Direct imaging of Titan's extended haze layer from HST observations

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[1] In the early 1980s, both Voyager spacecraft imaged a detached haze layer surrounding Titan, separated from the main haze distribution by a gap at around ~300 km and merging into a hood of more concentrated haze at Titan's north pole. We have processed Hubble Space Telescope images of Titan with Lucy-Richardson and PIXON deconvolution software and point spread functions generated by TinyTim 6.0 to detect the extended haze layer for the first time since the Voyager encounters. Images taken from 1994 through 2000 show not only that the extended haze layer still exists, but also that it has migrated from south to north during that interval. *INDEX TERMS:* 6006 Planetology: Comets and Small Bodies: Atmospheres—evolution; 6007 Planetology: Comets and Small Bodies: Atmospheres—structure and dynamics; 6297 Planetology: Solar System Objects: Instruments and techniques; 6280 Planetology: Solar System Objects: Saturnian satellites. **Citation:** Young, E. F., R. Puetter, and A. Yahil (2004), Direct imaging of Titan's extended haze layer from HST observations, *Geophys. Res. Lett.*, *31*, L17S09, doi:10.1029/2004GL020135.

1. Introduction

[2] In 1981, both Voyager spacecraft imaged Titan's limb with enough resolution to characterize a gap in Titan's haze at around ~300 km [*Rages and Pollack*, 1983]. This detached haze layer extended from the "north polar hood" (a concentration of haze at the north pole) all the way to Titan's south pole (Figure 1). This detached haze layer is a potential observational constraint to address the questions of where haze is formed and how it is transported.

[3] *Rannou et al.* [2002] have published results of a coupled GCM/Radiative Transfer/Microphysical model for Titan's haze. They report that strong horizontal transport should whisk away aerosols to the poles before they have a chance to sink to the surface. One plausible scenario to describe the observed gap is one where haze forms through UV photolysis of methane in a nitrogen environment in Titan's upper atmosphere (perhaps 400–600 km). The very small aerosols would take decades to fall, except that the hypothesized pole-to-pole Hadley-type circulation removes the haze as it settles from the upper atmosphere and creates an observable gap at ~300 km and a pile-up of haze at one of the poles. If this scenario turns out to be realistic, then the detached haze layer and the polar hoods are useful observables for constraining models of haze formation and Titan GCMs.

[4] The north/south migration cycle of Titan's lower altitude haze has been observed for several years. At the time of the Voyager encounters, Titan's north pole was covered with a significantly thicker haze column than the south pole. This distribution had reversed by the early 1990s, such that 16 years after the Voyager encounters the Hubble Space Telescope (HST) images of Titan showed a concentration of haze over Titan's south pole [*Lorenz et al.*, 2001].

[5] Although Titan subtends less than an arcsecond when observed from the Earth, both HST and ground based adaptive optics images have resolved around 20 pixels across Titan's diameter, equivalent to about 250 km (on Titan) per pixel. At this resolution, Titan's main haze layer is about 1.5 pixels wide, and a detached haze layer is just not visible. However, we have observed that an extended haze layer is detectable in sharpened HST images. We have used the Space Telescope Science Institute's TinyTim modeling program to generate synthetic point spread functions (PSFs) for each HST image and Lucy-Richardson or PIXON software to deconvolve each image. The results reveal an extended haze layer that changes noticeably from year to year. We cannot determine if this haze layer is simply extended or detached.

2. Data Sets

[6] Titan has been observed at roughly yearly intervals from HST since 1992. Here we examine WFPC2 images taken in 1994, 1996 and 2000 (Table 1). The native resolution of WFPC2 images is 0.0455″ per pixel.

[7] Titan's aerosols have very bright single scattering albedos at wavelengths longer than 0.7 μm [*Khare et al.*, 1993]. The brightest regions of HST images at .889, .953, or 1.042 μm occur where the concentrations of haze are highest.

