Final Technical Report
University Of Wisconsin-Madison

(To be completed by RSP or the Department)

Project Title:	**Investigating Atmospheric Change on Uranus and Neptune**
Award Number:	**NNG05GF00G**
UW Account Number:	**144NL93**
For the Period of:	**06/01/05 through 05/31/10**
Principal Investigator:	**Lawrence Sromovsky**
Date Submitted:	**9/7/2010**
Location:	**University of Wisconsin Madison Space Science and Engineering Center 1225 West Dayton Street Madison, WI 53706**
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SSEC Number (Internal)	***6395*** **I:/jennys/Reports/6395Final.doc**

(To be completed by the Principal Investigator)

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)

1. Sromovsky, L. A. and P. M. Fry. 2005. Uranus. IAU Circular 8586. (Description of our discovery of Uranus' brightest ever cloud feature.)

The following publications received significant support by this grant (NNG05GF00G) and from a NASA Planetary Atmospheres Grant (NNG05G084G) as well as minor support from several Space Telescope Science Institute Grants:

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

3. Hammel, H.B., L.A. Sromovsky, P.M. Fry, K. Rages, M. Showalter, I. de Pater, M. van Dam, R. P. LeBeau, and X. Deng 2008. The Dark Spot in the atmosphere of Uranus in 2006: Discovery, description, and dynamical simulations. Icarus 201, 257-271.

The following publications received major support by this grant (NNG05GF00G) and minor support from a Space Telescope Science Institute Grant HST-GO-10805.01-A:

4. Sromovsky, L. A., P. M. Fry, H. B. Hammel, I. de Pater, K. A. Rages, and M. R. Showalter 2007. Dynamics, Evolution, and Structure of Uranus' Brightest Cloud Feature, Icarus 192, 558-575.

5. Sromovsky, L. A., and P. M. Fry 2007. The methane abundance and structure of Uranus' cloud bands inferred from spatially resolved 2006 Keck grism spectra. Icarus 2008, 252-266.

The following publication received major support by this grant (NNG05GF00G) and the prior Planetary Astronomy Grant (NAG5-12206) and minor support from the Space Telescope Science Institute:

6. Sromovsky, L. A., and P. M. Fry 2007. Spatially Resolved Cloud Structure on Uranus: Implications of Near-IR Adaptive Optics Imaging. Icarus 192, 527-557.

The following publications received partial support from this grant (NNG05GF00G) and partial support from (NNG05GG93G):

7. Sromovsky, L. A., P. G. J. Irwin, and P. M. Fry 2006. Near-IR methane absorption in outer planet atmospheres: Improved models of temperature dependence and implications for Uranus cloud structure, Icarus, 182, 577-593.

8. Irwin, P. G. J., L. A. Sromovsky, E. K. Strong, K. Sihra, N. Bowles, S. B. Calcutt, and J. J. Remedios. 2006. Improved near-infrared methane band models and k-distribution parameters from 2000 to 9500 cm-1 and implications for interpretation of outer planet spectra. Icarus 181, 309-319.

9. Sromovsky, L. A., and P. M. Fry. 2006. Deep Uranus Cloud Structure and Methane Mixing Ratio as Constrained by Keck AO Imaging Observations. Bull. Am. Astron. Soc. 38, p. 489.

10. Sromovsky, L. A., and P. M. Fry. 2005. Cloud structure on Uranus as constrained by 1.1-1.8 micron spectra. Bull. Am. Astron. Soc. 37, 662.

11. Fry, P. M., and L. A. Sromovsky. 2005. NIRC2 Photometry of Uranus, Uranian Satellites, and Triton in August 2004. Bull. Am. Astron. Soc. 37, 678.

12. P.G.J. Irwin, L. A. Sromovsky, K. Sihra, N. Bowles, J. Remedios, and S. B. Calcutt. 2005. Near Infrared Transmission of Methane: Revised Band and k-distribution Parameters. Bull. Am. Astron. Soc. 37, 773.

The following publication received major support by this grant (NNG05GF00G) and minor support from NAG5-12012:

13. Sromovsky, L. A., and P. M. Fry 2005. Dynamics of cloud features on Uranus. Icarus 179, 459-484.

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

BACKGROUND:

We proposed a 3-year project to make new near-IR adaptive optics (AO) observations of Uranus and Neptune and to analyze new observations in combination with prior observations to develop improved characterization of atmospheric motions and models of cloud and haze structures and of temporal changes that might be a result of seasonal forcing. We aimed to improve our understanding of Neptune's circulation to help explain why new Great Dark Spots have not drifted towards the equator as numerical models

suggest they should have. The proposed observations were also meant to advance our understanding secular variations of Neptune's disk-integrated brightness, which has increased 10% at visible wavelengths since 1980, but has changed in more dramatic and perplexing ways at near IR wavelengths. The observations of Uranus were intended to accurately characterize what seems to be a north-south asymmetry in the circulation of Uranus, to extend circulation measurements to previously unobserved (northern) latitudes, and to constrain the response time of expected seasonal variations.

