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1. Introduction

Saturn and its satellites are currently of extreme interest to the scientific community because of the large amount of new information being brought to light by the Cassini-Huygens mission. The data from this mission regarding Saturn's satellites, especially Titan, is of interest because of Titan's many Earth-like attributes. Titan, which is both the largest and densest moon of Saturn, is like Earth mainly because of its atmosphere, especially as it is the only satellite in our system with more than a trace atmosphere. The atmosphere is composed of mostly N_2, varying between 94 and 98%, a substantial amount of CH_4 that varies between 1.8% in the stratosphere and 4.9% in the lower atmosphere, and large number of different hydrocarbons and nitrites formed by destruction of methane in the upper atmosphere.[i,ii] Analysis and modeling of radiative transfer in this atmosphere is significant because it reveals important information about the optical properties of the different layers of the atmosphere, which is an important insight when studying atmospheric composition and the dynamics of an active atmosphere such as Titan's. This report discusses the methods taken to model radiative transfer in the many layers of Titan's haze at a variety of wavelengths. Additionally, it comments on the visible changes that were found near August 2, 2009, Titan's vernal equinox[iii], while attempting to model the atmosphere at different points in time.

2. Background

The National Astrobiology Institute JPL-Titan Team, which mentor Dr. Robert West is a member of, is interested in aerosol formation and distribution in Titan's dense haze. The group is currently modeling the many layers of Titan's haze by looking at the radiative properties of the haze using a spherical shell model for radiative transfer, designed by Dr. Philip Dumont of JPL. The basis of the model is constructed using the data published by Tomasko et al.[iv] regarding the phase function, single-scatter albedo, and optical depth of the haze at different heights for different wavelengths. The code creates an atmosphere based on these original parameters, and then the parameters are modified to make it accurately model the data from the Imaging Science System, an array of two CCD cameras on board the Cassini satellite[v].

The radiative behavior in the stratosphere and mesospheric layers of the atmosphere is of major interest because it will give insight to the peculiar composition of Titan's atmosphere. The inner layers are well documented by data from the Huygens probe, but less is known about the molecular composition of the uppermost layers near the limb, or apparent edge of the disc. An especially interesting feature of Titan's upper atmosphere is a 'detached' haze layer that appears most prevalent in light wavelengths < 500 nm. This haze layer was originally thought to be a condensation region at a local temperature minimum as proposed by Liang et al. (2007)[vi], but also could be a product of non-volatile aerosols that form at a higher altitude. The particles in this hypothesis are monomers that aggregate and form this thin haze.[vii]

There has been speculation for over two decades now that Titan's atmosphere is going under large changes seasonally. Different brightness bands in the northern and southern hemispheres that can be seen using a methane filter appear to change in time, which has been proposed to be a seasonal change. It has also been suggested that the difference between the altitude of Titan's haze in data from Voyager and data from Cassini could be due to a seasonal atmospheric change. The analysis of the Voyager images showed that there was a detached haze layer at approximately 360 km, that the main haze terminated between 300 and 350 km, and that the shape of the atmosphere was slightly elliptical. All publications on Cassini data until this point have shown a spherical detached haze layer being steadily located at an altitude of approximately 505 km which is located proximately 20 km

Filter	λ_{eff} –NAC (nm)	λ_{eff}– WAC (nm)
UV1	264	-
UV3	343	-
BL2	441	-
BL1	455	463
GRN	569	568
MT1	619	-
CB1	619	-
RED	649	647
MT2	727	728
CB2	750	752
MT3	889	890
CB3	939	938

