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Stellar Occultation Studies of Saturn's Stratosphere I: Imaging Mode

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ABSTRACT

This is a very rough draft intended to serve as an outline of the paper I want to have ready to present at DPS 2023. In this paper I will describe Cassini VIMS's suite of stellar occultation experiments of Saturn's atmosphere, and how they were reduced to recover and clean the spectral signal of the stratosphere occulting the background star. I will describe each unique imaging-mode experiment. During each imaging-mode experiment, Saturn enters the field of view, altering the background level and requiring a model of the planet's limb to correct this out. As the planet moves through the field of view, the star's image (smaller than a pixel) moves due to refraction through Saturn's atmosphere, complicating star-finding. These complications were addressed thanks to PRF scans taken by the Cassini team, and the analysis described in the Methods section. These imaging-mode experiments help us calibrate and understand the bulk of the data, which was taken in occultation-mode. Imaging-mode data has a larger field of view (context and calibration) at the expense of a slower frame rate (radial resolution). The bulk occultation-mode experiments and their preliminary analysis is presented here (maybe), with a more in-depth dive into the chemistry revealed left as future work. These spectra are colored by molecular absorption in Saturn's atmosphere (atmospheric chemistry), the radial gradient of the index of refraction (atmospheric temperature-pressure profile), and potentially mie scattering from suspended particles (atmospheric haze).

Keywords: Saturn, Photochemistry, Cassini, VIMS, Seasons

1. INTRODUCTION

1.1. *Saturn's Atmosphere: Theory and Current Understanding*

Pre-*Cassini* observations of Saturn's temperature show a peak in seasonal variation at around 3 mbar (Orton & Yanamandra-Fisher 2005), the region that the VIMS stellar occultation data probe. CIRS observations by Flasar et al. (2004, 2005); Fletcher et al. (2007) confirm this. Our proposed analysis can provide far better altitude resolution than the CIRS results in this critical region. Furthermore, the CIRS results are derived from thermal emission in the methane band at 8µmand cannot easily disentangle variations in temperature from variations in methane mixing ratio. We expect methane abundances also to depend on latitude and season as described by Moses & Greathouse (2005) and Fouchet et al. (2009). The proposed analysis will allow us to recover temperature profiles and methane abundances *independently of each other* at various latitudes and at seasons spanning almost half of a Saturnian year.

The chemical abundance profiles calculated in Moses & Greathouse (2005) match the "methane cycle" described in Strobel (1969). Methane diffuses up through the stratosphere to the homopause, slowly dropping in abundance through the region of the stratosphere to which VIMS occultations are sensitive. Far above this region of the stratosphere, methane undergoes photodissociation and is converted to higher-order hydrocarbons which diffuse back down to the troposphere where they are converted back to methane. The gases diffuse from their source to their sink via turbulence- or wind-driven eddy diffusion. The rates of diffusion, production, and destruction of these gases determine the shape of the abundance profiles through the stratosphere seen in figure 1.

As noted by Fouchet et al. (2009), important byproducts of these multiple profiles will be a better determi-

