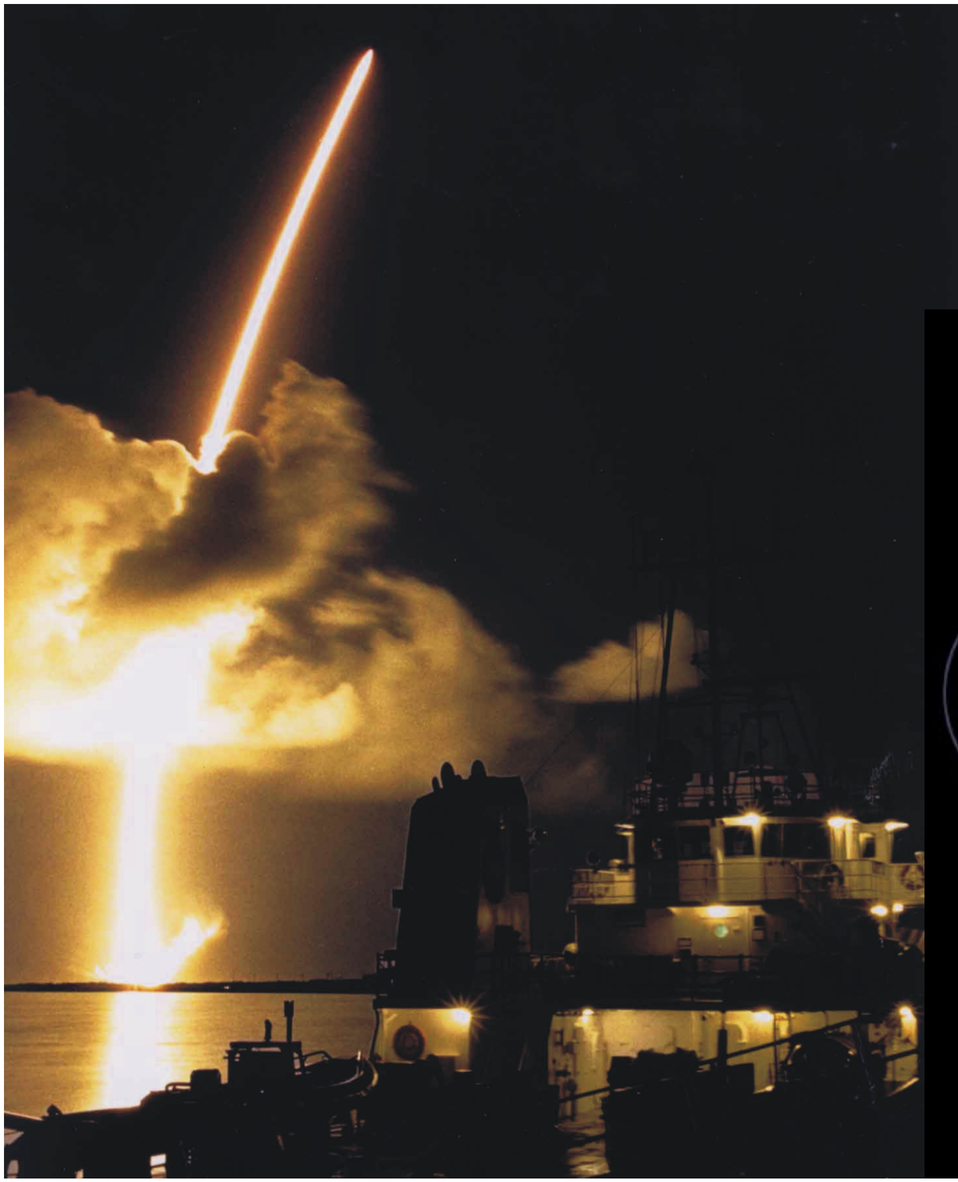
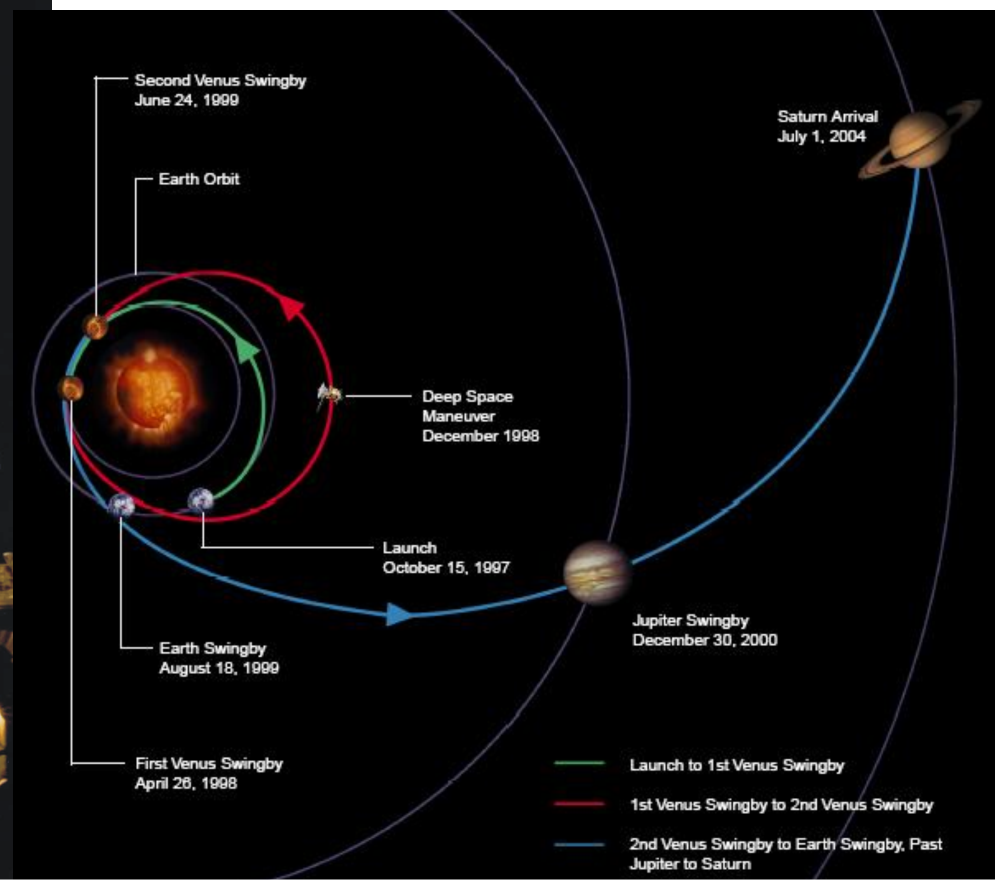
UV spectroscopy of the Saturn System: implications for composition, history, life.

