Final Technical Report
University Of Wisconsin-Madison

(To be completed by RSP or the Department)

Project Title:	**Investigating Atmopheric Change on Uranus and Neptune**
Award Number:	**NNX08AO51G**
UW Account Number:	**PRJ22HX**
For the Period of:	**5/2/2008 through 5/1/2012**
Principal Investigator:	**Lawrence Sromovsky**
Date Submitted:	**8/8/2012**
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SSEC Number (Internal)	***6385*** **I:/jennys/6385Final.doc**

(To be completed by the Principal Investigator)

<u>Inventions Report:</u>

☒ No Inventions resulted from this award
☐ Yes

Inventory Report:

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

Publications: (Please list)

This grant supported revision of the following paper, now published.

1. Sromovsky, L.A., P.M. Fry, H.B. Hammel, W.M. Ahue, I. de Pater, K.A. Rages, M.R. Showalter, and M.A. van Dam. 2009. Uranus at Equinox: cloud morphology and dynamics. Icarus, 203, 265-286.

This grant provided partial support to the following DPS papers.

2. Fry, P. M. and L. A. Sromovsky. 2009. Implications of New Methane Absorption Coefficients on Uranus Vertical Structure Derived from Near-IR Spectra. Bull. Am. Met. Soc. 41, 1010.

3. Fry, P. M., L. A. Sromovsky, I. de Pater, H. B. Hammel, and K. A. Rages. 2010. Detection and tracking of subtle cloud features on Uranus. Bull. Am. Met. Soc. 42, 1022.

The following publications were partially supported by this grant:

4. de Pater, I., L. A. Sromovsky, H. B. Hammel, P. M. Fry, R.P. LeBeau, K. A. Rages, M. Showalter, and Keith Matthews. 2011. Post-equinox observations of Uranus: Berg's evolution, vertical structure, and track toward the equator, Icarus 215, 332-345,

5. Fry, P. M., L. A. Sromovsky, I. de Pater, H. B. Hammel, and K. A. Rages. 2011. Detection and tracking of subtle cloud features on Uranus. Astronomical Journal 143, 150(12pp).

6. Sromovsky, L. A., Fry, P. M., Boudon, V., Campargue, A., and Nikitin, A. 2012. Comparison of line-by-line and band models of near-IR methane absorption applied to outer planet atmospheres. Icarus, 218, 1-23.

7. Sromovsky, L. A., H. B. Hammel, I de Pater, I., P. M. Fry, K. A. Rages, M. R. Showalter, W. J. Merline, P. Tamblyn, C. Neyman, J.-L. Margot, J. Fang, F. Colas, J.-L. Dauvergne, J. M. Gomez-Forrellad, R. Hueso, A. Sanchez-Lavega, T. Stallard 2012. Episodic bright and dark spots on Uranus. Icarus 220, 6-22.

8. Sromovsky, L. A., Fry, P. M., Hammel, H.~B., de Pater, I., Rages, K.A. 2012. Post-equinox dynamics and polar cloud structure on Uranus. Icarus, in press.

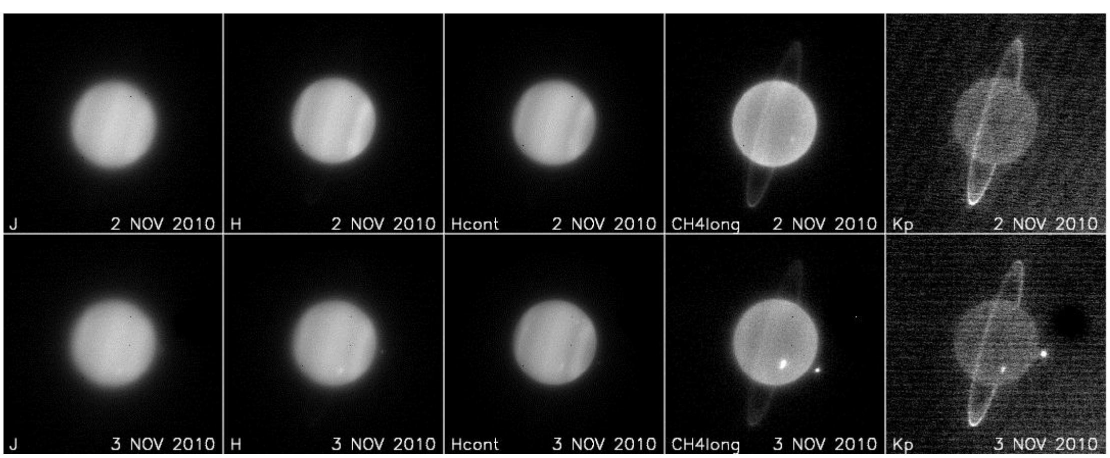
Summary of Technical Effort: (Usually several paragraphs. Please feel free to attach additional pages if you wish.)

