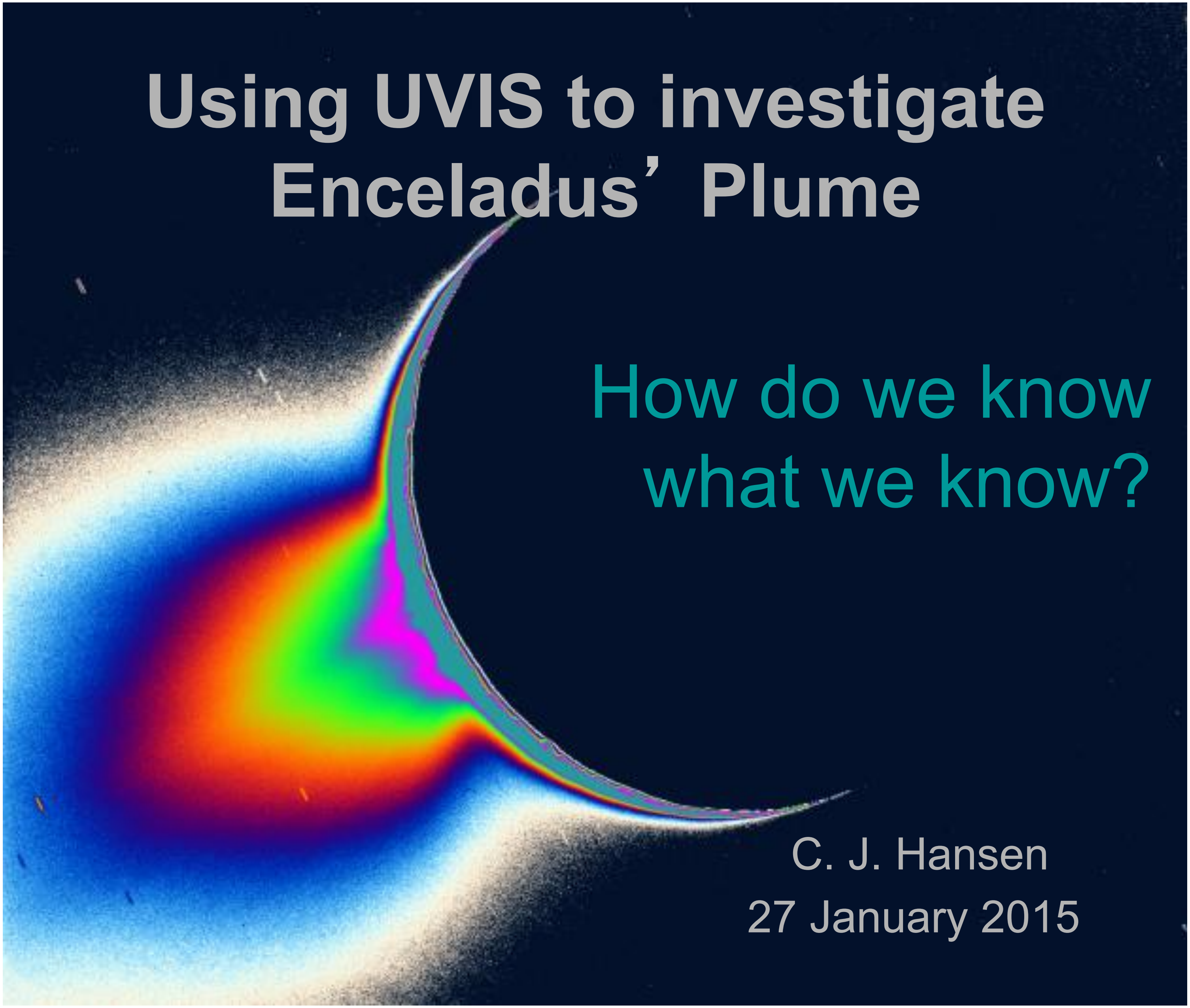
Using UVIS to investigate Enceladus' Plume

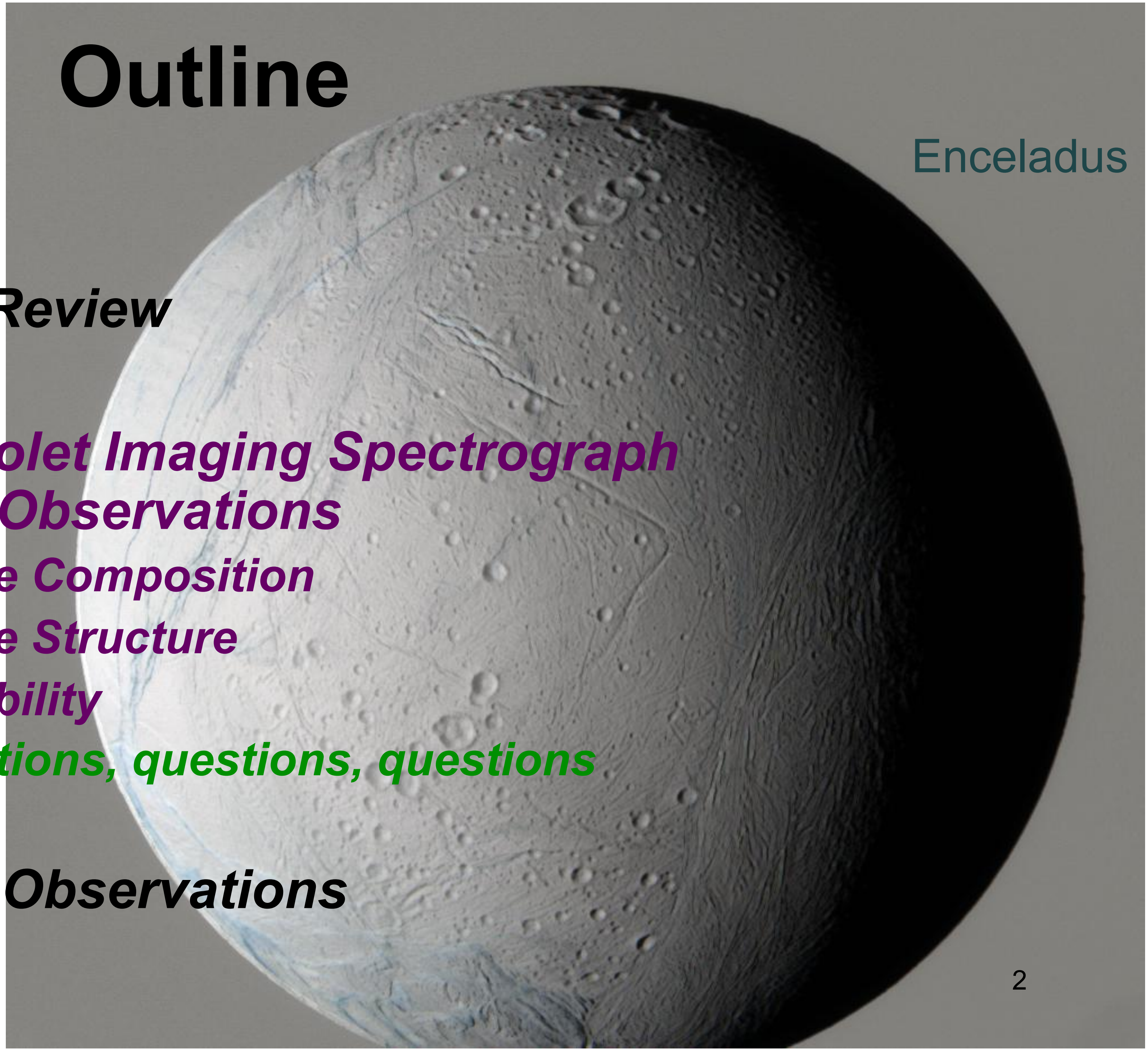


How do we know what we know?

C. J. Hansen

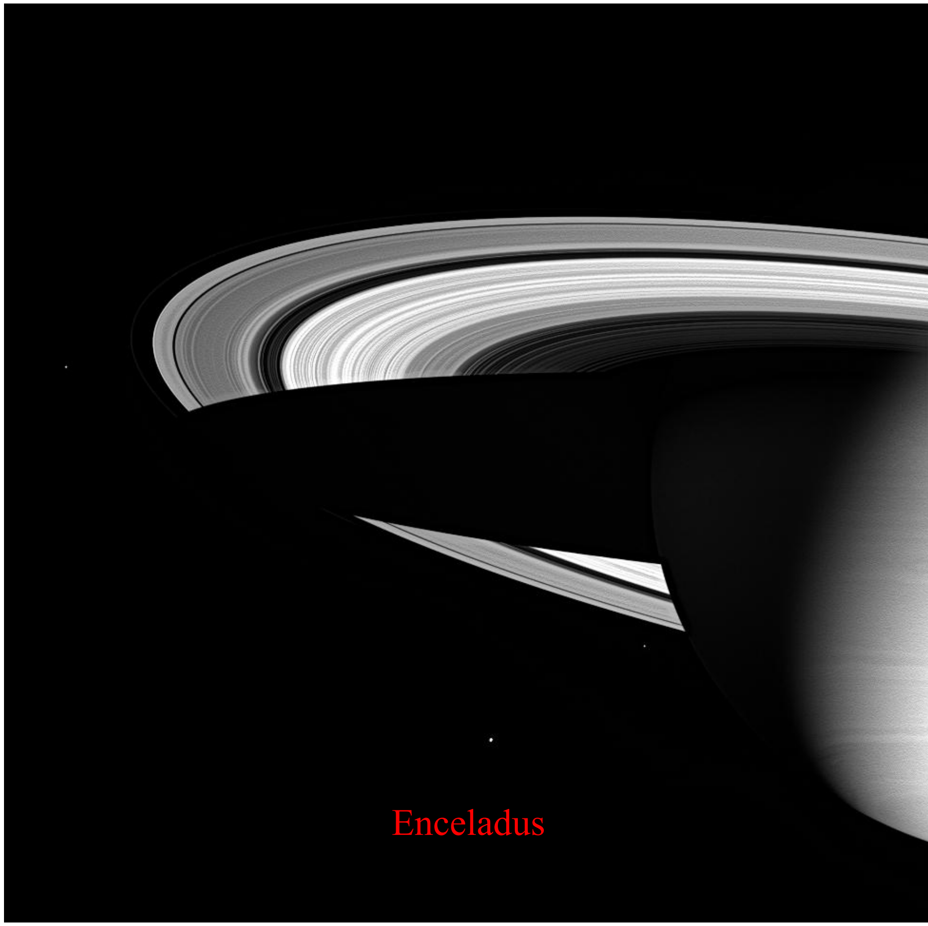
27 January 2015

Outline



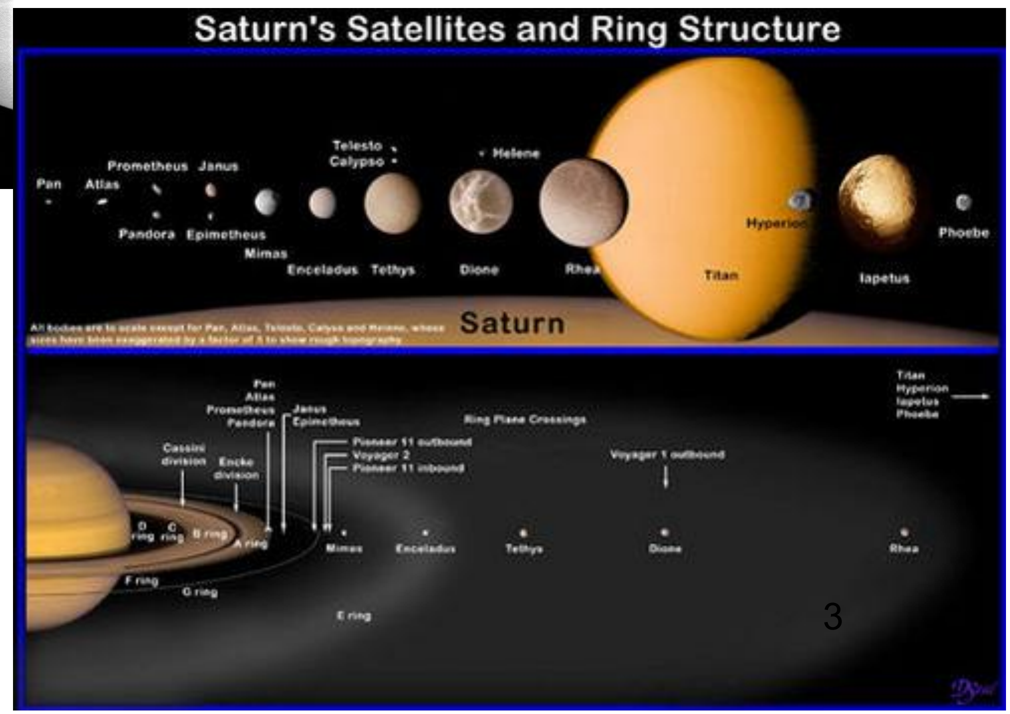
Enceladus

- ***Quick Review***
- ***UltraViolet Imaging Spectrograph (UVIS) Observations***
  - ***Plume Composition***
  - ***Plume Structure***
  - ***Variability***
  - ***Questions, questions, questions***
- ***Future Observations***



Enceladus

- One of Saturn's small icy moons
  - Mean density ~ 1.6 gm/cm^3
- Radius ~252 km
- Voyager images showed a geologically young surface



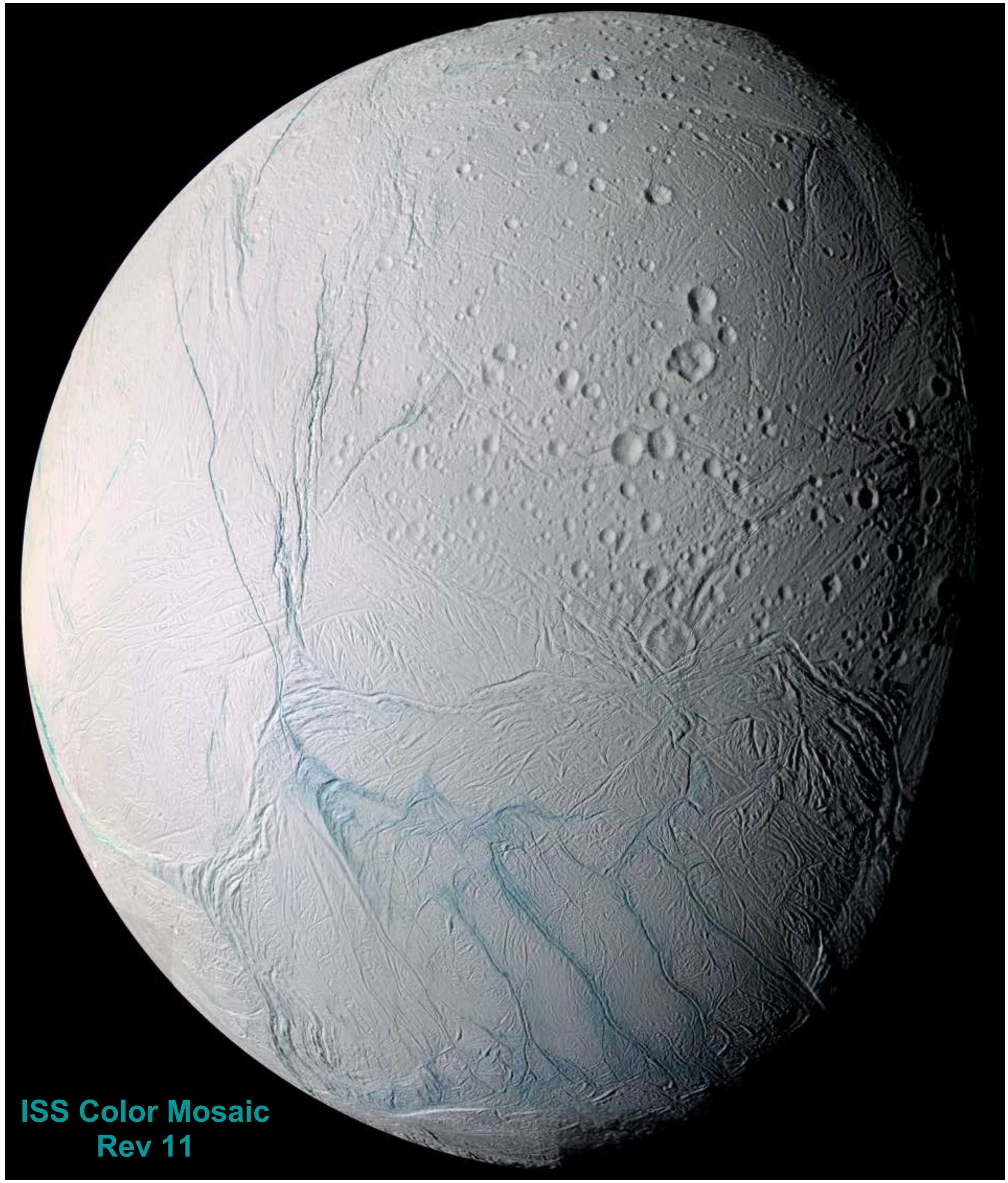
- Enceladus' orbit co-incides with the thickest portion of Saturn's E ring at ~4 R_s

