Enceladus: Cassini Finds Another Active World

John Spencer
Southwest Research Institute, Boulder

Cassini CHARM Telecon
April 24th 2007

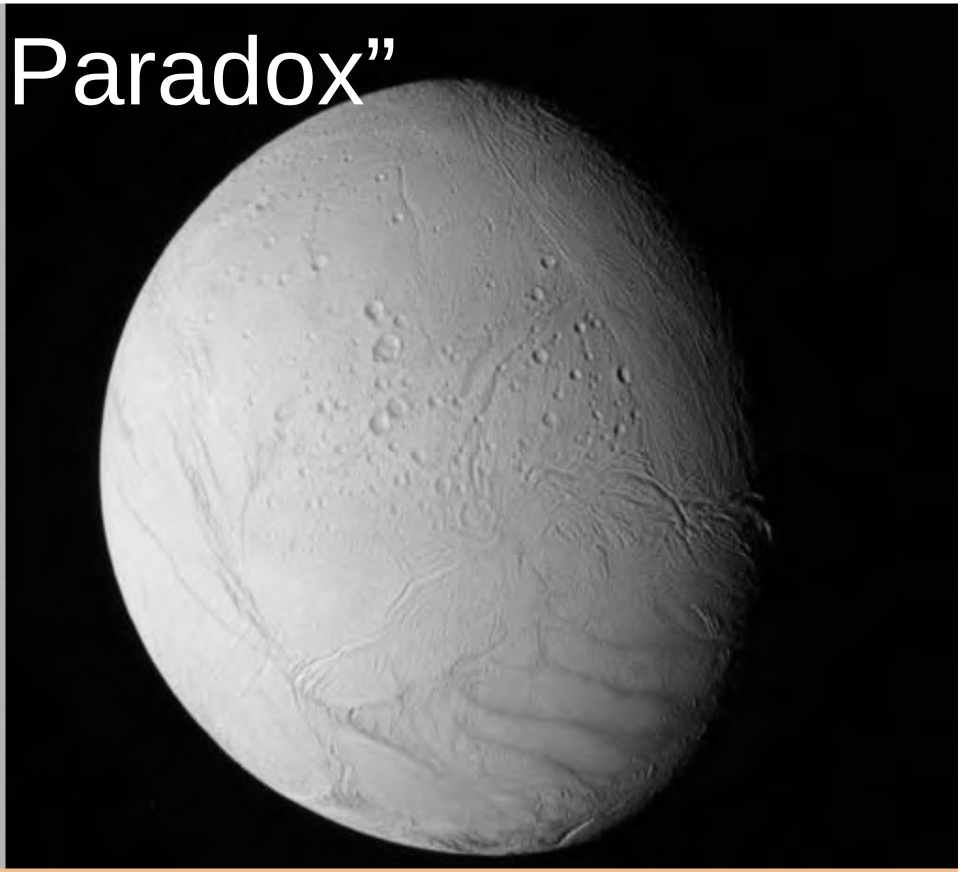
Voyager: 1980, 1981

- Very high albedo
- Extensive tectonism, crater relaxation

Tidal Heating: Pre-Cassini Ideas

- 2:1 orbital resonance with Dione produces forced eccentricity of 0.0047 (similar to Io)
- Estimates of equilibrium tidal heating rate depend highly on interior structure: few 100 MW to many GW (Peale et al. 1980, Yoder 1981, Squyres et al. 1983, Ross and Schubert 1989…)
  - Crude long-term upper limit of ~4 GW set by the stability of the Dione resonance and estimates of the internal structure of Saturn (Ross and Schubert 1989)
- Heating by spin/orbit resonance also possible? Wisdom (2004)

“Mimas Paradox”



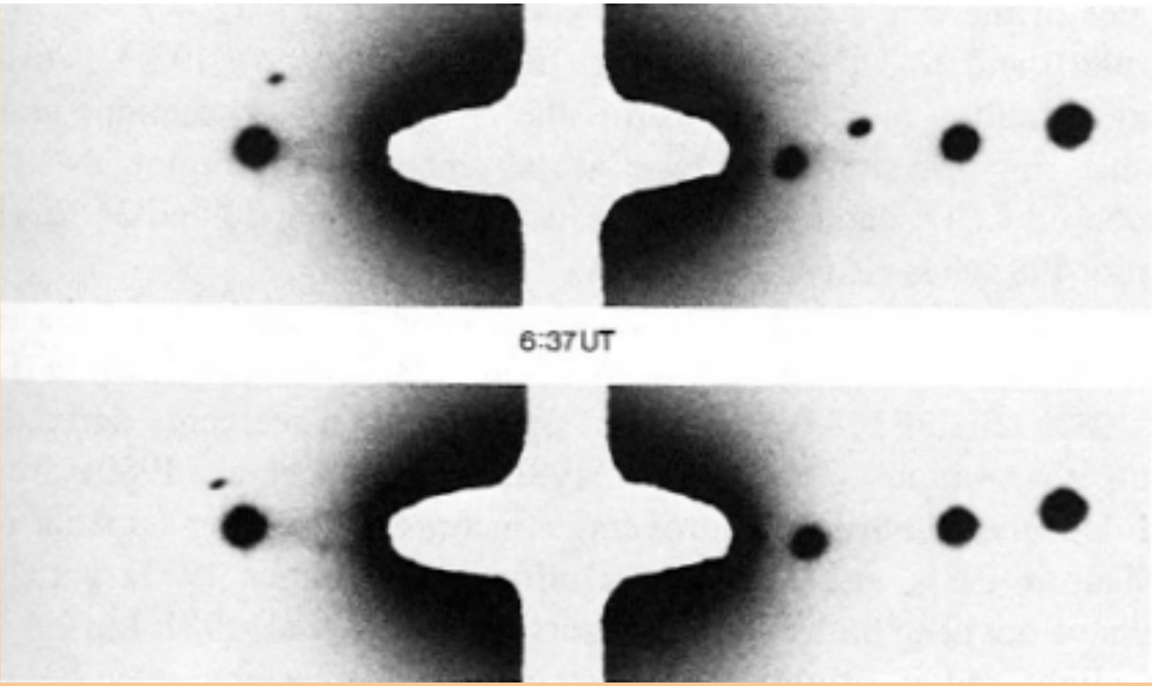
	Mimas	Enceladus
Diameter	420 km	504 km
Density	1.2	1.6
Distance from Saturn	3.1 R_S	3.9 R_S
Orbital Eccentricity	0.0206	0.0047
Tidal heating, solid ice rigidity, Q = 20	160 MW	16 MW

Bistable tidal heating?

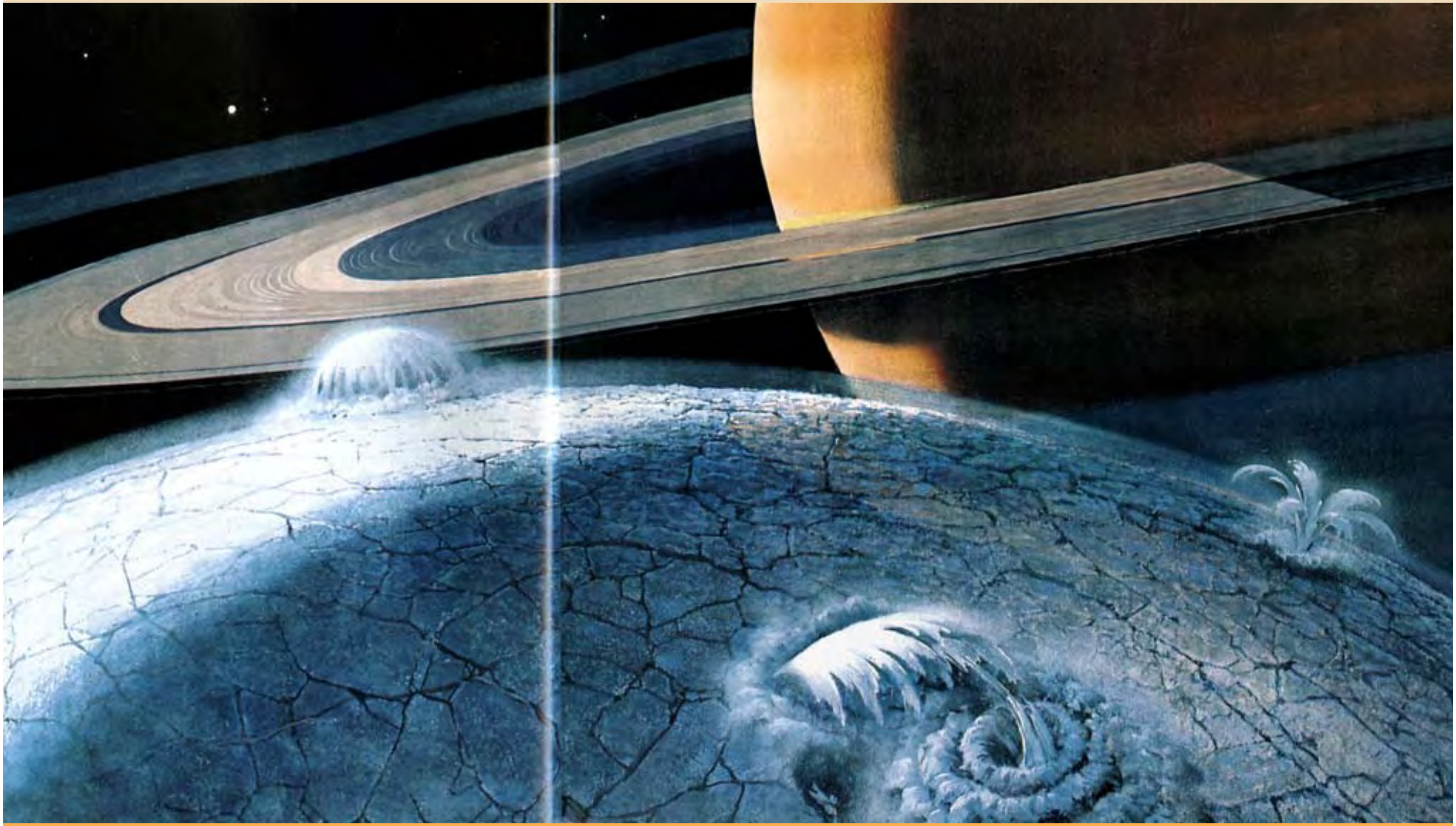
- Enceladus is warm, dissipative, stays warm.
- Mimas is cold, rigid, stays cold.

Need a way to “kick start” Enceladus initially

E-ring



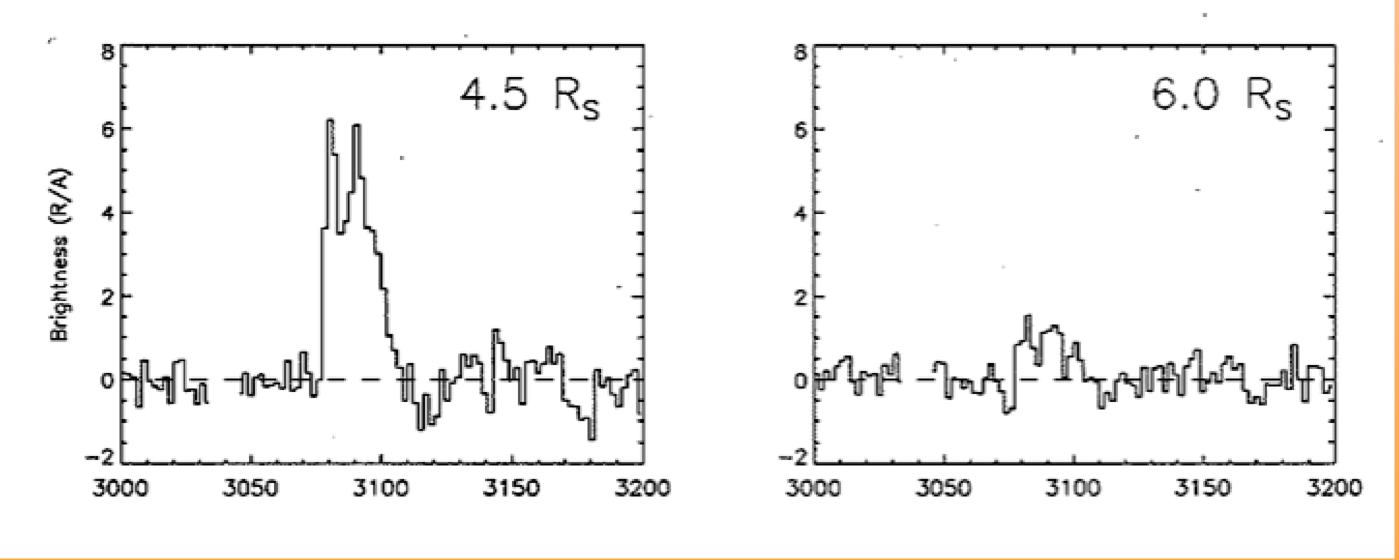
- Diffuse outer ring of Saturn, discovered in 1966
- Density peak at Enceladus (Baum et al. 1980, Reitsema et al. 1980, Larson et al. 1981)
- Blue color (Larson et al. 1981, 1984)
- Haff et al. 1983: Sputtering lifetime of E-ring particles is only a few thousand years: need a continuous source at Enceladus
  - Geysers??
- Photometry implies peculiar size/frequency distribution: geyser origin? (Pang et al. 1984)



National Geographic, 1981

OH Torus

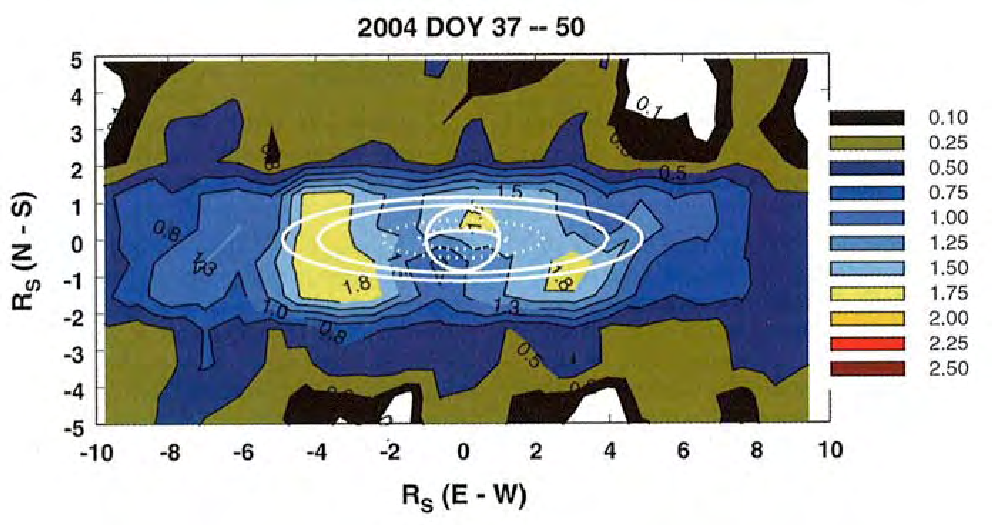
- Discovered by HST near the E-ring (Shemansky et al. 1993):
  - 20x more OH than expected from micrometeorites, sputtering: Need additional source (Jurac et al. 2001, 2002)



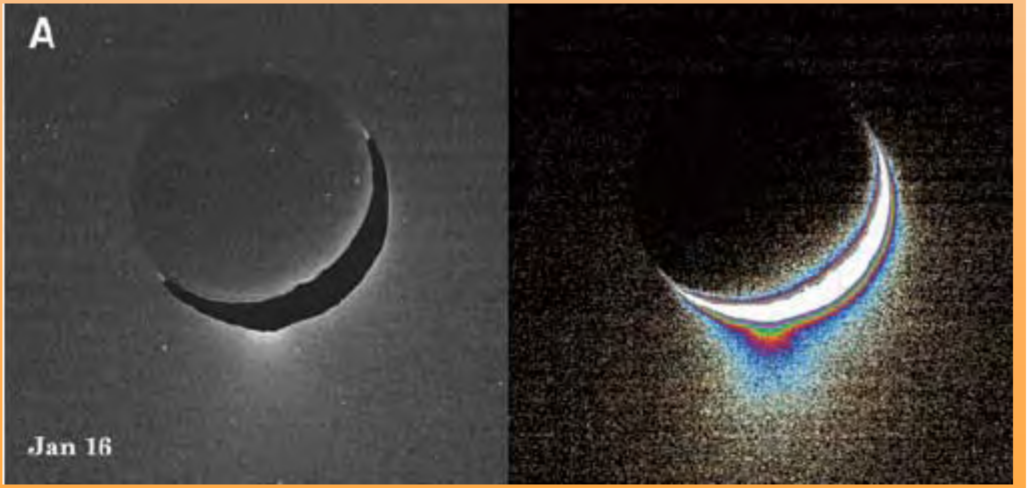
Richardson et al. 1998

Early Cassini Observations

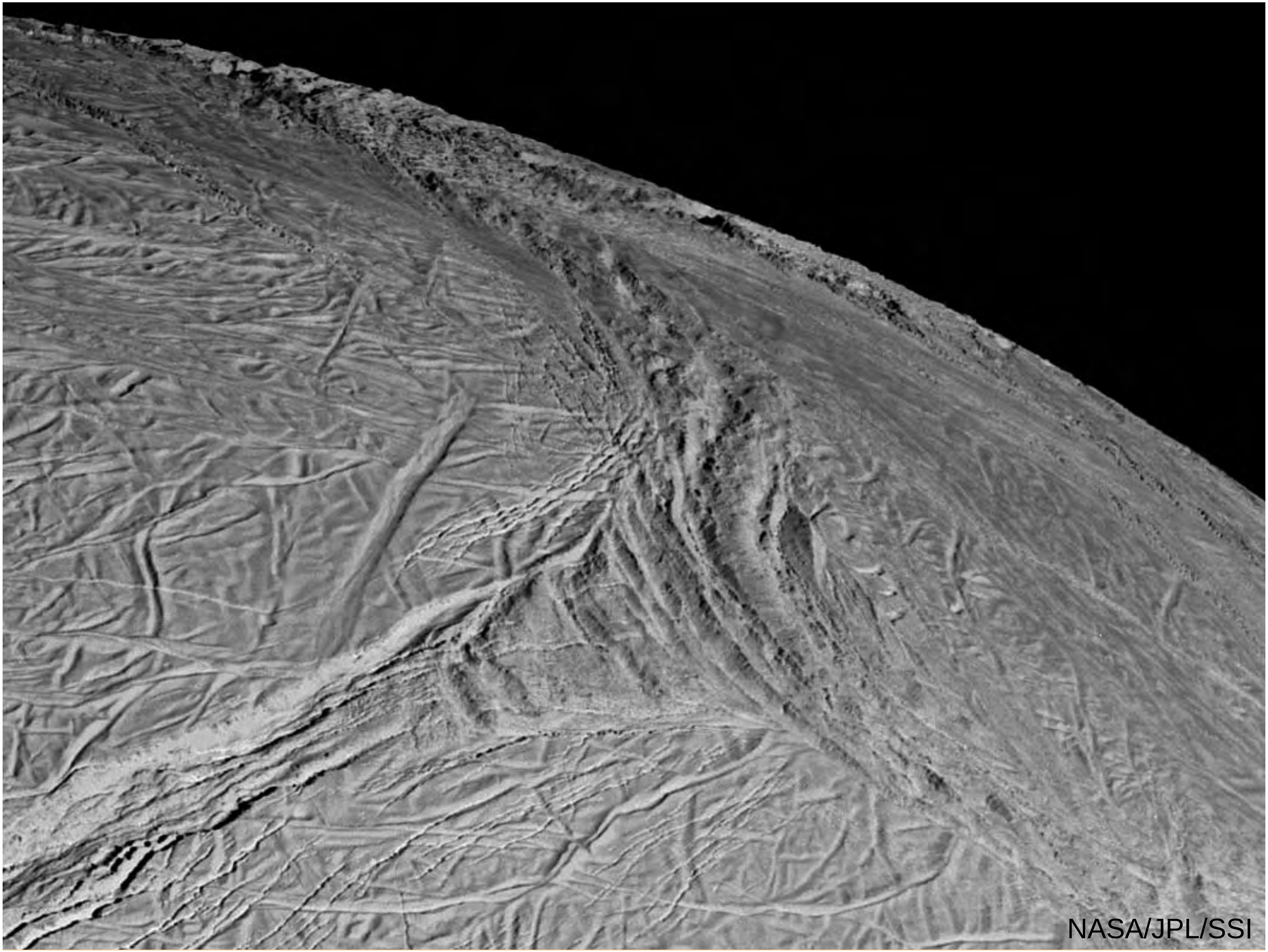
- Approach to Saturn, early 2004: UVIS observations of neutral O throughout the Saturn system, complementing the OH already known
- Distant high-phase imaging in Jan., Feb. 2005 showed south polar plume: not recognized at the time
- First close Enceladus flybys in early 2005…
  - Feb 17th 2005, 1260 km altitude
  - Mar 9th 2005, 500 km altitude

