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Seasonal change in Titan's haze 1992–2002 from Hubble Space Telescope observations

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[1] Images from the Hubble Space Telescope (HST) document the seasonal migration of haze in Titan's atmosphere. Image profiles show darkening of the north relative to the south at 439 nm (blue) but no change at 619 nm. The limb profile at 889 nm has inverted, becoming north-bright, a variation consistent with haze transport towards the winter hemisphere by winds. The complex altitude-time variation of the north-south haze differences are indicated in resolved spectra acquired with the Space Telescope Imaging Spectrograph (STIS): the continuum slope of a north/south ratio spectrum changes sign, becoming red, between 2000 and 2002, although the 889 nm band had already reversed by 2000, suggesting the haze distribution changes most rapidly at high altitudes. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0343 Atmospheric Composition and Structure: Planetary atmospheres (5405, 5407, 5409, 5704, 5705, 5707); 6280 Planetology: Solar System Objects: Saturnian satellites; 5739 Planetology: Fluid Planets: Meteorology (3346). **Citation:** Lorenz, R. D., P. H. Smith, and M. T. Lemmon (2004), Seasonal change in Titan's haze 1992–2002 from Hubble Space Telescope observations, *Geophys. Res. Lett.*, *31*, L10702, doi:10.1029/2004GL019864.

1. Introduction

[2] Titan has a thick, haze-laden atmosphere, and an obliquity which drives seasonal change in that atmosphere over Titan's 29.5 year orbit around the sun. The joint NASA-ESA Cassini mission will begin to observe Titan as it approaches Saturn in April 2004 with a resolution comparable with the best Earth-based techniques. It is just after Southern Summer Solstice on Titan (L_s ~292°, where L_s is the solar longitude [see, e.g., *Tokano et al.*, 1999]. Cassini's nominal mission runs to May 2008 with a possible extended mission of >~2 years, to Northern Spring Equinox (see Table 1).

[3] In order to place Cassini data in context, and to link them with earlier spacecraft observations (Pioneer 11, and Voyagers 1 and 2) in 1979–1981, we present results from HST observations over the last 12 years. We provide the results, which show continuing year-to-year seasonal change, in one-dimensional forms suitable for easy comparison with numerical models [e.g., *Tokano et al.*, 1999; *Rannou et al.*, 2002]. Recovery of e.g., haze particle number densities requires assumptions on haze scattering function, optical properties of tholin, and methane absorption coefficients. Since ongoing laboratory work and Cassini data will lead to refinement of these quantities, we report only the derived image products to permit maximum flexibility in future modeling.

[4] We focus on the bulk interhemispheric transport of stratospheric haze which has been shown [*Lorenz et al.*, 1997, 1999] to be responsible for the so-called North-South Asymmetry (NSA) notable in Voyager images [e.g., *Sromovsky et al.*, 1981]. We note only in passing that a complex UV-dark polar hood exists during some seasons.

2. Observations

[5] Titan's changing appearance is shown in Figure 1. This compilation uses images acquired with the Wide Field and Planetary Camera 2 (WFPC2 [see also *Lorenz et al.*, 1997, 1999, 2001]) together with a set of somewhat blurred images acquired with WF-PC in 1992, prior to the first Hubble servicing mission. To ensure no artifacts have been introduced, we have not deconvolved our images. In some cases where images were not acquired we have substituted images synthesized from STIS data. Data from the Advanced Camera for Surveys (ACS) will be reported elsewhere.

[6] The filters used are F336W, F439M, F547M, FQCH4N-B (the shallow 619 nm methane band) F673N, FQCH4N-D (the deeper 889 nm methane band) and F953N, where the number is wavelength in nm and N,M or W denotes narrow, medium or wide. Further details, and comparison with Voyager and Pioneer data are given by *Lorenz et al.* [1997].

[7] Features evident in Figure 1 are the flat (and noisy) disk at 336 nm and limb-brightening at 889 nm with limb-darkening at other wavelengths, the changing NSA at 439 nm and 547 nm, and the inverting 'smile' at 889 nm which is now a 'frown'. Figure 2 shows north-south cuts along the central meridian of images in 1994, 1997 and 2002 (we note that image data of Titan is often only reported in image form: for convenient model comparison, we urge observers to also provide north-south cuts or limb profiles.) The reversal of the NSA at 439 nm is evident in 2002. STIS data from 2000 [*Lorenz et al.*, 2001] show reversal at 550 nm where the appearance is much the same as at 439 nm.

