Enceladus: An Active Ice World in the Saturn System

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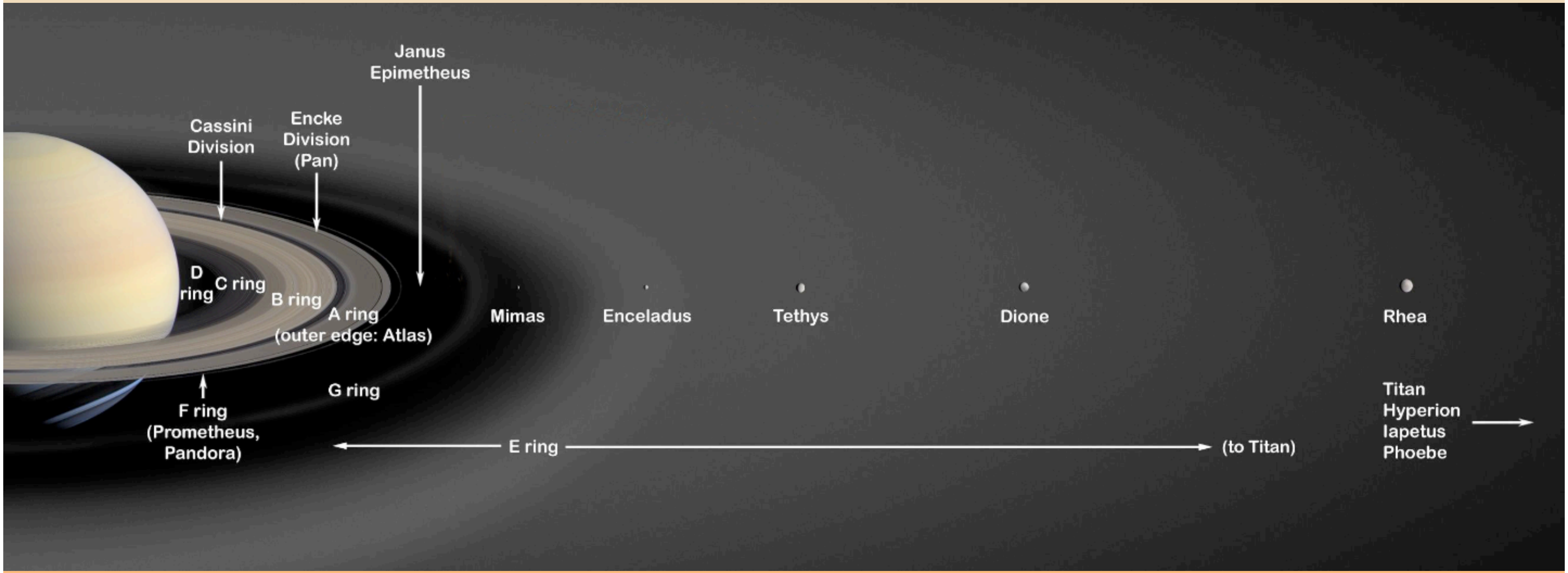
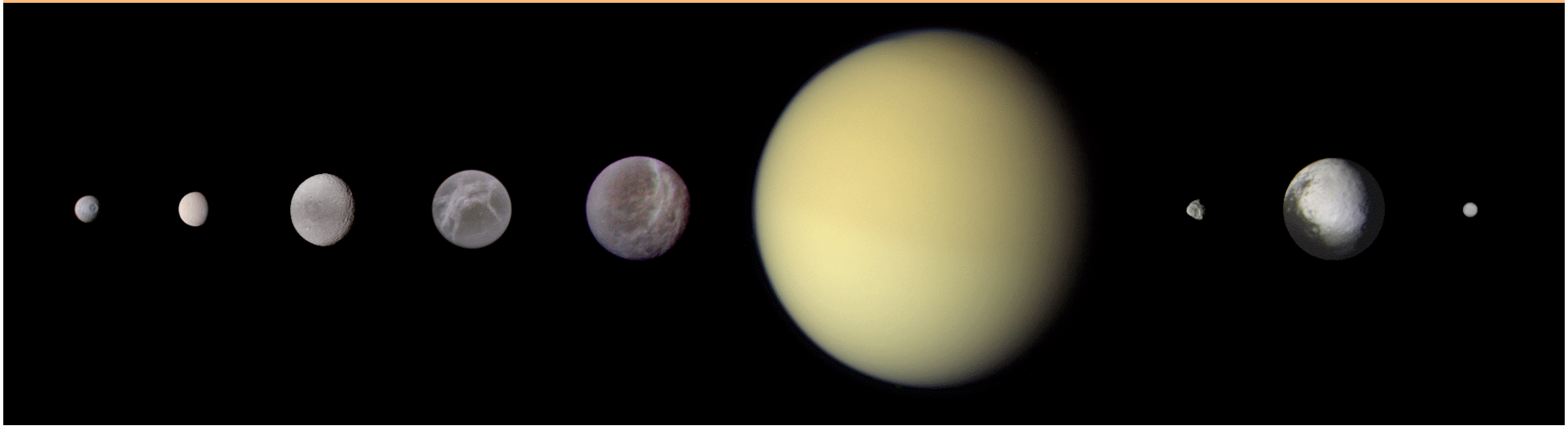
Earth and Space Science Colloquium, JPL
February 25th 2008

