FINAL REPORT

Submitted to
National Aeronautics and Space Administration

Research Performed under Cooperative Agreement NCC1-80
July 1983 - April 2000

By

Investigators:  PI: Dr. D. Chris Benner
Department of Physics
The College of William and Mary
Williamsburg, Virginia 23187-8795
Telephone: (757) 221-3531/(757)-864-5699
E mail: dcbenn@facstaff.wm.edu

Co-I: Dr. Malathy Devi Venkataraman
Department of Physics
The College of William and Mary
Williamsburg, Virginia 23187-8795
Telephone: (757) 221-3531/(757)-864-5521
E mail: m.d.venkataraman@larc.nasa.gov
Title: High Resolution Spectroscopy to Support Atmospheric Measurements

The major research activities performed during the cooperative agreement enhanced our spectroscopic knowledge of molecules of atmospheric interest such as carbon dioxide, water vapor, ozone, methane, and carbon monoxide, to name a few. Measurements were made using the NASA Langley Tunable Diode Laser Spectrometer System (TDL) and several Fourier Transform Spectrometer Systems (FTS) around the globe. The results from these studies made remarkable improvements in the line positions and intensities for several molecules, particularly ozone and carbon dioxide in the 2 to 17-μm spectral region. Measurements of pressure broadening and pressure induced line shift coefficients and the temperature dependence of pressure broadening and pressure induced line shift coefficients for infrared transitions of ozone, methane, and water vapor were also performed. Results from these studies have been used for retrievals of stratospheric gas concentration profiles from data collected by several Upper Atmospheric Research satellite (UARS) infrared instruments as well as in the analysis of high resolution atmospheric spectra such as those acquired by space-based, ground-based, and various balloon- and aircraft-borne experiments. Our results made significant contributions in several updates of the HITRAN (HIgh resolution TRANsmission) spectral line parameters database. This database enjoys worldwide recognition in research involving diversified scientific fields.

The high lights of the results from this cooperative agreement include:


4. 75 Research papers have been published in several reputable journals (see list attached).

5. More than 85 oral / poster presentations have been given in several International Spectroscopic Symposia /Conferences held in the US and abroad.

**Brief descriptions of the various projects:**

1. Because of its very important contribution to atmospheric absorption in the infrared, the vibration-rotation spectrum of CO₂ has been the subject of numerous high-resolution studies. We undertook a comprehensive and extensive analysis of accurate positions and intensities of individual absorption lines of CO₂ in the 1800 to 4000 cm⁻¹ spectral region. The analyses of several high resolution long path absorption spectra of a natural sample of CO₂ have yielded accurate positions and intensities of over 10000 transitions belonging to more than 200 vibration rotation bands of eight isotopic species of CO₂. Pressure-broadening and pressure-induced line shift coefficients in the v₃ fundamental band in the 4.3 μm region, and in the laser band regions around 9-11 μm, as well as line mixing coefficients in several Q branches in the 2 to 5 μm spectral region were determined. These results were obtained by analyzing high-resolution Fourier transform laboratory absorption spectra.

2. Methane is another molecule of importance to atmospheric studies. Due to the high methane abundance (~1.6 ppmv) in the atmosphere, even lines belonging to isotopic methane (such as ¹³CH₄ and ¹²CH₃D) contribute significant absorption in many regions of atmospheric spectra. Accurate measurements of spectroscopic parameters such as pressure-broadening coefficients, pressure-induced line-shift coefficients, line mixing coefficients and their temperature dependence are needed for accurate simulations of methane features in atmospheric spectra.