July 2005

Cassini's 2005 flyby of Enceladus was ~over the south pole

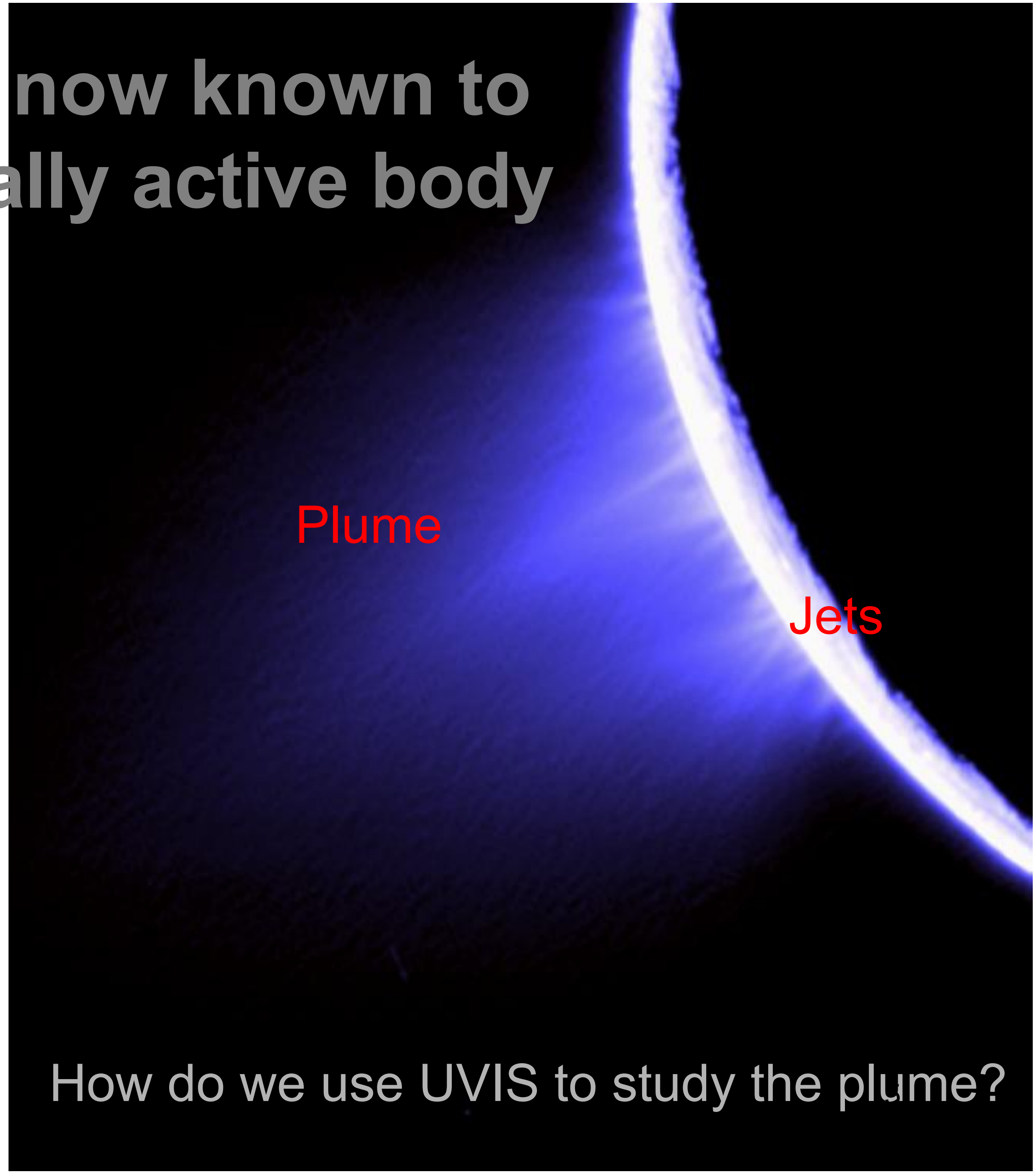
Enceladus' youthful geology suddenly made sense when we realized we were seeing evidence in numerous instruments' data for eruptions at the south pole

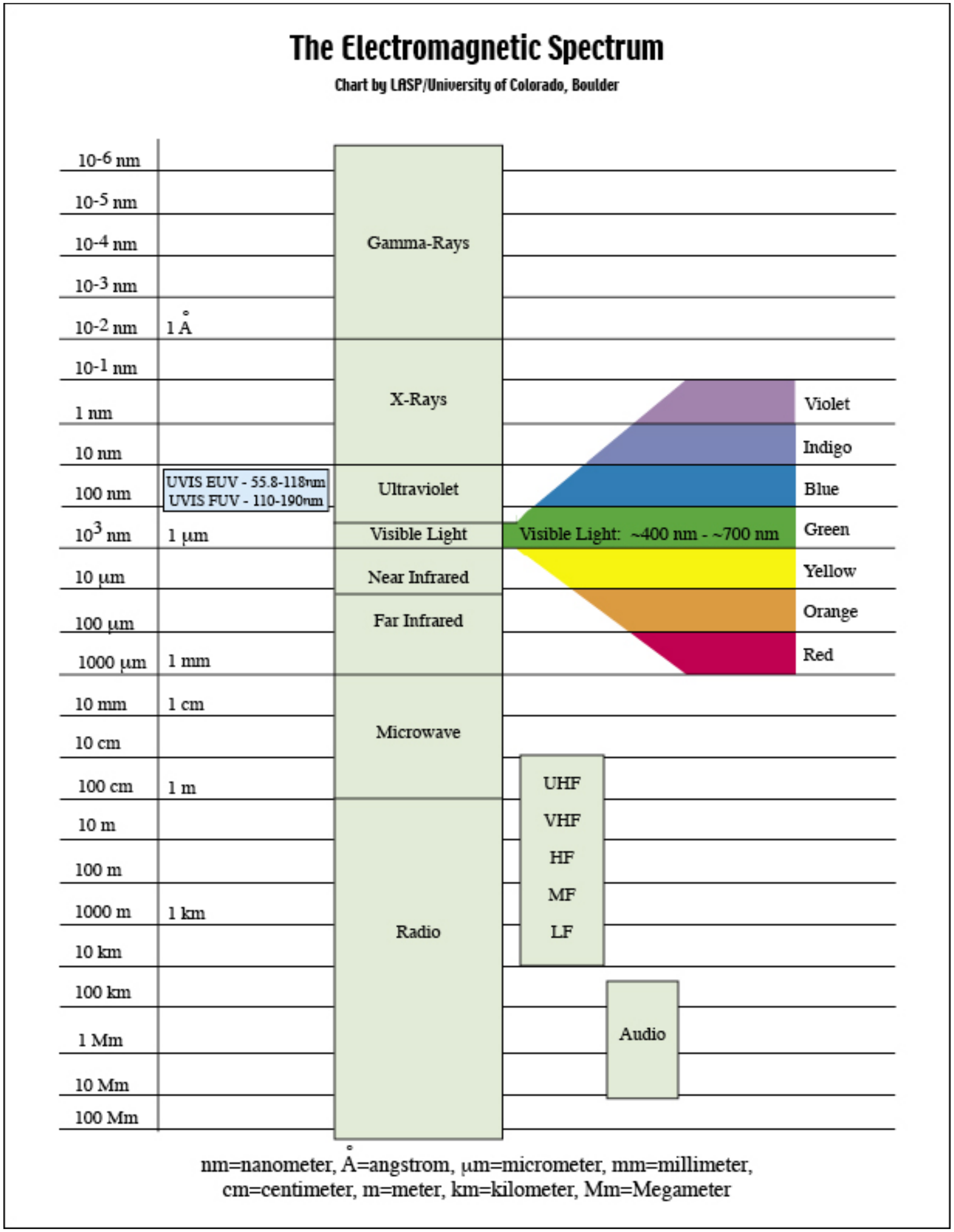
Bluish fractures crossing the south pole were dubbed "tiger stripes"



Enceladus is now known to be a geologically active body

We now know that
A plume of water vapor and jets of ice particles come from the “tiger stripe” fissures across the southern pole





Ultraviolet Light

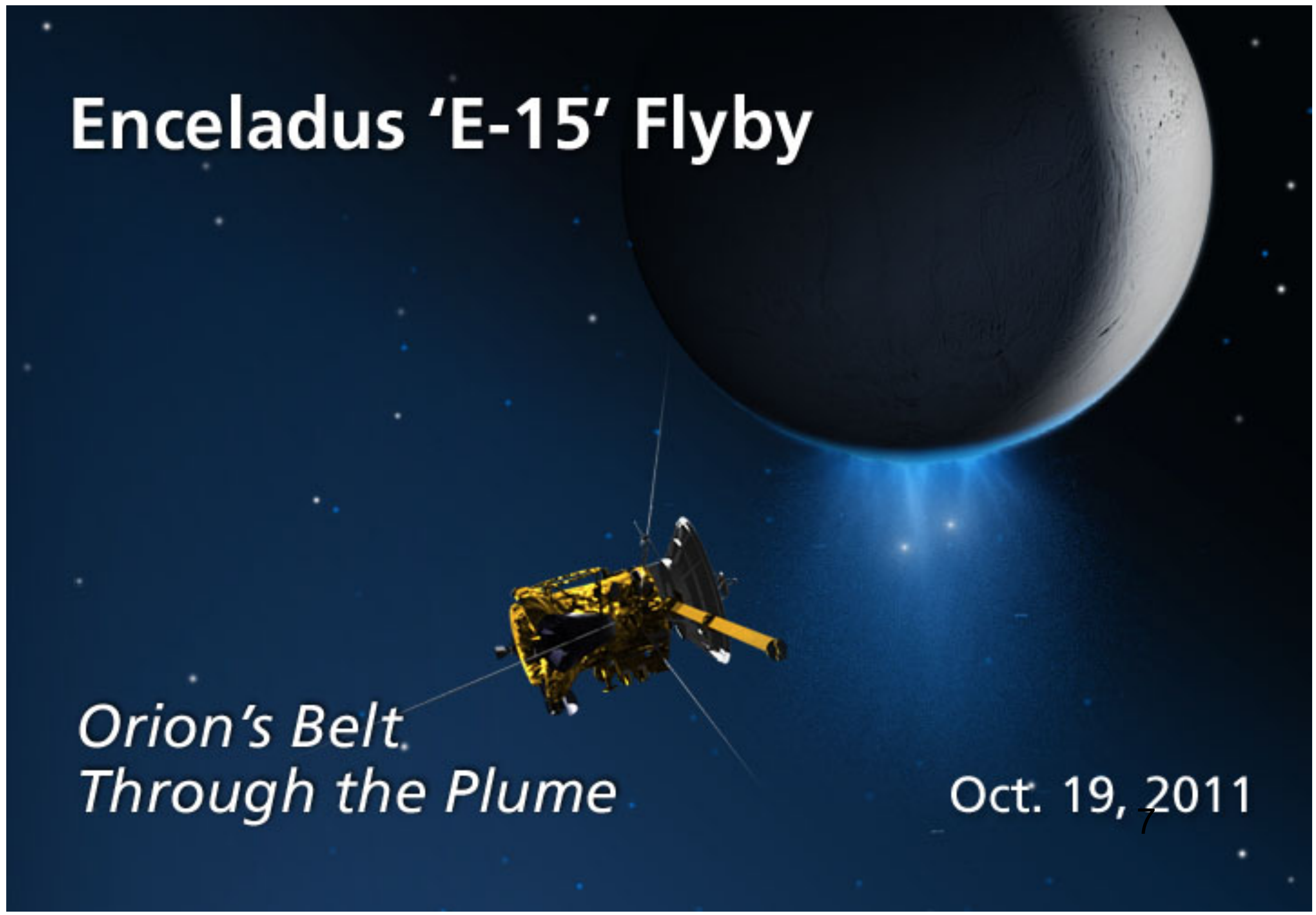
- Gases absorb light at ultraviolet wavelengths
  - The wavelengths are unique to the gas, so absorption wavelengths are diagnostic of composition
- Gases emit light at ultraviolet wavelengths
- Surfaces reflect light at ultraviolet wavelengths

“Occultations” of Stars

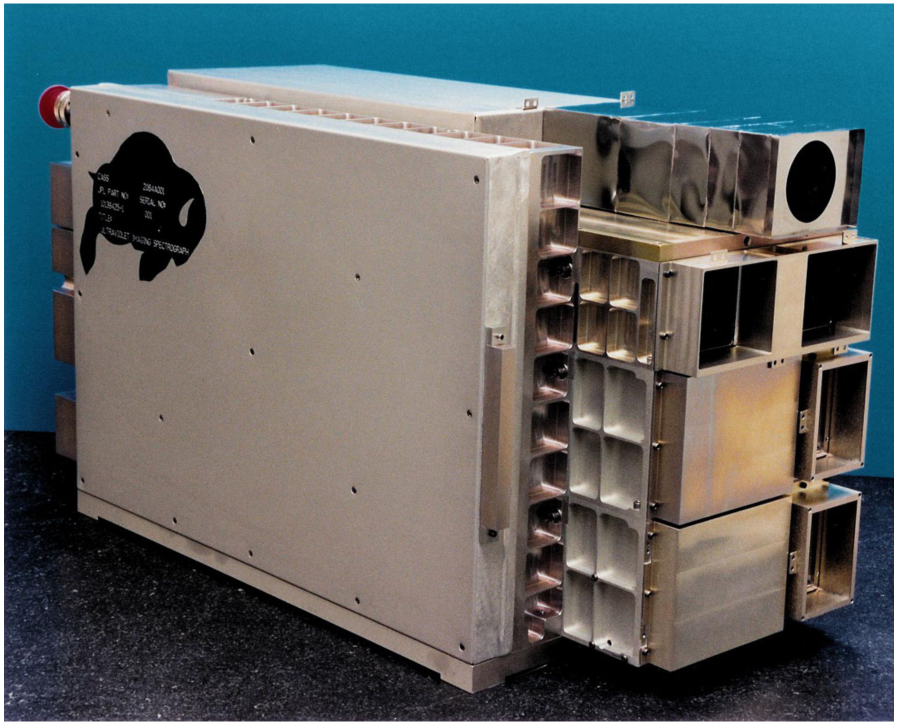
The most important ultraviolet data is collected by watching a star or the sun go behind Enceladus’ plume as seen from the spacecraft

From this data

- we can determine the composition of the gases in the plume
- we see the structure of the plume



UVIS Characteristics



UVIS has 4 separate channels

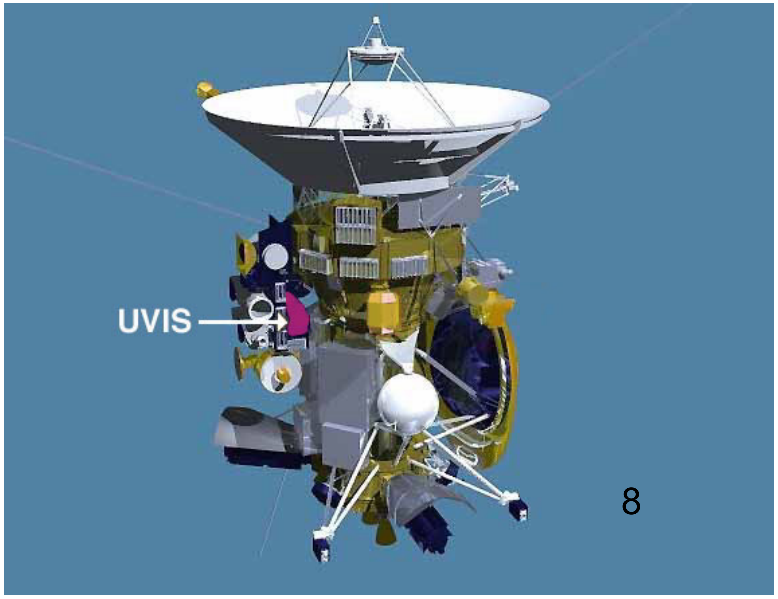
For stellar occultations we use:

- **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

For the solar occultation we used:

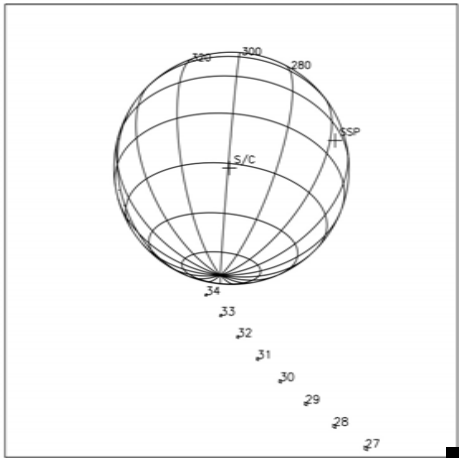
- **Extreme UltraViolet (EUV)** solar port
  - 550 to 1100 Å
  - 2D detector: 1024 spectral x 64 one-mrad spatial pixels
  - two windows of 27 rows each
  - 1 sec integration



UVIS Observations of Enceladus' Plume

- Cassini's Ultraviolet Imaging Spectrograph (UVIS) observes occultations of stars and the sun to probe Enceladus' plume
  - ***Composition, mass flux, and plume and jet structure***
- Four stellar and one solar occultation observed to-date

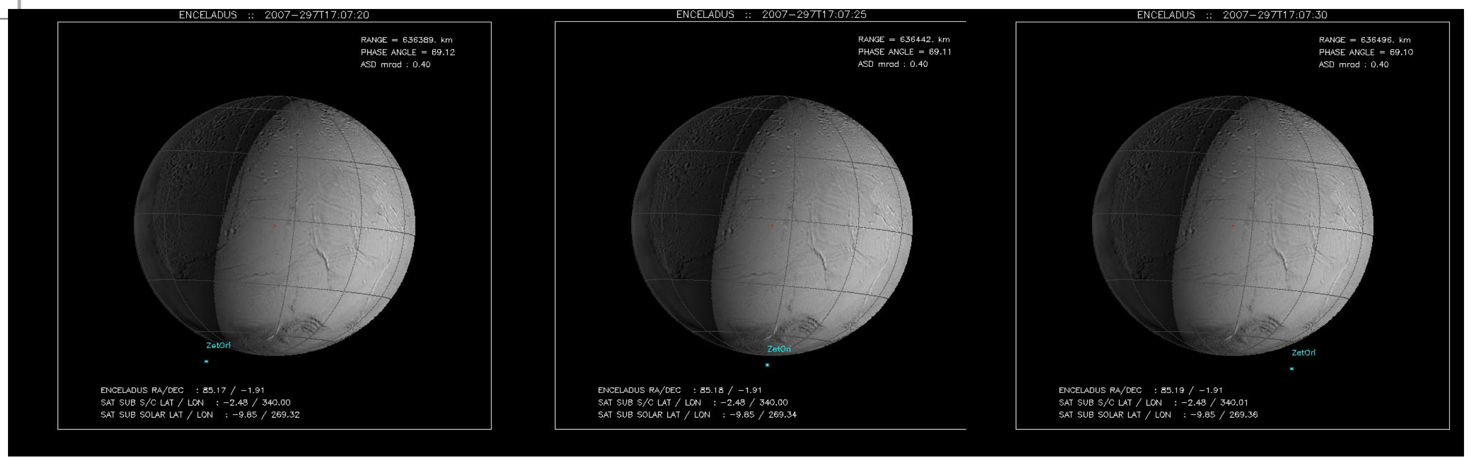
- Feb. 2005 - lambda Sco
  - No detection (equatorial)
- July 2005 - gamma Orionis
  - Composition, mass flux
- Oct. 2007 - zeta Orionis
  - Gas jets
- May 2010 - Sun
  - Composition, jets
- Oct. 2011 – epsilon and zeta Orionis dual occultation