OBJECTIVES: We proposed high spatial resolution near-IR imaging of Uranus and Neptune to investigate Uranus' changing asymmetries in vertical cloud structure, zonal wind speed, and dynamical behavior of discrete features as Uranus moves past its 7 December 2007 equinox, and to investigate Neptune's winds, cloud structure, large secular variation, the relation between near-IR and visible variations, and the connection to solar forcing. For both planets, ground-based AO imaging and spectroscopic observations were proposed to be analyzed in combination with HST and ground-based disk-integrated observations to constrain parameters of seasonal models of variation.

BACKGROUND: This project start was delayed by processing problems at the UW Office of Research and Sponsored Programs, from its nominal start date of 1 May 2008 until 1 February 2009, a nine-month delay. That resulted in relatively little work being done during the nominal first year. We thus exercised the option of a 1-year extension request allowable under FDP terms.

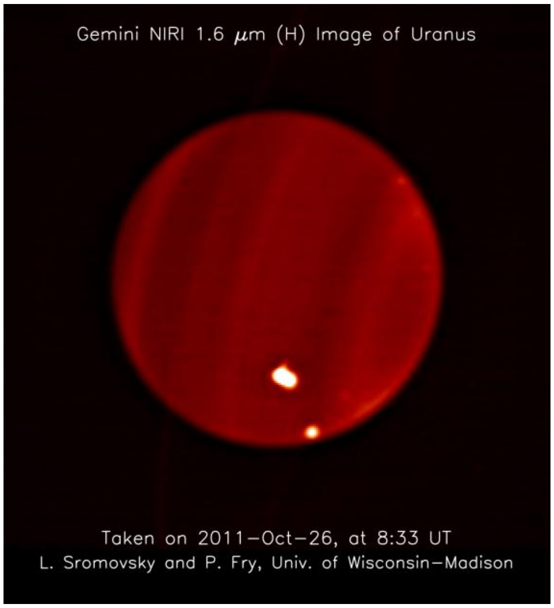
RESULTS:

Task 1. Planning and Executing Observations: Our Keck observing proposals for 2009A, 2009B, 2010A, and 2010B were all rejected. We finally did succeed in getting our 2011A Keck proposal accepted and observations were made on July 25 and 26 2011, which were impacted by slightly out of adjustment AO on the first night and also by very bad seeing on the second night. Nevertheless, we obtained sufficient numbers of high quality images to make significant new measurements of winds and cloud structure at high northern latitudes on Uranus. We also obtained a small sampling of Neptune images to enable tracking of secular variations. The Uranus results were published in above reference 8 and described later in this report. These observations also contributed to a paper on the episodic behavior of bright and dark spots on Uranus (above reference 7). We also prepared a 2011B Keck observing proposal that focused on getting high S/N imaging in two spectral bands (H and Hcont) that would enable us to not only detect subtle cloud features, but also to locate them vertically, using their contrast ratios, a technique that was applied in reference 8 above. That proposal was rejected by the Keck TAC, although subsequent similar proposals for Keck 2012A and 2012B semesters were



accepted. However, the subject grant expired before the planned execution of these observations.

