Mon. Not. R. Astron. Soc. **369,** 1683–1687 (2006) doi:10.1111/j.1365-2966.2006.10405.x

Seasonal evolution of Titan's dark polar hood: midsummer disappearance observed by the *Hubble Space Telescope*

Ralph D. Lorenz,[1★] Mark T. Lemmon[2] and Peter H. Smith[1]

[1]*Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721, USA*
[2]*Department of Atmospheric Science, Texas A & M University, College Station, TX 77843-3150, USA*

Accepted 2006 March 29. Received 2006 March 27; in original form 2006 January 4

ABSTRACT

Titan, Saturn's largest moon, has a dense organic-laden atmosphere that displays dramatic seasonal variations in composition and appearance. Here we document the evolution of the dark polar hood, first seen in 1980 by Voyager 1 around the north pole, and report quantitative measurements of the hood's disappearance from the south pole in 2002–2003 using previously unpublished observations with the *Hubble Space Telescope* Advanced Camera for Surveys (*HST*/ACS). These data support a model of the hood as a transient structure associated with downwelling during polar winter.

Key words: planets and satellites: individual: Titan – ultraviolet: Solar system.

1 INTRODUCTION – THE SEASONAL EVOLUTION OF TITAN'S APPEARANCE

Optical images of Saturn's haze-shrouded moon Titan from the Voyager encounters in 1980–1981 (Smith et al. 1981, 1982) show relatively few features, namely a north–south asymmetry (NSA) in hemispheric albedo, a dark polar hood and a detached haze layer. Observations during the last 30 yr show that all these features vary with time.

So far, the best-documented seasonal change is the most prominent one, namely the NSA (e.g. Lorenz et al. 1997). The NSA is the principal cause of the periodic (14.5 yr) variation in Titan's disc-integrated albedo (Sromovsky et al. 1981), and is due to the seasonal transport of haze from one hemisphere to another (Lorenz et al. 1999). The summer hemisphere becomes brighter at blue wavelengths as the blue-dark haze (lying above the bulk of the bright Rayleigh-scattering nitrogen atmosphere) is transported away – this accumulation of haze in the winter hemisphere causes the asymmetry to be largest around equinox. During the Voyager encounter in 1980 (Titan northern spring equinox – see Table 1), the Southern hemisphere was darker, while the situation was reversed two seasons later when Titan was observed by *Hubble Space Telescope* (*HST*) in 1994–1995. Because the haze is bright relative to the lower atmosphere in near-infrared methane bands, the sense of the asymmetry at these wavelengths is opposite that in blue and green where the asymmetry has its strongest optical appearance.

The dark polar hood is most prominent at near-ultraviolet (UV) wavelengths. It was observed at latitudes above about 70°N by Voyager 1 in 1980. There was no south counterpart at that epoch, but there was some evidence of a UV-dark south polar feature in *HST* images (Lorenz et al. 1999; Lorenz, Young & Lemmon 2001) two Titan seasons later, from about 1997 onwards. In 1994–1995, the south pole was at or beyond the limb of Titan as seen from the Earth, and while the feature may have been radiometrically prominent, it was geometrically invisible. The north polar hood seen by Voyager was not observed (when geometrically it was exposed to Earth) in 1994 (Lorenz et al. 1997) nor was it obvious in images acquired in 1990 and 1992 prior to the *HST* repair. In ground-based images using adaptive optics on Keck II in 1999–2001, an elevated ring was observed at high southern latitudes, bright in the near-infrared (Roe et al. 2002).

Finally, the detached haze is a thin layer that is visible only at grazing incidence. It appears to be contiguous with the polar hood, in that the haze over the pole appears to extend above the main haze deck and link to the 'detached' layer. This term may in fact be somewhat misleading in that it implies some sort of levitation of the haze. As discussed by Rannou, Hourdin & McKay (2002), the feature may emerge as a result of dynamical clearing (horizontal transport to the pole) of material beneath the haze formation altitude. We will discuss this model later in the present paper in the light of the new observations.

