Summary of Research (Final Report) on NAG5-8057.

Interpretation of Radiative Energy Fluxes in Jupiter's Atmosphere

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1 Specific Aims

The aims of our original proposal were to combine Galileo Probe and Orbiter observations, together with earth-based and HST observations, to obtain new constraints on Jovian cloud structure, the vertical distribution of condensible gases, and the source of excess absorption of red light deeper than 4 bars.

2 Results

The most substantial results were obtained from radiation transfer modeling of cloud variations in Jupiter's North Equatorial Belt (NEB), which contains the latitude of the Galileo Probe entry (6.5° N). The probe entered at the edge of a 5-μm hot spot, a region in which cloud optical depths and condensible mixing ratios are low compared to expectations for Jovian average values (Niemann *et al.*1998). The very low mixing ratio of water that was observed, even at relatively high pressures ($\sim$20 bars) raised questions about the relevance of the probe observations at one location to general characteristics of the Jovian atmosphere. It was also suggested, based on an analysis of HST observations of hot spot regions (Chanover *et al.*1997), that the probe observations might not even represent typical hot-spot conditions.

2.1 Analysis Approach

We used Nephelometer observations (Ragent *et al.*1998) and Net Flux Radiometer observations (Sromovsky *et al.*1998) to constrain the pressure levels cloud layers in the 5-micron hot spot regions, which are also dark regions at 953 nm. In essence the cloud structure consisted of a physically thin upper cloud (somewhere above the 450 mb level) and a physically thin middle cloud near 1.2 bars. Additional components not constrained by probe observations were a high altitude haze and a deep cloud (deeper than the 14-bar level). We then used center-to-limb variations of specific bright and dark features in the NEB as constraints on the upper cloud optical depth and pressure, and the middle cloud optical depth. Four wavelengths were used to sample different degrees of methane absorption and Rayleigh scattering: 619 nm, 673 nm, 893 nm, and 953 nm. In the latter wavelength the hot spots appear as dark features.

We used a shotgun approach to fitting the observations. We selected parameters to be adjusted, a range of variations for each parameter, then computed thousands of I/F models, one for each combination of parameters. We selected individual targets, gathered I/F values for as many images as possible, then computed, for every I/F profile in our data base, the value of χ^2 relative to the observed profile. We computed the goodness of fit for each model as the sum of χ^2 for each wavelength independently and for combinations of wavelengths when fitting multiple wavelengths to the same structure. For each parameter we plot the values of χ^2 as a function of parameter value. The minimum for each value is then fit to a quadratic to estimate its interpolated best value and the change required to change the normalized χ^2 by one unit provides an estimate for the 1-σ uncertainty in the constrained parameter. The normalized χ^2 we compute is the raw sum of χ^2 for all observations at all wavelengths, scaled so that its minimum value equals the number of observations minus the number fitted parameters. If our error estimates were accurate, the normalized and actual values would agree. But in general, variations are often somewhat larger than our a priori estimates. The normalization procedure is in effect saying that the true errors are better represented by the variances from the best-fit models than by our a priori estimates.

There are several advantages of the shotgun approach we used to fit models to observations. First, the uncertainties in the fitted parameters are immediately apparent from the behavior of χ^2 as a function of parameter value. Well-constrained parameters are easy to distinguish from those that are poorly constrained. From a single set of I/F calculations many different target feature observations can be modeled; and if calibration adjustments are needed, new fits can be made without doing new calculations. Finally, the parameter space is explored so thoroughly that fitting process cannot be trapped in local minima.

2.2 Analysis Conclusions

Our general conclusion is that there is no significant inconsistency between the in situ Probe observations and the external HST observations, although the implied cloud structure is not in keeping with past inferences. The most robust conclusions from adapting the parameters of this model to HST observations are as follows:

1. *In the latitude region near 6.5° N, we find that the upper cloud pressure and optical depth are remarkably invariant for both bright and dark features and from October 1995 to May 1996.* An effective pressure of $\sim$ 260 mb (1995) and $\sim$ 280 mb (1996) were accompanied by respective upper cloud opacities (at 0.9 μm) of 1.6-1.9 (1995) and 2.2-2.4 (1996). The rather small variation in the vertical position and optical thickness of this cloud are remarkable, and probably inconsistent with this cloud reaching the 700 mb level at any longitude within the latitude band of investigation (near 6.5° N). It is also inconsistent with the Banfield *et al.*(2001) conclusion that the ammonia ice cloud is the main source of variability. It is much more consistent with the results of Irwin *et al.*(2001) suggesting that most of the variability is between 1 and 2 bars.

2. *The main variation in cloud properties was found to be in the middle cloud, fixed at a pressure of 1.2 bars to match the peak in the Nephelometer backscatter observations.* Its optical depth varied from 1-2 in the darkest regions, to 8-30 in the brightest regions. It is somewhat surprising that the Probe-based constraint that the middle cloud effective

pressure be 1.2 bars also results in high quality fits in regions where that cloud has double-digit optical depths. It is reasonable to expect altitude variations as an accompaniment to the large optical depth variations, although such variations do not seem to be required to fit the observations. It remains to be seen whether adjusting the effective pressure might provide some improvement in fit quality.

3. *In general, in or near hot-spot regions sampled by the Galileo entry Probe, a cloud model can be constructed that is both consistent with Probe observations and matches external center-to-limb radiance profiles.* Conflicting results of Chanover *et al.*(1997) are mainly a consequence of inappropriate assumptions, especially the presence of a semi-infinite cloud at 2 bars and an ammonia cloud base at 0.7 bars.

