Enceladus’ Water Vapour Plumes

C. J. Hansen
Jet Propulsion Laboratory, California Institute of Technology

L. Esposito, J. Colwell, A. Hendrix, D. Matson, C. Parkinson, W. Pryor, D. Shemansky, I. Stewart, J. Tew, Y. Yung

1 June 2006

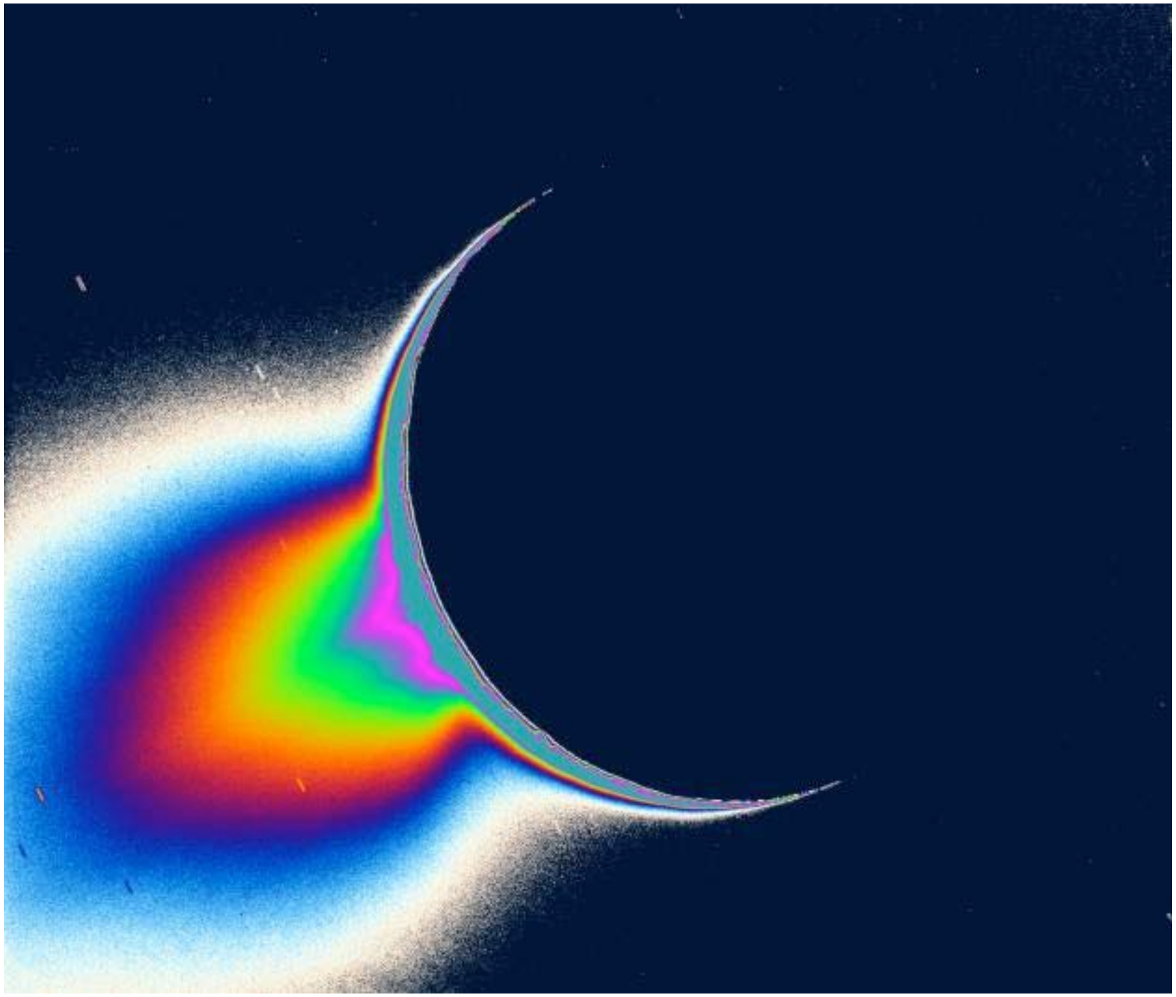
Enceladus is now known to be a geologically active body

Cassini flew by Enceladus three times in 2005, in February, March and July

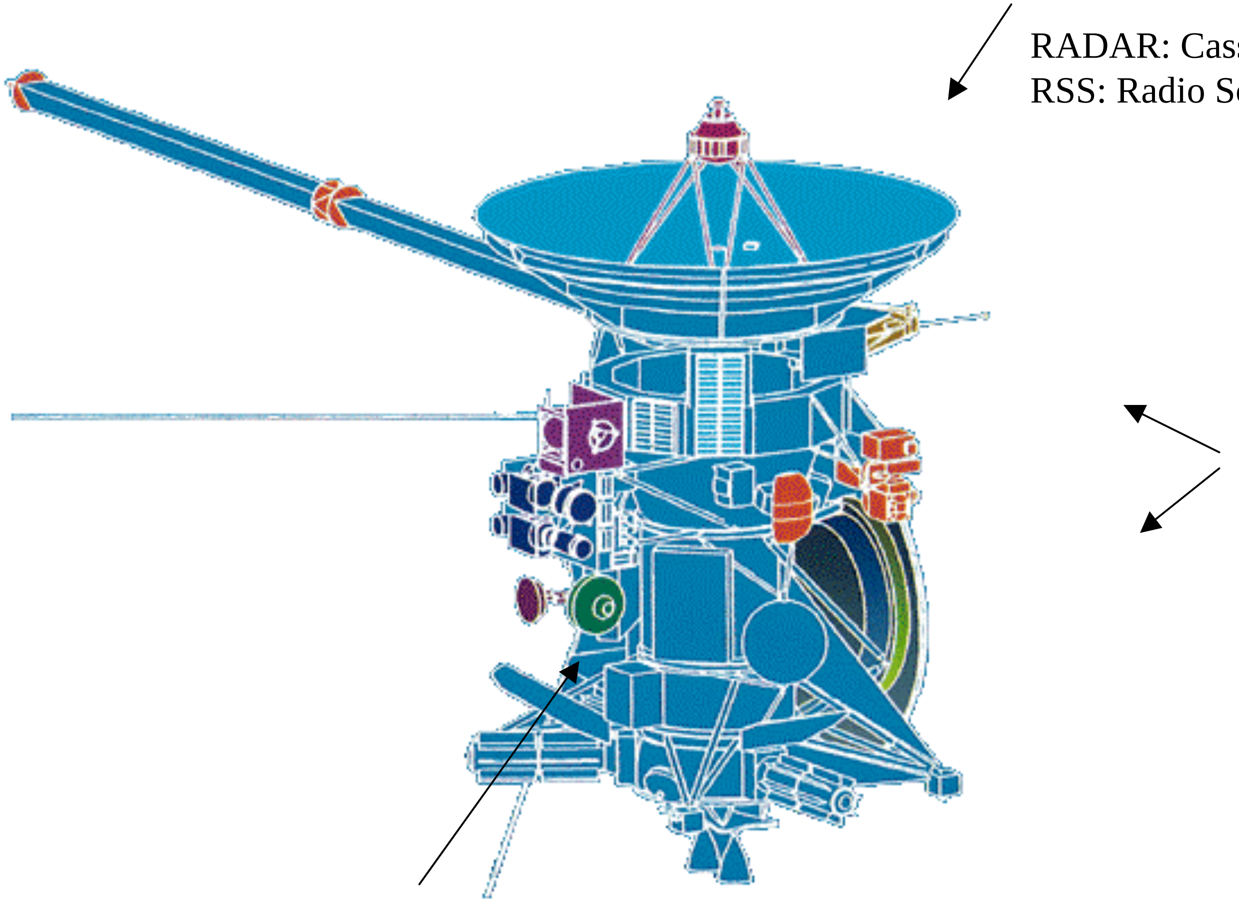
We made the remarkable discovery of plumes coming from the southern pole

All Cassini's instruments contributed to our understanding of this fascinating phenomena

This image was acquired in November 2005, and shows Enceladus' plume extending 435 km



CASSINI - HUYGENS



<u>Microwave Remote Sensing</u>

RADAR: Cassini Radar
RSS: Radio Science Subsystem

<u>Magnetosphere and Plasma Science</u>

CAPS: Cassini Plasma Spectrometer
CDA: Cosmic Dust Analyzer
INMS: Ion and Neutral Mass Spectrometer
MAG: Dual Technique Magnetometer
MIMI: Magnetospheric Imaging Instrument
RPWS: Radio and Plasma Wave Science

<u>Optical Remote Sensing (ORS)</u>

CIRS: Composite Infrared Spectrometer
ISS: Imaging Science Subsystem
UVIS: Ultraviolet Imaging Spectrograph
VIMS: Visible and Infrared Mapping Spectrometer

Cassini Tour Overview

Cassini's prime mission is 4 years

In that time the spacecraft

- orbits Saturn 78 times
- flies by Titan 45 times
- has 8 close flybys of Saturn's icy moons, including 4 of Enceladus

Pre-Cassini View of Enceladus

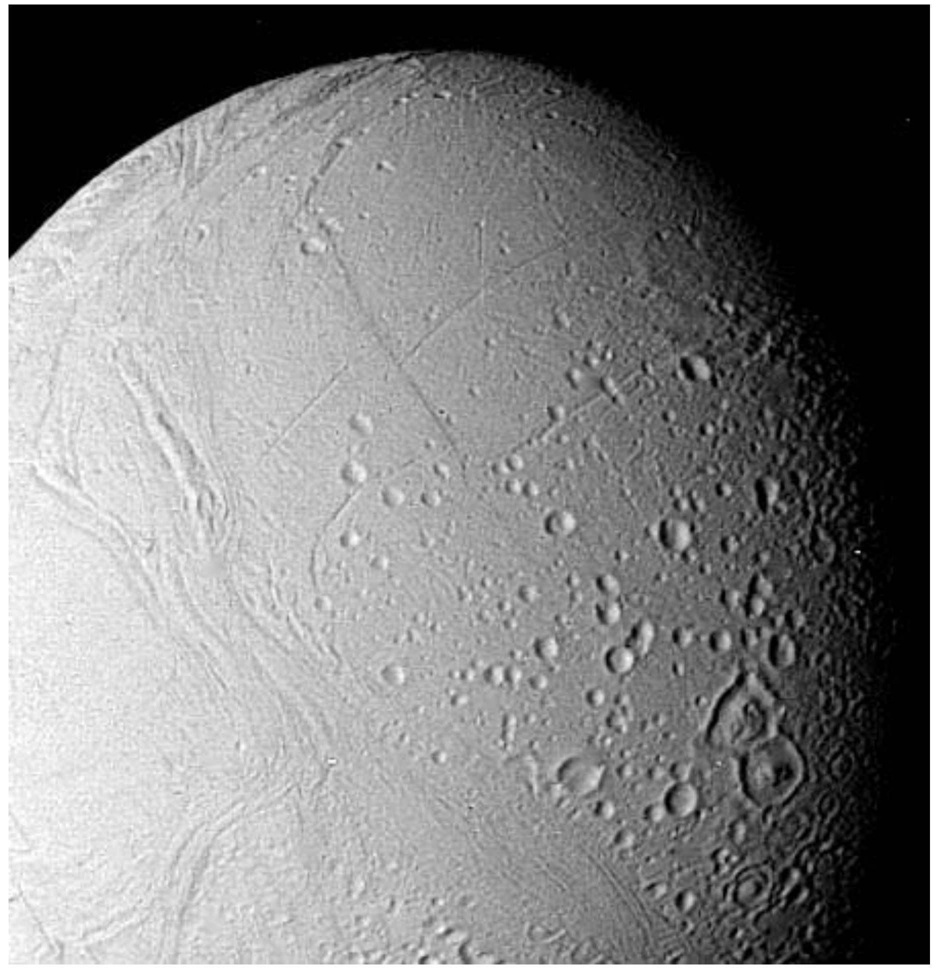
- The best Voyager images of Enceladus showed a geologically young surface

- Enceladus' orbit co-incides with the peak E ring density

Hypothesis: Eruptive activity on Enceladus is the source of the E ring

-> Enceladus was a major target for the Cassini mission

Four close flybys were planned into Cassini's tour of the Saturnian system (3 in 2005, 1 in 2008)



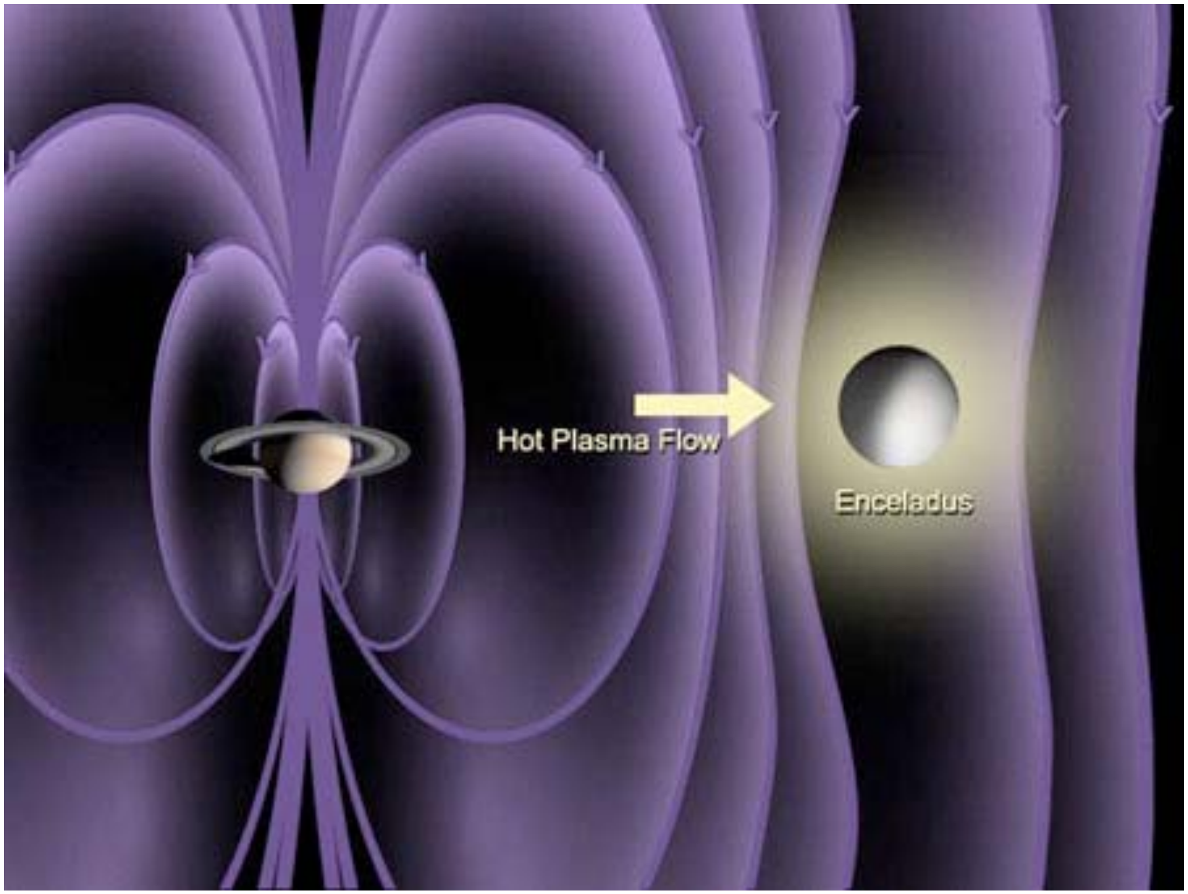
Summary of Major Enceladus flybys

Rev	Date	Distance (km)
003	17 Feb 2005	1200
004	9 March 2005	500
005	29 March 2005	64,000
008	21 May 2005	93,000
011	14 July 2005	175
028	8 Sept 2006	40,000
032	9 Nov 2006	94,000
047	28 June 2007	90,000
050	30 Sept 2007	88,000
061	12 March 2008	100
074	30 June 2008	99,000