The detached haze, lying only ~200 km above the optical limb of Titan, is difficult to observe from Earth – the only (tentative) direct detection is in strongly deconvolved *HST* images in 1996–2001 by Young, Puetter & Yahill (2004). Evidence of a raised extinction altitude (in principle undistinguishable from a thicker main haze layer, but plausibly interpreted as the existence of the detached haze) was found in stellar occultation data (Hubbard et al. 1993), and in the projection of Titan's shadow on Saturn, observed by *HST* in 1995 (Karkoschka & Lorenz 1997).

Most recently, the arrival of Cassini in the Saturnian system has afforded a new perspective on Titan. Assuming that the seasonal cycle repeats, the northern spring equinox seen by Voyager 1 will

★E-mail: rlorenz@lpl.arizona.edu

Table 1. Seasonal change in Titan's haze features.

Date	Observation/event	Ls (°)	Solar lat	NP hood	SP hood	Detached haze	Ref[a]
1979 Sep	Pioneer 11 encounter	354	−2.9				
1980 Feb	Vernal equinox	360	0				
1980 Nov	Voyager 1 encounter	8	+4.1	Yes	No		S81
1981 Aug	Voyager 2 encounter	16	+8.0	Yes	No	Southwards of ∼45N	S82, R83
1987 Nov	Northern summer solstice	90	+26.7				
1989 Jul	28 Sgr occultation	109	+25.4			Northern hemisphere[b]	H92
1990 Aug	*HST* WFPC	122	+23.0	No?	–[c]		
1992 Aug	*HST* WFPC	145	+16.0	No?	–		
1994 Oct	*HST* WFPC2	168	+5.8	No	No		
1995 Aug	*HST* WFPC2	177	+1.3	No	No	Northern hemisphere[b]	K97
1995 Nov	Autumnal equinox	180	0				
1996 Oct	*HST* WFPC2	190	−5.0			Southern hemisphere?	Y04
1997 Nov	*HST* WFPC2/STIS	202	−10.7	No	Yes		L99
1999 Oct	Keck AO	227	−11.2	–	Yes		R02
2000 Dec	*HST* WFPC2/STIS	242	−24.0	–	Yes	Planetwide?	L04, Y04
2002 Oct	Southern summer solstice	270	−26.7				
2002 Dec	*HST* WFPC2/STIS/ACS	271	−26.7	–	Yes		L06
2003 Dec	*HST* STIS/ACS	288	−25.6	–	Yes		L06
2004 Apr	Cassini approach science	292	−25.0	–	No		
2004 Oct	First Cassini flyby (Ta)	300	−23.5	Yes	No	Planetwide	P05
2008 May	End nominal Cassini tour	345	−7.2				
2009 Aug	Vernal equinox	360	0				
2010 May	Cassini extended mission	8	+4.1				

[a]References: S81, S82 – Smith et al. (1981, 1982); R83 – Rages & Pollack (1983); H92 – Hubbard et al. (1993); K97 – Karkoschka & Lorenz (1997); Y04 – Young et al. (2004); L99, L04 – Lorenz et al. (1999, 2004); R02 – Roe et al. (2002); P05 – Porco et al. (2005).
[b]An increase in extinction altitude is interpreted as the presence of the detached haze layer.
[c]Denotes no determination (pole was geometrically unobservable).

be observable by Cassini's extended mission in 2009–2010. Indeed, several features reminiscent of the Voyager appearance are already observable in data from Cassini's first close encounters (TA and TB) in 2004 October and December. As reported in Porco et al. (2005) there is no south polar hood visible in 2004. A detached haze layer is observable against the blackness of space at all latitudes [although at an altitude somewhat higher (∼500 km) than was the case for Voyager], and appears to merge with a complex of haze material standing high above the north polar region. However, the material does not appear to have yet accumulated over the pole in sufficient optical depth to render the underlying main haze layer more than slightly dark. Thus the 'dark polar hood' as observed by Voyager and *HST* is in the process of forming.

The observations to date are summarized in Table 1. It is evident, then, that the south polar hood disappeared sometime between its observation in 2001 by the Wide-Field Planetary Camera 2 (WFPC2) on *HST* (Lorenz et al. 2001) and the arrival of Cassini. Here we report previously unpublished images from the Advanced Camera for Surveys (ACS) that show this process in action in 2002–2003.

