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Clouds on Neptune: Motions, Evolution, and Structure

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1 Specific Aims

The aims of our original proposal were these: (1) improving measurements of Neptune's circulation, (2) understanding the spatial distribution of cloud features, (3) discovery of new cloud features and understanding their evolutionary process, (4) understanding the vertical structure of zonal cloud patterns, (5) defining the structure of discrete cloud features, and (6) defining the near IR albedo and light curve of Triton. Towards these aims we proposed analysis of existing 1996 groundbased NSFCAM/IRTF observations and nearly simultaneous WFPC2 observations from the Hubble Space Telescope. We also proposed to acquire new observations from both HST and the IRTF.

2 New Observations

Under this grant we carried out observing runs at the IRTF during 20-24 September 1997, 13-15 June 1998, 11-14 August 1998, 18-21 July 99 (UT), and 22-25 July 2000. Useful observations were obtained during all of these runs. The 1998 observations were overlapped by our HST observations using WFPC2 and NICMOS. In 1998 and 1999 we obtained NSFCAM imaging of Neptune, grism spectra of Neptune with separated traces of individual cloud bands during a period of unusually good seeing, grism spectra of Triton at four different orbital longitudes spanning 4 days of its 5.7-day orbital period, and imaging of the Uranus system that will permitted a new determination of NSFCAM image scales from satellite position measurements.

3 Scientific Results

1. Determination of Neptune's cloud-top motions from 1994 through 1996, increasing the number of wind vectors for this period by more than a factor of 10 relative to previous publications; these can be segregated into two distinct components: those that closely match the 1989 Voyager mean profile and those associated with waves that appear to be generated by a northern dark spot.

2. Determination that the bright cloud feature complex in 1994 HST images previously identified by Hammel and Lockwood (*Icarus* **129**, 1997) has component elements with rapid meridional motions and sufficient integrated brightness to cause a hemispheric asymmetry

comparable to that associated with the 1986-1989 "outburst" event reported by Hammel et al. (*Icarus* **132**, 1992). Determination that the even greater outburst of 1976 (Joyce et al., *Astrophys. J.* **214**, 1977) could be modeled as an increase in effective fractional coverage of discrete cloud features to 3.9% (compared to 0.6% in 1996).

3. Identification of new cloud structures: discovery of a new kind of Great Dark Spot at 15° N latitude, in both August 1996 and March 1996 HST images, which is remarkable in having no discernible bright companion feature; identification of a wavenumber-one cloud band near 60° S latitude during August 1996, and also that it was present in 1989; identification of a persistent wave-number two pattern of bright clouds at 45° S, which exhibit strong variations in brightness.

4. New Neptune disk-integrated albedos at J-K wavelengths that are only half the groundbased values of Fink and Larsen (*Astrophys. J.* **233**, 1979), underlining the importance of the highly variable contribution of discrete bright cloud features in the near IR, as is confirmed by our new determinations of Neptune's albedo as a function of rotational phase, and model calculations that can reproduce the main spectral features of both observations, but require that the putative H_2S cloud be very dark or of very low opacity at near IR wavelengths.

5. The first determinations of cloud-top pressures for discrete cloud features from spatially resolved IRTF spectral samples of cloud features in the 2-2.4 microns spectral range, where factor-of-10 variations in I/F are observed; we found ~70 mb for the bright companion to the northern Great Dark Spot, and 300 mb for a bright feature at 45° S.

6. Determinations of Triton's disk-integrated albedo from HST and IRTF observations which are consistent with previous groundbased and Voyager measurements, and thus did not confirm albedo changes expected from global warming results of Elliot et al. (*Nature* **393**, 1998).

7. New measurements of Triton's light curve, which deviates substantially from Voyager models in the UV to long visible range (Hillier et al., *J. Geophys. Res.* **96**, 1991), suggesting that a significant spectral light curve should also be observed at near IR wavelengths where strong ice absorption features should provide a easily detected variations.

8. The earliest (1998) groundbased detection of discrete bright cloud features on Uranus, and the demonstration that a bright feature detected in 1999 groundbased IRTF observations is the brightest discrete cloud feature ever observed on Uranus, by a factor of four, also demonstrates the potential of groundbased IRTF observations in characterizing expected increases in observable weather on Uranus.

9. New constraints established for lifetime and evolution of Neptune's two northern dark spots, including long-term tracking of companion features of a 32° N dark spot from October 1994 through at least 1996, and defining drift periods with 77 times the accuracy of the best measurement of Neptune's rotational period, and establishing long residence at fixed latitudes in regions where current models of dark spots imply substantial equatorword drift. This firmly establishes results that are difficult for circulation models to explain, both that northern dark spots remain at nearly constant latitudes and that their behavior is dramatically different from Neptune's southern Great Dark Spot.

4 Publications

The following publications are based on research supported partly by this grant and partly by grants from the Space Telescope Science Institute.

1. Sromovsky, L.A., P.M. Fry, K.H. Baines, S.S. Limaye, G.S. Orton, and T.E. Dowling (2001) Coordinated 1996 HST and IRTF Observations of Neptune and Triton. I: Observations, Navigation, and Differential Deconvolution. *Icarus,* **149**, 416-434.

2. Sromovsky, L.A., P.M. Fry, K.H. Baines, and T.E. Dowling, (2001) Coordinated 1996 HST and IRTF Observations of Neptune and Triton II: Implications of Disk-Integrated Photometry. *Icarus,* **149**, 435-458.

3. Sromovsky, L.A., P.M. Fry, T.E. Dowling, K.H. Baines, and S.S. Limaye (2001) Coordinated 1996 HST and IRTF Observations of Neptune and Triton III: Neptune's Atmospheric Circulation and Cloud Structure. *Icarus,* **149**, 459-488.

4. Stratman, P.W., A.P. Showman, T.E. Dowling, and L.A. Sromovsky (2001) EPIC simulations of Bright Companions to Neptune's Great Dark Spots. *Icarus,* **151**, 275-285.

5. Sromovsky, L.A., J.R. Spencer, K.H. Baines, and P.M. Fry (2000) Ground-based Observations of Cloud Features on Uranus. *Icarus* **146**, 307-311.

6. Sromovsky, L.A., P.M. Fry, K.H. Baines, and T.E. Dowling (2001) Neptune's Atmospheric Circulation and Cloud Morphology: changes revealed by 1998 HST Imaging. *Icarus,* **150**, 244-260

7. Sromovsky, L.A., P.M. Fry, and K.H. Baines 2001. The Unusual Dynamics of Northern Dark Spots on Neptune. *Icarus* **revision submitted.**