We also were successful in getting 10 hours of 2010B Gemini Band-3 time for mainly NIFS (integrated field spectrometer) observations of Uranus in combination with the Altair AO system. Uranus is not in the Gemini North Semester-A visibility range but falls well within the Semester B visibility range, for both NGS and LGS observations. A considerable effort was made to plan those observations so that they could be run as queued observations. These were successfully executed during November 2-4, and November 22, 2010. The November observations were a repeat of J-band observations on November 4 that suffered from poor seeing conditions. Data quality is fairly decent for November 2, as evident from the above sample NIRI supporting imaging observations in various near-IR filters. Note in the November 2 images, that the northern bright band in the H image is now brighter than the southern bright band, which is a surprisingly rapid reversal (south is to the left in these images). Also note the bright feature in the November 3 images. This is the only feature visible in the K' image, implying that it extends up to relatively low pressures (a few 100 mb). This is likely the 30 N feature that has waxed and waned for many years and has been associated with the only dark spot seen on Uranus at visible wavelengths. We also collaborated on Gemini observations with Pat Irwin, who had proposed a similar program, but with lower seeing requirements, and will share our combined data sets. Irwin's observations were executed between September 19 and November 2, 2010, during which he obtained good sets of NIFS H-band observations covering the entire disc and 3-4 sets of J, H-cont, and CH4-long NIRI imaging observations. However, the sample images we've seen so far have had considerably worse seeing than our data. We also obtained Gemini NIRI time for 2011B, which yielded relatively high image quality due to excellent seeing that was present during the observations. A sample image containing an unusually bright discrete cloud feature is shown at the upper right. This discovery led to a collaborative effort to track the motion and evolution of the feature, involving professional and amateur observers, and included both ground based and HST imaging contributions. The results were presented in reference 7 above.

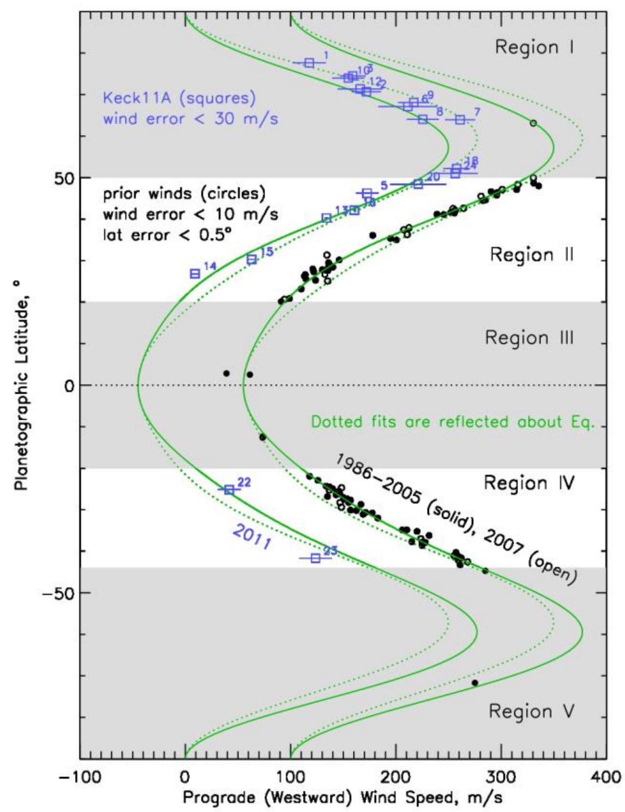


We were awarded one night of IRTF time on 17 September 2010, during which we obtained SpeX spectra of Uranus and Neptune. We had clear skies, median seeing (~0.7 arcsec in H). We captured disk-integrated spectra of Uranus and Neptune, and a central meridian spectrum of Uranus.

Task 2. Data Reduction of New Observations: We downloaded and installed Gemini iraf support packages and the Gemini iraf package and so far have used it to create quick-look figures and initial analysis of spectra. The analysis of the NIFS IFU (Integrated Field

Unit spectrometer) data is complex and has only been partially completed. We have also not completed the processing of the IRTF spectral observations from 2010, nor those from 2007 and 2008. We have navigated a number of Keck images in support of the de Pater et al. paper on the characteristics of the Berg feature (reference 4 above). To support a collaboration with L. Trafton, we have also navigated all the archived NICMOS observations of Uranus taken during equinox in preparation for constraining the asymmetries in uranian cloud structure at equinox. This amounted to 133 single images and 33 combined images (coadded to improve S/N ratios). No paper has yet resulted from this collaboration, however. We also processed all the images obtained from 2011 Keck and Gemini runs, the results of which appeared in above references 7 and 8.

