Summary of Research

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VERTICAL STRUCTURE IN OUTER PLANET ATMOSPHERES

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Submitted to

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Vertical Structure in Outer Planet Atmospheres

The period covered by this cooperative agreement included 1) the analysis of data acquired by both Voyager spacecraft during their encounters with Saturn in 1979 and 1980; 2) work on Uranus' seasonal variability and transient albedo features on both Uranus and Neptune using observations made by the Hubble Space Telescope beginning in 2000; 3) a search for lightning on Jupiter using HST; and 4) the analysis of Pathfinder images of Martian surface features.

Analysis of Voyager Saturn Limb Images

High-resolution images of planetary limbs can be used to derive information about the vertical structure and single scattering properties of scatterers in the upper atmosphere of a planet or satellite. Because of the very long slant path through the atmosphere of lines of sight grazing the edge of the planet, such observations generally reveal information about altitudes corresponding to optical depths in the range 10^{-5} to ~0.03. In this respect limb studies complement observations of the disk of the planet, which are most sensitive to structure and composition at optical depths of 0.1 to ~3. In addition, extinction as a function of altitude can be derived directly from a limb intensity scan. If there are any discrete scattering layers present they can be observed directly instead of being inferred from (probably ambiguous) fits of atmospheric scattering models to observations of specific intensity from the planet as a whole.

Voyager images of Saturn's limb presented a unique data set because they included images obtained at solar phase angles up to 169°. These images, taken in the violet filter, had spatial resolution of ~20 km/pixel. Voyager 1 also took violet images of the same region (mid-southern latitudes) at phase angles of 141° and 155°, with spatial resolutions of ~12 km/pixel. Procedures first developed to study Titan's limb hazes (Rages and Pollack 1983) and subsequently refined and applied to limb hazes on Uranus (Pollack *et al.* 1987) and Neptune (Moses *et al.* 1995) were used to invert radial intensity profiles across the limbs of these images to get radial extinction profiles down to optical depths of ~0.03 from 40°S to 60°S latitude, plus albedo-weighted single scattering phase functions for the entire range of phase angles between ~170° and ~165°, as well as 155° and 141°. The resulting single scattering phase function indicates the presence of a relatively low concentration of large haze particles (radii >0.45 μm, the wavelength of the scattered light) mixed with Rayleigh scattering gas in Saturn's stratosphere, with the gas being responsible for 70-80% of the total scattering.

These particle sizes are in conflict with the 0.1 μm radius inferred for lower latitudes from Pioneer photometry at phase angles up to 151° (Tomasko *et al.* 1980), and from polarimetry carried out by both Pioneer (Tomasko and Doose 1984), and Voyager 2 (West *et al.* 1983). This may indicate latitudinal variation in the haze properties, since the 0.1 μm particle size was derived for near-equatorial regions of Saturn. Alternatively, it may indicate a conflict between high-phase photometry and polarimetry, such as that exhibited by Titan's stratospheric hazes, which can probably be resolved by the use of non-spherical aggregate scatterers (West and Smith 1991). These matters should be considered in the design of Cassini observations of Saturn's atmosphere, due to begin in December 2004.

Latitude Bands and Temporal Variability on Uranus

Uranus undergoes extreme seasonal variations as a result of its 98° axial tilt. Since the Voyager encounter in January 1986, the subsolar latitude has shifted from its southern solstice position of 82°S to about 30°S. Only Uranus' southern hemisphere was visible to Voyager, so it has been necessary to assume hemispheric symmetry to calculate disk integrated brightnesses as far back as 1972. Direct observations of much of the northern hemisphere have now become possible as Uranus moves toward equinox in 2007.

Hubble Space Telescope (HST) images of Uranus, obtained between 1997 and 2001, show pronounced latitudinal banding as far as 30°N. Uranus displays a bright southern polar cap at wavelengths longward of 600 nm, with a brighter collar at the edge of the polar cap (~45°S) which is slowly becoming more prominent. A darker band has recently appeared near the south pole (~85°S) at 791 nm. The Uranus images also reveal transient bright spots which appear and disappear on time scales of weeks to months. In the southern hemisphere, "iceberg-like" clouds break off from the south polar collar and drift north from 40-45°S until they disappear. Bright spots also appear near 30°N, while the brightest spots of all are seen north of 40°N, near the northern limb (and perhaps not coincidentally, near the morning terminator, where the sun is making its first appearance in half a century.) The albedo features shown in the table below have been used to trace Uranus' zonal winds between 45°S and 42°N, with the results published in *Icarus* (Hammel *et al.* 2001). To date there is no indication of a northern polar cap, despite the fact that latitudes as high as 50°N are now visible.