Enceladus Flybys

Geometry plots will go here

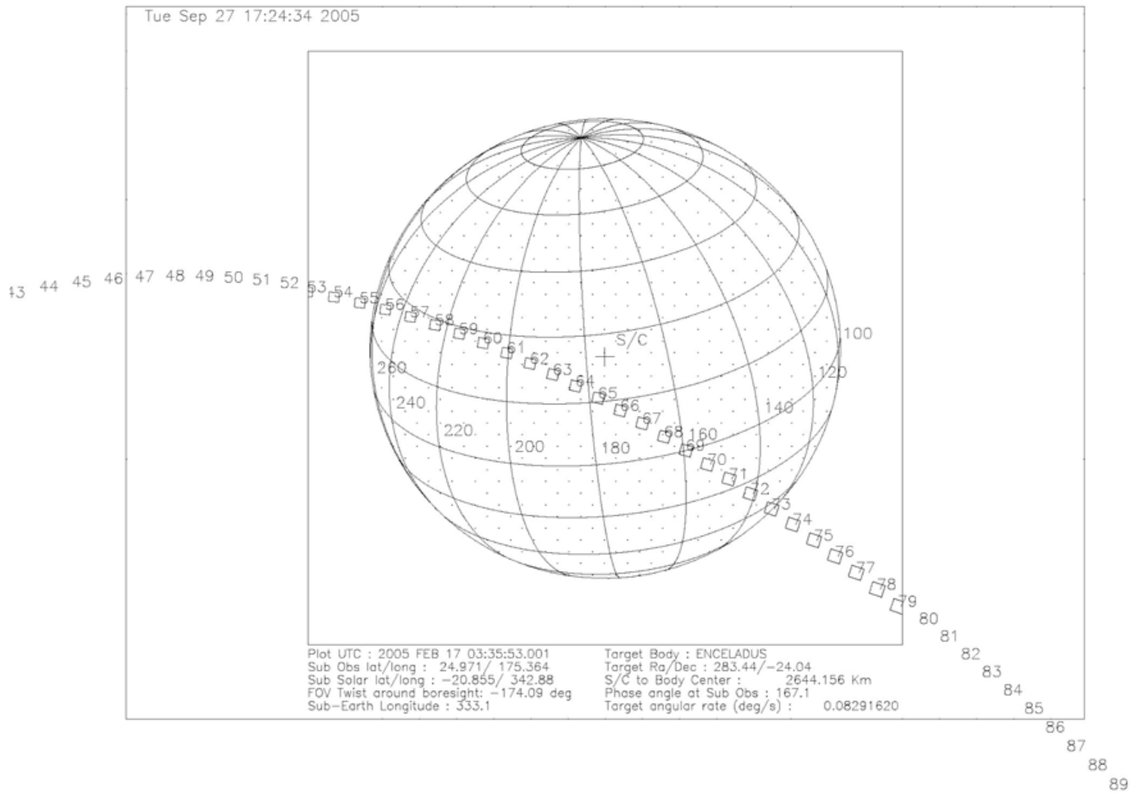
Atmosphere on Enceladus?



Draped field lines observed by the Magnetometer in February were the first evidence for some sort of an atmosphere

Enceladus lambda Scorpii Occultation

Enceladus' youthful geology motivated UVIS observations of stellar occultations, to search for tenuous atmosphere and/or eruptive plumes *but no signature of an atmosphere* was observed by UVIS in February



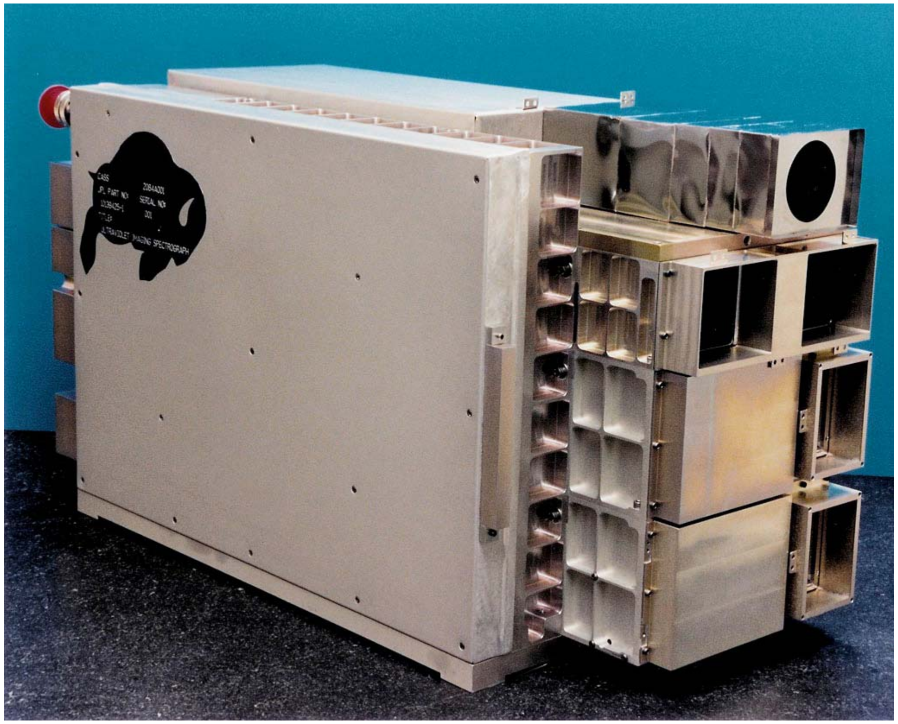
February Lambda Scorpii Occultation

Ingress **Egress**

UVIS Characteristics

UVIS has 4 separate channels:

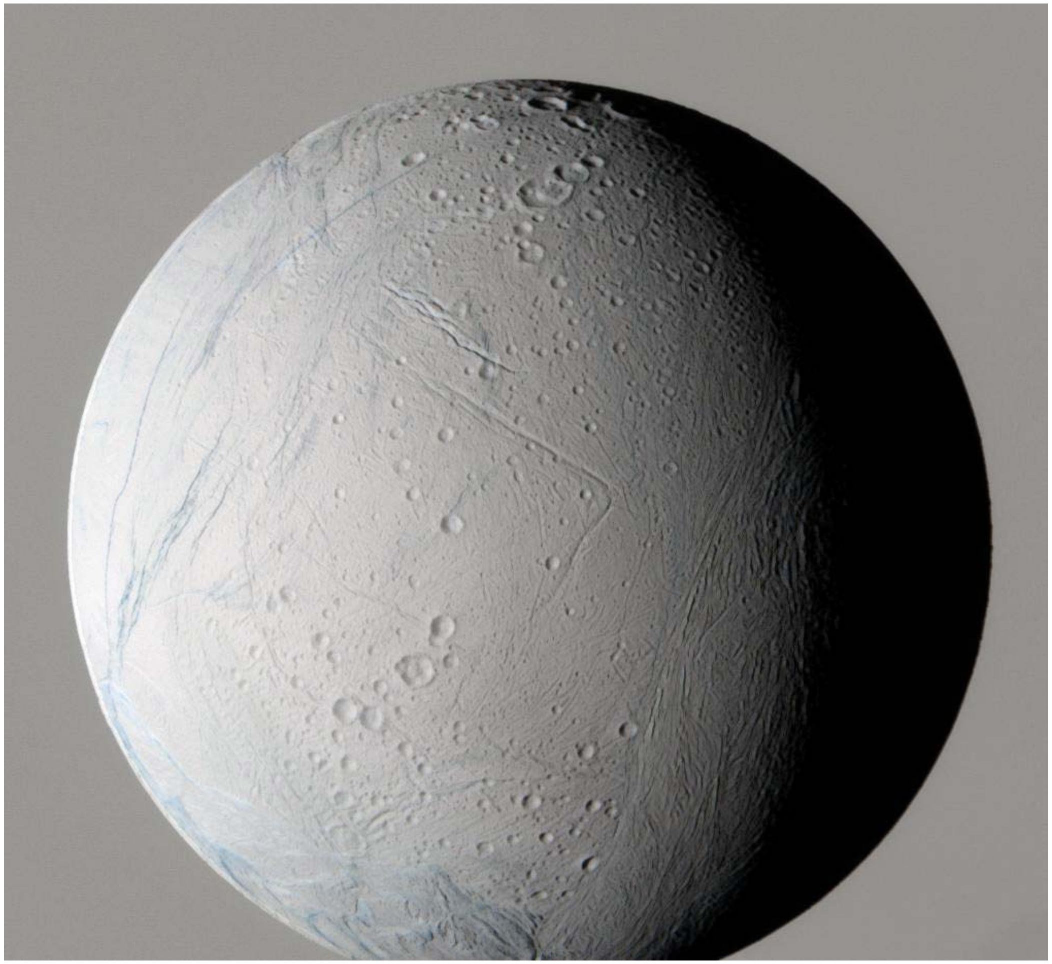
- Far UltraViolet (FUV)
  - 110 to 190 nm
  - 3 slit widths => 2.8, 4.8, 24.9 nm spectral resolution
  - 2D detector: 1024 spectral x 64 one-mrad spatial pixels
- Extreme UltraViolet (EUV)
  - 55 to 110 nm
  - 3 slit widths => 2.8, 4.8, 19.4 nm spectral resolution
  - 2D detector: 1024 spectral x 64 one-mrad spatial pixels
  - Solar occultation port
- High Speed Photometer (HSP)
  - 2 or 8 msec time resolution
- Hydrogen – Deuterium Absorption Cell (HDAC)



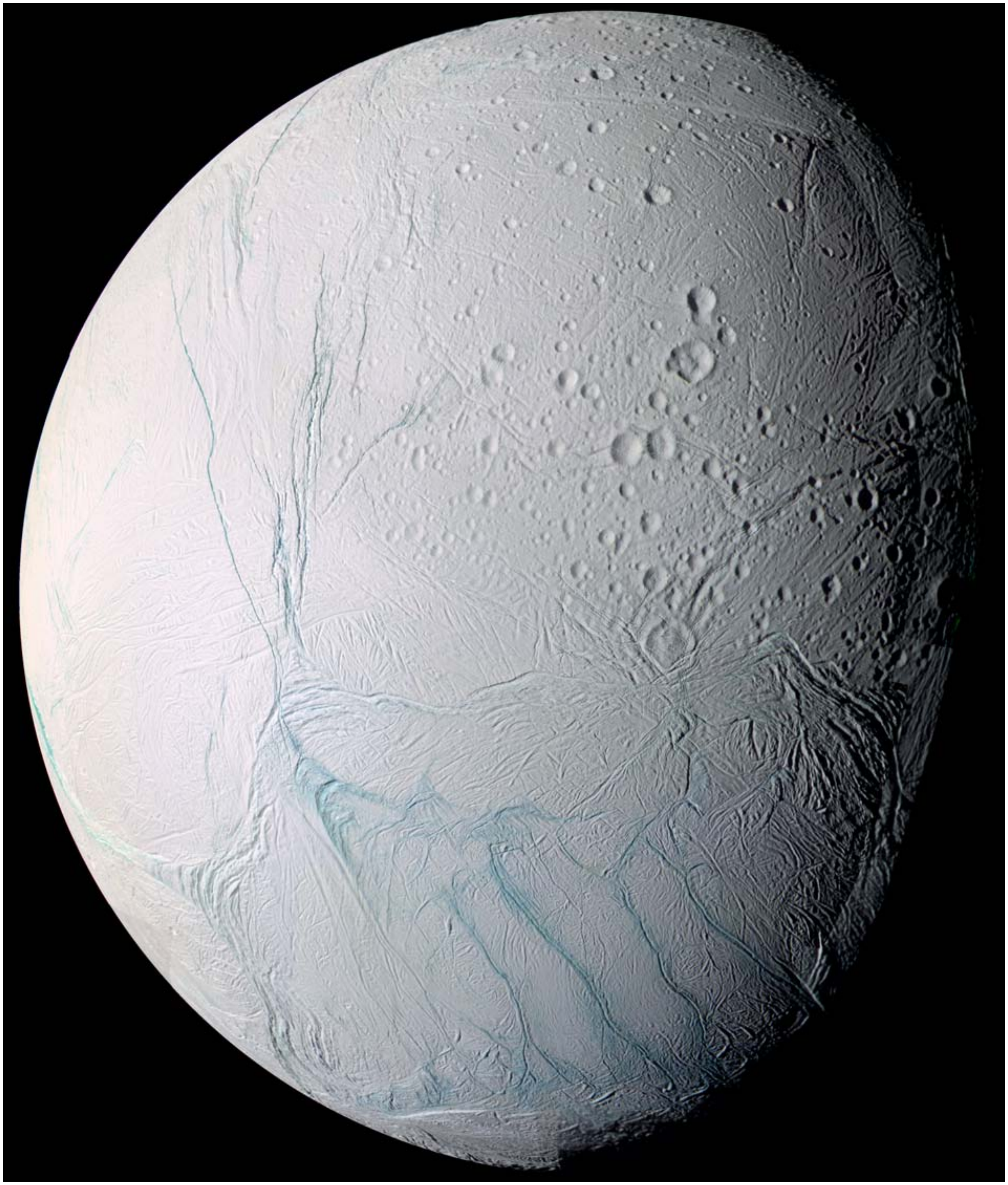
For the occultations we used the

- **HSP with 2 msec time resolution**
- **FUV with 512 spectral channels (1.56 nm resolution), 5 sec integration time**