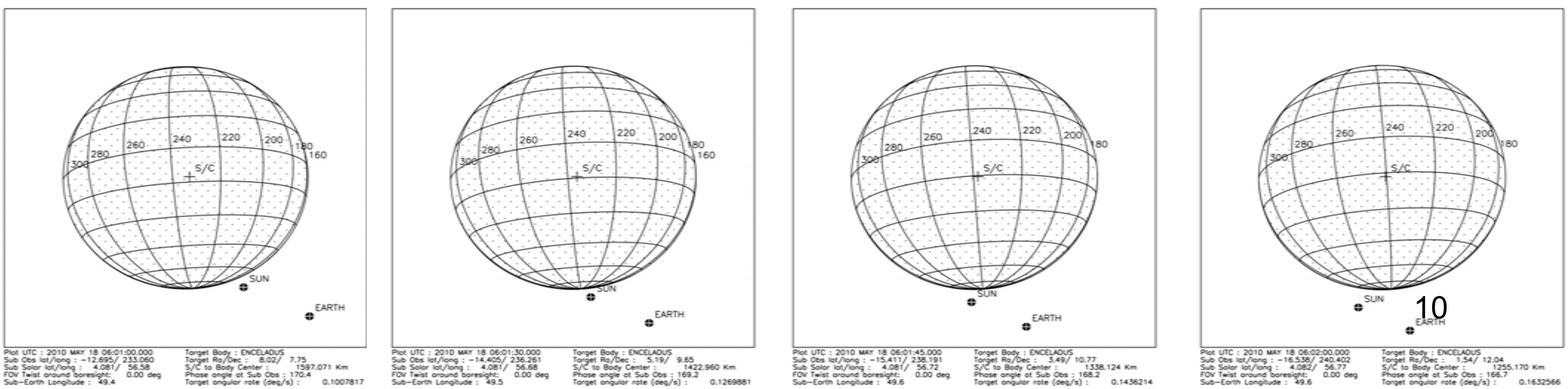
2005 - gamma Orionis Occultation

The Occultation Collection

2007 - zeta Orionis Occultation



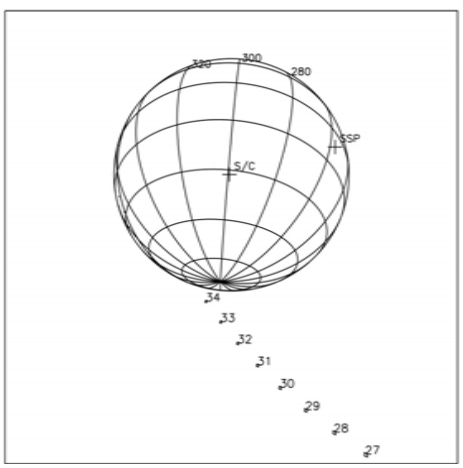
2010 - Solar Occultation

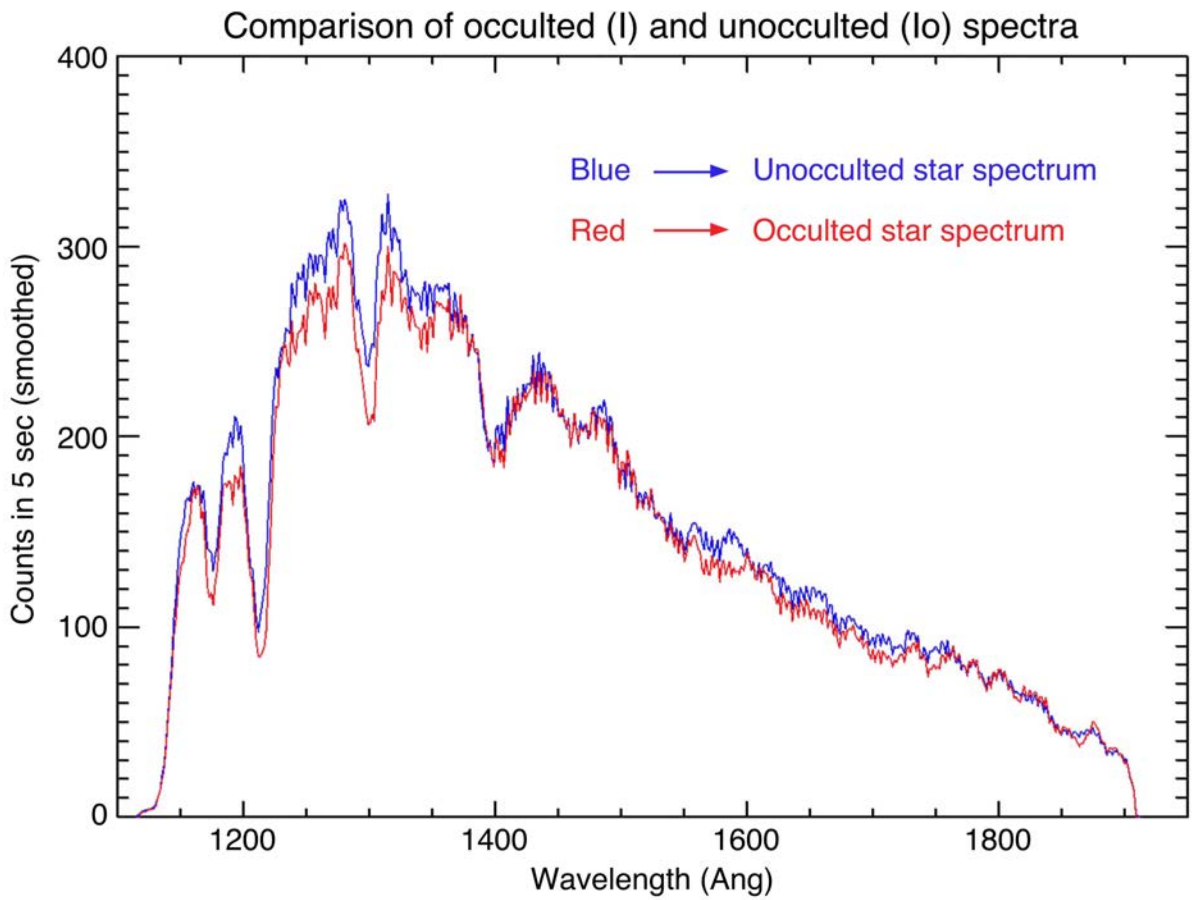


How do we know what the composition of the plume is?

Gamma Orionis Spectrum

Time record 33, the last full 5 sec integration prior to ingress, shows the deepest absorption. The ray altitude above Enceladus' surface corresponding to time record 33 ranged from 30 to 7 km.

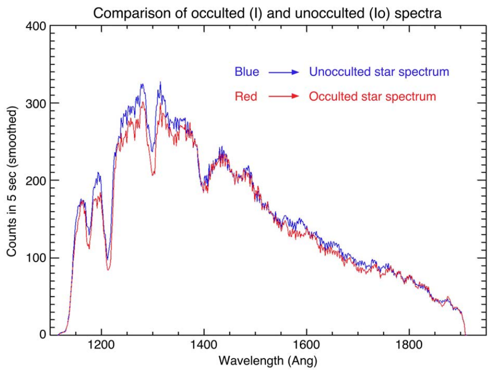




Clear signature of an absorbing gas is present – both relatively narrow and broad absorption features

What is it? How much is there?

Ultraviolet Data Analysis – Composition and Quantity of Gases



Step 1: Wavelength by wavelength (512 channels) divide occulted data (I) by unocculted data (I_0) to see at which wavelengths starlight has been absorbed by the plume

Step 2: Plot I/I_0 to see absorption features

Step 3: Compare I/I_0 to various gas absorption spectra; At Enceladus we have a clear match to water vapor

Step 4: How much water vapor is obscuring the star?

$I=I_0 \exp(-n^*\sigma)$

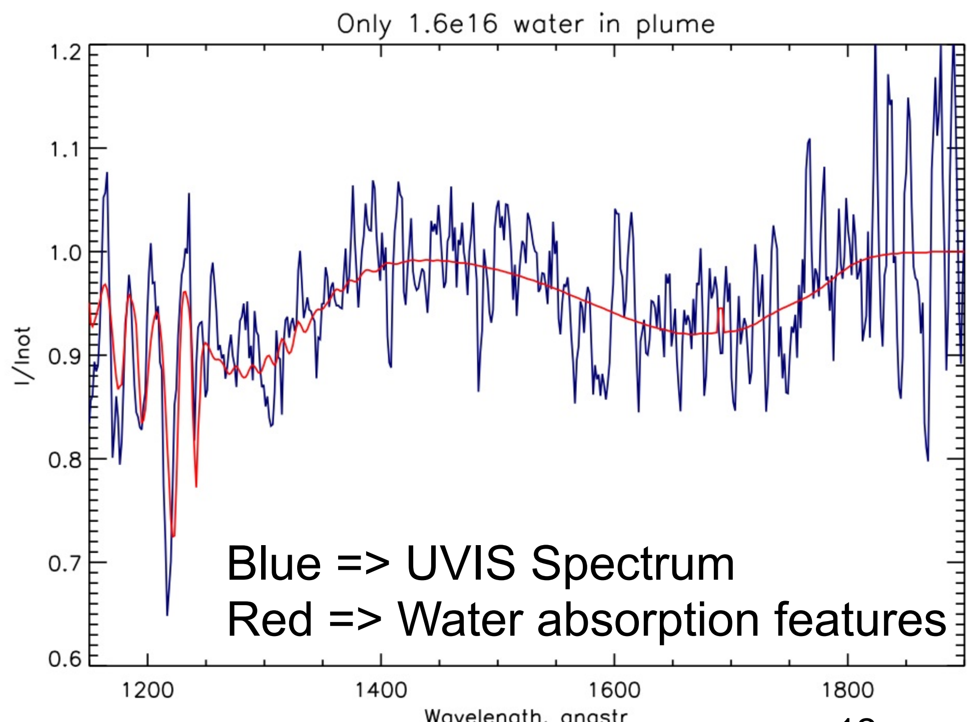
Where n is "column density" and

σ is the cross-section (area) at each wavelength

Column density is the amount of water vapor along the line of sight

Crossections are measured in the lab

Step 5: Vary n until a good fit to the data is found



Best fit column density = 1.6×10^{16} H_2O molecules/ cm^2

How much Water is coming from Enceladus?

S = source rate

$= N * h^2 * v$

$= n/h * h^2 * v$

$= n * h * v$

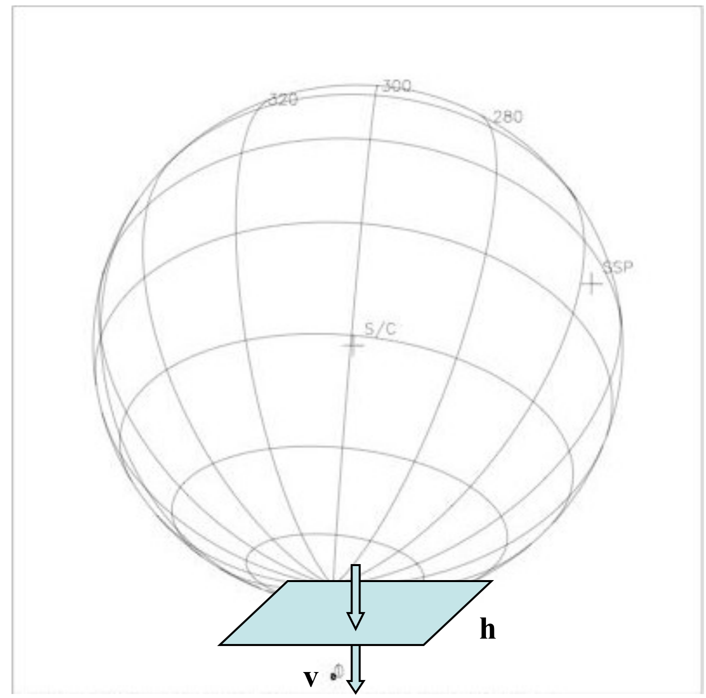
Where

N = number density / cm^3

h^2 = area

v = velocity

n = column density measured by UVIS



Estimate **h** from plume dimension ~ 80 km = 80 x 10^5 cm

Estimate **v** from thermal velocity of water molecules in a gas with a temperature of 170K = 45,000 cm/sec

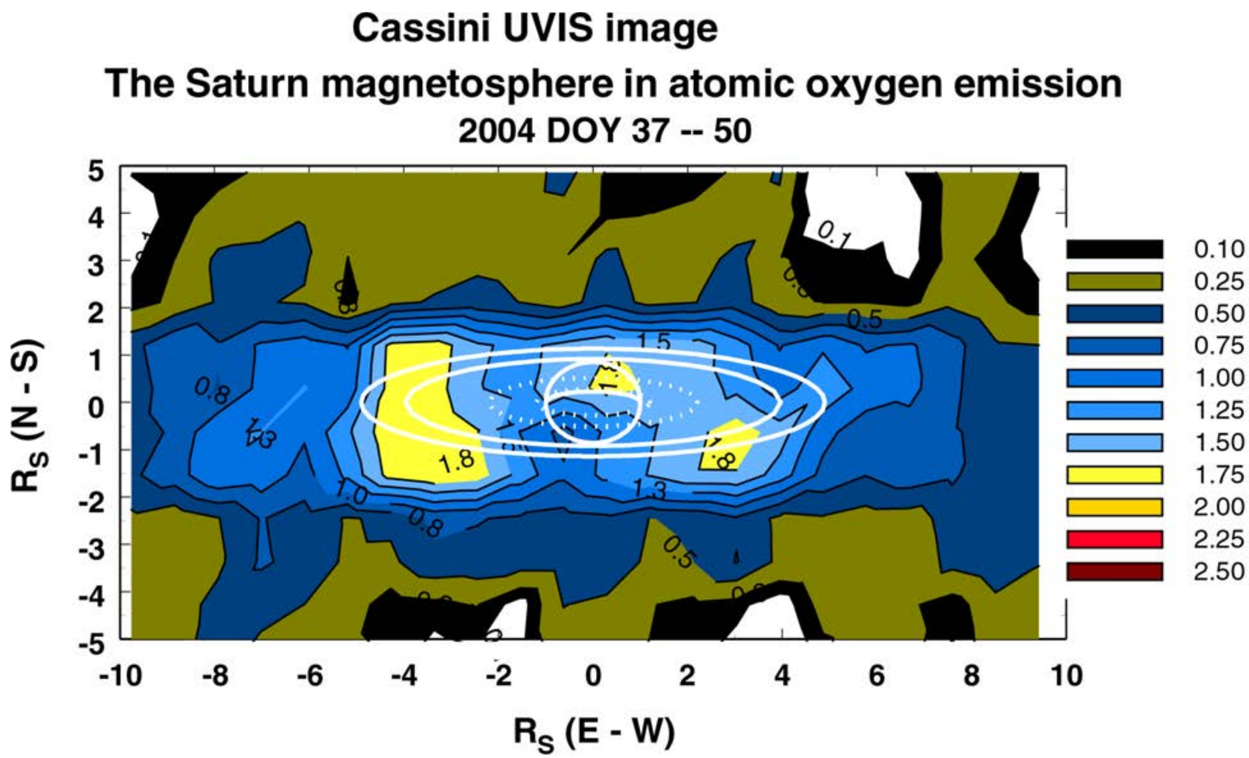
[note that escape velocity = 23,000 cm/sec]

S = 1.6 x 10^{16} * (80 x 10^5) * (46 x 10^3) = 5.8 x 10^{27} H_2O molecules / sec = ~170 kg / sec

Is this enough to explain all the water products in the we see in the Saturn system?

Water Products in Saturn's System

- The Saturnian system is filled with the products of water molecules:
  - H detected by Voyager in 1980, 1981
  - OH detected by Hubble Space Telescope in 1992
  - Atomic Oxygen imaged by UVIS in 2004



Water and its products are lost from the system by collisions, photo- and electron-dissociation and ionization

Estimates of required re-supply rates range from 3×10^{27} to 2×10^{28} water molecules/sec

Water Vapor Plume

1. What is the rate of water vapor coming from Enceladus?
   – Is it enough to explain all the atomic O in the system? Yes, mystery solved!

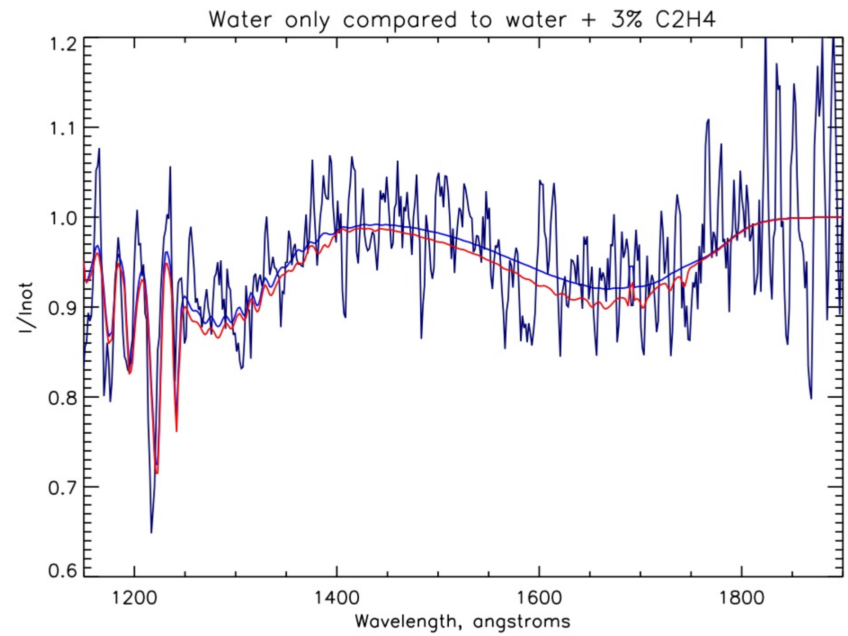
2. Are there other constituents?
   – Up to ~10% of the plume could consist of other gases
   – UVIS data can set upper limits on some of these

Any other constituents?