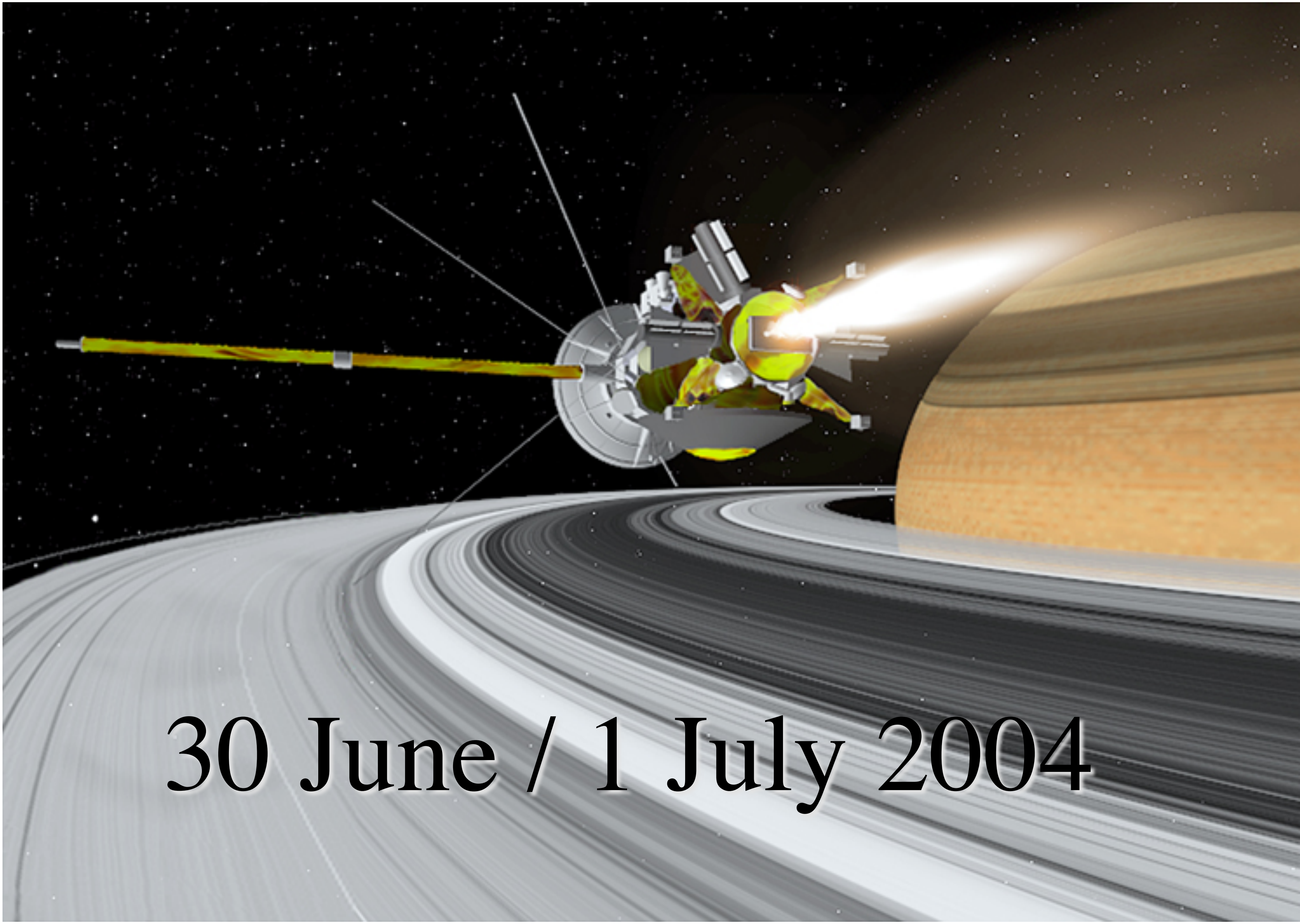
LW Esposito
LASP
23 October 2010

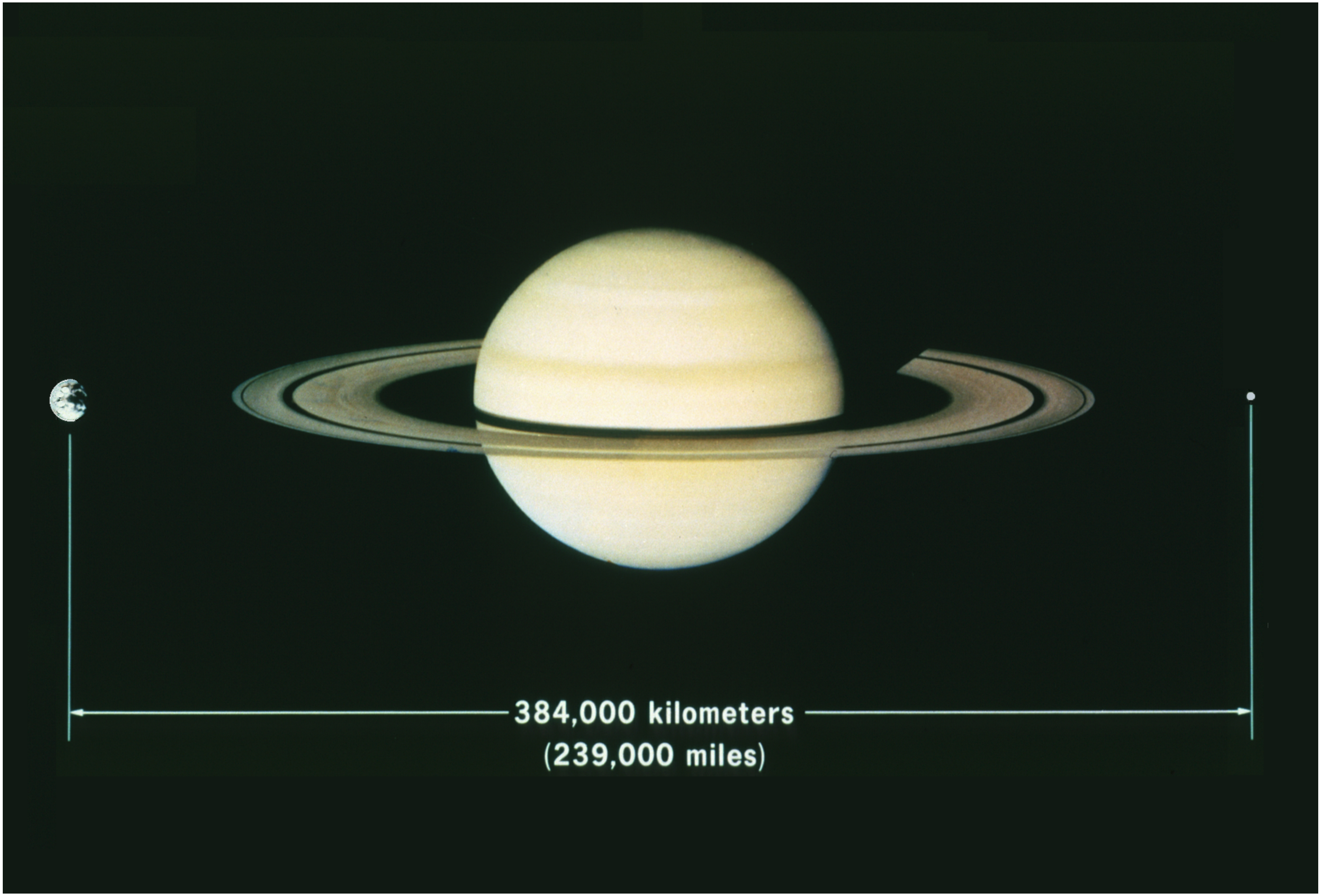
Launched on October 15, 1997 from KSC



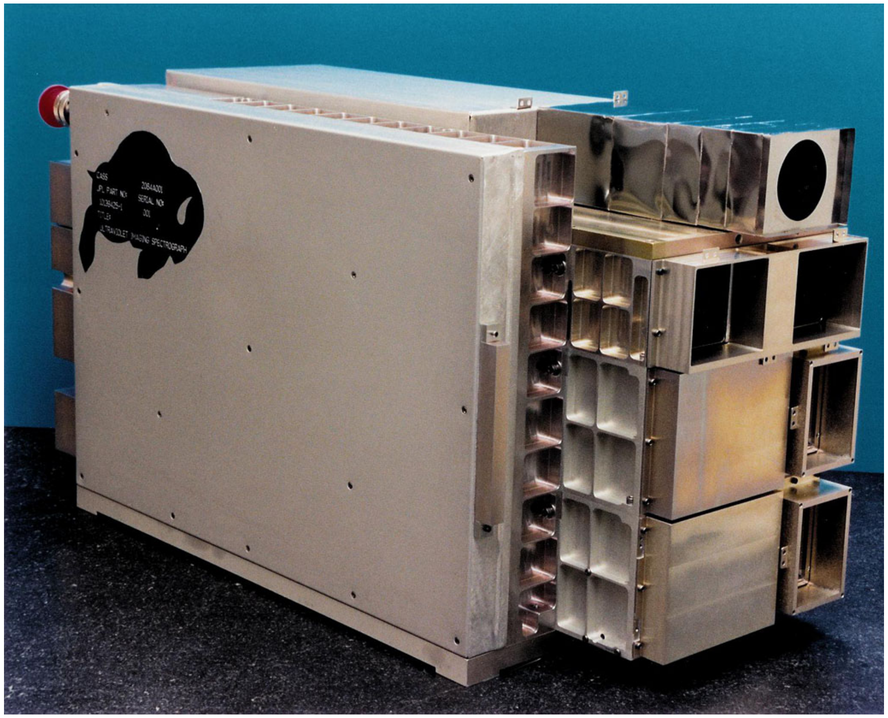
7 Year cruise on Venus-Venus-Earth-Jupiter Gravity Assist trajectory




30 June / 1 July 2004


384,000 kilometers
(239,000 miles)

UVIS Characteristics



UVIS has 4 separate channels

For stellar occultations we use:

- **Far UltraViolet (FUV)**
  - 1115 to 1915 Å
  - 2D detector: 1024 spectral x 64 one-mrad spatial pixels
    - Binned to 512 spectral elements
  - 5 sec integration time
- **High Speed Photometer (HSP)**
  - 2 or 8 msec time resolution
  - Sensitive to 1140 to 1915 Å
- Hydrogen-Deuterium Absorption Cell (HDAC) not used

For solar occultation we use:

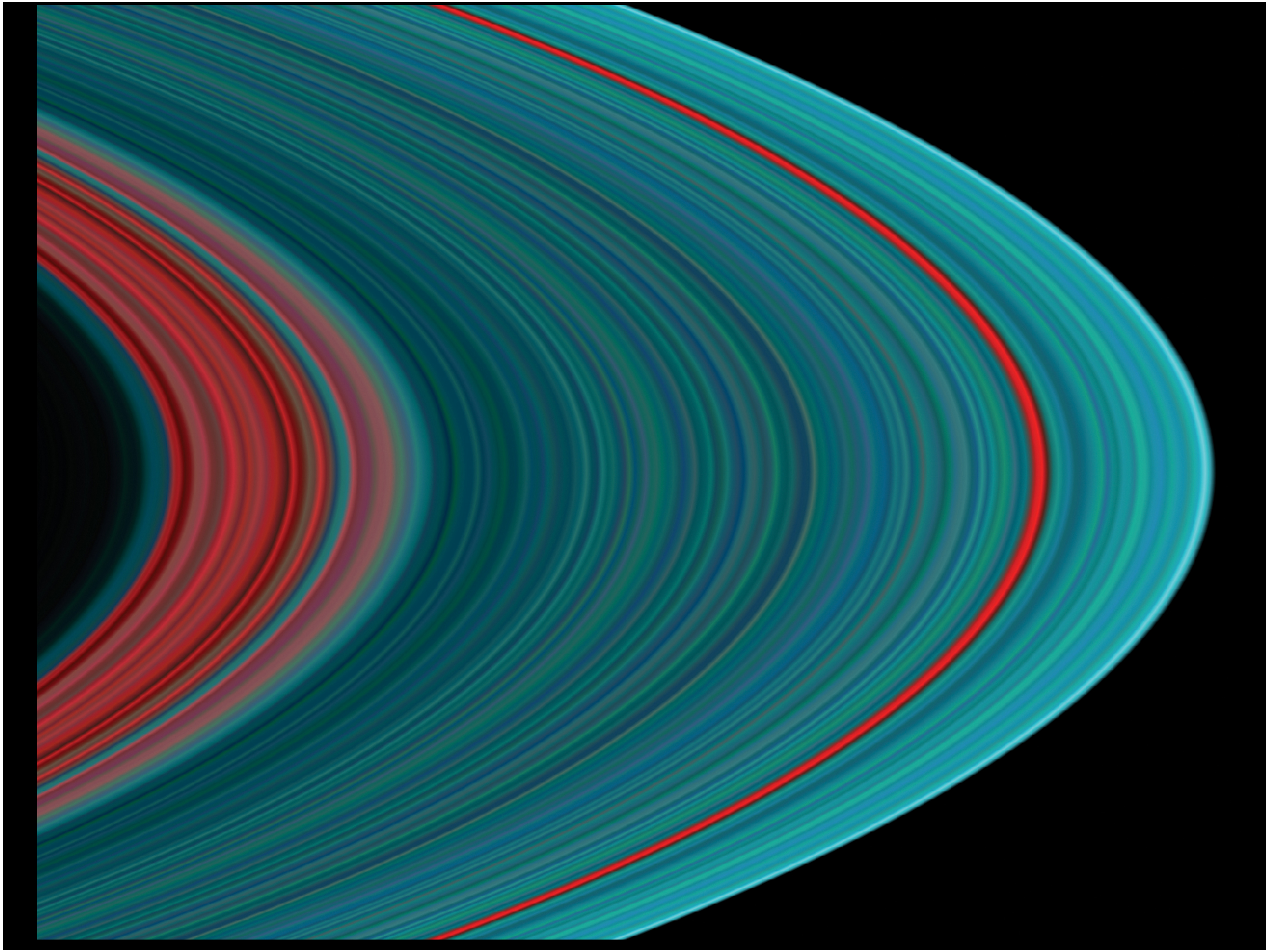
- **Extreme UltraViolet (EUV)** solar port
  - 550 to 1100 Å
  - 2D detector: 1024 spectral x 64 one-mrad spatial pixels
  - No spatial information because signal from sun is spread across the detector (deliberately)
    - Spatial rows 5 - 58 binned to two windows of 27 rows each
  - 1 sec integration

Spectra: Pedagogic Difficulties

- Spectra are basically squiggly lines
- Spectra provide detailed info, not big picture
- Interpretation involves physics and chemistry