Figure 1: List of Cassini ISS filters used and their wavelengths

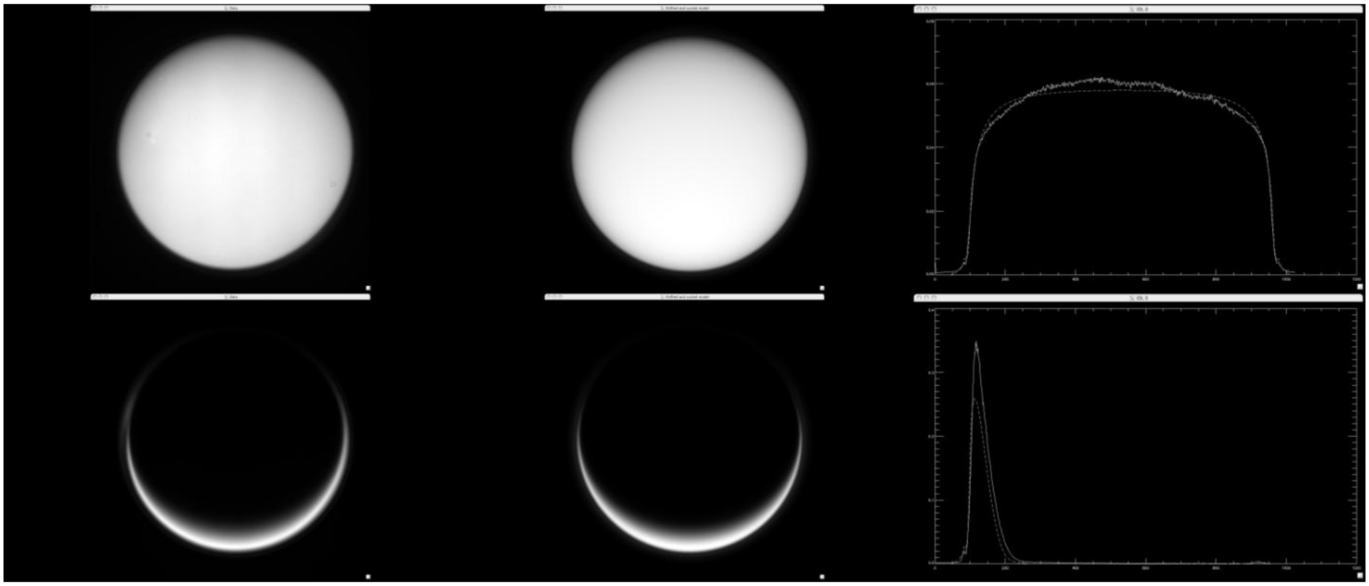

Figure 2: Across the top: Cassini NAC UV3 image from 2005 w/ phase angle of 10.1 degrees, scaled model image of the 10.1 degree phase image, and plots comparing brightness of each image across the middle of the disc. Across the bottom: Cassini NAC UV3 image from 2006 w/ phase angle of 146.8 degrees, scaled model image of the 146.8 degree phase image, plots comparing brightness of each image across the middle of the disc.

off of the moon's main haze everywhere except for where the detached haze disappears into the north winter polar vortex, located above 55 degrees latitude. However, until now this seasonal change has not been more than just speculation. Titan is slow rotating at about 16 days per rotation and takes roughly 29.46 Earth-years to make a full revolution of the sun; as such each of seasons is about 7 years long. Titan's seasons are similar to Earth's in the relative solar exposure of the north poles because Titan has an axial tilt similar to that of the Earth. Titan's northern hemisphere was in winter for the entire time that Cassini was relaying data on Titan until the equinox in 2009, which is significant because the flybys of both Voyager I and II occurred just after the previous spring equinox. Now that Cassini has started pushing into the same seasonal time frame as Voyager, it is possible to examine the possibility of a seasonal correlation to the difference in the Voyager and Cassini data.

The main motivation for this research is to create a model for the haze properties and vertical structure of Titan's atmosphere throughout the entire Cassini mission. This will benefit all future missions to Titan by allowing there to be a better understanding of the properties and behavior of this haze, and will also possibly give us a better understanding of the composition and behavior of all planetary atmospheres including our own.