Enceladus in the Saturn System

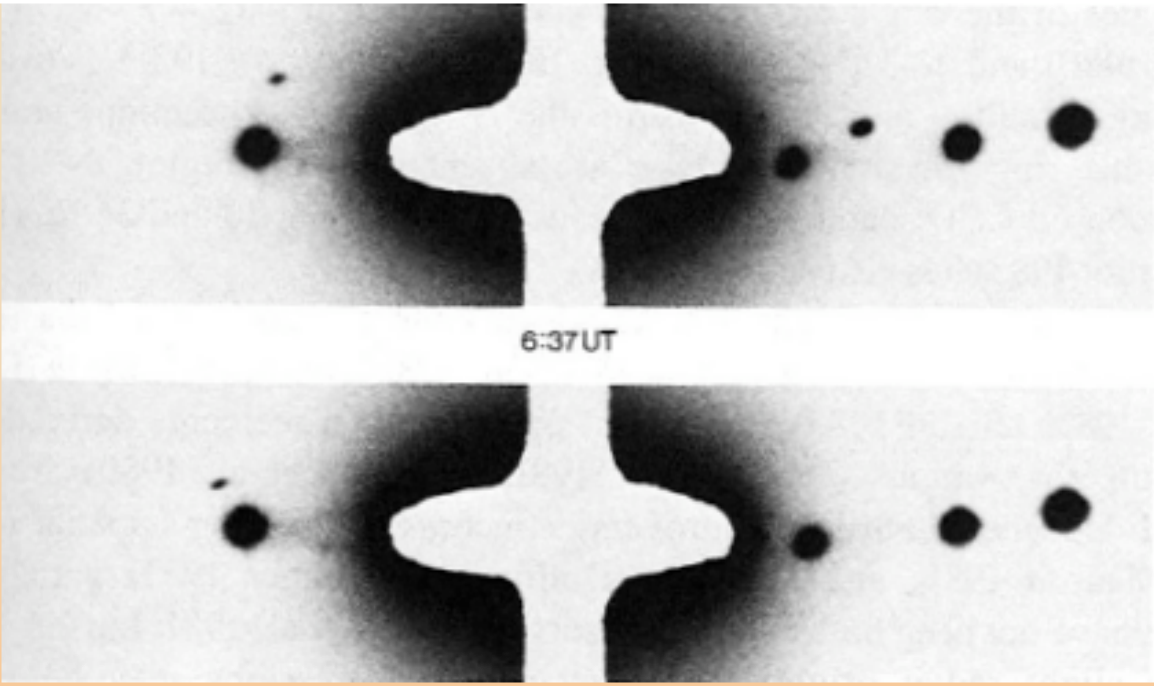




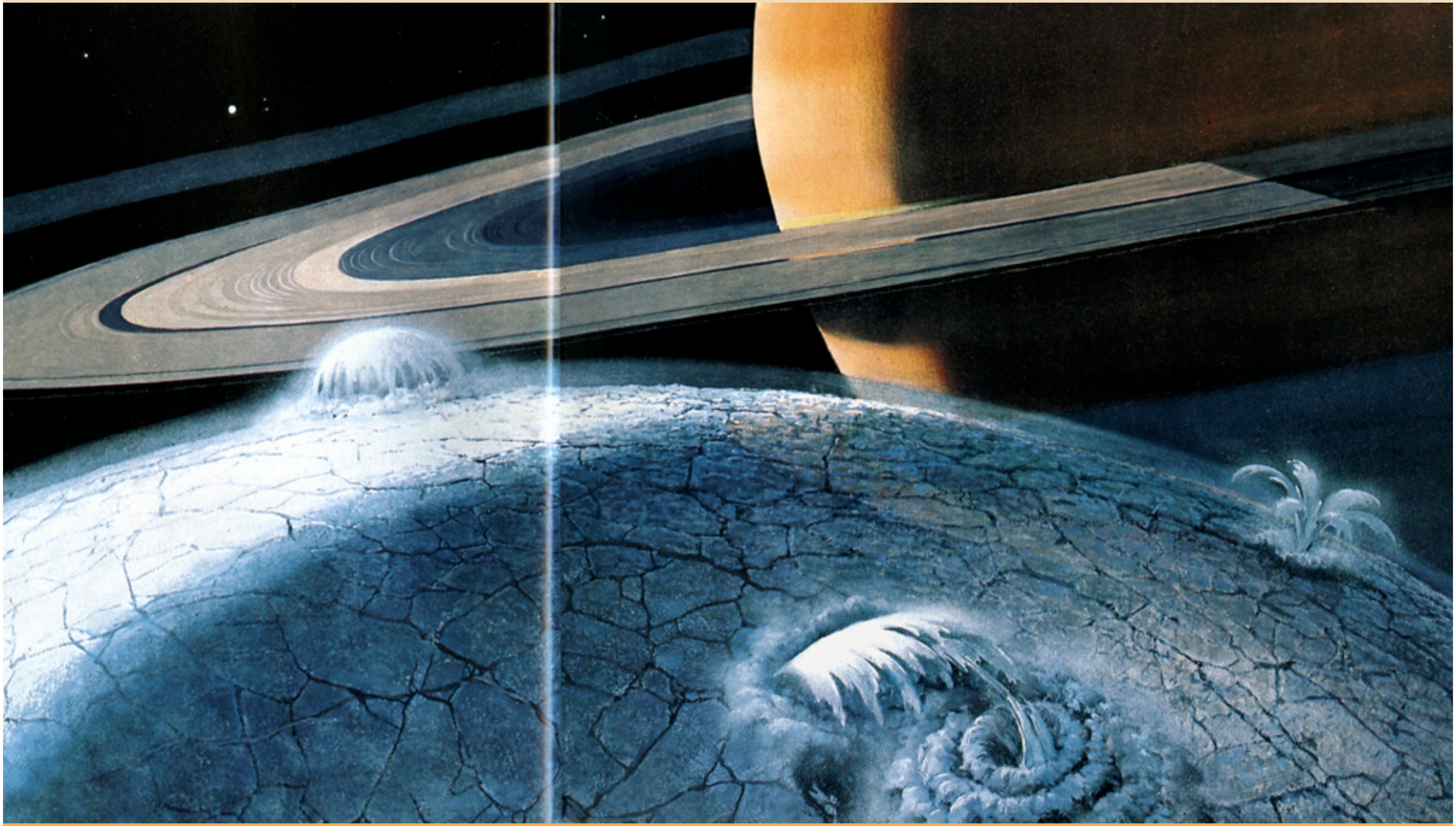
Voyager: 1980, 1981

- 500 km diameter
- Very high albedo
- Heavily modified, fractured surface

E-ring



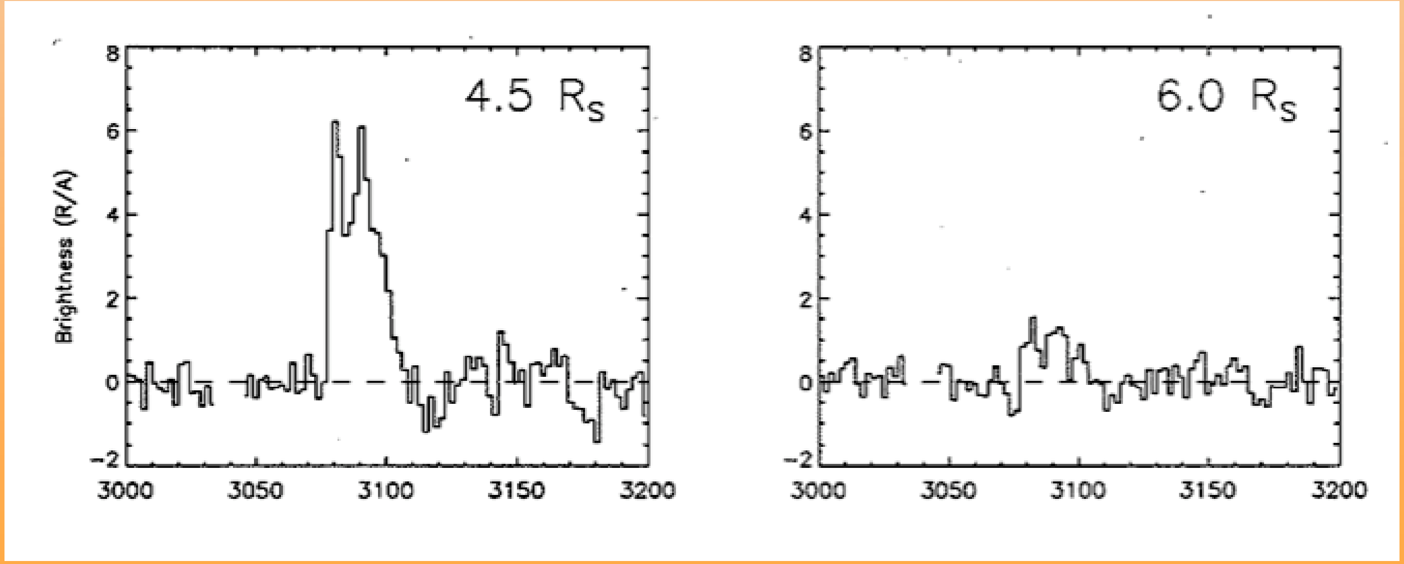
- Diffuse outer ring of Saturn, discovered in 1966
- Density peak at Enceladus (Baum et al. 1980, Reitsema et al. 1980, Larson et al. 1981)
- Haff et al. 1983: Sputtering lifetime of E-ring particles is only a few thousand years: need a continuous source at Enceladus
  - Geysers??
- Color implies a peculiar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