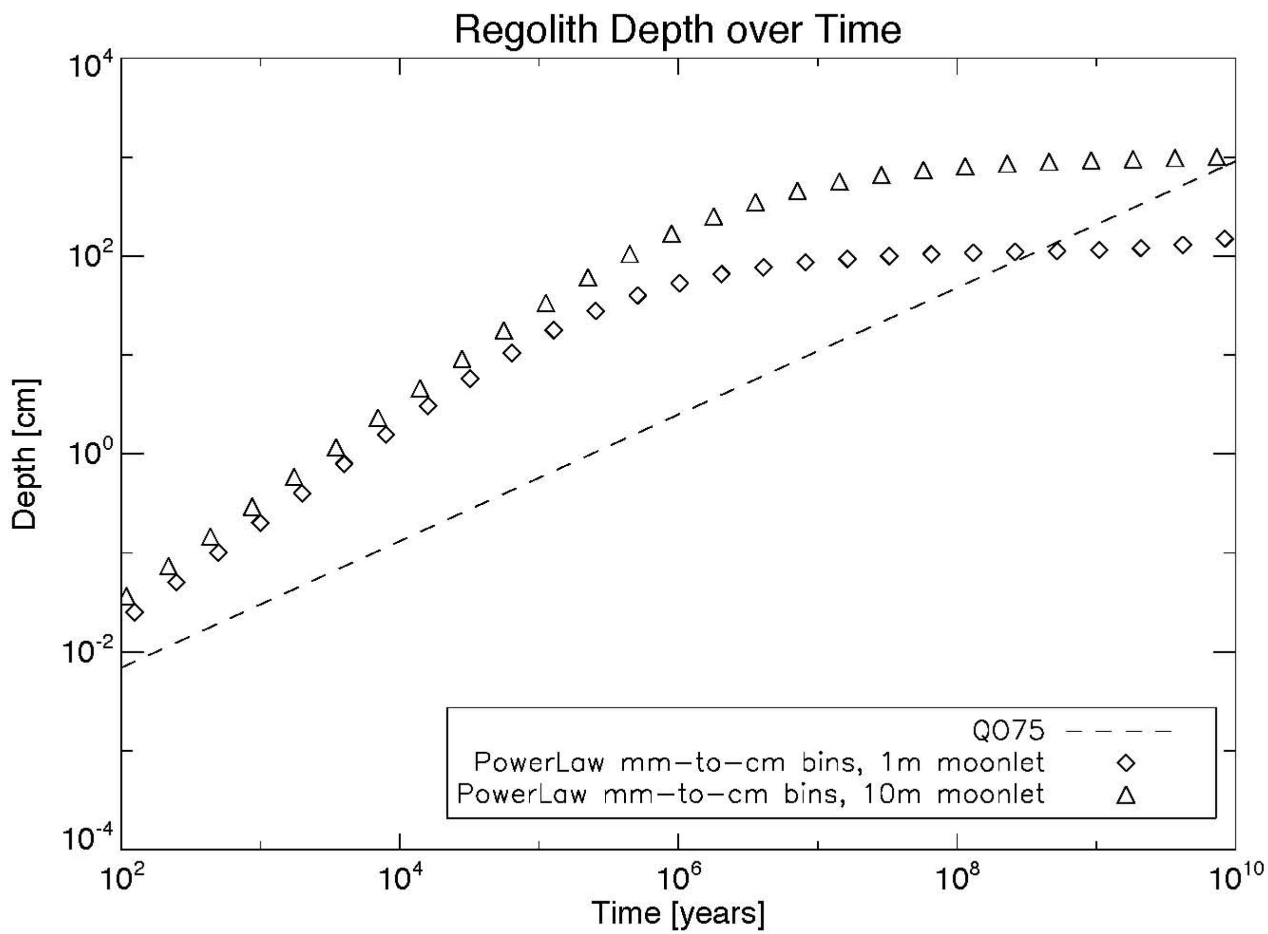
Solutions

- Convert to false color images
- Example: composition and history of Saturn’s rings

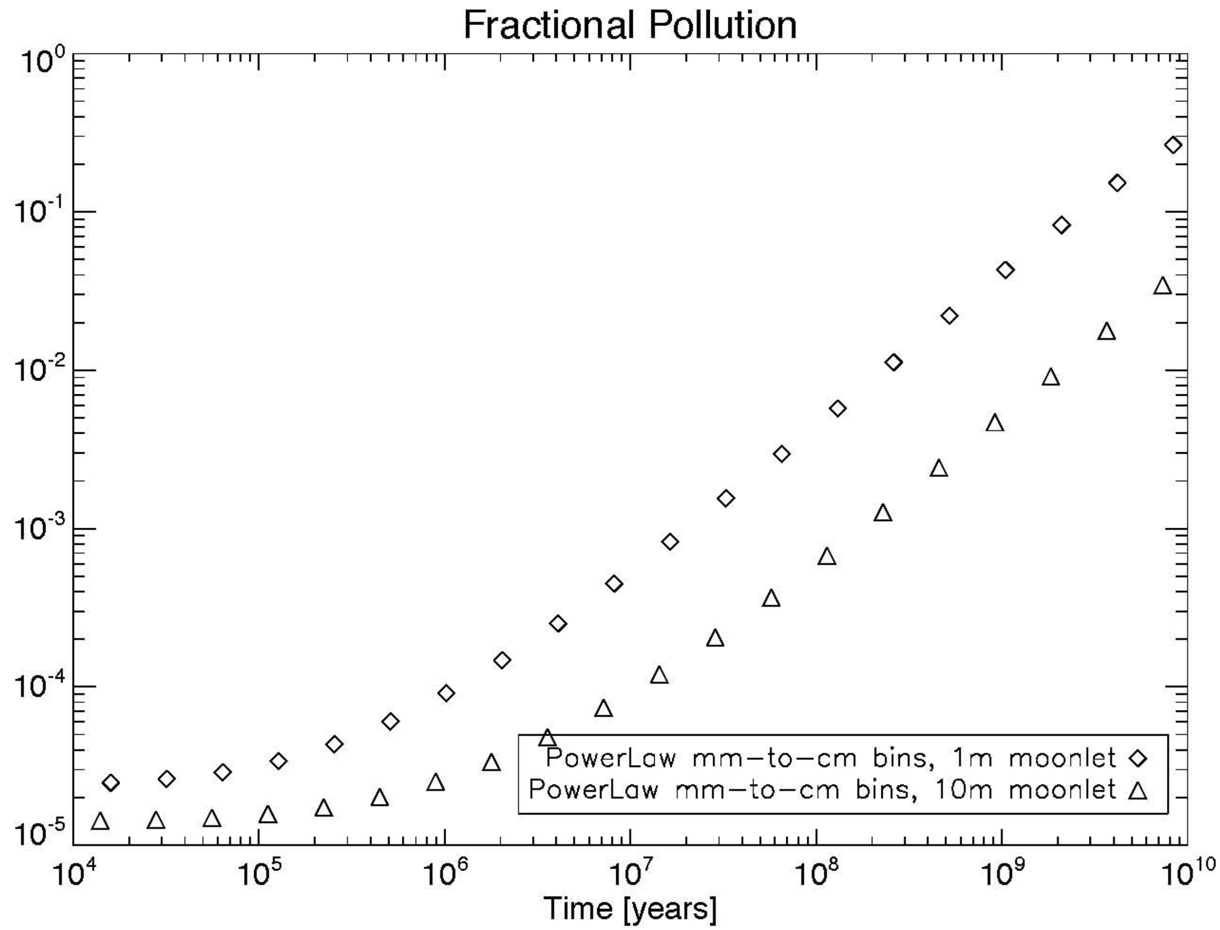


Math Models of Spectra

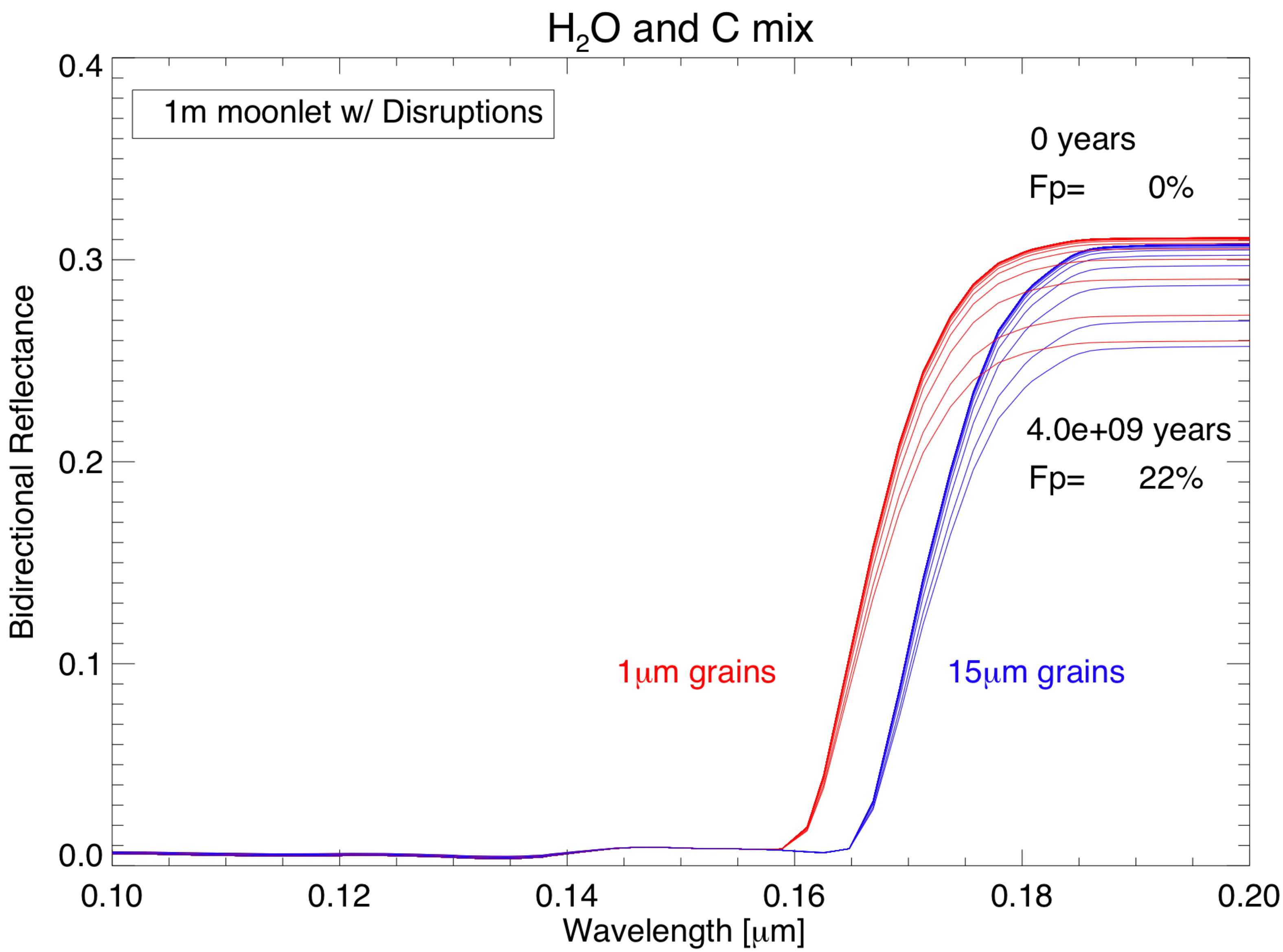
- Computer simulates physical situation (e.g., ring history)
- Compare computer results to spectroscopy
- Adjust parameters to fit spectra
- Interpret observations (e.g., age of rings)



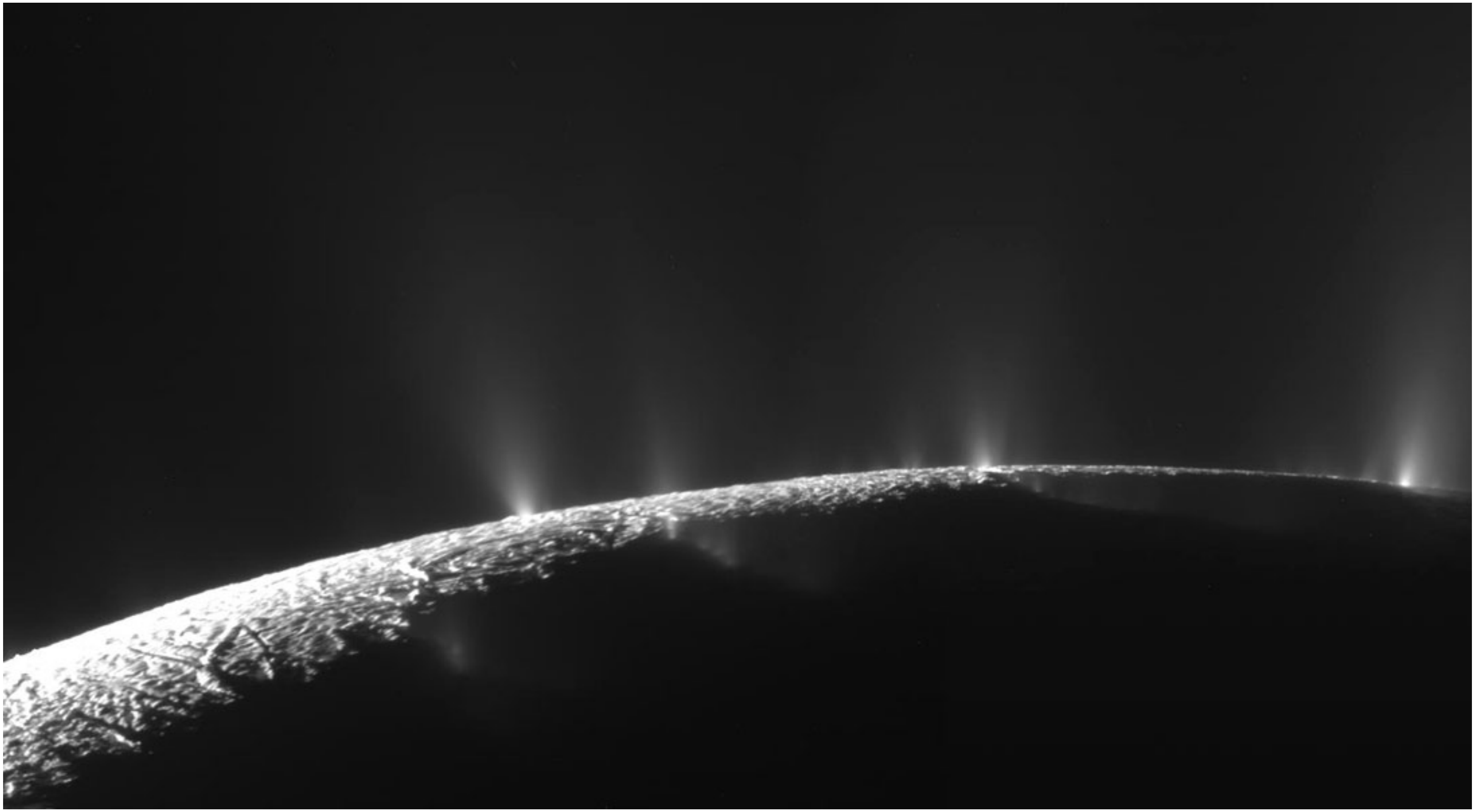
Larger ring particles grow deeper regoliths