   Based upon these requirements, we have recorded more than 300 high-resolution laboratory FTS spectra of CH₄ and its isotopes. The majority of these spectra have been obtained at 0.005 to 0.01 cm⁻¹ resolution using the McMath-Pierce FTS. About 100 of these spectra (CH₄) were recorded
with the FTS at LPM (Laboratoire de Photophysique Moléculaire, CNRS, Orsay), France. We have determined air- and N$_2$-broadening and shift coefficients at room temperature for a large number of lines in the 7.5-μm, 3.3-μm, and 2.3-μm bands of methane. Temperature dependence of these coefficients has been determined in the 7.5-μm region and in the 2.3-μm region. O$_2$-broadening and shift coefficients for CH$_4$ have been experimentally determined in the 3.3-μm region at room temperature.

Pressure broadening coefficients of $^{12}$CH$_4$, $^{13}$CH$_4$ and $^{12}$CH$_3$D molecules in several spectral regions including the fundamental, combination and overtone bands have been determined using TDL and FTS instruments. First measurements of the temperature dependence exponents of broadening and shift coefficients for hundreds of spectral lines in the $v_4$ fundamental bands of $^{12}$CH$_4$ and $^{13}$CH$_4$ were measured from analyzing spectra obtained with a FTS in conjunction with a coolable absorption cell.

We determined the temperature dependence of air-broadening, pressure shifting and line mixing for $^{12}$CH$_4$ transitions in the $v_3$ band region by analyzing high-resolution spectra of methane recorded with 3 Fourier transform spectrometers. More than 60 laboratory absorption spectra of $^{12}$CH$_4$, $^{13}$CH$_4$ and $^{12}$CH$_3$D obtained at various temperatures (-60°C to +25°C) were used in the analysis. The spectra were recorded with the McMath FTS (0.01 cm$^{-1}$ resolution), with the FTS at LPM (Laboratoire de Photophysique Moléculaire, CNRS, Orsay-France) with 0.003 cm$^{-1}$ resolution and with the FTS at the Pacific Northwest National Laboratory (PNNL) with 0.0015 cm$^{-1}$. Absorption cells with path lengths from 1.7 cm to 2500 cm and pressures from less than one torr to more than 500 torr were used in obtaining the spectra. The line mixing model incorporated into the least-squares fitting procedure determines separate relaxation matrix coefficients related to air-broadening and self-broadening. Using these techniques, it is possible to determine the temperature dependence exponents for the broadening, shifting and the off-diagonal relaxation matrix coefficients associated with line mixing. Our results so far include the P(11) to P(3) manifolds of methane. These results will facilitate developing a more accurate database of methane positions, intensities, broadening, shifting, line mixing and the temperature dependence of broadening, shifting and line mixing coefficients for the $v_3$ region.
Accurate laboratory measurements of positions, intensities, pressure broadening and pressure induced shift coefficients of CH$_3$D lines are crucial for quantitative analysis (e.g., determination of CH$_3$D abundance and D/H ratio) of the spectral signatures of this molecule observed in the terrestrial and planetary atmospheres. The multispectrum fitting technique capable of interpreting the line mixing effects have successfully been applied in the analyses of the triad region (v$_3$, v$_5$, and v$_6$ bands) of $^{12}$CH$_3$D in the 6-10$\mu$m spectral region.

We recently presented detailed measurements of ten methane spectra recorded at 0.011 cm$^{-1}$ resolution in the following MOPITT (Measurements Of Pollution In The Troposphere) spectral regions: 4265-4305 cm$^{-1}$ (the MOPITT CO channel) and 4350-4500 cm$^{-1}$ (the MOPITT CH$_4$ channel). These two spectral channels are part of the crowded methane “octad region” containing eight overtone and combination bands. These spectra were recorded using the MaMath-Pierce FTS. Using the multispectrum fitting technique we have measured accurate line intensities, self- and air-broadened half width and pressure shift coefficients for more than 1000 methane transitions.

3. Water vapor plays a crucial role in atmospheric chemistry. Many remote sensing experiments utilize the pure rotation and vibration-rotation bands of water vapor for soundings of H$_2$O in the Earth's atmosphere. We measured transitions belonging to several infrared bands of H$_2^{16}$O and its deuterated species (H$_2^{18}$O, HDO and D$_2$O) using both the TDL and FTS systems. Using our heatable multipass absorption cell, we have recorded ‘hot’ water spectra to determine the variation of the width and shift coefficients of water vapor lines (broadened with foreign gases such as air, N$_2$) in the v$_1$ and v$_3$ fundamentals near the 3-$\mu$m spectral region.