3. Approach and Methods

3.1. Radiative Modeling of the Haze

The atmospheric modeling program created by Dr. Phillip Dumont for spacecraft navigation using gas covered planets was used to model the radiative transfer in Titan's atmosphere. Written in FORTRAN, the program is a spherical shell model composed of a series of spherical layers. Illumination by the sun imposes cylindrical symmetry on the radiation field, symmetric about the vector pointing in the direction of the Sun from Titan. The input for the code is a scattering profile that contains the number of layers, then number of global radial divisions that divide the layers into angular widths, the phase function at specific scattering angles, the depth of the layers, and the absorption and scattering coefficients for each of the layers. The code creates an atmosphere by first calculating a single-scatter result and then an iterative multiple scatter result from a scattering profile. The last part of the program is an estimator program that is used to generate a 1024x1024 pixel image of the model at a certain phase angle and distance. The estimator also has the ability to compare the images generated by the model to real data, and then with a Levenberg-Marquardt algorithm modifies the atmosphere's radiative properties, but this was not used by the group. The single-scatter solution for the haze becomes the input of the multiple-scatter algorithm. The multi-scatter algorithm uses a variable quadrature, or discrete sum, to integrate over the phase function input for each individual scatter at the intersection of a radial line with an atmospheric layer. The program iterates until the difference between the radiative outputs of two successive iterations differs by less than 1 percent at all of the angles relative to the Sun. This creates an array of I/F values, which stands for the ratio of scattered intensity to incident solar flux, that the estimator uses to create an image.

IDL 7.1 was used to analyze the images. A code provided for Cassini images called CISSCAL was used to calibrate the I/F values in the Cassini data, and then after calibrating and using a deconvolution code written in IDL by Dr. West, the images could be compared in IDL by plotting the I/F values of the brightness across a certain pixel column or row of the array.

The spectral data used to create the atmospheric profiles was taken mostly Tomasko et al. (2008) that analyzes the Huygens data. This paper provides very thorough documentation of the optical properties of the atmosphere below 144 km; it supplied the optical depth at all phase angles, and the absorption and scattering coefficients at different wavelengths in categories of below 30 km, between 30-80 km, and above 80 km. It is believed for the moment that all of the data given in Tomasko is relevant for the first 450 km of atmosphere out from the planet surface, but was slightly modified to fit the data in the analysis.

It was decided by the group to use a scale height of 65 km because it had worked well for Dr. West in the past. Further modifications to the initial input data included truncating the phase function for the multi-scatter code. The phase functions provided by Tomasko et al. (2008) are extremely highly peaked at very low scattering angles. The quadrature for this code is not fine enough to handle such a high peak, so it was decided to truncate the phase function at a value of 1 and replace the truncated scattering angles with the average value of the discrete sum over the truncated angles.

The data used from Cassini involved 12 different filters from the ISS camera that spanned a variety of wavelengths from the UV up to the higher IR wavelengths, as shown in Figure 1. For each filter, images were selected from the Cassini image database called CICLOPS,[viii] which stands for Cassini Imaging Central Laboratory for Operations. This is the database of all of the images ever taken by the ISS, but for this project only picture of Titan in full view in each image. The images are binned by filter, phase angle, and year take when being acquired for this project. Also, original 12-bit uncompressed images are preferred, but not always available for certain years or phase angles, in which case LS8B mode, which converts an image to its least significant 8 bits, lossless 12-bit to 8-bit compression, and 2x2 summation modes are all acceptably converted images. Lossy conversion and 4x4 summations are two examples of image compression types that are not used in this project. By using the database search, a significant number of images (about 10, three to four for each of the “2004-2006”, “2007-2009”, and “2010” year dependent sub-bins) which should give a good, diverse representation of the angles within each 30 degree phase angle bin. This project is initially focused on the images taken with the Narrow Angle Camera of the ISS because it has a less distorted view of the limb, but images from the Wide Angle Camera will be used to fill in binning gaps.