[8] Saturn's last ring plane crossing occurred in late 1995. Titan's subsolar latitude was +5.9° in the 1994 WFPC2 data set, −5.2° for the 1996 set, and −23.6° for the 2000 set. The relative positions of the subsolar and sub-observer points are shown in Figure 2. The location of the subsolar point is of interest because it may be responsible for apparent asymmetries in Titan's haze distribution. In the 1994 and 1996 data sets the subsolar longitude is slightly toward the evening limb. In the 2000 data set the images are

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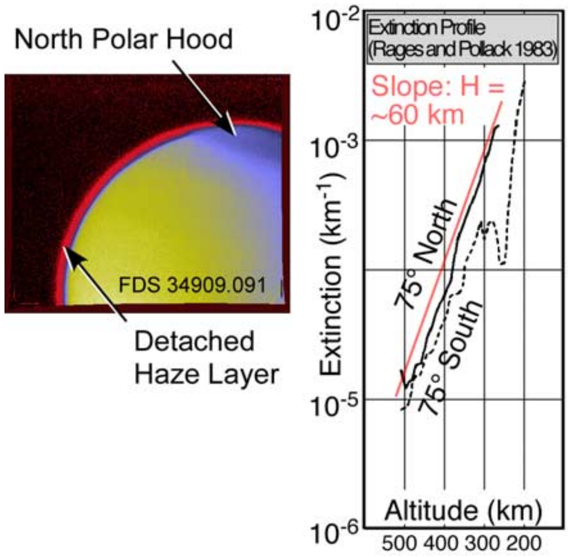

Figure 1. Voyager close-up of Titan's detached haze layer and north polar hood, circa 1981. *Rages and Pollack* [1983] estimated the extinction profile of the haze between altitudes of 200–500 km.

taken only four days before or four days after opposition, and the subsolar longitudes are less than half of a degree east or west of the central meridian. In all cases we see slightly brighter extended haze on the morning limb.

3. Deconvolution

[9] The HST WFPC2 images have high S/N ratios and reasonably well-known point spread functions (PSFs), making them good candidates for deconvolution processing. We have used a Lucy-Richardson deconvolution algorithm (as implemented in the IDL Astron library) to process selected wavelengths from the GO-5508, GO-6377 and GO-8580 data sets, with 200 iterations per image. We also processed the images with the PIXON algorithm [*Pina and Puetter*, 1993; *Puetter*, 1995], with generally similar results. The figures in this paper are based on the Lucy-Richardson routine, except for Figure 6, which shows an image based on PIXON reconstruction.

[10] Since no point sources are available in the WFPC2 frames to serve as PSFs, we use computed PSFs (Figure 3) generated by TinyTim 6.0 (an HST PSF-modeling program by John Krist and Richard Hook, available from http://www.stsci.edu/software/tinytim).

3.1. Results

[11] Figure 4 shows an array of images from 1994, 1996 and 2000 at three wavelengths: 889 nm (a methane band), 953 nm (a methane window), and 1042 nm (a methane window). In general, these images show that

[12] • In 1994 and 1996, the tropospheric haze abundance is greatest over the south pole at all wavelengths. This is significant in terms of the vertical distribution of haze. The contribution function in the 890 nm filter peaks at about 70 km, while the 953 nm images (slightly wider than the methane window at 940 nm) peaks at around 20 km. By 2000, the bright haze has clearly migrated from south towards the north in the 890-nm images, but remains concentrated in the south in the 953 nm images, indicating that the south-to-north migration began at altitudes above the 40 km tropopause. This is not a new result, simply a confirmation of the tropospheric haze migration reported by *Lorenz et al.* [2001].