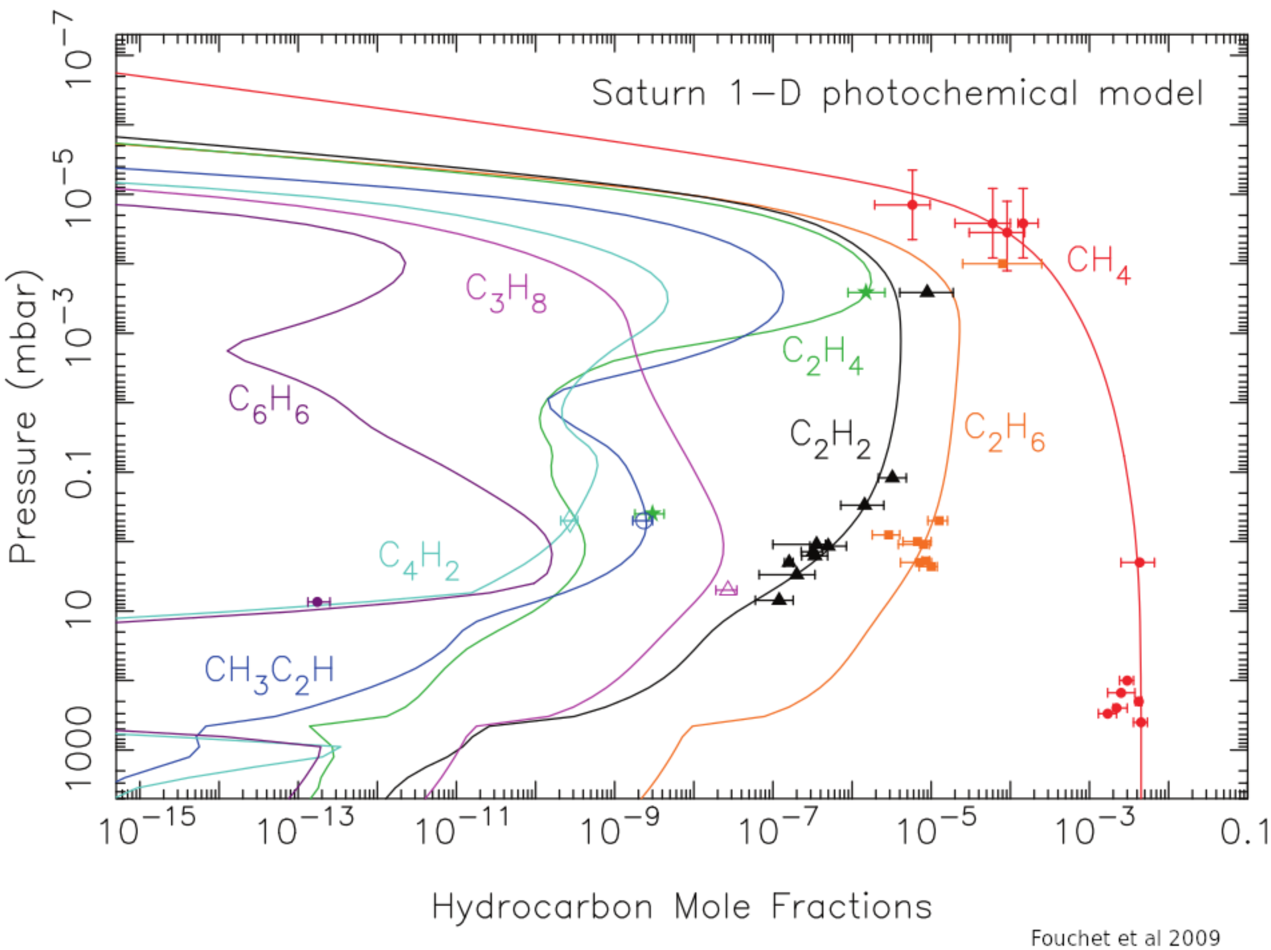

Figure 1. Figure taken from Fouchet et al. (2009). Hydrocarbon mole fractions as a function of pressure in Saturn's upper atmosphere as derived from the "Model C" 1-D steady-state photochemical model of Moses & Greathouse (2005). The solid curves represent the model profiles for the individual hydrocarbons (as labeled), and the symbols with associated error bars represent current infrared and ultraviolet observations. Methane is created in the troposphere and diffuses upwards to the homopause and the thermosphere where it is photochemically destroyed. Ethane and acetylene are produced at around $\times 10^{-4}$ mbar and diffuse down to the troposphere where they are converted back to methane. This is the methane cycle described in Strobel (1969)

nation of the altitude of the CH_4 homopause on Saturn (which is known to be quite variable with latitude from UV occultations Koskinen & Guerlet 2018). This is a function of the rate of photochemistry, which destroys CH4 in the upper atmosphere (Fouchet et al. 2009), and the speed of zonal winds in the stratosphere which distort the shape of the planet through the centrifugal force (Merritt & Nicholson 2019).