The research effort on this grant was completed in 2009, but an additional one-year extension was requested and given to permit completion of EPO efforts associated with the research grant. The EPO objectives and results are presented following the science results.

SCIENCE RESULTS:

Ground-based Observing Time.

We proposed for and obtained Keck 2 time for the summer of 2005, during which a summit power failure eliminated one of our three nights and a second was degraded by an AO system that was out of adjustment.

We collaborated with Heidi Hammel and Imke de Pater in preparing a joint Keck proposal to observe Uranus and Neptune during the first semester of 2006. The collaboration was awarded four half nights (28-29 July, Sromovsky PI; 30-31 July, Hammel PI). We also submitted a collaborative Keck proposal for the second semester, which was awarded time in October.

We proposed independent observations of Uranus with the NASA IRTF SpeX near-IR spectrometer and awarded time on 30-31 July. A second-semester 2006 IRTF proposal for SpeX observations of Uranus was also awarded time in October.

Observing results during 2006 were impacted by unforseen events. The July-August observations were limited by bad weather and bad seeing. We did obtain narrow-band imaging of Uranus but high humidity and bad weather prevented the acquisition of grism spectra. The Keck October observations were limited to one night, the rest being aborted due to a significant earthquake that damaged the remote observing facility and the telescope system. This defeated our dynamical objective of getting two views of each side of Uranus, requiring four half nights instead of one. However, on that first night we did get grism spectra, though with shorter than desired exposures due to approaching cloud cover.

Besides our successful independent proposal to observe Uranus with the NASA IRTF SpeX near-IR spectrometer, which was awarded time on 30-31 July 2006, our second-semester 2006 IRTF proposal for SpeX observations of Uranus was also accepted. We had bad weather and bad seeing during our IRTF run in early August, but did manage to get useful disk-averaged spectra of Uranus.

We submitted collaborative proposals for 2007 Keck observations of Uranus near equinox, which yielded two half nights at the Keck II observatory in both fall and spring semesters. In collaboration with ring observers and other atmosphere observers and engineering time we netted 12 half nights of Uranus atmospheric observations between 7 June 2007 and 9 September 2007, from which we obtained cloud tracked winds of very high accuracy (see below).

We submitted observing proposals for 2008, but very little Keck time was available because of observatory commitments to interferometry observations. We did not get any Keck time, although our collaborators did get a small amount of time, mainly for ring observations. We did propose for 2 nights of 2nd semester IRTF time for SpeX observations, and did acquire good spectra of Uranus and Neptune. We were not successful in getting any 2009 Keck observing time.

Data Analysis and Publication of Science Results.

We analyzed 2003 and 2004 Keck AO Uranus imaging for our Icarus paper on cloud dynamics (paper 13 above). A color composite image of these observations was prepared for the Icarus cover, and was also widely distributed to various news organizations and publishers (we had many requests for use in a wide variety of books). We published a new zonal wind profile and interesting dynamical results for the major cloud (and circulation) feature near 34 S. We estimated a minimum lifetime of nearly two decades for this feature, during which it exhibited oscillations in latitude and longitude, with 1000-day and 17-hour periods, likely governed by Rossby wave and inertial oscillations respectively. Considerable effort was expended in establishing photometric calibrations for these observations, which contributed to two papers, one on photometry (paper 11) and one on interpretation of imaging results in terms of vertical cloud structure (papers 5 and 6). To support the latter papers we developed improved models for temperature dependence of methane absorption (papers 7 and 8), and with the help of Randy Campbell of the Keck Observatory we were able to verify spectral properties of two key NIRC2 narrowband filters.

In spite of problems encountered during the 2005 Keck observing run, we nevertheless did obtain useful observations, including the discovery of a very unusual northern hemisphere bright feature that is the brightest ever observed (this was described in the IAU circular: paper 1). We also obtained position measurements of this feature from other observers (HST and groundbased), which yielded a collaborative paper describing the morphology, motions, lifetime, evolution, and vertical structure of this unusual feature (paper 4). Preliminary results indicate that it also exhibits latitudinal oscillations of some sort. We also obtained narrowband filter observations in a new filter (J-continuum), which provides optimal vertical sensitivity for distinguishing clouds in the 1.2-1.3 bar region (where Voyager occultation observations suggested a cloud layer) from those that are deeper than 2 bars. The Keck images clearly show that there is no significant latitudinal variation produced by clouds in the 1.2-1.3 bar region where methane clouds were thought to be present.

Analysis of the extensive set of 2007 observations yielded cloud-tracked winds of very high accuracy, revealing a zonal wind profile that was asymmetric about the equator and in very close agreement with prior accurate wind observations from Voyager as well as Hubble and most prior Keck observation. This suggests that the small asymmetry observed is not a seasonally reversible effect. The mid-latitude bright bands do seem to be reversible. Comparing 2007 with prior observations we find that the southern band is declining, while the northern band is brightening. We also found that the major southern feature that had oscillated between 32 deg S and 36 deg S, very possibly ever since 1986, and began to drift equatorward in 2005, continued that drift in 2007, during which it also underwent spectacular changes in morphology and varying vertical development as well. We expected this feature might dissipate sometime in 2008 or 2009, but it appears to have survived into early 2010. We also observed the bright complex of features near 30 deg N, which seems to be organized around the dark spot discovered in 2006 HST images. The results from the 2007 data set were published in Icarus (paper 2) and presented at the Ithaca DPS meeting. The 2007 observations also supported an Icarus paper (paper 3) on the Uranus Dark Spot.