[8] Images may be interpreted thus: in blue, the Rayleigh-scattering atmosphere would be bright, like

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Table 1. Season on Titan

Date	Observation/Event	L_s (deg)	Solar Latitude (deg)
Sep 1979	Pioneer 11 encounter	354	−2.9
Feb 1980	vernal equinox	360	0
Nov 1980	Voyager 1 encounter	8	+4.1
Aug 1981	Voyager 2 encounter	16	+8.0
Nov 1987	northern summer solstice	90	+26.7
Aug 1990	HST WFPC	122	+23.0
Aug 1992	HST WFPC	145	+16.0
Oct 1994	HST WFPC2	168	+5.8
Aug 1995	HST WFPC2	177	+1.3
Nov 1995	autumnal equinox	180	0
Nov 1997	HST WFPC2/STIS	202	−10.7
Dec 2000	HST WFPC2/STIS	242	−24.0
Oct 2002	southern summer solstice	270	−26.7
Dec 2002	HST WFPC2/STIS/ACS	271	−26.7
Apr 2004	Cassini approach science	292	−25.0
Oct 2004	first Cassini flyby (Ta)	300	−23.5
May 2008	end of nominal Cassini tour	345	−7.2
Aug 2009	vernal equinox	360	0
May 2010	possible Cassini extension	8	+4.1

Earth's. However, the tholin haze is blue-absorbing, and so image darkness implies a relative enhancement of dark haze above the bright atmosphere. In near-infrared methane bands the lower atmosphere is dark, while haze is bright, and thus abundant haze at high altitudes leads to a bright appearance.

[9] The observations are consistent with a seasonal cycle wherein circulation like that of thermally-direct winds (i.e., a pole-to-pole Hadley cell) chases haze away from the summer hemisphere to the winter one [e.g., *Hutzell et al.*, 1996]. This conceptual picture, a simple analytical model of which was developed and compared with HST data in the work of *Lorenz et al.* [1999] has been captured in detail in numerical models that couple general circulation with haze transport [e.g., *Tokano et al.*, 1999; *Rannou et al.*, 2002].

[10] Remarkably, the 619 nm profile is essentially unchanged (see Figure 2) over the 8 year period and indicates an enhanced opacity in the S hemisphere. 953 nm images (Figure 1 and *Lorenz et al.* [2001]), probing down to Titan's surface also show a persistent brightness in the deep southern hemisphere.

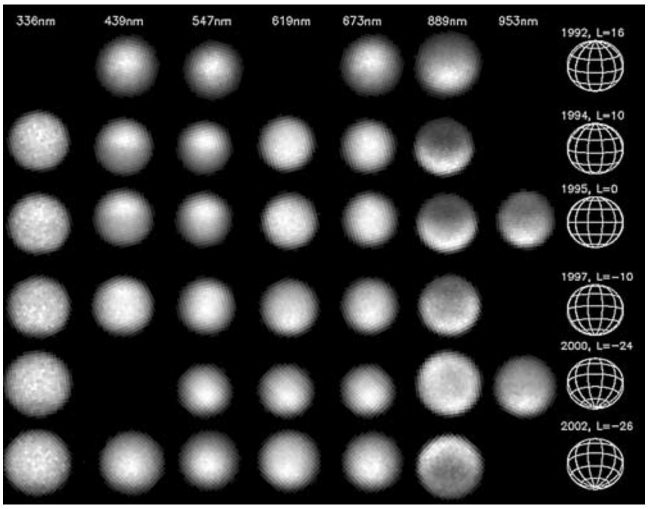

Figure 1. HST Titan images from the UV to the Near-IR since 1992. All images are north-up, scaled to same maximum brightness, and show brightness cubed to enhance contrast. Globes at right show the changing aspect: L is the declination or Subsolar Latitude. The apparent change in diameter with wavelength is due to changing limb-darkening. 1990 images (not shown) are of poor quality [see *Caldwell et al.*, 1992].