Photodissociated methane is partially converted into ethane on its way to becoming aerosols composed of higher order hydrocarbons. Chemical abundances in the stratosphere impact the thermal profile of the entire atmosphere since trace gasses are the major absorbers of radiation from the sun and Saturn's blackbody emissions from lower levels. The proposed analysis will constrain both the methane and ethane mixing ratios, giving us insight into seasonal variations in photochemistry and eddy-diffusion rates that we can compare to models such as those described in Moses & Greathouse (2005).

Photochemistry also leads to aerosol production. Although not very spectrally active in our observations, aerosols are thought to be chemically important as a factor in cloud formation because they sediment downwards to serve as cloud-condensation nuclei for condensible volatiles in the troposphere (Fletcher et al. 2018). We will constrain photochemistry and eddy-diffusion rates through a direct measurement of the relative mixing ratios of methane to ethane, which will help future investigators understand aerosol production in the thermosphere and cloud formation processes in the convective regions of the troposphere. We will measure these abundances with high radial resolution over the course of nearly half of a Saturnian year at a multitude of latitudes thanks to *Cassini*'s long-lasting mission in the Saturn system.

Finally, uncertainties in the production and optical properties of photochemical haze are a major stumbling blocks in current hot-Jupiter exoplanet atmospheric models and retrievals, as they are thought to be the cause of the flattening of the transit spectra of gaseous exoplanets (Fraine et al. 2013). Through providing a ground-truth understanding of the atmosphere of one of our local giant planets whose atmospheric chemistry is also photochemically driven, our analysis will help future studies constrain the atmospheres of these exciting bodies that we will soon be able to probe in greater detail with the James Webb Space Telescope, ELT-class ground-based telescopes, and other future telescopes.

1.2. *The Data: A Part of the Suite of Cassini Stellar Occultation Studies*

During the 13-year Cassini mission, the spacecraft observed over 100 occultations of stars by Saturn using the Visual and Infrared Mapping Spectrometer (VIMS) instrument. These occultations probe Saturn's atmosphere between pressures of $\approx$20 μbar and $\approx$5 mbar. Extinction of light from these stars is driven primarily by differential refraction and molecular absorption by hydrocarbons (chiefly CH_4 and C_2H_6). We have proposed to tackle three scientific projects using these data: (1) to verify the seasonal and latitudinal temperature maps of Saturn's stratosphere generated by the Cassini Composite Infrared Spectrometer (CIRS) by Fletcher et al. 2007 at higher radial resolution, (2) to measure the altitude of the methane homopause from the dropoff of methane abundance with altitude, and (3) to test theoretical models of Saturn's photochemistry and eddy-diffusion rates (Moses & Greathouse 2005). Our results for Saturn's atmosphere should complement similar analyses of VIMS solar occultation data for Titan by Maltagliati et al. (2015) and Bellucci et al. (2009).

A handful of these $\approx$100 occultation observations were observed through a series of small-frame images instead of a single spatial pixel pointed at the star's initial location on the sky. These imaging-mode occultations provide a chance to directly observe the stars' refraction through the outer layers of Saturn's atmosphere and constrain the relative importance of differential refraction to other sources of attenuation in the photometry of an occultation. This is an important calibration for the higher-radial-resolution occultation-mode data, for which the image of the star much more quickly gets refracted out of the field of view. This paper focuses on these imaging occultation experiments and relevant instrumental calibrations.

TODO: Describe each of the six useful imaging-mode occultations. Two are 8x8 low-res. Two are 16x6 hi-res. Two are 16x4 hi-res. Describe geometry, vperp, and the angle that the star's image gets refracted relative to the X axis. Put all of this in a table, maybe include a figure.

2. DATA REDUCTION

The data reduction requires four major steps.

First comes initial background subtractions and 5-σ clipping to mask out erroneous points (one experiment has a cosmic ray strike that messes up centering and flux calibration).