- One of Cassini's other instruments reported detection of a species with an atomic mass of 28 amu; candidates:
  - CO, C_2H_4, N_2

We looked at ethylene (C_2H_4)

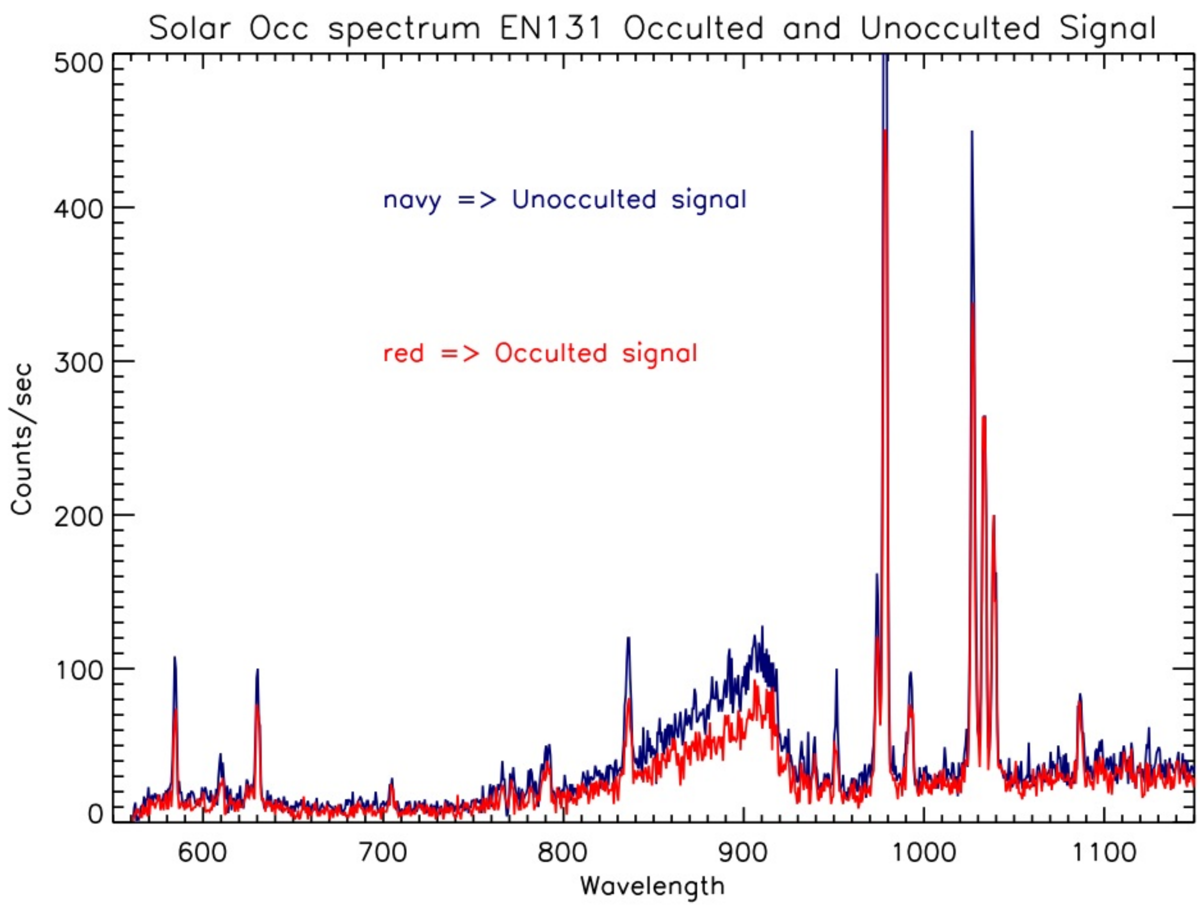
- Ethylene plus water compared to water only
- C_2H_4 column density = 4.8×10^{14} cm^{-2}
- H_2O column density = 1.6×10^{16} cm^{-2}
- Water only is still best fit to occulted spectrum although there are some interesting matches to small dips with ethylene added in



- Similarly, UVIS does not detect CO
  - formal 2-σ upper limit is 3.6×10^{14} cm^{-2}
    - corresponds to mixing ratio with H_2O of 3.0%

- What about N_2?

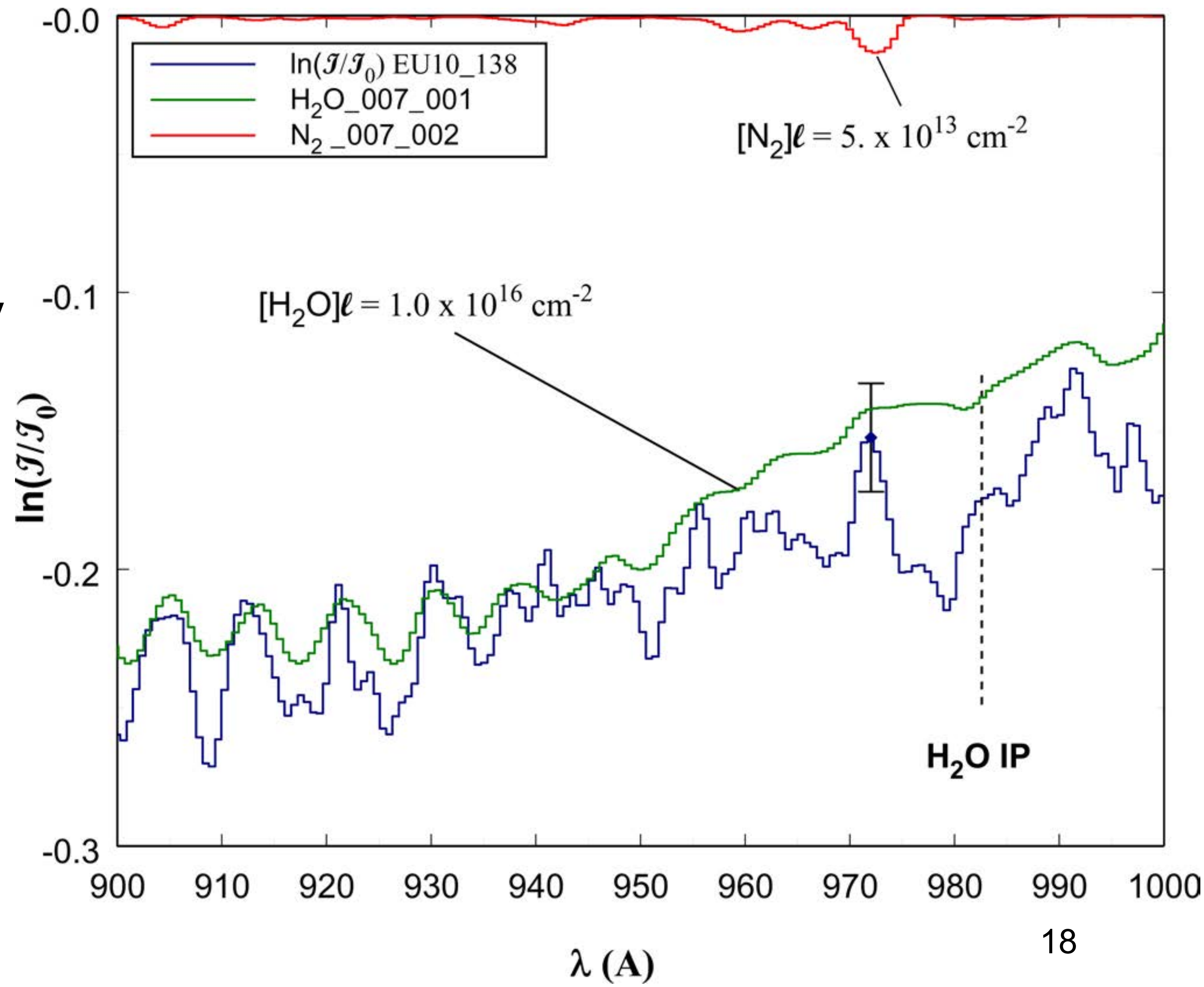
2010 EUV Spectrum from the Solar Occultation



Navy is unocculted solar spectrum, with typical solar emissions
Red is solar spectrum attenuated by Enceladus' plume – all attenuation is due to water vapor absorption

Solar Occultation results – Plume Composition

- H_20 fit to absorption spectrum
- Column density of H_2O = 0.9 x 10^{16} cm^{-2}
- No N_2 absorption feature -> N_2 upper limit of 5 x 10^{13} cm^{-2}



Jets in the Plume

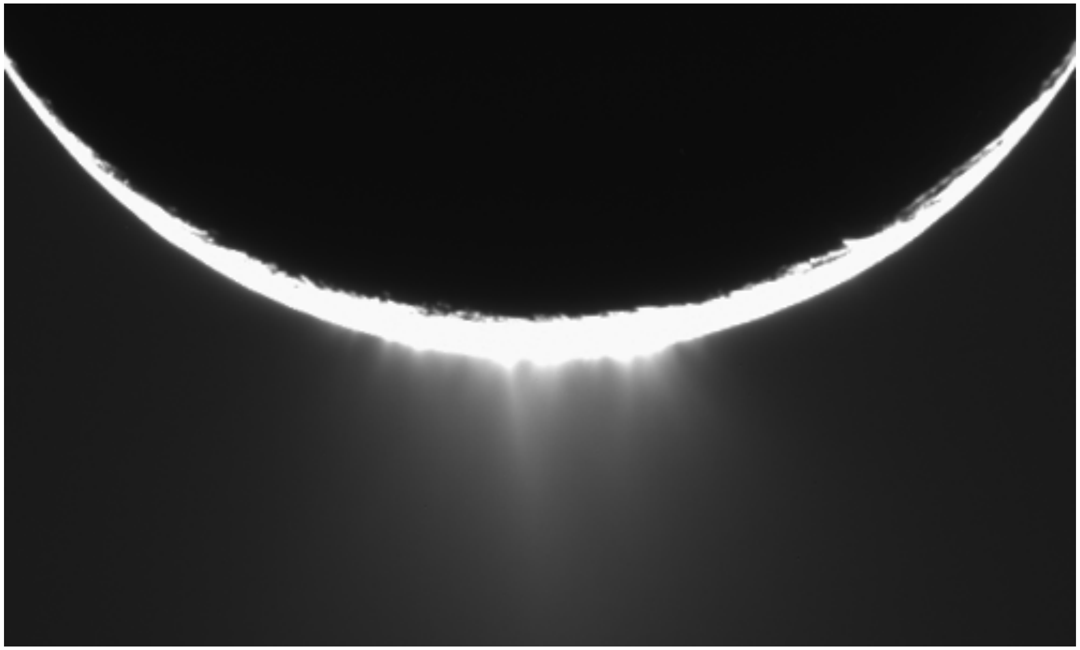
1. What is the structure of Enceladus plume?
   – We have several “cuts” through the plume, what do they tell us?

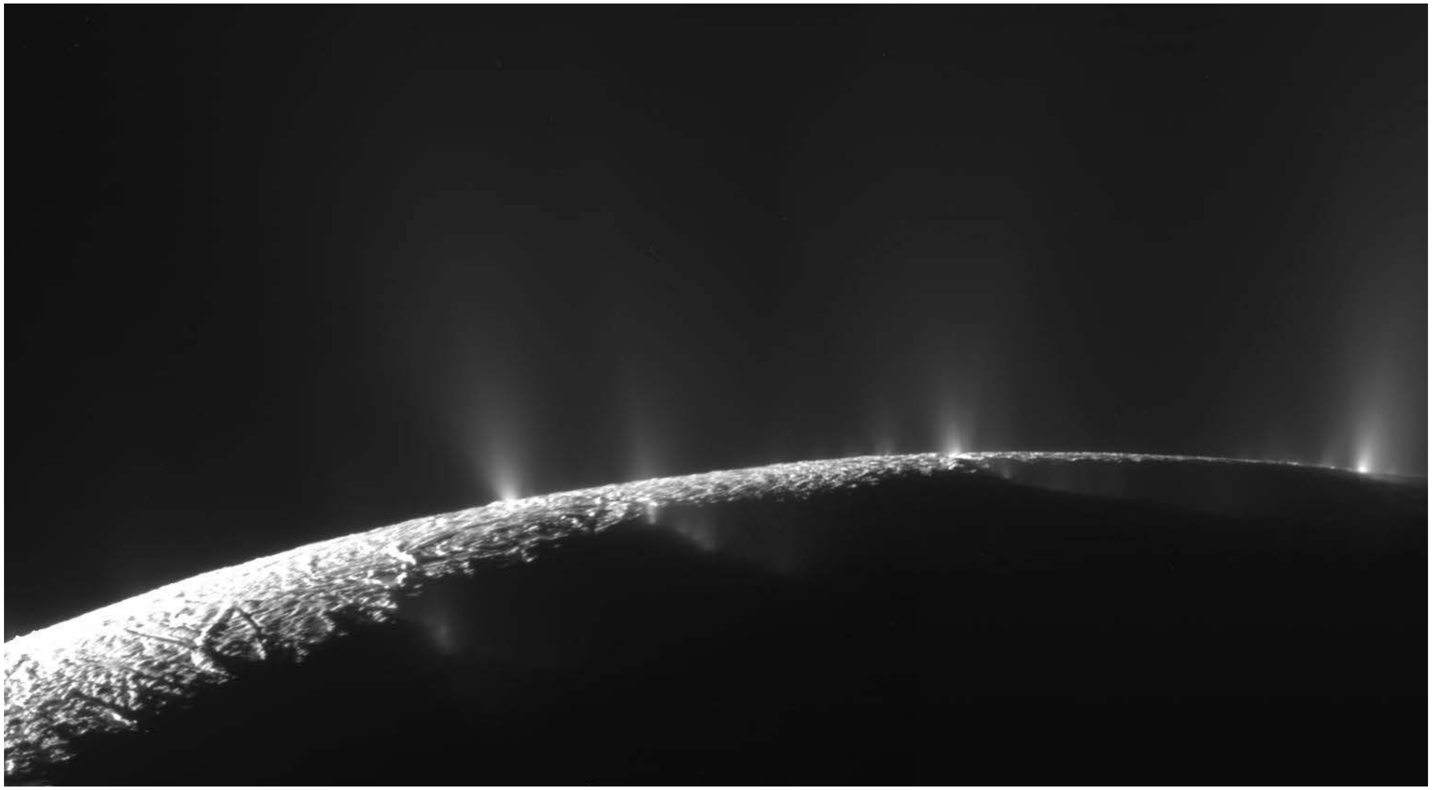
2. Do we see jets of gas that might correlate to the jets of ice particles?

Jets

Numerous dust jets are observed coming from the tiger stripes

These are very small particles of ice, visible only when the jets are backlit



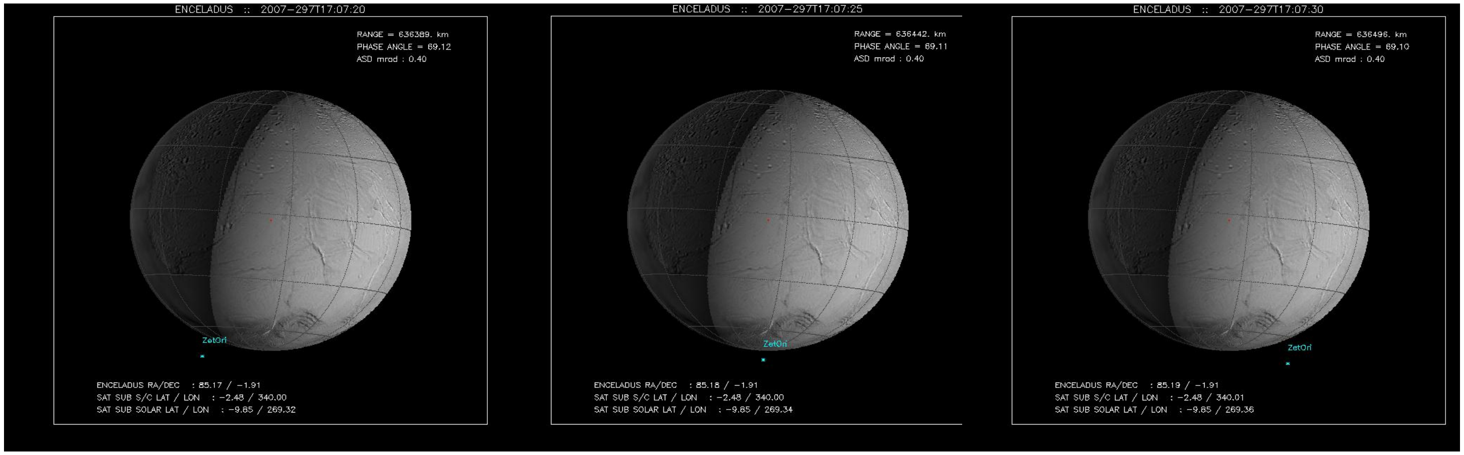


Are there also collimated gas jets that would be detectable by UVIS? Can they be correlated?

