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University Of Wisconsin-Madison

(To be completed by RSP or the Department)

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Inventions Report:

☒ No Inventions resulted from this award
☐ Yes

Inventory Report:

☒ No federally owned equipment is in the custody of the PI
☐ Yes

Publications: (Please list)

The following were partially supported by this grant and partially supported by a grant from the Jupiter Data Analysis Program.

Sromovsky, L.A., and P.M. Fry 2010. The source of 3-micron absorption in Jupiter's clouds: a reanalysis of ISO observations with new NH3 absorption models. Icarus, in press.

Sromovsky, L.A., and P.M. Fry, 2010. The source of 3-micron absorption in Jupiter's clouds: constraints from 2000 VIMS observations. Icarus, in press.

Sromovsky, L.A., P.M. Fry, I. de Pater, and M. H. Wong, 2010. Jupiter's low-latitude cloud structure: implications of 2005 NICMOS observations. In preparation for submission to Icarus.

Sromovsky, L.A. and P.M. Fry. 2009. Evidence for widely distributed ammonia ice on Jupiter. Bull. Am. Astron. Soc. 41, 1006.

Summary of Technical Effort: (Usually several paragraphs. Please feel free to attach additional pages if you wish.)

BACKGROUND: We proposed to derive improved models of Jovian cloud structure using a combination of Cassini and Galileo imaging and spectral observations acquired during the Cassini flyby of Jupiter in 2000. Weak, strong, and intermediate methane band and continuum images obtained by the Cassini ISS, enhanced by VIMS CCD spatially resolved spectral observations, would be used to constrain the vertical cloud structure at CCD wavelengths. Near IR observations by the Galileo NIMS and Cassini VIMS in the 1-5 micron range, analyzed with recently improved models of methane absorption, would provide cloud structure constraints at near IR wavelengths, which have the advantage of being less affected by Rayleigh scattering, Raman scattering, and polarization. By combining analysis of near IR and visible imaging, spectroscopy, and phase angle variations, aided by variable absorption by methane, ammonia, hydrogen, and assisted by polarimetry, we intended to resolve the controversy regarding the location of the main variations in cloudiness in the Jovian atmosphere.

DATA PROCESSING RESULTS:

Cassini ISS Processing: We began by selecting and preparing two Cassini data sets for analysis, one ISS data set and one VIMS data set. We selected ISS data that covered a large enough number of Jupiter rotations that we were able to observe the same features at a wide range of angles, to provide good center-to-limb constraints on the vertical cloud structure. Because of the ISS imaging sequence design, to obtain a large number of angles of view of the same cloud feature requires sampling multiple rotations of Jupiter, which give the zonal winds time to move the cloud targets to different longitudes so they can be seen over a more continuous range of angles. But including more rotations of Jupiter provides more time for a cloud to evolve, so that its properties are not the same at all view angles. We found that there was a sweet spot that allowed good sampling as well as limited evolution. This covered the image number range from 1.352E9 to 1.353E9. We used CISSCAL to produce radiometrically calibrated I/F images for all ISSNA full-resolution (non-binned) images in the selected data set. We navigated the images using planet centers and orientation information provided in the image headers. To facilitate this effort, we developed a display and data selection program that displayed stacked strips of narrow latitude bands showing cloud evolution over time, and displaying limb-to-limb I/F values by filter, and included data from all images in the data set, not just those displayed. This program provides an important quality control tool to make sure that we select cloud targets for analysis that are not rapidly evolving or shearing during the period we need to accumulate different view angles. The data set and program were made ready for use in constraining cloud structure models, although the analysis was not completed due to unexpected efforts required in the infrared analysis.

Cassini VIMS Processing. The second data set we prepared is from the Cassini VIMS; we began with the Near-IR spectra because of data analysis advantages (lack of Rayleigh scattering and reduced cloud opacity). The data we used (cube identifier CM_1356976257_3) are from the Jupiter flyby sequence and were acquired on 31 December 2000 from 17:39:17 UT to 17:40:47 UT, at a phase angle of 67.83 degrees and a range of 9.874 million km. At this range, the VIMS image imaging pixel size of 102.1 arcseconds corresponds to a sub- spacecraft cloud-top resolution of 4880 km (29 pixels across the equatorial diameter of Jupiter). We later added a cube obtained on 11 December 2000 at a much lower phase angle (2.5 degrees) and at about twice the range, providing more suitable observing conditions for comparison with earth-based observations. From such comparisons we found that the near IR VIMS spectra have large calibration errors near 1.66 microns, where there is a joint between different order-sorting filters and a very large responsivity correction is required. We decided to skip this region in our spectral analysis. We also determined by comparison with other spectral observations by Banfield et al. (1998, Icarus 134, 11-23) and HST NICMOS observations with the F237M filter that at very low signal levels VIMS measurements are likely contaminated by light scattered from its grating. This affects atmospheric observations in deep absorption bands, which appear brighter than is actually the case, leading to inferences of much more upper level haze than is actually present.