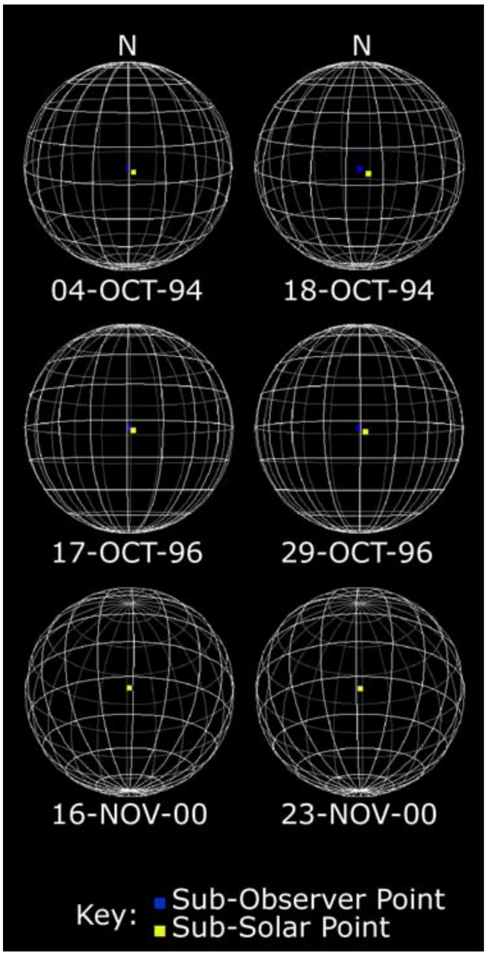

Figure 2. The sub-observer point (blue) and subsolar point (yellow) at dates corresponding to the Titan observations in 1994, 1996 and 2000. The subsolar offsets are roughly 3 degrees west (right) and 2 degrees south of the disk center in 1994, 2 degrees west and 1.5 degrees south in 1996, and 0 degrees west and 0.15 degrees south in 2000. The November 16 and November 23 (2000) observations were four days before and after Titan's opposition, with respective subsolar longitudes 0.5 degrees east and west of the sub-observer point.

Table 1. List of HST Programs

Program	Obs Date	Filters
GO-5508	4-OCT-94	F336W, F439W, F547M, F588N, F673N, F791W, F850LP, FQCH4N-D, FQCH4N-B, F1042M
GO-6733	17-OCT-96	FQCH4N-D, FQCH4N-B, F953N
GO-8580	16-NOV-00	F255W, F336W, F439W, F547M, F588N, F673N, F850LP, F953N, F1042M, FQCH4N15, FQCH4P15

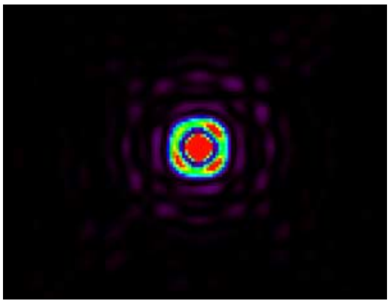

Figure 3. An example of a point spread function generated by TinyTim 6.0.

[13] • There is an extended haze layer that is evident over Titan's southern hemisphere in the 1994 image at 1042 nm and the 1996 image at 953 nm. Some extended haze may be present in the 890 nm images in 1994 and 1996, but with a weaker north/south asymmetry relative to the methane continuum images.

[14] • By 2000, the extended haze layer has moved from the south pole to a roughly even north-south distribution.

[15] • The extended haze layer is consistently brighter on the morning limb, regardless of the subsolar longitude. The subsolar longitude is actually a few degrees closer to the evening limb in the 1994 and 1996 data sets.

3.2. Credibility of the Deconvolution Procedure

[16] Three aspects of the deconvolution procedure are worth close examination.

[17] *Is the PSF too broad?* A broad PSF will produce ringing around a source that could look suspiciously like an extended haze.

[18] *Are the residuals reasonable?* The residuals should be small (smaller than the estimated noise values) and uniformly distributed (i.e., the residuals should look like white noise).

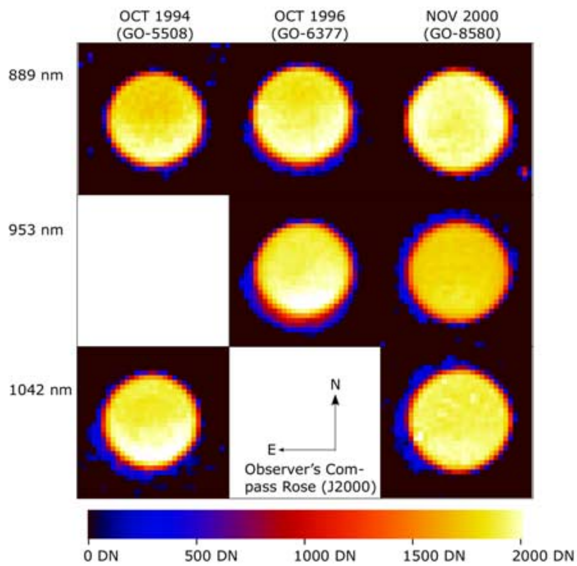

Figure 4. A sequence of Lucy-Richardson image reconstructions in various wavelengths from 1994, 1996 and 2000. The extended haze layer over the south pole in 1994 and 1996 has migrated towards the north pole by 2000.

[19] *Is the extended haze an artifact of the viewing geometry?* The atmosphere may simply be brighter near the subsolar point, especially if the aerosols have a backscattering peak in their phase function.