March 2005 Flyby - Strange Geology

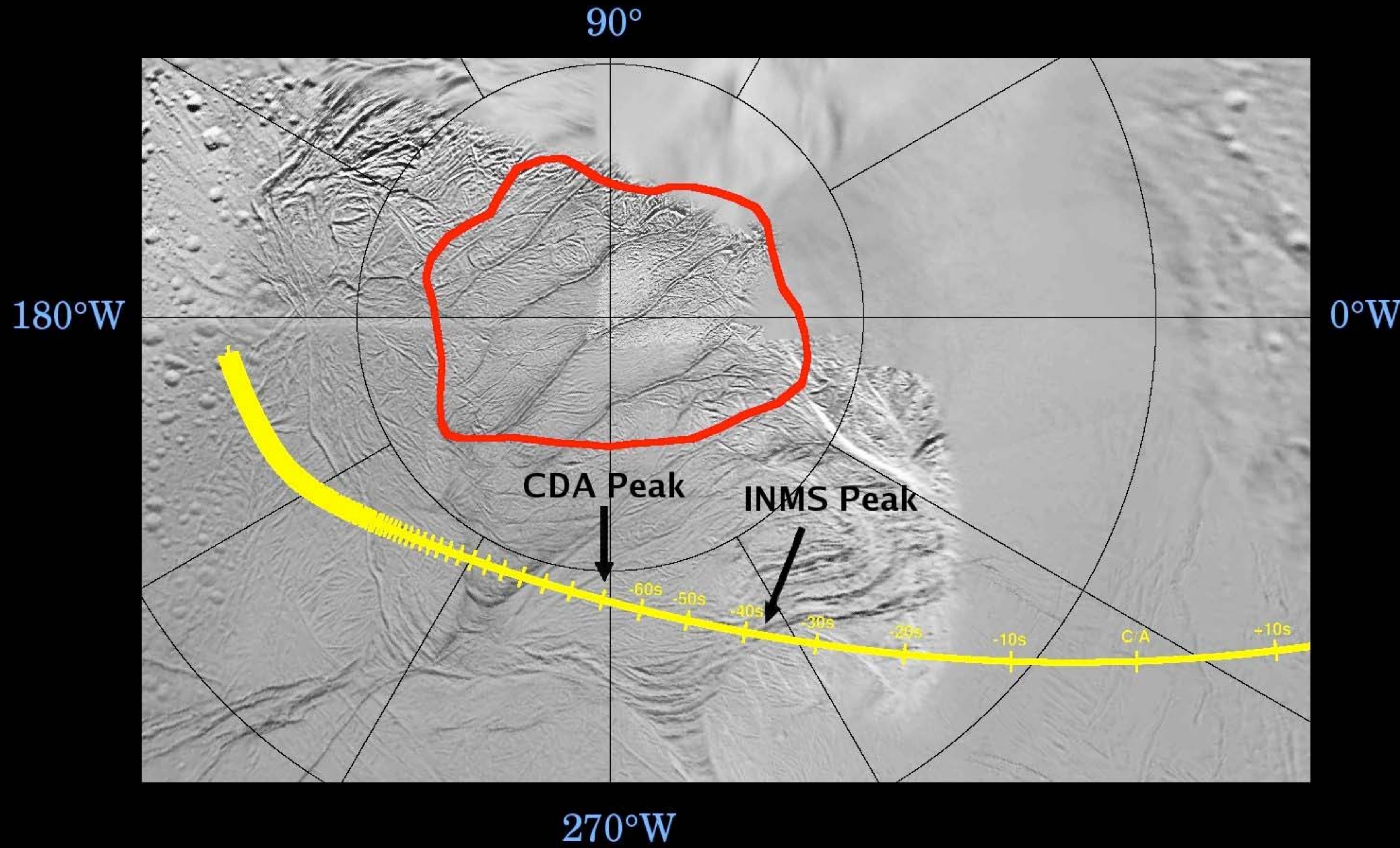


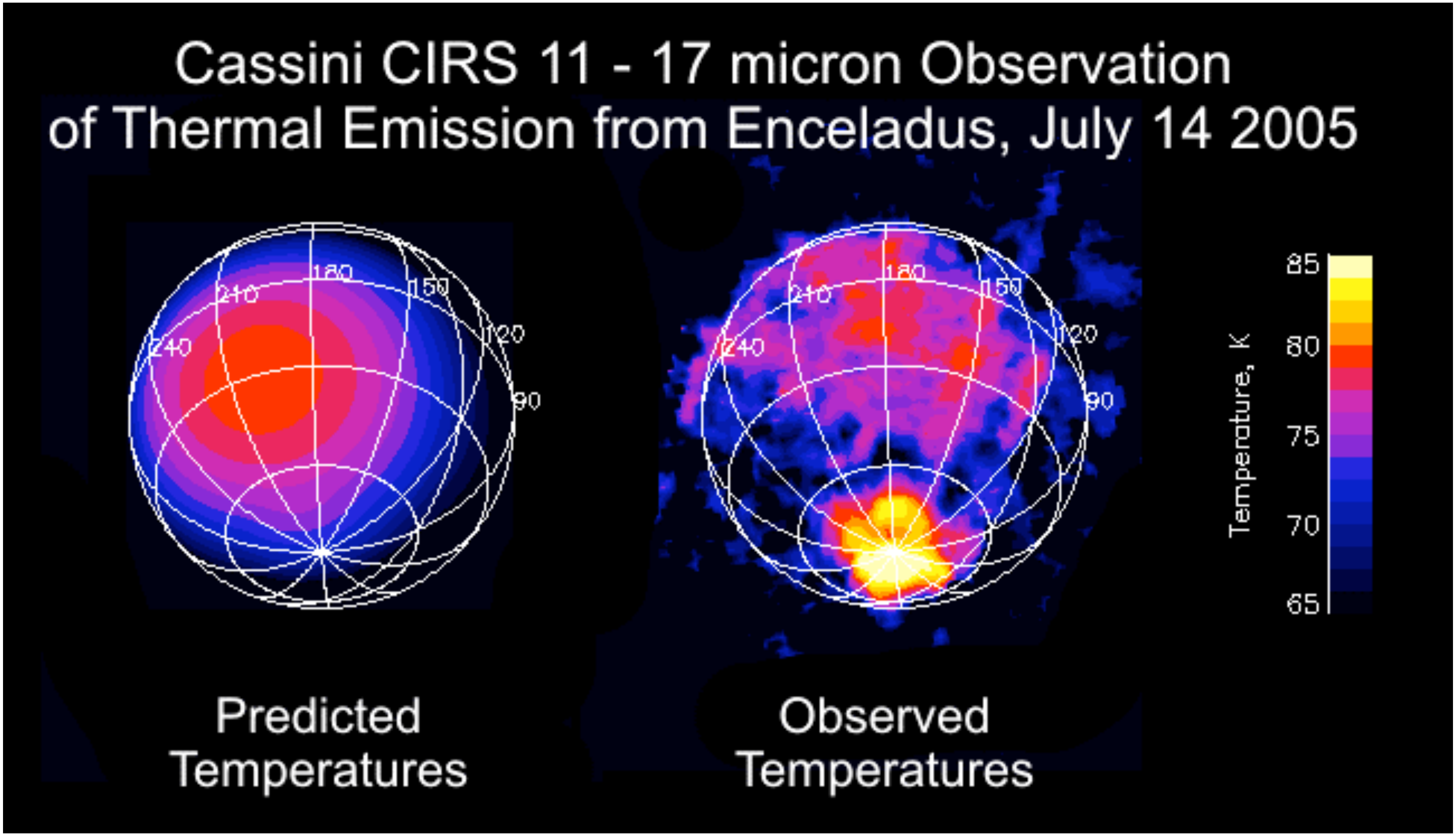
The July flyby flew more directly over the south pole of Enceladus



ISS Color Mosaic
Rev 11

ENCELADUS JULY 14, 2005 FLYBY - CASSINI GROUND TRACK



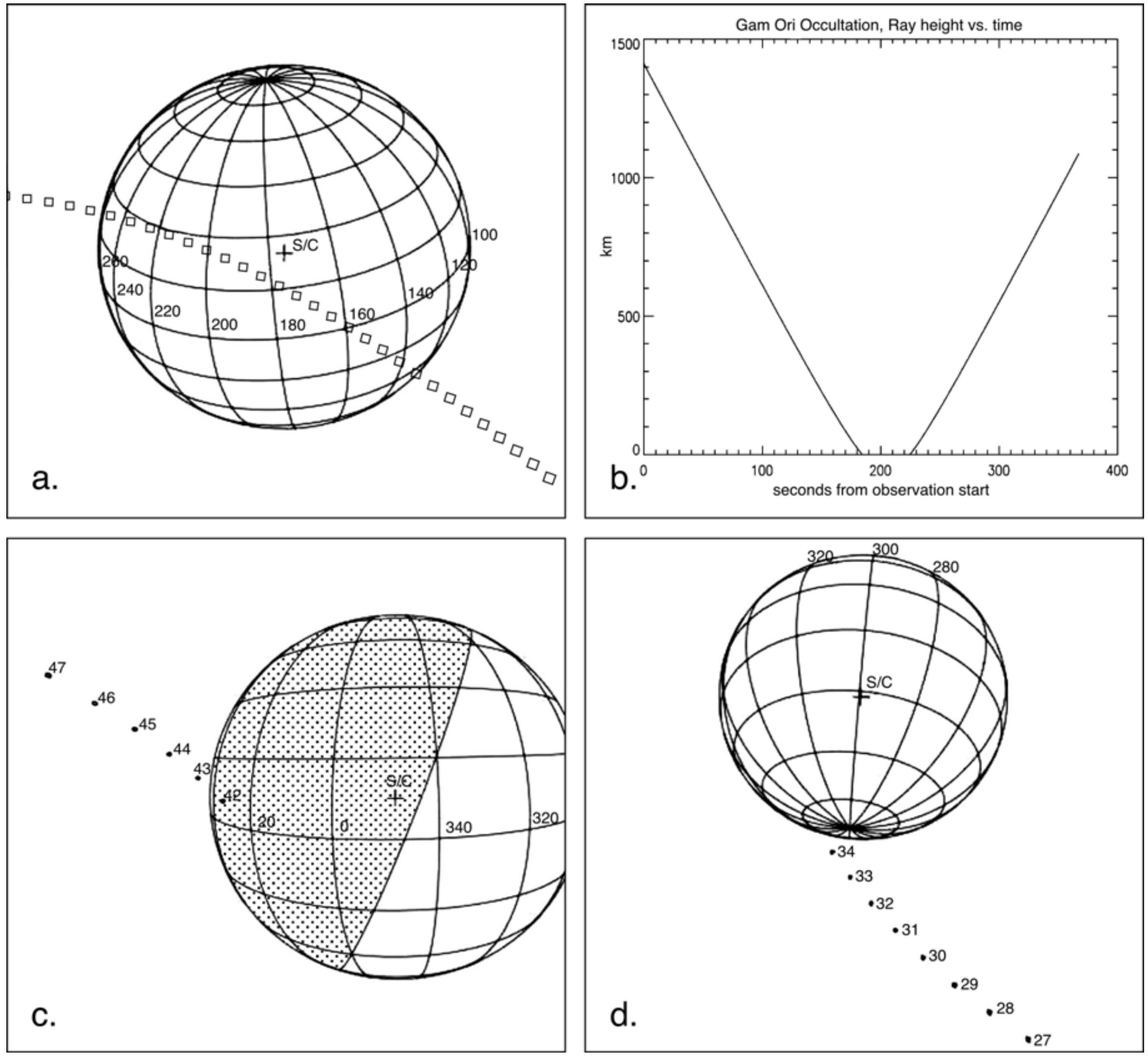

Cassini CIRS 11 - 17 micron Observation
of Thermal Emission from Enceladus, July 14 2005
180
210
150
240
120
90
Predicted
Temperatures
Observed
Temperatures
Temperature, K
85
80
75
70
65


80 79 80 81 91 87 78 74 78 74

Enceladus Occultation Geometries

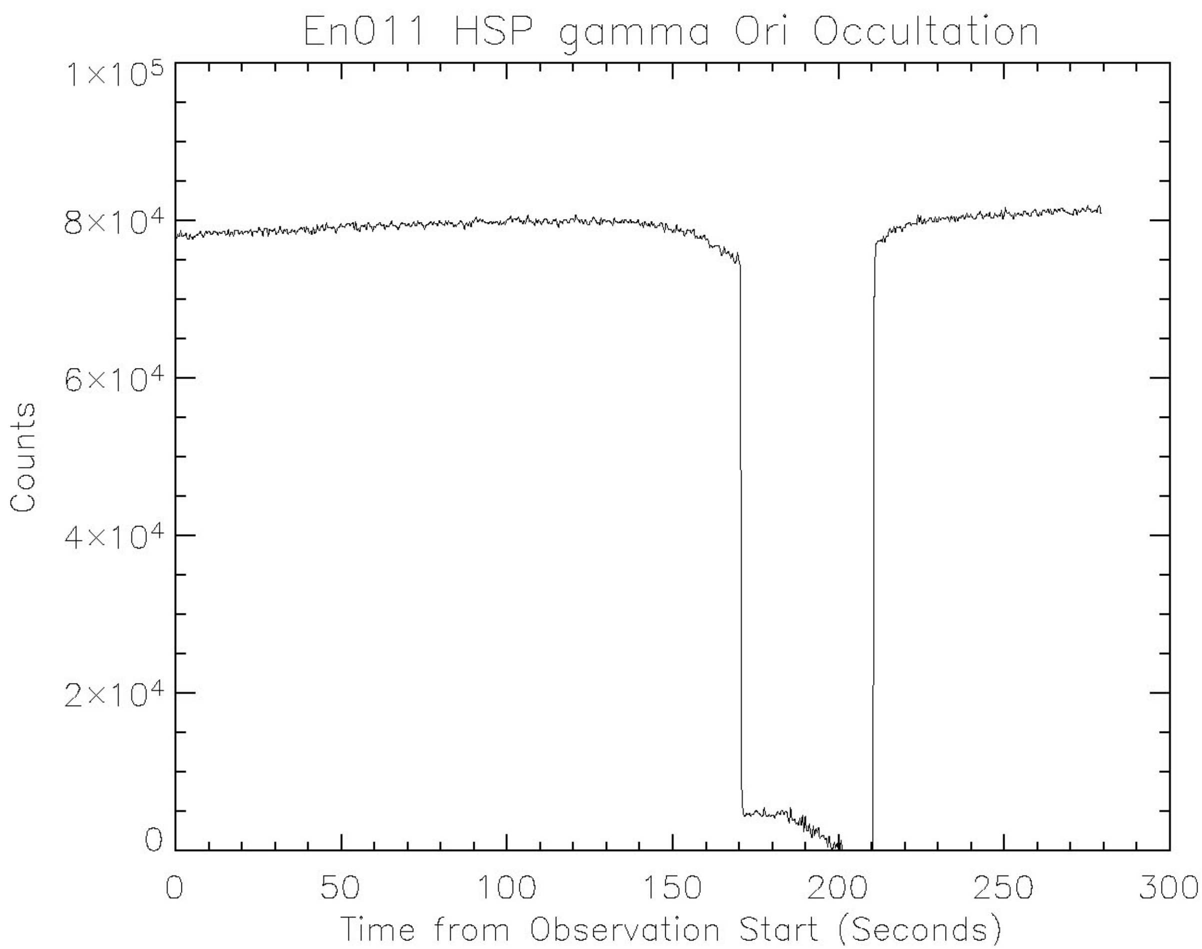
February Lambda Scorpii Occultation

July Gamma Orionis Occultation



Egress **Ingress**

Detection of Plume: High Speed Photometer (HSP) vs. Time



- Clear indication of attenuation of signal during occultation ingress; egress is signature of HSP warmup
- Start to sense atmosphere ~24 sec prior to hard limb occultation, maybe as much as 30 sec (FUV)
- Ray height at –24 sec is ~ 155 km

Localization of Enceladus' Plume

(Not a global atmosphere)