2 *HST* OBSERVATIONS

Titan's southern summer solstice occurred in 2002 late October. We observed Titan on 2002 December 2 and 2003 December 31 with the ACS on the *HST*, with the sub-Earth latitude 26°.1 S. Images in 2002 were obtained in 11 filters from ultraviolet to near-infrared wavelengths. The images show strong zonal variations, but no discrete features within latitude bands (Fig. 1).

This data set includes the first high-quality images of Titan shortwards of 300 nm and show that the NSA vanishes in the UV. This has not previously been reported, although earlier images at 340 nm have shown a reduced contrast compared to violet and blue wavelengths (A NSA for a much lower resolution 255 nm *HST*/WF image was reported in Lorenz et al. 1997, but Titan in this Saturn image was somewhat smeared).

The images also show a banding that is more complex than the simple two-hemisphere model that adequately describes Titan's appearance near equinox. Thus quantitative determination of the NSA as a single number (an albedo ratio) is a simplification which is not meaningful near equinox and we thus do not report values here.

The key result is the firm detection of a UV-dark south polar hood, made possible by Titan's changing aspect as well as the unique high-resolution ultraviolet capabilities of *HST*. After removal of limb darkening, the hood is the dominant feature at wavelengths from 300 to 440 nm. Fig. 2 shows the spectral contrast of the polar hood, which approaches 10 per cent. The hood is spectrally different from any previously observed feature on Titan. The NSA contrast peaks between 450 and 500 nm, and is reversed in methane bands. The polar hood contrast peaks between 300 and 350 nm. It appears enhanced in the 892-nm methane band image, but this seems likely be a gradient in brightness with latitude (an extension of the NSA). In the UV, the boundary of the hood is quite sharp, spanning less than 10° of latitude.

Fig. 3 shows comparison images where the hood is most prominent (330 and 440 nm) in 2002 and 2003. Despite being only one terrestrial year apart, the change is quite dramatic – the contrast of the hood is substantially reduced. This is shown more quantitatively in Fig. 4.

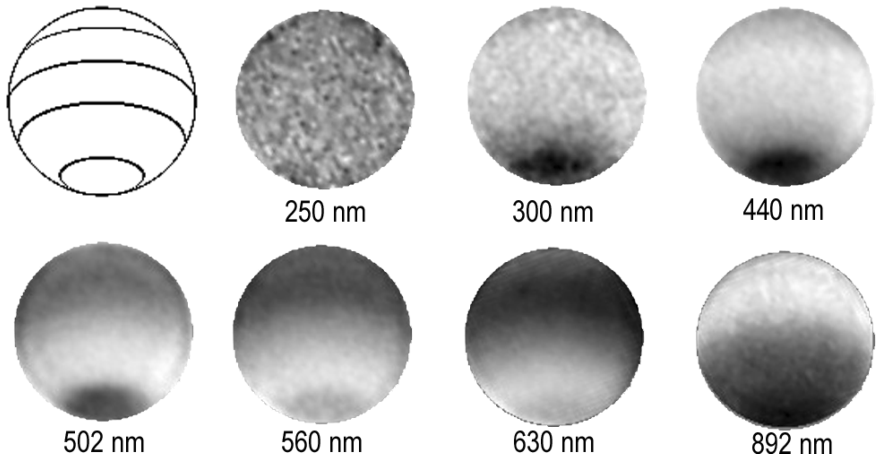

Figure 1. Titan images in 2002 December show a north–south asymmetry and a dark polar hood. The images are labelled according to effective wavelength and show the orientation of Titan with latitude lines indicating the equator, the tropics and the antarctic circle projected at 300-km altitude; images through the F220W, F330W and F435W filters (top); and images through the F502N, F550M, 625W and F892N filters (bottom). Titan appears about 35 pixels across in individual ACS images; we employed a spatial dithering strategy to halve the pixel scale in the images from 300–502 nm. Titan's appearance is dominated by limb darkening at most wavelengths, limb brightening in methane bands. We removed limb effects by fitting an empirical law within narrow latitude bands, and the limb has been masked out. The prominent features include the expected NSA, with the north darker at visible wavelengths and the south darker in the 892-nm filter, which probes a strong methane band.