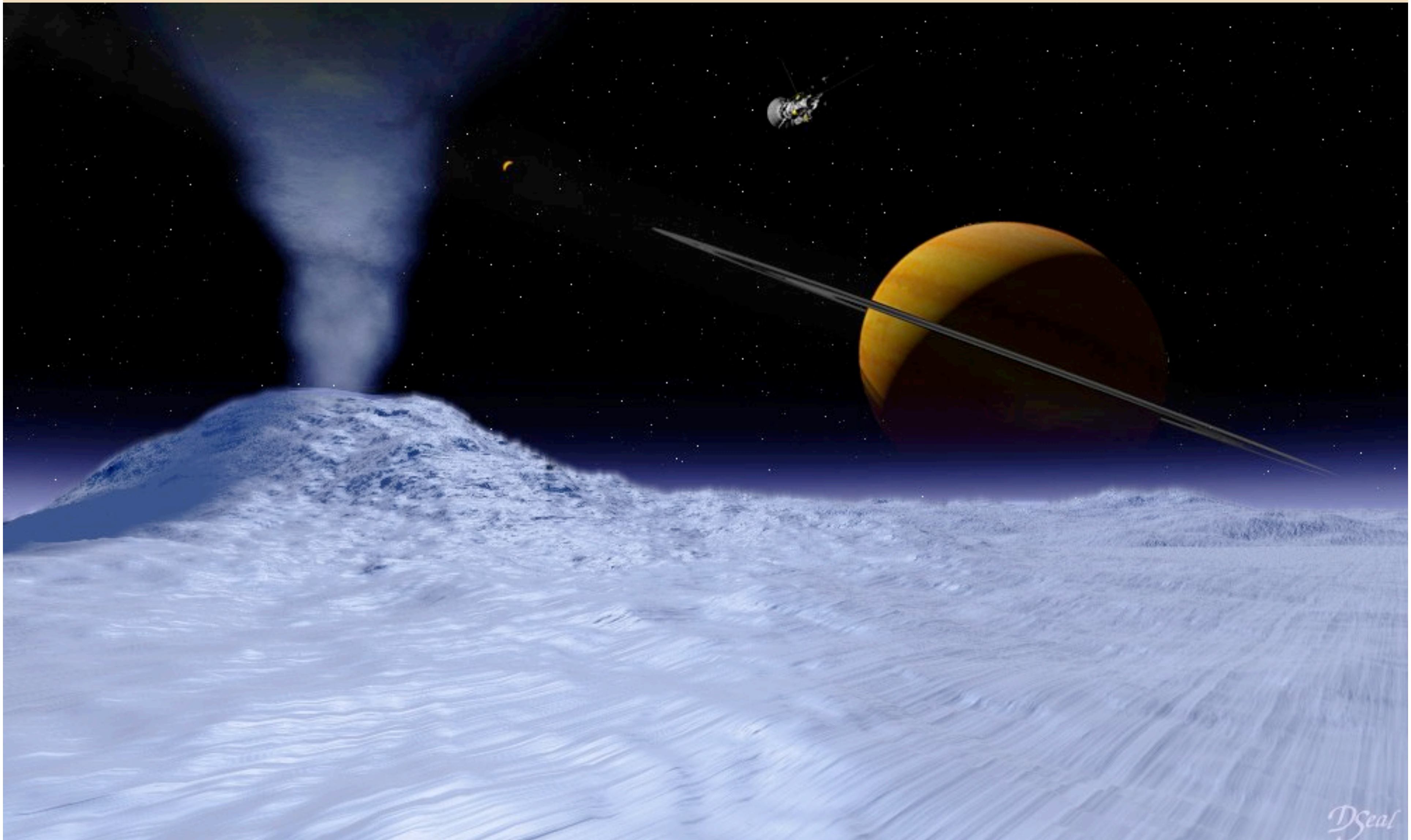
National Geographic, 1981

1990s: Discovery of OH Torus

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

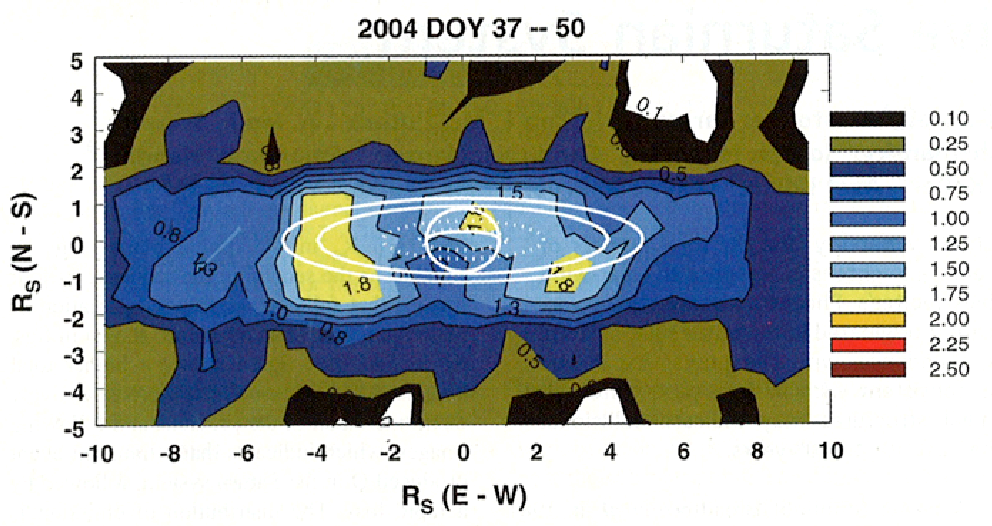


Richardson et al. 1998