NICMOS Processing. The VIMS spectra we selected were analyzed in combination with the NICMOS observations that we began work on under prior support by a Planetary Atmospheres grant. The NICMOS observations provide higher spatial resolution than is available from the Cassini flyby of Jupiter, and allows us to investigate the depth of variations in cloud structure from the ratio of modulations in different filter bands. Deconvolution and navigation of these images were carried out under the prior grant.

MODELING RESULTS:

Gas Absorption Models. We focused the first year's analysis efforts on the near-IR portion of the spectrum, where the modeling is simplified by not having to use multiple-scattering for the atmospheric contributions. We initially computed new line-by-line opacities (using the HITRAN 2004 line database) for the 3-micron NH_3 absorption feature and derived exponential sum models for use in correlated-k calculations of opacity. However, we found it difficult to fit VIMS spectra accurately with this model, and had to expend considerable effort to obtain better models in this region. We compared new laboratory measurements by Bowles et al. (2008, Icarus 196, 612-624) with HITRAN 2004 (2008 has same ammonia lines), HITRAN 1996 (used by Brooke et al. 1998, Icarus 136, 1-13), and with VIMS observations via model calculations. We found that the Goody-Lorentz model of Bowles et al. was the best choice in most spectral regions, but where line-by-line calculations matched the G-L model under lab conditions, we decided to use the LBL results for Jovian conditions because of its better accounting for temperature dependence, foreign broadening, and pressure dependence. One peculiar result we found is that HITRAN96 has more lines in the 2.74-2.9 micron region than HITRAN04 and provides a better match to observed spectra than the GL model in that region as well. We thus found that a composite of sources provided the best overall absorption model. We fit the band and LBL models to ten-term exponential sum models (aka correlated-k) for use in the multiple scattering calculations.

Radiation Transfer Modeling. We are also adapting our radiation transfer programs for more efficient handling of near-IR multiple scattering calculations by making use of our 20-node computer cluster. While most of our preliminary analysis was handled by single-scattering calculations of atmospheric contributions and broken reflecting layer models of clouds, this only provided decent accuracy for cloud layers of relatively low reflectivity. We found cloud reflectivity values were generally large enough to need multiple scattering. This can be quite time consuming for Jupiter because of the addition of correlated-k models of NH_3 absorption that must be convolved with the correlated-k models of CH_4 absorption, the net result of which is that 100 individual radiation transfer calculations have to be done for each wavelength, after which a weighted average must be computed. This was later accelerated by resorting the100 correlated-k cross terms and refitting to a ten-term model, following Lacis and Oinas (1991, JGR 96, 9027-9064).

Modeling NICMOS observations. Using the higher spatial resolution of the NICMOS observations in combination with center-to-limb observations acquired within a single jovian rotation (which was not available from ISS imagery), we tried to infer the depth of variations in cloud structure from the ratio of modulations in different filter bands. Of particular importance was the ratio of I/F variability for the F187N filter and the F204M filter. The first penetrates more deeply and is highly sensitive cloud reflections from the 1-2 bar region, where a putative NH_4SH cloud might exist, while the latter has very low sensitivity to that region, but can easily sense cloud reflections from the 0.5-1 bar region, where the putative methane cloud was expected to condense. We observe a very small ratio of F204M/F187N, indicating that the significant cloud variations are occurring in the 1-2 bar region. This is in rough agreement with the Irwin et al. (Icarus 149, 397–415, 2001) results, which were based on less accurate modeling of methane absorption. However, in trying to make a model cloud structure that would fit the F166N, F204M, and F187N filters, we found a serious inconsistency, most of which was due to a programming error that was detected only after months of modeling calculations. But after correcting the error, we still were left with the implication that a purely conservative cloud model would be unable to match all three NICMOS filters simultaneously. It appeared that extra absorption was needed to reduce the F204M I/F relative to the F166N I/F. Such an absorption might be produced by an NH_3 ice cloud. Since a cloud of that composition should have a distinct spectral signature, we turned our attention to analysis of spectral observations and did not complete the NICMOS analysis under the subject grant. Because a spectrally varying cloud absorption can distort the inferred pressure obtained from pressure modulation ratios, the nature of that absorption was needed to accurately interpret the modulation results.