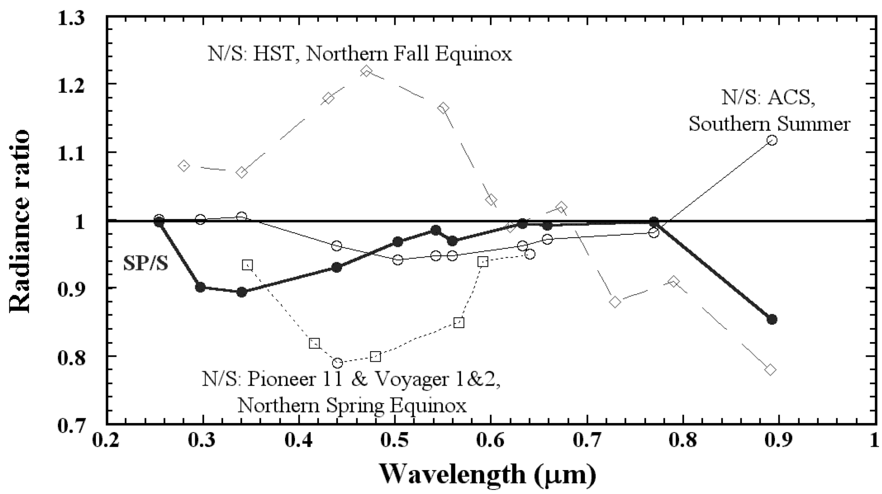

Figure 2. The polar hood is spectrally distinct from the NSA. The spectral contrast of the NSA is shown (open symbols) for northern spring equinox (squares, dotted line), northern fall equinox (diamonds, dashed line) and southern summer solstice (circles, solid line). The polar hood spectral contrast (filled circles, solid line) including some filters not shown in Fig. 1 peaks in the near-UV.

It has been known for some time (e.g. Sromovsky et al. 1981; Lorenz et al. 1999) that the 14.9-yr cyclic variation in disc-integrated albedo of Titan is produced with the correct phase by the changing aspect of Titan and the seasonally varying (lagged by about one season – strongest NSA at equinox) hemispheric albedo. However, the amplitude of the observed albedo variation at blue wavelengths was not quite satisfactorily reproduced. The known hemispheric albedo contrast yielded an albedo cycle with a peak-to-peak amplitude of ∼6 per cent, while observations suggest an amplitude of 8–9 per cent. The presentation of the dark (by ∼10 per cent) polar hood towards the Earth in late spring for each hemisphere, occupying around 10 per cent of Titan's disc, can account for at least part of the discrepancy. Other idealizations in the model (a strictly sinusoidal contrast history, and the simplification of the latitude-albedo variation to two uniform hemispheres) may explain the rest.

The spectral character of the polar hood was not determined by Voyager over as wide a spectral range, although it was noted that the feature was most prominent in images with Voyager's violet filter. Model comparisons (not shown here) suggest that an additional layer of haze, made of small (0.02–0.03 μm) spherical particles with the same optical properties as laboratory tholins (Khare et al. 1984), lying above the main haze deck captures the broad spectral character of the hood, and requires an additional column mass of material of 2–5 $\mu g\,cm^{-2}$ is accounted for in the polar hood, compared with ∼25 $\mu g\,cm^{-2}$ in the main haze. The main haze appears to be composed of particles with a characteristic size of ∼0.3 μm, presumably as fractal aggregates of these spherical monomers.