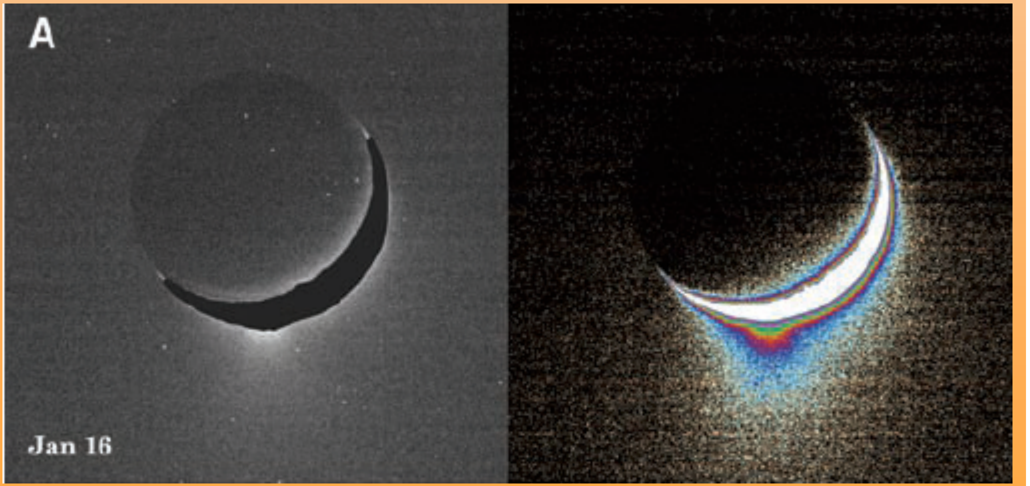

DSeal

Early Cassini Observations

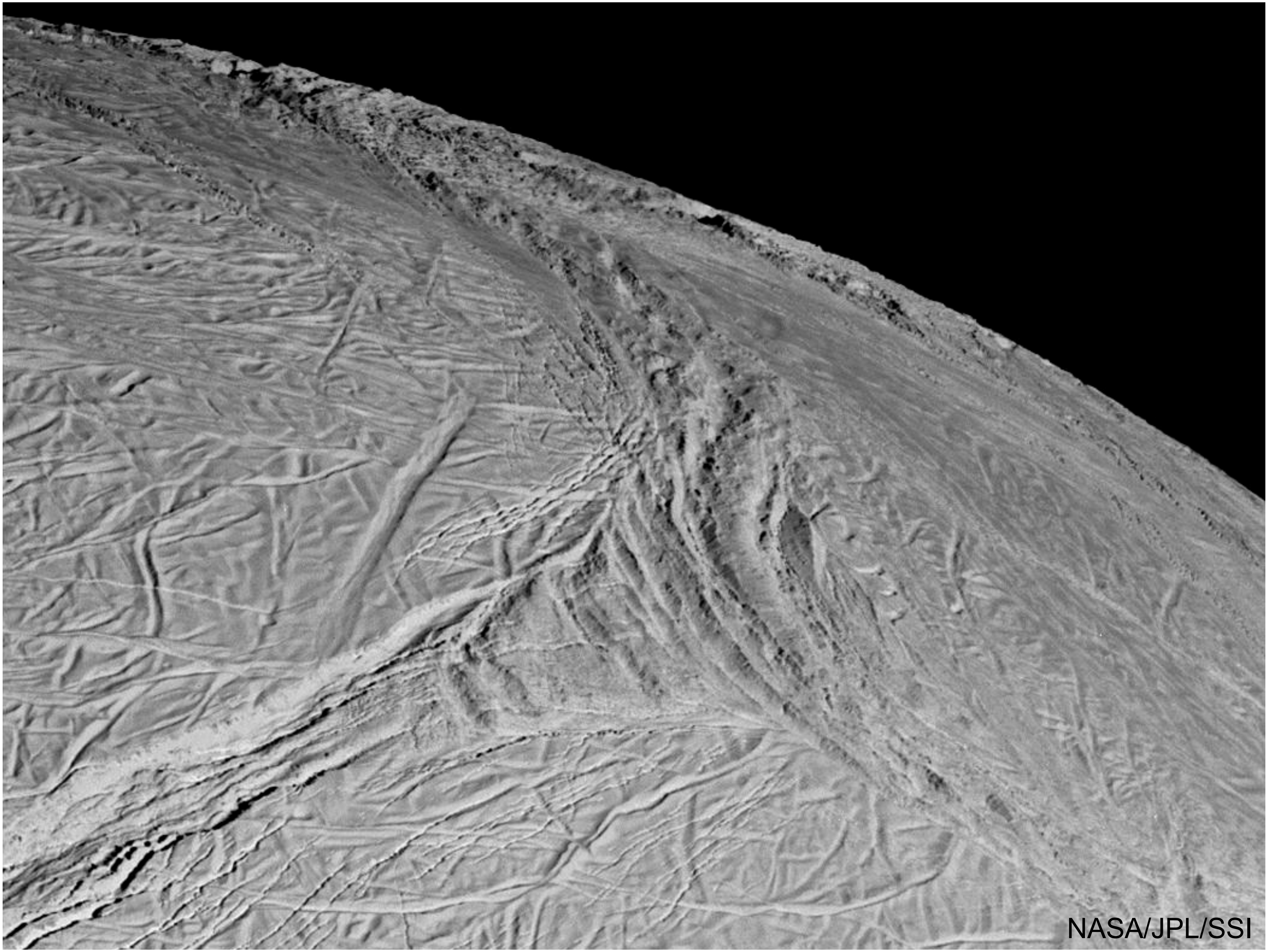
- Approach to Saturn, early 2004: Cassini UV observations of neutral oxygen throughout the Saturn system
  - More evidence for a large water source near Enceladus
- Distant high-phase imaging in Jan., Feb. 2005 showed south polar plume: not recognized at the time
- First close Enceladus flybys in early 2005…
  - Feb 17th 2005, 1260 km altitude
  - Mar 9th 2005, 500 km altitude