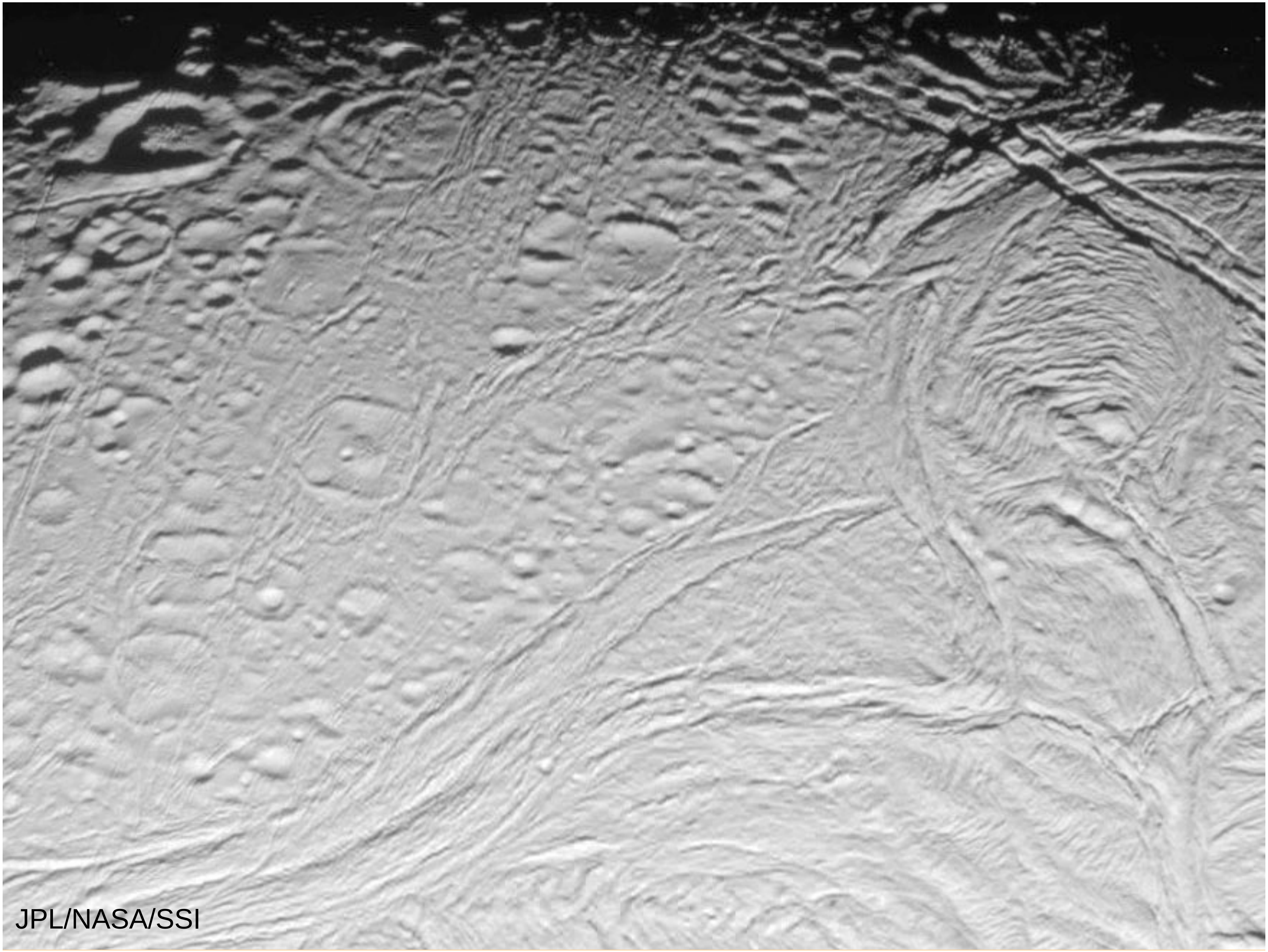


Esposito et al. 2005



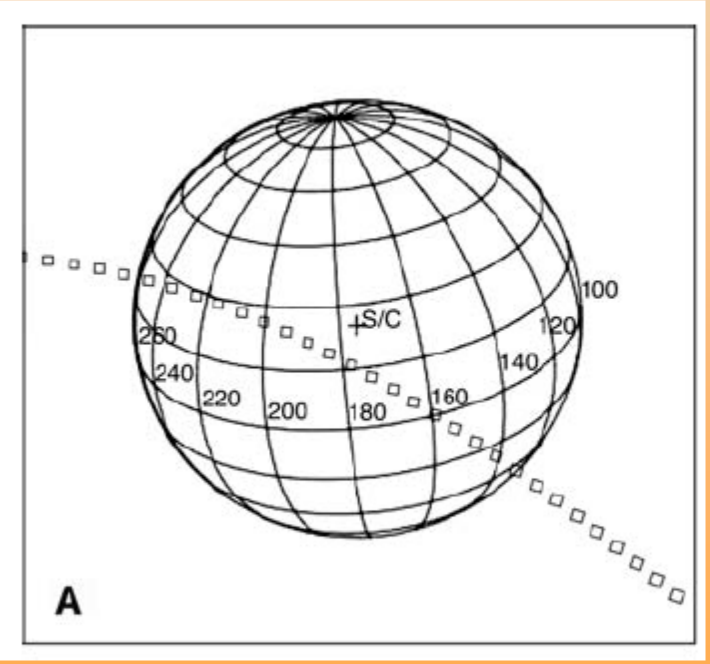
Porco et al. 2006

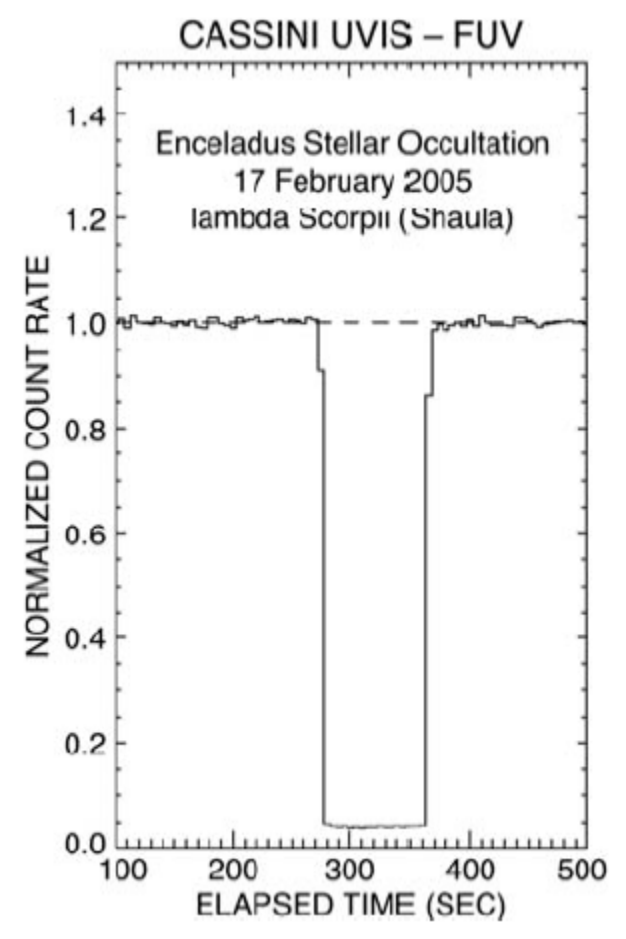

NASA/JPL/SSI


JPL/NASA/SSI

Feb. 2005 UVIS Stellar occultation

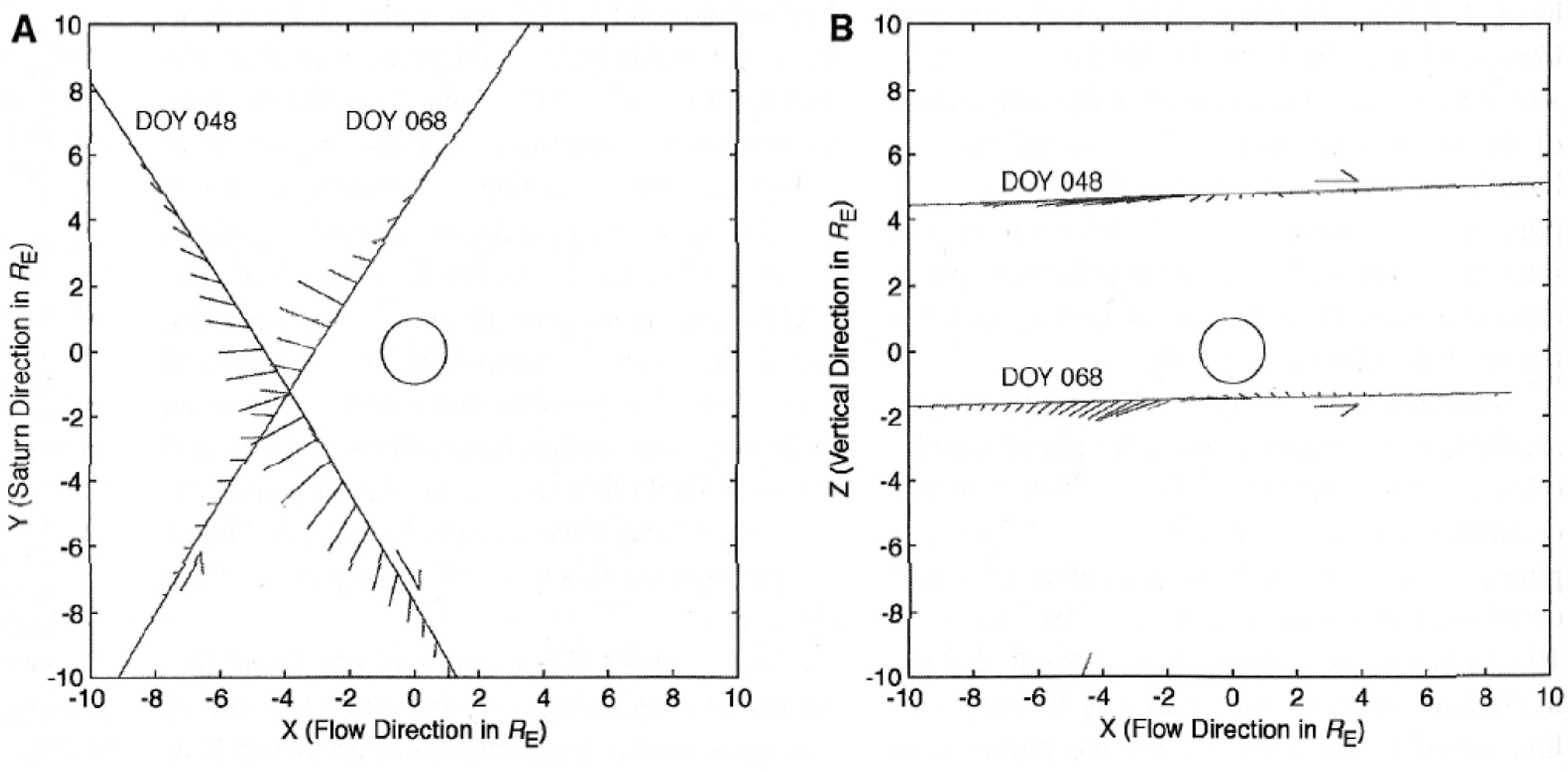
- Low latitudes: No atmospheric signature seen (Hansen et al. 2006)





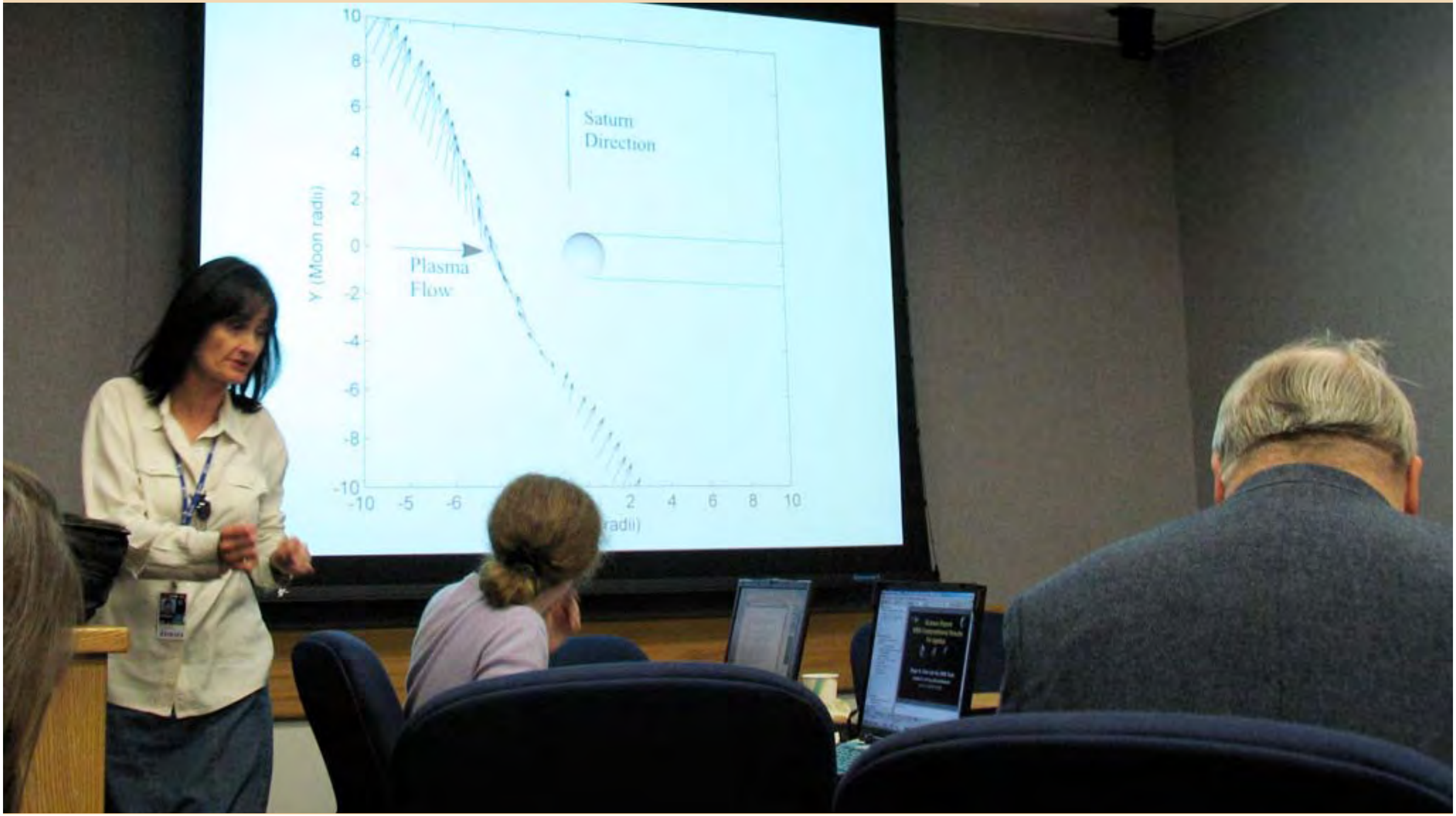
Feb., Mar. 2005 Magnetometer results

- Field perturbations by a conducting barrier larger than Enceladus (Dougherty et al. 2006)



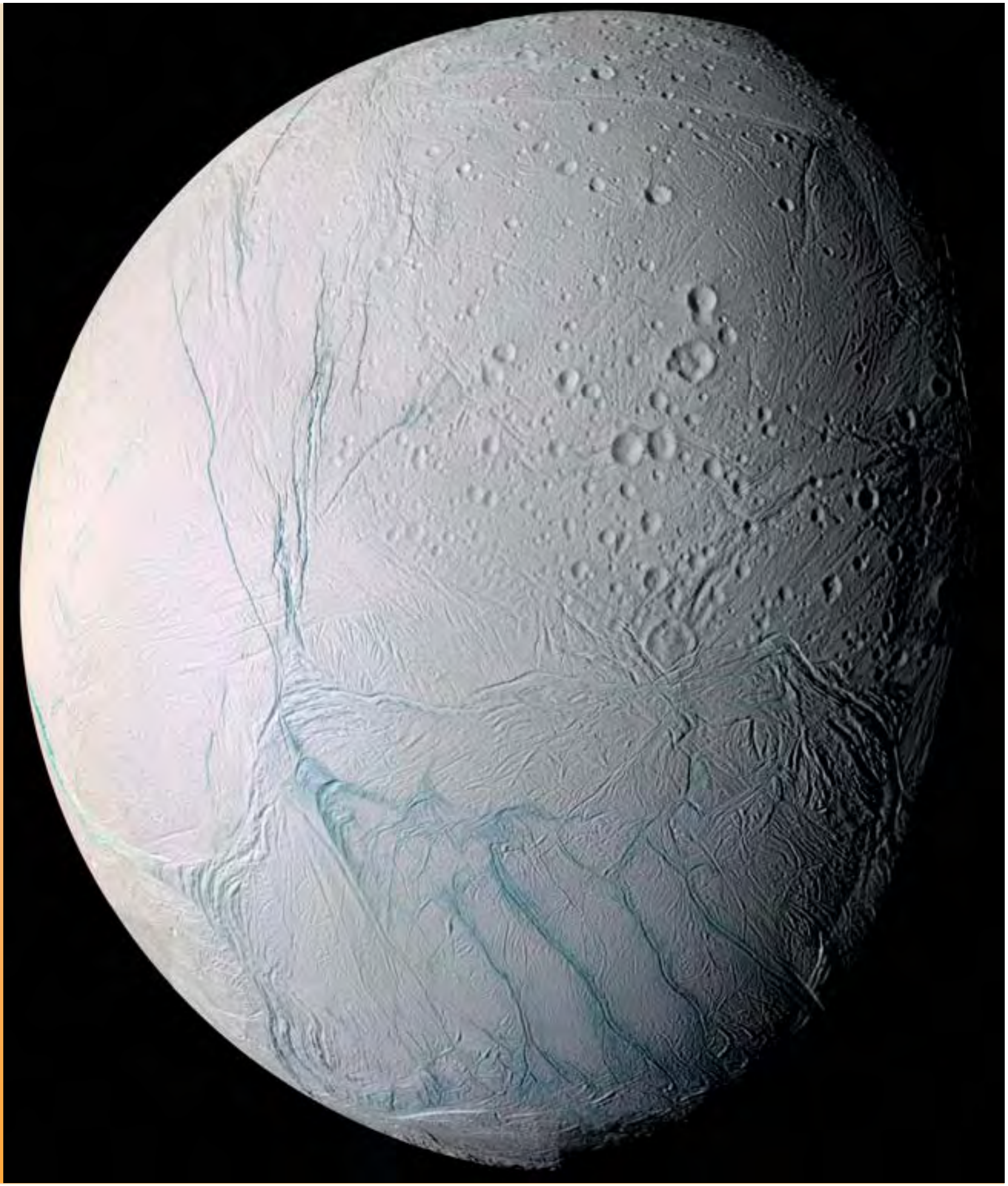
April 2005: Cassini satellite Workshop,JPL

Michelle Dougherty argues for lowering the planned 1000 km periapse of the July 2005 flyby to ~175 km to investigate more closely.

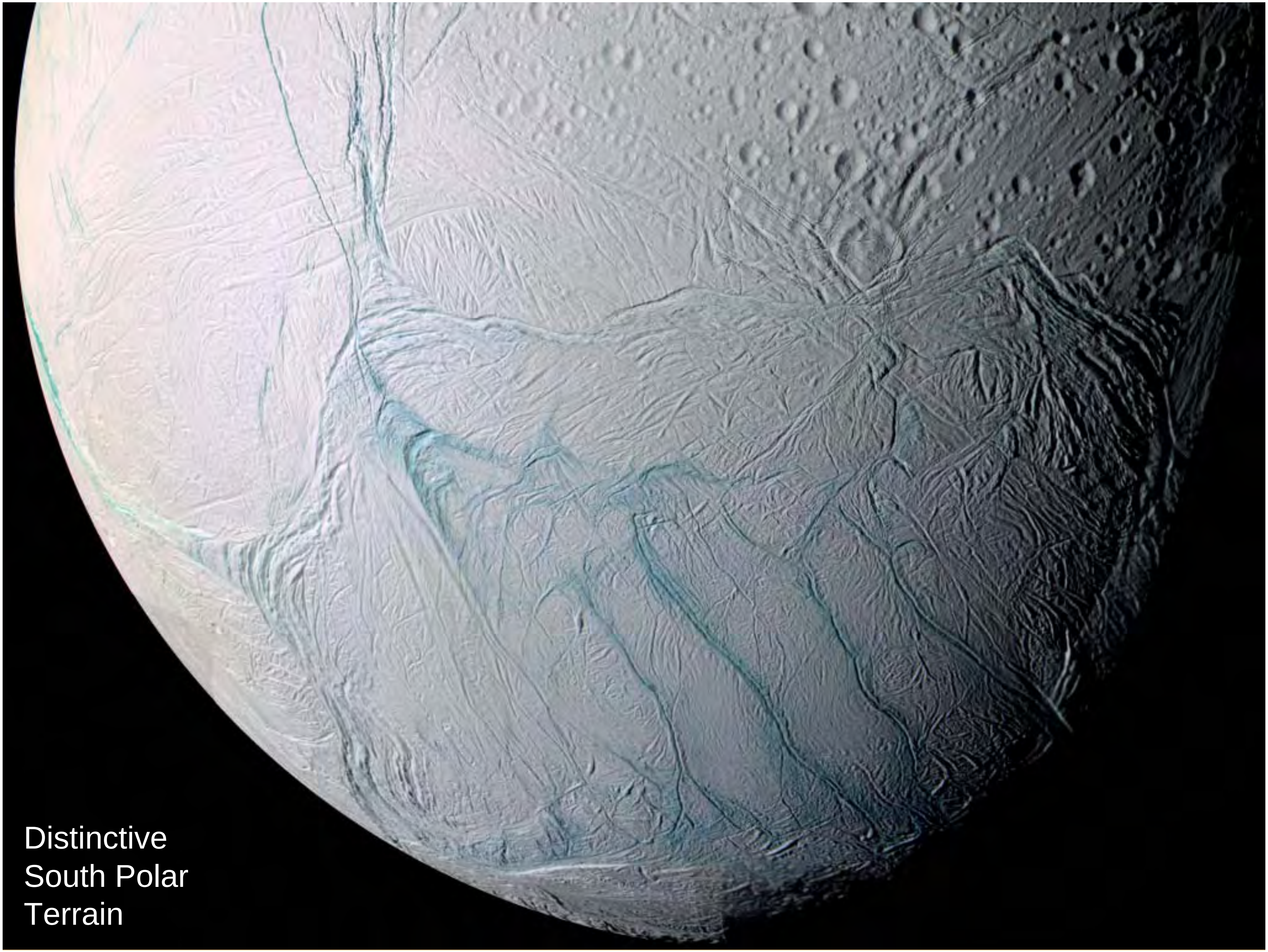


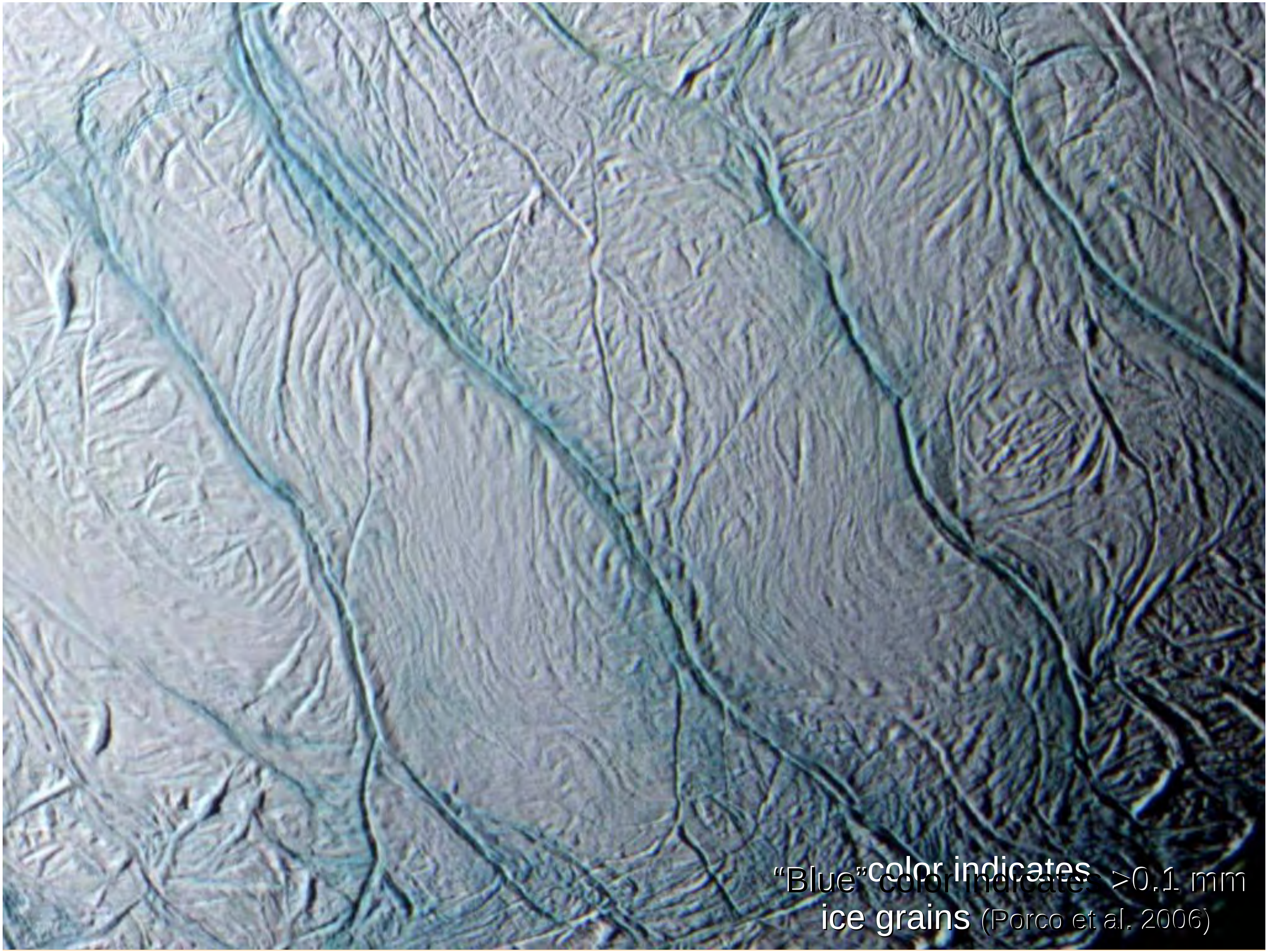
July 14 2005: Imaging on Approach

- First good view of south polar “tiger stripes”