Second is locating the center of the star in each frame as it is refracted across the Field of View. This is complicated because the PSF of a star is smaller than a pixel in the X direction. A two-step centering process described in two subsections below. The first step is to use PRF scans to map subpixel sensitivity. The second step is to use the relative brightness of neighboring pixels to calculate the subpixel stellar center location.

Third is correcting out a limb model of background light from Saturn. Using the star centers, and knowing that the stellar image tracks the limb of the planet, we know where the limb of Saturn is. Using rows of pixels far from the star image, we calculate the variable background associated with Saturn's limb.

Fourth is using the subpixel sensitivity variations and the stellar centers to calculate the "true" flux of the star, including light that falls in the gaps between pixels.

2.1. *initial background corrections*

Task 1

2.2. *Center Finding via Subpixel Sensitivity*

Tracking the center of a star in a VIMS image is a difficult task because the PSF of the star is less than one pixel. Still, the star is rarely centered in a pixel, and so centering can be achieved by looking at how much light spills into the neighbors of the brightest pixel. Fortunately, the Pixel Response Function (PRF) is well-defined for the single VIMS spatial pixel as a function of the angle between the center of the pixel and the star. This has been done by slewing the spacecraft so that the star AlpOri (Betelgeuse) raster-scans across the pixel. From these, we can calculate the theoretical relative brightnesses of the pixels on either side of the brightest pixel relative to the brightest pixel, and compare this to the measured value in the VIMS frame.

First, we must determine which two pixels share the most starlight. To do so, we:

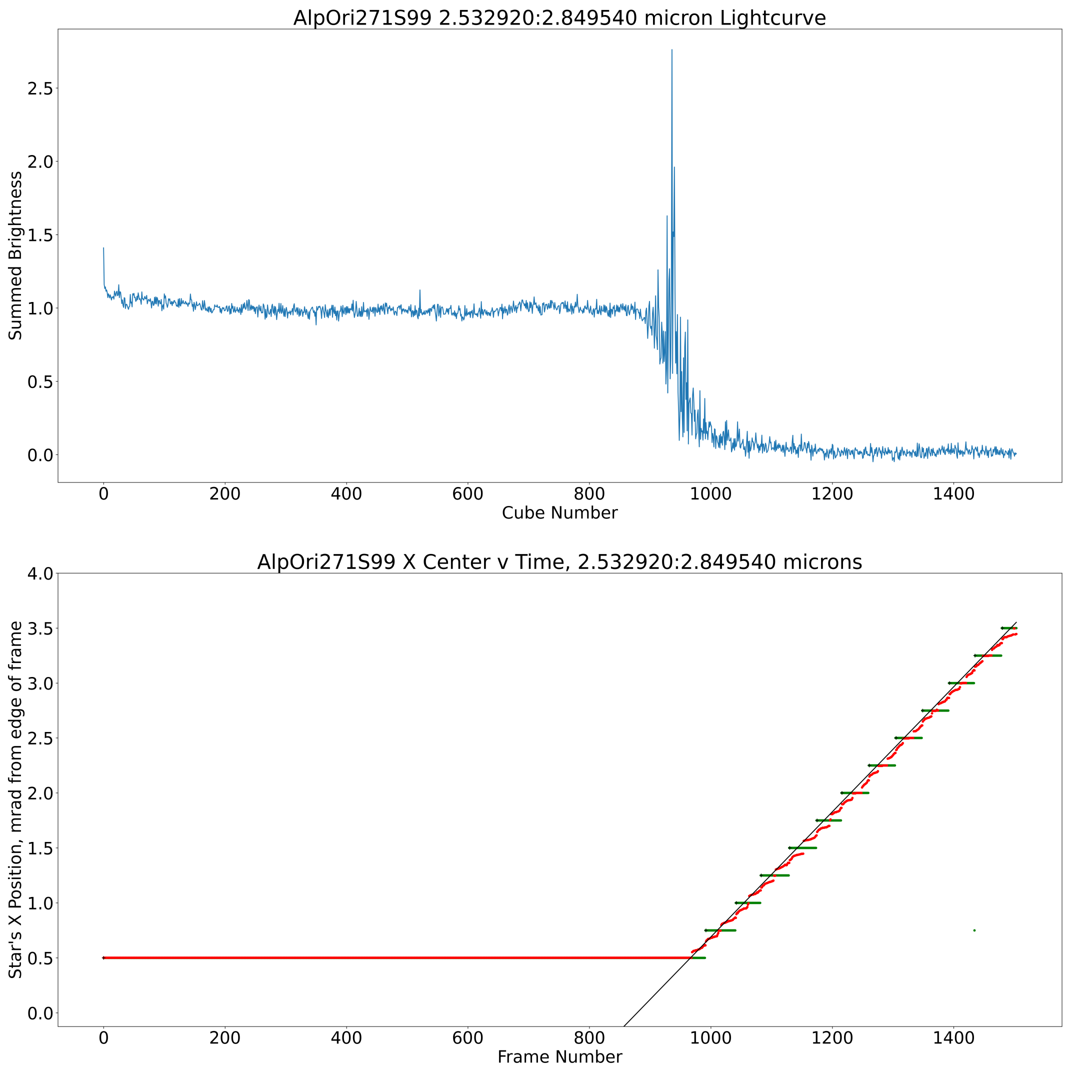

Figure 2. Lightcurve and centering results for an occultation of AlpOri (Betelgeuse) on orbit 271, observed in the 2.7 μm continuum band. The top plot displays the flux dropping and twinkling through the atmosphere. The bottom plot displays the pixel that the majority of starlight in (green), subpixel centering using the light spilling into a neighboring pixel (red), and a comparison with a line of slope matching the spacecraft's velocity perpendicular to the planet's limb (black). This is one of four types of plots produced by the code.

1. integrate over a continuum bandpass to improve signal to noise (e.g. 2.53-2.85 microns)

2. perform a boxcar smoothing in time (usually 10 frames)

3. record the brightest pixel for each resulting timestep

4. locate "transition times" when the brightest pixel changes from one timestep to the next

5. at each timestep select the brightest pixel and the brightest pixel on the other side of the nearest "trans ition"

We measure the direction to the star by taking the ratio (R_{data}) of the measured flux in these two selected pixels. We compare this ratio to the same ratio calculated from the PRF scans $R_{scans}(t)$ at each time step t. We calculate the value of $t = t_0$ for which $\chi^2 = (R_{data} - R_{scans}(t_0))^2$ is minimized, and then calculate $\theta(t_0)$ which is the offset of the star from the center of the pixel at t_0.

This metric has many properties which make it useful. Theoretically, it should be monotonically increasing or decreasing as the star moves steadily in pixel position. For PSFs smaller than a pixel, there will be a plateau at zero where there is no light observed in the neighboring pixel. Away from this plateau (near the pixel boundaries) we have the best sensitivity to the position of the star. At metric values $R = 1$ the center of the star's PSF straddles the boundary with the neighboring pixel and we have the most sensitivity.

The current version of the code performs fits in each direction independently, and using manually-selected PRF scan track numbers. A planned improvement is to fit both simultaneously, which will allow the algorithm to self-select the best track for each direction.

After this step, we have occultation profiles in the same form as the occultation-mode data. This ends the imaging-mode specific portion of the code. The following two subsections describe code that will be run on all occultation data.

2.3. *creating and correcting out limb model*

Task 2

2.4. *calculating total observed flux*

Task 3

3. RESULTS

Can the flux observed in continuum wavelengths be described by refraction alone, or will there be haze absorption that we will need to correct out of the occultation-mode data? Can we see a feature at 2.7 μmindicating an observation of ring rain? Preliminary Methane-Ethane abundances? Seasonal and latitudinal variations?

4. CONCLUSIONS

In conclusion, we have done some cool science.

Thank you Phil for helping me return to graduate school.

Facilities: Cornell and Cassini

Software: numpy, scipy, matplotlib, pysis, etc

APPENDIX

A. GORY DETAILS

Here we present the gory details of how we did science.

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