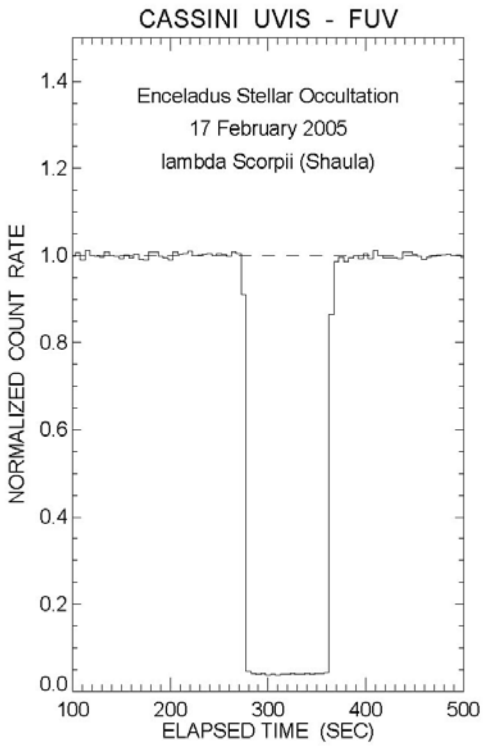
- Ray intercepts were at latitude / west longitude:

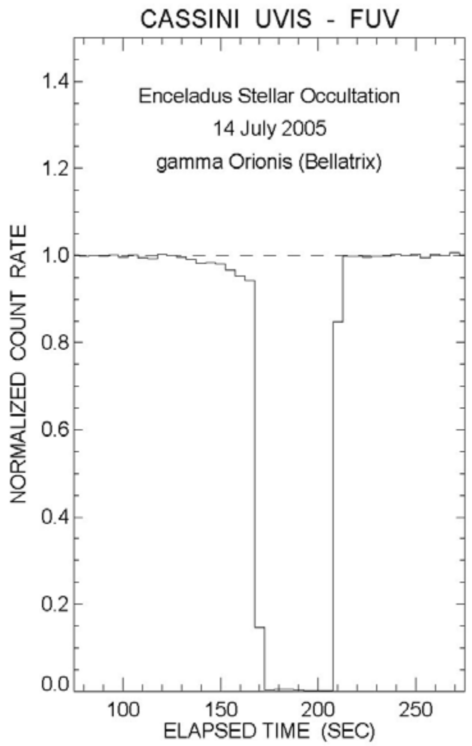
15 / 300	Lambda Sco ingress (non-detection)
-31 / 141	Lambda Sco egress (non-detection)
-76 / 86	Gamma Ori ingress
-0.2 / 28	Gamma Ori egress (non-detection)

Consistent with localized plume or jet:

– Enceladus' gravity insufficient to hold gravitationally bound sputtered atmosphere

– Also, the combination of other Cassini data sets are consistent with a plume of water vapor coming from Enceladus' "Tiger Stripes" driven by the hot spot at the south pole detected by CIRS



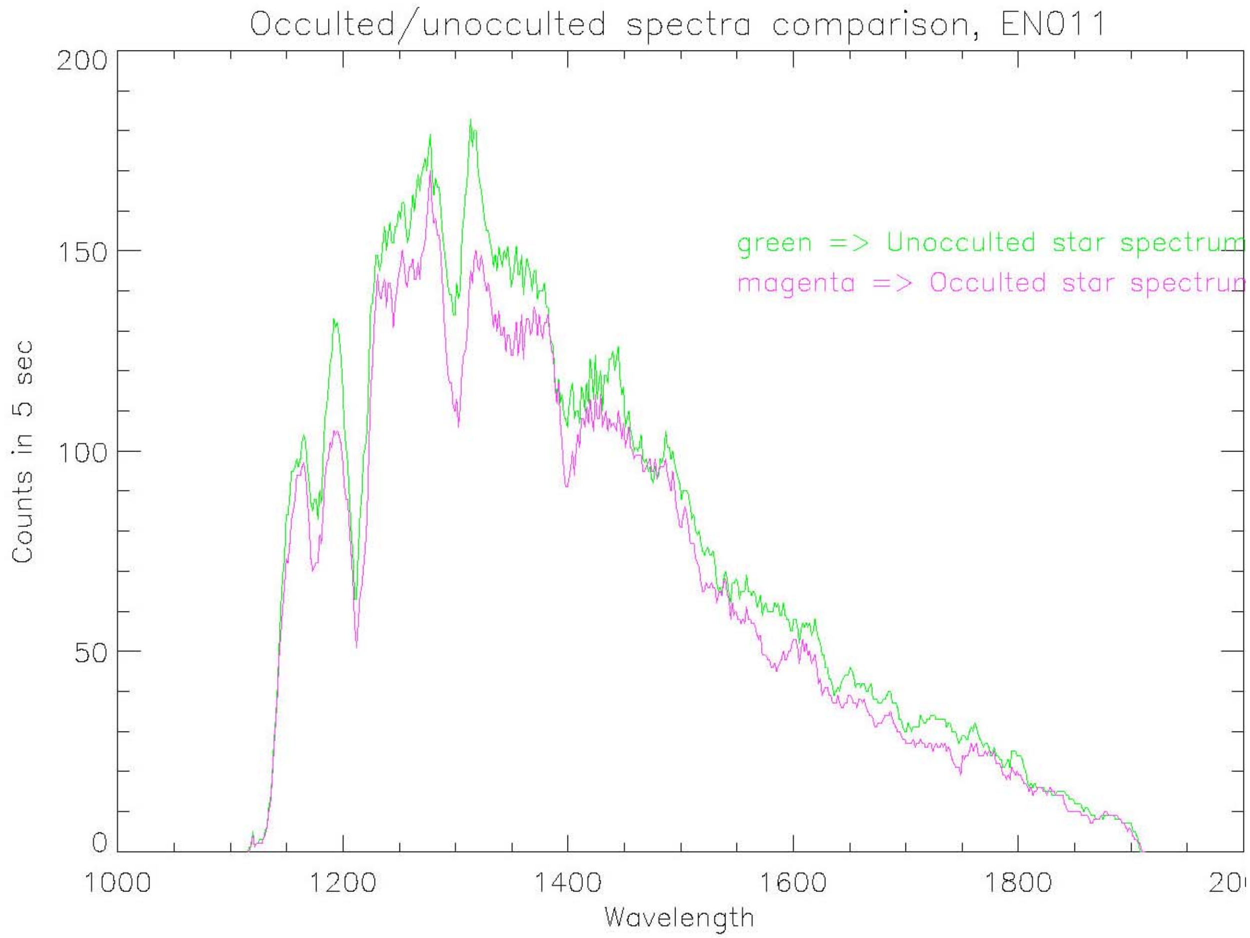


FUV Data: Comparison of Occulted to Unocculted Spectra

FUV configuration:

- **spectral channels binned by 2 (512 spectral channels from 113.5 nm to 191 nm)**
- **low resolution slit width**
- **5 sec integration time**
- **full spatial resolution**

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 atmosphere is present – both relatively narrow and broad absorption features

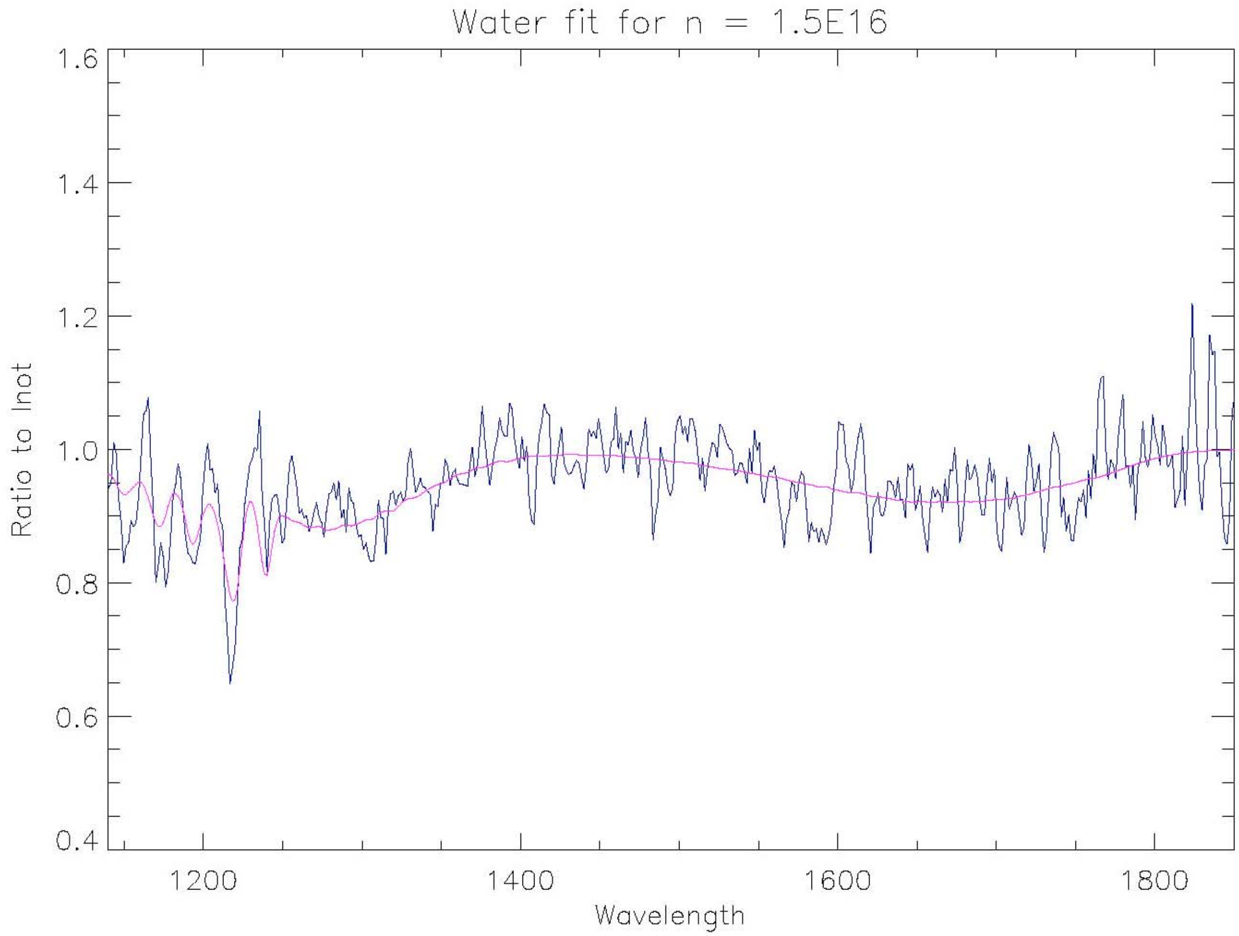
Composition of Plume is Water Vapour

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

I_0 computed from 25 unocculted samples

n = column density

σ = absorption cross-section, function of wavelength



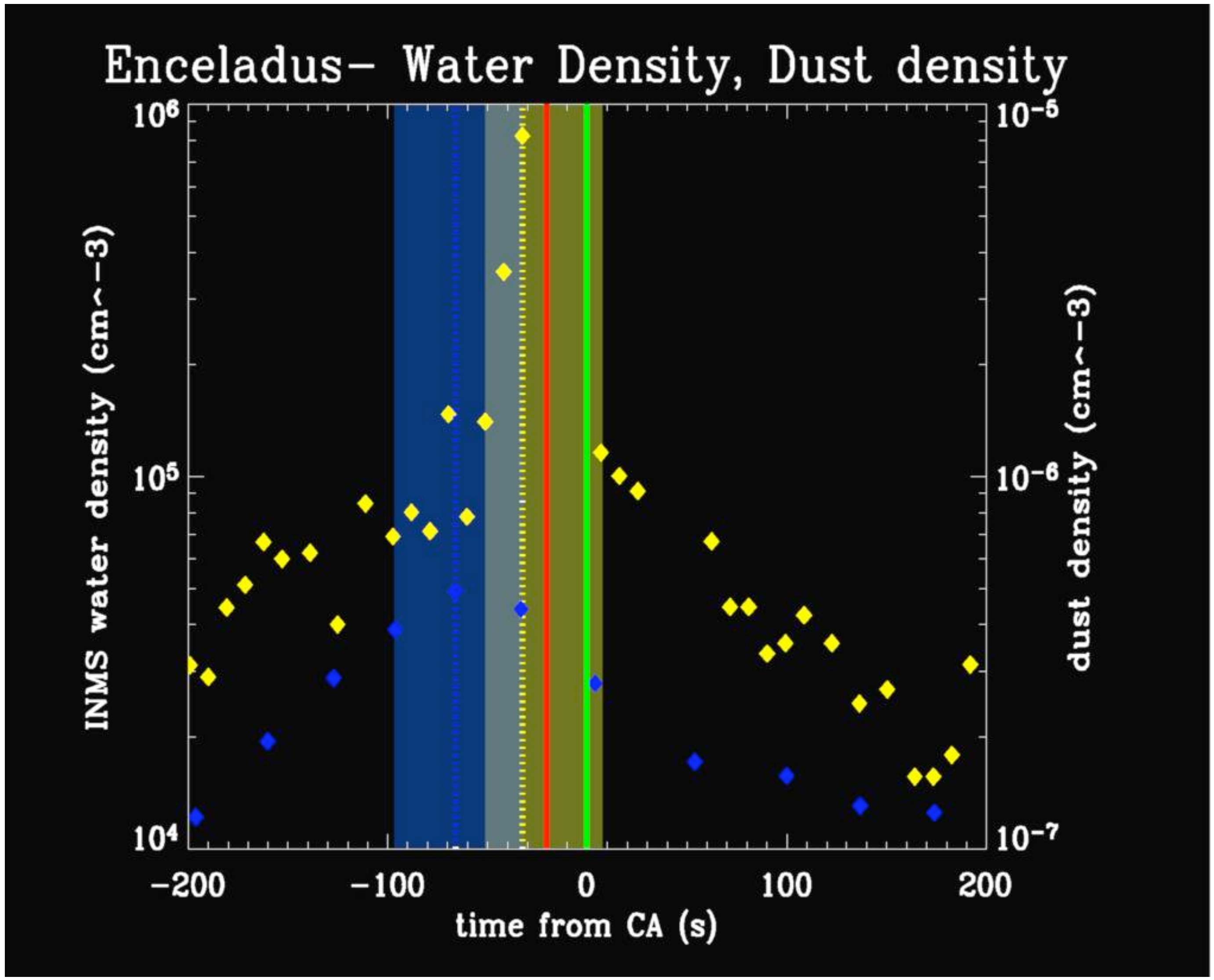
The absorption spectrum of water (pink line) is shown compared to Enceladus' plume spectrum (I/I_0) for a column density of $n = 1.5 \times 10^{16}$ cm^{-2}

INMS, CDA Results

- ~1 minute before closest approach the Cosmic Dust Analyzer detected a peak in the number of small particles (blue diamonds), 460 km altitude

- 35 seconds before closest approach the Ion Neutral Mass Spectrometer measured a large peak in water vapor (yellow diamonds), 270 km altitude

- Gas and dust plumes are decoupled



INMS Plume Composition

Cassini's Ion Neutral Mass Spectrometer detected mass spectra consistent with a plume composition of:

91 %	+/- 3%	H_2O
3.2 %	+/- 0.6%	CO_2
4 %	+/- 1%	CO or N_2 (28 amu)
1.6 %	+/- 0.4 %	CH_4

Trace quantities, <0.5 - 1 %, of

- Propane
- Acetylene
- HCN

CO Limit

- The Ion Neutral Mass Spectrometer (INMS) detected a species with mass = 28 amu, consistent with either N_2 or CO

- UVIS should have detected CO:

  - Used absorption cross-sections from Eidelsberg, 1992

  - "Require" 10% dip in signal for positive detection

    $I/I_0 = 0.9 = \exp(-n\alpha)$

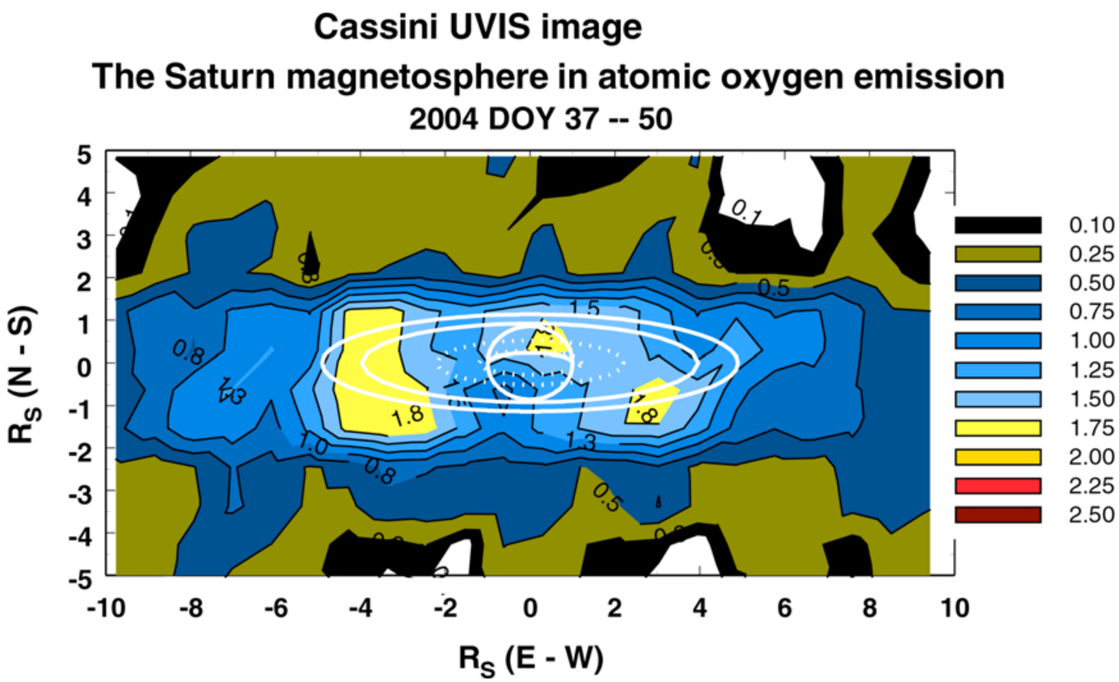
    for $\alpha = 820 \times 10^{-18}$ at 1477.6 Å

    -> $n = 1.3 \times 10^{14}$ cm^{-2} upper limit, ~1%

- Implies an INMS detection of N2 since UVIS should have seen 3% CO

Neutral Species in Saturn's System

- The Saturnian system is filled with the products of water molecules:
  - H detected by Voyager
  - OH detected by HST
  - Atomic Oxygen imaged by UVIS



"Search for the Missing Water Source"[1]

Neutral Species

- Water and its products are lost from the system by collisions, photo- and electron- dissociation and ionization
- Estimates of required re-supply rates, water molecules/sec:

• 2.8×10^{27}	1993	Shemansky, *et al.*
• 3.75×10^{27}	2002	[1]Jurac, *et al.*
• 10^{28}	2005	Jurac and Richardson
• 2×10^{28}	2005	Shemansky, *et al.*

E Ring

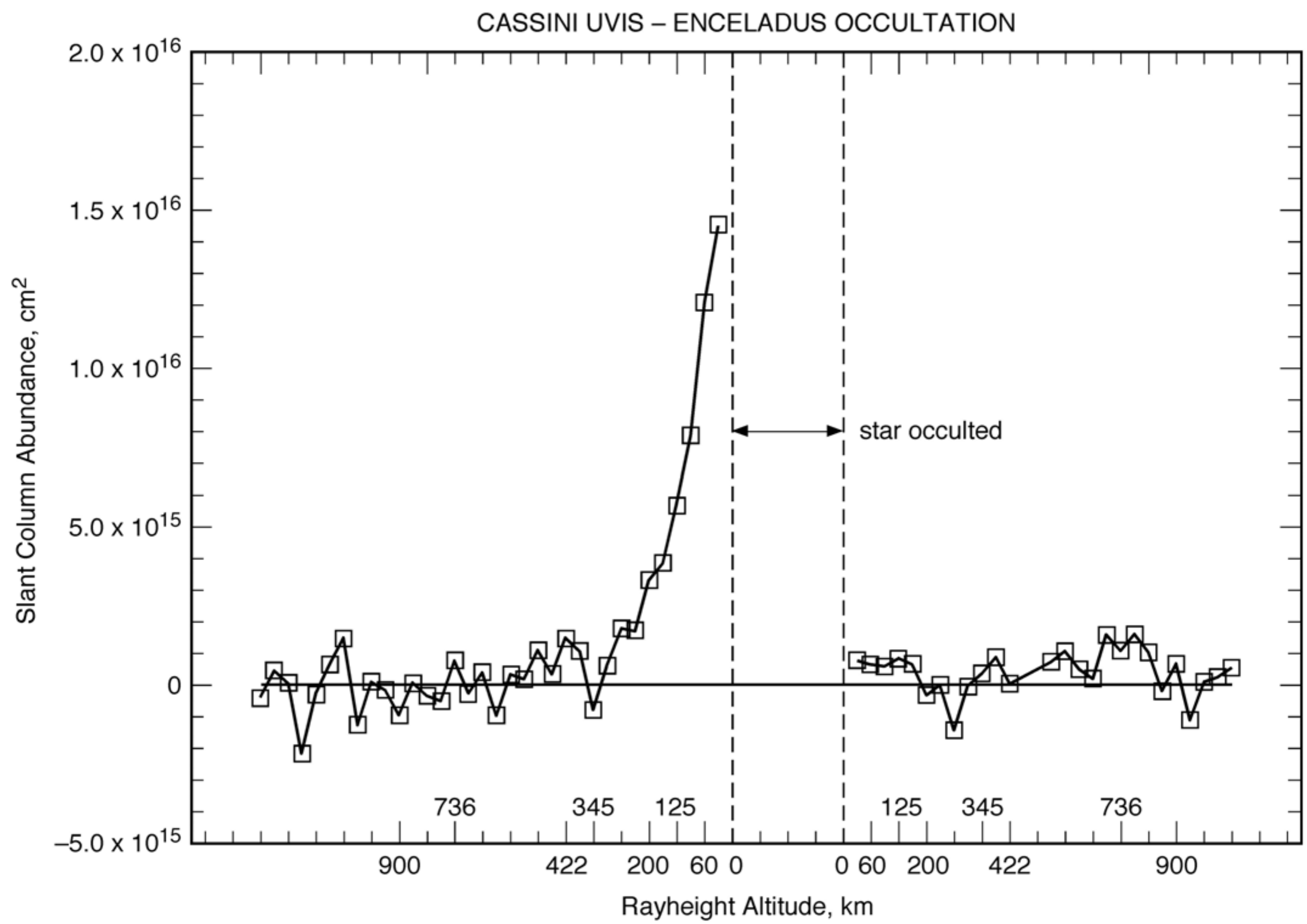
- Saturn's E ring, composed primarily of 1 micron particles, is also subject to erosion and loss due to sputtering of water from the surface of the E ring's dust particles and collisions of particles with Saturn's moons
- Estimate of required re-supply rate:

• 1 kg / sec	2002	Juhasz and Horanyi

Structure of the Plume

The increase in water abundance is best fit by an exponential curve – a comet-like evaporating atmosphere ($1/R^2$) does not fit the data well, nor do global hydrostatic cases

The best fit scale length is 80 km



Estimation of Water Flux from Enceladus

- S = flux

  = N * h^2 * v

  = n/h * h^2 * v

  = n * h * v

Where

N = number density / cm^3

h^2 = area

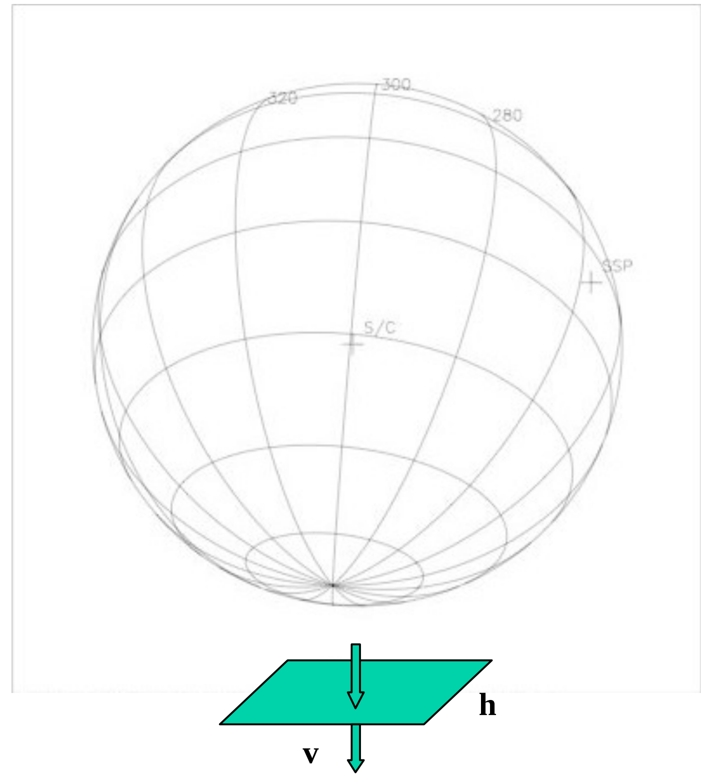
v = velocity

n = column density measured by UVIS

The biggest uncertainty is what to use for **h**

Estimate **h** from plume dimension, = 80 (from scale length) or 175 km (from horizontal distance traversed)

Estimate **v** from thermal velocity of water molecules in vapor pressure equilibrium with warm ice (41,200 at 145 K or 46,000 cm/sec at 180 K – note that escape velocity = 23,000 cm/sec)



S = 1.5 x 10^{16} * (80 or 175) x 10^5 * (41 or 46) x 10^3 = 0.5 to 1.2 x 10^{28} H_2O molecules / sec

= 150 to 360 kg / sec

Other ways to Estimate Water Flux

- S = flux

  = $N * h^2 * v$

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

  = $n * h * v$

Where

N = number density / cm^3

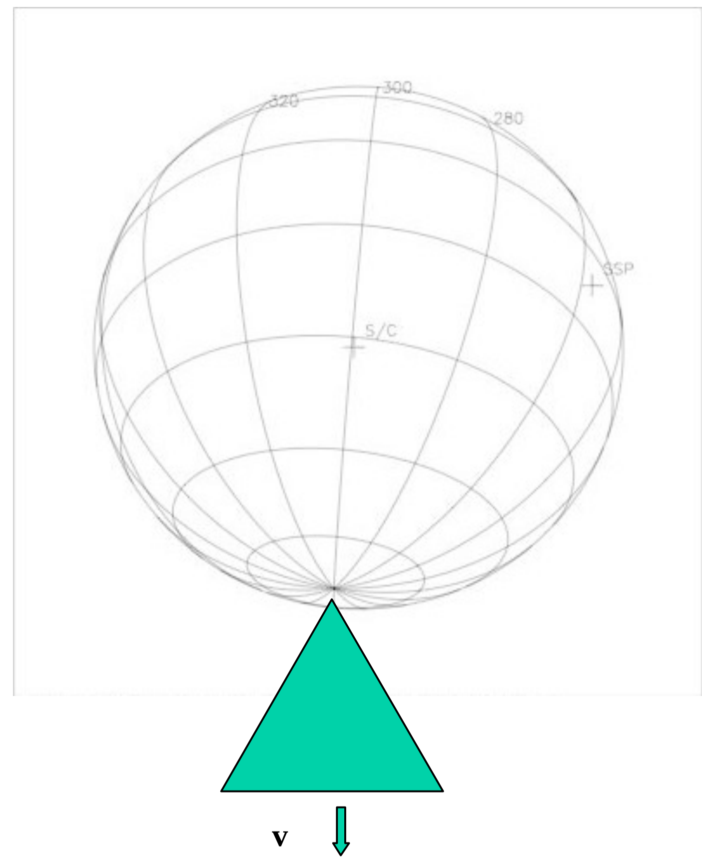
h^2 = area

v = velocity

n = column density measured by UVIS

Estimate **h** from plume dimension, = 80 (from scale length) or 175 km (from horizontal distance traversed)

Estimate **v** from thermal velocity of water molecules in vapor pressure equilibrium with warm ice (41,200 at 145 K or 46,000 cm/sec at 180 K – note that escape velocity = 23,000 cm/sec)



$S = 1.5 \times 10^{16} * (80 \text{ or } 175) \times 10^5 * (41 \text{ or } 46) \times 10^3 = 0.5 \text{ to } 1.2 \times 10^{28}$ H_2O molecules / sec