Uranian Spots — June 2000

Name	Latitude	Period (hr)	Velocity (m/s W)
Big Boy	42N	15.93±0.04	161±6
Leader	36N	16.52±0.12	92±16
Follower	28N	17.10±0.13	19±17
North Berg	28S	16.96±0.12	38±17
South Berg	39S	16.19±0.06	132±8
Otherberg	44S	15.88±0.21	160±27

The center-to-limb brightness variation (CTL) in the methane bands at 893 nm and especially 619 nm is strongly influenced by Uranus' methane cloud optical depth. Radiative transfer analysis of the center-to-limb profiles of the southern polar cap in the images indicates that Uranus' methane cloud at 1.3 bars darkened and probably decreased in optical depth at 65°S between 1997 and 2000, after its optical depth had already decreased by a factor of 3 between 1986 (Voyager encounter) and 1997.

Between August 2000 and June 2001, HST obtained images of Neptune on 13 separate occasions. Neptune continues to show vigorous activity in a band near 40°S latitude, but did not displayed any Voyager-style Great Dark Spots during this period. Five images taken during one 36-hour period in the last week of June 2001 show a dramatic appearance and subsequent dissipation of Neptune's South Polar Feature. This bright feature at 70°S was first detected and characterized by Voyager in 1989. At its peak it can be 2.5-3.0 times as bright as its surroundings at 619 nm, and it reaches this brightness in only a few hours, fading to invisibility again over 1-2 Neptunian days (~30 hours). These observations have been published in *Icarus* (Rages *et al.* 2002).

Jovian lightning search

Both Voyager spacecraft observed several large, energetic lightning storms on the nightside of Jupiter during their flybys. The geographical distribution and intensity of the storms were substantially different from those of terrestrial storms and raise questions about both the nature of the lightning activity and the dynamical properties of the atmosphere that produce it. Because neither the Voyager nor the Galileo spacecraft could search for lightning on the dayside of Jupiter and because of the rapidity of the Voyager flybys and the distance and limited bits-to-ground of the Galileo nightside passes, all that is known about Jovian lightning comes from less than twenty images of the nightside taken at distances of several hundred thousand km; i.e. the distance between the Earth and the Moon. No information is available about the evolution and longevity of the storms, or whether the storm bands move.

Earth based telescopes have not been able to detect Jovian lightning because sunlight reflected from the atmosphere and clouds overwhelms the lightning signal. The angular resolution of the HST Planetary Camera (0.046″) provides a signal to noise ratio (SNR) for lightning against reflected sunlight by a factor of 400 over ground based telescopes. Thirty five short-exposure images of Jupiter in F656N (corresponding to the Hα line at 6563 Å) were obtained in July 1997. The images were high-pass filtered by replacing each pixel in each image with the difference between its value and the average of the eight surrounding pixels. Each high-pass filtered image was rotated to a common orientation, and the rotated images were coadded to create a single composite image. This increased the SNR by the square root of the number of exposures (a factor of ~6). Although several small bright features are present, in general, they are due either to bright albedo features extending over ~10 pixels or are due to single bright events which cannot be distinguished from cosmic ray hits. Therefore there was no unambiguous detection of Jovian lightning.

Martian photometry

Martian scenes are illuminated not only by direct sunlight, but also by sunlight that has been scattered by dust particles in the atmosphere. There was enough atmospheric dust at the Pathfinder landing site to produce ~0.5 optical depths of extinction and to contribute ~30% of the total illumination (Thomas *et al.* (1998). The color of the sky varies markedly with position, and varying solar illumination can cause spurious color perceptions for surface features. In order to present an accurate picture of color variations on the Martian surface, it is highly desirable to remove the effects of diffuse illumination from the sky to create a "no atmosphere" rendering of the surface features.

The atmospheric contribution to the illumination of Martian surface features has been calculated for Imager for Mars Pathfinder (IMP) filters from 400 nm to 800 nm, using the dust model of Tomasko *et al.* (1999). Illumination due to both the atmosphere and direct sunlight has been combined with Hapke models of the surface scattering from rocks and soil in the vicinity of Pathfinder to produce improved estimates of the surface single scattering albedos as functions of wavelength.

Single scattering albedo as a function of wavelength has been calculated for two fairly smooth areas of the rock called Yogi. One of these points is on Yogi's eastern end, which had appeared bluer than the rest of the rock in earlier analyses which did not include diffuse illumination; the other was near the center of Yogi, in the redder-appearing region. Since the sky is tinted red, and since the "blueness" of Yogi's various surfaces seemed most evident under direct solar illumination, there was speculation that the apparent variation in color at Yogi's eastern end was an artifact of an insufficiently detailed illumination model (Thomas *et al.* 1999). Single scattering albedos and two-parameter single scattering phase functions which fit the measured radiances at four wavelengths and four times of day have now been derived for both areas of Yogi, with diffuse illumination included, and the ratio of red_albedo/blue_albedo is still about twice as high at Yogi's eastern end as it is near the middle of the rock's southern face. This favors the alternative explanation of Yogi's color differential—that it is due to a surface dust layer being scoured off the eastern end by the prevailing winds. This result was presented at the Lunar and Planetary Science Conference in March 2002 (Stoker and Rages 2002).

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APPENDIX

Subject Inventions Certification

There were no subject inventions required to be disclosed to NASA which resulted from this work. There were no subcontracts awarded under this Cooperative Agreement.