Stratospheric Haze Bands Observed in Cassini VIMS N. Kutsop[1] (nwk25@cornell.edu), P. M. Corlies[2], A. G. Hayes[1,3], S. Le Mouélic[4], J. I. Lunine[1], P. Rannou[5], S. Rodriguez[6], C. Sotin[4,7] and The Cassini VIMS Team [1]Cornell University, Ithaca NY, [2]MIT, Cambridge MA, [3]Cornell CCAPS, Ithaca NY, [4]LPG, Nantes, France, [5]GSMA, Reims, France, [6]AIM, Gif sur Yvette, France [7]JPL, Pasadena CA,

Introduction: The Visual and Infrared Mapping Spectrometer (VIMS) aboard the Cassini satellite made observations of Titan from 2004-2017. Images acquired at wavelength shorter than 600nm reveal dark bands in Titan's atmosphere, while images acquired at methane absorption channels show the bands as bright. We present our results on the seasonality, altitude, and production of these bands.

Data: VIMS consisted of two imaging spectrometers with 352 spectroscopic channels between .35 and 5.13 μm. Figure 1 (Right) shows the north polar annulus (**NPA**) observed on Titan flyby T96 (2013-12-01), and Figure 1 (Left) shows the equatorial annulus (**EQA**) observed on flyby T61 (2009-08-25). Both observations were taken at ~1.15 μm (which is a methane absorption channel) and have been processed to highlight the contrast of the atmosphere and the bright bands. Both the NPA and EQA show the same spectral characteristics, and are locally brighter or darker than the surrounding atmosphere at the same VIMS channels. This is largely true for all observations and flybys, except for observations of the NPA towards the end of the mission; we will discuss the implications of this below in ***Seasonality***.

For every observation of the NPA or EQA we determined the relevant pixel's location (latitude and longitude), viewing geometry (incidence, emission, phase, etc) and other ancillary information using the SPICE toolkit from NAIF. Using this information, we constructed transects along lines of longitude and analyzed the resulting curves of latitude vs brightness (I/F) for channels of interest. We found that the bands we observed in the images (Figure 1) presented as deviations in the otherwise featureless curves. We used the deviations to identify the bands spectrally. The definition used to identify the NPA or EQA is a concave deviation at ~500nm, and convex deviations at ~900nm and ~1150nm. Using these definitions, we made transects of Titan for the entire mission, binning the data every 10 degrees of longitude.

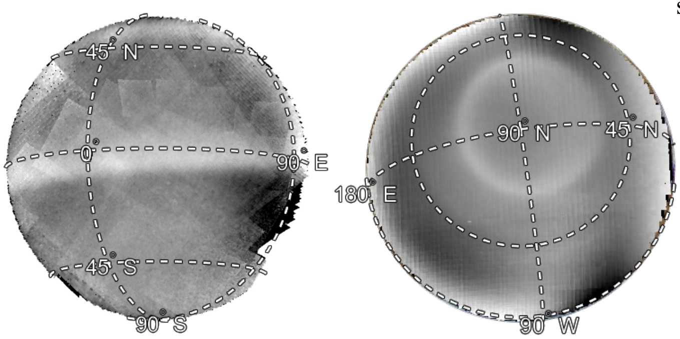

Figure 1: 1155nm mosaics with post processing. (Left) T061, 2009-08-25, .5 sidereal days after vernal equinox, (Right) T096,2013-12-01, 53 sidereal days after vernal equinox.

Haze: We acquired differential spectra of the bands by first removing the deviations from the transects. We then fitted a straight line to the gap, and subtracted this line from the deviation for all 352 channels. The differential spectra are negative at wavelengths shorter than 600 nm, with the darkest point occurring at ~500 nm. This suggests that the bands are either more absorptive than the surrounding atmosphere, or obscuring a backlit source of illumination. The differential spectra steadily increase to a maximum positive value between 850 and 1000nm. We see multiple peaks of decreasing intensity at wavelengths where methane absorbs. **We propose that this is consistent with a localized increase in high altitude haze.**

The dark feature short of 600nm is due to the haze obscuring Rayleigh scattering by the higher density nitrogen and methane in the lower atmosphere. As wavelength increases beyond 500nm, the effect of Rayleigh scattering from below diminishes and the contrast between annulus and atmosphere decreases. Further redwards, Mie scattering from the top of the haze dominates, inverts the contrast, and leads to a bright feature. The haze has the highest positive contrast at methane absorption wavelengths. There, most photons are absorbed in the atmosphere, especially at depth, while those photons that encounter the high altitude haze are scattered back to VIMS.

Seasonality: We investigated each transect and noted the location of the inflection point of any deviations matching our definition of the NPA or EQA. When the inflection points were plotted as longitude vs latitude, it was clear that a sinusoidal function could be fitted to them where the latitude, ϕ, is given by

$$\phi = O_{NP}\,cos(O_{PM} + \theta) + \bar{\phi}, Eq. 1$$

where θ is the longitude, O_{NP} is north polar offset, O_{PM}, highest longitude, and $\bar{\phi}$, mean latitude. We acquired the mean latitude for each flyby and plotted them vs their time of observation. This revealed a seasonal nature to the haze bands.