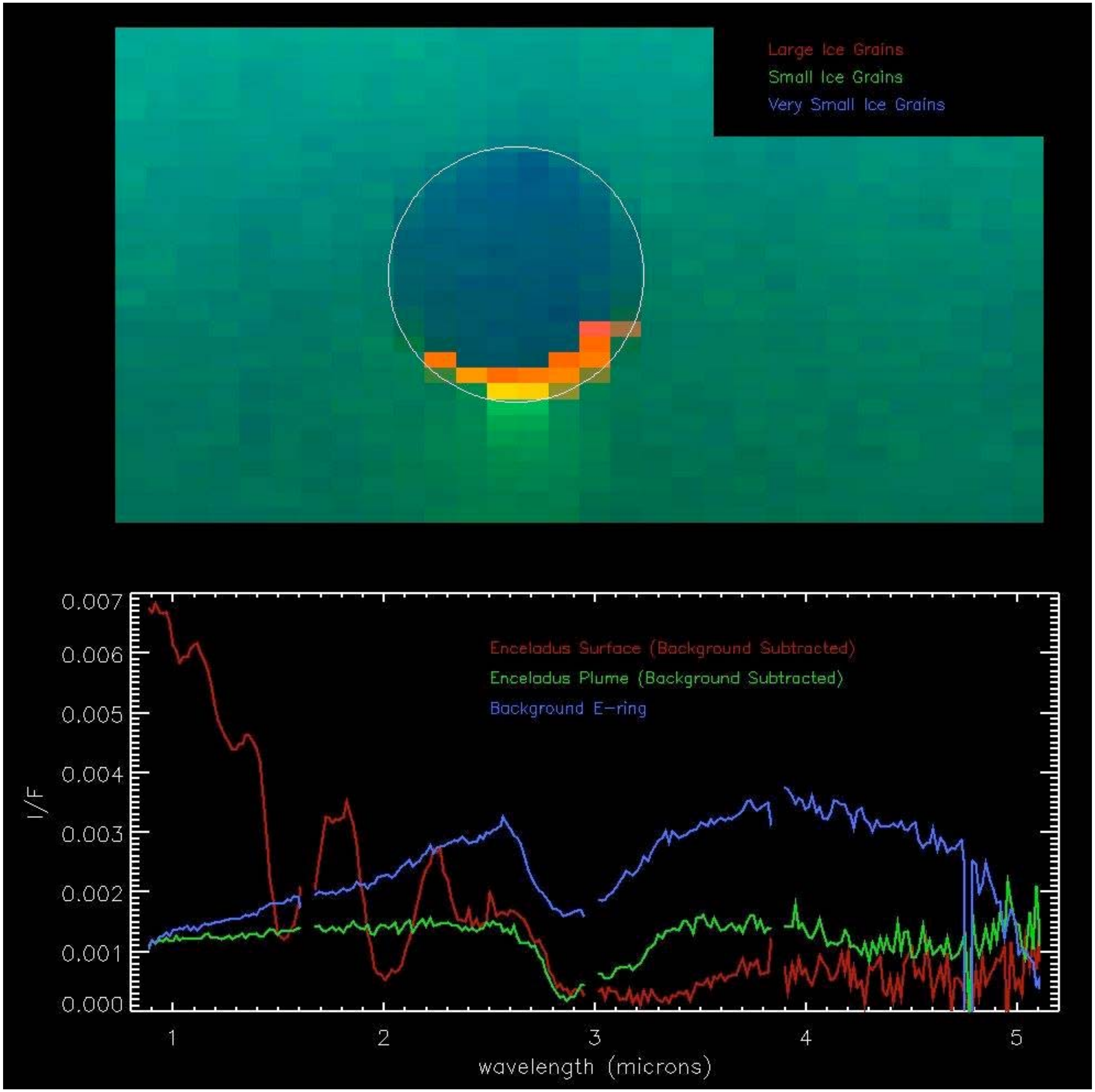
= 150 to 360 kg / sec

Dust in Plume

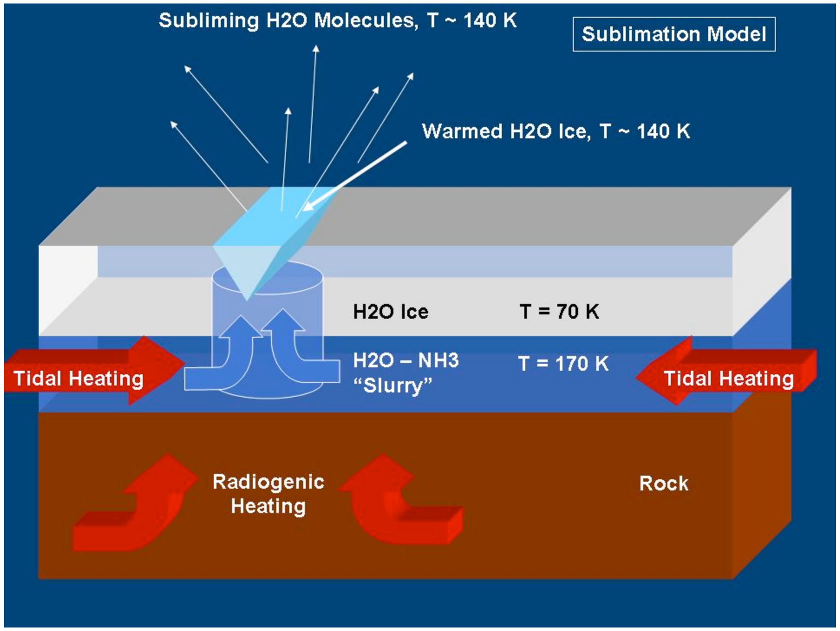
- CDA
- E ring re-supply
  - Comet analogy
    - If dust-to-gas ratio is comet-like then ratio ranges from 0.1 to 2
    - 0.1 x 150 kg/sec > 1 kg/sec required
- How high are dust densities? Waiting for ISS
- Implications for source mechanism - entraining particulates

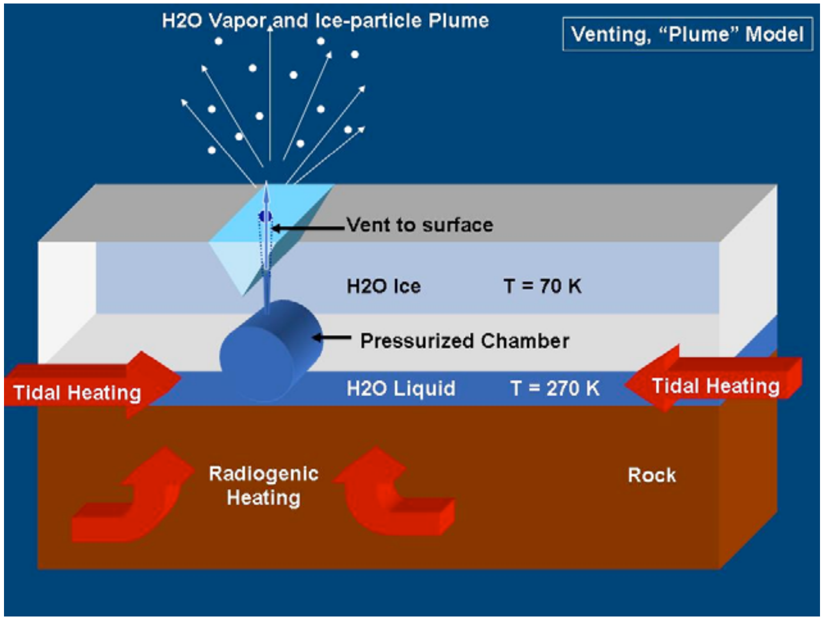
VIMS data confirm that Enceladus is the source of the E ring:

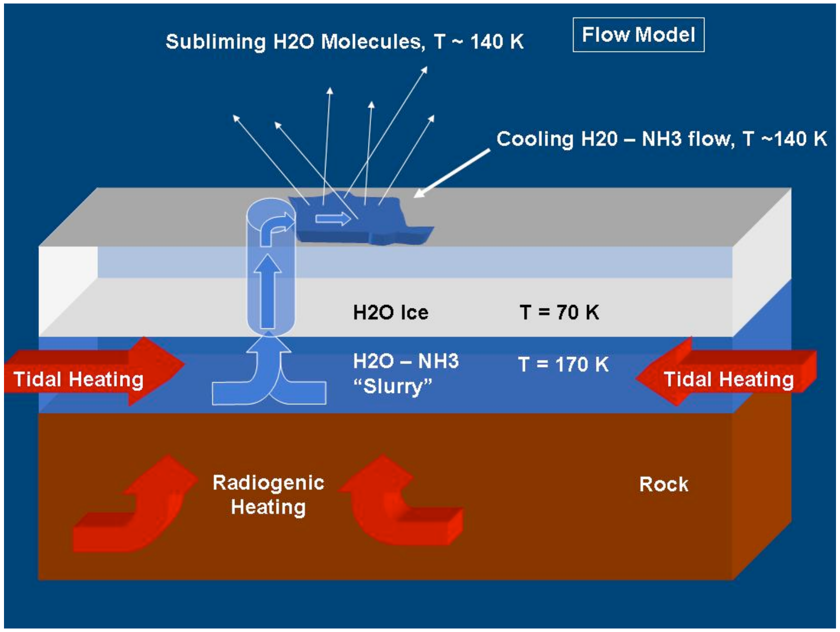
Spectrum of the plume is a match to the E ring



Models for Enceladus' Plumes







These preliminary models illustrate possible mechanisms for powering Enceladus' plume

Enceladus’ Biological Potential

- The infered presence of liquid water immediately leads to the question of Enceladus’ biological potential
- In addition a source of energy and minerals is required
- Enceladus’ internal heat may provide the needed energy
- Minerals may come from rocky material in contact with liquid water

Limits on Detection of other Species

- The lack of absorption features in the UVIS FUV spectrum allows us to put upper limits on a number of gaseous species:

O_2	<	2.5×10^{18} per cm^2
CH_4	<	5.6×10^{15}
C_2H_2	<	1.6×10^{15}
C_2H_6	<	4.0×10^{15}
HCN	<	2.7×10^{15}
NH_3	<	1.3×10^{16}
SO_2	<	2.2×10^{15}

The Future

Summary of UVIS Results:

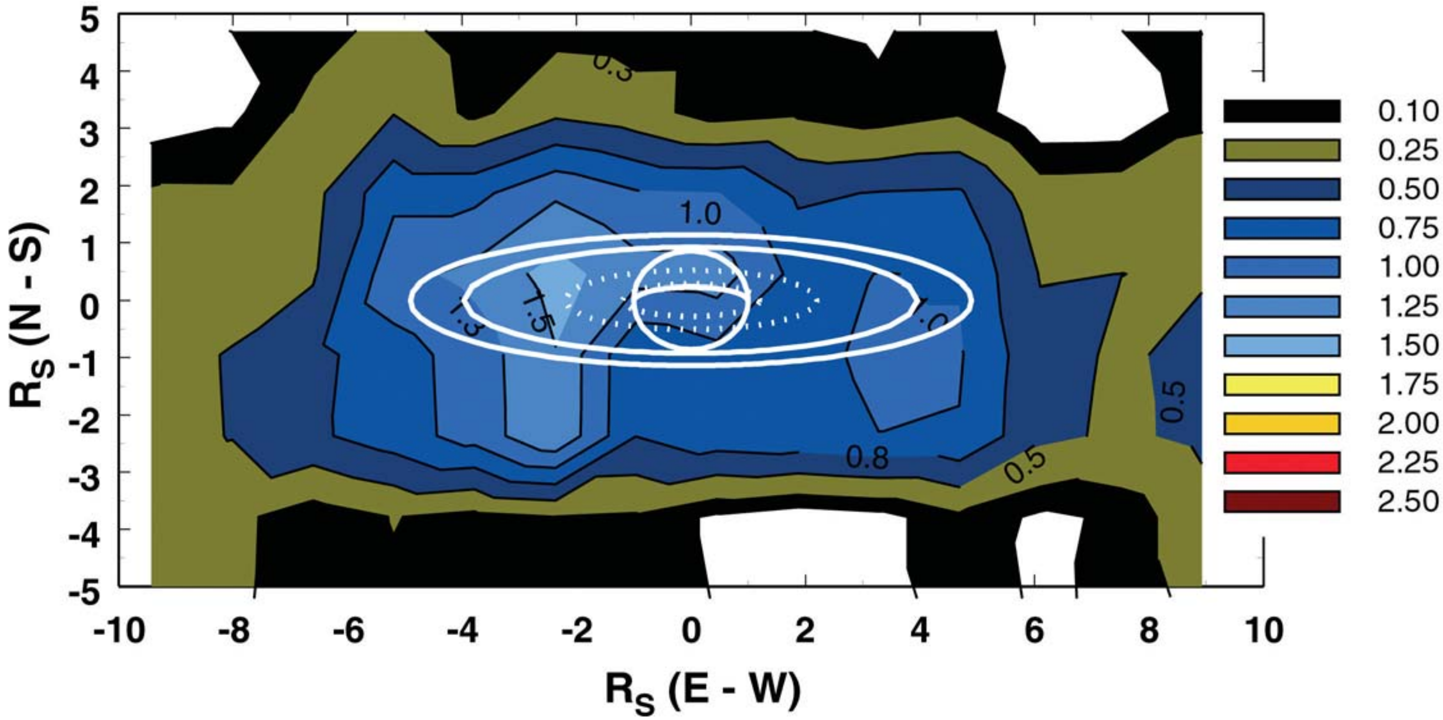
The water budget derived from the water vapor abundance is adequate to supply most if not all of the OH detected by HST, atomic oxygen in the Saturn system detected by UVIS, and to re-supply Saturn's E ring

Since the oxygen in the system comes from Enceladus we may be able to remotely monitor Enceladus' activity levels