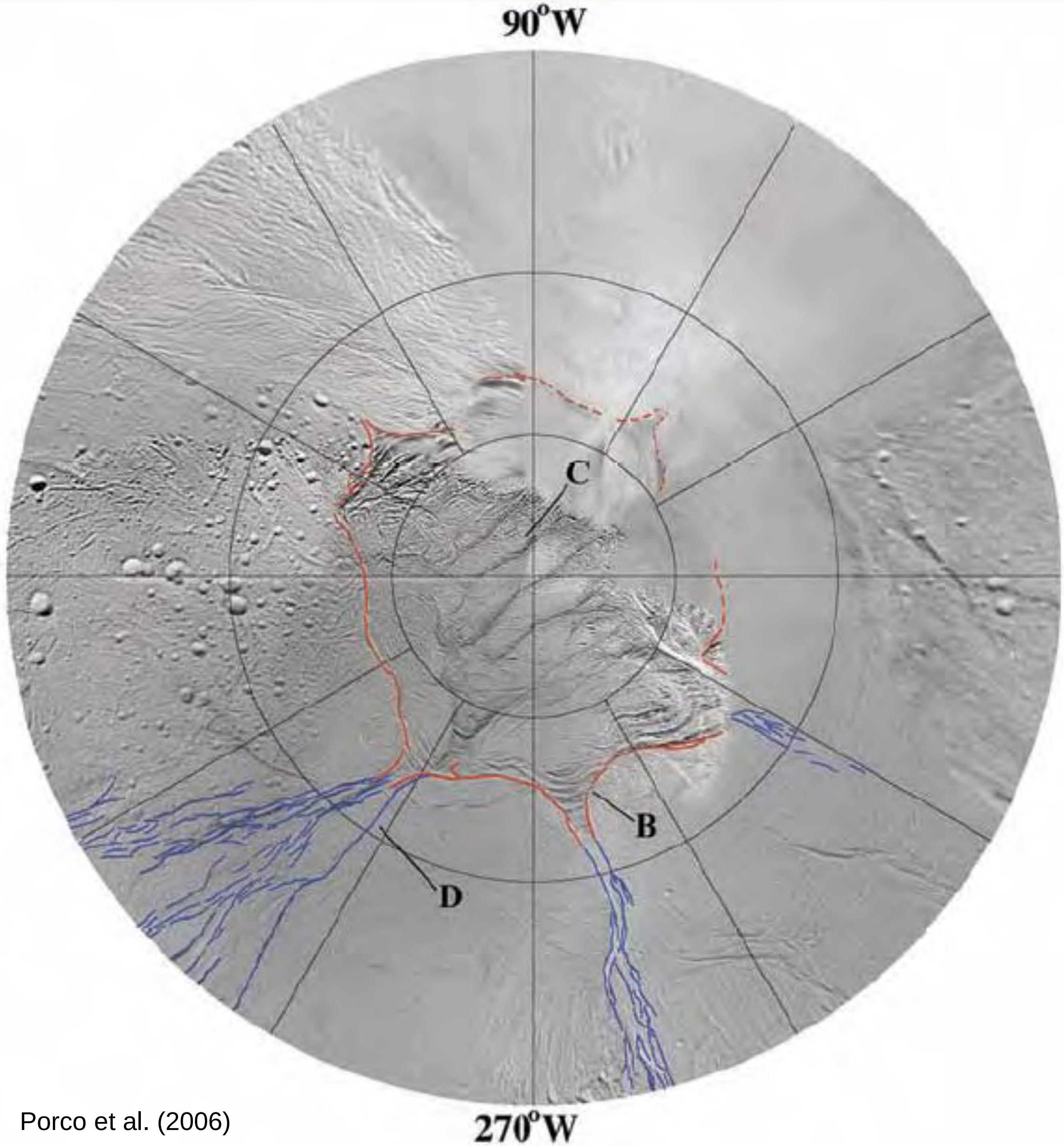
NASA/JPL/SSI


Distinctive
South Polar
Terrain

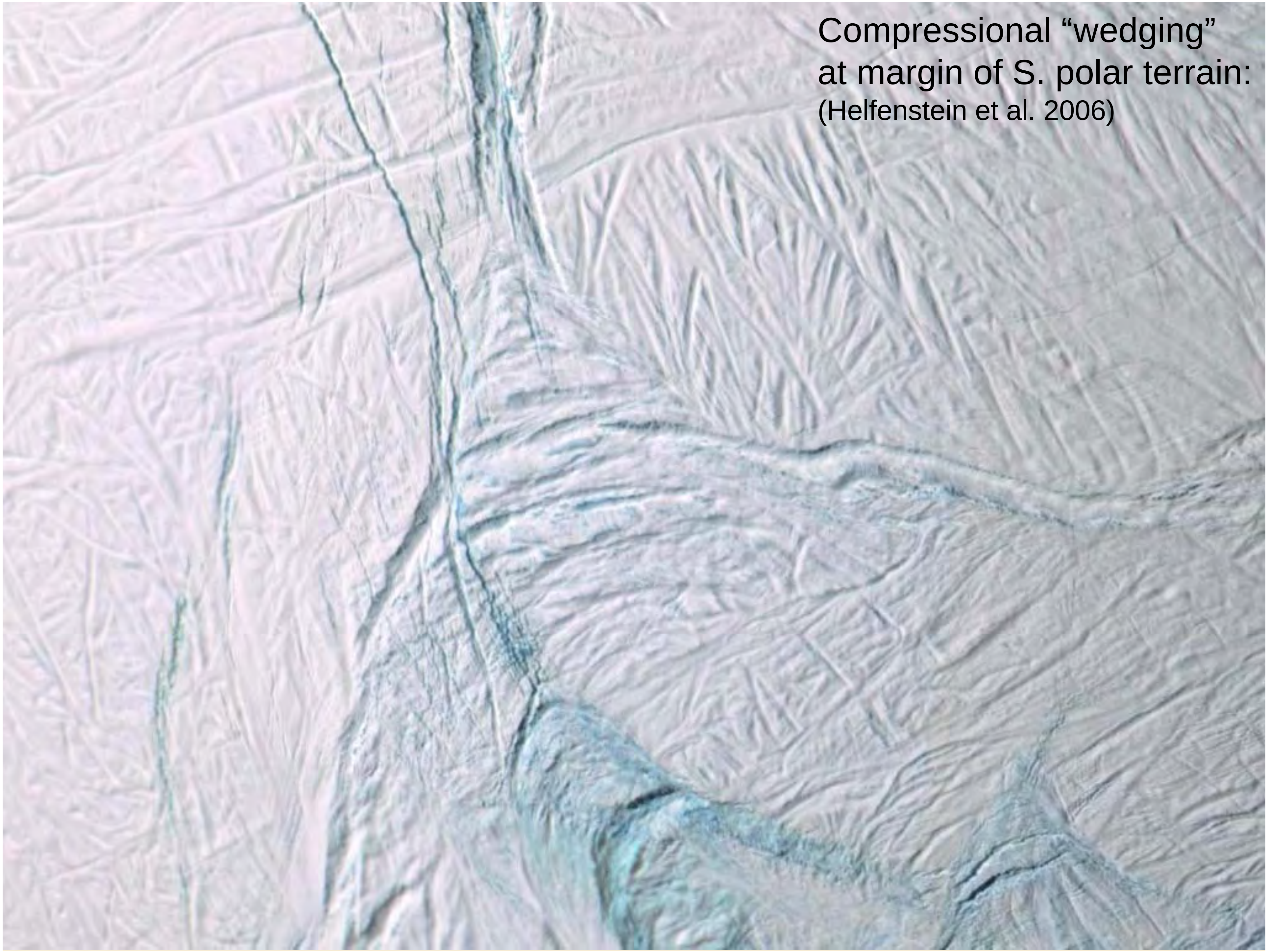


“Blue” color indicates >0.1 mm ice grains (Porco et al. 2006)

- Distinctive terrain precisely centered on the south pole
- Bordered by scalloped scarps at ~55 S
- Tension fractures radiate northwards from the scallops
- At most, a small number of impact craters: age < 1 m.y.?



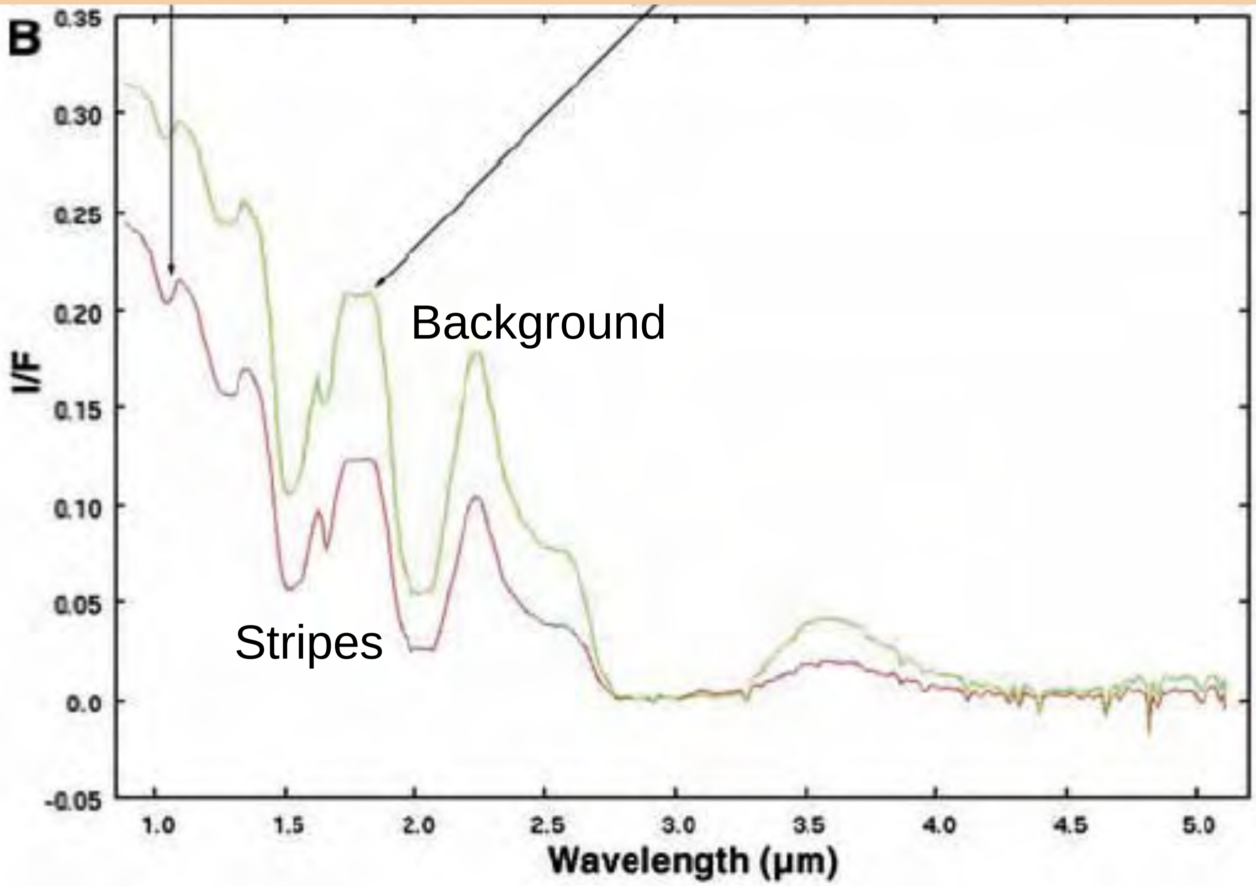
Porco et al. (2006)

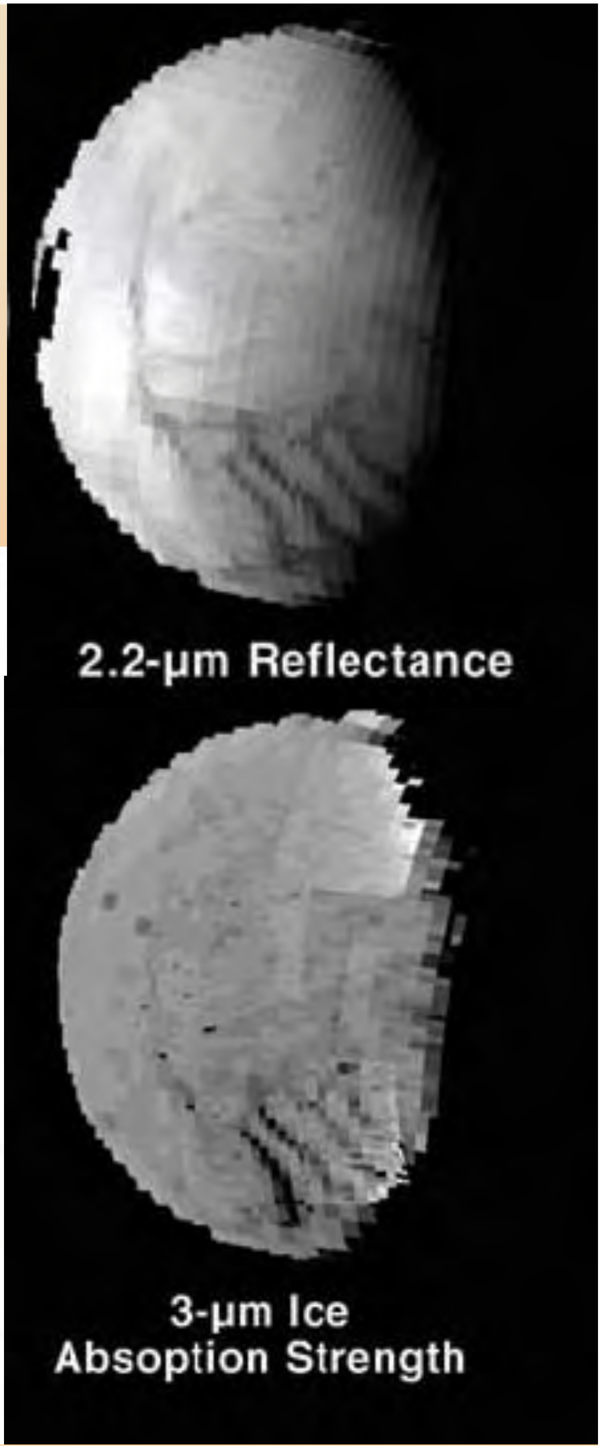

Compressional “wedging”
at margin of S. polar terrain:
(Helfenstein et al. 2006)

Tiger Stripe Spectrum

VIMS (Brown et al. 2006):

- Coarser grains (0.1 – 0.3 mm) in tiger stripes
- Ice is mostly crystalline
- No thermal emission seen





Tiger Stripe Spectrum, contd.

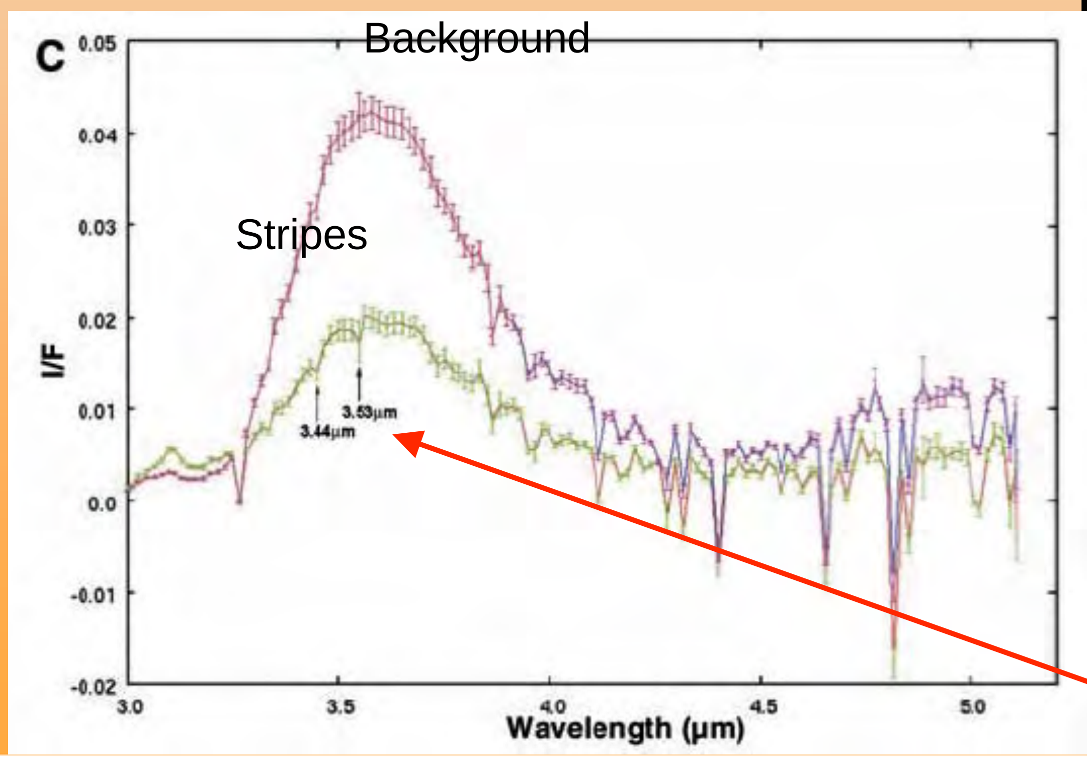
Stripes are also enriched in

- CO_2
- Organics

NH_3 frost not seen

CO gas also not seen (strong upper limit)

(Brown et al. 2006)



CIRS Thermal IR Observations

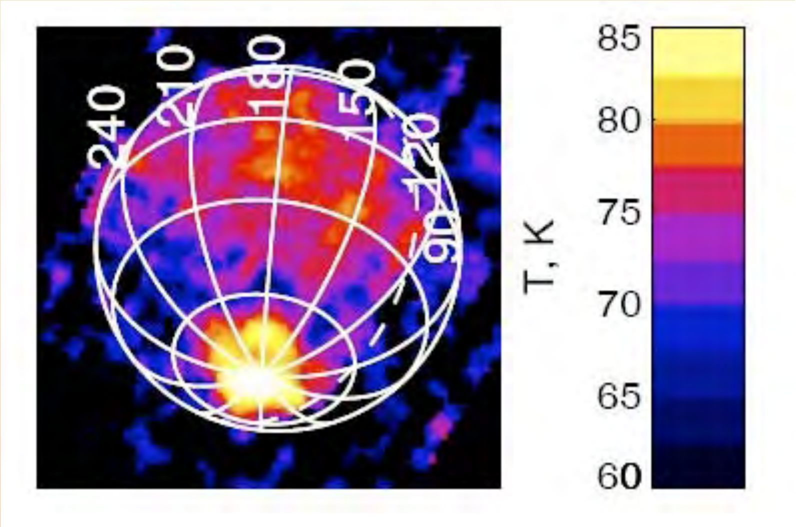
Spencer et al. (2006)

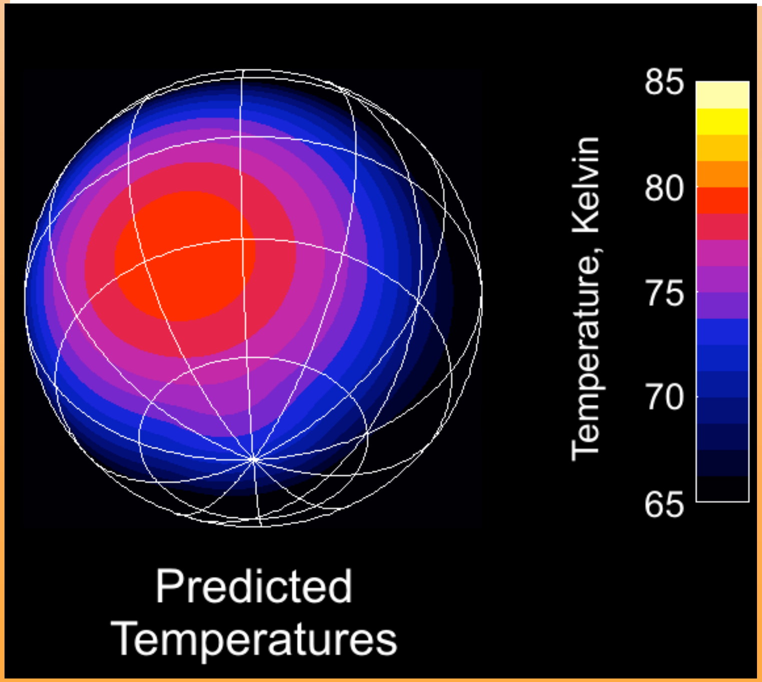
- Effective wavelength = 12 – 16 μm
- Resolution = 25 km

South polar hot spot!

- Simple passive model cannot produce a warm pole

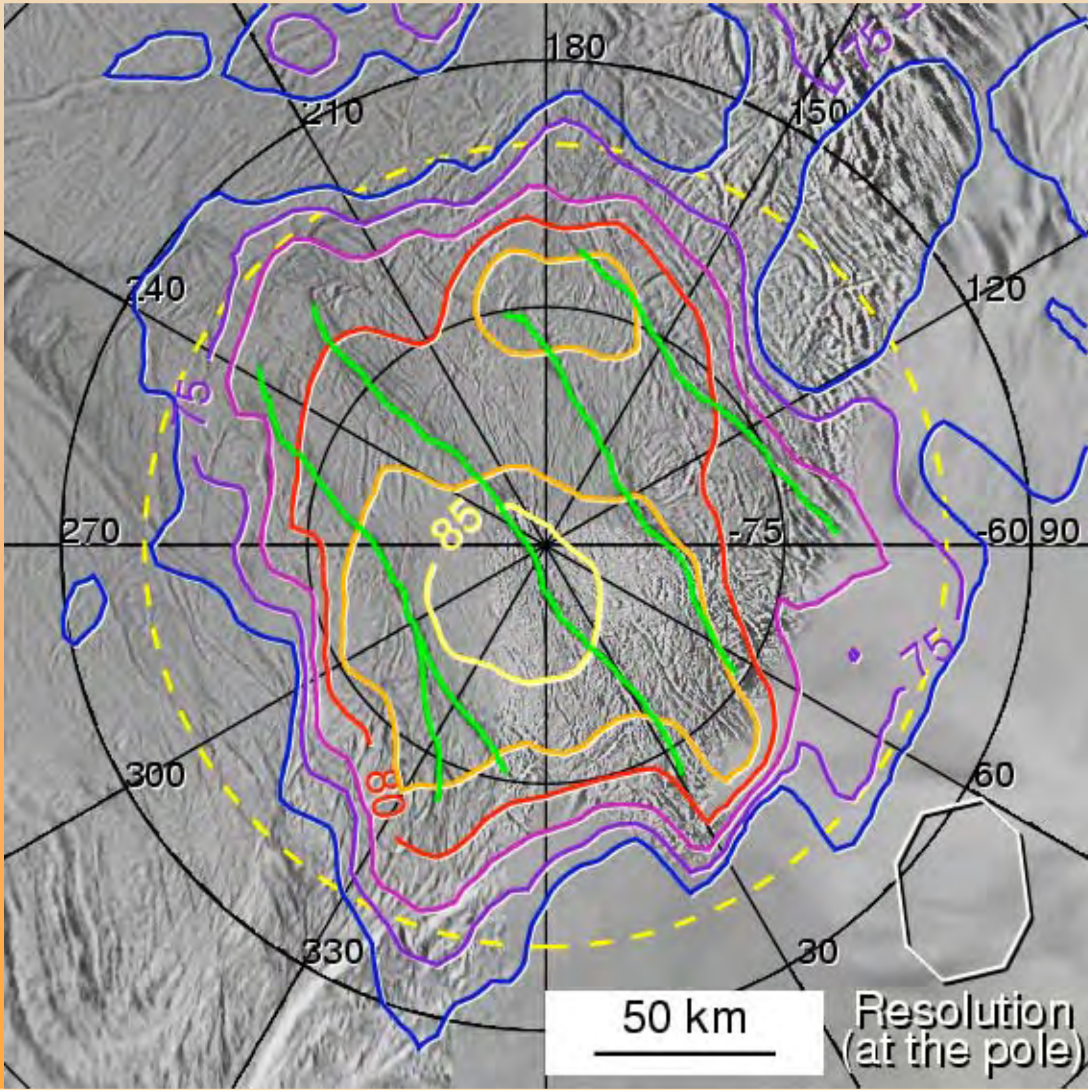
Best-fit blackbody temperature





Location of Warm Region

- Centered on the south pole
- Corresponds closely to the “tiger stripe” fractures (rather than the larger south polar terrain)