4. Determination of accurate line positions, assignments, and intensities of the normal (16O$_3$) and 18O- and 17O- isotopomers of ozone in the 2 to 17 $\mu$m spectral regions has been the major focus of our research during the past decade. We have recorded numerous high-resolution (0.0027 to 0.01 cm$^{-1}$) room temperature laboratory absorption spectra of nearly pure ozone since 1984. We used the McMath-Pierce FTS as well as the Tunable Diode Laser spectrometer at NASA Langley Research Center to obtain hundreds of ozone spectra. Analyses of the spectra were performed collaborating
with investigators from Laboratoire de Photophysique Moleculaire in Orsay, France. Several of the earlier ozone spectra recorded during 1984 to 1988 resulted in improved line positions and intensities for the fundamental bands of $^{16}$O$_3$, $^{18}$O- monosubstituted species $^{16}$O$^{18}$O$^{16}$O, $^{16}$O$^{16}$O$^{18}$O, $^{17}$O-monosubstituted species $^{16}$O$^{17}$O$^{16}$O and $^{16}$O$^{16}$O$^{17}$O as well as the overtone, combination, and a number of 'hot' bands of $^{16}$O$_3$. The results from these studies were used to update the line parameters in the 1992 HITRAN database. The new line parameters significantly improved the retrievals of stratospheric ozone and other trace gases from infrared remote sensing measurements.

Laboratory measurements of nitrogen and oxygen broadening and shift coefficients of ozone are particularly important to verify theoretical calculations which are useful to predict values for lines not measured by experiments. In 1990 and 1991 we recorded a large number of high resolution spectra of pure ozone and lean mixtures of ozone broadened with dry air at various temperatures from room temperature down to -63°C. These spectra were recorded using the McMath-Pierce FTS at Kitt Peak and the 50cm long coolable absorption cell. In addition to covering the ozone fundamental bands, $v_1$ and $v_2$, these spectra also cover the combination band $v_1+v_3$. We have made the first air broadening and shift measurements for over 440 lines in the $v_1$ band and over 350 lines in the $v_2$ band. The pressure induced shift coefficients and the temperature dependence of the shift coefficients for these ozone bands has never been determined before.

In September 1999 we recorded 8 high-resolution spectra of normal ($^{16}$O$_3$) and isotopic ($^{16}$O$^{18}$O$^{16}$O, $^{16}$O$^{16}$O$^{18}$O, $^{18}$O$^{16}$O$^{16}$O, $^{18}$O$^{18}$O$^{16}$O, $^{16}$O$^{16}$O$^{17}$O and $^{18}$O$_3$) species of ozone. These spectra were recorded at a resolution of 0.002 cm$^{-1}$ using the Denver University Bruker IFS 120 HR Fourier transform spectrometer. The wavenumber range of these spectra is 1988 to 2550 cm$^{-1}$. This spectral region involves the 2 overtone bands $2v_1$ and $2v_3$ as well as the combination band $v_1 + v_3$.

Note: We would like to point out that not all the work undertaken in this cooperative agreement is included above. More details may be available through the publications listed below.
Research Publications resulting from this Cooperative Agreement:


7. Tentative identification of the 780-cm$^{-1}$ ν$_4$ Band Q branch of Chlorine Nitrate in High Resolution Solar Absorption Spectra of the stratosphere.