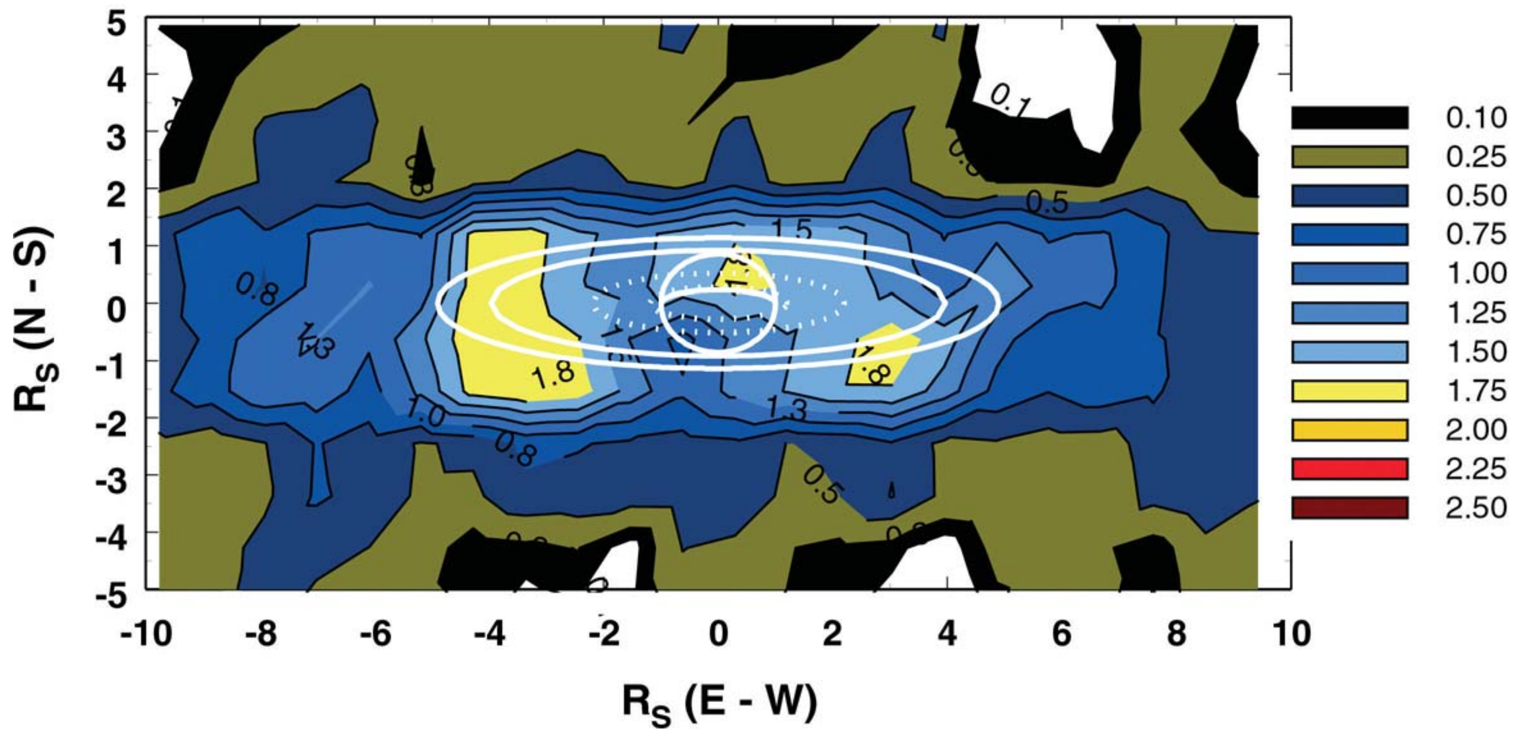
Cassini UVIS image

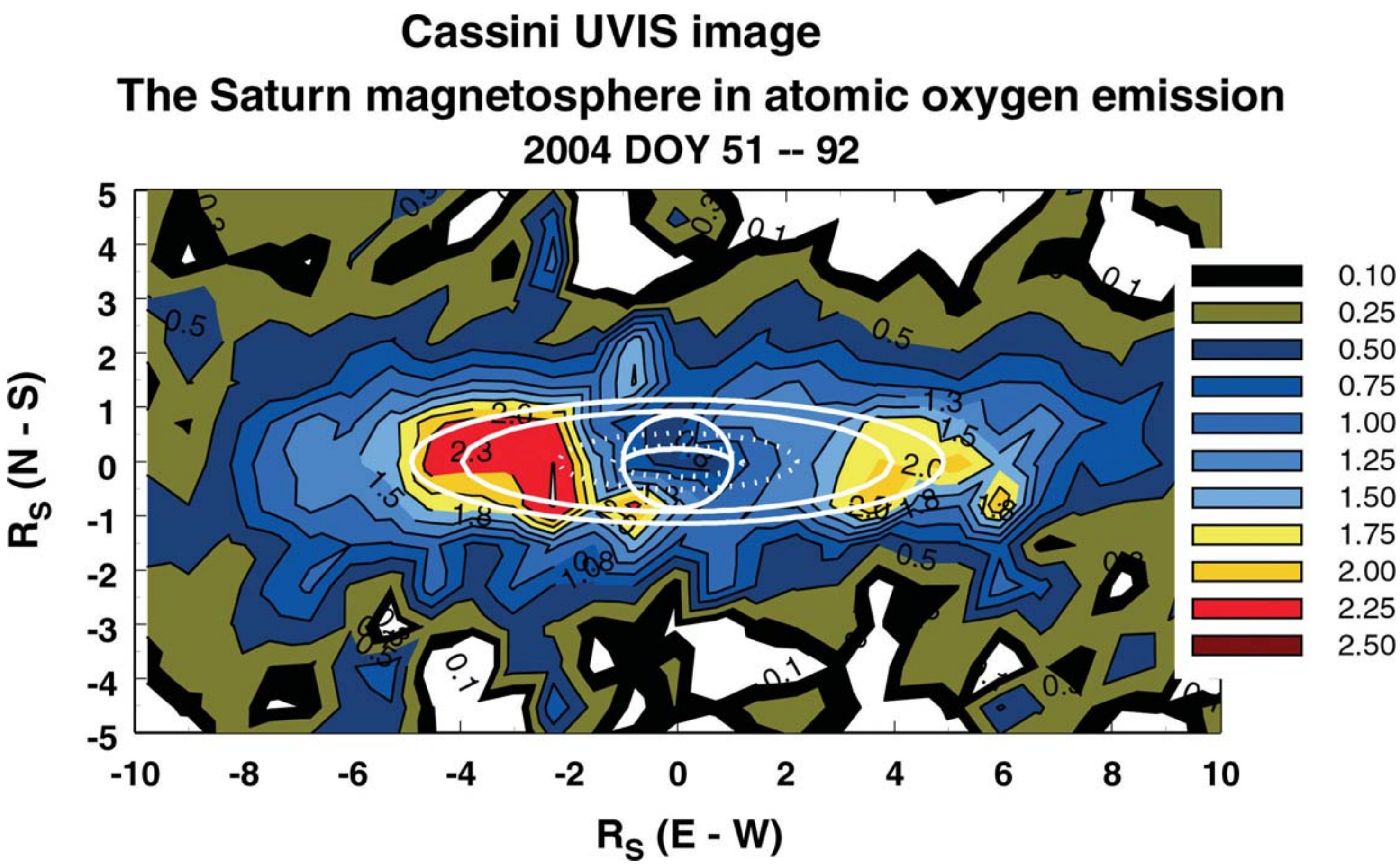
The Saturn magnetosphere in atomic oxygen emission

2003 DOY 356 -- 2004 DOY 11



Cassini UVIS image
The Saturn magnetosphere in atomic oxygen emission
2004 DOY 37 -- 50



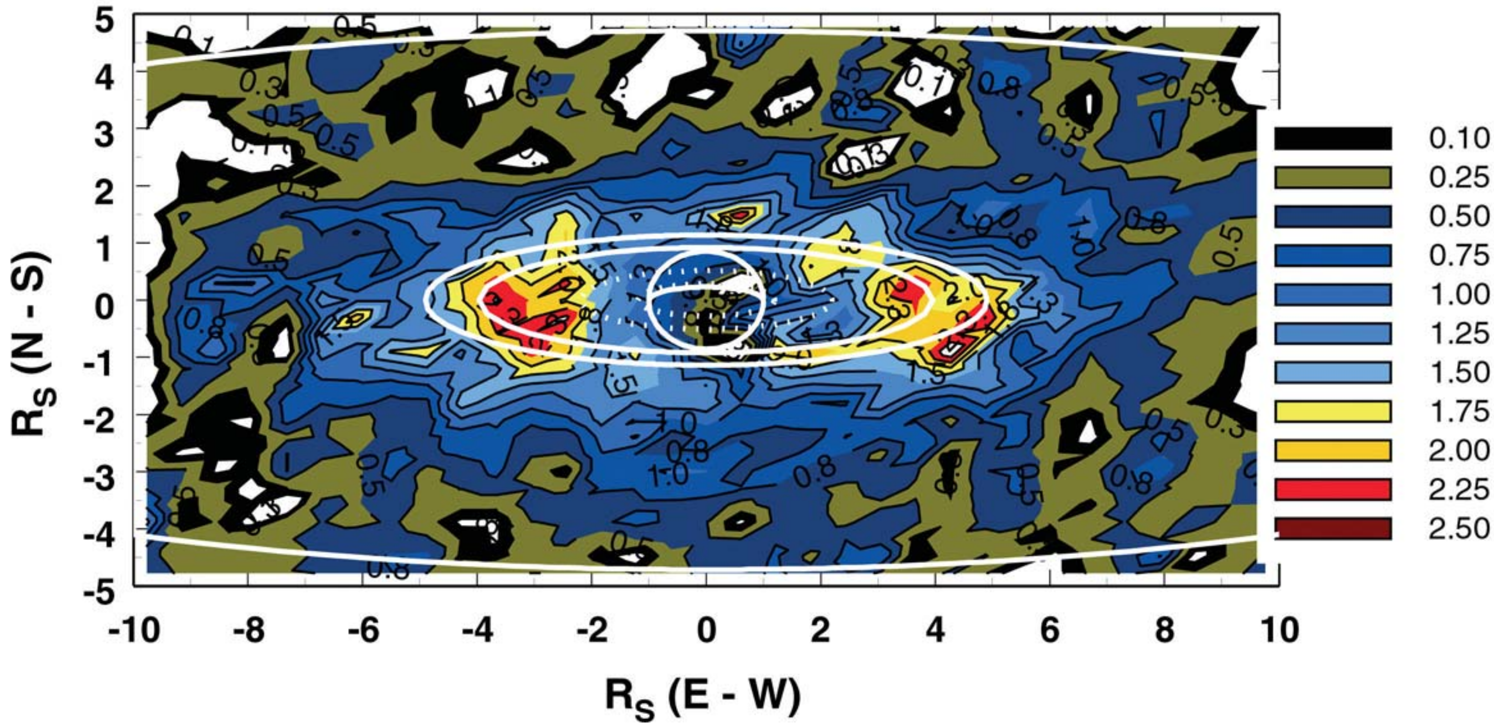


Cassini UVIS image
The Saturn magnetosphere in atomic oxygen emission
2004 DOY 51 -- 92
R_S (N - S)
R_S (E - W)
0.10
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