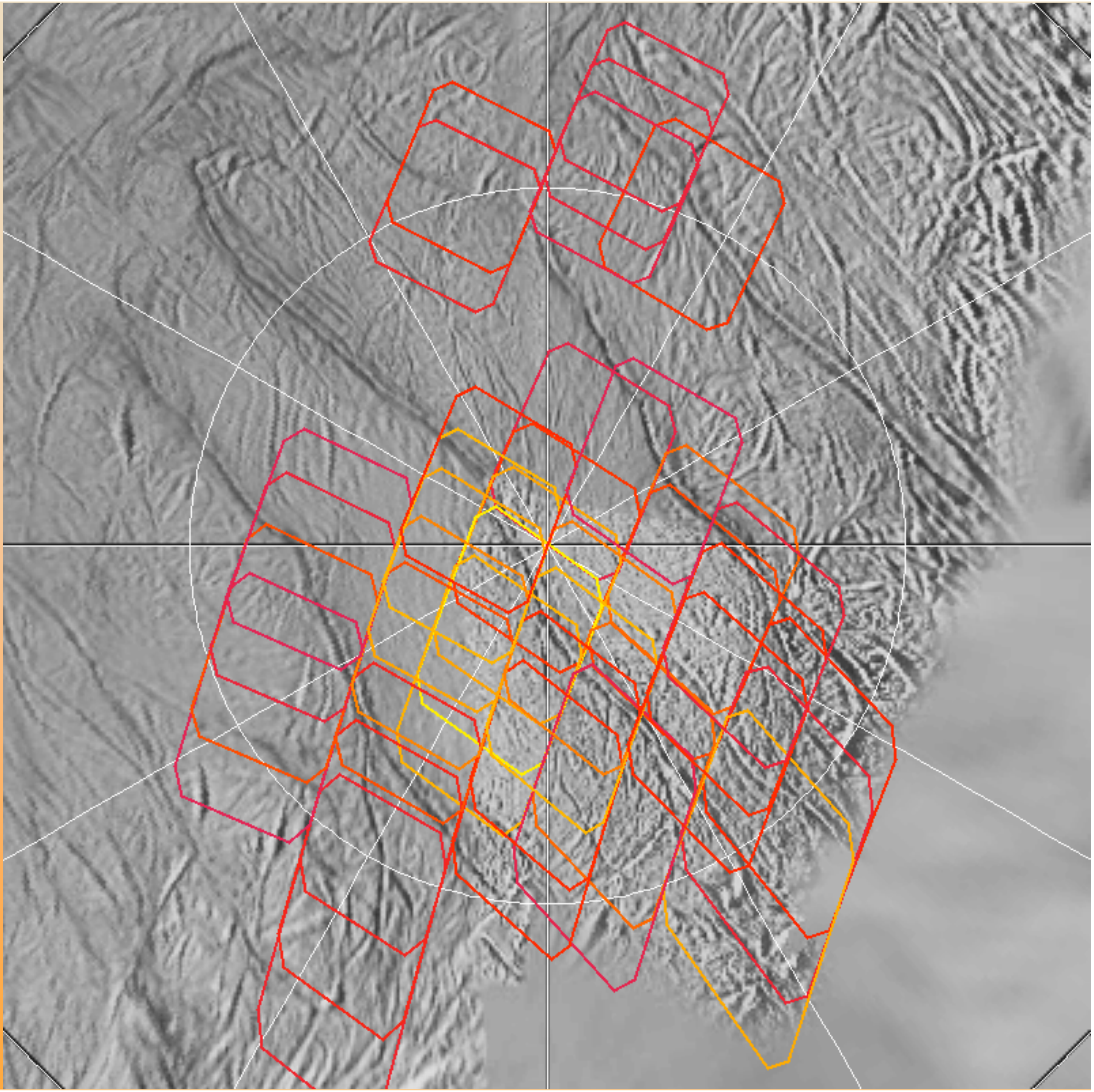


Brightness Temperature Contours

(Spencer et al. 2006)

Spectra with T_B > 84 K

- Heat distribution is not uniform along the tiger stripes
- The stripe closet to the south pole is the warmest, and is warmest near the south pole



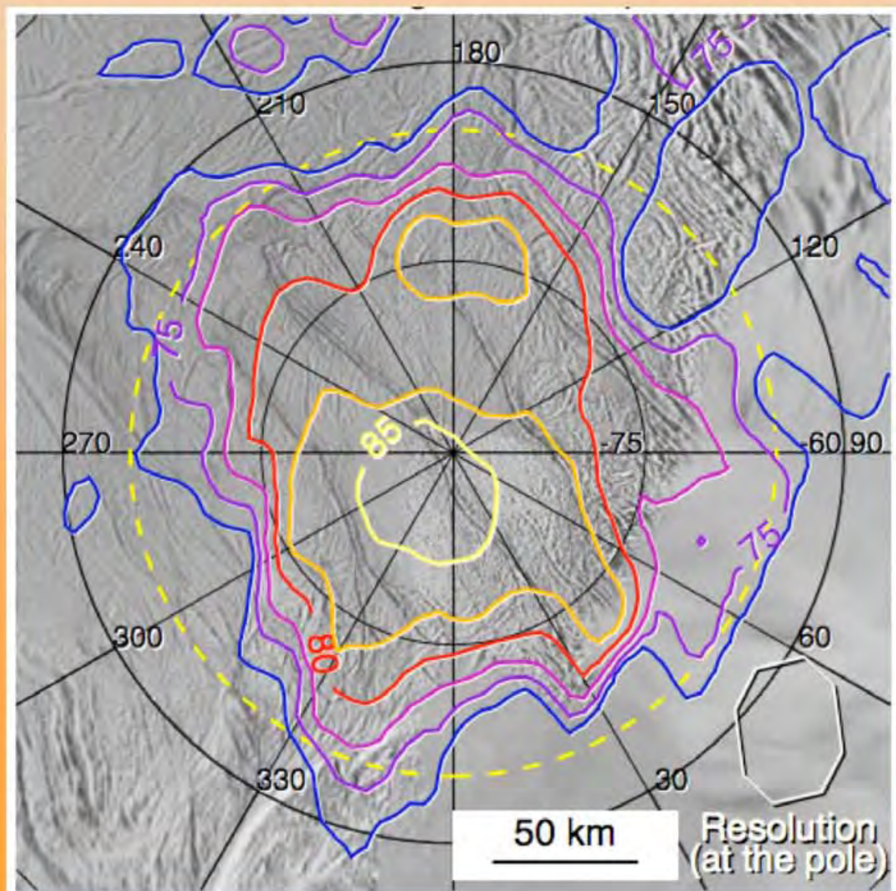
Emission Variations Along Tiger Stripes

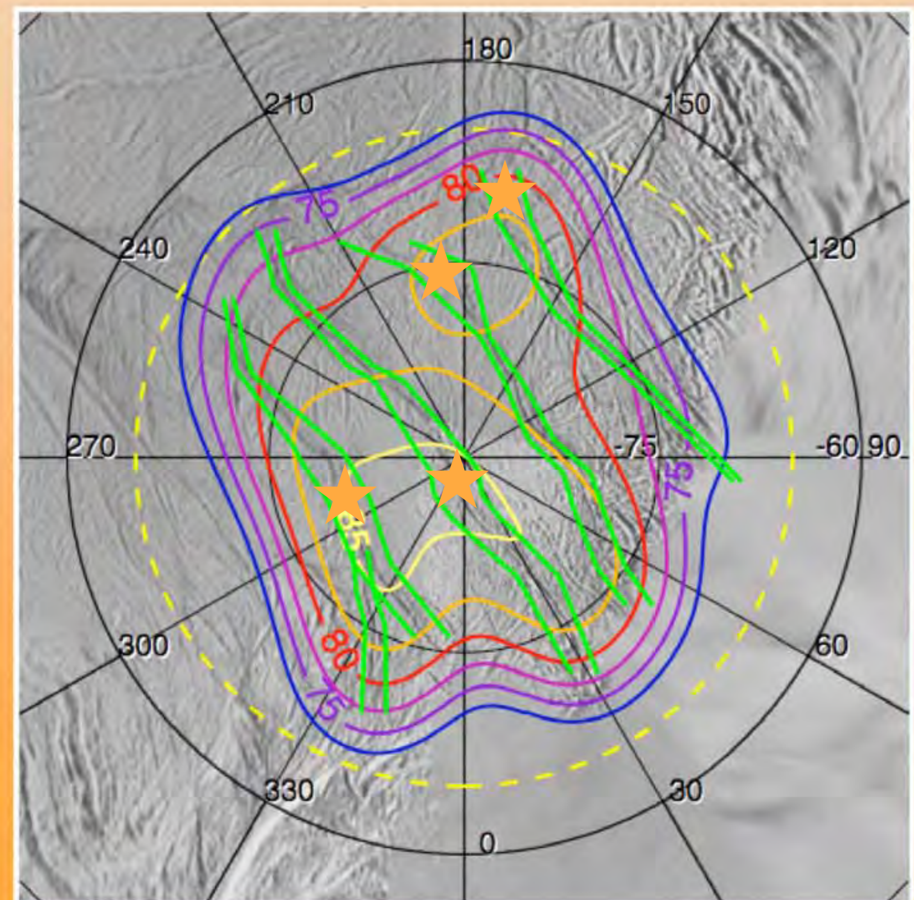
Model 2: 120 - 600 m wide zone at 135 K along all tiger stripes

- Width adjusted manually to roughly match observed emission

- Matches observations well
  - > 5-fold variations in thermal emission exist along the stripes

Peak brightness of all four stripes is similar

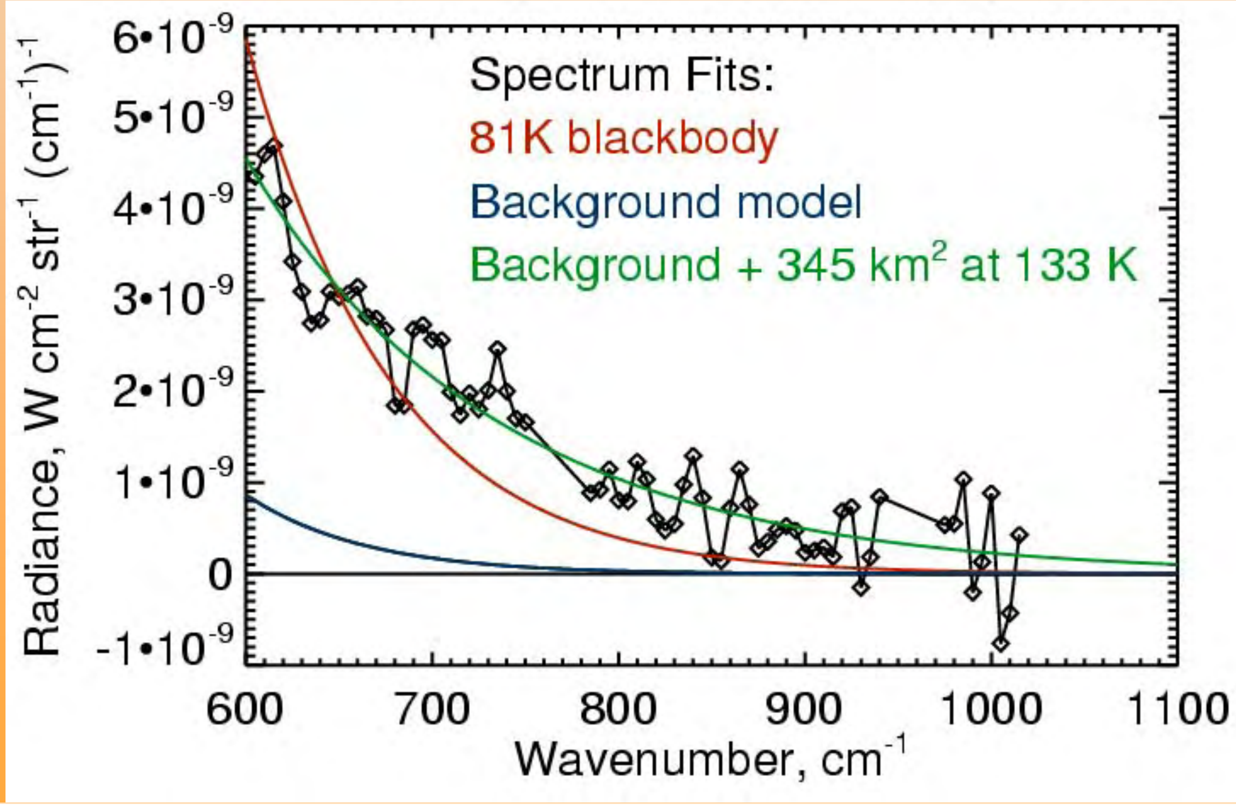




Spectrum of South Polar Warm Region

Average spectrum south of 65 S

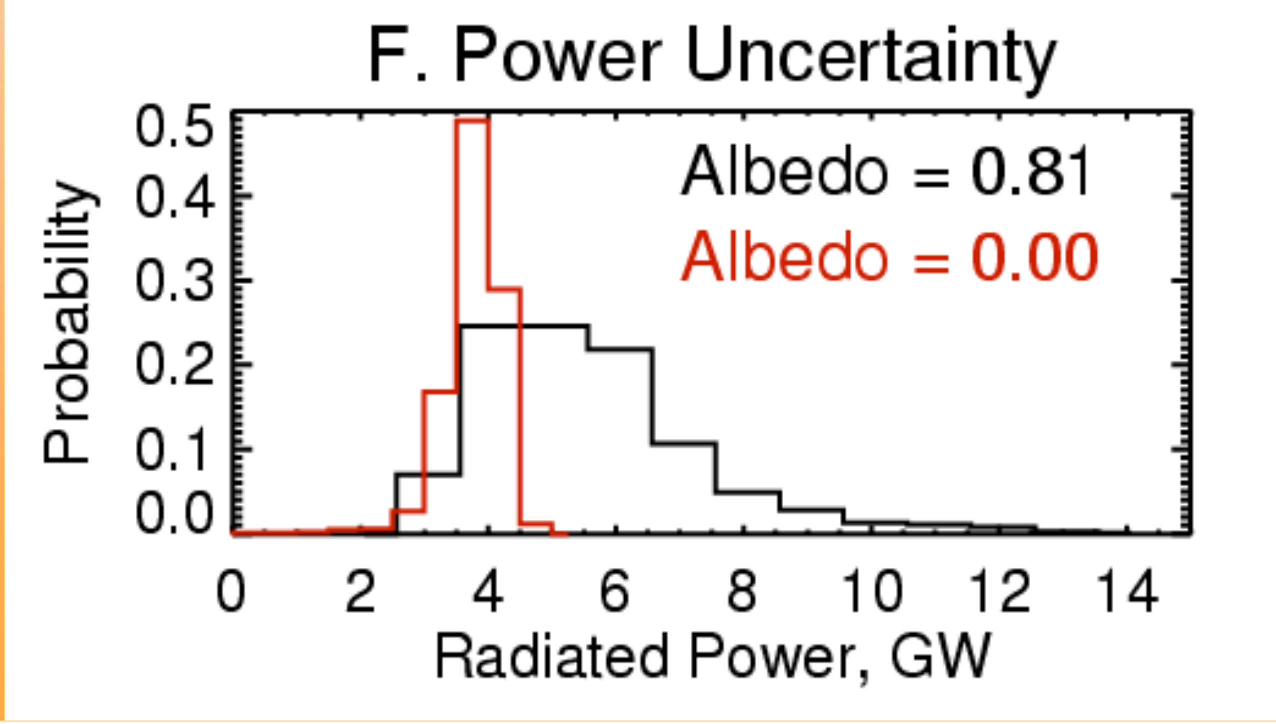
- Not consistent with a blackbody
- Best fit after subtracting expected background:
  - 345 km^2 (~1% of the surface) at 133 K
- Average ~660 m width of warm material along the 500 km tiger stripes



Spencer et al. (2006)

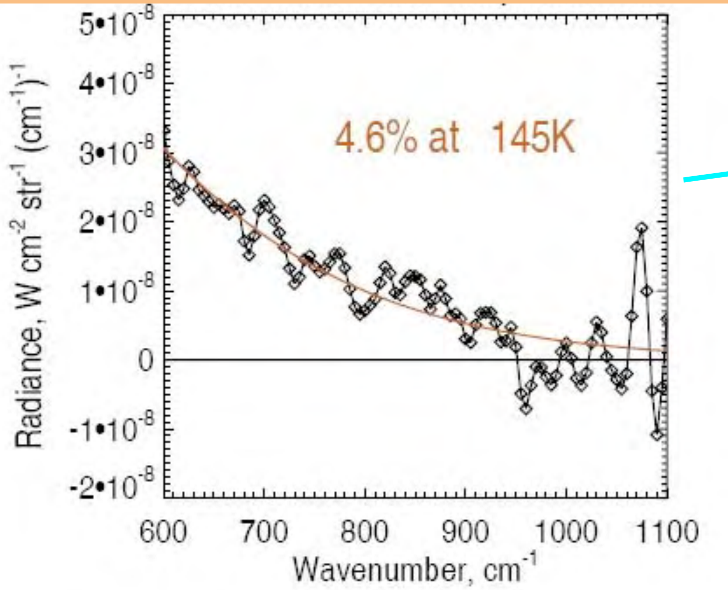
South Polar Radiated Power

- If all power is radiated at a single temperature
  - Radiated power south of 65 S = 5.8 ± 1.9 GW
- Additional power at lower temperatures is likely

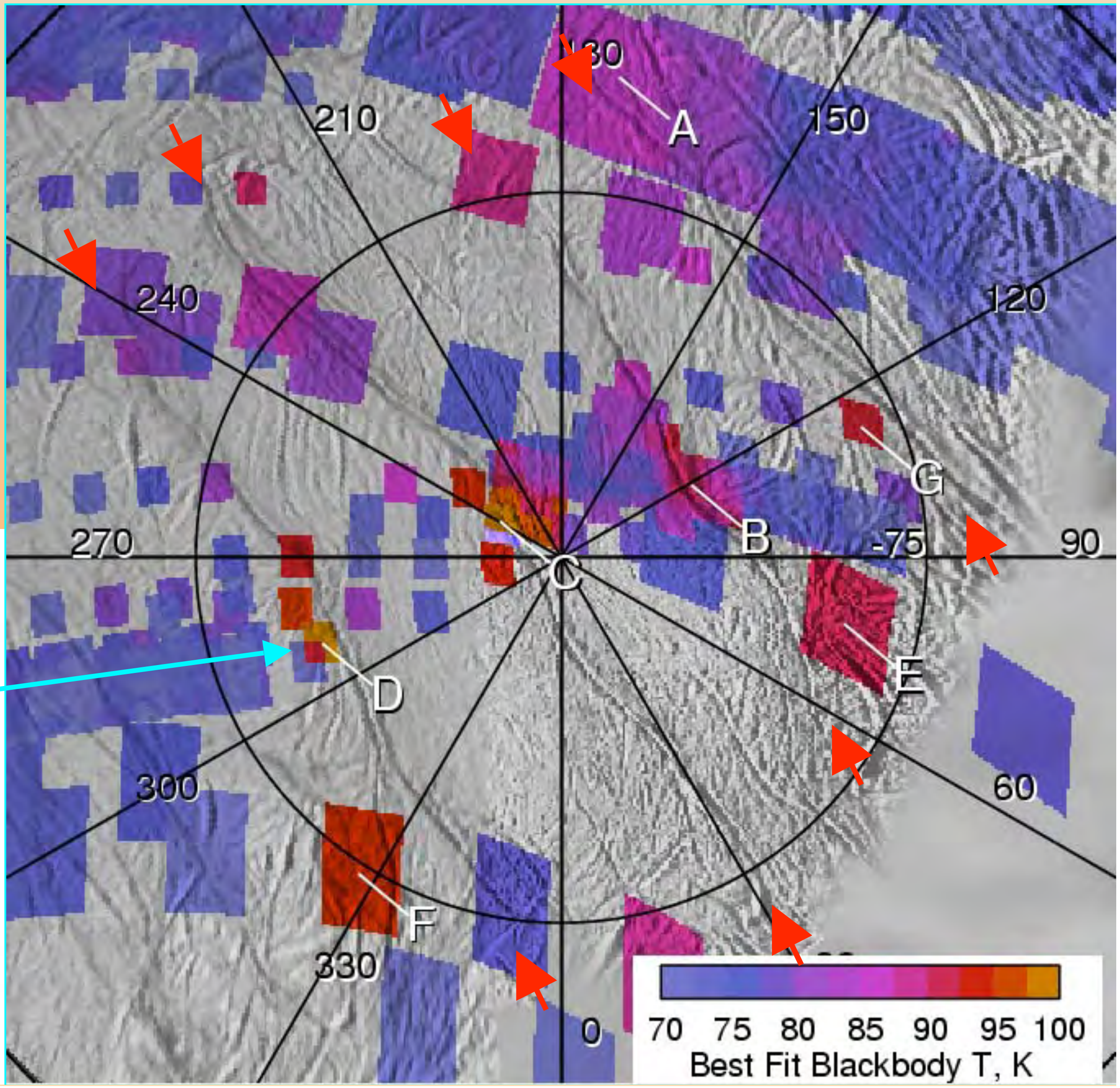


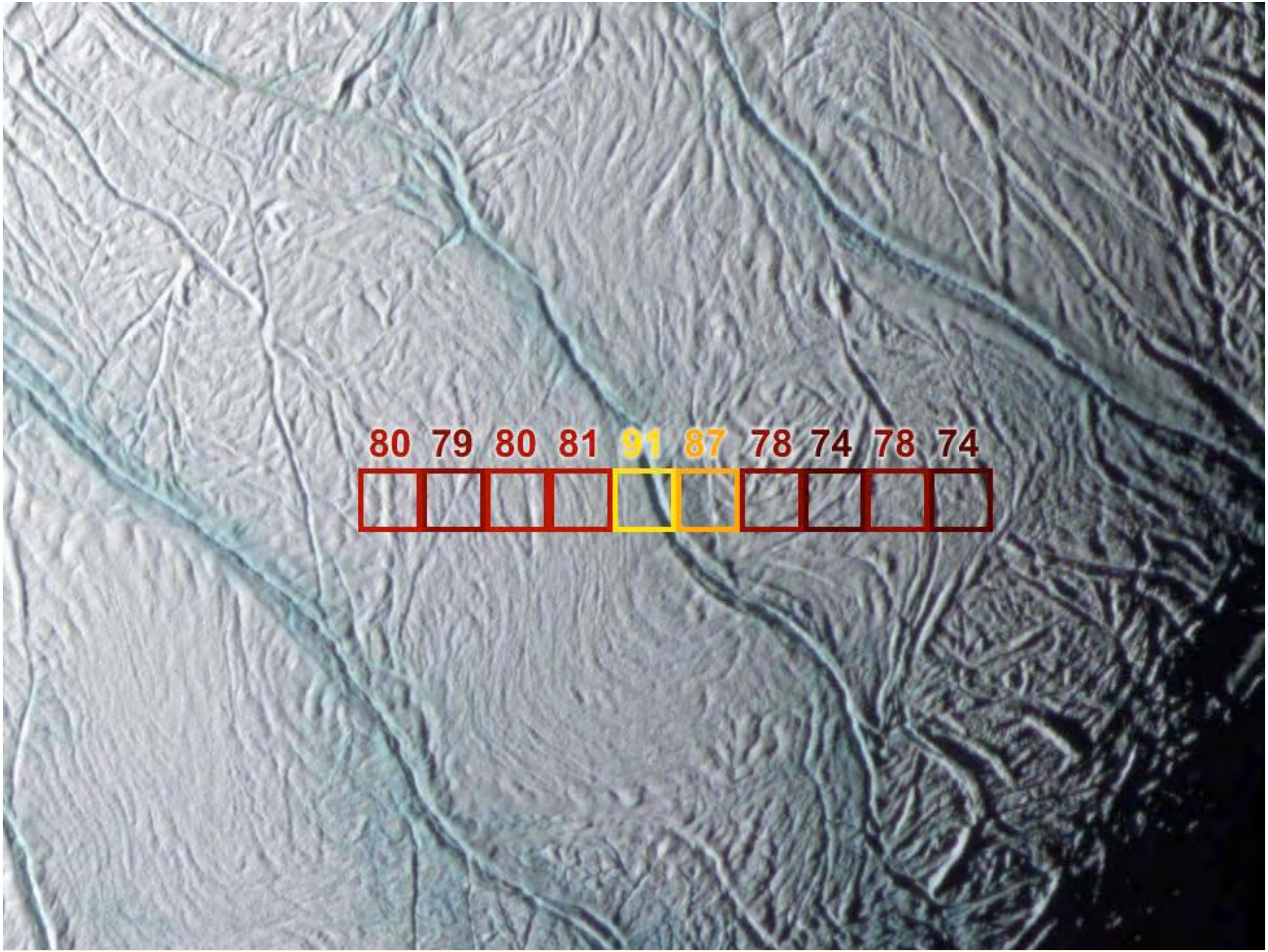
High Resolution CIRS Observations

- Scattered "ridealong" observations at 20 – 0.6 km resolution
- Confirm localization of warm material along the tiger stripes
- Most powerful spectrum
  - 145 ± 14 K



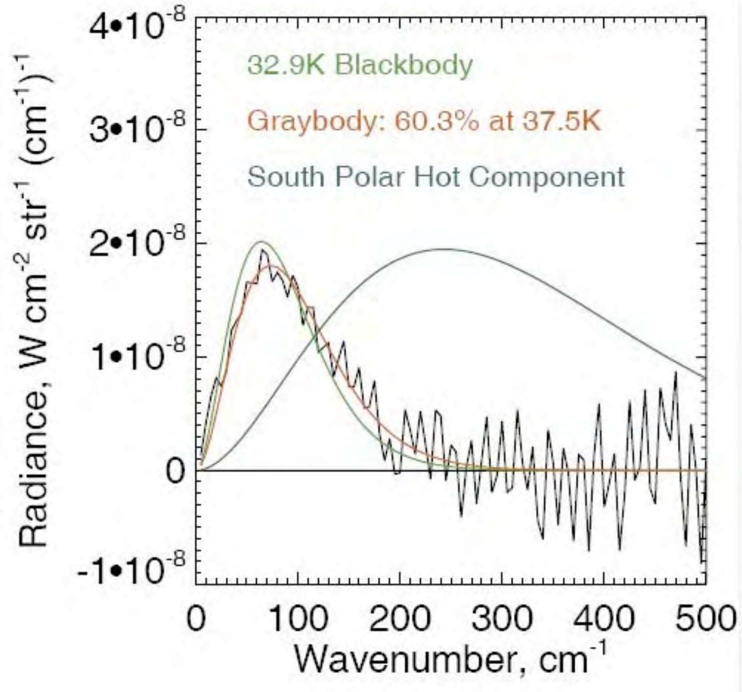
Spencer et al. (2006)