Modeling Cassini VIMS and ISO observations. To further investigate the source of possible 2-micron absorption suggested by the NICMOS observations, we tried to model VIMS spectra first. Beginning with conservative reflecting-layer cloud models, we found evidence for a weak absorption near 2 microns, but a much stronger absorption at 3 microns, which was a strong indicator of the presence of ammonia ice. In fact, the 3-micron absorption had already been inferred from an ISO spectrum by Brooke et al. (1998, Icarus 136, 1-13) and was well fit by them using a cloud structure containing one layer of ammonia ice. However, Irwin et al. (2001, Icarus 149, 397-415) pointed out that the Brooke et al. model would produce a large 2-micron signature that was not seen in NIMS spectra (the ISO spectrum only covered the 2.5-3.2 micron region). However, we found that for smaller particles, at least in some regions we could approximately fit the 3-micron absorption feature with ammonia ice without producing a significant 2-micron feature. The VIMS observations also showed that the 3-micron absorption feature was present at virtually every location on Jupiter, and thus not correlated with the extremely rare spectrally identifiable ammonia ice clouds (SIACs) described by Baines et al. (2002, Icarus 159, 74-94). These points were highlighted in a paper given at the 2009 DPS meeting (see publications section), which suggested that they provided evidence for widespread existence of ammonia ice on Jupiter.

The early fits using multiple scattering calculations made use of a shotgun approach that proved to be very time consuming as we attempted to find more accurate fits. To carry out the more extensive fits with a variety of different cloud structures required much greater efficiency, which was obtained using the Levenberg-Marquardt algorithm implemented with support of a subsequent JDAP grant. As more accurate fits were pursued for more locations, we discovered that only the regions with lower-opacity clouds were consistent with ammonia ice models, and that the regions with more opaque clouds were more difficult to fit, especially in the 2-micron region, reinforcing the point made by Irwin et al. (2001). This led us to consider other options for cloud composition, including ammonium hydrosulfide (NH_4SH) particles and particles coated by ammonia instead of pure ammonia particles. We also made use of ISO observations to make take advantage of its higher spectral resolution to better constrain the composition of the 3-micron absorber.

This effort resulted in two Icarus papers (see publications section). The first dealt with modeling of the ISO spectrum and concluded that NH_4SH was a significantly better fit than either water ice or ammonia ice, but that the best fit was obtained when both NH_4SH and NH_3 ice were present, with the latter possibly present as a coating on small photochemical haze particles. The second paper dealt with the modeling of the VIMS spectra for both low and medium phase angles. This analysis, completed under a subsequent grant from the Jupiter Data Analysis program also concluded that the best fits were obtained with NH_4SH and a component of NH_3 ice present as a minor constituent either as a core or a coating of sub-micron haze particles. When present as a thin coating or small core, the spectral features of ammonia ice can be greatly altered, providing a plausible explanation for why NH_3 ice is difficult to detect at 9.4 microns and never seen at 26 microns, even though the ammonia contribution is often found to be a pressures less than 500 mb. From the VIMS analysis of eight different spatial regions, we found the ammonia-coated layer of small (about 0.3 microns in radius) particles had 2-micron optical depths averaging 0.38 with a standard deviation of 0.05, but varied in pressure from 330 mb to 550 mb., while the main 3-micron absorbing layer of rather large (roughly 10 microns in radius) particles had optical depths ranging from 0.23 to 2.1, a factor of 9, with pressures ranging from about 360 mb to 640 mb, generally not much deeper than the ammonia containing layer. A third cloud layer of indeterminate composition is required; when modeled as a sheet cloud its pressure varies between 800 mb and 1.3 bars, with optical depths from 4 to 20. All cloud pressures were found to be higher in the NEB than in the Equatorial Zone.