3.2. Changes Occurring Near Vernal Equinox

It was found while modeling the atmosphere at a 934 nm wavelength that when the model matched pre-2008 data well it was with a much larger than Titan for some of the post-2008 images. This motivated an investigation of the radius and overall geometry of Titan as it changes in time. To investigate this, another group of images were collected from CICLOPS that gave a full disc view of Titan and a clear view of the limb and the detached haze. First the geometry of these images was analyzed to find the width of each pixel on Titan. Then these images were imported to IDL and using a program written in IDL by the group, the detached haze was fitted to a circle. This, combined with the image geometry, gave the group an accurate estimate for the location of center of the Titan and a good estimate (within 7%) of the distance of the haze from the surface. Afterwards, a further investigation was done to show the eccentricity of the shape of Titan’s haze in time. Eccentricity is a measure of how non-circular an ellipse is. Given that the semi-major axis of the ellipse is “b” and the semi-minor axis of the ellipse is a, the eccentricity of an ellipse is given by[ix]:

$$\epsilon = \frac{\sqrt{b^2-a^2}}{b}. \tag{1}$$

By fitting an ellipse to a few of the images acquired for studying the radius, the group was able to study the change in the eccentricity of the haze in time as well.

4. Results

4.1. Radiative Transfer Model of UV3

After finishing modeling the change in the detached haze radius over time, the group was able to successful begin modeling the radiative transfer at the 343 nm wavelength. Giving focus to the matching the model to the data near the limb, the I/F values were modeled to within less than 5% difference for the atmosphere above 250 km for two images: one, N1496586265_1, that was taken in April 2005 and shows Titan from 1.147E+06 km away with a 10.1 degree phase angle, and a second, N1525327324_1, which was taken in March 2006 and shows Titan from 1.206E+06 km away with a phase angle of 146.8. The

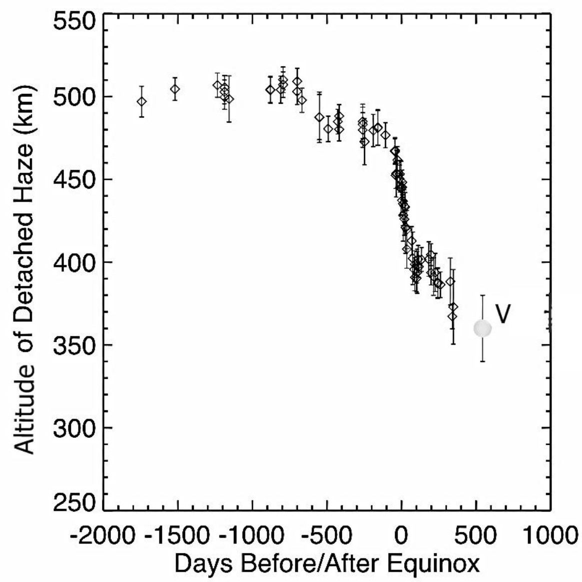

Figure 3: This figure shows the altitude of the detached haze relative to the spring equinox on August 2, 2009. The diamond points are all Cassini ISS data from the NAC. Appended here and labeled with a "V" is the altitude at the equator of Titan's haze in Voyager 2 image c43996.24, from August 25, 1981, and it is given relative to the previous spring equinox on February 28, 1980. This the same image that was analyzed by Rages and Pollack (1983).

model was fitted by modifying the scattering and absorption coefficients manually without the estimator program.

4.2. Change of the Haze in Time

After re-centering and finding the radius of over 80 images that spanned the last seven years of the Cassini timeline, all of which were full-disc images of Titan that showed the detached haze, the data quite conclusively points to the rapid collapse of the upper atmosphere around the spring equinox. The detached haze remains between 20-30 kilometers off of the edge of the main haze for the entire time period, but both the main haze and the detached haze decrease in altitude. The brightest part of the detached haze decreased in altitude from approximately 505 km, which was the height of the haze from the first images in 2004 through 2007, to as low as 375 km in 2010. This 130 km decrease in altitude started as early as the beginning days of 2008 and it is not certain that it has stopped yet, now with us well into 2010, but the majority of the collapse took place very rapidly in a span of only about 400 days around centered on the equinox. At the equinox, the detached haze was nicely in between the current maximum and minimum values for haze altitude at approximately 440 km. The radius of the image taken by Voyager 2 and analyzed Rages an Pollack (1983) is around 360, which matches up well with the rest of the data.