80 79 80 81 91 87 78 74 78 74

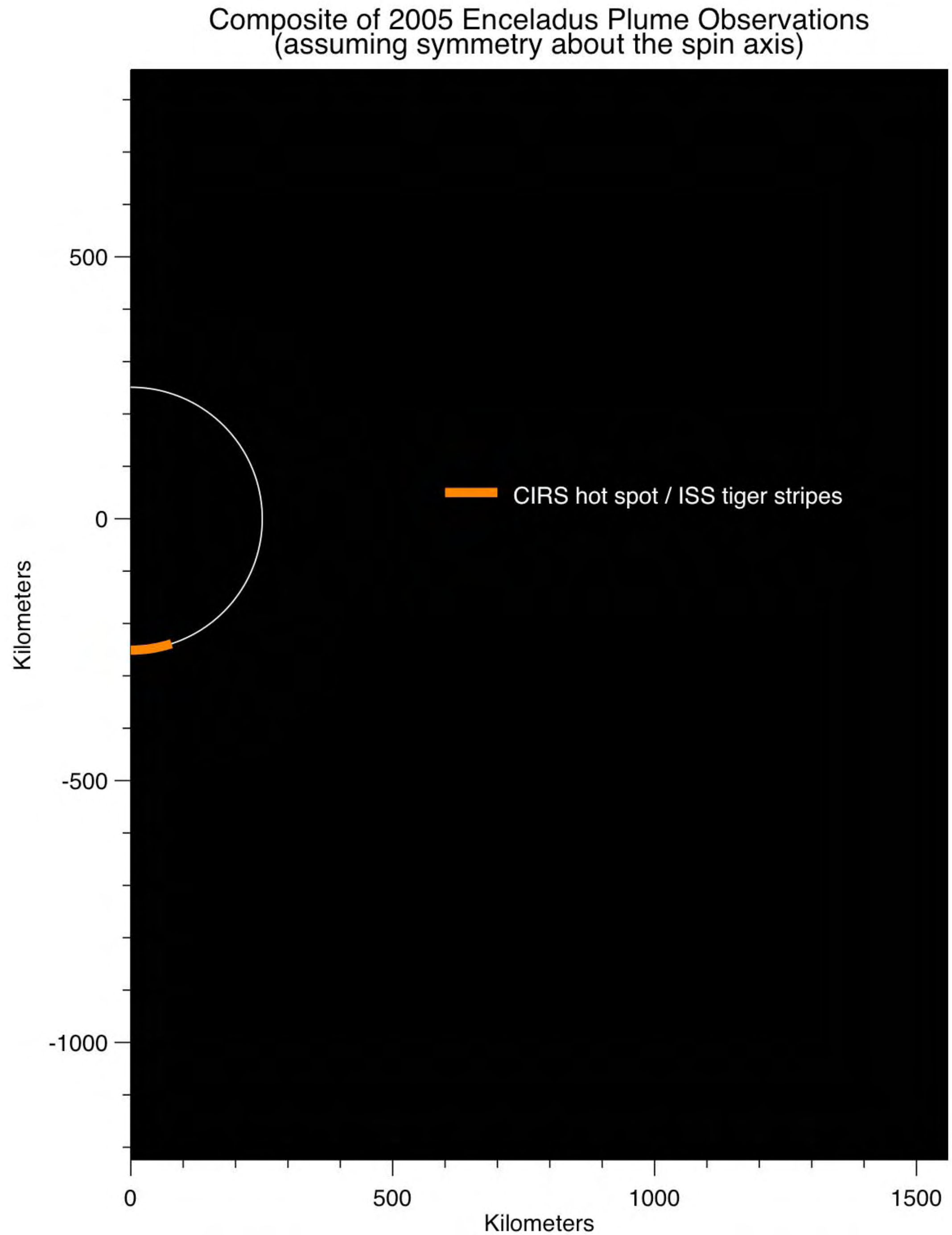
North Pole

- In darkness since 1995
- Long-wavelength CIRS observations in July 2004
  - T < ~ 33 K
  - No north polar hot spot
- Consistent with old, cratered, surface there



Putting Together the Big Picture

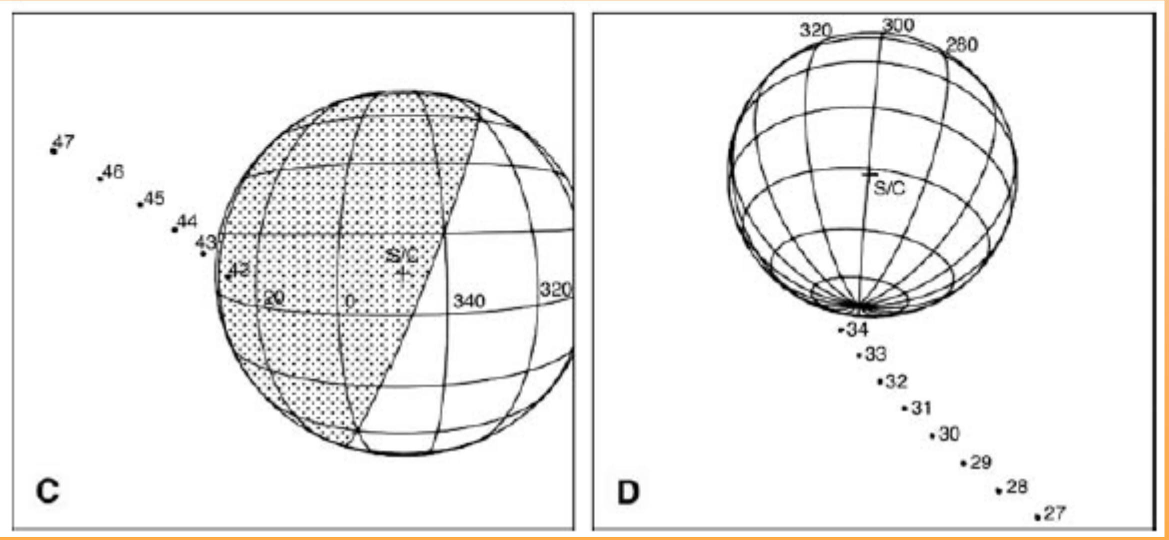
- Assume everything is symmetrical about the south pole

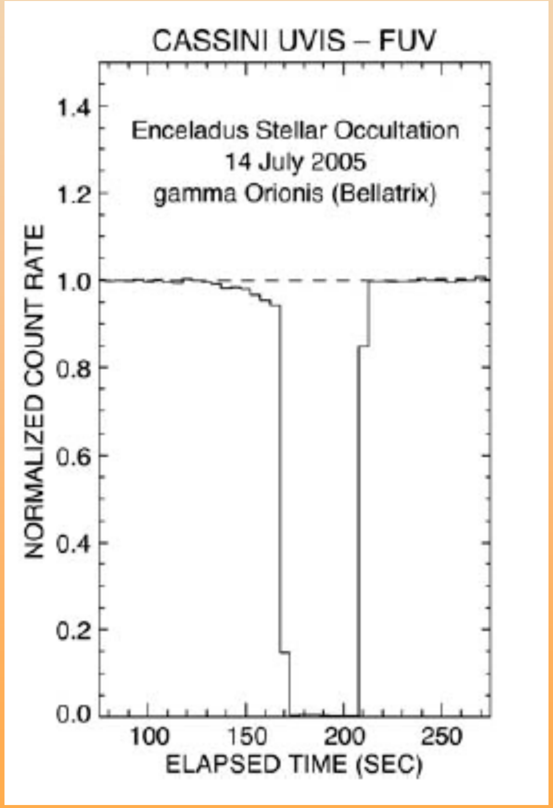


July 2005 UVIS Stellar Occultation

Hansen et al. (2006):

- South polar ingress: gas over the pole!
- Equatorial egress: no signature

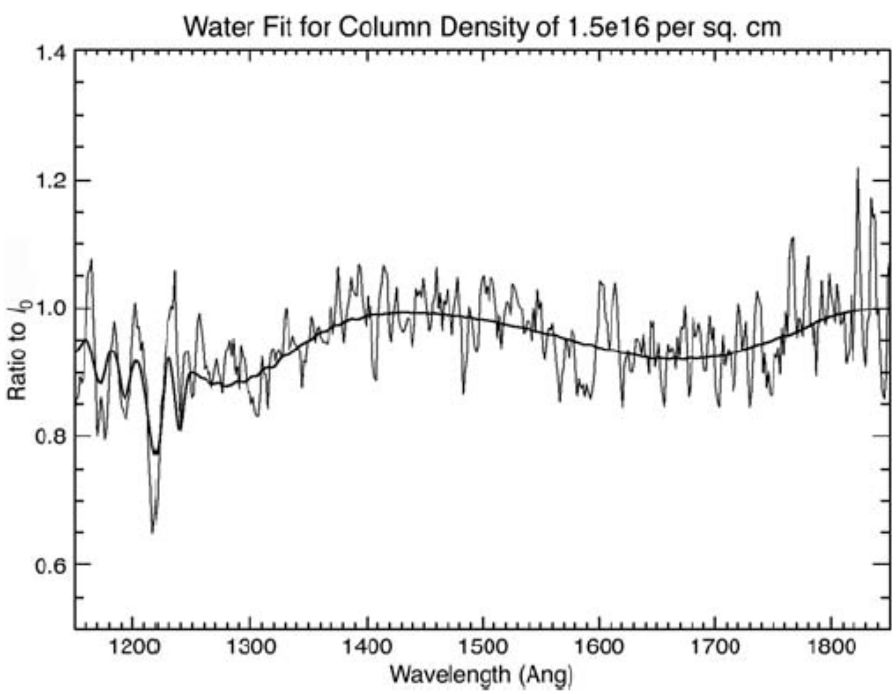


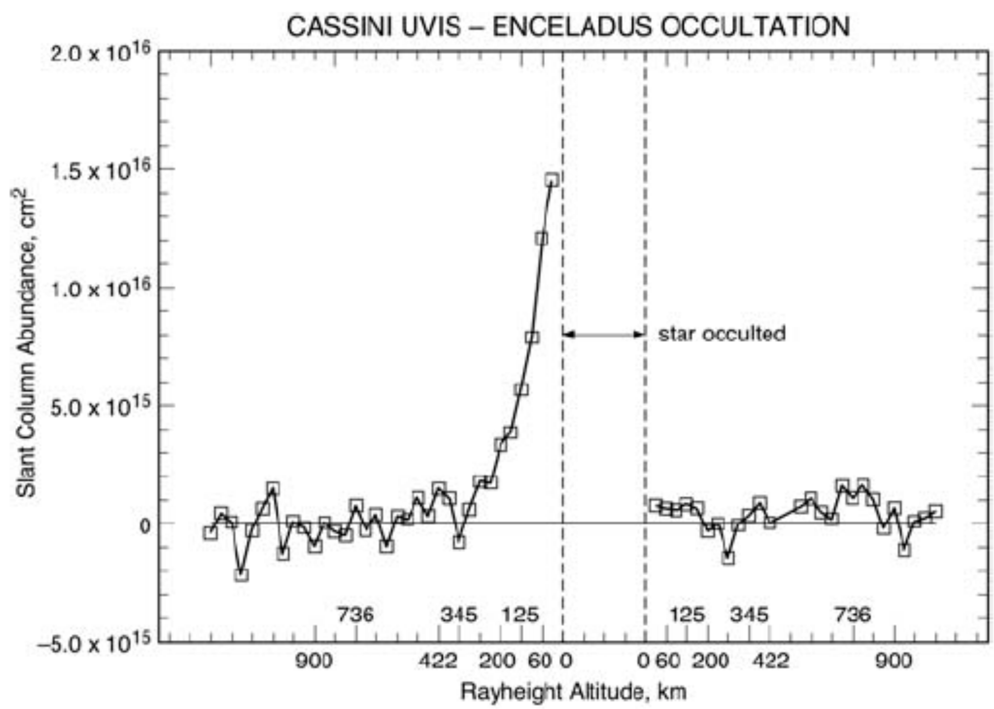


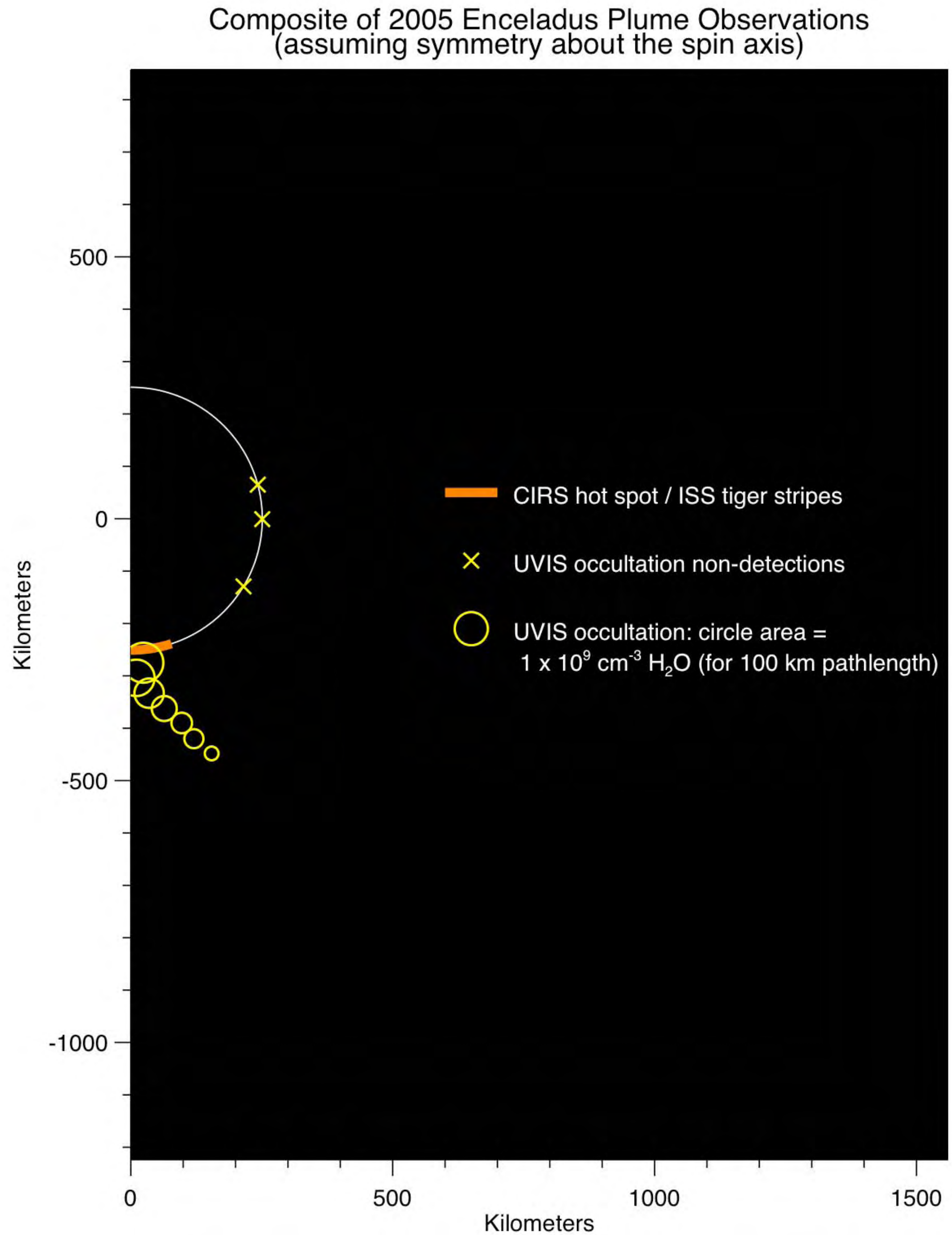
UVIS Stellar Occultation, contd.

- H_2O absorption: 1.5 x 10^{16} molecules cm^{-2} over the south pole
  - Most of the H_2O escapes
    - Speed ~ 400 m/sec
    - Enceladus escape velocity = 240 m/sec
  - Escape rate 120 – 180 kg/sec (Tian et al. 2006)
  - ~0.2 Enceladus masses in 4 b.y.! (Kargel 2006)
  - Probable source of the observed OH, O clouds

Hansen et al. (2006)





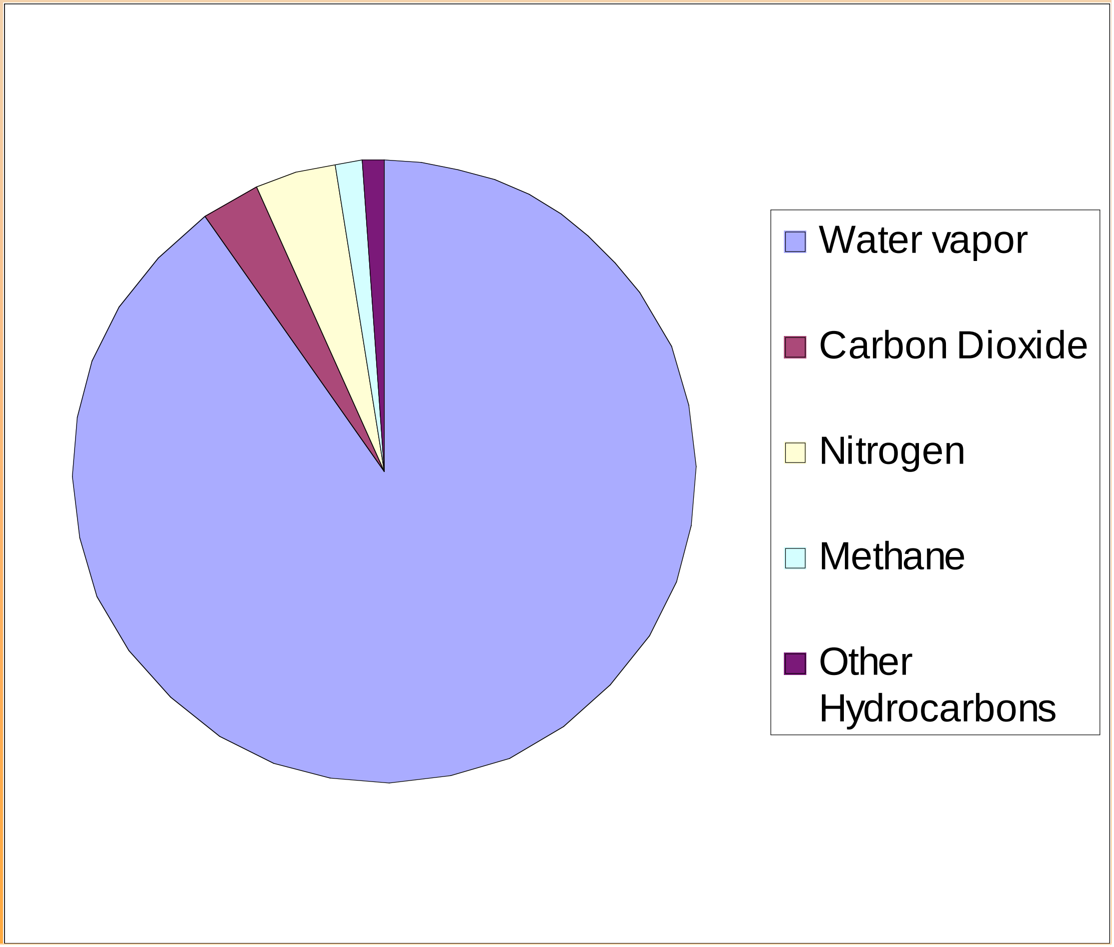


Composite of 2005 Enceladus Plume Observations
(assuming symmetry about the spin axis)
500
0
-500
-1000
Kilometers
CIRS hot spot / ISS tiger stripes
UVIS occultation non-detections
UVIS occultation: circle area =
1 x 10^9 cm^-3 H2O (for 100 km pathlength)
0
500
1000
1500
Kilometers

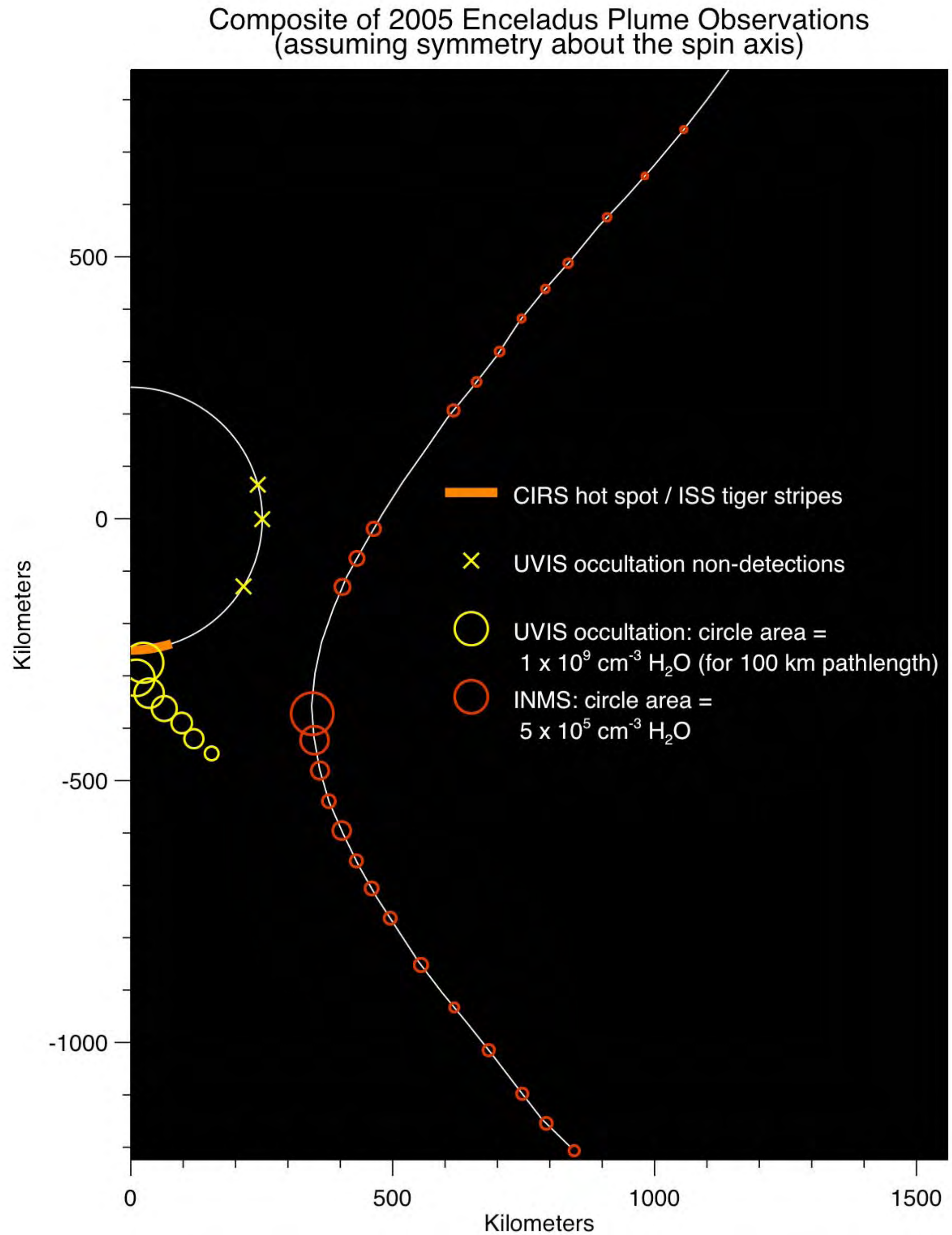
July 2005 INMS Observations

Ion & Neutral Mass Spectrometer: *in situ* measurements of the gas cloud (Waite et al. 2006)

- Gas composition:
  - 91% H_2O, plus
  - CO_2
  - N_2
  - CH_4
  - C_2H_2, C_3H_8
- Clathrate decomposition is a plausible source (Kargel 2006)
- No ammonia!