Such a simplistic model overestimates the contrast at 250 nm. While a large parameter space of haze particle size, geometry and altitude distribution, and not least optical properties (since work in recent years has shown that tholins with a wide variety of optical

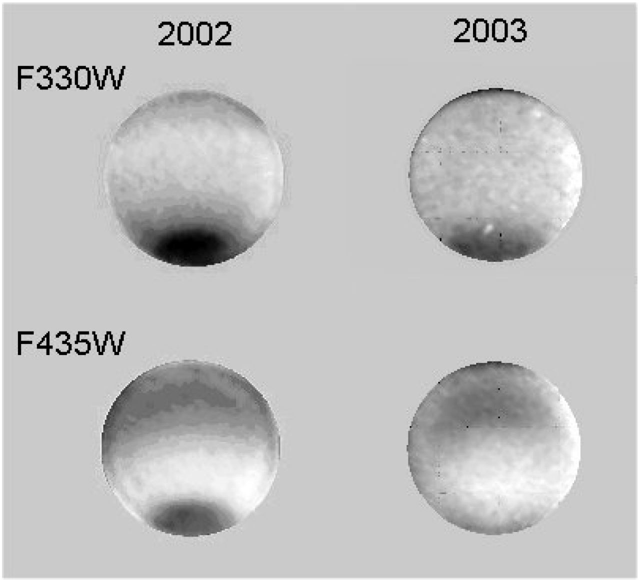

Figure 3. Comparison of equivalent images for 2002 Dec and 2003 Dec (the aspect is nearly identical). Both sets are enhanced by removal of limb darkening. Note that the contrast stretch is different for each image in order to enhance the features of each.

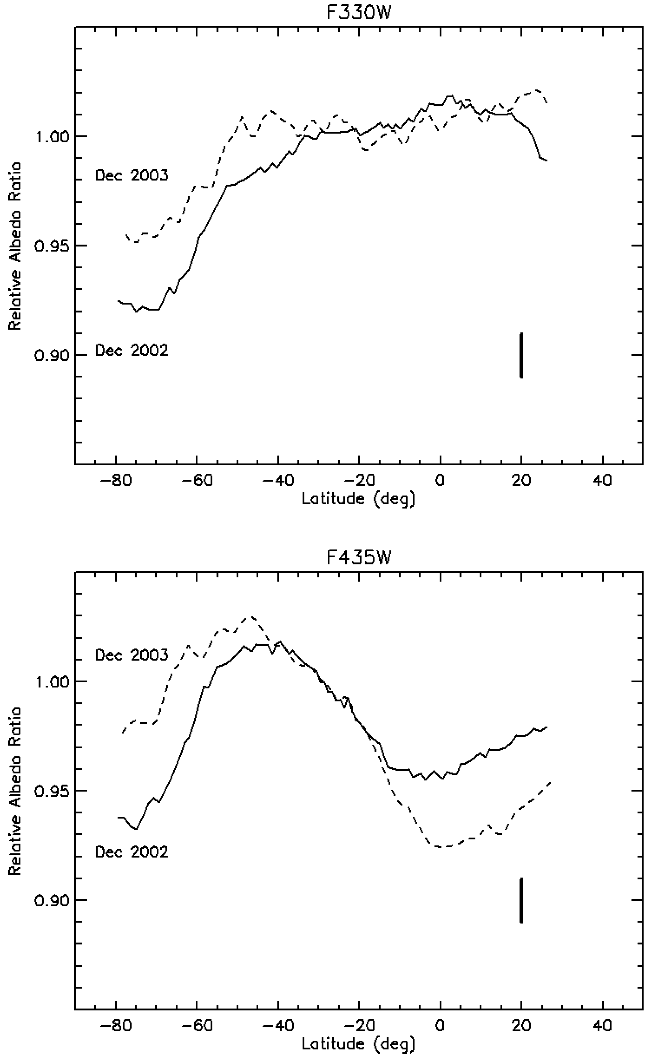

Figure 4. Quantitative decay of the South polar hood 2002–2003. Shown are north–south profiles of intensity divided by a uniform but limb-darkened disc. At 330 nm, the polar hood decays in intensity from ~8 to ~4 per cent, while at 435 nm it drops from ~6 to ~2 per cent – the north–south asymmetry evidently evolves at this wavelength too. Bars at 20°N are representative errors, primarily due to range of limb-darkening fits.

properties can be produced) could be explored, such an effort would only be worthwhile in comparison with Cassini data (e.g. Fig. 5) which offers phase angle coverage and rather precise altitude distribution information.

