Typeset using LaTeX **twocolumn** style in AASTeX631

A Temporal Analysis of Cassini/VIMS Limb Brightness Profiles of Titan from 2004-2017

Aadvik Vashist ,[1,2] Jason W. Barnes ,[2] and Gabriel Steward [2]

[1] *Stanford University; Stanford, CA 94305*

[2] *Department of Physics; University of Idaho; Moscow, ID 83844*

ABSTRACT

We analyze the evolution of brightness profiles from *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) spectral mapping cubes to gain insights into the vertical structure of Titan's atmosphere. Using low-phase angle observations from 2004-2017, we observe changes in the behavior of limb brightening transects with regard to wavelength and time. These transects can independently track the development of different atmospheric layers on a global level. We show that Titan's limb brightening depends on wavelength, and vary with time. A comparison of brightness profiles from the northern hemisphere and southern hemisphere supports existing analyses of asymmetry behavior. Limb observations of Titan's upper atmosphere presage existing observations of the lower stratospheric dichotomy, as characterized by Vashist et al. (2023). By using a combination of both observations, we are able to develop a greater understanding of the underlying seasonal dynamics of Titan's haze, specifically its vertical structure.

Keywords: Titan, Upper atmosphere, Seasonal phenomena

1. INTRODUCTION

2. OBSERVATIONS

As shown in Table 1, we analyze Cassini VIMS-V and VIMS-IR observations from 24 targeted flybys and 5non-targeted flybys, spanning the Cassini probe's 13 year operational period from 2004-2017. The VIMS instruments have been well characterized Brown et al. (2004), with the VIMS-V (Visual) channel of the using a two-dimensional array detector covering a spectral range from 0.30 to 1.05 µm with 96 distinct bands and the VIMS-IR (Infrared) channel using a one-dimensional detector covering a broader spectral range of 0.3 to 5.1 µm with 256 wavelength bands.

2.1. *Cube Selection*

We selected flybys using the following criteria: (1) simultaneous observations from both the VIMS-V and VIMS-IR instruments; (2) a low phase angle (¡30° preferred); (3) full-disk coverage with high limb visibility; (4) sufficient spatial resolution (200km/pixel); (5) sub-spacecraft longitude between 20°S and 20°N; and (6) sufficient time cadence so as to obtain a comprehensive distribution of measurements during the *Cassini* mission. It is important to note that during the latter half of the *Cassini* mission, the spacecraft was in a polar orbit, which limited the number of flybys that met the above criteria, leading to the selection of non-targeted flybys, expansion of criteria, and sparser temporal coverage.

Corresponding author: Aadvik Vashist
avashist@uidaho.edu

3. METHODS

3.1. *SRTC++*

3.2. *Image Processing*

Calibrated VIMS-V data was processed to remove any variations in vertical pixel arrangements. Since all cubes were full disks with limb visiblity, destriping was able to be performed using the sky pixels as a baseline from each vertical pixel line, eliminating a majority of the inconsistencies in the transects **cite the paper that talks about VIMS-V destriping here**. All post-processed data was human validated through a comparison of the original and processed images. There was no post-processing on calibrated VIMS-IR cubes, nor on any SRTC++ cubes. Known surface bands from **paper to cite on known Titan surface window wavelengths** were not included in the analysis to avoid contamination of the haze signal.

Limb profiles were sampled from flyby observations of Titan using a transect method. The center of the disk for each cube was determined by locating where the line normal to the stellar surface is collinear with the line of sight of the observer within each cube and determining where the emission angle would be 0. To maximize sampling density, images were upsampled 5x. Transects were sampled for various angles relative to North, aiming to sample the northern and southern hemispheres. As shown in **transect fig**, transects are selected based on the angle relative to the equator and the direction relative to East/West. We select two transects, one sampling the Northern hemisphere 30° North of the equator and the other 30° South of the equator. The choice of East/West facing transects is determined based on the viewing geometry, sampling data on the hemisphere that does not contain the terminator. Functionally, this is determined based on the hemispheric location of the point with the lowest angle between the incoming sunlight and