[11] The 619 nm data require comment. Either (1) there is no seasonal cycle at this wavelength, that the altitudes probed are so stagnant that the total haze amount at each latitude, dominated by lower altitudes, does not change with time. If so, the persistent asymmetry requires an explanation, perhaps due to the eccentricity of Saturn's orbit around the sun such that southern summers are hotter but shorter. More probably (2) the phase of the seasonal cycle down to these altitudes is delayed with respect to that seen above 100 km or so at 439 nm and 889 nm. It is known that the disk-integrated albedo cycle recorded by Lockwood [see *Lorenz et al.*, 1999] is delayed by ~0.5–1 year at 550 nm compared with 467 nm: at these wavelengths where the haze reflectivity is low, the corresponding unity optical depth levels are ~100 km and 85 km [*Lorenz et al.*, 1997]. The corresponding phase lag at 619 nm is evidently >5 years. At this wavelength, where the haze scatters rather than absorbs, the altitude probed is somewhere between ~70 km where the haze optical depth is unity and ~15km where the methane absorption optical depth is unity [*Young et al.*, 2002]. Thus, if haze is responsible for the 619 nm NSA, there is a substantial phase lag between 85-100 km and 15–70 km. We point out that the opacity appeared stronger in the south before the subsolar point crossed into the south in 1995: this would be inconsistent with a tropospheric cirrus origin (i.e. indirectly related to convective activity, which is now seen to dominate in the South, e.g., *Brown et al.* [2002]).

[12] The changes are most obvious at 889 nm which probes only the stratosphere. The limb brightness profiles at this wavelength are shown in Figure 3a, which gives a quantitative representation of the reversal of Titan's "smile" into a "frown" [*Lorenz et al.*, 2001]. The limb brightness corresponds to the high-altitude haze number density. The model results of *Tokano et al.* [1999] show a similar trends with time (see Figure 3b) although the detailed shape differs since 889 nm data probe only the stratosphere while the model 640 nm opacity is a total column.

3. Comparison With Other Observations

[13] Variable seeing for groundbased observers, and different filter widths, make comparison between data difficult,

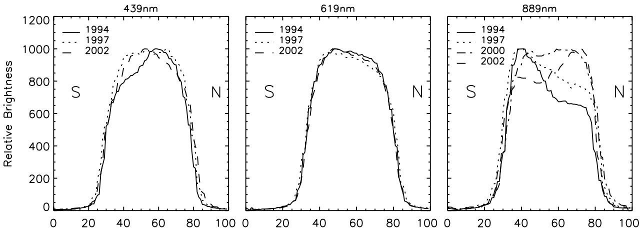

Figure 2. North-South cuts along the central meridian of images in 1994,1997 and 2002. All data are normalized to the same maximum brightness (1000). The reversal of the north-south asymmetry in blue (439 nm) and (in the opposite sense) in the 889 nm methane band is obvious. The 619 nm data is remarkably unchanged.

but the timing of changes may usefully constrain models. All near-IR observations prior to 2000 (e.g., the 1994 adaptive optics (AO) images of *Combes et al.* [1997], the late 1996 speckle imaging of *Gibbard et al.* [1999] and 1997 HST data [*Meier et al.*, 2000] show the south as the brighter hemisphere. *Chanover et al.* [2003] determine in 1999 AO images using a tunable filter that the S was brighter, although this was not strongly apparent at 890 nm.

[14] Later, *Roe et al.* [2002] show late 2001 AO images (at ~2.26 μm) with a brighter N hemisphere, not unlike our 889 nm late 2002 image. *Coustenis et al.* [2001] report late 2001 images showing the south brighter in deep-sounding filters, but a 'suggestion of a reversal' in Fe-II (1.64 μm) and K-continuum filters.

[15] This exchangeability between wavelength (a proxy for altitude, since methane absorption is the main altitude discriminator, and the methane abundance is believed to be invariant) and time is illustrated in Figure 4 which shows N/S ratio spectra acquired in 1997, 2000 and 2002 with HST/STIS, specifically flux from 0.22 arcsec north of the center of the disk divided by that 0.22 arcsec south of center. The trend is clear at wavelengths longward of 600 nm or so - the north becomes progressively brighter (presumably as haze migrates to the winter hemisphere). The more rapid change in deep methane bands such as 889 nm is evident - higher altitudes change first.