EPO BACKGROUND AND OBJECTIVES:

The original E/PO supplemental proposal was entitled "Weather in the Solar System: Using NASA Data to Enhance Teacher Content Knowledge and Understanding." The original E/PO supplemental grant funding period was May 2005 through May 2008. Due to late receipt of funding in October of 2005, the project activities began in Spring of 2006 to coincide with the schedules of the participating school districts.

The stated goals of the proposal were to; 1) develop graduate course eligible coursework (2 science credits) for teachers in Northern Illinois, and 2) provide support for content integration, standards alignment and classroom follow-up support for 5th through 8th grade teachers, and 3) support workshops in other states using resources originally designed for Illinois science educators.

EPO RESULTS:

Winter/Spring 2006 : In coordination with Ms. Brenda Cox, Science Curriculum Specialist for the Crystal Lake Illinois Unified School Districts, a preliminary in-service session with prospective teacher participants was conducted in March of 2006. The district's Science scope and sequence plans were reviewed to identify appropriate aspects of the curriculum where NASA content (Uranus & Neptune data) could be effectively integrated. Key elements of the curriculum for improvement included; 1) Seasons (6th Grade), 2) Weather and Clouds (Grades 7 & 8), and 3) Astronomy and Solar System (Grades 3 & 4). Based on consultation with Ms. Cox and district teachers, content and activities were defined and developed for a summer course (one week workshop format).

Summer 2006: Teacher professional development workshop was conducted in August of 2006 at the Hannah Beardsley Middle School in Crystal Lake, Illinois. Eleven participants from the represented districts attended. The 40-hour course was certified through the University of WI-Madison Department of Atmospheric and Oceanic Sciences and provided 1 credit for workshop attendance and an additional credit for classroom implementation and follow-up in the subsequent school year. Seven of the original eleven participants participated in the 2-credit option.

Fall 2006 – Spring 2007: One day follow-up sessions were conducted during teacher in-service days (at Hannah Beardsley Middle School) in October of 2006 and April of 2007. Due to the range in grade levels taught (3rd through 8th), teachers were allowed a great deal of flexibility in their usage. In addition to graduate level science credits, customized materials developed by teachers became part of required professional development portfolios. Evaluation/feedback from teacher participants emphasized appreciation for science content and presentations by actual researchers and the need for flexibility in adapting content to their unique classroom situation. Also in October of 2006, science content and background materials were included as part of the Solar System 101 Teacher Professional Development workshop at the 38th meeting of the Division of Planetary Sciences meeting in Pasadena, CA.

Summer 2008 : Science content and concepts (Weather around the Solar System) including classroom application resources were included in two summer workshops conducted in July 2008 at the Astrobiology Laboratory Institute (University of Hawaii, Manoa) in Honolulu, HI (21 teachers) and to the Livermore Unified School District in Livermore, CA (8 teachers and 1 district science curriculum specialist). Follow-up with both districts occurred in Spring 2009 with a return request from the University of Hawaii,

Fall 2008: Two additional teachers from the original workshop group (Summer 2006) completed the second credit option (classroom implementation).

2009/10 Activities: In July 2009 and January 2010 E/PO staff participated as presenters in two separate workshops conducted by the University of Hawaii, Manoa, at the request of the program coordinator. These workshops are designed to support middle/high school and two-year college instructors in the use and application of education resources using authentic planetary data in their classroom environments. The atmospheric circulation data from my research provides an excellent opportunity to contrast and compare the unique atmospheric circulation data and patterns of the outer planets. The teacher participants from these workshops have consistently demonstrated exceptional interest and follow through in the implementation of activities in their classrooms. Resources presented are currently being used in several schools in Hawaii, as well as Washington and Colorado. As a direct result, we plan to submit a larger proposal to more fully develop the resources used into a middle and high school curriculum that will include several of these teachers. In April of 2010 we were able to also present the Outer Planets resources at the Oneida Nation High School, a tribal school in Keshena, WI as well as the UW-Madison PEOPLE program, a three week summer session for college

bound minority and low-income students. We have been invited to a follow-up Conference this fall with the Oneida Community as a direct result of these opportunities.

The EPO activities were carried out primarily by Rosalyn Pertzborn (Director of SSEC's Office of Space Science Education), planetary scientist Sanjay Limaye, and graduate student Hsuan-Yun Pi. Our E/PO staff has been very appreciative of the opportunity to bring our outer planets research to schools in Wisconsin and other states across the nation and we look forward to future opportunities to expand upon the baseline work that has been made possible through this grant.