9. Measurements of $^{12}$CH$_4$ $v_4$ band halfwidths using a tunable diode laser system and a Fourier transform spectrometer.
V. Malathy Devi, C. P. Rinsland, M. A. H. Smith, and D. Chris Benner

10. Tunable diode laser measurements of widths of air- and nitrogen-broadened lines in the $v_4$ band of $^{13}$CH$_4$.
V. Malathy Devi, C. P. Rinsland, M. A. H. Smith, and D. Chris Benner

11. Tunable diode laser measurements of N$_2$- and air-broadened halfwidths: Lines in the $(v_4 + v_3)^0$ band of $^{12}$C$_2$H$_2$ near 7.4 μm

12. Tunable diode laser measurements of widths of air- and N$_2$- broadened lines in the $v_2$ band of D$_2$O.
V. Malathy Devi, C. P. Rinsland, D. Chris Benner, and M. A. H. Smith

13. Absolute Line Intensities in CO$_2$ Bands Near 4.8 μm.
C. P. Rinsland, D. Chris Benner, and V. Malathy Devi

14. Absolute intensities and self-, N$_2$-, and air-broadened Lorentz halfwidths for selected lines in the $v_3$ band of $^{12}$CH$_3$D from measurements with a tunable diode laser spectrometer.
15. Tunable diode laser measurements of air-broadened linewidths in the v6 band of H2O.
V. Malathy Devi, C. P. Rinsland, M. A. H. Smith, D. Chris Benner, and Bernard Fridovich

16. Diode Laser Measurements of Air and Nitrogen Broadening in the v2 bands of HDO,
H2^{16}O, and H2^{18}O.
J. Mol. Spectrosc. 117, 403 (1986).

17. Absolute line intensity measurements in the v2 bands of HDO, D2O using a tunable
diode laser spectrometer.
K. B. Thakur, C. P. Rinsland, M. A. H. Smith, D. Chris Benner, and V. Malathy Devi
J. Mol. Spectrosc. 120, 239 (1987).

18. The v1 and v3 Bands H2^{16}O^{18}O: Line Positions and Intensities.

19. The Hybrid-Type Bands v1 and v3 of H2^{16}O^{18}O: Line Positions and Intensities.

20. Q branches of the v7 Fundamental of Ethane (C2H6): Integrated Intensity Measurements
for Atmospheric Measurement Applications.
C. P. Rinsland, Gale A. Harvey, V. Malathy Devi, K. B. Thakur, Joel S. Levine,
and M. A. H. Smith

22. Diode Laser Measurements of Intensities and Halfwidths in the $v_6$ band of $^{12}$CH$_3$D.

23. The $v_1$ and $v_3$ Bands of $^{18}$O$_3$ and $^{18}$O$^{16}$O$^{18}$O : Line Positions and Intensities.

24. The $v_1$ and $v_3$ Bands of $^{16}$O$_3$: Line Positions and Intensities.

25. Line Position and Intensities for $v_1+v_2$ and $v_2+v_3$ Bands of $^{16}$O$_3$.

26. Air-Broadened and Nitrogen-Broadened Lorentz Width Coefficients and Pressure
   Shift Coefficients in the $v_4$ and $v_2$ bands of $^{12}$CH$_4$.
   C. P. Rinsland, V. Malathy Devi, M. A. H. Smith, and D. Chris Benner

27. Air-Broadened Lorentz Halfwidths and Pressure-Induced Line Shifts in the $v_4$ band of $^{13}$CH$_4$.
   V. Malathy Devi, C. P. Rinsland, M. A. H. Smith, and D. Chris Benner

28. Measurements of Air-Broadened and Nitrogen-Broadened Halfwidths and Shifts of
   Ozone Lines Near 9 $\mu$m.

29. Absolute intensities of CO$_2$ Lines in the 3140 to 3410 cm$^{-1}$ Spectral Region.
   D. Chris Benner, V. Malathy Devi, and C. P. Rinsland

30. Vibrational and Rotational Spectra of Normal Ozone for the (0,1,0) and (0,2,0) States.
31. Line Positions and Intensities of the $2\nu_3$, $\nu_1 + \nu_3$ and $2\nu_1$ Bands of $^{16}\text{O}_3$.
   C. P. Rinsland, M. A. H. Smith, J.-M. Flaud, C. Camy-Peyret, and V. Malathy Devi
   J. Mol. Spectrosc. 130, 204 (1988).