10 meter ring particles reach 1% pollution in 2×10^9 years



H2O and C mix
1m moonlet w/ Disruptions
0 years
Fp= 0%
4.0e+09 years
Fp= 22%
1μm grains
15μm grains
Bidirectional Reflectance
Wavelength [μm]
0.0
0.1
0.2
0.3
0.4
0.10
0.12
0.14
0.16
0.18
0.20



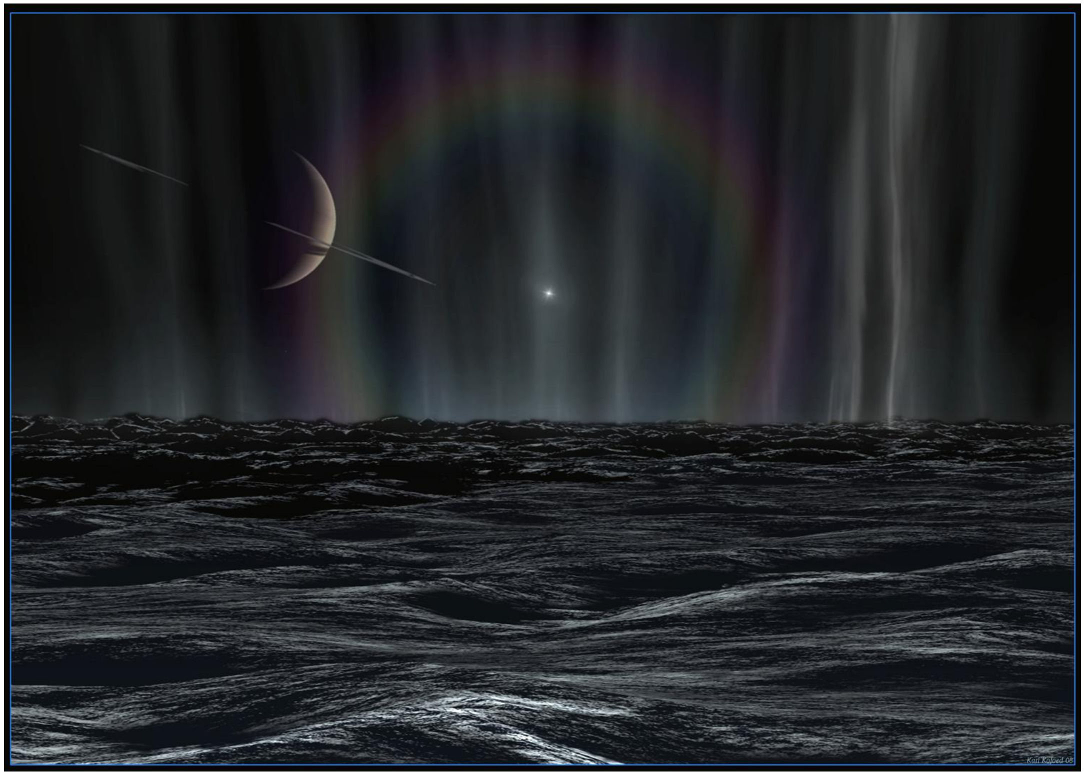
Enceladus studies

- Use stellar and solar occultation technique
- Interpret physical and chemical properties of geysers

Three UVIS Observations of Enceladus' Plume

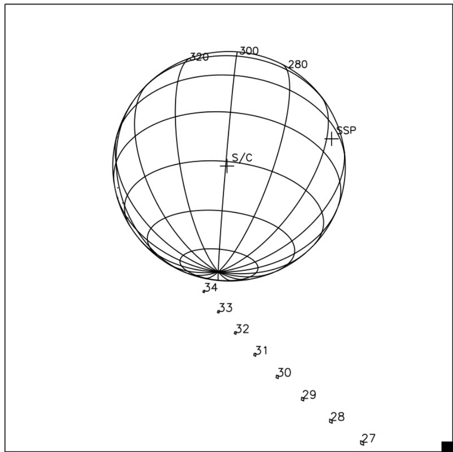
- UVIS observes occultations of stars and the Sun to probe Enceladus' plume: Composition, mass flux, and plume and jet structure

- Feb. 2005 - lambda Sco
  - No detection (equatorial)
- July 2005 - gamma Orionis
  - Composition, mass flux
- Oct. 2007 - zeta Orionis
  - Gas jets
- May 2010 - Sun
  - Composition, jets

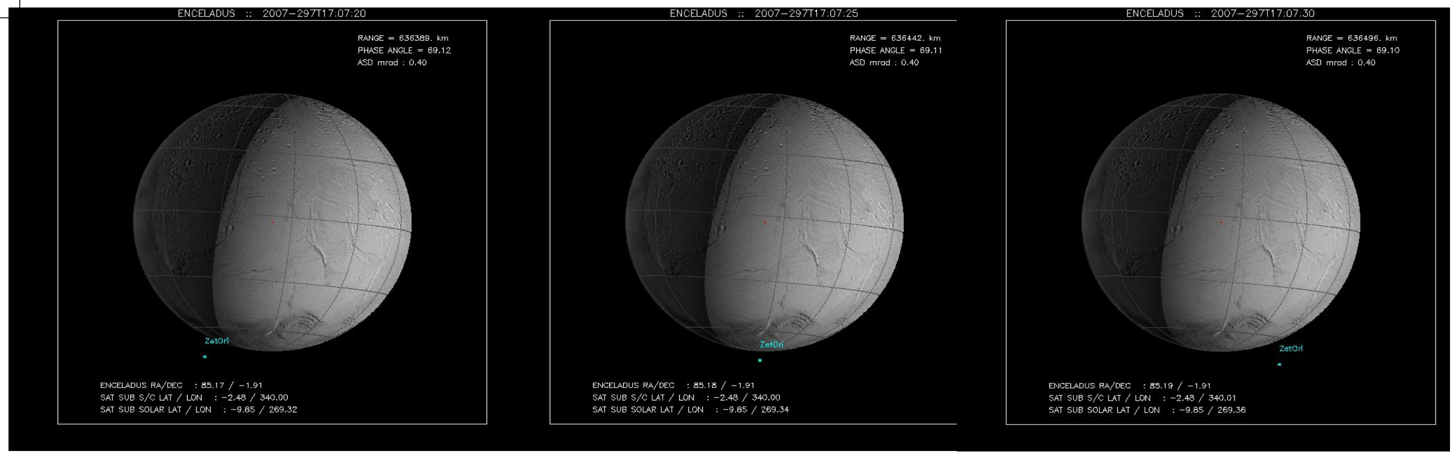


The Occultation Collection

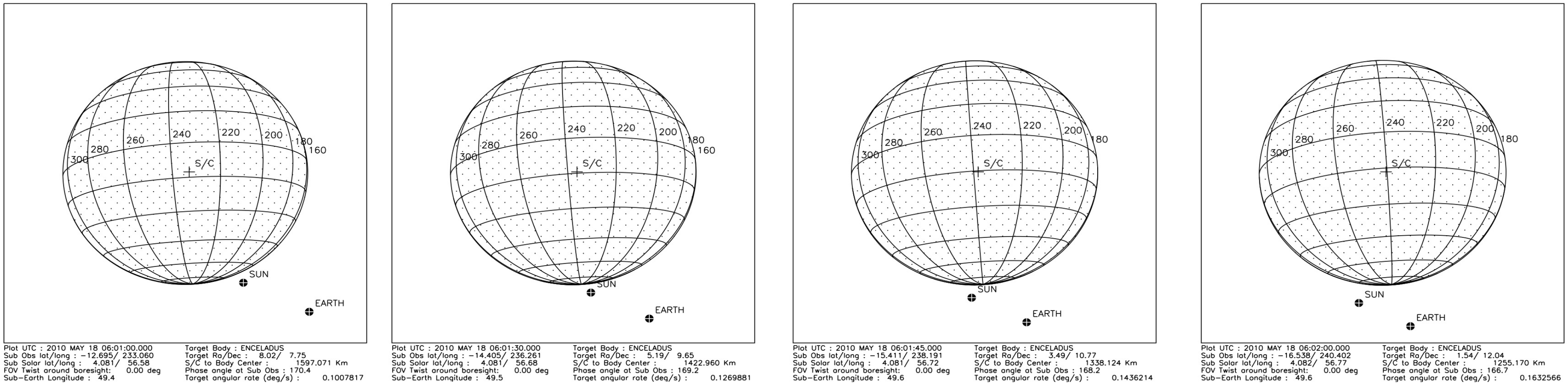
2005 - gamma Orionis Occultation



2007 - zeta Orionis Occultation



2010 - Solar Occultation



2005 - gamma Orionis Occultation

(Bellatrix)

Key results:

- Dominant composition = water vapor
- Plume column density = 1.6 x 10^{16} /cm^2
- Water vapor flux ~ 180 kg/sec
- Results documented in Science, 2006

Vertical cut through plume

2007 - Zeta Orionis Occultation

(Alnitak)

Key results:

- Average column density = 1.5 x 10^{16} cm^{-2}
- Max column density = 3.0 x 10^{16} cm^{-2}
- Gas jets detected correspond to dust jets
- Results documented in Nature, 2008

Horizontal density profile

18 May 2010 - Solar Occultation

Two science objectives enabled by solar (rather than stellar) occultation:

1. Composition of the plume

   New wavelength range: EUV

2. Structure of the jets and plume

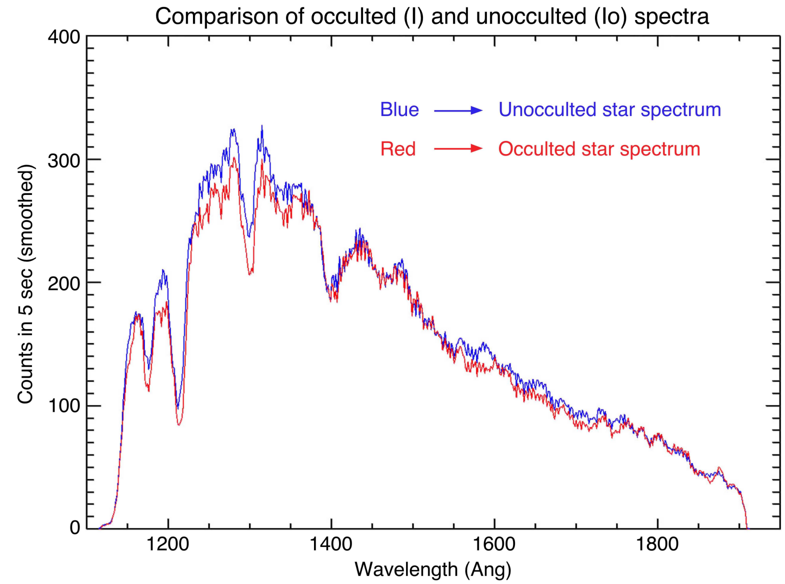
   Higher time resolution

Plume: FUV Results from Stellar Occ's

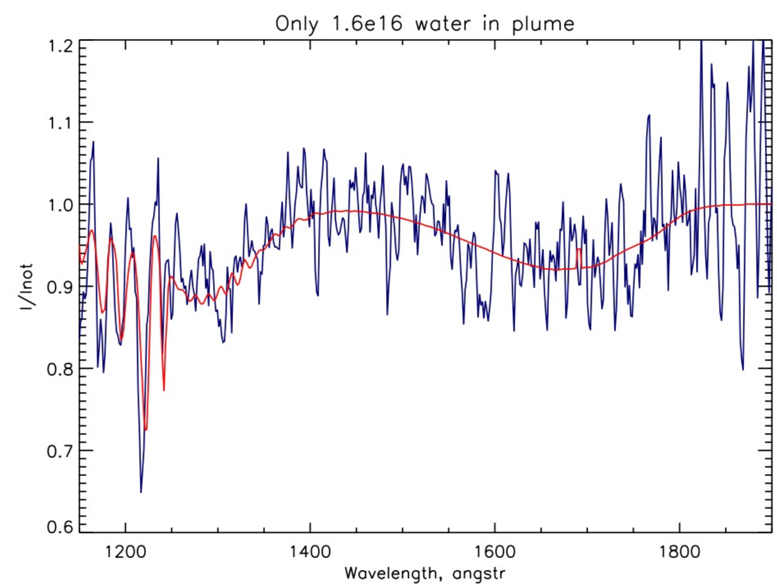
- Absorption is best fit by water vapor
  - 2007 best fit average column density = 1.5×10^{16} cm^{-2}
    - Error bar: +/- 1.4×10^{15} cm^{-2}

- Comparison to 2005 at 15 km altitude
  - 2007 peak column density = 3.0×10^{16} cm^{-2}
  - 2005 = 1.6×10^{16} cm^{-2}

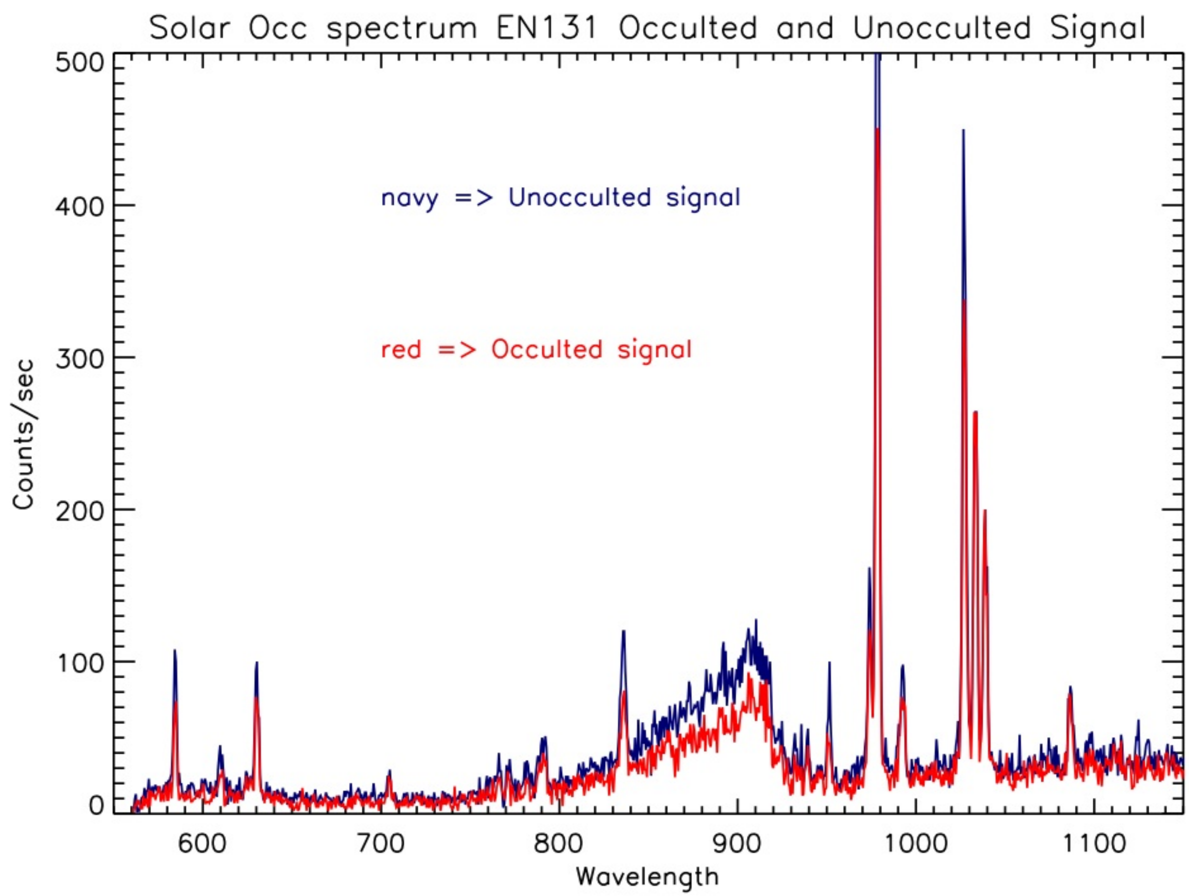
- No detection of CO
  - formal 2-σ upper limit is 3.6×10^{14} cm^{-2} corresponds to mixing ratio with H_2O of 3% and thus excludes 3% CO in the plume at the 2 sigma level



I/I_0



2010 EUV Spectrum from Solar Occultation



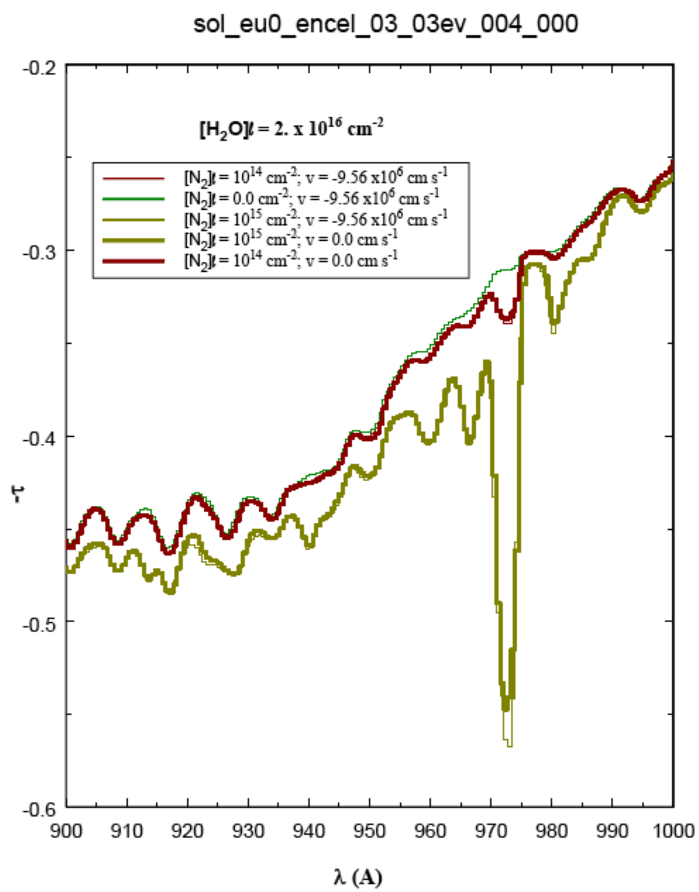
Navy is unocculted solar spectrum, with typical solar emissions
Red is solar spectrum attenuated by Enceladus' plume

Composition

- H_2O and N_2 have diagnostic absorption features at EUV wavelengths
- The primary goal was to look for N_2, on basis of INMS detecting a species with amu=28

- No N_2 (upper limit = 3×10^{13}, so < 0.3%)
  - AMU = 28 detected by INMS is not N_2
  - It is not CO in the plume (or UVIS would have seen it in our stellar occs) or it is < 3%

Nitrogen feature at 97.2 nm not detected



Predict

- N_2 feature at 97.2 nm fortuitously coincides with strong lyman gamma emission so lots of signal available
- Very sensitive test!

Actual

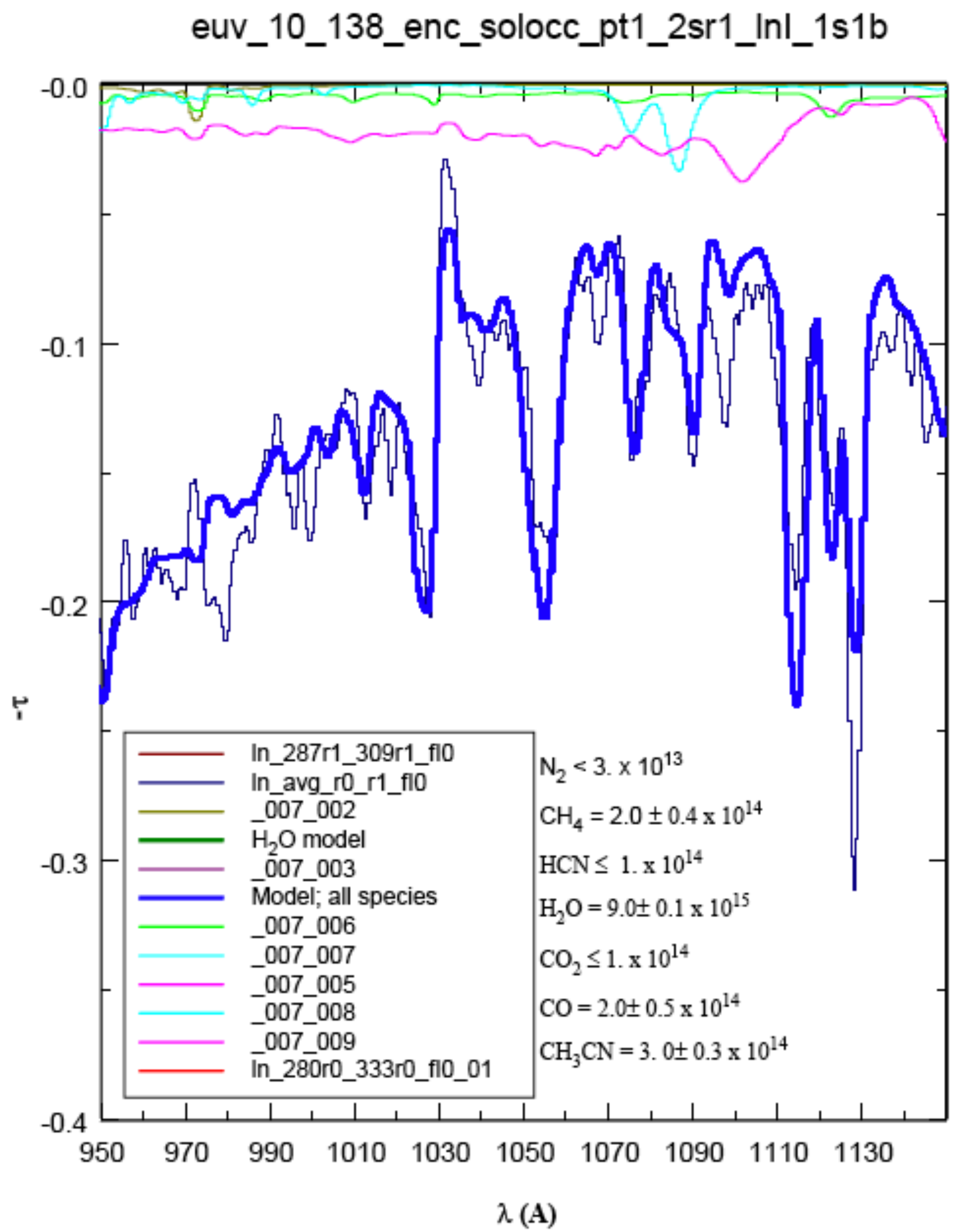
- No dip is seen at all at 97.2 nm
- Upper limit < 0.3%

