceedings or Abstracts

T.R. Hanley and P.G. Steffes, "New High-Precision Laboratory Measurements of the Hydrogen and Helium Broadened Microwave Absorption of Ammonia under Simulated Jovian Conditions," Bulletin of the American Astronomical Society, vol. 38, no. 3, 2006, p. 608. Presented at the 38th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Pasadena, CA, October 12, 2006.

P.G. Steffes and T.R. Hanley, "An Enhanced System for Laboratory Measurements of the Centimeter-Wave Properties of Ammonia under Simulated Conditions for the Outer Planets," Bulletin of the American Astronomical Society, vol. 38, no. 3, 2006, pp. 608-609. Presented at the 38th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Pasadena, CA, October 12, 2006.

B.M. Karpowicz, P.G. Steffes, and J.P. Hoffman, "A View of Outer Planet Composition from Orbiting Spacecraft via Microwave Emission: Results from a New Hybrid Ray-Tracing Radiative Transfer Model," Bulletin of the American Astronomical Society, vol. 39, no. 3, 2007, p. 414. Presented at the 39th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, October 8, 2007.

K. Devaraj and P.G. Steffes, "Preliminary Results for the 2-4 Millimeter Wavelength Continuum Opacity of Ammonia based on New Laboratory Measurements under Simulated Jovian Conditions," Bulletin of the American Astronomical Society, vol. 39, no. 3, 2007, p. 447. Presented at the 39th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, October 9, 2007

T.R. Hanley and P.G. Steffes, "New High-Precision Laboratory Measurements of the Hydrogen and Helium Broadened Microwave Opacity of Ammonia under Simulated Deeper Atmospheric Jovian Conditions," Bulletin of the American Astronomical Society, vol. 39, no. 3, 2007, p. 447. Presented at the 39th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, October 9, 2007.

P.G. Steffes, T.R. Hanley, B.M. Karpowicz, and K. Devaraj, "Laboratory Measurements of the Microwave and Millimeter-Wave Properties of Planetary Atmospheric Constituents: The Georgia Tech System," In *Workshop on Planetary Atmospheres*, pp. 117-118. LPI Contribution No. 1376, Lunar and Planetary Institute, Houston. Presented at the 2007 Workshop on Planetary Atmospheres, Greenbelt, MD, November 6, 2007.

K. Devaraj and P.G. Steffes, "Laboratory Measurements of W-band Continuum Opacity of Ammonia Using a Fully Confocal Fabry-Perot Resonator," International Union of Radio Science Programs and Abstracts: 2008 National Radio Science Meeting, pp. J1-4. Presented at the 2008 URSI National Radio Science Meeting, Boulder, CO, January 3, 2008.

T.R. Hanley and P.G. Steffes, "New Laboratory Measurements of the Microwave Absorption Coefficient of Ammonia and Water Vapor under Jovian Conditions," International Union of Radio Science Programs and Abstracts: 2008 National Radio Science Meeting, pp. J1-5. Presented at the 2008 URSI National Radio Science Meeting, Boulder, CO, January 3, 2008.

B.M. Karpowicz and P.G. Steffes, "From Modeling to Laboratory Measurements: Simulated Microwave Radiometer Sensitivity to Water Vapor Abundance and a New High Pressure System to Measure Water Vapor under Jovian Conditions," International Union of Radio Science Programs and Abstracts: 2008 National Radio Science Meeting, pp. J1-6. Presented at the 2008 URSI National Radio Science Meeting, Boulder, CO, January 3, 2008.

P.G. Steffes, "Microwave Remote Sensing of Planetary Atmospheres: From Staelin and Barrett to the NASA Juno Mission," 2008 IEEE International Geoscience and Remote Sensing Symposium Proceedings, vol. I, pp. 679-682. Presented at the 2008IEEEInternational Geoscience and Remote Sensing Symposium, Boston, MA, July 7, 2008 (invited).

