Final Report for NAG5-4426

A Grant from NASA's Office of Space Science, Planetary Atmosphere's Program to Boston University

Roger V. Yelle, Principle Investigator

1 Past Accomplishments

In the past three years of this program we have made contributions to a variety of subjects. The highpoints are briefly summarized below. A list of papers supported partly or wholly by this program is provided in Appendix A.

There were no inventions or commercially valuable products produced under the activities supported by this program.

1.1 Jupiter's Thermosphere

In late 1995, just prior to the entry of the Galileo probe to the Jovian atmosphere, we undertook a review of data on the temperature profile of the upper atmosphere and came to the conclusion that the thermal structure must be different from the currently accepted model. We argued that all the data (H_3^+ emissions, UV occultations, groundbased stellar occultations, UV spectroscopy) could be understood if the Jovian thermosphere possessed a strong temperature gradient right above the homopause. We further argued that such a gradient was evidence that the jovian thermosphere was heated by gravity waves (Yelle et al. 1996). In situ data from the Atmospheric Structure Instrument (ASI) on the Galileo probe verified the general properties of our prediction and also discovered large amplitude gravity waves in jovian atmosphere (Sieff et al. 1996). We helped to analyze the ASI data and determine the wave characteristics (Sieff et al. 1998, Young et al. 1997) and estimated the heating rate due to dissipation of the waves by molecular viscosity and thermal conduction (Young et al. 1998). Our heating rate calculations were based on the theory developed by French and Gierasch (1974). Matcheva and Strobel (1999) have criticized our approach; however, careful analysis of their work shows that their calculations contain questionable approximations. This topic is discussed further in Section 3.1.

1.2 Jupiter's Stratosphere

We calculated the radiative heating rates in the jovian stratosphere at a latitude of 6 N, using the ASI data to constrain the temperature profile and observations of hydrocarbon emissions to constrain their abundance. The motivation behind this work was that the simultaneous constraints on temperature, composition, and aerosol properties provided the opportunity for a more in depth examination of energy balance than had been previously possible. We found that the stratosphere was close to radiative equilibrium in the 0.3-3 mbar region, that emissions from C_2H_2 and C_2H_6 are important terms in energy balance, and that C_2H_2 is less abundant than predicted in the upper stratosphere. The importance of C_2H_2 and C_2H_6 and the well-established latitudinal variations of these species imply that compositional variations with latitude may be an important driver of stratospheric dynamics on Jupiter. This fact had not been appreciated previously. A paper has been submitted to *Icarus* and is being revised (Yelle et al. 1999).

1.3 UV Spectroscopy of Jupiter

We have made significant progress in the reduction, analysis, and interpretation of HST/FOS spectra of Jupiter. To analyze the observations we have developed a radiative transfer code that includes raman scattering in more accurate manner than in any previous work. Our calculations calculate the effect of raman scattering directly, rather than applying empirical corrections, a common technique in earlier studies. The only approximations made are that raman scattering is treated as isotropic and that distribution of H_2 quantum states is such that photons only lose energy in the raman scattering process. We find that the consequences of raman scattering are large and have identified numerous features caused by raman scattering in FOS spectra of Jupiter (Bétrémieux and Yelle, 1999a). Our improved treatment has lead to tighter constraints on the distribution of absorbers. The first application of our code to analysis of FOS spectra of Jupiter determined that the C_2H_2 abundance in the jovian atmosphere has a local maximum in the troposphere of Jupiter. The abundance appears to be consistent with generation by lightning (Bétrémieux and Yelle, 1999b). This is the most compelling evidence to date for organic synthesis in the jovian atmosphere caused by lightning. We also determined that NH_3 is depleted in the upper troposphere relative to its vapor pressure (Bétrémieux and Yelle, 1999b).