- INMS saw the most gas when Cassini was closest to the south pole

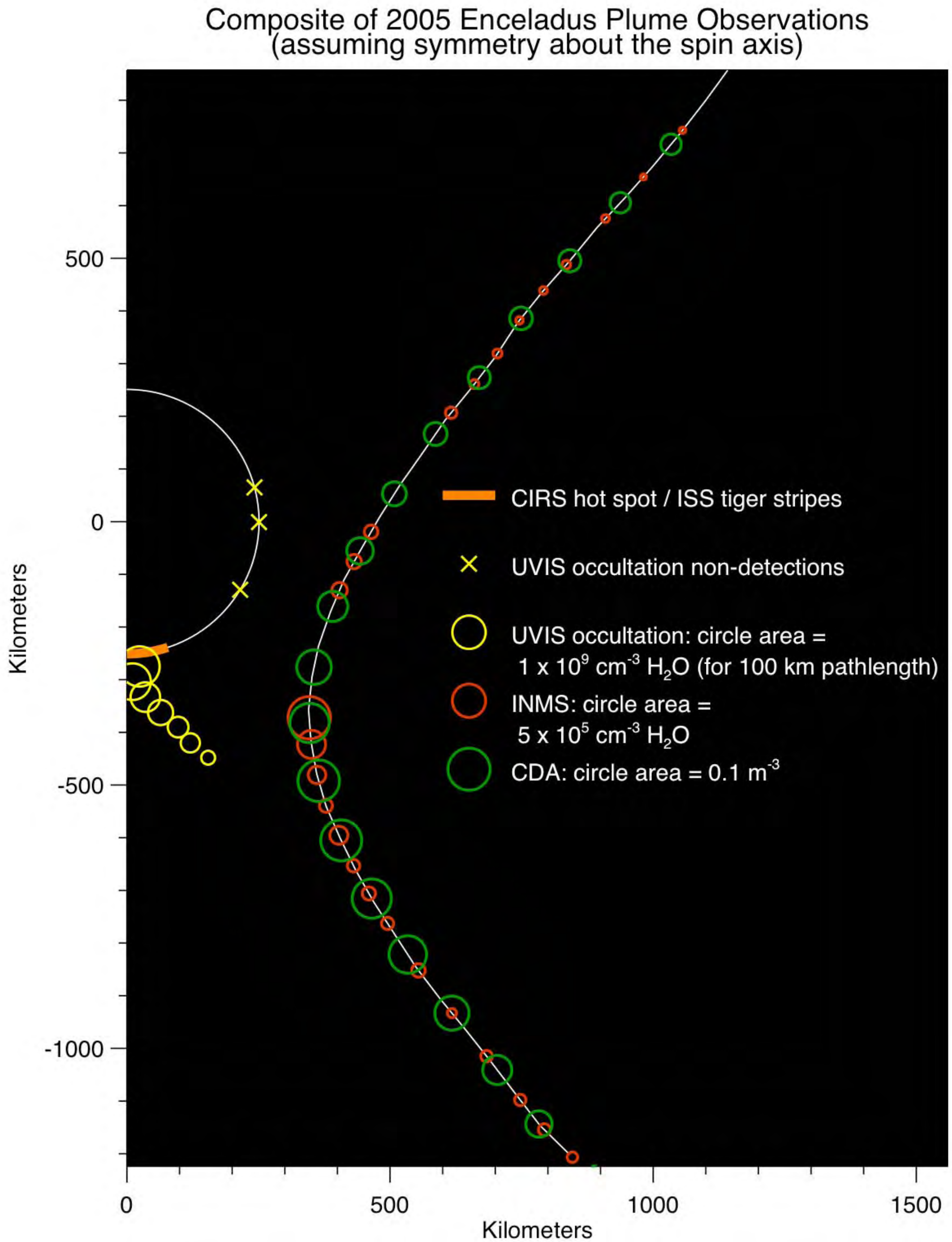


CDA Dust Observations

Cosmic Dust Analyzer: Spahn et al. (2006)

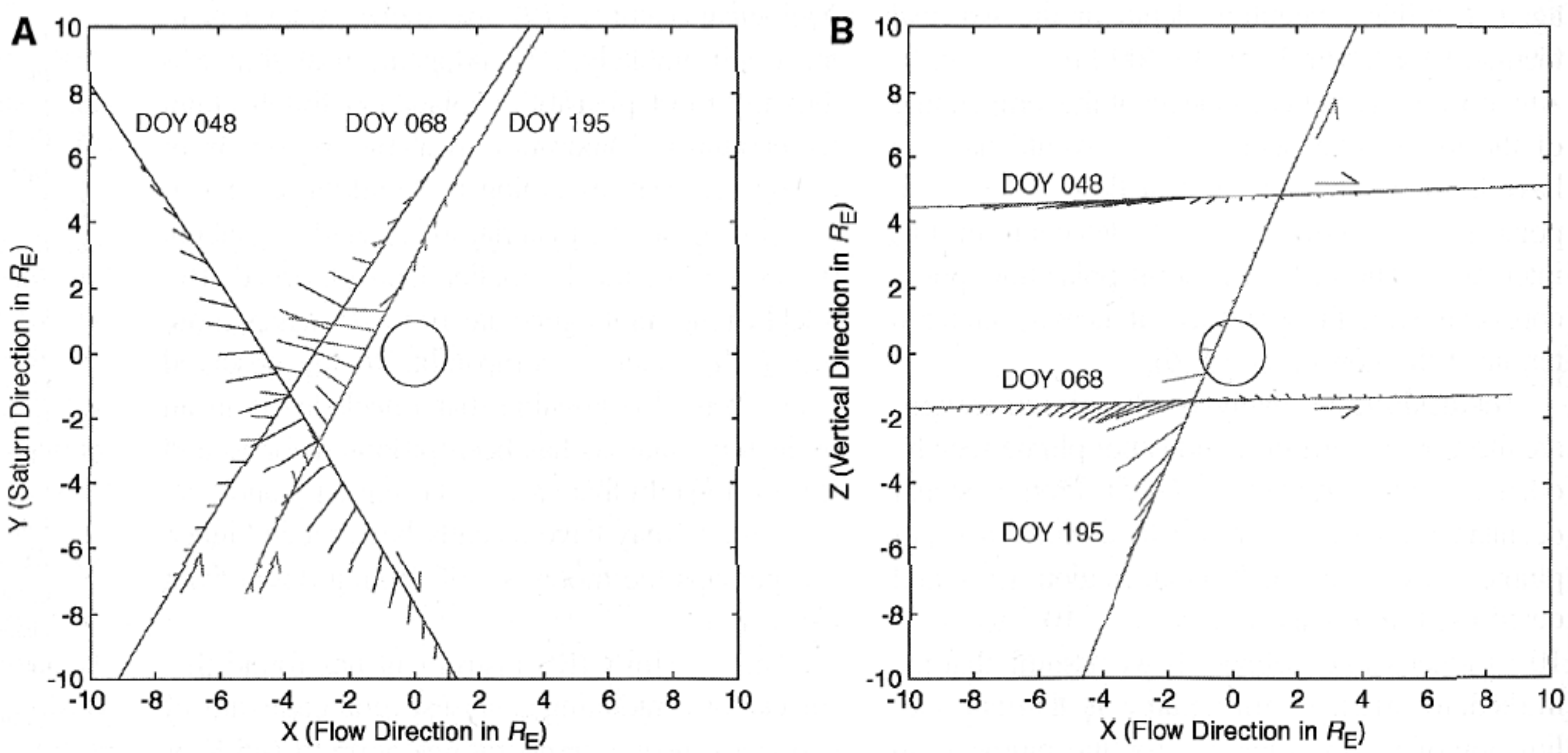
- July 2005 flyby data sensitive to > 4 µm diameter particles (bigger than most E-ring particles)
- Peak dust ~1 minute before C/A
- Modeled dust production rate > 0.2 kg s^{-1}
  - Could be much higher, depending on size distribution

The south polar plume is probably the dominant source of the E-ring



July 2005 Magnetometer, Plasma Results

- Field perturbation is strongest over the south pole (Dougherty et al. 2006)

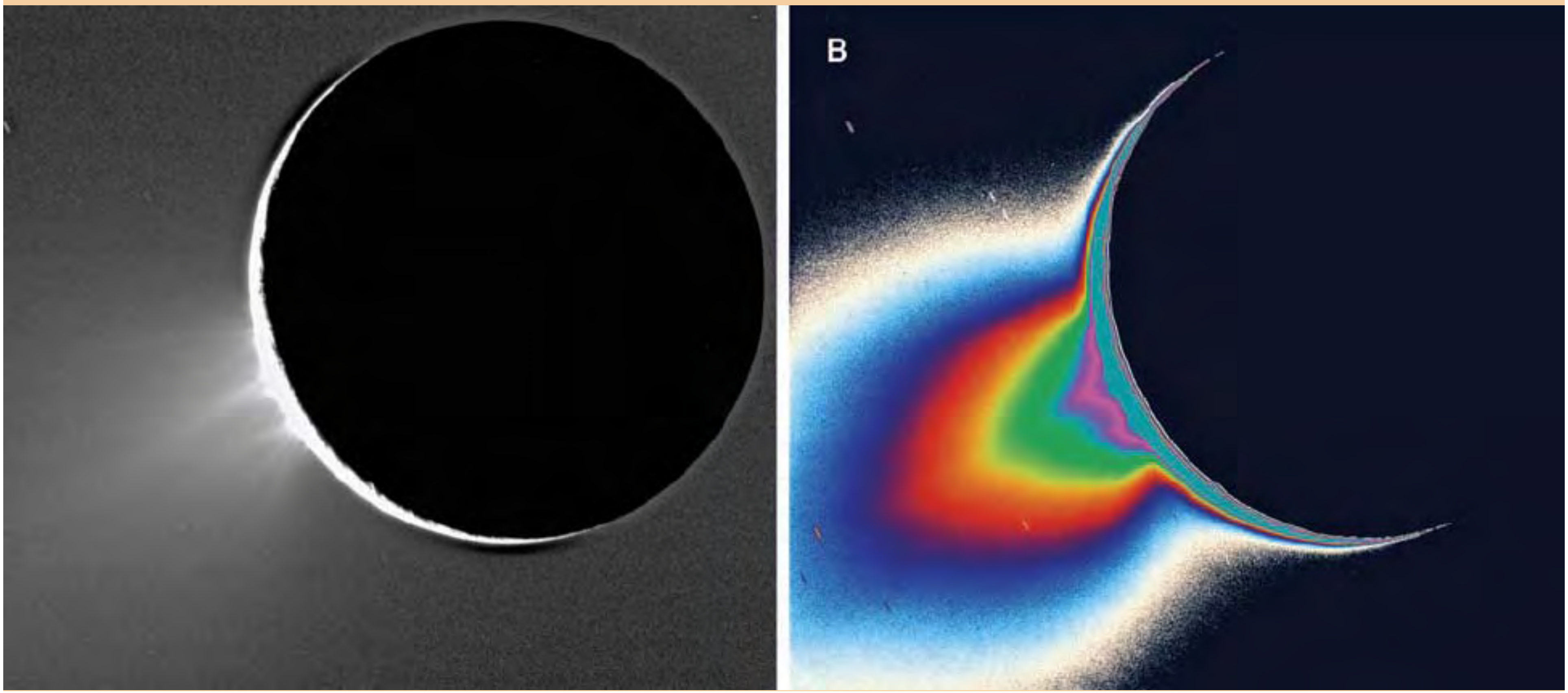


Cassini plume images

Higher-resolution images taken in November 2005

- Confirm reality of Feb., Mar. 2006 plume detection
- Multiple plume sources
- Source locations are consistent with the tiger stripes

Porco et al. (2006)

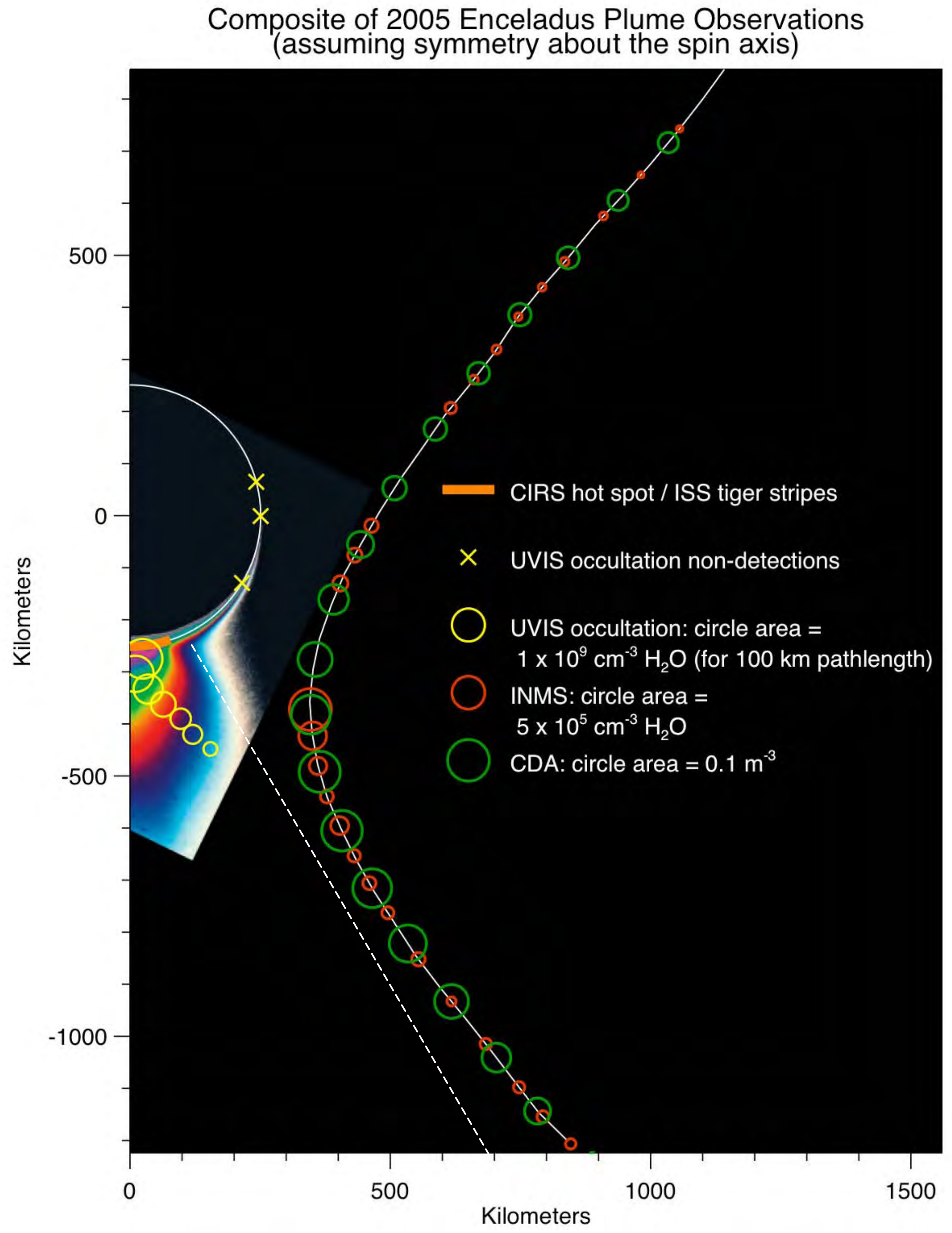


ISS Camera Plume Observations, contd.

Porco et al. (2006)

- Dust scale height ~30 km near the surface:
  - Mean vertical speed ~ 60 m s^{-1}
    - Much less than escape velocity, 240 m s^{-1}
    - Most particles re-impact the surface!
- More gradual falloff at higher altitudes
  - ~1% of particles escape

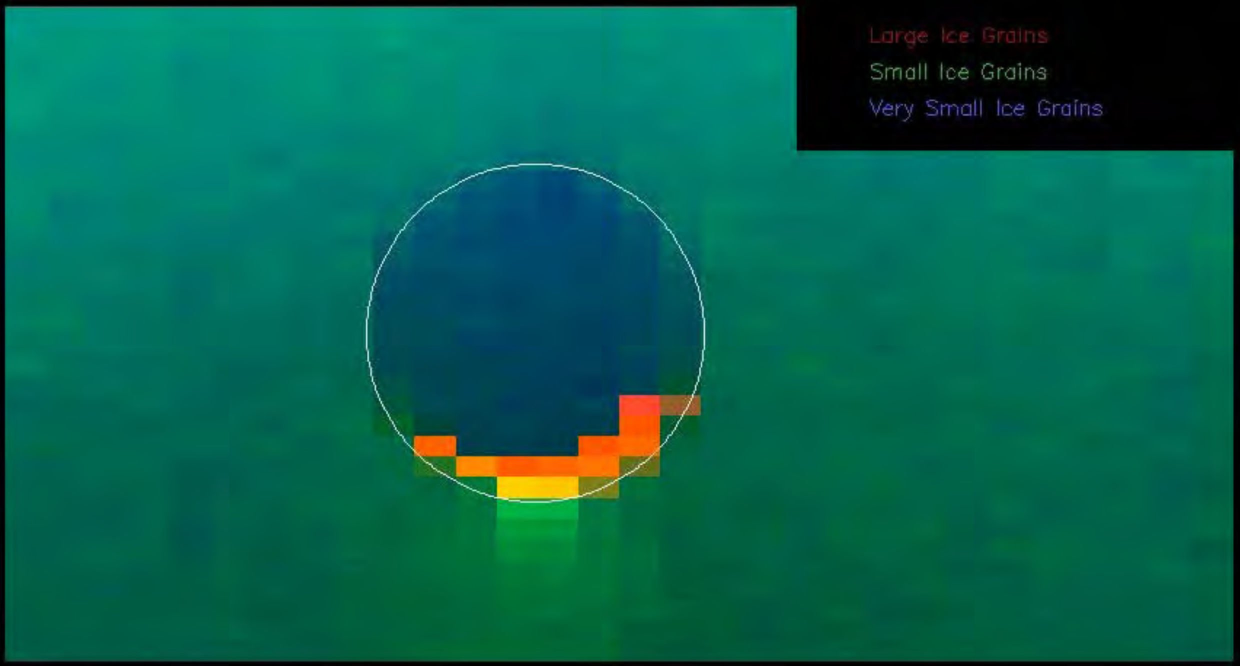
- Cassini trajectory skirted the edge of the plume seen by the Cassini cameras

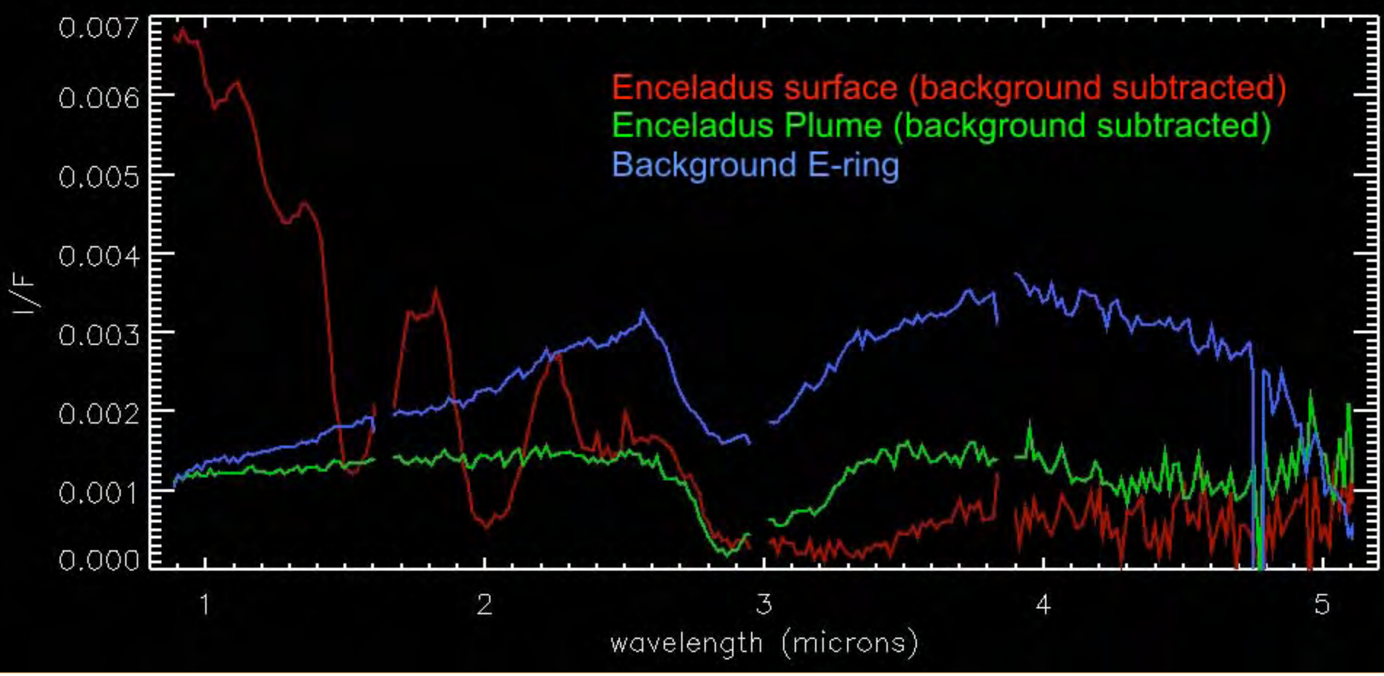


VIMS Plume Spectrum

Simultaneous with November ISS images

Plume particle spectrum is very similar to E-ring: ~micron-sized ice particles





NASA/JPL/U. Arizona

Power and Heat Flow: Implications

- Endogenic power > ~ 7 GW (including plume latent heat)
  - Approaching limits for steady-state tidal heating, given estimates of Saturn's internal properties (Ross and Schubert 1989)
    - …or exceeds that limit by an order of magnitude (Meyer and Wisdom 2007)
  - Need a way to "kick start" tidal heating on Enceladus but not Mimas
    - Short-lived radioactive elements like Al^{26}, just after the solar system formed? (Matson and Castillo 2006)
      - Requires continuous activity since then
    - Long-term radiogenic heating (Schubert et al. 2007)
      - Requires favorable early conditions
    - Impact? (Wisdom 2004, Porco et al. 2006)
- Average south-polar heat flow is 0.15 W m^{-2} (6% that of Io)
  - Near-surface temperatures of 145 K imply local heat flow of 24 W m^{-2}
    - Melting at a depth of 20 m if heat is transported conductively through the ice

Particle Source?

Porco et al. (2006)

- From UVIS stellar occultation, July 2005 near-surface column density of gas
  $= 7 \times 10^{-6}$ kg m^{-2}
- Column density of ice particles
  $= 3 \times 10^{-6}$ kg m^{-2} ??
- Comparable gas and particle masses argue against condensation of particles from the gas
  - [Though gas:particle *production* mass ratio, accounting for much lower dust speed, is ~40:1]
- Entrainment of ice particles in the gas is unlikely due to likely sintering of particles by condensing vapor
- Particle production by boiling of liquid water?

Role of Clathrates?

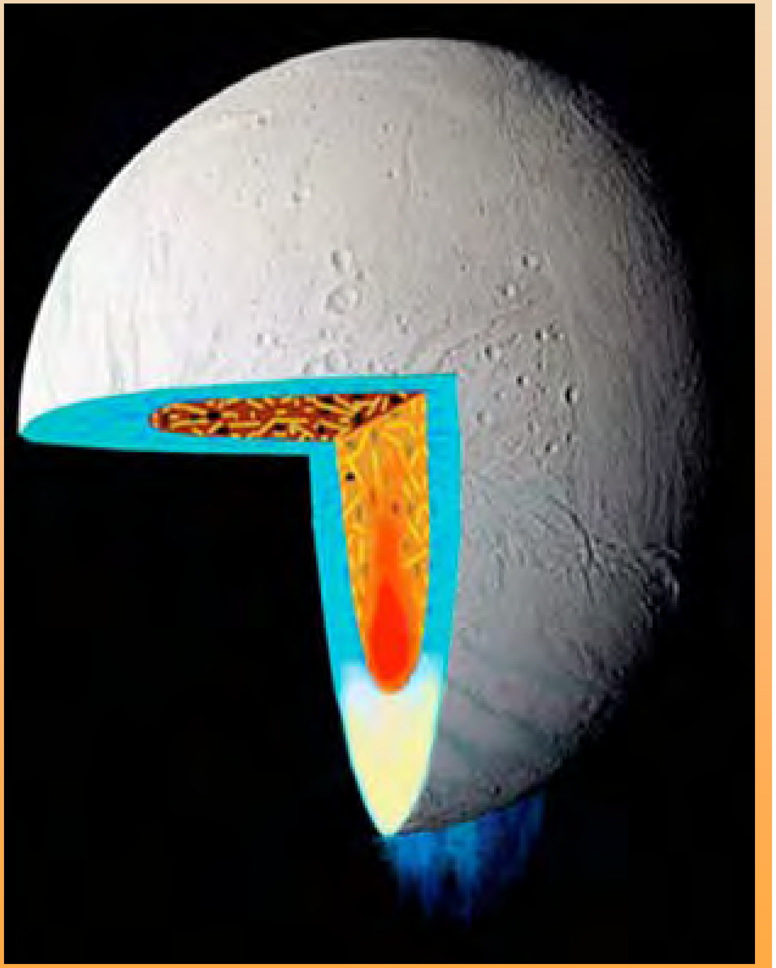
Keiffer et al. (2006)

- ~10% abundance of gases other than H_2O in the plume requires a reservoir other than liquid water
- Plume composition is consistent with clathrates (water ice with other molecules like CO_2, N_2, trapped in the molecular structure)
- Explosive dissociation of clathrates could power the plumes?
- Vaporization of the H_2O (in addition to the more volatile gases) still requires fairly high temperatures (>190 K)

Why the South Pole?