Consequences of no N_2 for models of the interior

- High temperature liquid not required for dissociation of NH_3 (if there is NH_3 in the plume)
- Percolation of H_2O and NH_3 through hot rock is not required
- A catalyst for decomposition is not required at lower temperatures
- Clathrate decomposition is not supported with N_2 as the plume propellant

Solar Occ results: Water in the Plume

- H_20 fit to absorption spectrum
- Column density of H_2O = 0.9 x 10^{16} cm^{-2}



Water Vapor Abundance

- To calculate water vapor abundance in the plume the spectra are summed during the center 60 sec of the occultation, then divided by a 650 sec average unocculted sum to compute I / I_0
  - I_0 computed at two different times, results were the same

- The extinction spectrum is well-matched by a water vapor spectrum with column density = $0.9 \pm 0.1 \times 10^{16}$ cm^{-2}

- Overall amount of water vapor is comparable to previous two (stellar) occultations
  - 2005: 1.6×10^{16} cm^{-2}
  - 2007: 1.5×10^{16} cm^{-2} (maximum value of 3.0×10^{16} cm^{-2} at center)

- Lower column abundance in 2010 is explained by the viewing geometry: all measurements give water flux about 200kg/sec, standard deviation of 15%

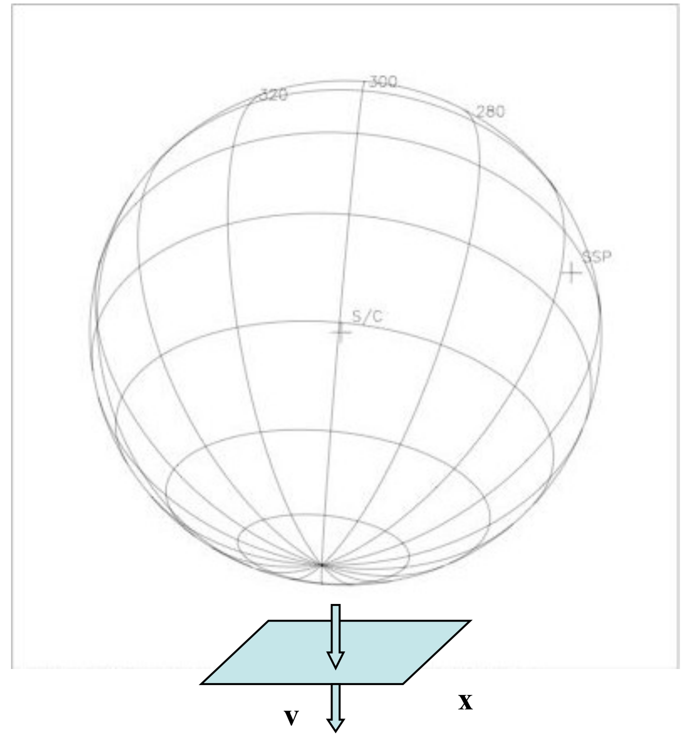
Estimate of Water Flux from Enceladus = 200 kg/sec

S = flux

$= N * x * y * v_{th}$

$= (n/x) * x * y * v_{th}$

$= n * y * v_{th}$



Where

N = number density / cm^3

x * y = area

$y = v_{los} * t$ => FWHM

v_{th} = thermal velocity = 45,000 cm/sec

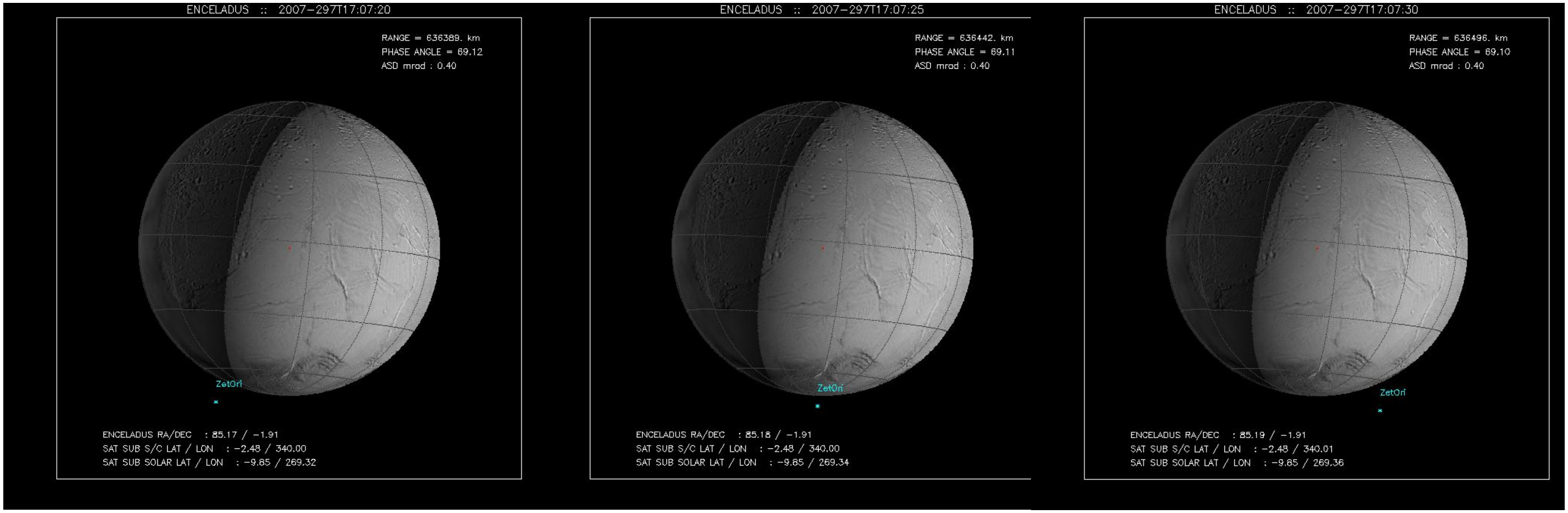
for T = 170K

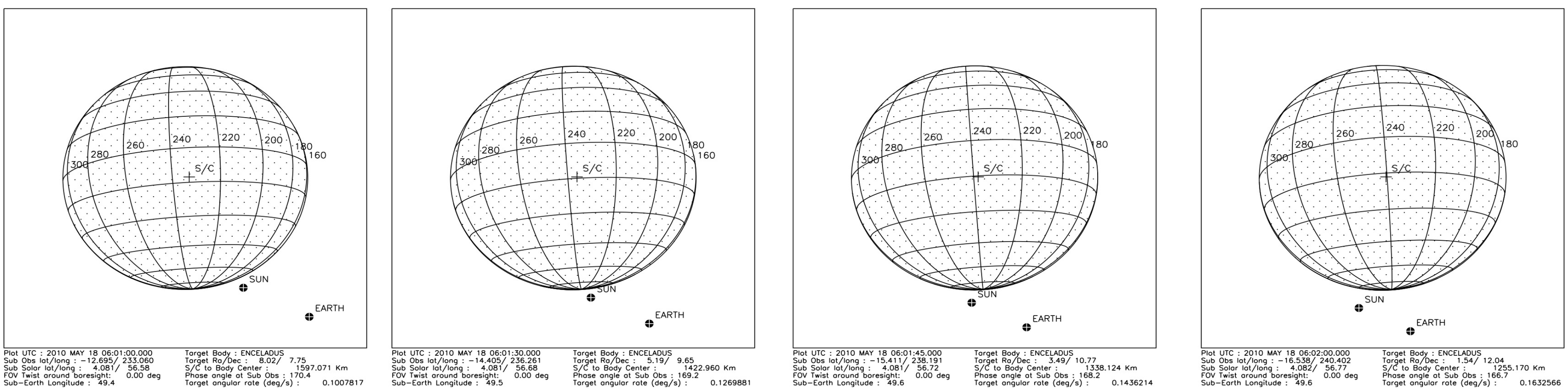
n = column density measured by UVIS

note that escape velocity = 23,000 cm/sec

Year	n (cm^{-2})	y (x 10^5 cm)	v_{th} (cm / sec)	Flux: Molecules / sec	Flux: Kg/sec
2005	1.6×10^{16}	80 (from vert scale)	45000	5.8×10^{27}	170
2007	1.5×10^{16}	110	45000	7.4×10^{27}	220
2010	0.9×10^{16}	160	45000	6.5×10^{27}	170

Detection of Gas Jets





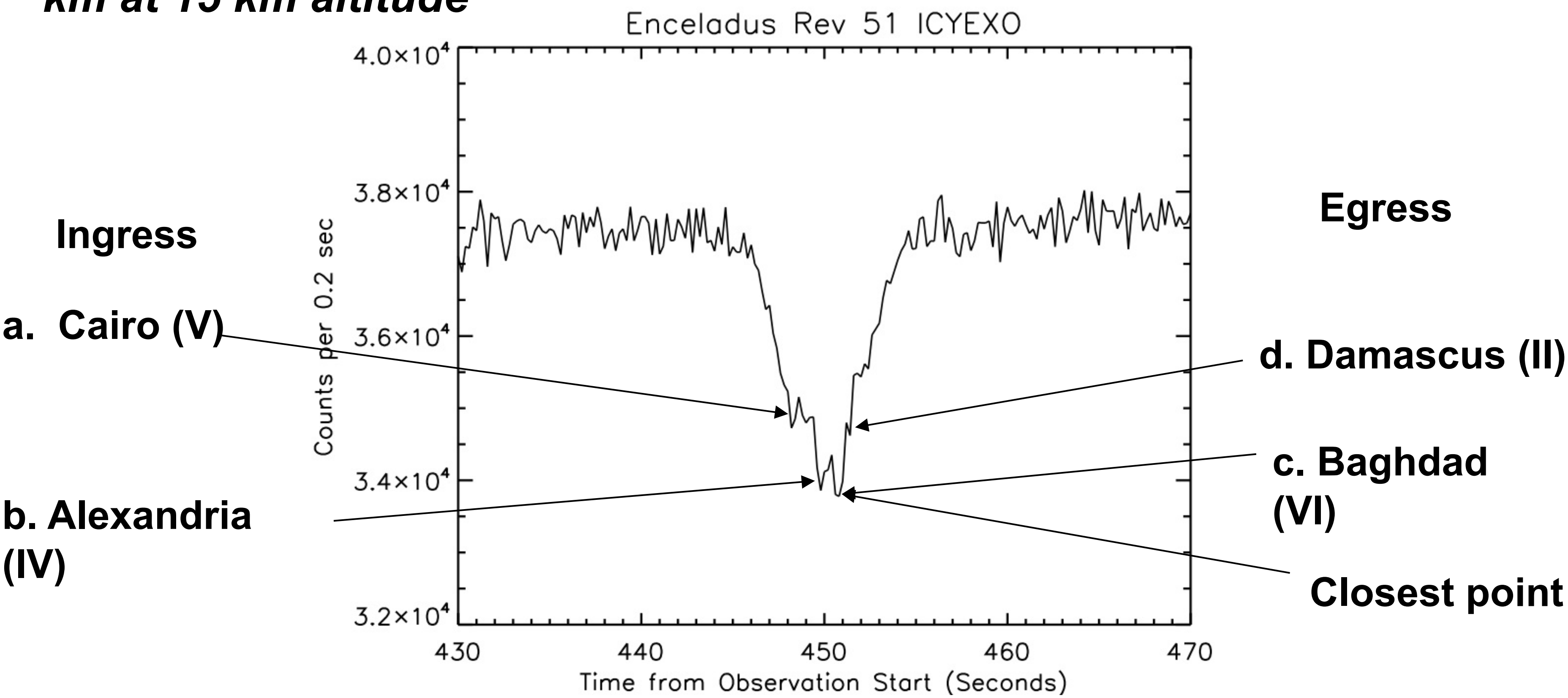
- **Perfect geometry to get a horizontal cut through the plume and detect density variations indicative of gas jets**