1.4 Pluto

In the first year of the previous program we finished two projects related to the abundance of CH_4 in the atmosphere of Pluto (Stansberry et al. 1996a, Young et al. 1997) and an in depth study of the emissivity of Pluto's surface (Stansberry et al. 1996b). Subsequently, we investigated the effect of the surface emissivity on the Pluto climate. We find that, for a wide variety of conditions, the change in emissivity associated with the phase transition in N_2 ice at 35.6 K buffers the atmospheric pressure to a value of about 4 μbar. Thus, the "collapse" of the atmosphere as Pluto moves away from the sun can be significantly delayed or avoided altogether.

1.5 Titan

Two separate projects on Titan have been completed. Along with Dr. Jane Fox we calculated the coupled ion-neutral chemistry in the atmosphere of Titan (Fox and Yelle 1997). This work discovered that the dominant species in the ionosphere is likely a complex hydrocarbon ion. This result is counter to previous investigations that found H_2CN^+ to be the most abundance species. We find that hydrocabon ions dominant primarily because H_2CN^+ reacts with $C_4H_2^+$ to produce $C_4H_3^-$, which then reacts with other hydrocarbons to create even more complex ions. This work makes important and testable predictions for the Cassini INMS investigation.

Along with Drs. Henry Risbeth and Michael Mendillo we performed the study of thermospheric dynamics on Titan (Risbeth et al. 1999). We find that, like the lower atmosphere, the thermosphere of Titan should be in cyclostrophic balance with curvature terms balancing pressure gradients. Coriolis and viscous forces are important but minor. Ion drag is unlikely to be important. Moreover, the dynamical time constant is shorter than a Titan day, suggesting that local time variations are small.

1.6 Brown Dwarfs

Along with collaborators Caitlin Griffith and Mark Marley, we completed an analysis of the recently obtained visible spectrum of the brown dwarf Gliese 229B (Gl229B) (Griffith et al. 1998). We find that the opacity in the visible is due predominantly to dust and H_2O and that both have interesting properties. The dust is reddish in color and therefore different from refractory minerals that are observed in atmospheres of cool stars. Instead the optical properties of the dust is similar to the aerosols in our own outer solar system. Pursuing this analogy with the outer solar system, we investigated a photochemical origin for the dust and find that photochemistry initiate by UV radiation from the primary star may explain the observations, provided that the vertical mixing rate in the atmosphere is slow. We also found that the abundance of oxygen in Gl229B was roughly a factor of 3 less than solar. Our work emphasizes the similarities between planetary stratospheres and the photospheres of brown dwarfs. Subsequently, we reanalyzed the spectral signature of CO from Gl229B obtained by Noll et al. (1997). CO on Gl229B is a puzzle because it is present with a abundance much greater than predicted by thermochemical equilibrium (Noll et al. 1997). We found that, as on Jupiter, transported from deeper levels by to the visible atmosphere can explain the observations. However, because the thermochemical region on Gl229B is much closer to the visible atmosphere than on Jupiter only weak vertical mixing ($K \sim 10^3$ $cm^2 s^{-1}$) is required to explain the observations (Griffith and Yelle, 1999a). This is consistent with our conclusion on the photochemical origin of the dust. We have also analyzed cesium features in the spectrum of Gl229B and find that the best match to the data is obtained if Cs is depleted relative to solar by a factor of 8 (Griffith and Yelle 1999b).

2 Publications from NAG5-4426

Publications supported partly or wholly by NAG5-4426 in the last 3 years are listed below.

1) R. V. Yelle and M. McGrath, Ultraviolet Spectroscopy of the SL-9 Impact Sites, I: The 175-230 nm Region, *Icarus*, 119, 90-111, 1996.

2) R. V. Yelle, L. A. Young, R. Vervack, Jr., R. E. Young, L. Pfister, and B. R. Sandel, The Structure of Jupiter's Upper Atmosphere: Predictions for Galileo, *J. Geophys. Res.*, 101,2149-2161, 1996.

3) J. A. Stansberry, D. J. Pisano, and R. V. Yelle, The Emissivity of Nitrogen Ice on Triton and Pluto, *Planetary and Space Science*, 44, 945-955, 1996.