32. The $\nu_2$ bands of $^{16}\text{O}^{18}\text{O}^{16}\text{O}$ and $^{16}\text{O}^{15}\text{O}^{18}\text{O}$: Line Positions and Intensities.

33. Line parameters for $^{16}\text{O}_3$ bands in the 7-µm region.

34. Measurements of Argon-Broadened Lorentz width and pressure-induced line shift coefficients in the $\nu_4$ band of $^{12}\text{CH}_4$.
   C. P. Rinsland, V. Malathy Devi, M. A. H. Smith, and D. Chris Benner

35. The 3.6 µm Region of Ozone: Line Positions and Intensities.

36. Line Parameters for Ozone Bands in the 4.8-µm Spectral Region.

37. The 3.3 µm Bands of Ozone: Line Positions and Intensities.
   C. Camy-Peyret, J.-M. Flaud, M. A. H. Smith, C. P. Rinsland, V. Malathy Devi,
   J. J. Plateaux, and A. Barbe

38. The $\nu_2$ bands of $^{18}\text{O}_3$, $^{18}\text{O}^{16}\text{O}^{18}\text{O}$ and $^{16}\text{O}^{18}\text{O}^{18}\text{O}$: Line Positions and Intensities.

39. Line Positions and Intensities for the \(v_2+3v_3\) Band of \(^{16}O_3\) around 7-\(\mu\)m.

40. Improved Line Parameters for Ozone Bands in the 10-\(\mu\)m Spectral Region.

41. Measurements of Air-, N\(_2\)-, and O\(_2\)-broadened Halfwidths and pressure-induced Line Shifts in the \(v_3\) band of \(^{13}\)CH\(_4\).

42. Analysis of High Resolution Spectrum of Acetylene in the 2.4 \(\mu\)m Region.

43. Measurements of Lorentz air-broadening coefficients and relative intensities in the \(H_2^{16}O\) pure rotational and \(v_2\) bands from long horizontal path atmospheric spectra.

44. Measurements of self-broadening of infrared absorption lines of ozone.

45. The \(v_2\) bands of \(^{16}O^{17}O^{16}O\) and \(^{16}O^{16}O^{17}O\): Line Positions and Intensities.
46. Measurements of Lorentz-broadening Coefficients and Pressure-Induced Line Shift Coefficients in the $v_2$ band of $D_2^{16}O$.  
C. P. Rinsland, M. A. H. Smith, V. Malathy Devi, and D. Chris Benner  

47. Measurements of Lorentz-broadening Coefficients and Pressure-Induced Line Shift Coefficients in the $v_2$ band of $HD^{16}O$.  
C. P. Rinsland, M. A. H. Smith, V. Malathy Devi, and D. Chris Benner  

48. Measurements of Pressure Broadening and Pressure Shifting by Nitrogen in the 4.3-$\mu$m band of $^{12}C^{16}O_2$.  
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland  

49. Temperature Dependence of Broadening and Shift Coefficients of Methane Lines in the $v_4$ band.  
M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and D. Chris Benner  

50. The $v_1$ and $v_3$ bands of $^{16}O^{17}O^{16}O$: Line Positions and Intensities.  

51. Measurements of Pressure Broadening and Pressure Shifting by Nitrogen in the $v_1$ and $v_3$ bands of $H_2^{16}O$.  
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland  


54. Measurements of Lorentz-Broadening Coefficients and Pressure-Induced Line Shift Coefficients in the $v_1$ band HD$^{16}$O and the $v_3$ band of D$_2^{16}$O.
C. P. Rinsland, M. A. H. Smith, V. Malathy Devi, and D. Chris Benner

55. Measurements of Air-Broadening and Pressure-Shifting of Methane Lines in the 2.3 $\mu$m Region.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland

56. The Hybrid-Type Bands $v_1$ and $v_3$ of $^{16}$O$^{16}$O$^{17}$O: Line Positions and Intensities.

57. Air-, N$_2$- and O$_2$-Broadening and Shift Coefficients in the $v_3$ spectral region of $^{12}$CH$_4$.
D. Chris Benner, V. Malathy Devi, M. A. H. Smith, and C. P. Rinsland

58. The Fundamental Bands of H$^{35}$Cl and H$^{37}$Cl: Line positions from High-Resolution Laboratory Data.
C. P. Rinsland, M. A. H. Rinsland, A. Goldman, V. Malathy Devi, and D. Chris Benner

59. Line parameters for ozone hot bands in the 3.3- 3-$\mu$m region.

60. Measurements of pressure broadening and shifts of O$_3$ lines in the 3-$\mu$m region.
M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and E. S. Prochaska
61. Temperature Dependence of Lorentz air-broadening and pressure-shift coefficients of $^{12}\text{CH}_4$ lines in the 2.3-μm spectral region.
   V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland

62. A multispectrum nonlinear least squares fitting technique.
   D. Chris Benner, C. P. Rinsland, V. Malathy Devi, M. A. H. Smith, and D. Atkins

63. Stretch-Bend Levels of Acetylene: Analysis of the Hot Bands in the 3300 cm$^{-1}$ Region.
   Y. A. Sarma, R. D'Cunha, G. Guelachvili, R. Farrenq, V. Malathy Devi, D. Chris Benner,
   and K. Narahari Rao

64. Infrared Spectroscopy of the CO$_2$ molecule.
   V. Malathy Devi, D. C. Benner, C. P. Rinsland, M. A. H. Smith, and D. S. Parmar
   In Recent Developments in Geophysical Research, ed. S. G. Pandali, pp. 119-148,
   Research Signpost, Trivandrum, India (1996).

65. Temperature dependence of air-broadening and shift coefficients of O$_3$ lines in the $v_1$ band.
   M. A. H. Smith, V. Malathy Devi, D. Chris Benner, and C. P. Rinsland

66. Air-broadening and shift coefficients of O$_3$ lines in the $v_2$ band and their temperature dependence.
   V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
   J. Mol. Spectrosc. 182, 221-238 (1997).

67. Air- and N$_2$-broadening coefficients and pressure-shift coefficients in the $^{12}\text{C}^{16}\text{O}_2$ laser bands.
   V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland

68. Absolute rovibrational intensities of $^{12}\text{C}^{16}\text{O}_2$ absorption bands in the 3090 to 3900 cm$^{-1}$
   spectral region.
   V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
69. Pressure broadening and pressure shift coefficients in the $2v_2^0$ and $v_1$ bands of $^{16}$O$^{13}$C$^{18}$O.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsalnd

70. Spectroscopic Parameters of ozone and its isotopes: Current status, prospects for improvement, and the identification of $^{16}$O$^{16}$O$^{17}$O and $^{16}$O$^{17}$O$^{16}$O lines in infrared ground-based and stratospheric solar absorption spectra.

71. Self-broadening and self-shift coefficients in the fundamental band of $^{12}$C$^{16}$O.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsalnd

72. Measurements of air-broadening, pressure shifting and off-diagonal relaxation-matrix coefficients in the $v_3$ band of $^{12}$CH$_3$D.

73. Measurements of air broadened width and air-induced shift coefficients and line mixing in the $v_6$ band of $^{12}$CH$_3$D.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsalnd

74. Measurements of air broadened width and air-induced shift coefficients and line mixing in the $v_5$ band of $^{12}$CH$_3$D.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsalnd

75. Absolute intensities of O$_3$ lines in the 9-11 $\mu$m region.
M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and D. C. Benner
List of Contributed Papers: (1995 and onwards) Papers presented prior to 1995 are not included in this list.