Zeta Orionis Occultation

Density in jets is twice the background plume

Gas jet typical width = 10 km at 15 km altitude

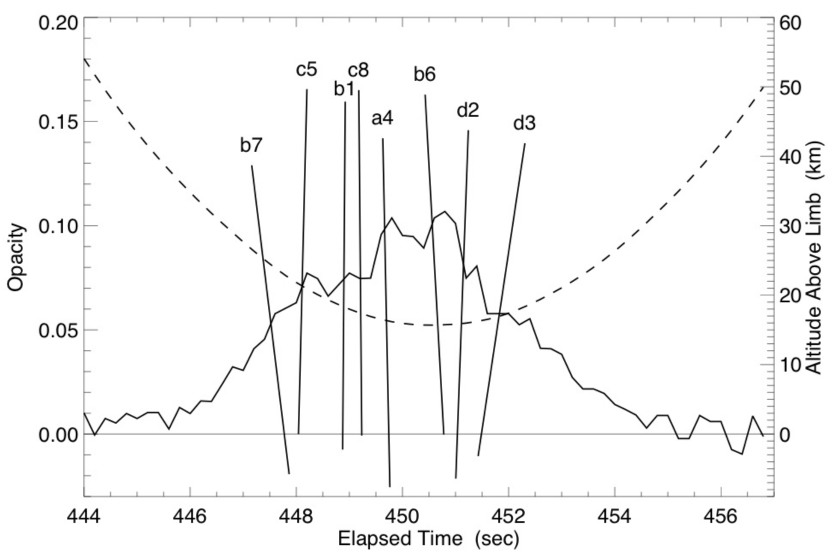
Feature Number	Feature Letter	m	Occultation latitude	Occultation west longitude	Likely associated dust jet
1	a	0.032	-79	82	Cairo (V)
2	b	0.000008	-86	112	Alexandria (IV)
3	c	0.00056	-86	192	Baghdad (VI)
6	d	0.026	-84	217	Damascus (II)



2007 - Plume Structure and Jets

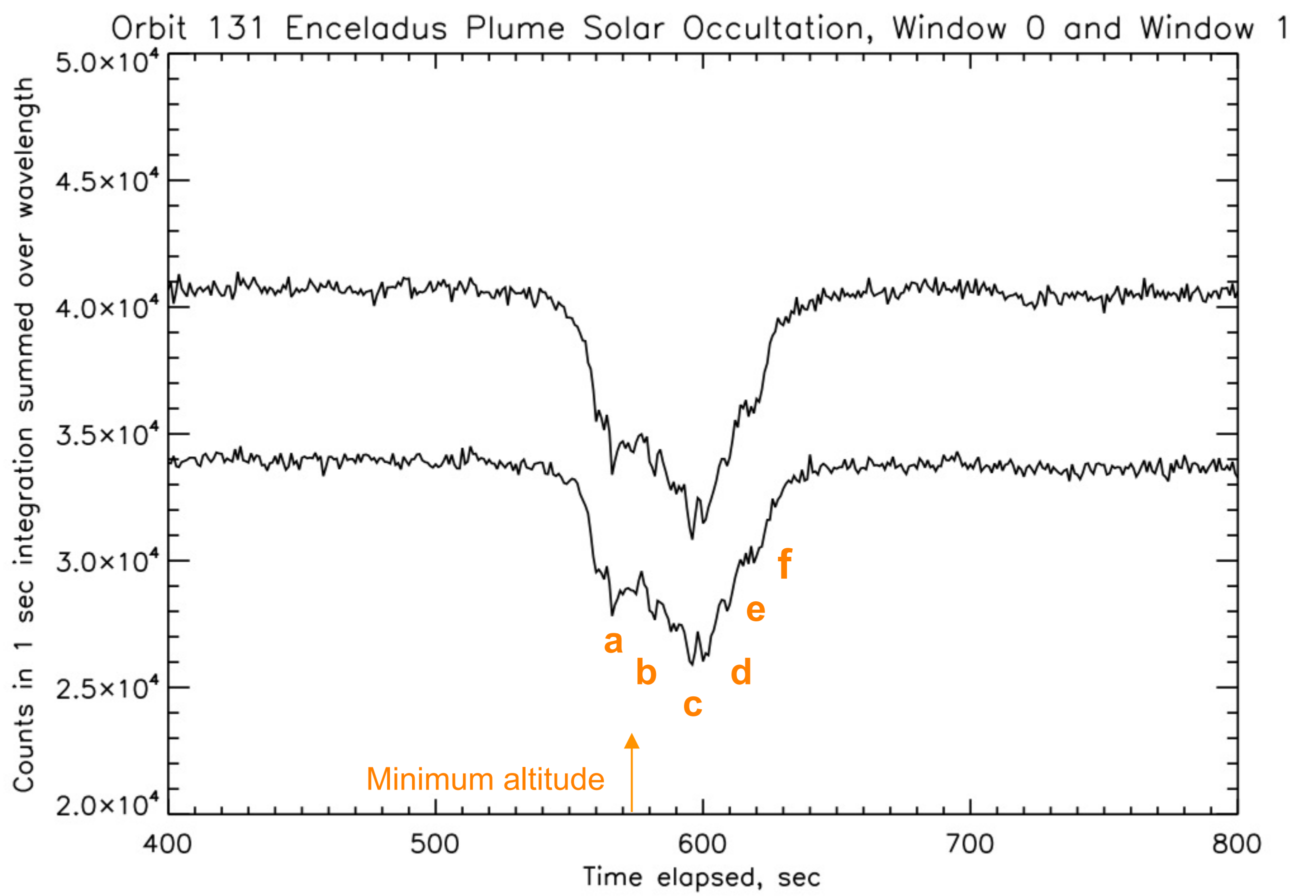
Summary of 2007 results

- Significant events are likely gas jets
- UVIS-observed gas jets correlate with dust jets in images
- We characterize jet widths, opacity, density
- Density in jets ~2x density in background plume
- Ratio of vertical velocity to bulk velocity = 1.5 (supersonic)



Supersonic gas jets are consistent with Schmidt et al. model of nozzle-accelerated gas coming from liquid water reservoir

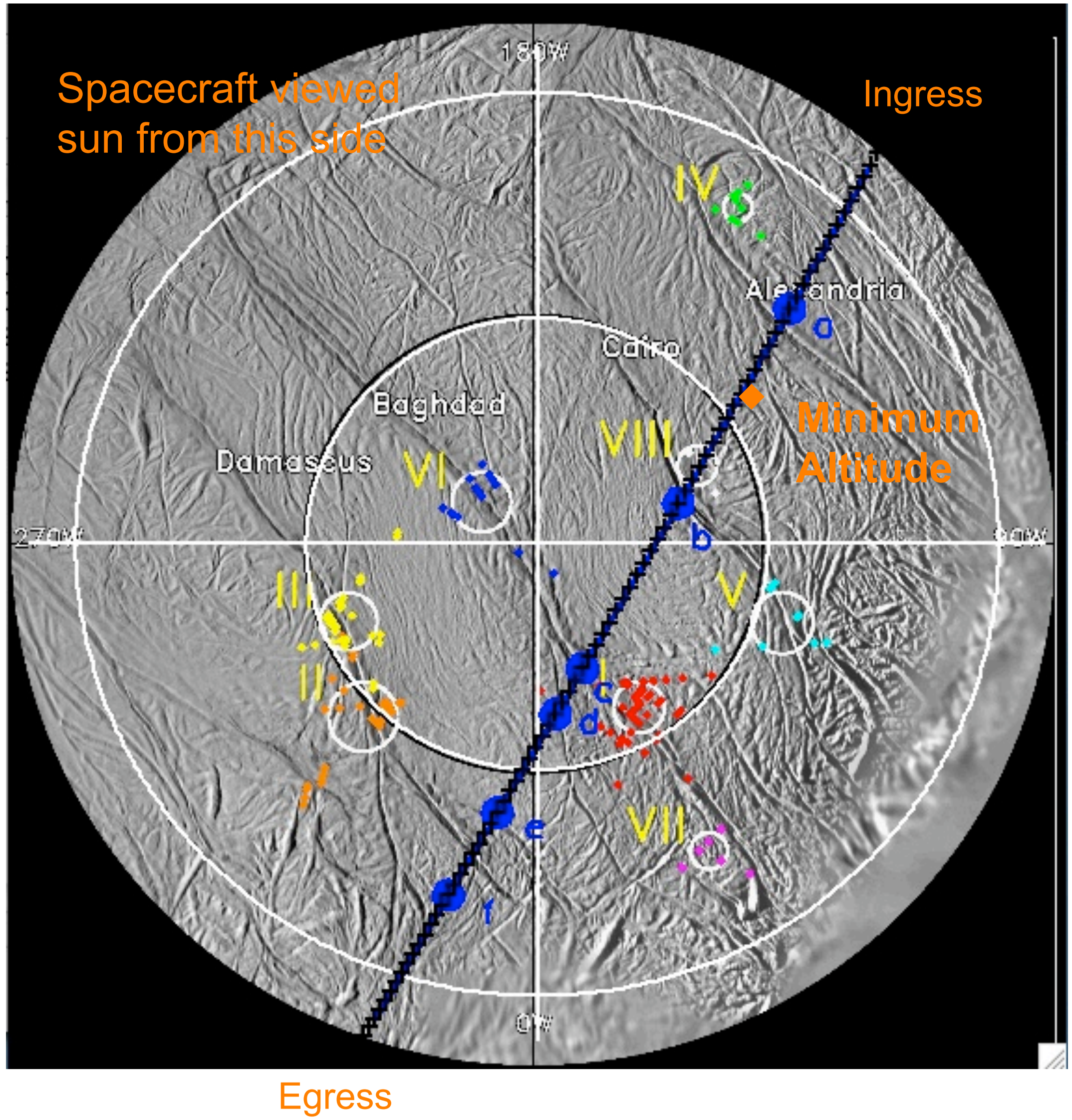
Solar Occ Jet Identifications



- Window 0 and 1 matching features => jets
- Repetition of features in window 0 and window 1 shows they are not due to shot noise, therefore likely to be real