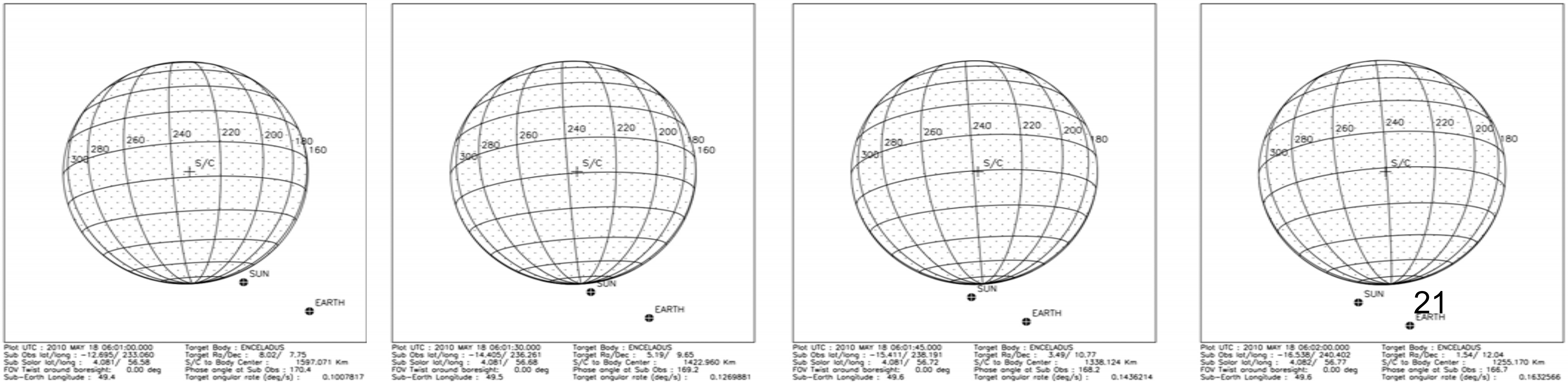
The Occultation Collection

Horizontal cuts through the plume

2007 - zeta Orionis Occultation

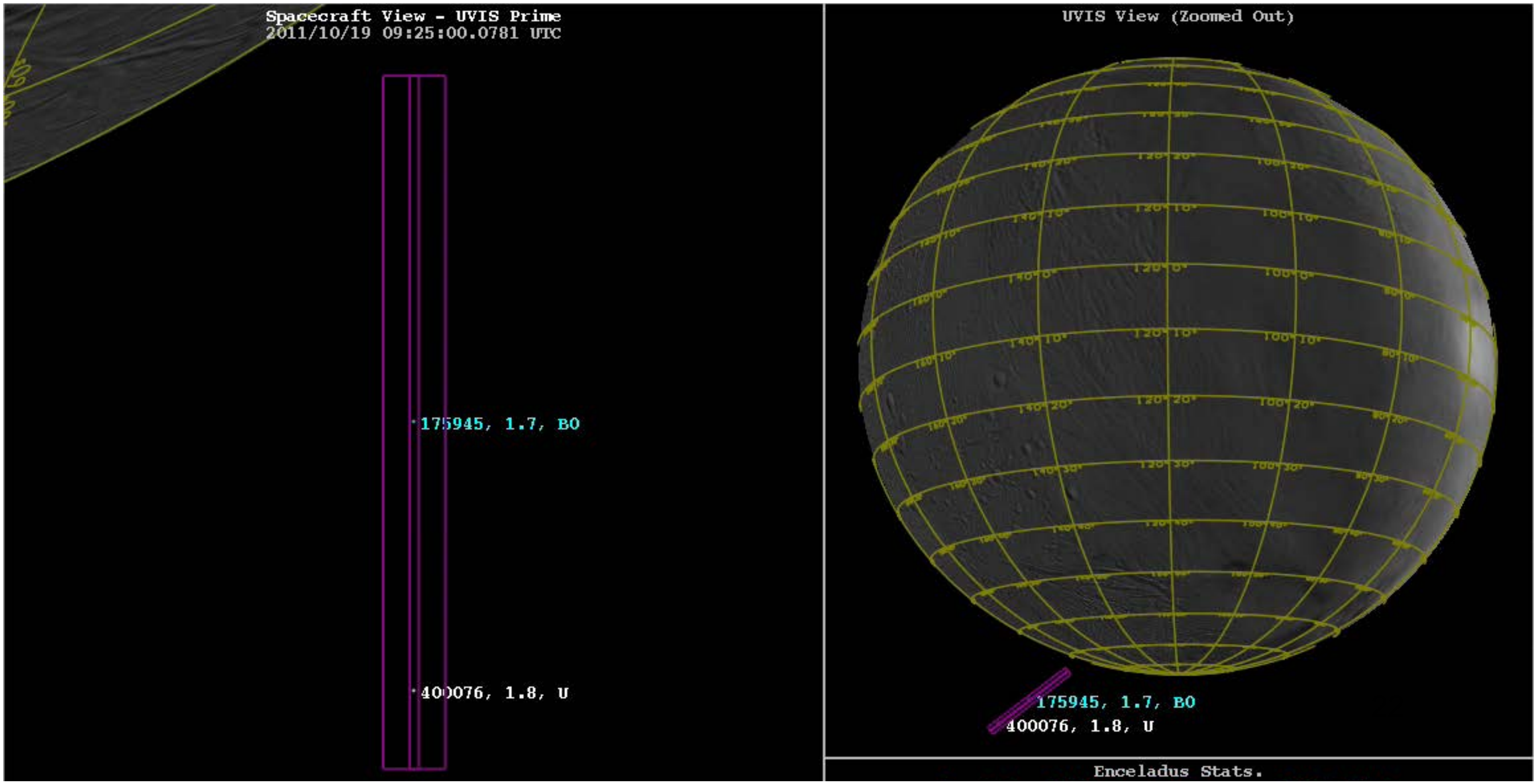


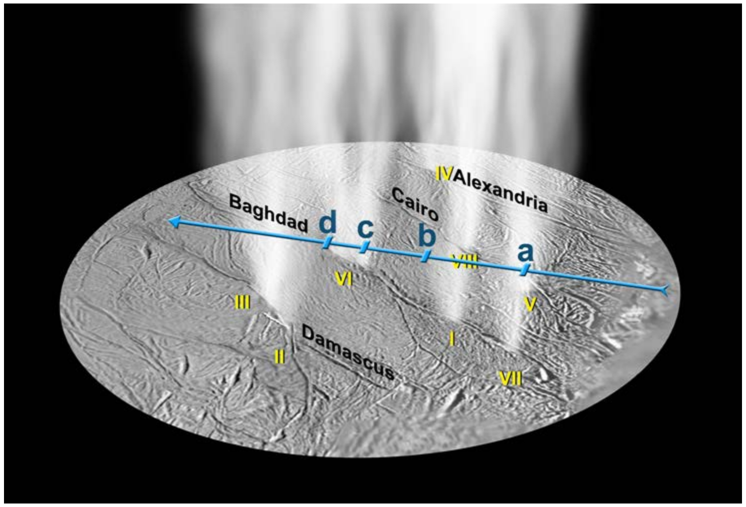
2010 - Solar Occultation



Orion's Belt Dual Occultation Geometry

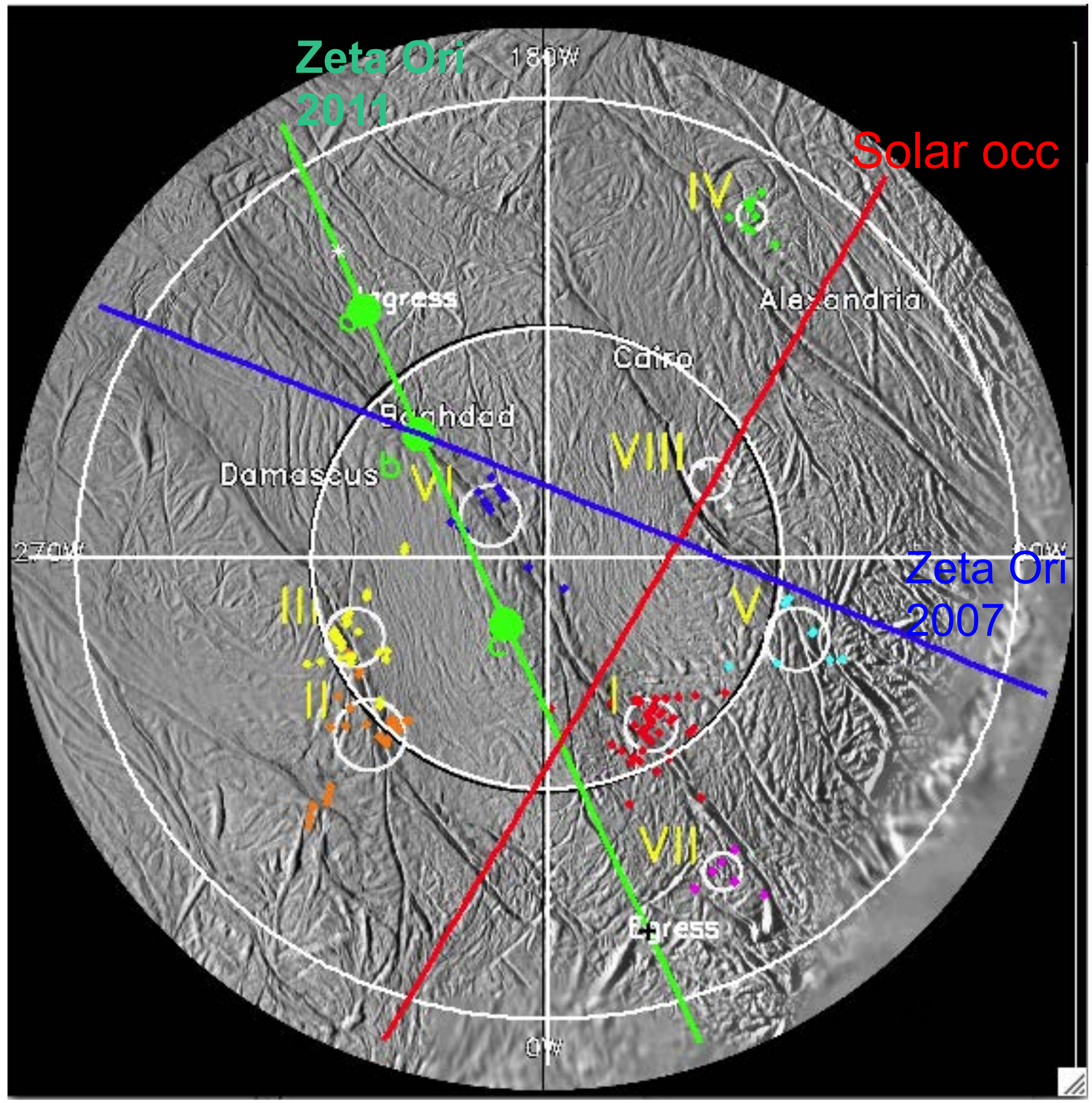
- Dual stellar occultation by Enceladus' plume, 19 October 2011, of epsilon Orionis (blue) and zeta Orionis (white)
- Horizontal cut through plume





Plume Horizontal Cuts

Basemap from Spitale & Porco, 2007

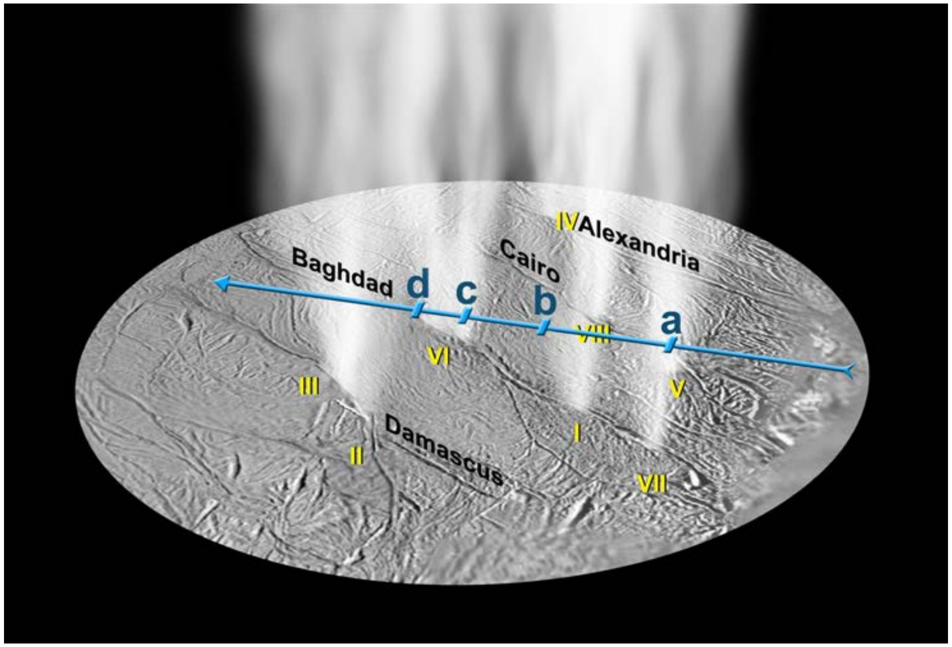


In all occultations we look through the plume

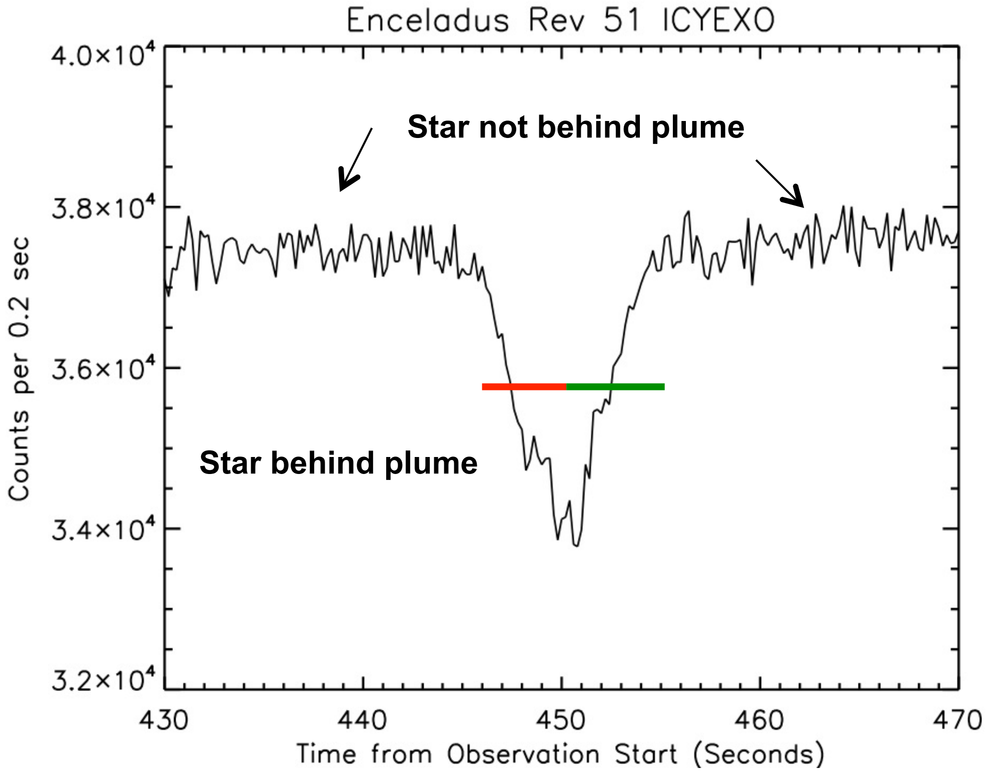
The groundtrack is the perpendicular dropped to the surface from the ray to the star

- Blue => zeta Orionis 2007
- Red => Solar occ 2010
- Green => zeta Orionis 2011

UVIS Discovery of Supersonic Gas Jets



- We use the High Speed Photometer (HSP) to look for enhanced absorption indicative of jets



- The High Speed Photometer (HSP) detects absorbed starlight over the same wavelengths as the FUV but with much higher time resolution
  - FUV integrations are 5 sec duration
  - HSP is 0.2 sec