1. CO$_2$ bands in the 3350 - 3700 cm$^{-1}$ spectral region: Ro-vibrational constants and absolute intensities.
   V. Malathy Devi, D. Chris Benner, C. P. Rinsland, and M. A. H. Smith

2. Measurements of O$_3$ line intensities in the $\nu_2$ band: Preliminary results.
   M. A. H. Smith, V. Malathy Devi, D. Chris Benner, and C. P. Rinsland

3. Vibrational energies and rotational constants of $^{12}$C$^{16}$O$_2$.
   D. Chris Benner, V. Malathy Devi, C. P. Rinsland, and M. A. H. Smith

4. Absolute intensities of CO$_2$ lines in the 1830 to 4000 cm$^{-1}$ spectral region.
   V. Malathy Devi, D. Chris Benner, C. P. Rinsland, and M. A. H. Smith

5. Comparison of CO$_2$ absolute intensities for bands near 4000 cm$^{-1}$.
   D. Chris Benner, Lawrence P. Giver, C. Chackerian, Jr., V. Malathy Devi, L. R. Brown,
   C. P. Rinsland, and M. A. H. Smith

6. Measurements of O$_3$ line intensities in the $\nu_3$ band.
   M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and D. Chris Benner

7. Line intensity measurements in the $\nu_3$ band of O$_3$.
   M. A. H. Smith, V. Malathy Devi, D. Chris Benner, and C. P. Rinsland
   Atmospheric Spectroscopy Applications Workshop, Reims, France Sept. 4-6, 1996
8. Temperature dependence of ozone air-broadening and shift coefficients.
M. A. H. Smith, V. Malathy Devi, D. Chris Benner, and C. P. Rinsland
14th International Conference on High Resolution Molecular Spectroscopy, Prague,

9. Spectroscopic parameters of CO$_2$ in the 2.5 to 5.5-$\mu$m spectral region.
V. Malathy Devi, D. Chris Benner, C. P. Rinsland, and M. A. H. Smith
14th International Conference on High Resolution Molecular Spectroscopy, Prague,

10. Absolute intensities of O$_3$ lines in the 9-11 $\mu$m region
M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and D. C. Benner
Fifty-second International Symposium on Molecular Spectroscopy, Ohio State
University, Columbus, Ohio, June 16-20, 1997. Paper RF03

11. Self-broadening and self-shift coefficients in the 1-0 band of $^{12}$C$^{16}$O
D. Chris Benner, V. Malathy Devi, M. A. H. Smith, and C. P. Rinsland
Fifty-second International Symposium on Molecular Spectroscopy, Ohio State
University, Columbus, Ohio, June 16-20, 1997. Paper RF05

12. Pressure broadening and pressure shift coefficients in the 2$\nu_2$ and $\nu_1$ bands of $^{16}$O$^{13}$C$^{18}$O.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
Fifty-second International Symposium on Molecular Spectroscopy, Ohio State
University, Columbus, Ohio, June 16-20, 1997. paper RF13

13. Air- and N$_2$-broadening coefficients and pressure shift coefficients in the $^{12}$C$^{16}$O$_2$ laser bands
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
Fifty-second International Symposium on Molecular Spectroscopy, Ohio State
University, Columbus, Ohio, June 16-20, 1997. Paper RF14

14. Pressure broadening and pressure shift coefficients in the 2$\nu_2$ and $\nu_1$ bands of $^{16}$O$^{13}$C$^{18}$O.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
15th Colloquium on High Resolution Molecular Spectroscopy, Strathclyde University,
Glasgow, 7-11 September 1997. Poster M7 (p.203)
15. Air- and N₂-broadening coefficients and pressure-shift coefficients in the $^{12}$C$^{16}$O₂ laser bands.
V. Malathy Devi, D. Chris Benner, M. A. H. Smith, and C. P. Rinsland
15th Colloquium on High Resolution Molecular Spectroscopy, Strathclyde University, Glasgow, 7-11 September 1997. Poster N8 (p. 242)