The EQA is visible for nearly the entire Cassini mission. The only times it does not appear are during the highly inclined orbits where Cassini flew over Titan's poles. The NPA, however, only becomes apparent around flyby T87 (2012-11-13) which is 40 sidereal Titan days after the vernal equinox (seasonal equivalent of late April). The NPA remains observable until end of mission in September 2017.

Similar to the EQA, the NPA is undetectable when Cassini moves from highly inclined orbits to equatorial orbits, but we suggest it remains present given subsequent detections during the next series of inclined orbits. Most of the northern inclined orbits did not begin until 30 sidereal days after vernal equinox, as the north pole was not well illuminated yet. This means that there is a degeneracy in whether the NPA is a seasonal feature or a constant feature which did have the appropriate conditions to be viewed. We propose that the NPA is a seasonal feature because its presence is similar to southern polar features observed by Roe 2002 [1] and Lorenz 2001 [2]. Observations made by the Keck observatory and HST in the early 2000s, revealed what has been called by others a south polar collar but here as the south polar annulus (**SPA**). The SPA appears as a bright band in Keck observations at 1158nm and as a dark band in HST at 336nm. This matches our spectral definition of the EQA and NPA.

The SPA is first observed in 1999 which would be about half way between autumnal equinox and winter solstice. When Cassini arrived at Saturn at 2004, no SPA was observed. Throughout our search we did not find any observations consistent with the SPA observed by Roe and Lorenz [1,2]. We suggest that between 2001 and 2004, the SPA disappeared as Titan entered southern summer solstice. As alluded to above we observed the spectral characteristics of the NPA start to diverge as Titan approached solstice. As time progressed the entire differential spectra shifted negative and while the brightest features shifted redwards. We propose that this is evidence that the haze bands descended through the atmosphere as summer approaches. The dark features bluewards of 600nm become darker as they are better able to obscure the Rayleigh scattering from below. The bright features become darker and move redwards, because the photons are scattered lower in the atmosphere. This causes fewer photons to be scattered and those that do must traverse a longer path length, allowing Rayleigh scattering to remove more short wavelength light. We suggest that this descent through the atmosphere is the first step to the NPA disappearing, which would mirror the seasonal behavior of the SPA.

Altitude: We determined the altitude of the annulus using a form of altimetry based on spectra. Methane is the primary absorber in Titan's atmosphere. Full opacity, $\tau > 1$, is reached at different depths, i.e. pressures, for different wavelength of light. Objects visible at one wavelength are assumed to be above the depth where $\tau > 1$. Likewise, when an object becomes undetectable , we assume that it is below that depth where $\tau = 1$. Using this technique and with our differential spectra and methane opacity measurements, we determined that the EQA and NPA are around ~200km high. We confirmed this measurement by triangulating the height and position of the annuli using multiple observations at varying viewing geometries. **At ~200km the annuli are in Titan's stratosphere.**

Discussion: While the NPA, SPA, and EQA are all stratospheric haze bands, they do not necessarily all have the same formation process. There are three hypotheses under investigation.

1. A circumpolar ethane cloud was detected by VIMS at the beginning of the Cassini mission during northern winter [3]. This cloud dissipated over the course of the mission as the north approached summer. As the cloud dissipated it could have left behind a ring of haze which had accumulated on its boundary. A similar process could happen in the south with the south polar vortex [4].
2. Titan has a 'detached' haze layer, first observed at ~300km. This haze layer is known to have previously been as high as 500km from 2005-2009. The layer descended and between 2012-2016 the haze layer was not visible [5]. In 2016 and 2017 the haze layer reappeared. These dates and the change that occurred are similar to the dates and changes for the NPA. The NPA could be a transition of the haze layer as it moves from mesosphere to stratosphere.
3. The annuli may be produced through wave-dynamical interactions, possibly similar to the hexagons seen on Saturn. Many possible explanations exist for Saturn's hexagon, and most of these include some form of Rossby waves [6,7]. Similar Rossby waves could act to trap or concentrate haze.

References: [1] Roe, H.G. et al. (2002) Icarus, 157, 254-258, [2] Lorenz, R. D., et al. GRL 28, no. 23 (2001): 4453-4456., [3] Griffith, C. A., et al. Science 313, no. 5793 (2006): 1620-1622. [4] Teanby, N. A., et al. Nature Com 8.1 (2017): 1-13. [5] West, Robert A., et al. Nature Ast 2.6 (2018): 495-500. [6] Sánchez-Lavega, A., et al. GRL 41.5 (2014): 1425-1431. [7] Yadav, R. K., & Bloxham, J. PNAS Sciences (2020).