[16] Note how the 729 nm methane band inverts itself, being pulled up from the center - strongest absorption and thus highest altitudes leads the change. The 619 nm flux ratio has stayed constant (consistent with the images), but the adjacent wavelengths have changed significantly. In the near-IR, the variation with wavelength is dramatic - images in different filters may see the NSA to have reversed (or not) depending on the relative altitude weights assigned by the filter bandpasses: for example, the north/south flux ratio in Figure 4 reverses from 0.95 to 1.3 between 880 and 890 nm. These data demonstrate that broadband imaging is poor for constraining models, since large altitude ranges are averaged together and information is thereby lost.

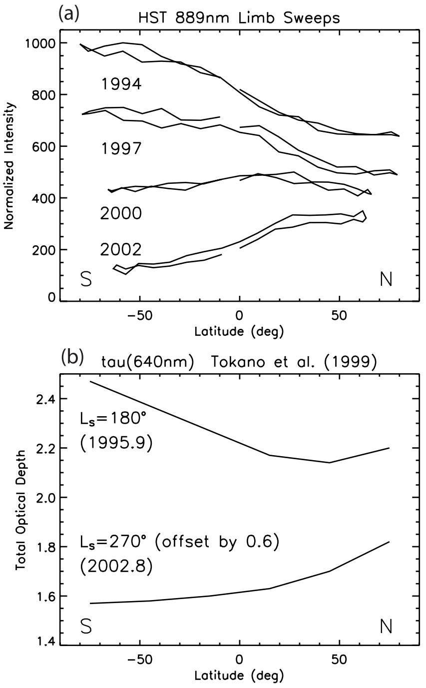

Figure 3. (a) Profiles of limb brightness vs. latitude for 889 nm images. Data are normalized to the same maximum (1000) for each profile, but are offset for clarity. The loop appearance is due to nonzero phase angle (and possibly center-finding errors.) Noise in the images is comparable with the span of the loops and thus these errors are not significant. Note the 'plateau' above 30°N in 2002. (b) Total column model optical depths at 640 nm.

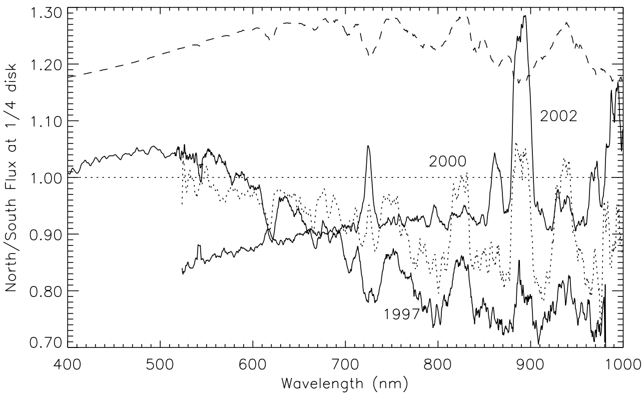

Figure 4. N/S Flux ratio (roughly speaking, a north:south albedo ratio that is comparable year-to-year, although slightly different latitudes are sampled in 1997). Dashed line at top is scaled disk-integrated albedo for reference.

4. Conclusions

[17] HST image profiles show a progressive darkening of the north relative to the south at 439 nm (blue) but no change 1994–2002 at 619 nm where the S hemisphere is fractionally brighter than the north. At 889 nm, the north has progressively brightened, and limb profiles show haze number density versus latitude varying with time similar to the total integrated haze opacity as a function of latitude computed in numerical models.

[18] The complex altitude-time variation of the N-S haze differences are indicated by STIS: the continuum slope of a N/S ratio spectrum changes sign, becoming red, between 2000 and 2002. The 889 nm band had already reversed by 2000, suggesting the haze distribution changes most rapidly at high altitudes. Titan's N/S brightness ratio can change sign over very short wavelength intervals. If the trends we have observed continue, wavelengths with progressively shallower methane absorptions will become north-bright in the next few years, including the 619 nm band.

[19] While improvements in groundbased AO systems have yielded dramatic results in mapping and in the detection of clouds, the stable performance and configuration of the HST has permitted consistent monitoring of Titan's atmosphere which has shown remarkable changes over the past few years. The arrival of Cassini will help us understand these changes better, but makes the HST record, and its overlap with Cassini, all the more important.

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