Nimmo and Pappalardo (2006)

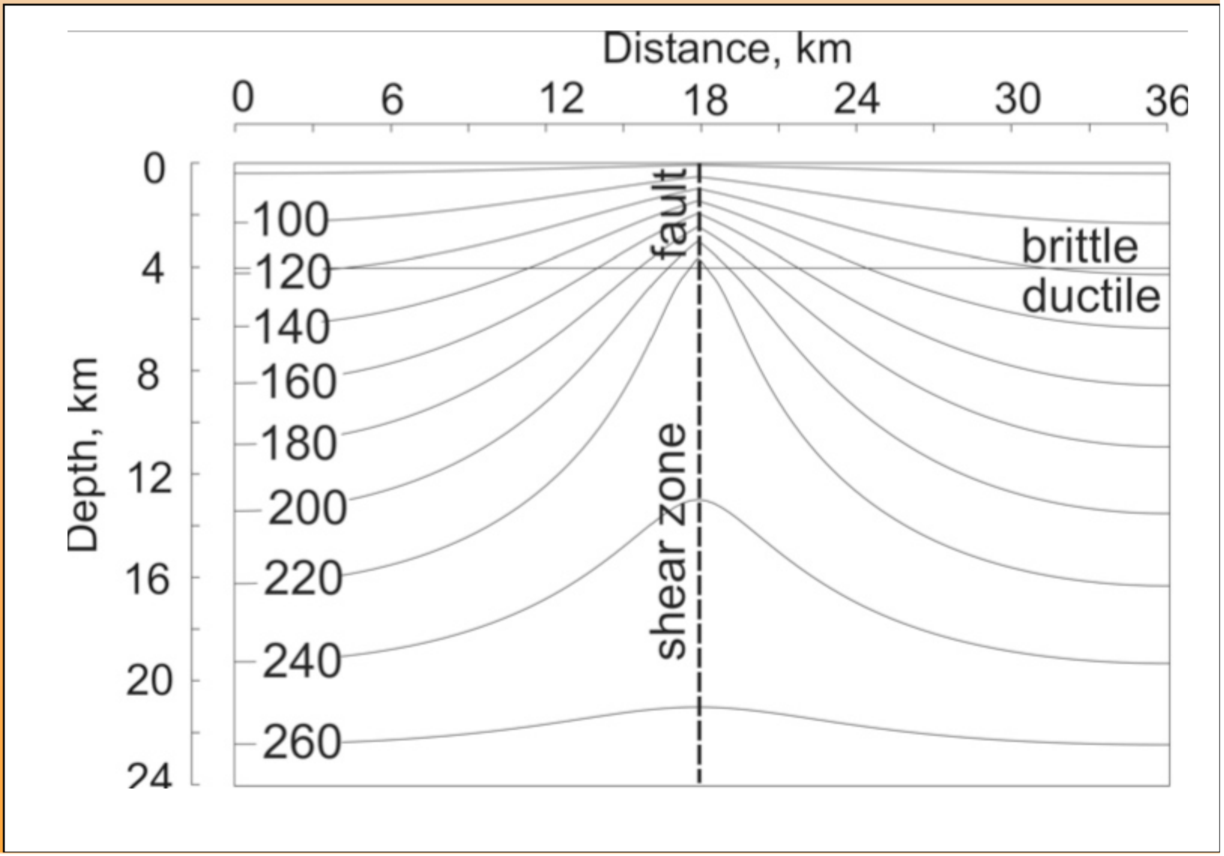
- Low-density silicate or ice diapir can be sufficient to overcome the equatorial bulge and reorient Enceladus
- Resulting stresses may be consistent with the observed tectonic patterns
- Few mgal gravity anomaly: might be detectable by Cassini?



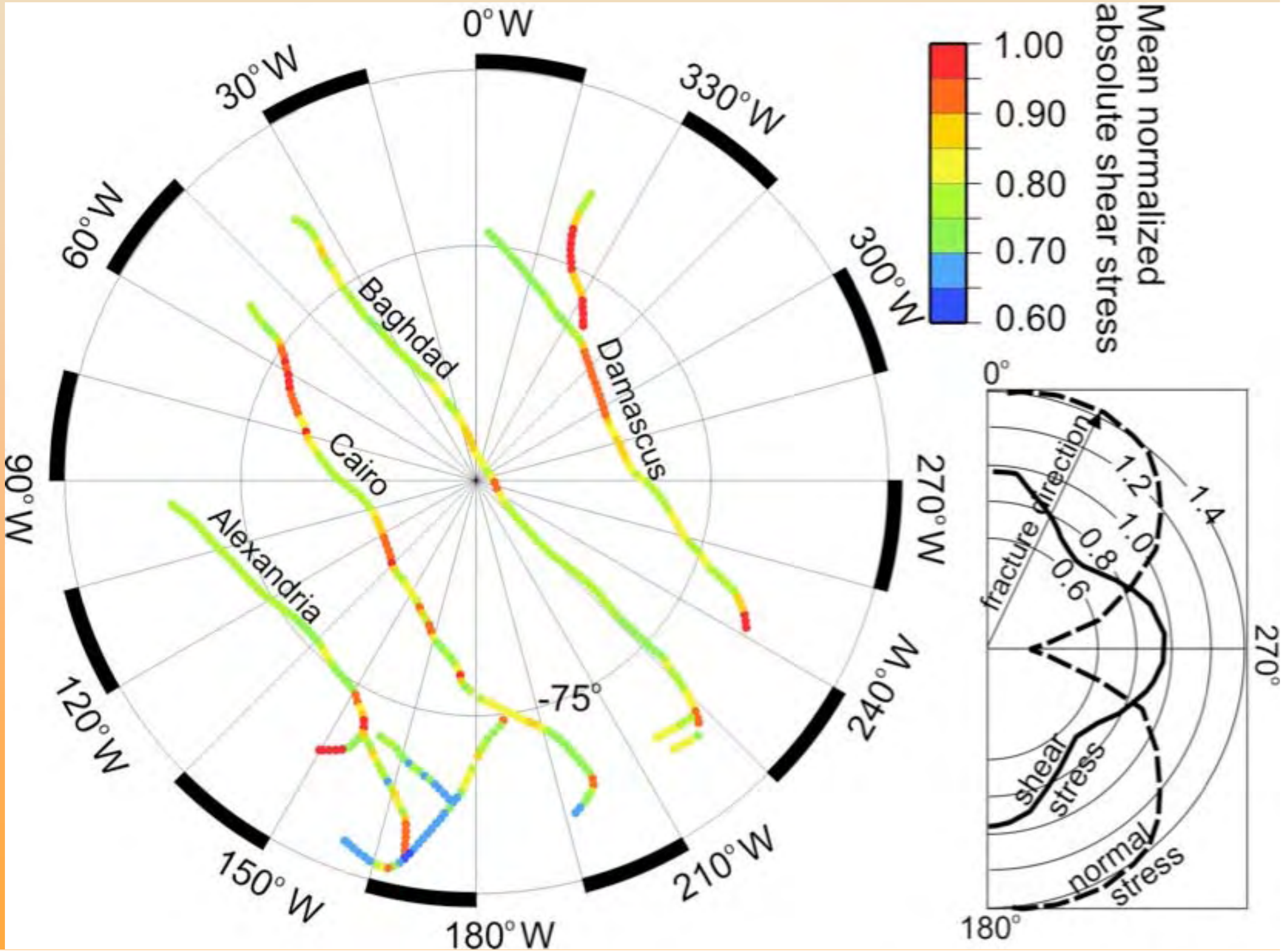
Heat Production Mechanism

Heating by diurnal shear? (Nimmo et al. 2007, Nature, in press)

- Daily tidal stresses cause frictional heating along the tiger stripe fractures at depth
- Ice is vaporized, rises to the surface, mostly condenses there (heating the fractures as observed)
- Some vapor escapes, forming the plume
- Numbers seem to work…
- Ocean is required for sufficient tidal stresses

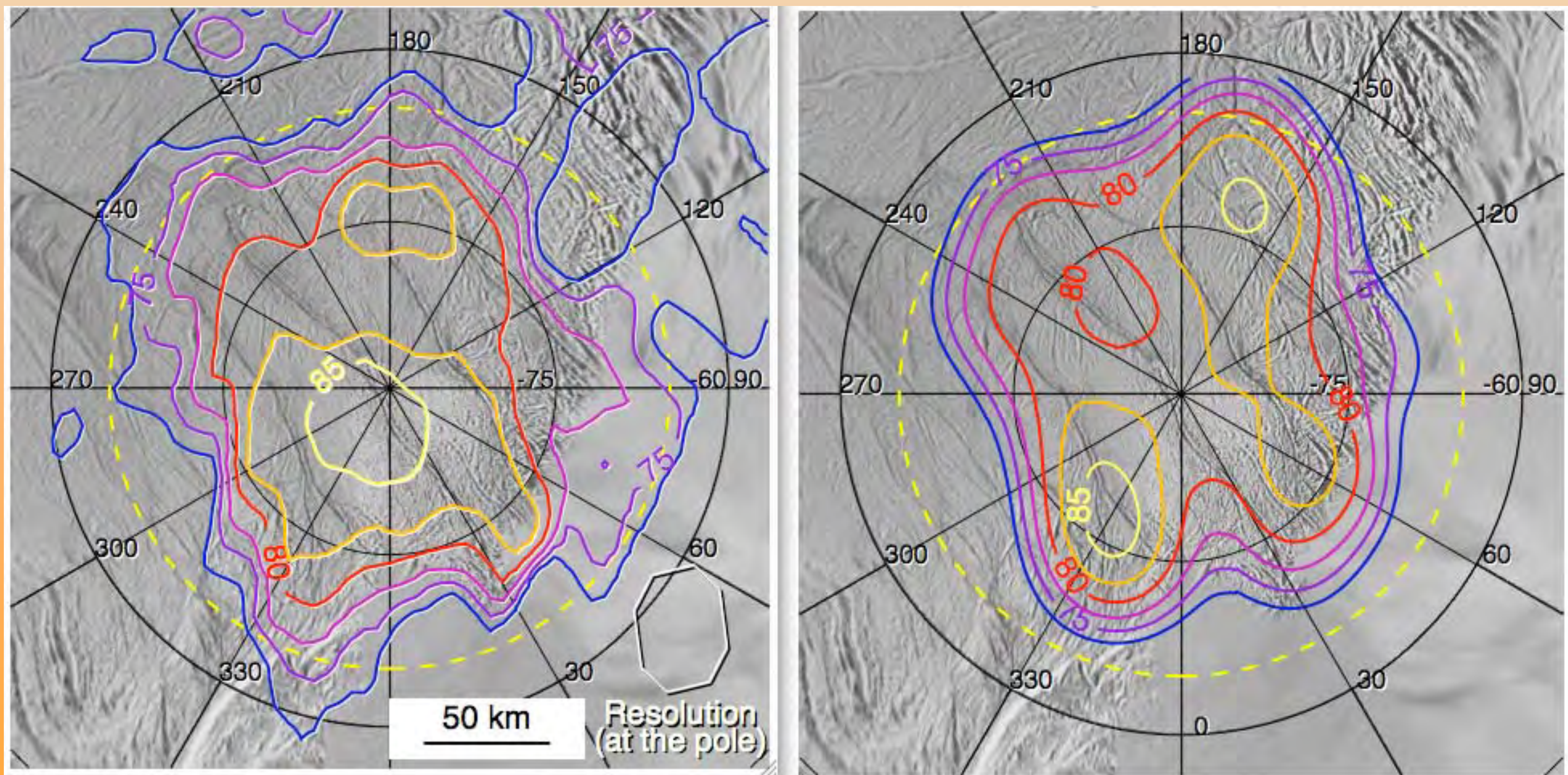


- Significant variation in heat flow along fractures?



Comparison to Observations

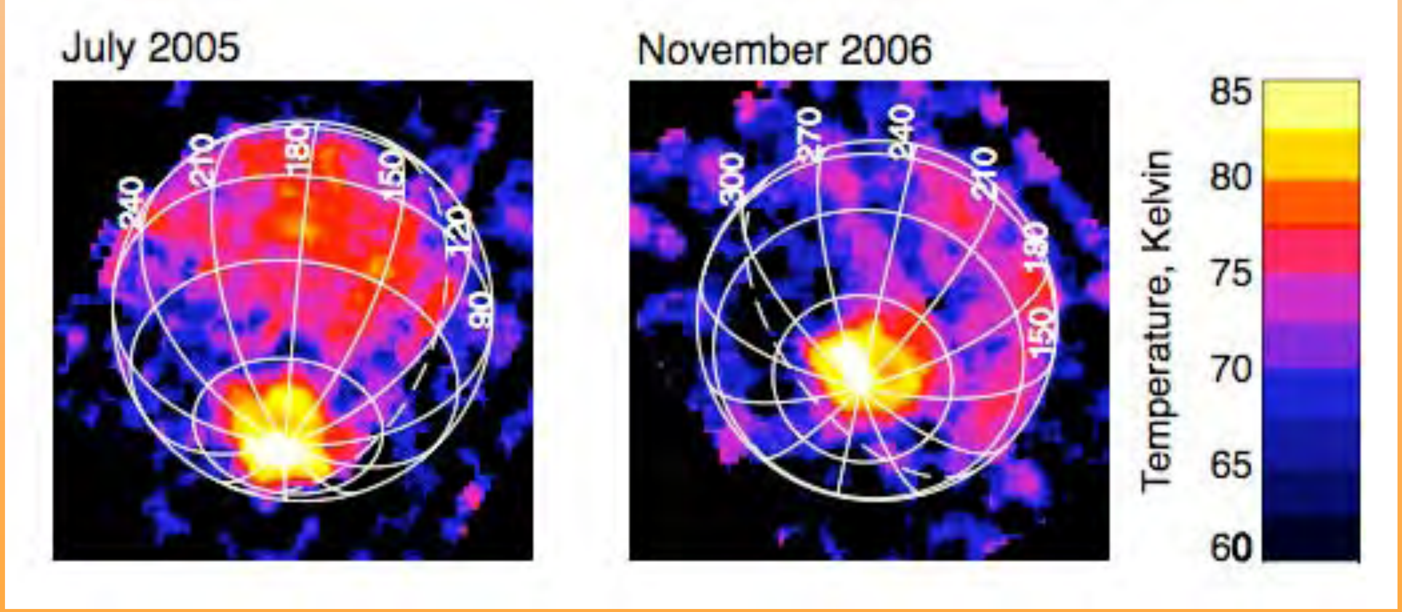
- Polar stripe (Baghdad) is more active than predicted by this model



November 2006 CIRS Observations

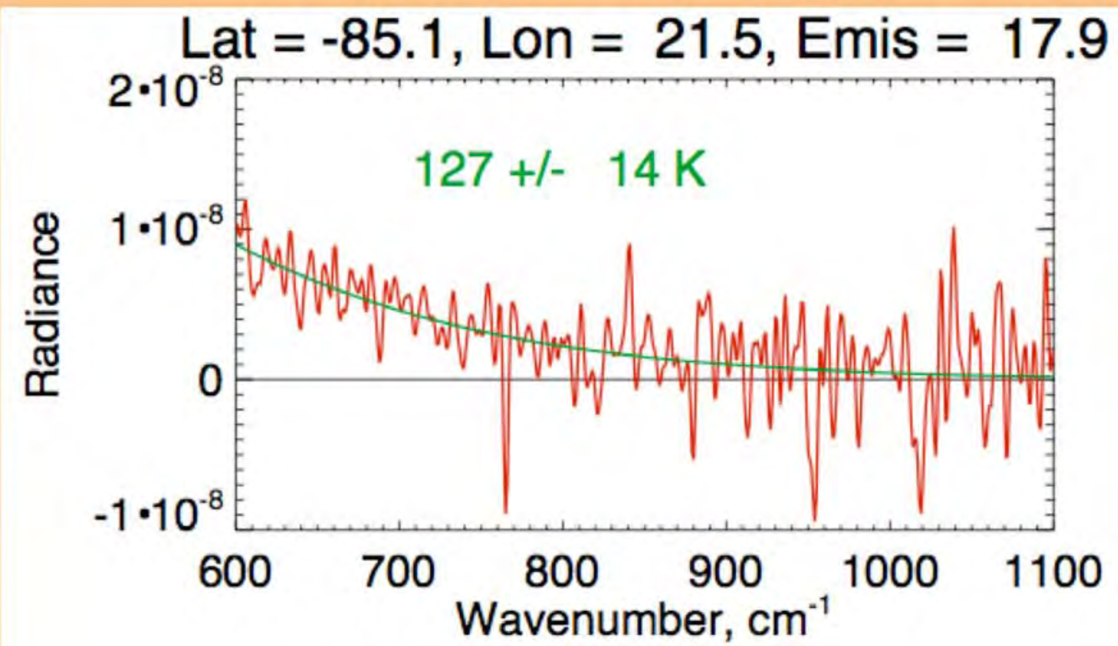
First view of the south polar terrain since July 2005

	July 14 2005	November 9 2006
Range, km	80,000	110,000
CIRS S. pole resolution, km	23 x 32	32 x 35
Subspacecraft Latitude	46 S	68 S
Subsolar Latitude	23 S	15 S



Hot Material in Cracks?

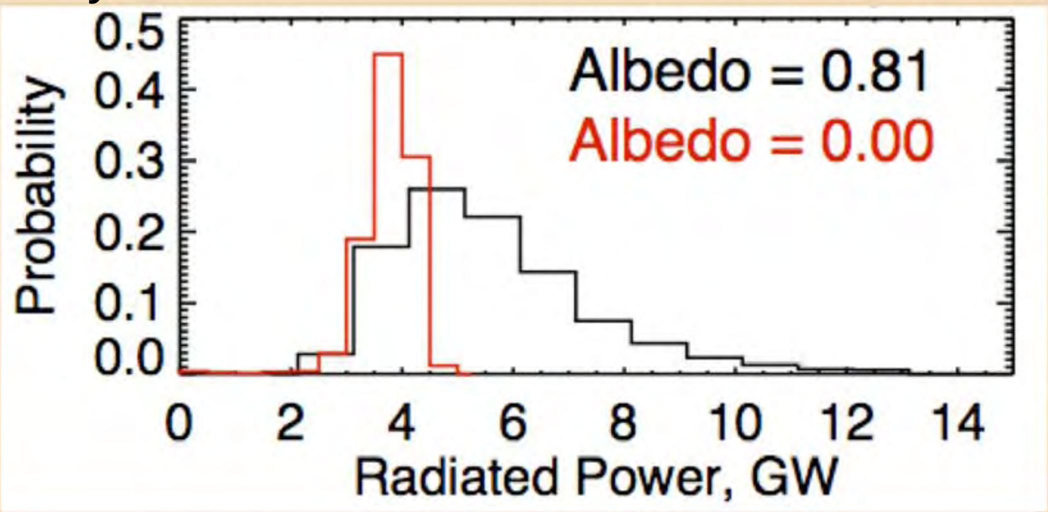
- July 2005 south polar spectra taken 44 degrees from vertical
- November 2006 spectra taken 22 degrees from vertical
  - Same temperature as more oblique July 2006 spectra
  - Little of the thermal emission is from hot material in narrow cracks



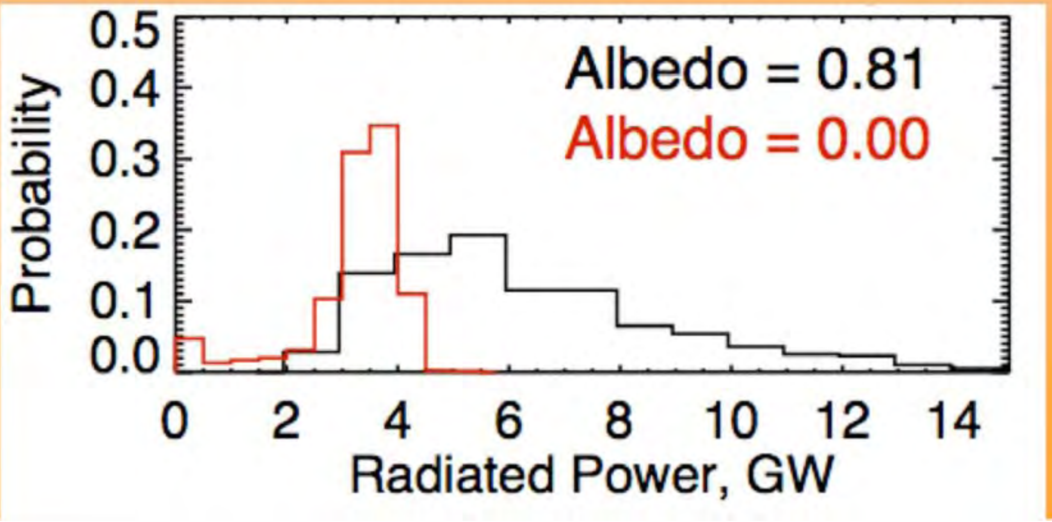
Power Variability?