Table 1. North-South Boundary Observations

Year	Month	Cassini flyby	Sub-Spacecraft Latitude (°)	Spatial Resolution (km/pixel)	Phase Angle (°)
2004	10	TA	-15 N	108 km/pixel	13
2005	2	T3	-3 N	147 km/pixel	20
2005	10	T8	n/a	79 km/pixel	23
2005	12	T9	n/a	82 km/pixel	28
2006	2	T11	n/a	100 km/pixel	18
2007	5	T30	15 N	137 km/pixel	28
2007	5	T31	10 N	87 km/pixel	23
2007	6	T32	2 N	109 km/pixel	15
2007	6	T33	n/a	134 km/pixel	12
2007	8	T35	-3 N	127 km/pixel	27
2007	10	051*TI*[1]	14 N	207 km/pixel	26
2009	7	T58	-28 N	116 km/pixel	28
2009	8	T61	-7 N	142 km/pixel	14
2009	10	T62	-1 N	145 km/pixel	11
2010	4	T67	n/a	88 km/pixel	16
2011	4	T75	n/a	124 km/pixel	16
2011	6	T77	n/a	89 km/pixel	22
2011	12	T79	n/a	124 km/pixel	17
2012	1	T81	-8 N	107 km/pixel	23
2012	5	T83	-8 N	116 km/pixel	23
2012	6	T84	-14 N	119 km/pixel	28
2013	5	191*TI*[1]	-9 N	267 km/pixel	28
2014	4	T100	50 N	130 km/pixel	35
2015	7	T112	n/a	117 km/pixel	26
2015	11	T114	-1 N	99 km/pixel	26
2016	1	T115	-1 N	120 km/pixel	27
2016	12	255*TI*[1]	46 N	326 km/pixel	20
2017	5	273*TI*[1]	38 N	243 km/pixel	16
2017	6	278*TI*[1]	53 N	179 km/pixel	28

[1] non-targeted flyby of Titan

the normal line to the planetary surface. Given that the latitude of the atmospheric dichotomy is rarely the same as the solid-body equator, transect data that is within a pixel of the North-South Boundary location,as determined by **cite the paper that shows this (maybe ours??)**, is removed, including any data points between the boundary and the center of the disk. The result is two transects for each band of each VIMS-V and VIMS-IR cube.

3.3. *Quadratic Limb Darkening Law Regression*

To determine the magnitude of limb darkening and brightening within each transect, we fit the data using the known stellar Quadratic Limb Darkening Law (QLDL) from Kopal (1950); Brown et al. (2001).

$$\frac{I(\mu)}{I(1)} = \left[1 - u_1(1-\mu) - u_2(1-\mu)^2\right] \tag{1}$$

Where μ is the cosine of the angle between a line normal to the stellar surface and the line of sight of the observer leading to a scale from 1 to 0, one representing the center of the disk and 0 being the limb. $I(1)$ represents the intensity at the center of the disk. u_1 and u_2 are limb darkening coefficients. The limb darkening coefficients alone are not well constrained. So to measure the magnitude of limb darkening/brightening, we use $\frac{1}{I(1)}\frac{dI}{d\mu}\Big|_{\mu=0.5} = u_1 + u_2$. Regression used a Levenberg-Marquardt algorithm **maybe cite?** with no parameter bounds applied, though initial values for positive values indicate limb darkening, while negative values indicate limb brightening. Since the sampling density decreases with emission angle, limb pixels gained increased weighting. Resulting fits are compared to the original data in **quadrant fig**. Variations in accuracy are largely attributed to noise in the raw data and lower sampling density at higher emission angles.

Visually, the limb darkening is prevalent at lower, visible, wavelengths, while the limb brightening is more prominent at higher, near-infrared, wavelengths, though the wavelength where darkening and brightening transition seemingly evolves. The differences in limb darkening and brightening are logical when factoring the low albedo of haze at visible wavelengths and the increased haze-ratio at higher altitudes. Limb observations also reinforce existing knowledge of the north-south asymmetry's visual shift, with a strong hemispheric dichotomy seen in most bands.

3.4. *Compiled Analysis*

4. RESULTS

5. CONCLUSION

AV is supported by the Dyess Fellowship at the University of Idaho. JWB is supported by NASA Cassini Data Analysis Program grant 80NSSC19K0896. We also acknowledge support from the NASA/ESA *Cassini* project.

REFERENCES

Brown, R. H., Baines, K. H., Bellucci, G., et al. 2004, Space Science Reviews, 115, 111

Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., & Burrows, A. 2001, The Astrophysical Journal, 552, 699

Kopal, Z. 1950, Harvard College Observatory Circular, 454, pp. 1-12, 454, 1

Vashist, A. S., Heslar, M. F., Barnes, J. W., Hennen, C., & Lorenz, R. D. 2023, The Planetary Science Journal, 4, 118