3 DISCUSSION

As demonstrated by Rannou et al. (2002), the polar hood seems to be a radiative-dynamical construct. During the long polar night, temperatures fall in the absence of solar heating (e.g. Yung 1987) – this leads to a downwelling which draws haze from the summer hemisphere and causes them to accumulate at the winter pole. As the haze is drawn horizontally from beneath the formation zone, a clearing is generated leading to the 'detached' haze. There is a positive feedback, in that haze provides radiative cooling during winter and thus the elevated haze concentrations provide even stronger cooling to reinforce the downwelling.

While this paradigm appears to capture the essence of the process, it is clear that there is much more going on. First, the haze population is evolving by coagulation – a large number density of small aerosols is not generally stable, as they stick together. Assuming that the aerosols are not a discrete layer but are well mixed in the atmosphere above 300 km, the observed abundance of 0.02-μm particles would coagulate to twice that size in 0.01 yr. Predicted electrical charging from galactic cosmic rays (Borucki et al. 1987) is quite small, but electrons generated via the photoelectric effect (Bakes, McKay & Bauschlicher 2002) could generate a positive charge of 1 (missing) e^- per particle. Thus, when exposed to sunlight, the haze may be charged which will retard coagulation, but on entering the winter polar hood, coagulation may accelerate.

Second, and probably much more important, is the interaction with the gas-phase chemistry. It was known from Voyager thermal emission spectra (Coustenis & Bezard 1995) that high northern latitudes were enhanced by an order of magnitude or more in nitriles (e.g. HCN, C_2N_2) and easily photolyzed hydrocarbons (C_3H_4, C_4H_2).

Recent Cassini observations (Flasar et al. 2005) show that now (2004 July–December) the north polar regions are enhanced in HC_3N and C_4H_2, while HCN has a somewhat uniform gradient, increasing by a factor of 10 in abundance from south to north. On the other hand, these observations show that C_4H_2 is depleted in the northern polar region – this compound had been observed in narrowband Keck images (Roe, DePater & McKay 2004) to be enhanced at the south pole in 1999–2002. Several processes are at work, competing with the 'steady state' balances of formation, destruction and latitudinal transport (e.g. Lebonnois et al. 2003). First, species which are normally photolyzed can accumulate in the darkness. Second, the downwelling enriches the atmosphere in some of these compounds, since it draws down air from the altitudes at which they are produced. Third, the low winter temperatures and elevated concentrations may favour the condensation of some of these compounds (e.g. C_4N_2, as observed by Samuelson et al. 1997a). In this sense, as discussed by Flasar et al. (2005), the polar hood may resemble

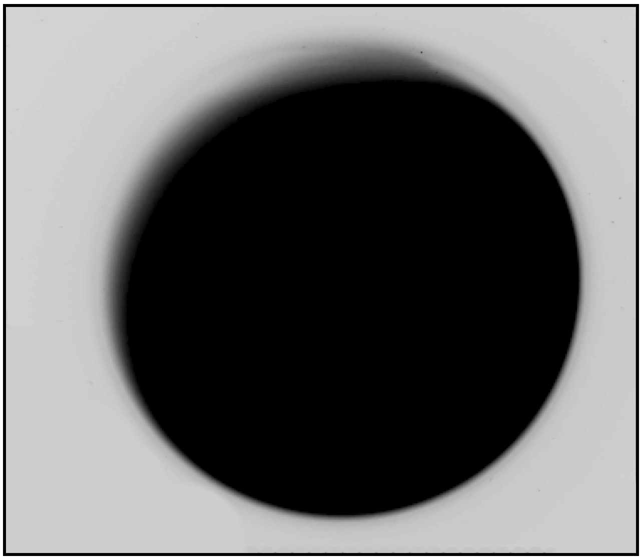

Figure 5. 338-nm (UV3) Cassini ISS image (N1481359512_1, shown as a negative image and slightly contrast stretched) acquired in 2004 December from 1.7 million km range. North is upwards, subspacecraft latitude is 8°.1 S – a better viewpoint than the 22°.8 S of the Earth to observe the forming north polar hood – the high-standing polar haze is evident, connecting to the detached haze layer. The south polar hood would be visible were it still present at the same intensity as observed by *HST* in 2002.

the Earth's ozone hole, in that it is a transient region of anomalous chemistry and particulates (the polar stratospheric clouds) that is dynamically isolated from the rest of the atmosphere by a circumpolar vortex. The elevated abundances also have a feedback effect, in that these compounds also provide infrared opacity to permit radiative cooling (e.g. Luz et al. 2003).