[20] We know that a broad PSF is not the source of the extended haze in the deconvolved images. The north polar region is about 2/3 as bright as the south in the 1994 and 1996 images, but no extended haze layer is seen around the north pole, even though it would be easily visible at the 66% level. In addition, Titan's on-chip orientation varied over the 1994 and 1996 data sets, yet the extended haze layer appeared around the south pole. If the asymmetrical N/S distribution of extended haze were due to a strangely shaped PSF, then the extended haze would maintain an orientation with respect to the CCD axes, not with respect to Titan's spin axis (which it does).

[21] The residuals, r, are the differences between the data and the model, normalized by σ, the estimated noise at each pixel.

$$r = \frac{(data - NFD)}{\sigma} \tag{1}$$

where *data* is the 2-D data array (the observations), *NFD* is the "noise-free data," which is the deconvolved image convolved with the PSF, and the σ array is the estimated noise at each pixel. We calculate σ as the quadratic sum of the background sky noise and the Poisson shot noise of the source counts. The residuals should all be comparable to σ at each pixel, and the residuals should look like uniform random noise. Any patterns in the residuals are an indication that the deconvolved image is not correct. Figure 5 shows the residuals for the deconvolved images. The residuals are comparable to σ, but not all of the residual

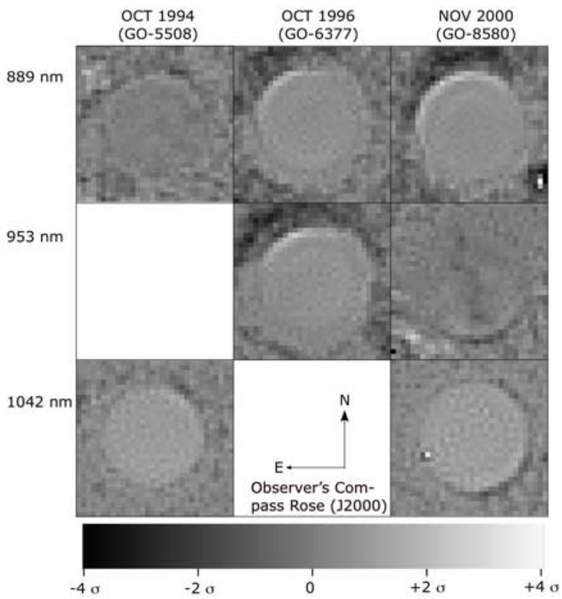

Figure 5. Residuals for the deconvolved images shown in Figure 4. The magnitude of the residuals is about the same as the noise in the data (including Poisson noise over Titan's disk). The distribution of residuals should resemble white noise (i.e., no pattern), so the presence of correlated structure (high and low residuals at the limb) is a problem.

arrays are as flat as we'd like to see. In particular, there are high residuals near Titan's northern limb in several cases.

[22] Finally, it is possible that the extended haze layer is an artifact due to the slightly southerly offset of the subsolar point and a narrow backscattering peak in the haze phase function. In 1994, the subsolar latitude was about 2 degrees south of the disk center, in 1996, it was about 1.5 degrees south. However, if the offset in the subsolar point were indeed responsible for the apparent extended haze layer, then we should see a preponderance of extended haze off the west (right) limb of Titan, since the subsolar longitudes are 2 to 3 degrees west of the disk center. In fact, there is more signal seen on the morning limb (the left side, for north pointing "up"). The extended haze may be an artifact of the viewing geometry, but only if there is a large morning brightening effect to overcome the subsolar point's proximity to the evening limb. As an aside, the brighter morning limb is consistent with the idea that condensates form in Titan's upper atmosphere during the 190-hour night cycle, but evaporate during the 190-hour day cycle before they reach the evening limb.

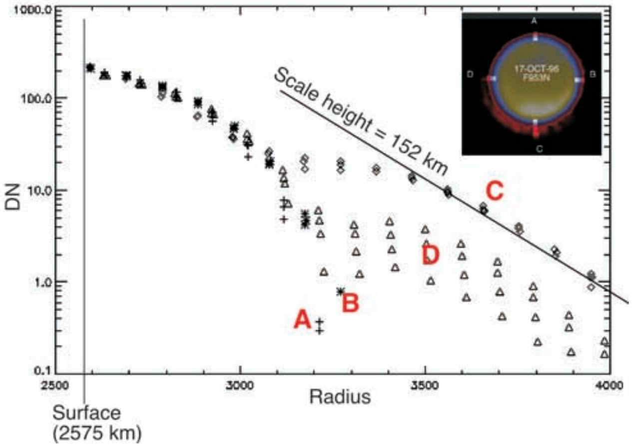

Figure 6. An attempt to quantify the extinction profile of a 1996 F953N WFPC2 image. The slope indicates a scale height of 152 km, probably too large by a factor of ~2 or 3. The gap, at 525 km above the surface, is too high and doesn't appear in the Lucy-Richardson deconvolutions.