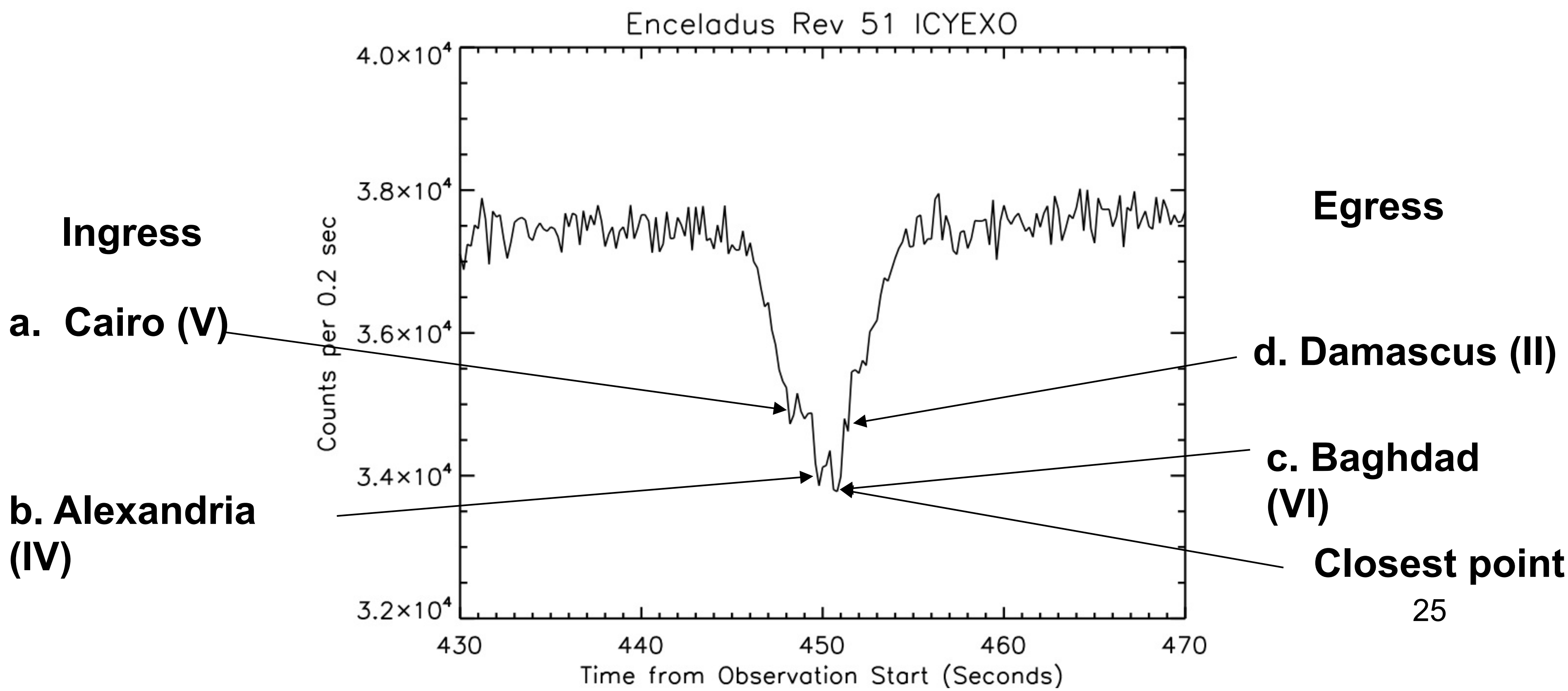
FUV time record 89

FUV time record 90

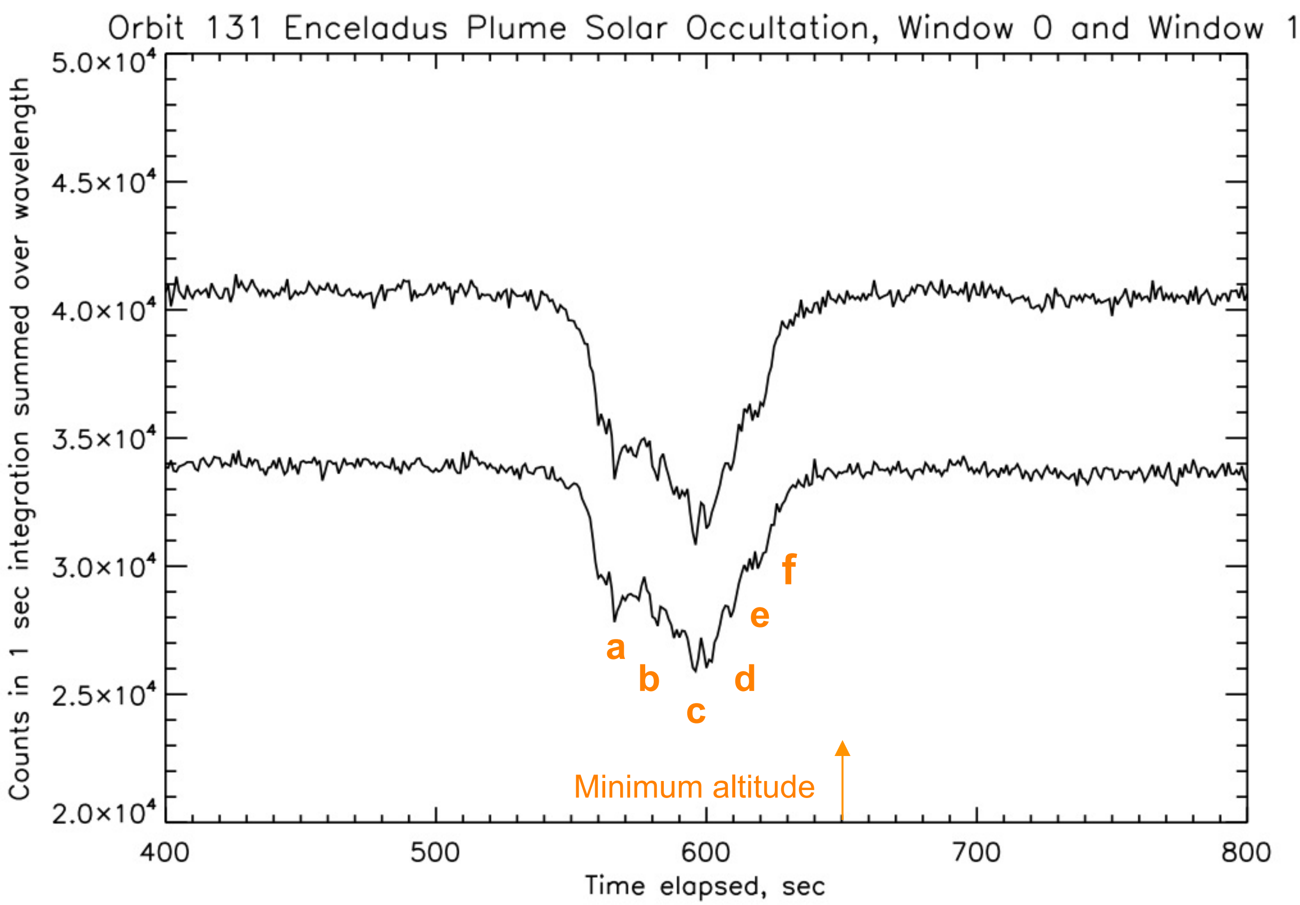
Zeta Orionis Occultation

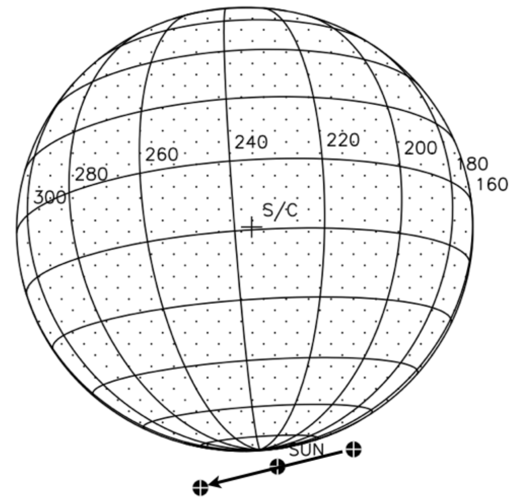
Density in jets is twice the background plume

Gas jet typical width = 10 km at 15 km altitude



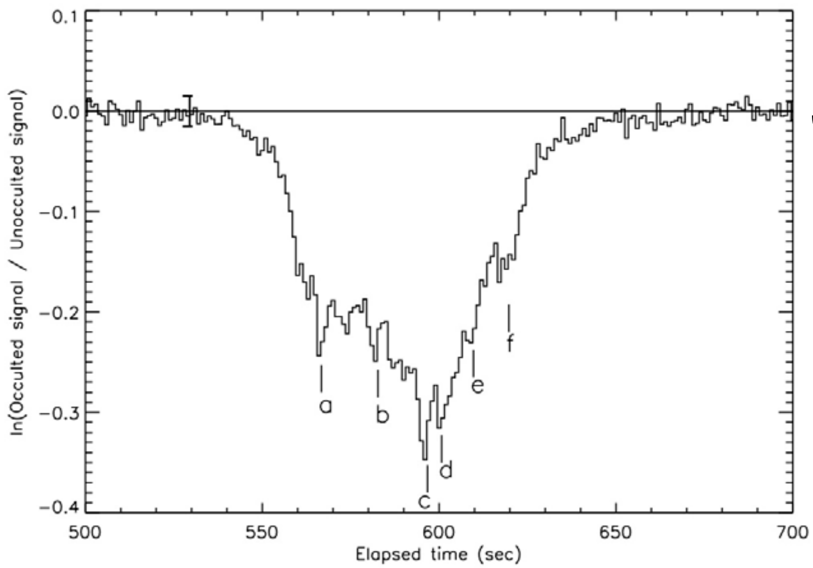
Solar Occ Jet Identifications

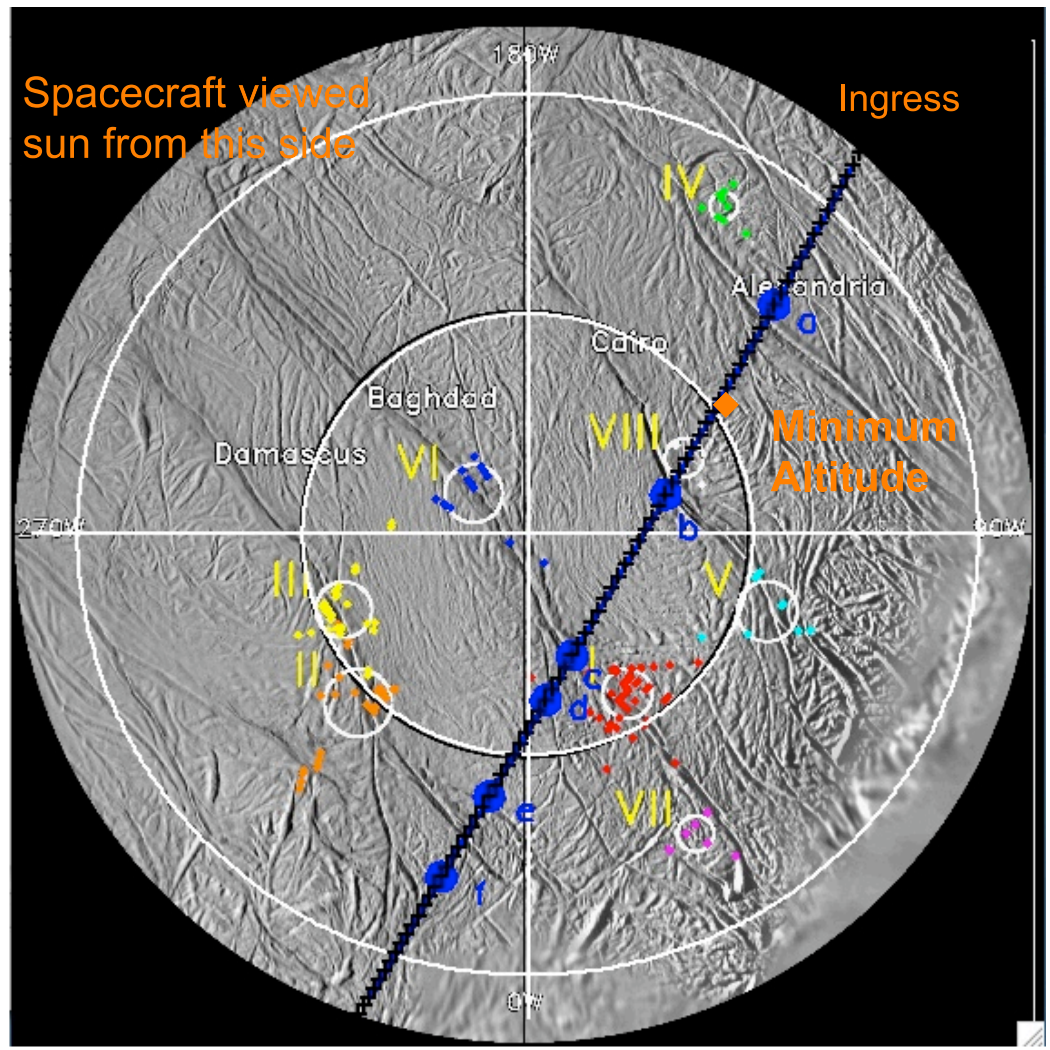




- Window 0 and 1 matching features => jets
- Repetition of features in window 0 and window 1 shows they are not due to shot noise, therefore likely to be real

Jets vs. Tiger Stripes



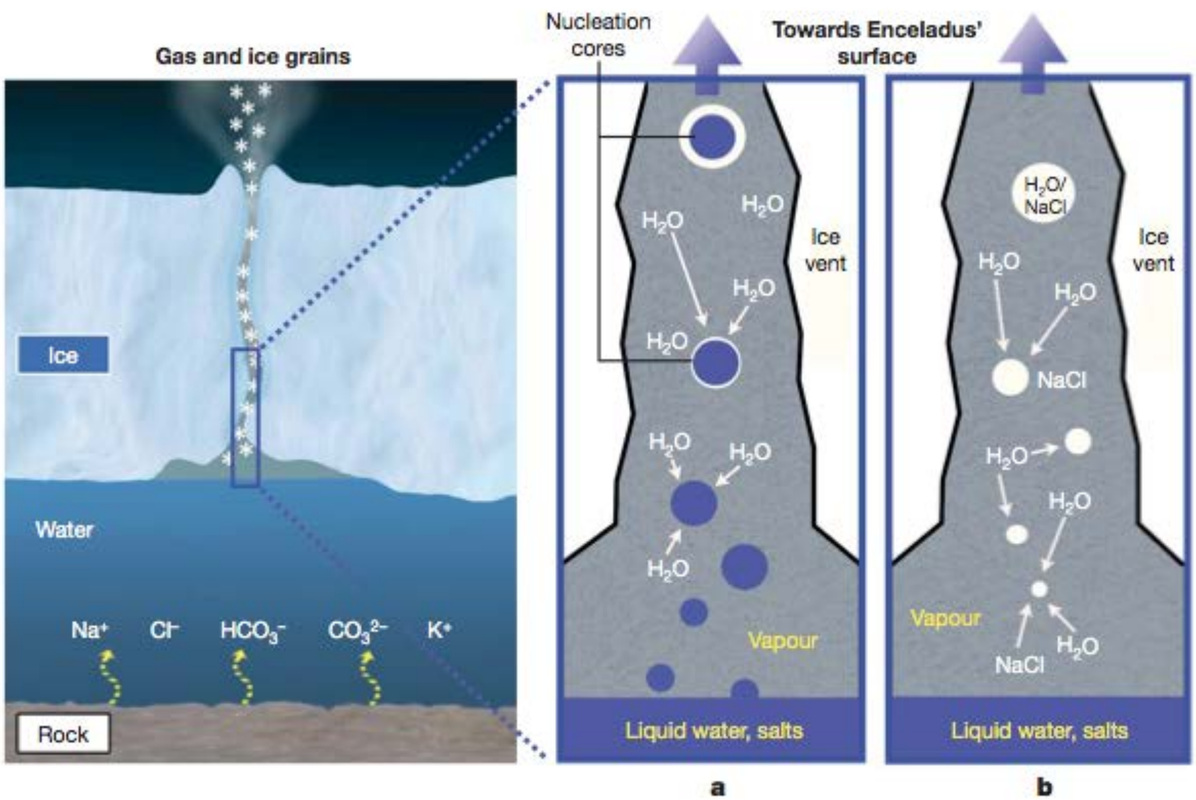


Feature	Altitude (km)	Dust Jet
a	20	Alexandria IV
Closest approach	19.7	
b	21	Cairo V and/or VIII
c	27	Baghdad I
d	30	Baghdad VII
e	38	Damascus III
f	46	Damascus II

Higher time resolution because sun's passage behind the plume was slower

Supersonic Jets

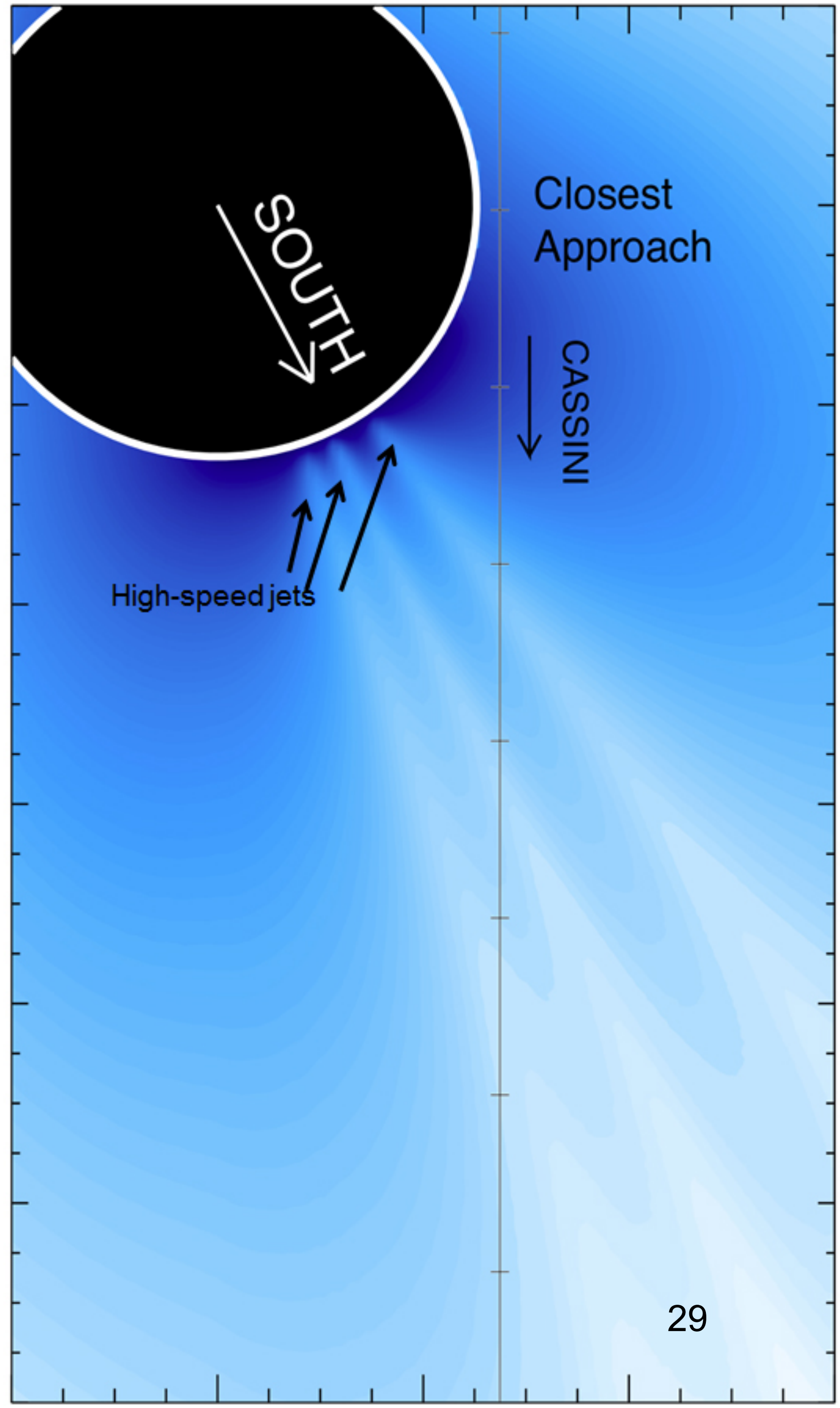
- Collimated jets are supersonic
- The full width half max (FWHM) of jet **c** (Baghdad I) is ~10 km at a jet intercept altitude of 29 km (z_0)
- Estimating the mach number as ~2 z_0/FWHM the gas in jet c is moving at a Mach number of 6; estimates for the other jets range from 5 to 8



- Consistent with model that gas is accelerated in nozzles to the surface to supersonic speeds

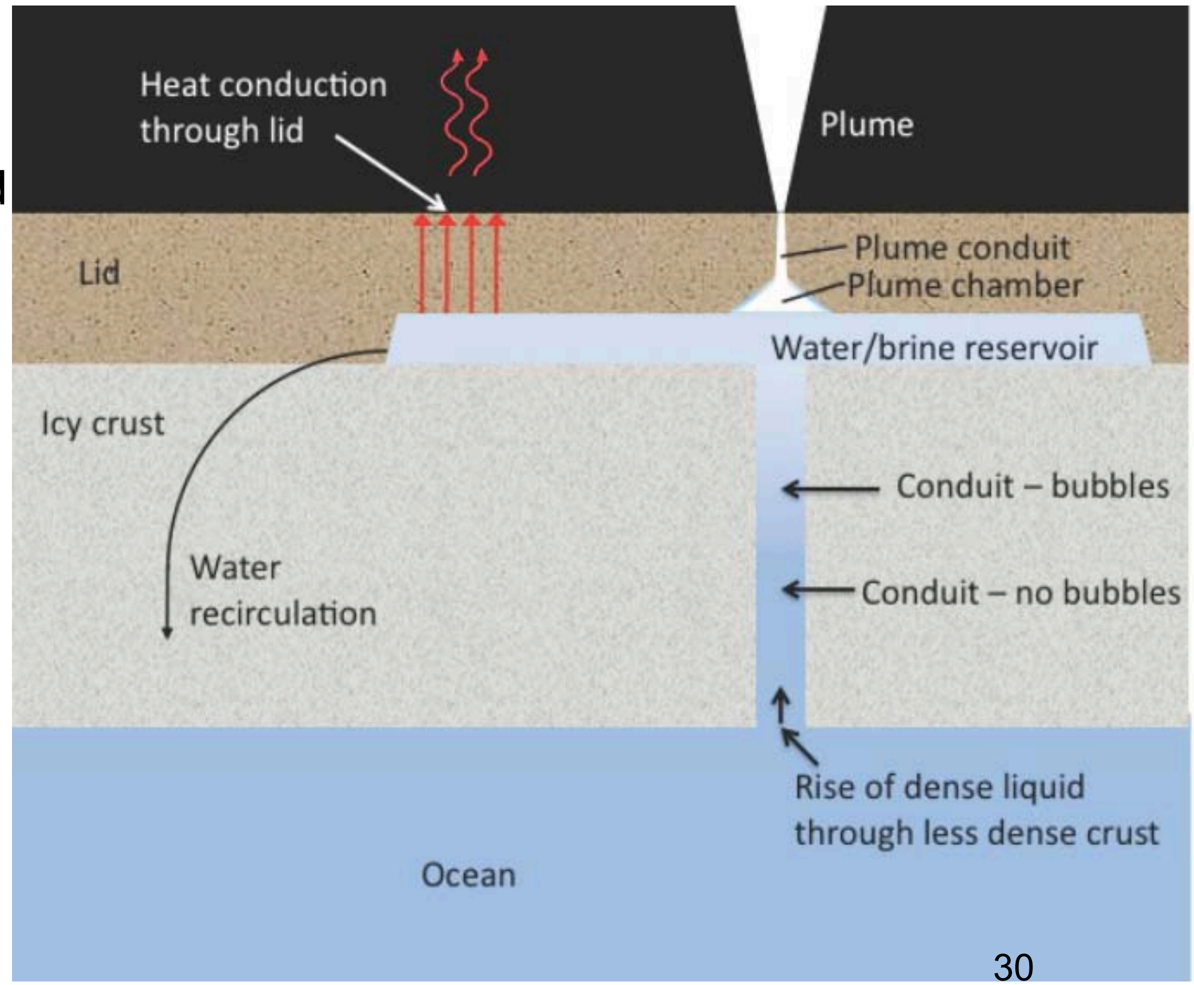
Particle Size and Composition

- Cassini's Dust Analyzer (CDA) detects two sizes of ice grains from Enceladus' south pole:
  - High speed gas jets, seen in UVIS data, propel mostly small (2 micron) pure ice (salt-poor) grains far out into space forming the E ring
  - The more diffuse plume lofts bigger, mostly salt-rich ice grains; these heavier grains are primarily found closer to the surface, deeper in the plume, and fall back to the surface



- Perrier ocean model puts this all together, loosely
- Subsurface ocean is charged with dissolved gases
- Bubbles come out of solution as liquid rises, when they pop (in the water/brine reservoir) the salt-rich aerosols detected by CDA are formed
- Gas and salt-rich particles escape along length of tiger stripe
- Gas is also accelerated in nozzles to surface where the smallest grains condense; CDA sees salt-poor particles, UVIS sees supersonic jets
- Tiger stripe / nozzle physical structure yet to be explained

The "Perrier" Ocean



Recap: What have we learned from occultations?