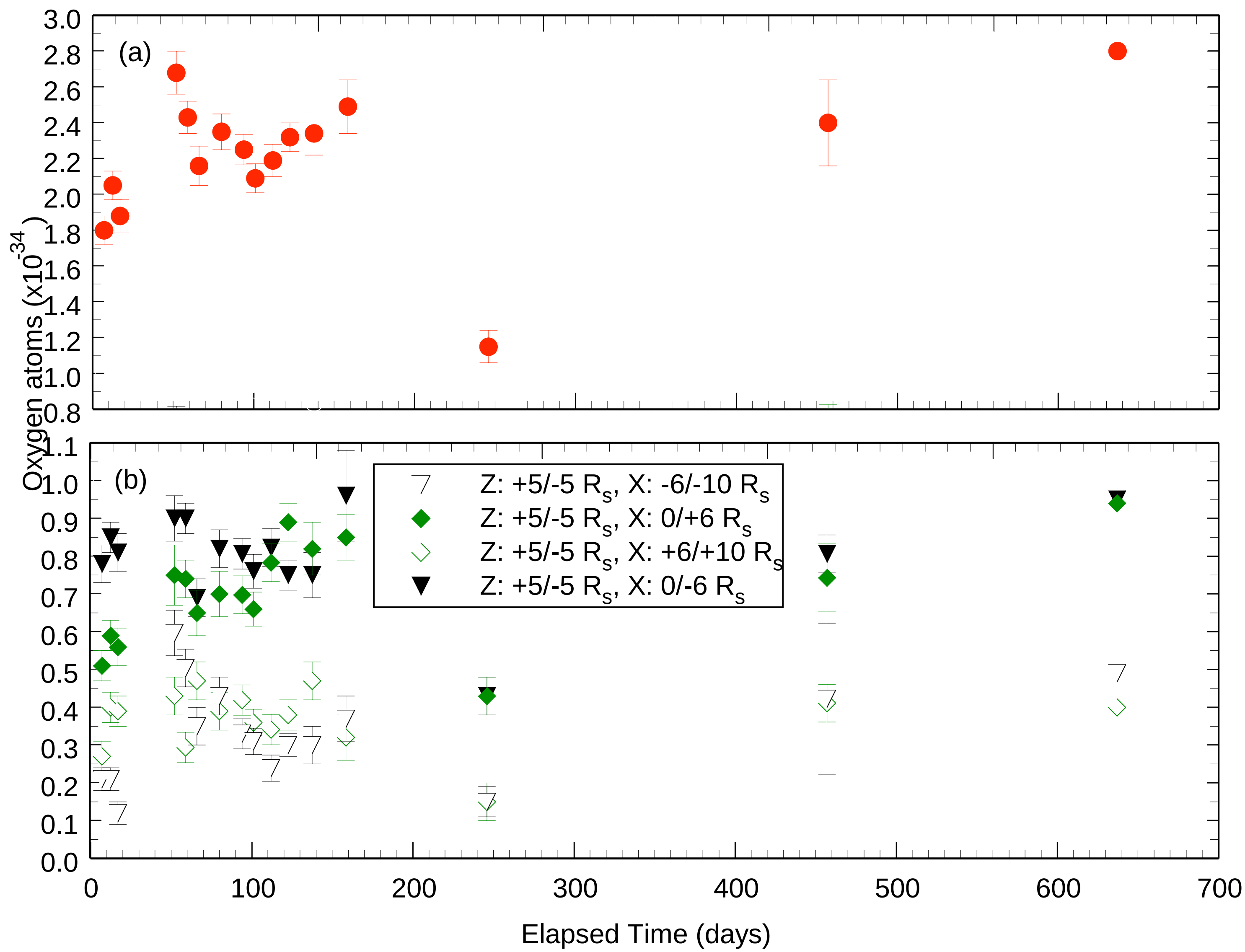
Cassini UVIS image

The Saturn magnetosphere in atomic oxygen emission

2004 DOY 93 -- 133



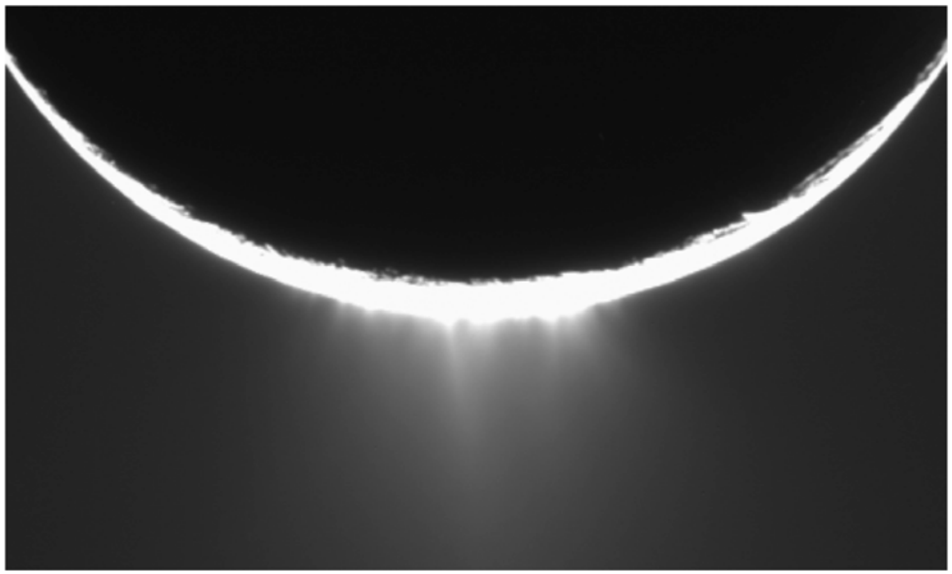
Weekly O1304 Trend



Conclusion

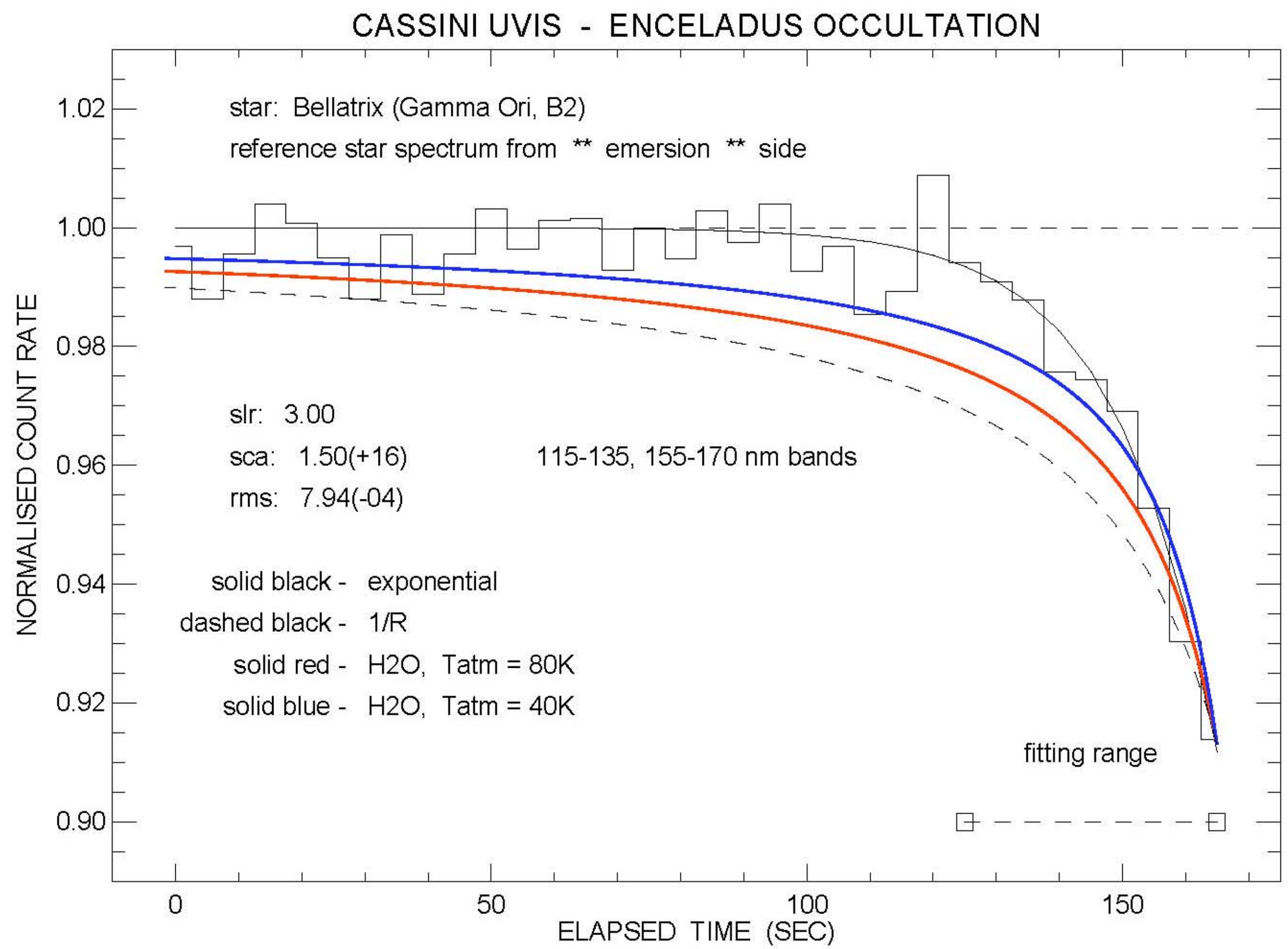
- Using simple, conservative modeling of the water vapor flux from Enceladus' plume we are able to conclude that Enceladus is a probable source of most (if not all) the water required to
  - Supply the neutrals in Saturn's system
  - Re-supply the E ring against losses
- We may be able to monitor eruptive activity on Enceladus remotely by continuing to track the oxygen content of the Saturn system

Plume Movie



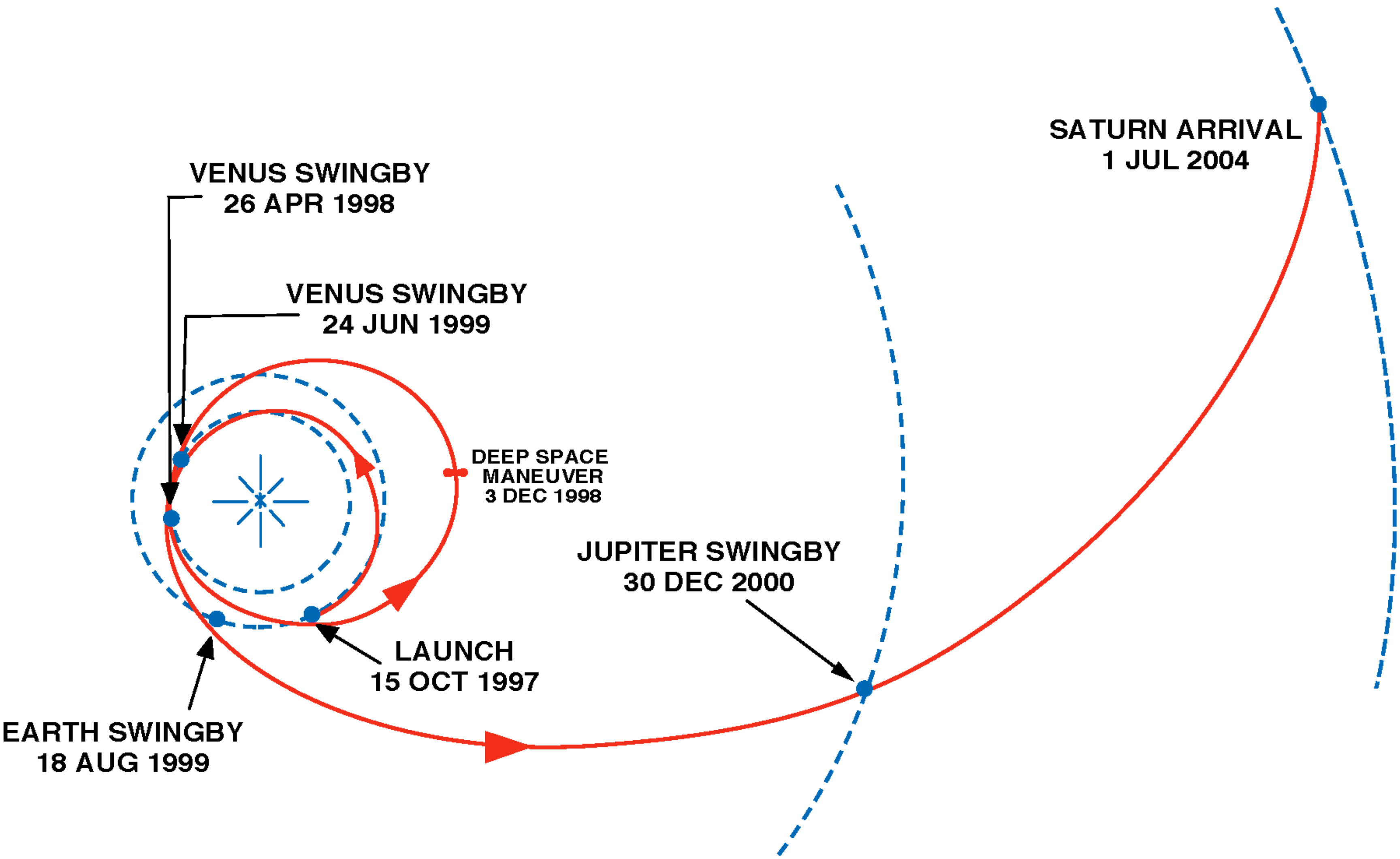
Backup Charts

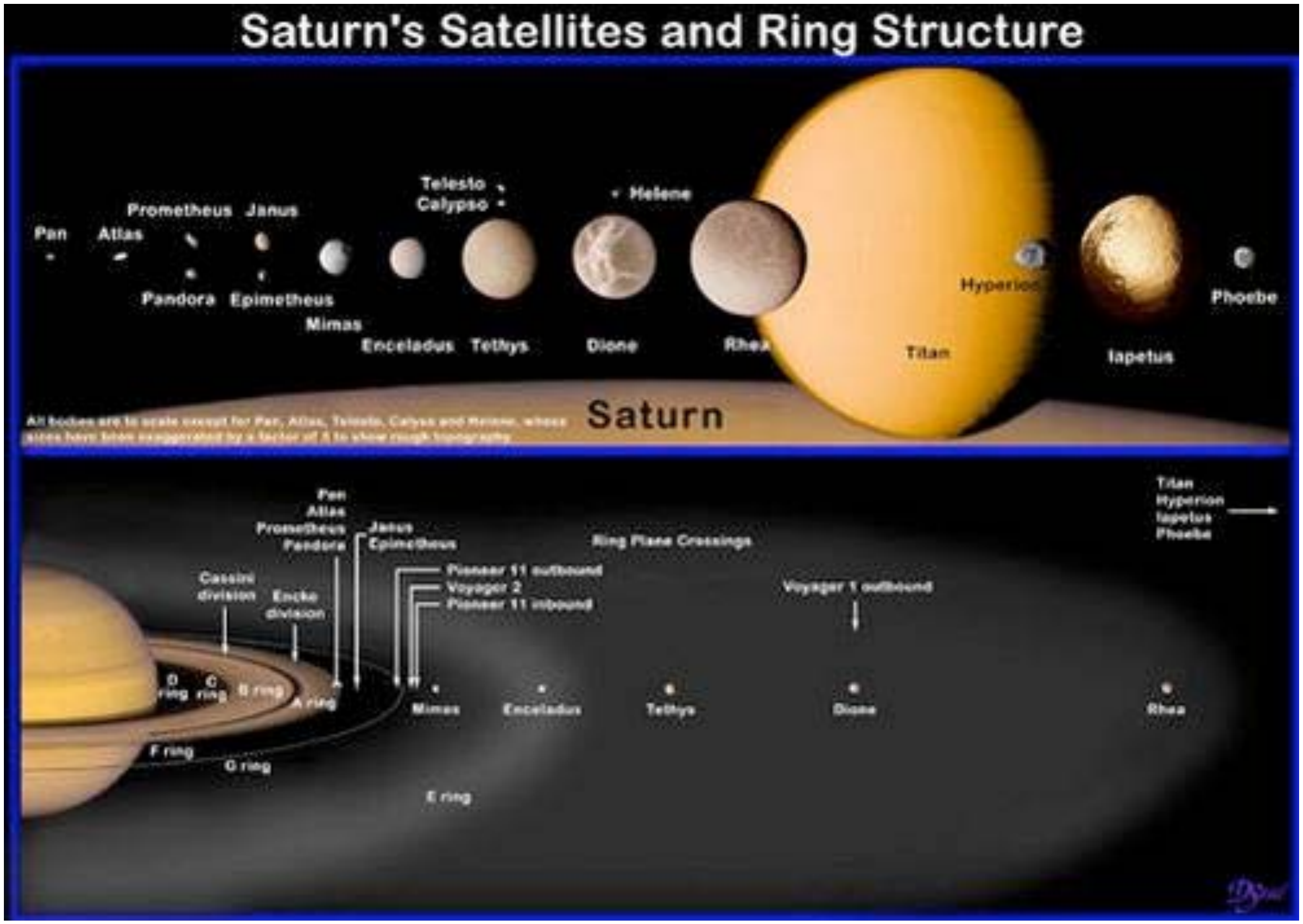
Structure of the Atmosphere



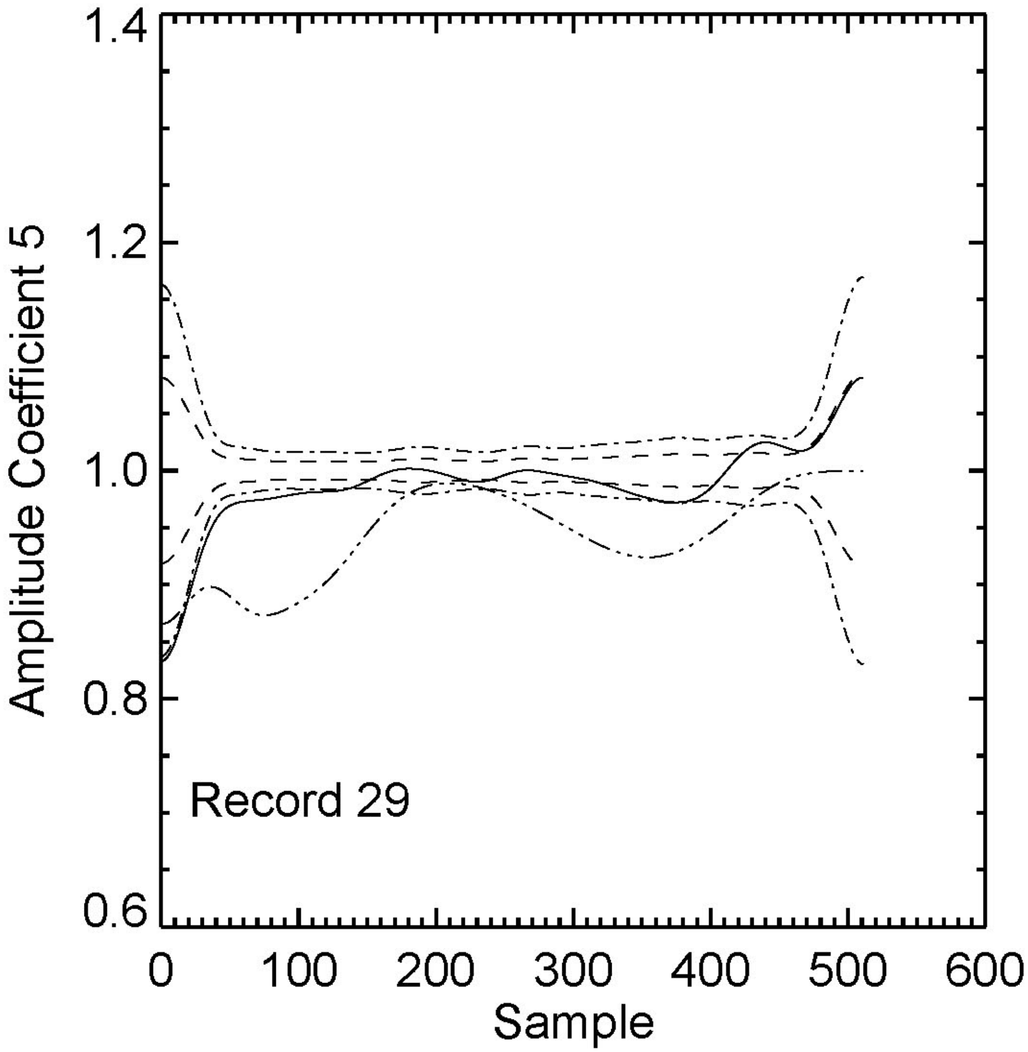
The drop in signal is best fit by an exponential curve – a comet-like evaporating atmosphere ($1/R^2$) does not fit the data well, nor do global hydrostatic cases (ruled out by our data anyway, but shown here for illustration).

CASSINI MISSION CRUISE TRAJECTORY




Saturn's Satellites and Ring Structure
Pan
Atlas
Prometheus
Janus
Pandora
Epimetheus
Mimas
Telesto
Calypso
Enceladus
Tethys
Helene
Dione
Rhea
Hyperion
Titan
Iapetus
Phoebe
Saturn
Pan
Atlas
Prometheus
Pandora
Janus
Epimetheus
Ring Plane Crossings
Cassini division
Encke division
Pioneer 11 outbound
Voyager 2
Pioneer 11 inbound
Voyager 1 outbound
Titan
Hyperion
Iapetus
Phoebe
D ring
C ring
B ring
A ring
F ring
G ring
E ring
Mimas
Enceladus
Tethys
Dione
Rhea

Statistical Analysis using FITS



Statistical Analysis using FITS