Task 3. Measurement and Analysis of Cloud Motions: Measurements of the Berg motion appeared in reference 4 above. More significant effort was applied to the preparation of the paper on detection and tracking of subtle cloud features in high S/N images (reference 5 above). It wasn't until 2011A that new Keck observations were obtained using the high S/N techniques. Although these observations were of lower than expected quality because of AO and seeing problems, we did obtain, with considerable effort, significant new results concerning the cloud and zonal wind structure at high northern latitudes on Uranus. The new high-latitude winds are illustrated in the figure at the right (from above reference 8), where the new results are plotted as blue squares. These greatly improve the constraints on the north polar jet peak, and also showed that the motions at high polar latitudes were close to solid body rotation at a rate of 4.3 deg/h relative to the interior. We also obtained new wind results from the Gemini observations and combined these with Keck and prior HST observations to show that there was a small N-S asymmetry in the zonal wind profile.

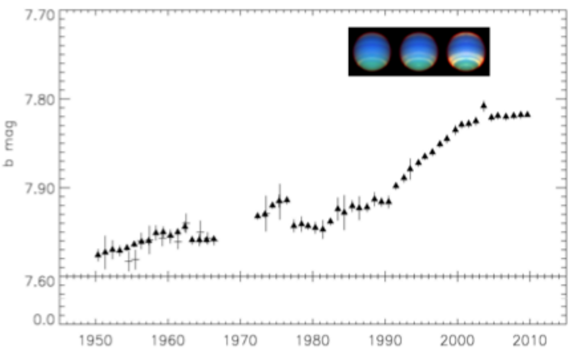


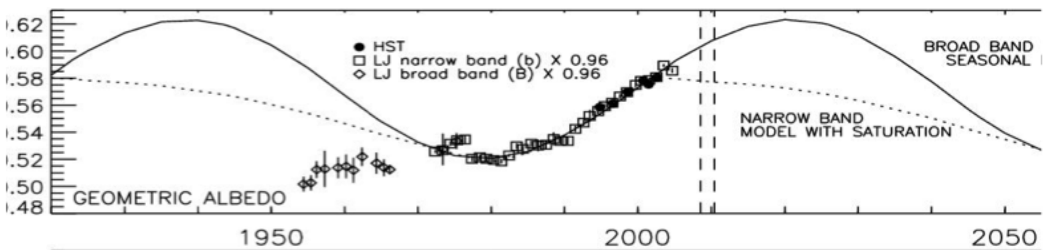
Task 4. Analysis of spatially resolved I/F Measurements. We completed modification of our near-IR radiation transfer code for Uranus to work with a Levenberg-Marquardt non-linear least squares inversion. We also incorporated the new near-IR methane absorption model developed by Erich Karkoschka and Tomasko (2010, Icarus 205, 674-694). However, we were not very successful in obtaining accurate spectral fits to both J and H spectra simultaneously. Another complication that had to be addressed was how to incorporate a latitude-dependent methane mixing ratio. In the initial work we had used

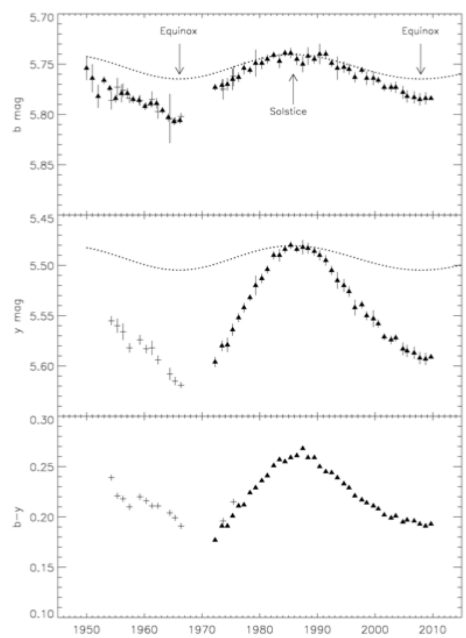
the Lindal et al. (1987, JGR 92,14987-15001) occultation solutions, which had deep methane volume mixing ratios ranging from zero to 4%. However, these solutions only applied at the latitude of the occultation (~5^o S), and significantly different temperature profiles accompanied the different methane solutions. If these different profiles were used at different latitudes, that would present two problems: (1) latitudinal temperature gradients would exceed the small observed values, and (2) there would be density variations with latitude that would be accompanied by large vertical wind shears, that are also not observed. In a paper supported other grants Sromovsky et al. (2011, Icarus 215, 292-312) argued that the latitudinal variation in methane, first derived by Karkoschka and Tomasko (2009, Icarus 202, 287-309), only occurred at high latitudes, and could only occur as a shallow depletion that did not extend to high pressures, partly because of the density gradient constraint, and partly because it was confirmed by fits to STIS spectra. This paper also provides a basis for the high methane mixing ratios in the above-cloud region of the atmosphere that were adopted by Karkoschka and Tomasko (2009).