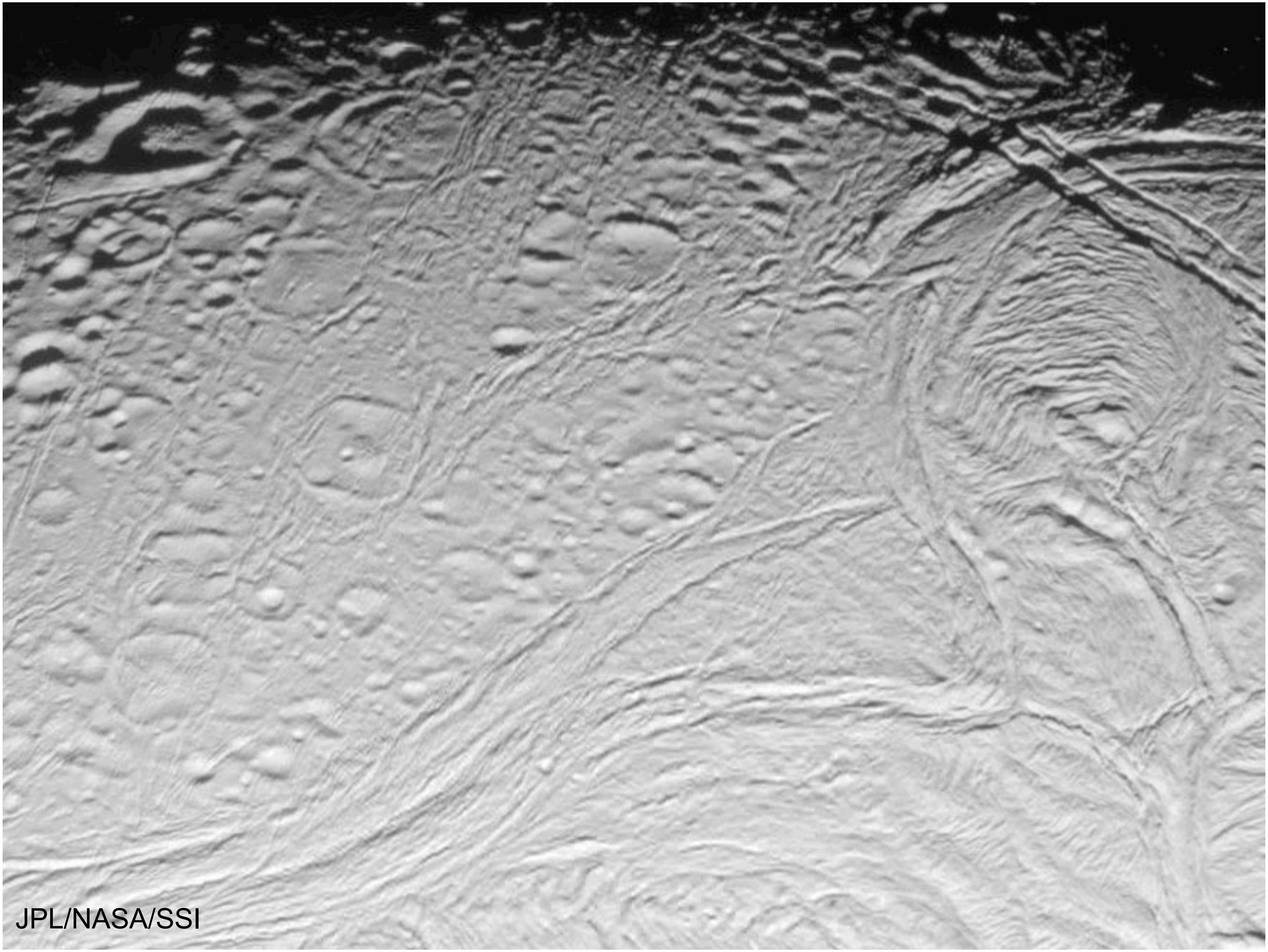