4. Discussion

[23] *Rages and Pollack* [1983] measured the extinction between 200–500 km due to haze from high-resolution Voyager images. Their log-plot of the extinction profile at lat = 75°N (Figure 1) is fairly straight, as expected for an exponential haze distribution, and the slope is around 60 km, about the same as the scale height of the N_2 gas at that altitude. (There's no reason to expect that the haze should be evenly mixed with the gas. In fact, the haze/N_2 ratio is much smaller below the tropopause than above it [*Young et al.*, 2002].

[24] The extended haze layer doesn't appear in the methane-band images (889 nm) because the bright aerosols are swamped by methane extinction. The 889 nm filter-averaged methane absorption coefficient is 24.1 inverse km-Am [*Young et al.*, 2002], using coefficients from *Karkoschka* [1998]. The optical depth along an arbitrary chord through an exponential atmosphere is given by

$$\tau = k\sqrt{2\pi RH} \quad (2)$$

where τ is the optical depth along the chord, H is the scale height, R is the minimum radius to the chord, and k is the extinction at R.

[25] If we assume (using values from *Lellouch et al.* [1989]) that the methane fractional abundance is 1.5% throughout the upper atmosphere and that the methane number densities are 3.58×10^{15} and 4.84×10^{14} for altitudes of 300 km and 400 km, respectively, then the extinctions due to methane at those altitudes are 0.003 km^{-1} and 0.0004 km^{-1}. Titan's scale height is around 60 km at those altitudes, which means that the optical depth due to methane absorption is 3.13 along a chord passing through 300 km and 0.45 along a 400 km chord. In contrast, the extinction in the 953 nm filter is about 15 times less than in the 889 nm filter, so the optical depths at 953 nm are 0.18 and 0.03 for 300 km chords and 400 km chords, respectively.

[26] We can also estimate the optical depths due to haze, assuming a haze extinction coefficient of 10^{-4} km^{-1} at an altitude of 400 km from *Rages and Pollack* [1983]. The haze optical depth along this chord will be 0.1 (or 0.7 at 300 km), and unlike the case with methane, the haze single scattering albedos are very high in the 889–1042 nm range. Note that a single WFPC2 pixel represents ~250 km at Titan, so the haze optical depth is thin once we look higher than 1.5 pixels above Titan's limb. The low optical depth is convenient, since it means that the albedo of the detached layer at a particular altitude is proportional to the optical depth (or extinction at R) of that specific line-of-sight chord. One could, in theory, plot the radial decrease in signal across the extended haze layer and determine the radial extinction profile, as we have attempted to do in Figure 6.

[27] From Figure 6, it is almost certain that the actual extended haze layer is not as broad as the deconvolved images show. The radial slope of the extended haze layer's brightness (or equivalently, its extinction) in Figure 6 yields a haze scale height of 152 km, much larger than the Voyager era scale height of 60 km [*Rages and Pollack*, 1983]. We can see the extended haze layer, but not at sufficient spatial resolution to characterize its vertical profile. Since an individual WFPC2 pixel is slightly larger than 250 km across, it's not surprising that we cannot resolve scale heights as small as small as 60 km with this data set.

5. Summary and Future Work

[28] By processing WFPC2 images of Titan, we have detected an extended haze layer that has not been seen since the 1981 Voyager encounters. Although the image processing is not currently good enough to quantify the extinction profile in the extended haze layer, it is sufficient to monitor the extended haze layer as it moves from south to north from 1994 to 2000. The PSFs generated by TinyTim are a good start. Our next step is to apply some techniques borrowed from the field of blind deconvolution [e.g., *Christou et al.*, 1999] to iteratively improve the TinyTim PSFs and get sharper WFPC2 reconstructions.

[29] If, as *Rannou et al.* [2002] have suggested, the gap in the haze distribution is due to pole-to-pole Hadley-cell

transport, then the observed extended haze layer migration may be evidence that aerosols are indeed produced under the subsolar point and quickly transported to the other pole. The Cassini encounter in 2004 comes about 2 years after the subsolar latitude minimum. Our expectation is that the extended haze at that time will reach from the south pole to the north, where there may be a polar hood of accumulated haze particles.

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