16. Absolute intensities of O₃ lines in the 9-11 mm
M. A. Smith, C. P. Rinsland, V. Malathy Devi, and D. Chris Benner
Fifty-third International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 15-19, 1998. Paper WF04

17. Pressure broadening and shift coefficients for water in the 2.5μm region
K. Keppler Albert, D. Chris Benner, V. Malathy Devi, and M. A. H. Smith
Fifty-third International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 15-19, 1998. Paper WF06

18. Self- and Air-broadening and shift coefficients of CH₄ lines in the 3 μm region
Fifty-third International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 15-19, 1998. Paper WF11

19. Temperature dependence of air-broadening and shift coefficients in the ν₃ band of $^{12}$CH₄
Fifty-third International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 15-19, 1998. Paper WF12

20. Line mixing coefficients in the ν₃ band of $^{12}$CH₄ and $^{13}$CH₄
Fifty-third International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 15-19, 1998. Paper WF13

21. Air-Broadening coefficients and pressure shift coefficients of $^{12}$CH₃D lines in the 7.7 to 10 μm spectral region
22. Precise line parameters of methane in the MOPITT CO and methane channels
OSA meeting on Fourier Transform Spectroscopy, June 1999.

23. Assigning Database Broadening and Shift Parameters: O₃ and CH₃D
M. A. H. Smith, V. Malathy Devi, D. Chris Benner, and C. P. Rinsland

24. Temperature dependence of line mixing in the ν₃ band of ¹²CH₄
Fifty-fourth International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 14-18, 1999. Paper WH02

25. Measurements of air-broadening and pressure-shift coefficients and line mixing in the ν₆ fundamental band of ¹²CH₃D
Fifty-fourth International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 14-18, 1999. Paper WH03

26. Air-broadening and shift coefficients and line mixing in the ν₃ fundamental band of ¹²CH₃D
Fifty-fourth International Symposium on Molecular Spectroscopy, Ohio State University, Columbus, Ohio, June 14-18, 1999. Paper WH04

27. Air-broadening and shift coefficients and line mixing in the ν₃, ν₅, and ν₆ bands of ¹²CH₃D
M. A. H. Smith, C. P. Rinsland, V. Malathy Devi, and D. Chris Benner
16th Colloquium on High Resolution Molecular Spectroscopy, Universite de Bourgogne, Dijon, France, 6-10 September 1999. Poster B23
28. Temperature dependence of pressure-broadening, pressure-shifting and line mixing due to air in the ν3 band region of 12CH4.


29. Water Vapor Line Parameters in the 3500-650 cm⁻¹ Region


16th Colloquim on High Resolution Molecular Spectroscopy, Universite de Bourgogne, Dijon, France, 6-10 September 1999. Poster D26

30. Line Parameters of Methane in the MOPITT Spectral Region


16th Colloquim on High Resolution Molecular Spectroscopy, Universite de Bourgogne, Dijon, France, 6-10 September 1999. Post-Deadline Poster, p.4

The following oral presentations are submitted for the 55th Ohio State University International Symposium on Molecular Spectroscopy, to be held in June 2000.

1. High Resolution Spectra of Isotopic Ozone in the 5 μm Region


2. Nitrogen Broadening and Shift Coefficients in the ν5 and ν6 fundamental bands of 12CH3D


3. Analysis of self-broadened spectra in the ν5 and ν6 fundamental bands of 12CH3D


4. Nitrogen- and Self-Broadening and shift Coefficients in the ν3 fundamental band of 12CH3D


5. Line Mixing in the triad of 12CH3D

D. Chris Benner, V. Malathy Devi, L. R. Brown, M. A. H. Smith and C. P. Rinsland

6. Temperature Dependence of Line Mixing in the P Branch of the ν3 Band of Methane

7. Measurements of 1-0 Band of Carbon Monoxide at Temperatures between 11 and 296 Kelvins
D. Ball and F. C. DeLucia