Regarding the other aspect of the problem, i.e. the absorption coefficient models, we were hopeful that new cavity ring-down measurements that were soon to be published would allow us to use line-by-line calculations in the H band region. This turned out to be the case. We proceeded to develop improved correlated-k models that do not rely on current band models, which all require significant extrapolations from measurement conditions. These were compared with the Karkoschka and Tomasko (2010) band model and the prior Irwin et al. (2006) band model in reference 6 above. The comparison shows that line-by-line calculations can be used to model methane absorption for wavelengths longer than 1.268 microns. Reference 6 included correlated-k fits as well as line lists and for a period of several months (Jan-March 2012) was number 8 on the list of 25 hottest articles published by Icarus (based on number of downloads).

Task 5. Modeling Temporal Changes. A summary of current results for observed temporal changes was presented at the IOP workshop at the 2010 DPS meeting. A comparison with two of our Neptune secular variation models is shown below.







The top curve shown the disk integrated light curve of Neptune's b-magnitude with an inset of HST rotation-averaged images from 1996, 1998, and 2002, when the disk-integrated brightness increase was caused by increased cloud development in a few restricted latitude bands. The secular model based on a seasonal variation of a broad band of bright clouds is shown as the solid curve in the lower figure. A narrow cloud band secular model with saturation of band brightness (which is more realistic) is shown as a dotted curve in the lower figure. The Lockwood observations are intermediate between these two models. Lockwood's curve does not seem to show any evidence of what appears to be a 3-year modulation in the overall near-IR brightness, as suggested by Keck and HST observations on the following page. Lockwood's latest disk-integrated curve for Uranus (right) shows a bottoming out very close to equinox and an asymmetry that remains to be understood. In the Uranus light-curve figure, the dotted curve is the variation expected from the variation in the cross-section of Uranus due to our changing views of its oblate figure. The brightness variation is amplified by the presumed seasonal variation in cloud distribution, with polar caps present at solstices, making them brighter than the cap-free equinoxes.

A new issue concerning the secular variation of Uranus is whether the south polar depletion of methane inferred from 2002 STIS observations by Karkoschka and Tomasko (2009, Icarus 202, 287-309) is also present in the north polar regions, which are now coming into much better view.

A plausible explanation for the southern depletion is the downwelling and mixing of "dry" stratospheric gas, which became dry at low latitudes via upwelling motions and methane condensation. This gas is possibly transported northward by a meridional circulation from low to high latitudes above the condensation level and from high to low latitudes at the several bar level. A possible constraint on this circulation is our discovery of numerous small (and presumably convective) cloud features in Keck II images of the north polar region. The top figure (below) shows a polar projection about the north pole in direct form at left and high pass filtered form at right, which reveals numerous small (possibly convective features) north of 50 N. But similar features are not seen in the south polar region (see below), possibly because there down-welling motions act to suppress formation of convective features. Such a local down-welling would be consistent with the local depletion of methane at high southern latitudes. The below image is a composite of Keck NIRC2 H-band images obtained in October 2003. No discrete features are visible poleward of 50 deg N, even in the high-pass filtered image at the right, and have never been seen at any other time since Voyager. The presence of convective features in the north seems to indicate that upwelling motions are more likely there than downwelling motions, and thus suggest that any meridional circulation cell that might be active is not currently symmetric about the equator. An accepted HST proposal to use STIS observations at 2012 or 2013 oppositions to measure the methane depletion in the north polar region of Uranus should clearly define whether there is a N-S asymmetry in methane as well as in cloud morphology, and bring a greater understanding to the presumably seasonal cycling of methane.