- No change in total power output seen in 16 months
- Uncertainties are large, however

July 2005



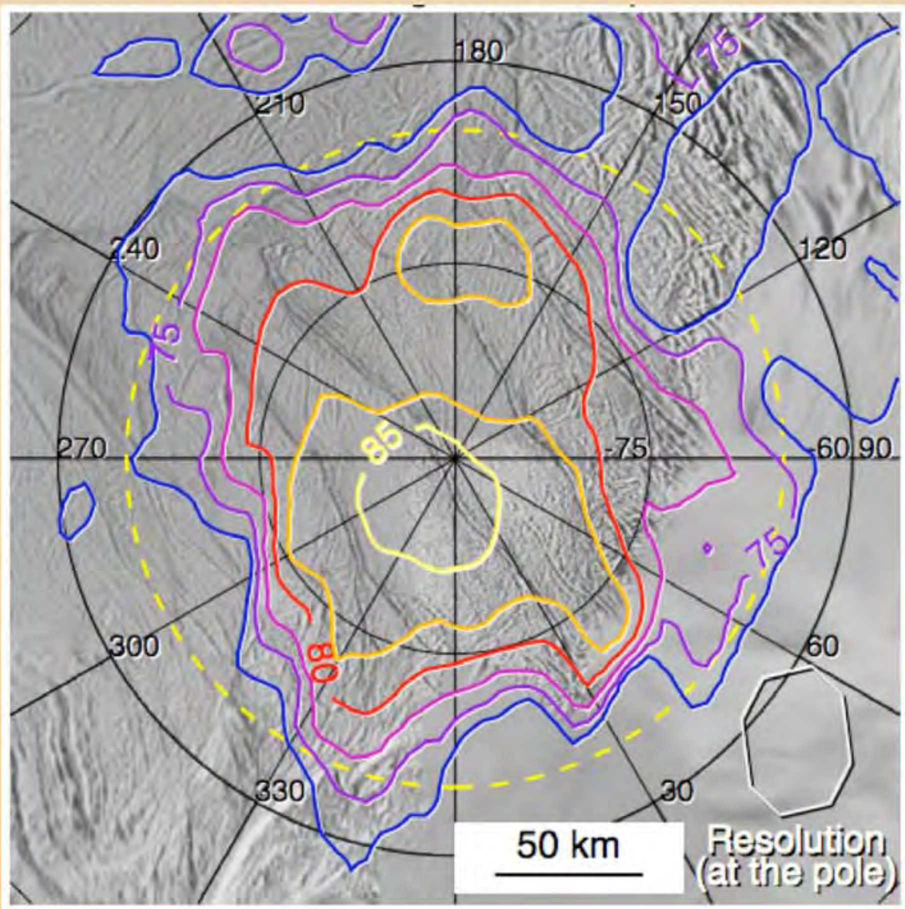
November 2006



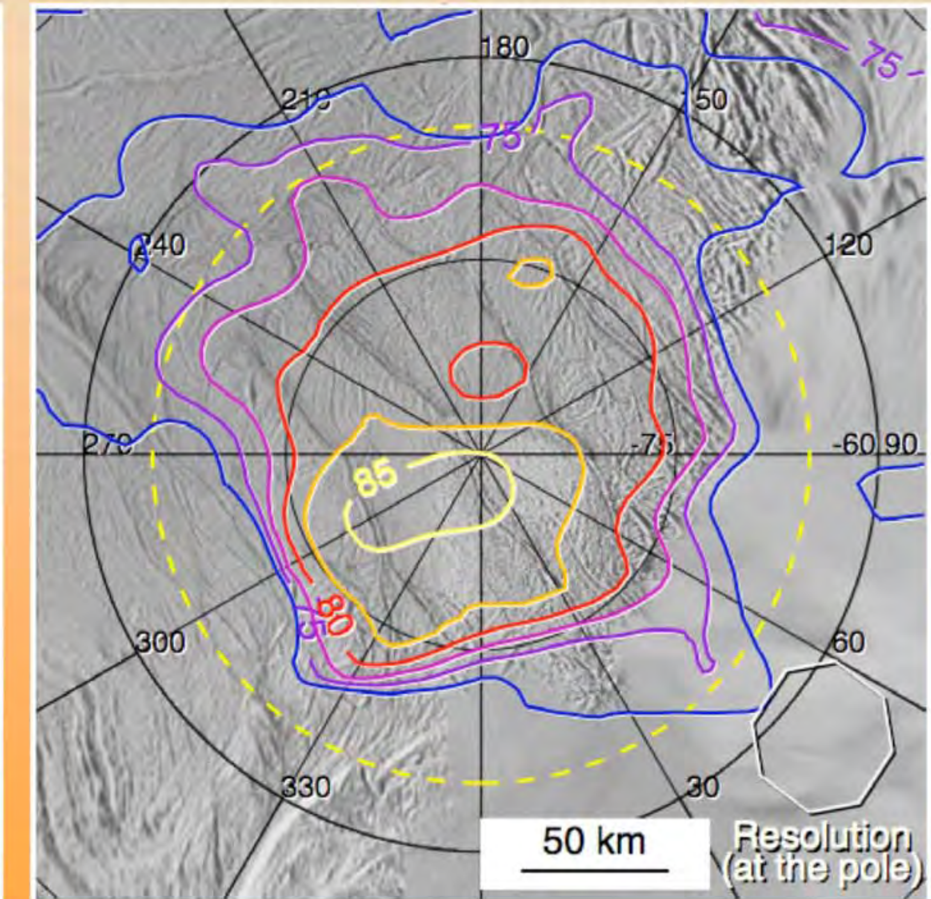
S. Polar Temperature Distribution

- Distribution is unchanged within S/N and calibration uncertainties
- Secondary bright region near 75 S, 165 W, is confirmed

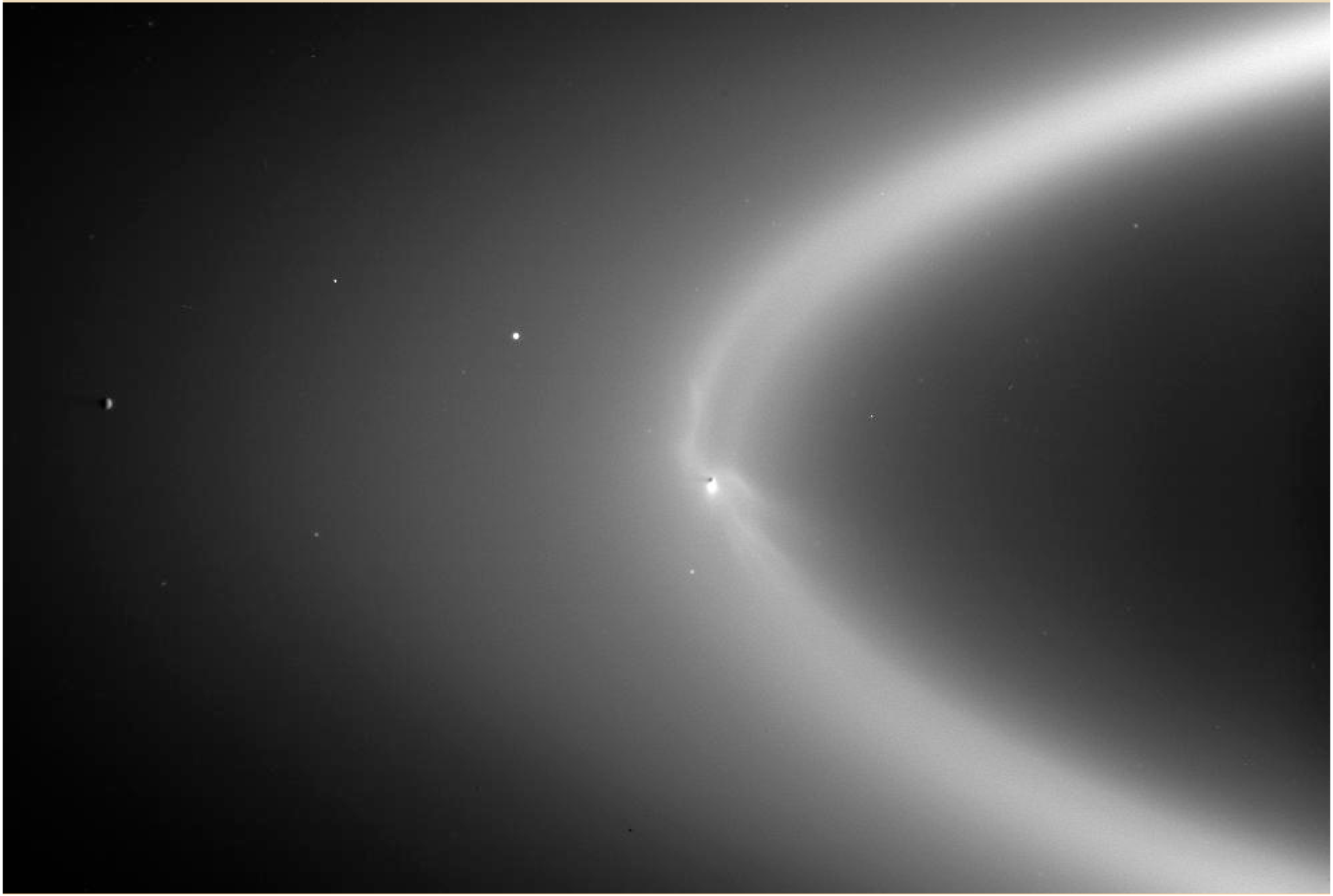
July 2005



November 2006

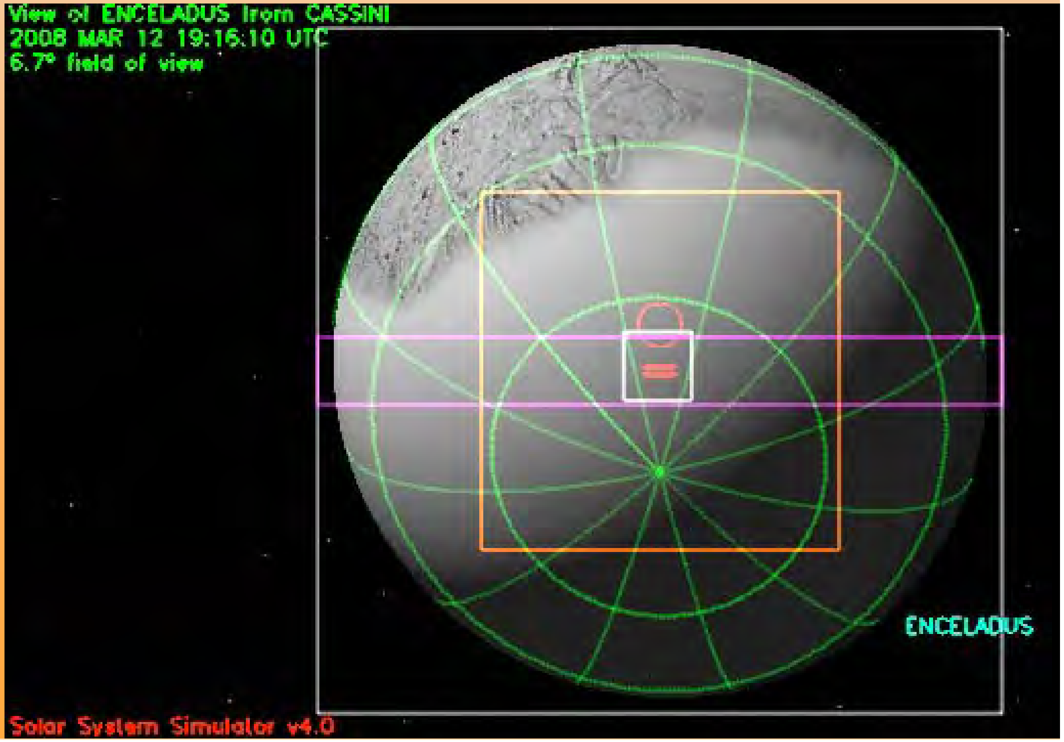


September 2006 High-Phase Imaging

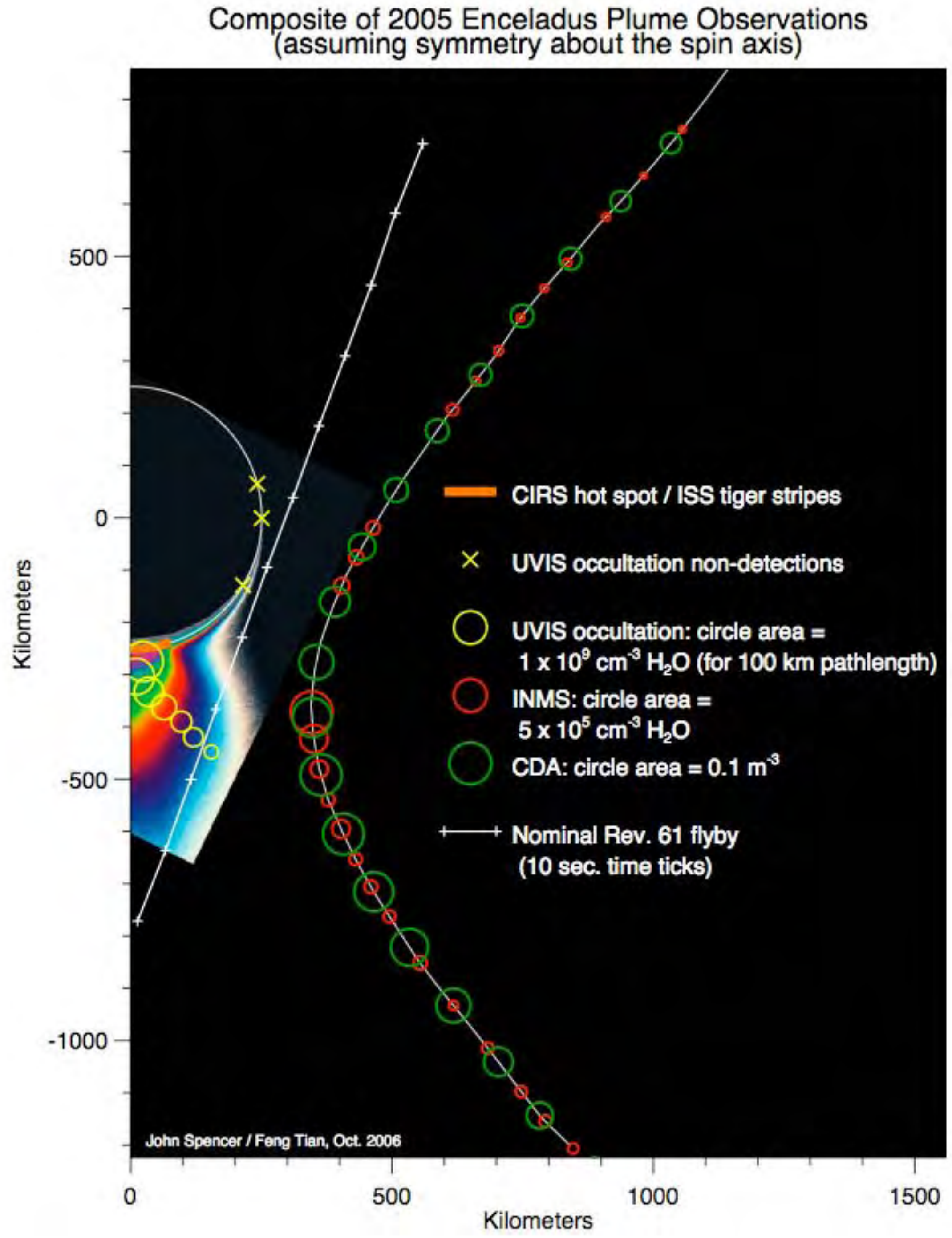


Future Observations: Prime Mission

- Next hi-res, hi-phase view of plume, April 24th 2007
- Next close flyby, March 12th 2008
  - Fly over low latitudes at 25 km altitude
  - Fly over south pole at 580 km altitude 55 seconds later
  - Remote sensing of south pole at ~10,000 km range 10 minutes later
    - Saturn eclipse: no imaging of the surface
    - CIRS mapping of thermal emission with 3 km resolution
    - VIMS search for high-T emission?
    - ISS search for non-thermal emission?



March 12 2008 Trajectory



10-second time ticks

Cassini Extended Mission

- Mid-2008 - mid-2010
  - Tour now decided
- Enceladus is a major priority
  - 7 additional close Enceladus flybys
  - Remote Sensing Goals include
    - Imaging of tiger stripe vents at 2 - 4 m/pixel
    - High-phase imaging of plumes at ~30 m/pixel
    - Sampling of thermal emission and composition at ~1 km/pixel
    - More UV stellar occultations for plume composition, density mapping
    - Search for activity at other latitudes
  - In situ goals include
    - Dust grain compositions
    - Neutral gas composition with greatly improved sensitivity
    - Comparison of upstream/downstream plasma conditions
    - Determination of gravity field to assess degree of differentiation, possible local anomalies over south pole

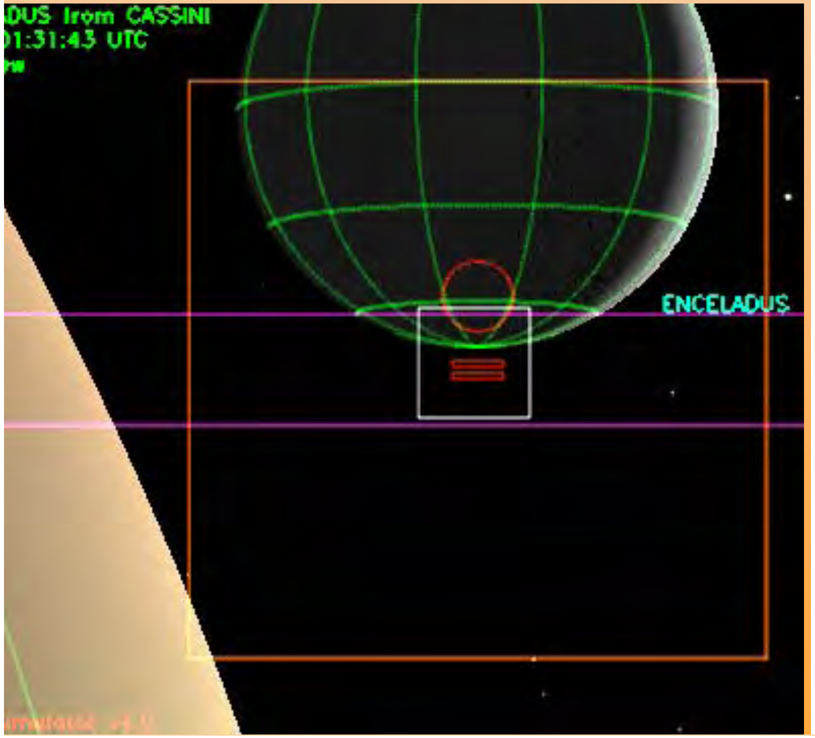
Enceladus Flyby Summary

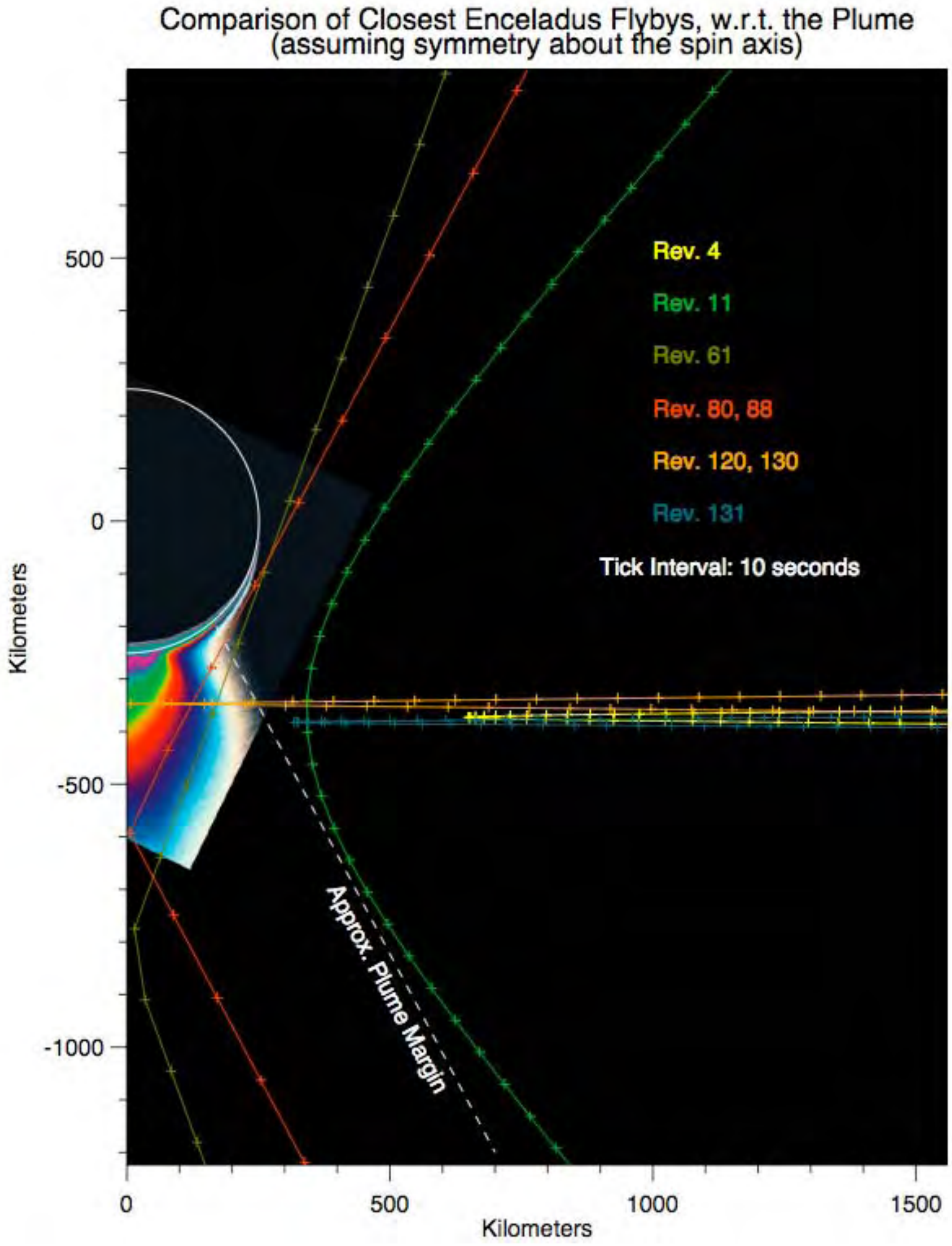
Date	Orbit	Speed km/s	Altitude	Orbit Inclination
12-Mar-08	*61*	*14.3*	*27*	*High*
11-Aug-08	80	17.7	21	High
9-Oct-08	88	17.7	21	High
31-Oct-08	91	17.7	200	High
2-Nov-09	120	7.7	96	Low
21-Nov-09	121	7.7	>1560	Low
28-Apr-10	130	6.5	96	Low
18-May-10	131	7	246	Low

Extended Mission Plume Observations

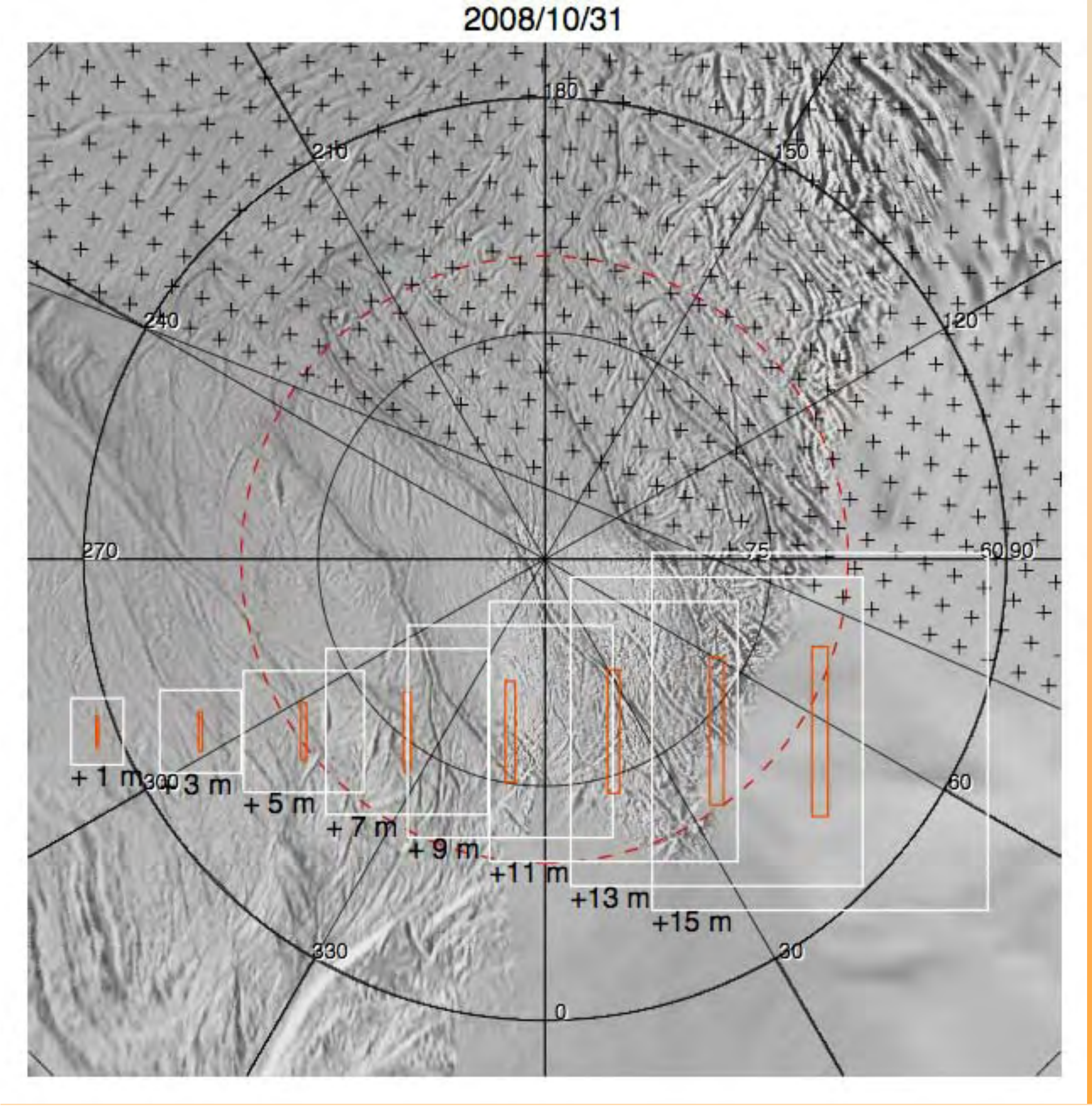
Much improved in situ and remote sensing

High phase, hi-res plume imaging





Extended Mission Remote Sensing



- 2-3 flybys optimized for hi-res remote sensing?
- Coverage is limited:
  - ISS color imaging at > 6 m/pix
  - VIMS compositional maps at >500 m/pix
  - CIRS 1x10 pixel temperature profiles at >500 m/pix

Enceladus at 16 m/pix

Conclusions

- A living ice world!
- Heat source is presumably tidal
    - Many questions remain
- Near-surface liquid water is plausible
    - But so are models without near-surface liquid water
- Major discoveries are still likely from Cassini
    - We ain’t seen nothing yet…