Although all of these processes are occurring at altitudes of hundreds of kilometers, it may be that they none the less affect Titan's surface. The polar haze enhancement may result in an enhanced deposition of photochemical material at high latitudes (including, perhaps, liquid ethane – Samuelson, Nath & Borysow 1997b) either directly, or by providing nucleation centers for condensation. The availability of condensation nuclei may be an important factor in regulating tropospheric opacity, which is known to vary with latitude (e.g. Young et al. 2002).

4 CONCLUSIONS – THE DECAY OF THE POLAR HOOD

The data shown here form only a small piece in a large and complicated puzzle. Elaborate modelling will be required to disentangle the various roles and causes of haze and gas in cooling the polar winter stratosphere. The spectral character of the polar hood we have observed is consistent with an enhancement of a high-altitude small-particle haze, and its disappearance in 2002–2003 acts as a powerful constraint on such models.

ACKNOWLEDGMENTS

Based on observations (GO-9385 and GO-9745) made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated for NASA by the Association of Universities for Research in Astronomy, Inc. The work was supported by a grant from the Space Telescope Science Institute.

REFERENCES

Bakes E. L. O., McKay C. P., Bauschlicher C. W., 2002, Icarus, 157, 464
Borucki W. J., Levin Z., Whitten R. C., Keesee R. G., Capone L. A., Summers A. L., Toon O. B., Dubach J., 1987, Icarus, 72, 604
Coustenis A., Bezard B., 1995, Icarus, 115, 126
Flasar F. M. et al., 2005, Sci, 308, 975
Hubbard W. B. et al., 1993, A&A, 269, 541
Karkoschka E., Lorenz R. D., 1997, Icarus, 125, 369
Khare B. N., Sagan C., Arakawa E. T., Suits F., Callcott T. A., Williams M. W., 1984, Icarus, 60, 127
Lebonnois S., Hourdin F., Rannou P., Luz D., Toublanc D., 2003, Icarus, 163, 164
Lorenz R. D., Smith P. H., Lemmon M. T., Karkoschka E., Lockwood G. W., Caldwell J., 1997, Icarus, 127, 173
Lorenz R. D., Lemmon M. T., Smith P. H., Lockwood G. W., 1999, Icarus, 142, 391
Lorenz R. D., Young E. F., Lemmon M. T., 2001, Geophys. Res. Lett., 28, 4453
Lorenz R. D., Lemmon M. T., Smith P. H., 2004, Geophys. Res. Lett., 31, 10702
Luz D., Hourdin F., Rannou P., Lebonnois S., 2003, Icarus, 166, 343
Porco C. C. et al., 2005, Nat, 434, 159
Rages K., Pollack J. B., 1983, Icarus, 55, 50
Rannou P., Hourdin F., McKay C. P., 2002, Nat, 418, 853
Roe H. G., DePater I., Macintosh B. A., Gibbard S. G., Max C. E., McKay C. P., 2002, Icarus, 157, 254
Roe H. G., DePater I., McKay C. P., 2004, Icarus, 169, 440
Samuelson R. E., Mayo L. A., Knuckles M. A., Khanna R. J., 1997a, Sci, 45, 941
Samuelson R. E., Nath N., Borysow A., 1997b, Planet. Space Sci., 45, 959
Smith B. A. et al., 1981, Sci, 212, 163
Smith B. A. et al., 1982, Sci, 215, 504
Sromovsky L. A., Suomi V. E., Pollack J. B., Kraus R. J., Limaye S. S., Owen T., Revercomb H. E., Sagan C., 1981, Nat, 292, 698
Young E. F., Rannou P., McKay C. P., Griffith C. A., Noll K., 2002, AJ, 123, 3473
Young E. F., Puetter R., Yahill A., 2004, Geophys. Res. Lett., 31, 17 809
Yung Y. L., 1987, Icarus, 72, 468

This paper has been typeset from a TEX/LATEX file prepared by the author.