K. Devaraj and P.G. Steffes, "A New Laboratory System for Measurement of the Millimeter-Wave Properties of Gases and Preliminary Results for the Continuum Opacity of Ammonia," Bulletin of the American Astronomical Society, vol. 40, no. 3, 2008, p. 497. Presented at the 40th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Ithaca, NY, October 14, 2008.

K. Devaraj and P.G. Steffes, "The 2-4 Millimeter-Wave Opacity of Ammonia: Extensive Laboratory Measurements and a New Model," Bulletin of the American Astronomical Society, vol. 41, no. 3, 2009, p. 1049. Presented at the 41st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Fajardo, PR, October 7, 2009.

B.J. Bulter, K. Devaraj, P.G. Steffes, and B. Hesman, "Observations of the Jupiter Impact with the VLA," Bulletin of the American Astronomical Society, vol. 41, no. 4, 2009, p. 1194. Presented at the 41st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Fajardo, PR, October 7, 2009.

K. Devaraj, and P. G. Steffes, "The 2-4 Millimeter-Wavelength Opacity of Ammonia," EGU General Assembly, Geophysical Research Abstracts, Vol. 12, 7675, May 2010, Vienna, Austria.

(Note that Ms. Devaraj --a Ph.D. student scheduled to graduate in 2011-- received the EGU Young Scientist Outstanding Poster Paper Award for this presentation.)

K. Devaraj, B. Butler, B. Hesman, P. G. Steffes, and R. Sault, "VLA Observations of the Jupiter Impact", EGU General Assembly, Geophysical Research Abstracts, Vol. 12, 7661, May 2010, Vienna, Austria.

VI. CONCLUSION

Over the 4-year duration of this grant, an effective program integrating microwave and millimeter-wave laboratory measurements with observations conducted from spacecraft experiments and earth-based radio astronomical observations has been conducted. Substantial new laboratory results have had direct impact on interpretation of radio science data from the Galileo Probe, Cassini-Saturn, and will have future impact on the Juno mission. These results have played a significant role in mission planning. It is expected that similar successes will continue as our new grant from NASA/GSFC commences.

VII. REFERENCES

Devaraj K. and P.G. Steffes 2007. "Preliminary Results for the 2-4 Millimeter Wavelength Continuum Opacity of Ammonia based on New Laboratory Measurements under Simulated Jovian Conditions," Bulletin of the American Astronomical Society, vol. 39, no. 3, p. 447. Presented at the 39th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, October 9, 2007.

Devaraj, K. and P.G. Steffes 2008a. "Laboratory Measurements of W-band Continuum Opacity of Ammonia Using a Fully Confocal Fabry-Perot Resonator," International Union of Radio Science Programs and Abstracts: 2008 National Radio Science Meeting, pp. J1-4. Presented at the 2008 URSI National Radio Science Meeting, Boulder, CO, January 3, 2008.

Devaraj, K. and P.G. Steffes 2008b. "A New Laboratory System for Measurement of the Millimeter-Wave Properties of Gases and Preliminary Results for the Continuum Opacity of Ammonia," Bulletin of the American Astronomical Society, vol. 40, no. 3, p. 497. Presented at the 40th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Ithaca, NY, October 14, 2008.

Devaraj, K. and P.G. Steffes 2009. "The 2-4 Millimeter-Wave Opacity of Ammonia: Extensive Laboaratory Measurements and a New Model," Bulletin of the American Astronomical Society, vol. 41, no. 3, 2009, p. 1049. Presented at the 41st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Fajardo, PR, October 7, 2009.

Devaraj, K., B. Butler, B. Hesman, P. G. Steffes, and R. Sault 2010. "VLA Observations of the Jupiter Impact", EGU General Assembly, Geophysical Research Abstracts, Vol. 12, 7661, May 2010, Vienna, Austria.