- Composition
  - The plume is primarily composed of water vapor
  - Upper limits have been set for CO, N_2, C_2H_4
- Source rate
  - Flux of water is ~200 kg/sec
    - Range is from 170 kg/sec to 220 kg/sec
    - Suggests that Enceladus has been steadily erupting for past 7 years
    - Enough to explain all the water products observed in the Saturn system (H, O, OH)
- Plume / jet structure
  - Collimated jets are detected with estimated mach number of > 5
  - Propel small ice particles out to become Saturn's E ring

We conclude…

Supersonic gas jets are consistent with the model of nozzle-accelerated gas coming from liquid water reservoir

High velocity jets are also consistent with Cassini Dust Analyzer data showing compositional partitioning: small salt-poor particles reaching the E ring and salt-rich particles in the diffuse component of the plume close to Enceladus

Lack of N_2 in presence of NH_3 means that a relatively cool liquid reservoir such as the "Perrier Ocean" proposed is viable

But this is not the end of the story

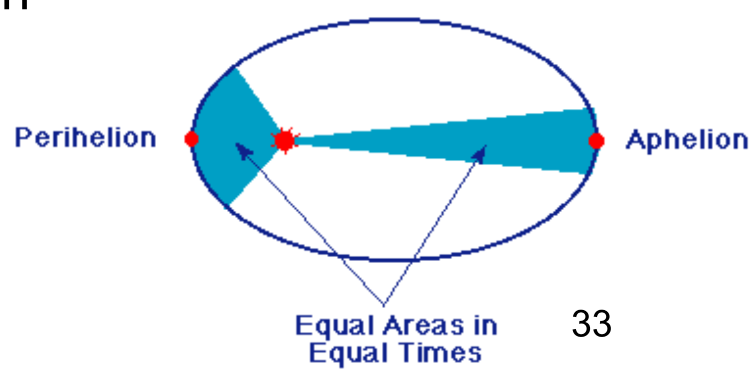
Why is all this happening at Enceladus?

- What is the energy source for all of this action?
  - Is it tidal energy?

- Do we see variability in the rate of water spewing from Enceladus depending on where it is in its orbit?
  - No? Maybe? Yes?

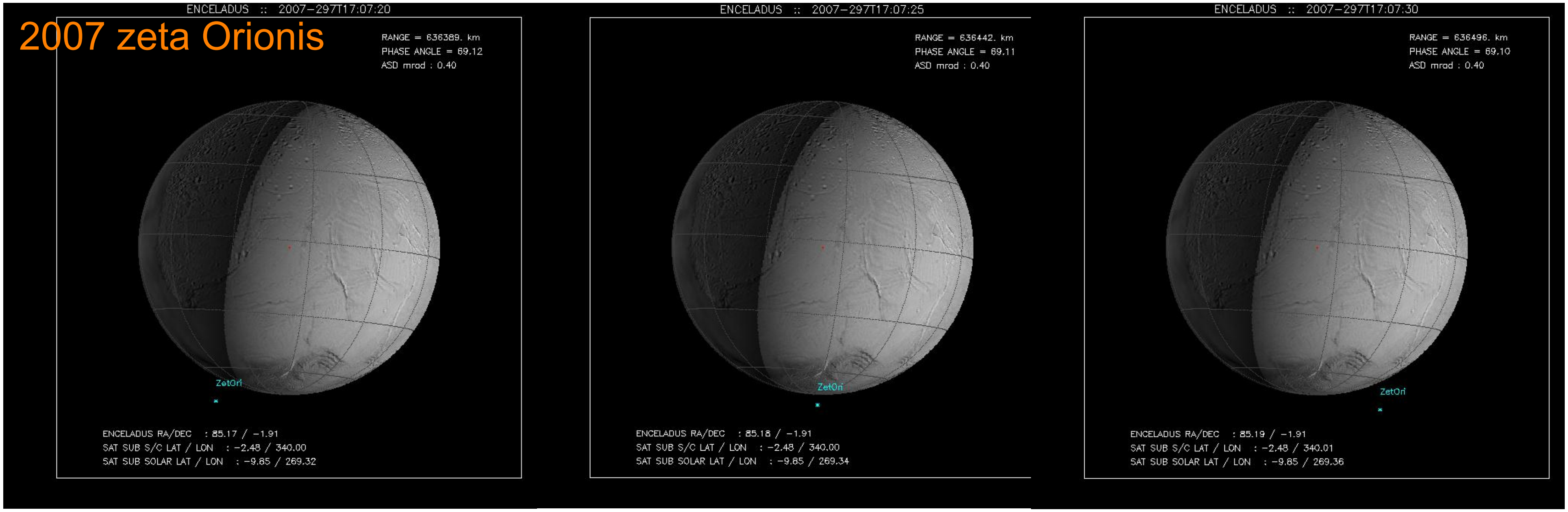
Enceladus is in an elliptical orbit around Saturn

- We describe where Enceladus is by its "mean anomaly" or "orbital longitude"
- Perikrone is the closest point, at 0^0 orbital longitude; apokrone the furthest, at 180^0
- Stresses will be different, depending on where Enceladus is in its orbit



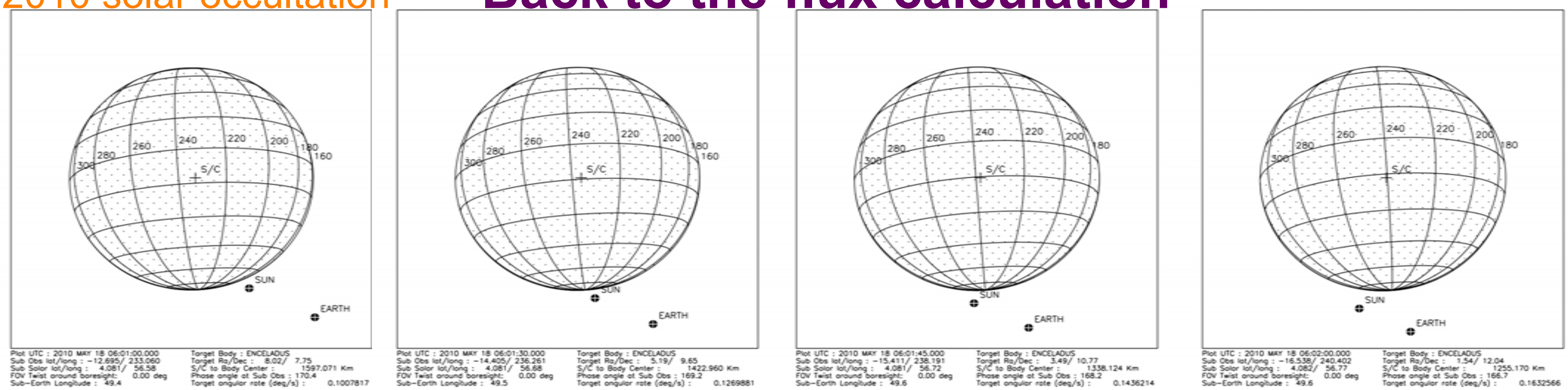
Do we see variability over an orbit?

2007 zeta Orionis



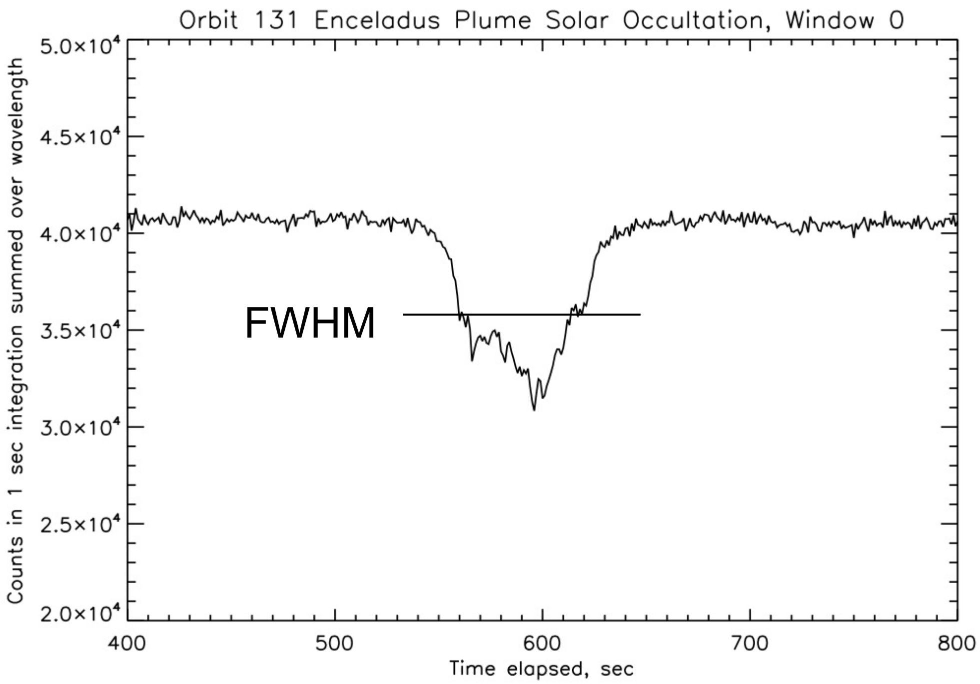
2010 solar occultation

Back to the flux calculation



With these horizontal cuts we get the boundary (full-width-half-max) of the plume

Calculate Plume Dimension



Total duration of Solar Occ:
2min 19sec

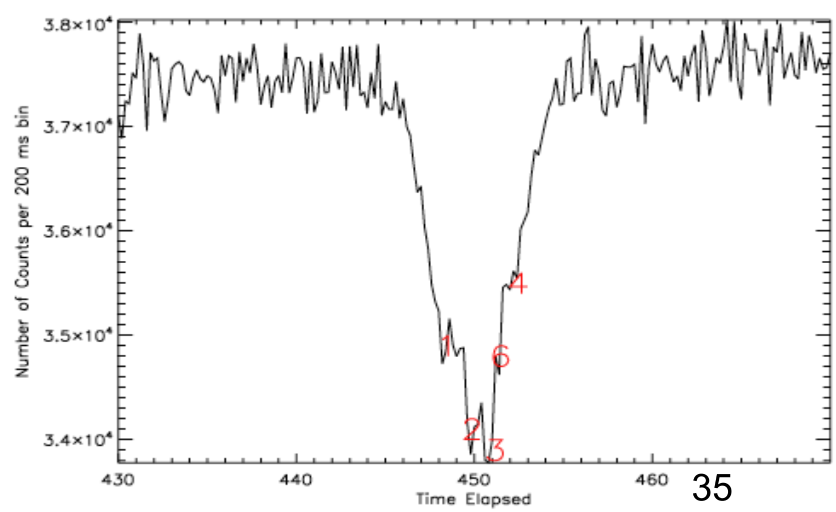
Duration for full-width half max:
56 sec

Line of sight velocity: 2.85 km/sec

Width of plume at FWHM:
56 sec * 2.85 = **160 km**

Zeta Orionis Occultation

- Zeta Orionis occultation lasted just 10 sec
- Line of sight velocity = 22.5 km/sec
- Width of plume at FWHM = **110 km**



Zeta Orionis occultation

Estimate of Water Source Rate from Enceladus = 200 kg/sec

S = flux (source rate)

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

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

$= n * y * v_{th}$

Where

N = number density / cm^3

x * y = area

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

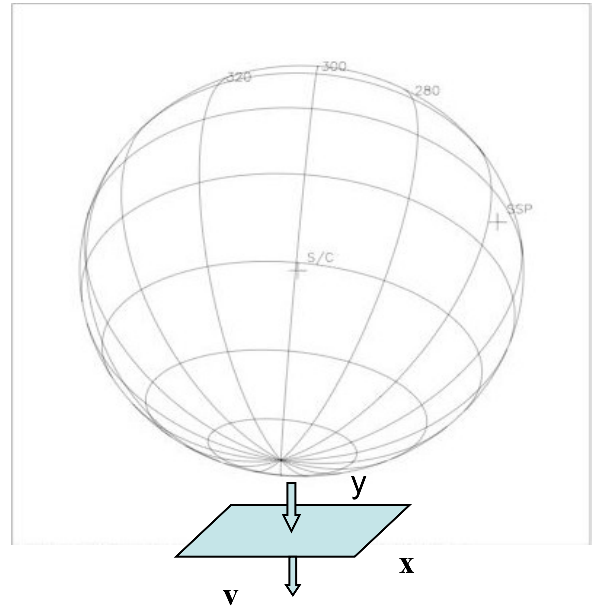
v_{th} = thermal velocity = 45,000 cm/sec for T = 170K

(note that escape velocity = 24,000 cm/sec)

n = column density measured by UVIS

2011:

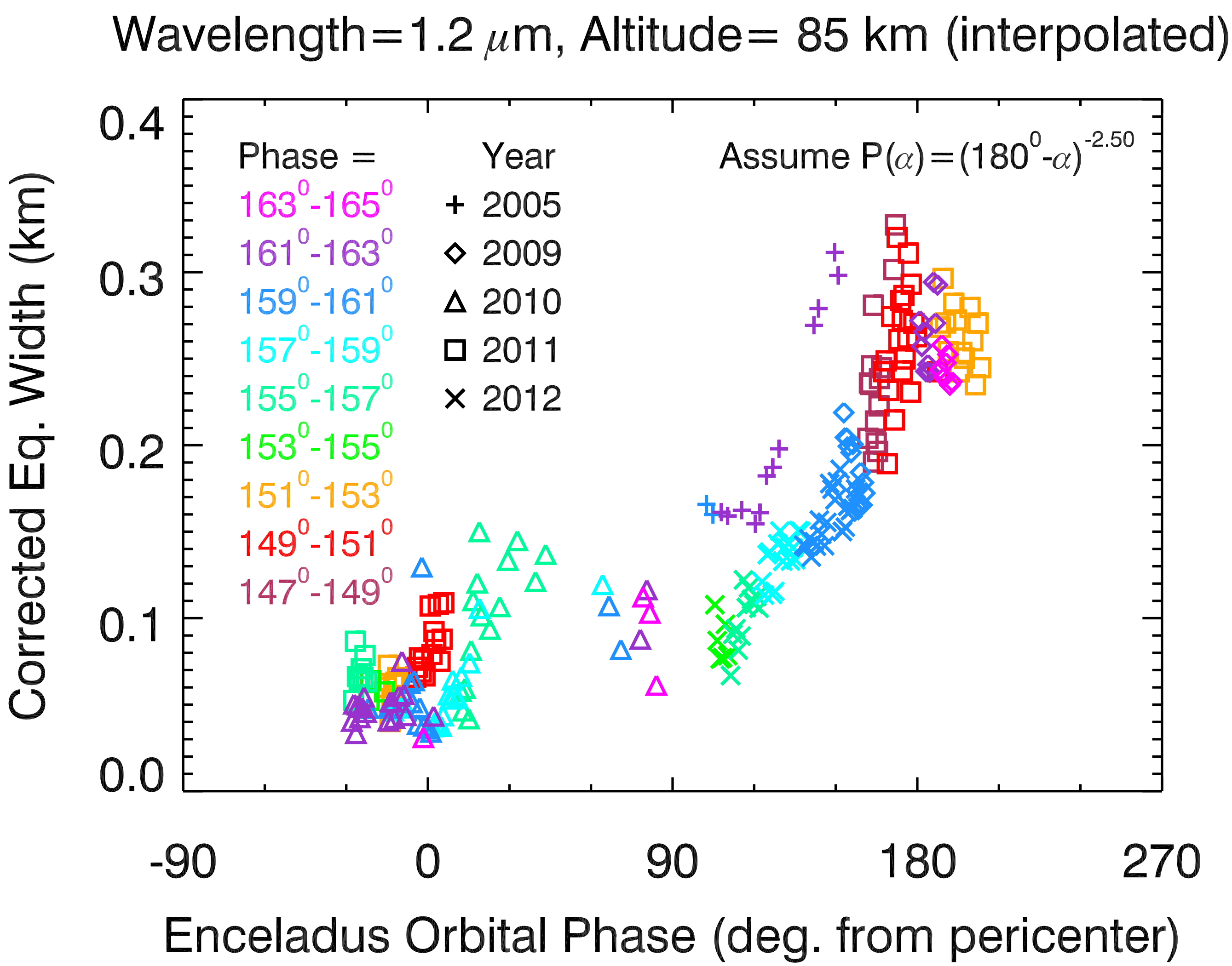
v_{los} = 7.48 km/sec



The source rate has not changed much in >6 years (deviation is <15%, not factors of 2)

Year	n (cm^{-2})	Uncert-ainty +/-	y (x 10^5 cm)	v_{th} (cm / sec)	Flux: Molecules / sec	Flux: Kg/sec	Fraction of orbit from periapsis
2005	1.6 x 10^{16}	0.15 x 10^{16}	80 (est.)	45000	5.8 x 10^{27}	170	0.27
2007	1.5 x 10^{16}	0.14 x 10^{16}	110	45000	7.4 x 10^{27}	220	0.70
2010	0.9 x 10^{16}	0.23 x 10^{16}	150	45000	6 x 10^{27}	180	0.19
2011 - e	1.35 x 10^{16}	0.15 x 10^{16}	120	45000	7.3 x 10^{27}	220	0.70
2011 - z	1.2 x 10^{16}	0.2 x 10^{16}	135	45000	7.3 x 10^{27}	220	

Plume Brightness vs. Orbital Phase



New data from Cassini's near infrared spectrometer (VIMS) shows that the intensity of the eruption of particles from Enceladus varies, depending on where it is in its orbit

Implicates tidal forces

These results are compelling…

So how do we explain what appears to be a fundamental inconsistency between UVIS and the near-infrared spectrometer (VIMS) results?