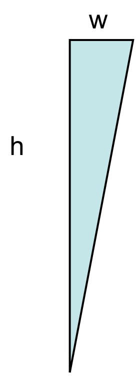
Jets vs. Tiger Stripes

- As before, gas jets correlate to dust jets
- Higher time resolution because sun's passage behind the plume was slower
- We see gas between jets, although no enhancement as a function of depth in the plume (time at which sun was closest to limb is not a deep attenuation)



Gas Velocity

- In the case of jet **c** (Baghdad I) the source of the jet is close enough to the occultation ground track to calculate the height and width
- Half-width of jet **c** = 2.5 sec * 2.85 km/sec = ~7 km (**w**) at ~27 km (**h**) altitude



$$w/h = \tan ß = v_{thermal} / v_{vert} = 7 / 27$$

$$\text{Mach number} = v_{vert} / v_{thermal} = 3.9$$

- Previously estimated mach number (from 2007 occultation) was 1.5
- Jets more collimated than previously estimated
- New estimate for vertical velocity: if $v_{thermal}$ = 450 m/sec (for ~170 K) then v_{vert} = 1755 m/sec

Enceladus and Life

- No need for clathrates, complex thermochemistry, cracks closing and opening
- Composition
  - Upper limit on N_2 of 3×10^{13} cm^{-2}
  - Only H_2O absorption seen
- Warm water provides a possible habitat for life
  - Flux of water from 3 occultations is ~200 kg/sec, constant over 5 years

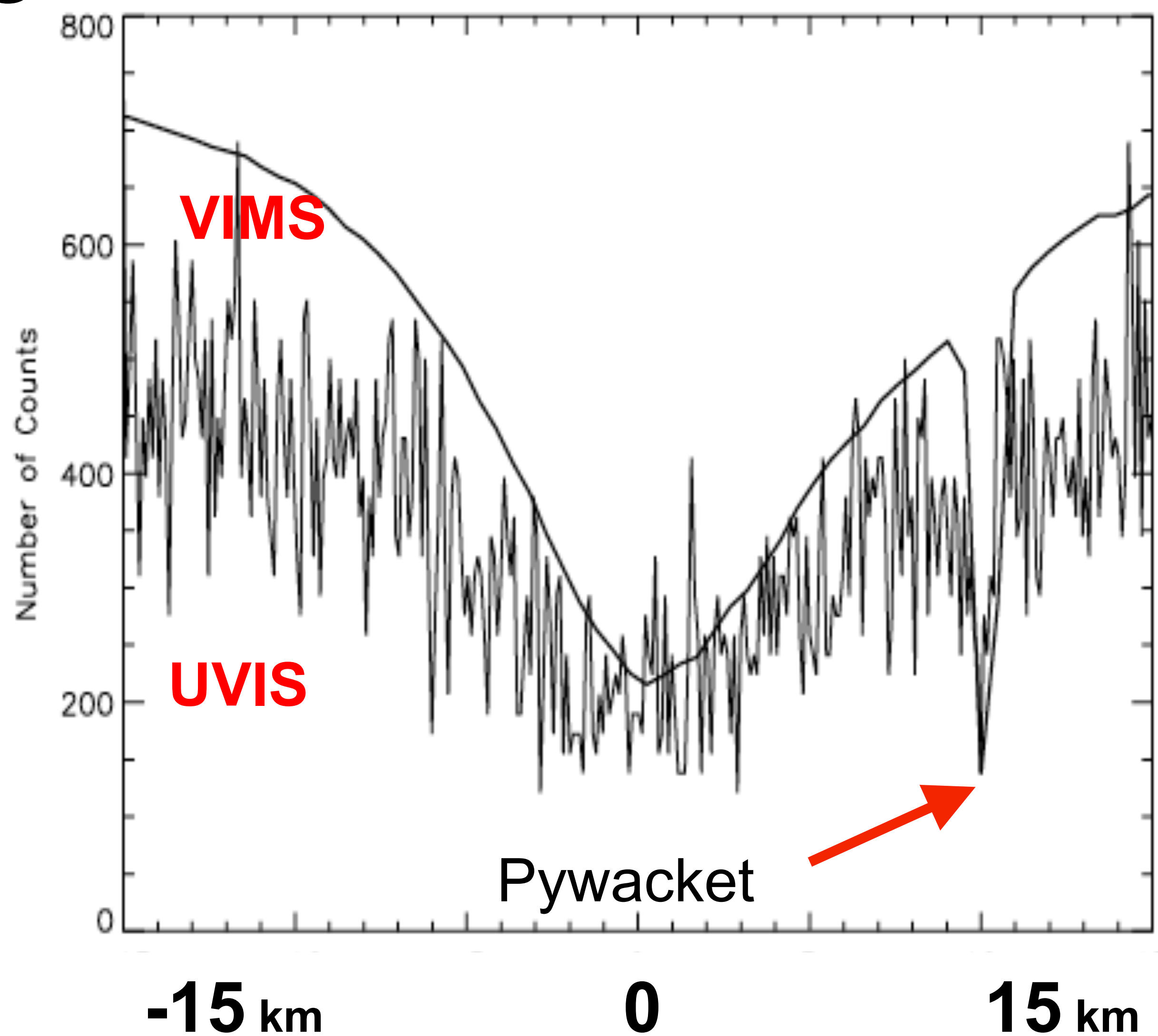
Summary:
Cassini UVIS Spectra

- Can be visualized with color
- Are compared with computer models
- Interpretations
  - Rings are polluted ice
  - Saturn's rings are ancient, but constantly renewed
  - Enceladus jets are mostly water (possible habitat?)

Backup Slides

F Ring Search Method

- Search was tuned for 1 VIMS-confirmed event:
  - Optimal data-bin size
  - τ threshold



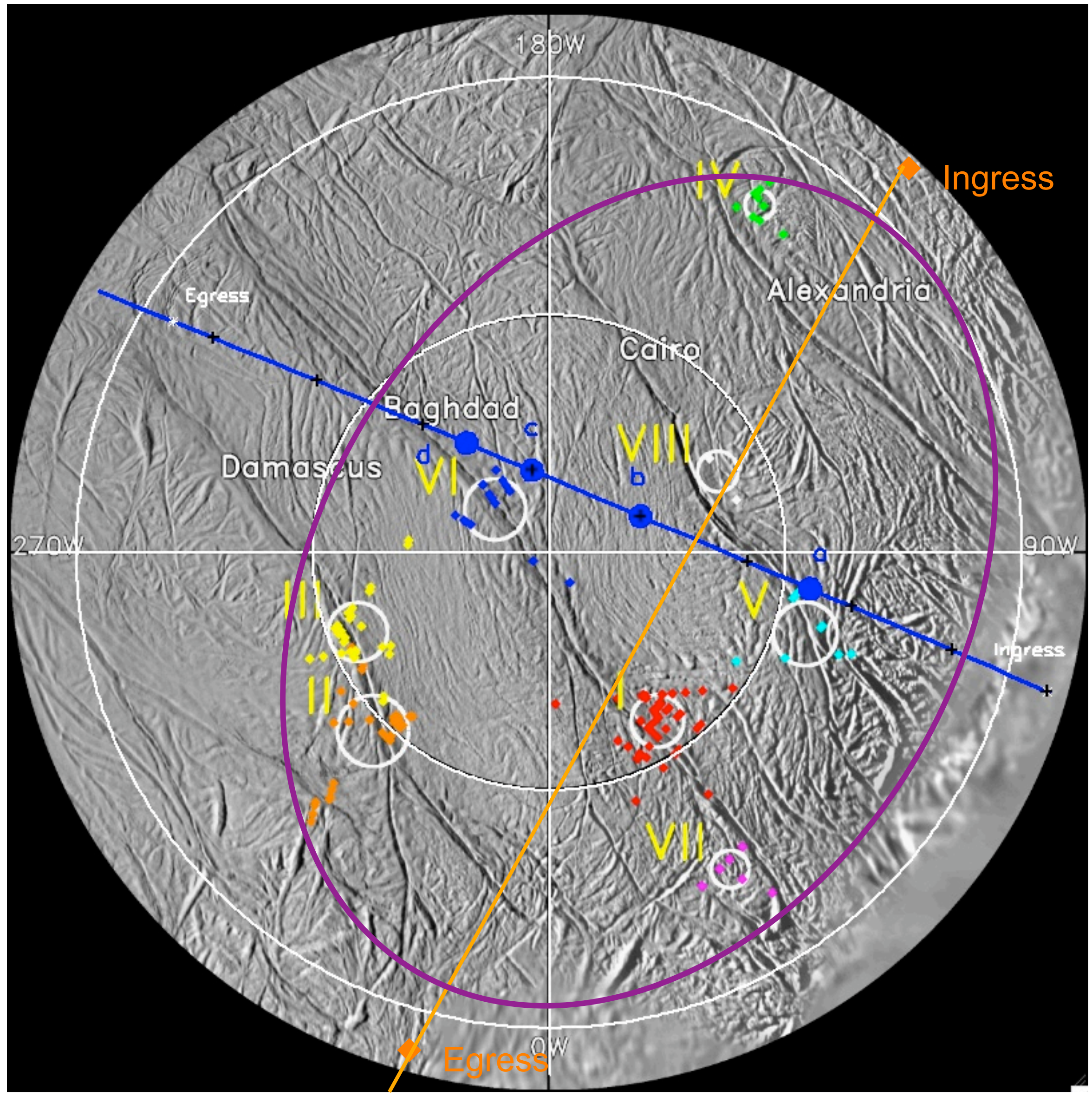
Ground Tracks

Blue ground track is from zeta Ori occ on Rev 51

Orange is solar occ track, ~orthogonal

Plume is elongated. If total flux is same then column density will be less by ~ 2/3

Preliminary result: 0.9×10^{16} cm^{-2}, ~2/3 of value in 2005



One more comparison to tidal energy model

- Hurford *et al* 2007 model predicts tidally-controlled differences in eruption activity as a function of where Enceladus is in its eccentric orbit
    - Expect fissures to open and close
- Substantial changes are not seen in the occultation data, although they would be predicted, based on this model
    - 2010 column density very similar to 2005

Position of Enceladus in its orbit at times of stellar occultations, and solar occultation

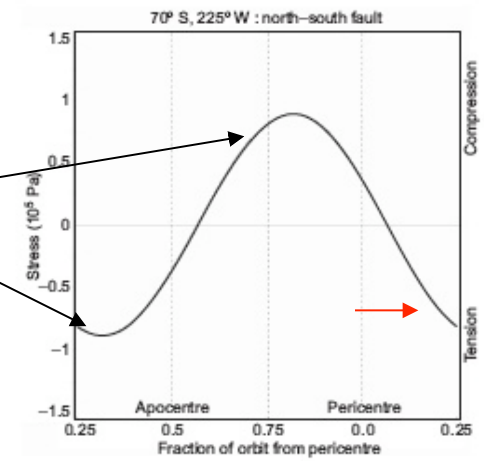


Figure 2 | Stress normal to a north–south-oriented fault. The stress across this fault, which is oriented north–south at a latitude of 70° S and longitude of 225° W is shown. At pericentre the fault is being held closed, because the stress normal to it is compressive. However, as Enceladus orbits, the stress changes from compression to tension, allowing the fault to open, possibly exposing liquid water or other volatiles and creating an eruption. The fault remains in tension for half of an orbit, at which point the normal stress once again becomes compressive, forcing the crack to close, ending any possibility of an eruption.

Taken from Hurford et al, Nature 447:292 (2007)

True Anomaly (deg)	Fraction of orbit from Periapsis	Position in Orbit	Stress 10^5 Pa
0	0.0	Periapsis	0.3
	0.186	May 18, 2010	
90	0.25	One quarter	-0.8
97.76	0.27	July 14, 2005	-0.77
180	0.5	Apoapsis	-0.4
254.13	0.7	October 24, 2007	0.4
270	0.75	Three quarter	0.6