4. *We were able to match observations without using significant absorption in the upper and middle cloud layers.* I/F variations were modeled with optical depth variations rather than by adjusting single-scattering albedo. By eliminating the often assumed semi-infinite lower cloud we made it possible to darken the atmosphere using deep atmosphere absorption by methane or a deep lower cloud, rather than by local absorption in the upper and middle cloud layers. This approach is more consistent with the putative constituents of these layers, which are very weak absorbers.

3 Publications

Papers supported significantly by this grant:

Sromovsky, L. A., and P. M. Fry (2002) Jupiter's Cloud Structure as Constrained by Galileo Probe and HST Observations. *Icarus* **157**, 373-400.

Sromovsky, L. A., and P. M. Fry (2001) A Jovian Cloud Structure Consistent with Both Galileo Probe and HST Observations. *Bull. Am. Astron. Soc.* **33**, 1032.

Sromovsky, L. A., and P. M. Fry (2001) Consistency of Galileo Probe cloud structure results with HST observations of low-latitude dark features at 893 and 953 nm. Proceedings of the Jupiter Conference, 25-30 June 2001, Laboratory for Atmospheric and Space Physics, Boulder, CO.

Minor contributions were also made to two DPS papers on Jovian atmospheric science:

Bjoraker, G.L., G.S. Orton, A.D. Collard, L.A. Sromovsky (1999) The spatial distribution of water and ammonia near Jupiter's Great Red Spot, *Bull. Am. Astron. Soc.* **31**, 1175.

Fisher, B.M., G.S. Orton, P. Yamanandra-Fisher, M. Ressler, P. Fukamura-Sawata, W. Golish, D. Greip, J. Spencer, L. Sromovsky, and P. Fry (1999) Metastable Cyclones in Jupiter: Interactions between White Ovals and the Rise of Very Dark Spots in 1998 and 1999. *Bull. Am. Astron. Soc.* **31**, 1158.

4 Outreach.

Our outreach efforts, which were coordinated and managed by Sanjay Limaye, director of SSEC's Office of Space Science Education (OSSE), consisted of public presentations, mainly at high schools, contribution towards development of a local course in astronomy, and development of a museum display. Part of this effort was focused on Jovian science and supported by the subject JSDAP grant.

4.1 School Programs.

The Office of Space Science Education conducted over 50 programs during 2001 and reached nearly 3,000 school students in different parts of Wisconsin. Most of these programs had solar system exploration as a theme. The programs were conducted in different parts of Wisconsin (Visiting Scientist) as well as locally at UW-Space Place.

4.2 Summer Workshop for Minority Middle School Students.

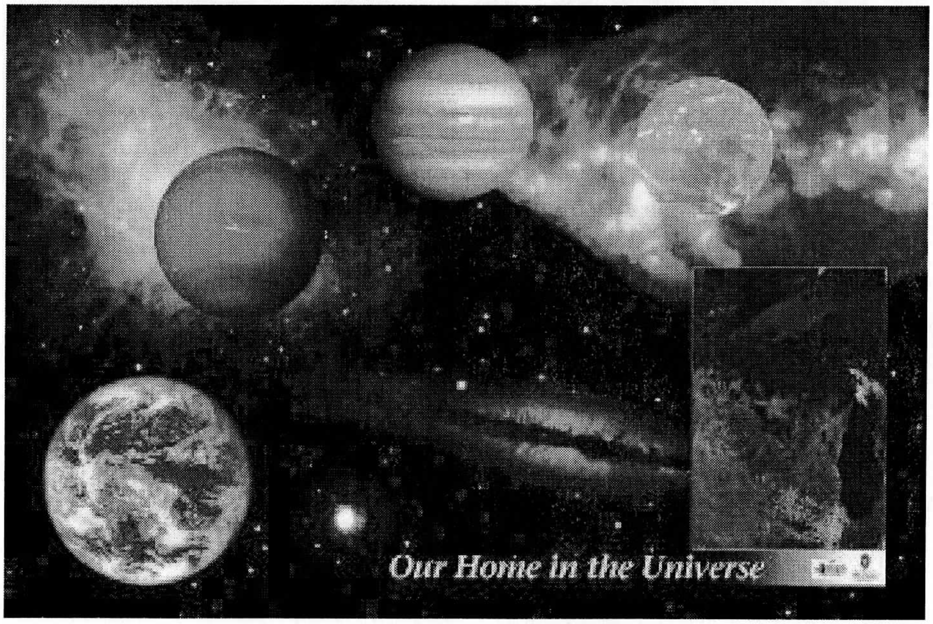
In association with the University of Wisconsin-Madison's PEOPLE Program, OSSE conducted a three-week workshop for middle school minority students during June in 2000, 2001 and 2002. These workshops were based on a solar system exploration theme.

4.3 Course Development

OSSE initiated a new High School Astronomy/Astrophysics Course offered as an elective to high school seniors (taught by a teacher from the Madison Metropolitan School District) which included approximately a fourth of the content on solar system exploration and a significant outer planet exploration component.

4.4 Poster Production

Jupiter was highlighted in a 24" x 32" full color poster printed by OSSE in 2002 for distribution to schools.



4.5 Museum Displays.

In partnership with the Science Museum of Minnesota (SMM) located in St. Paul, MN, OSSE is developing content material for the Planets Gallery. The effort will be featured in the Current Science programming area of SMM and will include posters, video kiosks and also sponsor public lectures and teacher workshops. An interactive slide show presentation as been completed and undergoing adaptation and review at SMM. A colloquium presentation by the PI (L. Sromovsky), entitled "Mysteries of Jovian Cloud Structure" was simplified and augmented with significant explanatory material to serve as a basis for one of the museum displays.

5 Patents

No patents were issued under this grant.

6 REFERENCES

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Sromovsky, L. A., and P. M. Fry (2002) Jupiter's Cloud Structure as Constrained by Galileo Probe and HST Observations. *Icarus* **157**, 373-400.