Devaraj K. and P.G. Steffes 2010a. "The Georgia Tech Millimeter Wavelength Measurement System and Some Applications to the Study of the Planetary Atmospheres" submitted to Radio Science, May 2010.

Devaraj, K., and P. G. Steffes 2010b, "The 2-4 Millimeter-Wavelength Opacity of Ammonia," EGU General Assembly, Geophysical Research Abstracts, Vol. 12, 7675, May 2010, Vienna, Austria.

Devaraj K. and P.G. Steffes 2010c, "The 2-4 Millimeter-Wave Opacity of Ammonia: Extensive Laboratory Measurements and a New Model," submitted to Icarus, June 2010.

Folkner, W.M., R. Woo, and S. Nandi 1998. Ammonia abundance in Jupiter's atmosphere derived from the attenuation of the Galileo Probe's signal. *Journal of Geophysical Research (Planets)* **103**, 22,847-22,855.

Hanley, T.R. and P.G. Steffes 2007. A High-Sensitivity Laboratory System for Measuring the Microwave Properties of Gases under Simulated Conditions for Planetary Atmospheres. Radio Science, vol 42, no. RS6010, pp.1-12.

Hanley, T.R. and P.G. Steffes 2007. "New High-Precision Laboratory Measurements of the Hydrogen and Helium Broadened Microwave Opacity of Ammonia under Simulated Deeper Atmospheric Jovian Conditions," Bulletin of the American Astronomical Society, vol. 39, no. 3, p. 447. Presented at the 39th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, October 9, 2007.

Hanley, T.R. and P.G. Steffes 2008. "New Laboratory Measurements of the Microwave Absorption Coefficient of Ammonia and Water Vapor under Jovian Conditions," International Union of Radio Science Programs and Abstracts: 2008 National Radio Science Meeting, pp. J1-5. Presented at the 2008 URSI National Radio Science Meeting, Boulder, CO, January 3, 2008.

Hanley, T.R., P.G. Steffes, and B.M. Karpowicz 2008. "A New Model of the Hydrogen and Helium-Broadened Microwave Opacity of Ammonia Based on Extensive Laboratory Measurements," Bulletin of the American Astronomical Society, vol. 40, no. 3, p. 497. Presented at the 40th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Ithaca, NY, October 14, 2008.

Hanley, T.R., P.G. Steffes, and B.M. Karpowicz 2009. A new model of the hydrogen and helium-brodened microwave opacity of ammonia based on extensive laboratory measurements. Icarus **202**, 316–335.

Hesman, B.E., G.R. Davis, H.E. Matthews, and G. S. Orton 2007. The abundance profile of CO in Neptune's atmosphere Icarus **186**, 342–353.

Joiner, J. and P.G. Steffes 1991. Modeling of Jupiter's millimeter wave emission utilizing laboratory measurements of ammonia (NH_3) opacity. *Journal of Geophysical Research (Planets)* **96**, 17,463-17,470.

Karpowicz, B.M. 2010. In search of water vapor on Jupiter: laboratory measurements of the microwave properties of water vapor and simulations of Jupiter's microwave emission in support of the Juno mission. *Ph.D. Dissertation*, Georgia Institute of Technology, January 2010.

Mohammed, P.N. and P.G. Steffes 2004. Laboratory Measurements of the W-band (3.2 mm) Properties of Phosphine (PH_3) and Ammonia (NH_3) Under Simulated for the Outer Planets. *Journal of Geophysical Research - Planets* **109**, no. E07S13, pp 1-9.

Orton, G. S., M. J. Griffin, P. A. R. Ade, I. G. Nolt, J. V. Radostitz, E. I. Robson, and W. K. Gear 1986. Submillimeter and millimeter observations of Uranus and Neptune, *Icarus* **67**, 289-304.

Van der Tak, F., I. dePater, A. Silva, and R. Millan 1999. Time variability in the radio brightness distribution of Saturn. *Icarus* **142**, 125-147.