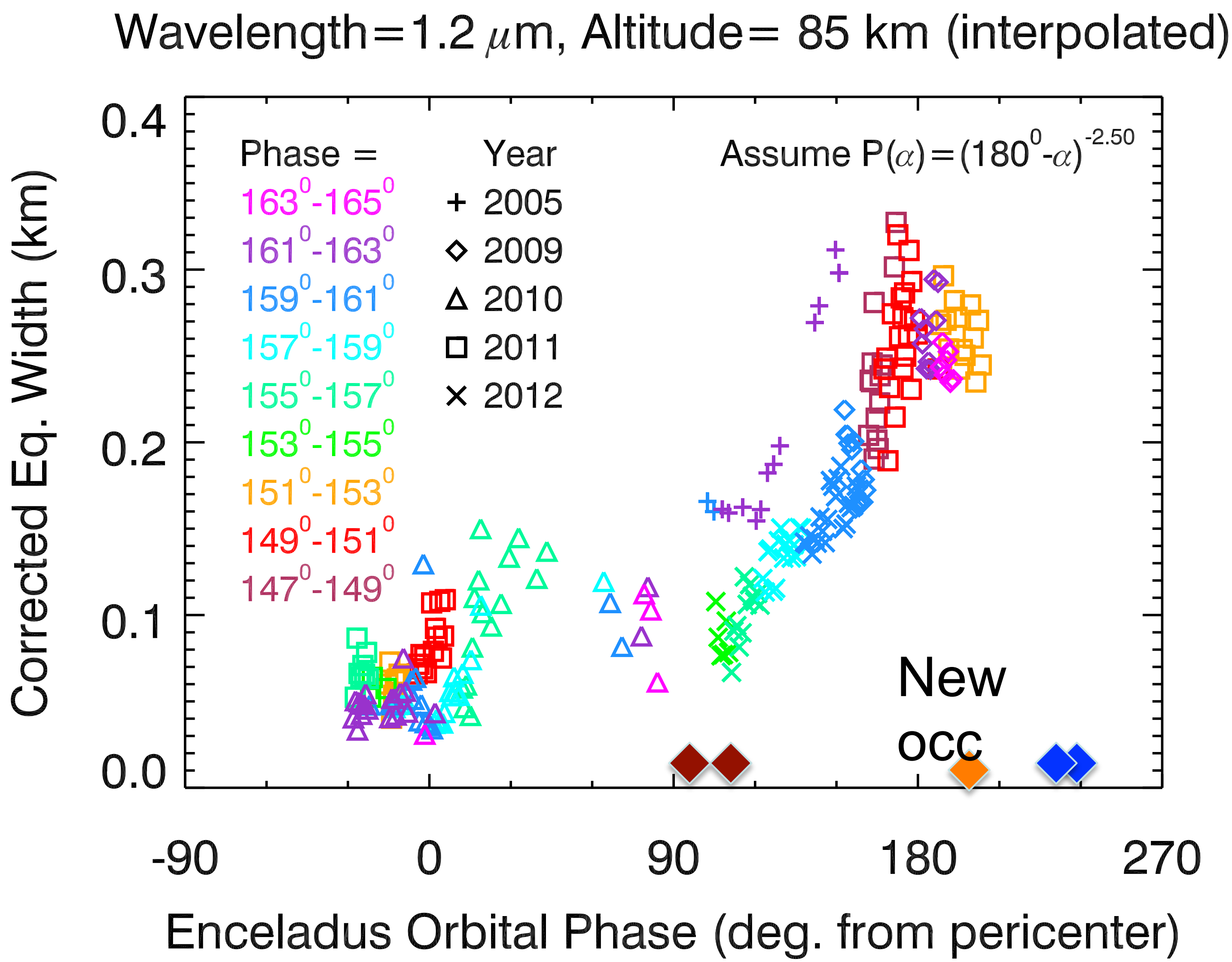
We have an opportunity in 2016 to figure this out

Enceladus Occultation Summary

Year	n (cm^{-2})	Uncert-ainty +/-	y (x 10^5 cm)	v_{th} (cm / sec)	Flux: Molecules / sec	Flux: Kg/ sec	Mean anomaly (orbital position)
2005	1.6 x 10^{16}	0.15 x 10^{16}	80 (est.)	45000	5.8 x 10^{27}	170	**117**
2007	1.5 x 10^{16}	0.14 x 10^{16}	110	45000	7.4 x 10^{27}	220	**236.1**
2010	0.9 x 10^{16}	0.23 x 10^{16}	150	45000	6 x 10^{27}	180	**97.7**
2011 - e	1.35 x 10^{16}	0.15 x 10^{16}	120	45000	7.3 x 10^{27}	220	**~237**
2011 - z	1.2 x 10^{16}	0.2 x 10^{16}	135	45000	7.3 x 10^{27}	220	
2016							**208.3**

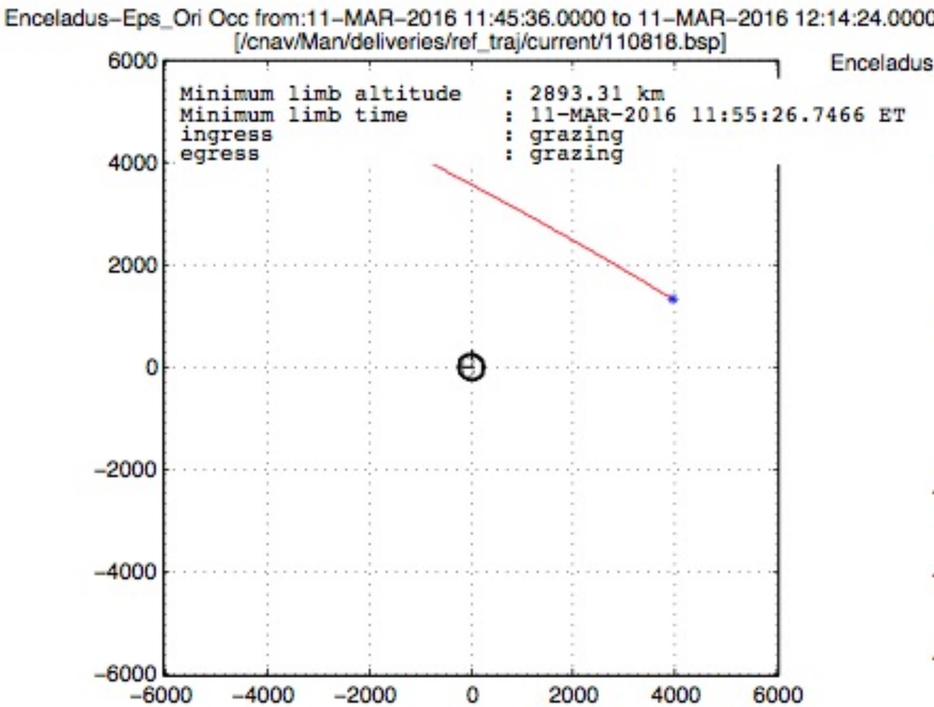
180 is where VIMS sees 3x enhancement in particle flux

UVIS Occultations compared to VIMS Results

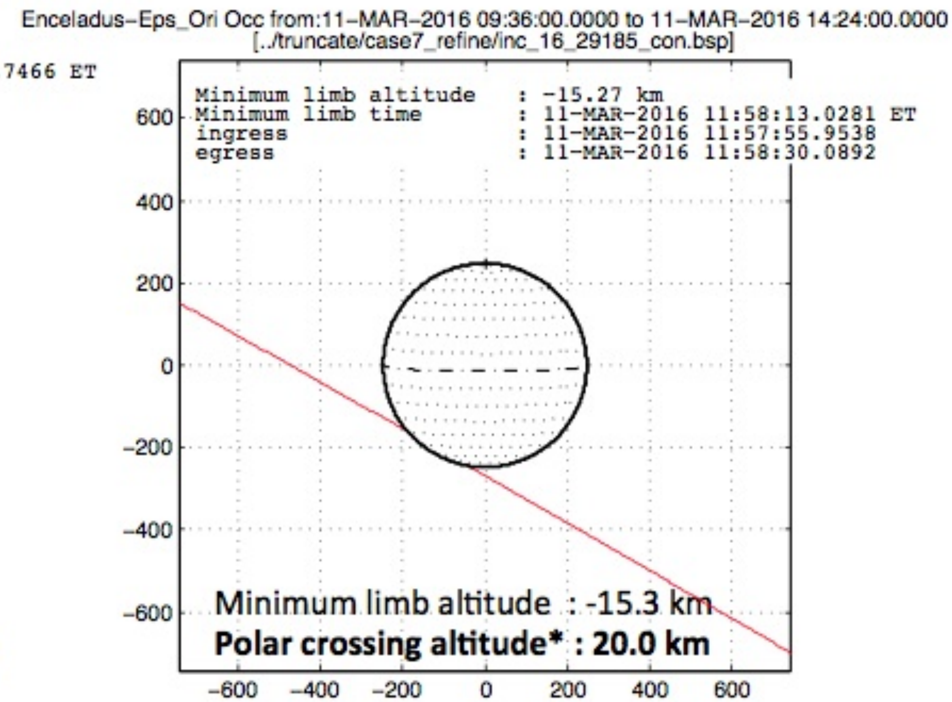


2016 Enceladus Occultation

110818 reference trajectory

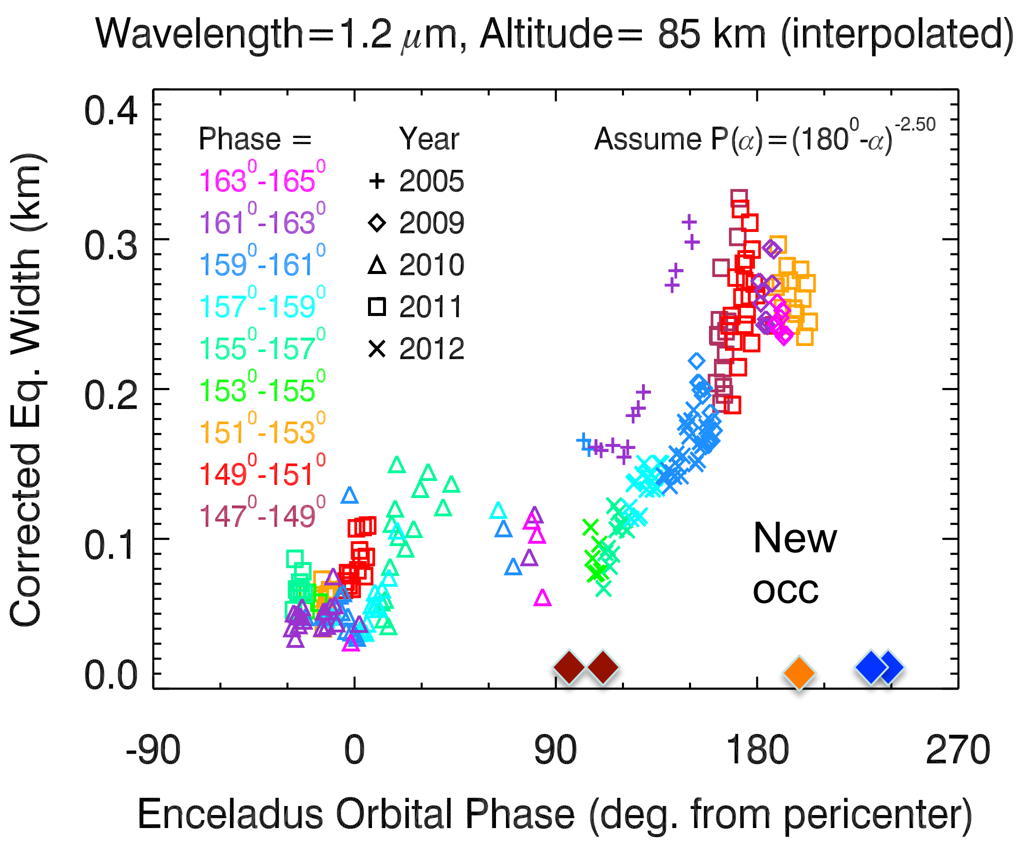


Case 7a – all flybys float (time and altitude)



- *The tour had a close (but not good enough) occultation in 2016*
- *UVIS requested a study to determine if the Enceladus plume occultation could be restored on Rev 233*
- *Nav agreed to take a look at the consequences of restoring the Enceladus occ – yes, it could be restored by using some fuel*

Advantages of the new occultation observation

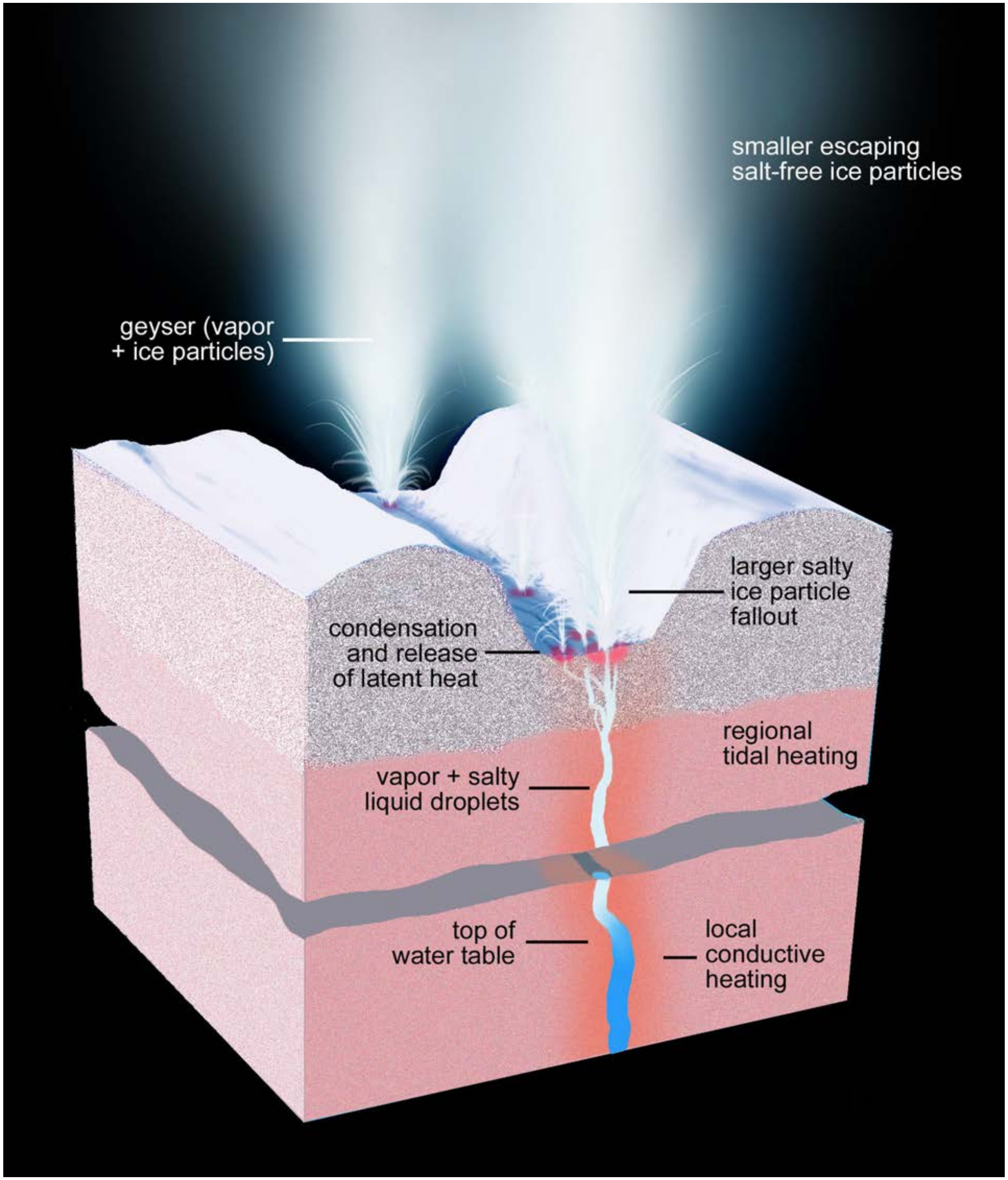


- There are no VIMS measurements from ~210 to -30 to compare to UVIS at 236 –> UVIS data fills in an important gap
- At 208 we should just overlap VIMS near the peak
- The source rate determined by UVIS at mean anomaly = 236 is higher than that at 98 and 117, although in the past we did not consider that necessarily to be significant

UVIS data fills in gap in the VIMS data, will allow us to say whether gas production also depends on the position of Enceladus in its orbit

What is changing below the surface?

- We can only see the products – must model what is below the surface
- ***What is different at perikrone vs. apokrone?***
  - Gas / ice ratio?
  - Nozzle diameter?
  - Temperature?



Looking Forward to the new Data

- Previous occultations have been at mean anomalies of 98^0, 117^0, 236^0

- The VIMS result is sharply peaked enough that UVIS would not have seen an unambiguous corresponding peak in gas flow at 236^0, but should at 208^0

- *UVIS detection of an enhancement in gas flow corresponding to the new VIMS result will motivate new models of Enceladus' interior, jets, and the source of energy for its plume*

- A UVIS non-detection of enhanced gas flow will drive the need for a different explanation of the VIMS observations that could also lead to new understanding of Enceladus' interior

Enceladus Supplying the E Ring