Furthermore, it was found that the atmosphere did not fit a prefect sphere near the equinox. The eccentricity of the moon ranged from about .1 to .37, and the data shows that Titan's shape was most elliptical right near the equinox.

These observations are both in agreement with the analysis of Voyager I & II data done by Rages and Pollack (1983), which until now did not match up with the analysis of Cassini data. These results were unexpected and will provide very important constraints on models of Titan's stratospheric chemistry, haze microphysical processes, and dynamics and circulation models

5. Discussion

Modeling the radiative transfer using the Dumont codes required more modification of the spectral data than was originally expected. The Tomasko et al. data did not fit the radiative transfer models very well when unmodified, especially in the outer layers. This result is understandable because the data was sampled from a very specific point in the atmosphere near the equator, where the Huygens probe descended, and because all of the raw data was taken below 150 km. This means is that the exponential fall off of the optical depth and therefore the brightness above 144 km is not actually as uniform as was originally predicted. A continuation of this study will likely calculate the single scatter albedo and the optical depth in the upper atmosphere and be able to more accurately model this behavior. From that, the group and associated groups that do General Circulation Models of Titan will be able to more thoroughly examine the types and sizes of particles that occupy the upper atmosphere.

The observations of the haze altitude collapse and

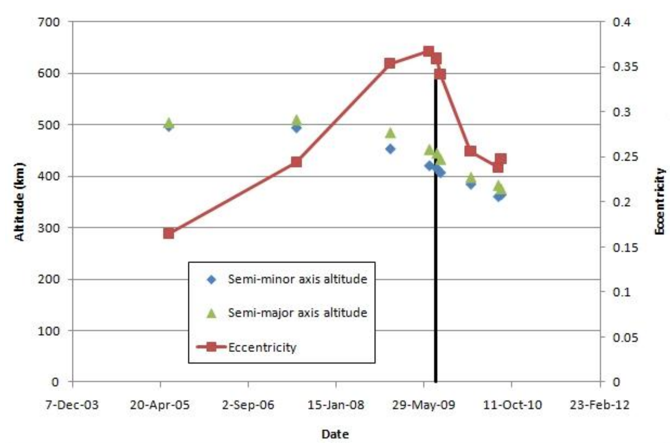

Figure 4: The squares connected by the line shows the trend of the eccentricity of Titan's atmosphere over the span of the Cassini mission. The vertical line represents the spring equinox on August 2, 2009. The triangles represent the semi-major axis and the diamonds represent the semi-minor axis of the eccentricity at that date.

the eccentricity change in time were unexpected and are very important for two reasons. Firstly, these observations are both in agreement with the analysis of Voyager I & II data done by Rages and Pollack from over 25 years ago, which until now did not match up with the analysis of Cassini data. This disagreement between the Rages and Pollack paper and the Cassini data was unsettling because there didn't appear to be any source of agreement between the two analyses. Porco et al. (2004) proposed that there could be a seasonal change in the atmosphere[x], but not only is this not predicted by any models, but Lavvas gave a strong argument against seasonal change explaining the difference between the Cassini and Voyager data[xi]. Secondly, these results will provide very important constraints on models of Titan's stratospheric chemistry, haze microphysical processes, and dynamics and circulation models. If this result does in fact show a seasonal change in

6. Conclusions

The observation of the collapse of the haze is a very important achievement and will have a large constraint on the future models of Titan. The next step for this project is to combine the two parts of this project and create a model that can reproduce the radiative transfer of Titan at any of the Cassini ISS wavelengths and over the entire time span of the Cassini mission.

8. Acknowledgments

I would like to thank my mentor Bob West and Phil Dumont for their infinite patience with me and all of the help that they gave me with my project and with my understanding of the physics behind radiative transfer in Titan's haze.

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