4) J. A. Stansberry, J. R. Spencer, B. Schmitt, A. Benchkoura, R. V. Yelle, and J. I. Lunine, A Model for the Overabundance of Methane in Pluto's Atmosphere, *Planetary and Space Science*, 44, 1051-1063, 1996.

5) R. V. Yelle and J. L. Elliot, Atmospheric Structure and Composition: Pluto and Charon, in *Pluto and Charon*, University of Arizona Press, D. Tholen and A. Stern, eds., 1996.

6) L. A. Young, R. V. Yelle, R. E. Young, A. Sieff, and D. B. Kirk, Gravity Waves in Jupiter's Thermosphere, *Science*, 276, 108-111, 1997.

7) Young, L. A., J. L. Elliot, A. Tokunaga, C. de Bergh, and T. Owen, Detection of Gaseous Methane on Pluto. *Icarus* 127, 258-262, 1997.

8) Seiff, A., D. B. Kirk, T. C. D. Knight, L. A. Young, F. S. Milos, E. Venkatapathy, J. D. Mihalov, R. C. Blanshard, R. E. Young, and G. Schubert, Thermal structure of Jupiter's upper atmosphere derived from the Galileo Probe. *Science* 276, 102-104, 1997.

9) S. A. Stern and R. V. Yelle, Pluto and Charon, a chapter in *The Encyclopedia of the Solar System,* T. V. Johnson and P. R. Weissman, eds., Academic Press, 1997.

10) J. L. Fox, and R. V. Yelle, Hydrocarbon Ions in Titan's Ionosphere, *Geophys. Res. Letts.*, 24, 2179-2182, 1997.

11) R. V. Yelle, E. Lellouch, D. Gautier, and D. F. Strobel, Engineering Models for Titan's Atmosphere, ESA SP-1177, pp 243-257, 1997.

12) Seiff, A., D. B. Kirk, T. C. D. Knight, R. E. Young, J. D. Mihalov, and L. A. Young, F. S. Milos, G. Schubert, R. C. Blanchard, D. Atkinson, Thermal structure of Jupiter's atmosphere in the North Equatorial Belt near the edge of a 5-micron hot spot. *Journal of Geophysical Research,* 103, 22857-22889, 1998.

13) Cooray, A. R., J. L. Elliot, A. S. Bosh, and L. A. Young, M. A. Shure, Stellar occultation observations of Saturn's north-polar temperature structure. *Icarus* 132, 298-310, 1998.

14) Olkin, C. B. and 19 others (including L. A. Young), The thermal structure of Triton's atmosphere: results from the 1993 and 1995 occultations. *Icarus* 128, 178-201, 1998.

15) J. A. Stansberry and R. V. Yelle, The Fate of Pluto's Atmosphere, in press *Icarus*, March 1999.

16) R. V. Yelle, C. A. Griffith, and L. A. Young, The Structure of Jupiter's Stratosphere at the Galileo Probe Entry Site, submitted to *Icarus,* August 1998

17) C. A. Griffith, R. V. Yelle, and M. S. Marley, The Dusty Atmosphere of the Brown Dwarf GL229B, *Science*, 282, 2063-2067, 1998.

18) Y. Bétrémieux and R. V. Yelle, HST Detection of H_2 Raman Scattering in the Jovian Atmosphere, *Icarus*, 142, 324-341, 1999.

19) H. Risbeth, R. V. Yelle, and M. Mendillo, Dynamics of Titan's Thermosphere, *Planet. Space Sci.*, 48, 51-58, 2000.

20) C. A. Griffith and R. V. Yelle, Disequilibrium Chemistry in a Brown Dwarf's Atmosphere: Carbon Monoxide in Gliese 229B, *Ap. J.*, 519, l85-l88, 1999.

21) Y. Bétrémieux and R. V. Yelle, HST Observation of Tropospheric C_2H_2 in the Jovian Equatorial Region: Evidence for Lightning Production, submitted to *Icarus*, June 1999.

22) C. A. Griffith and R. V. Yelle, Equilibrium Chemistry in a Brown Dwarf's Atmosphere: Cesium in Gliese 229B, *Ap. J.*, 532, L000-L000, 2000.