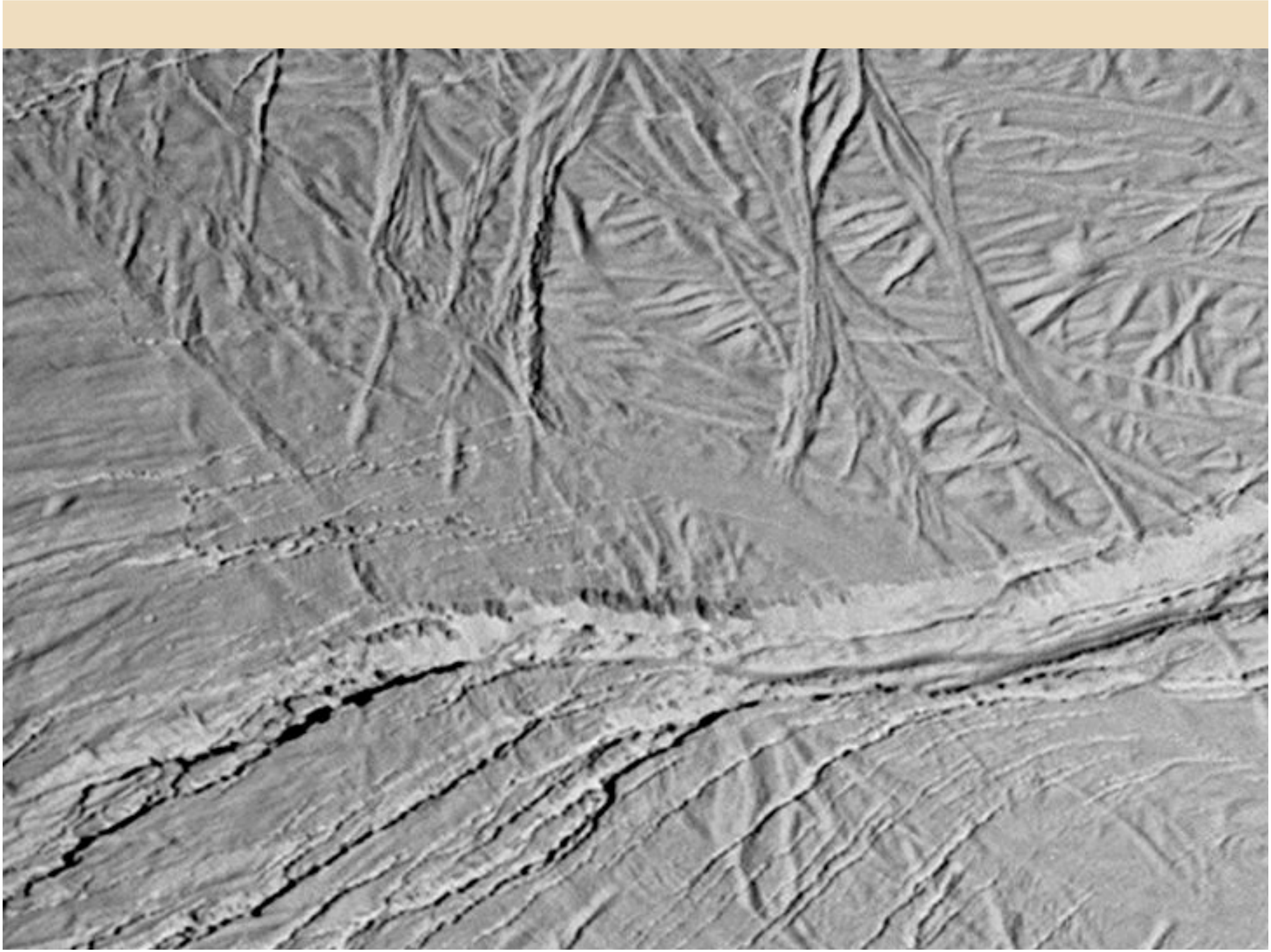
Esposito et al. 2005

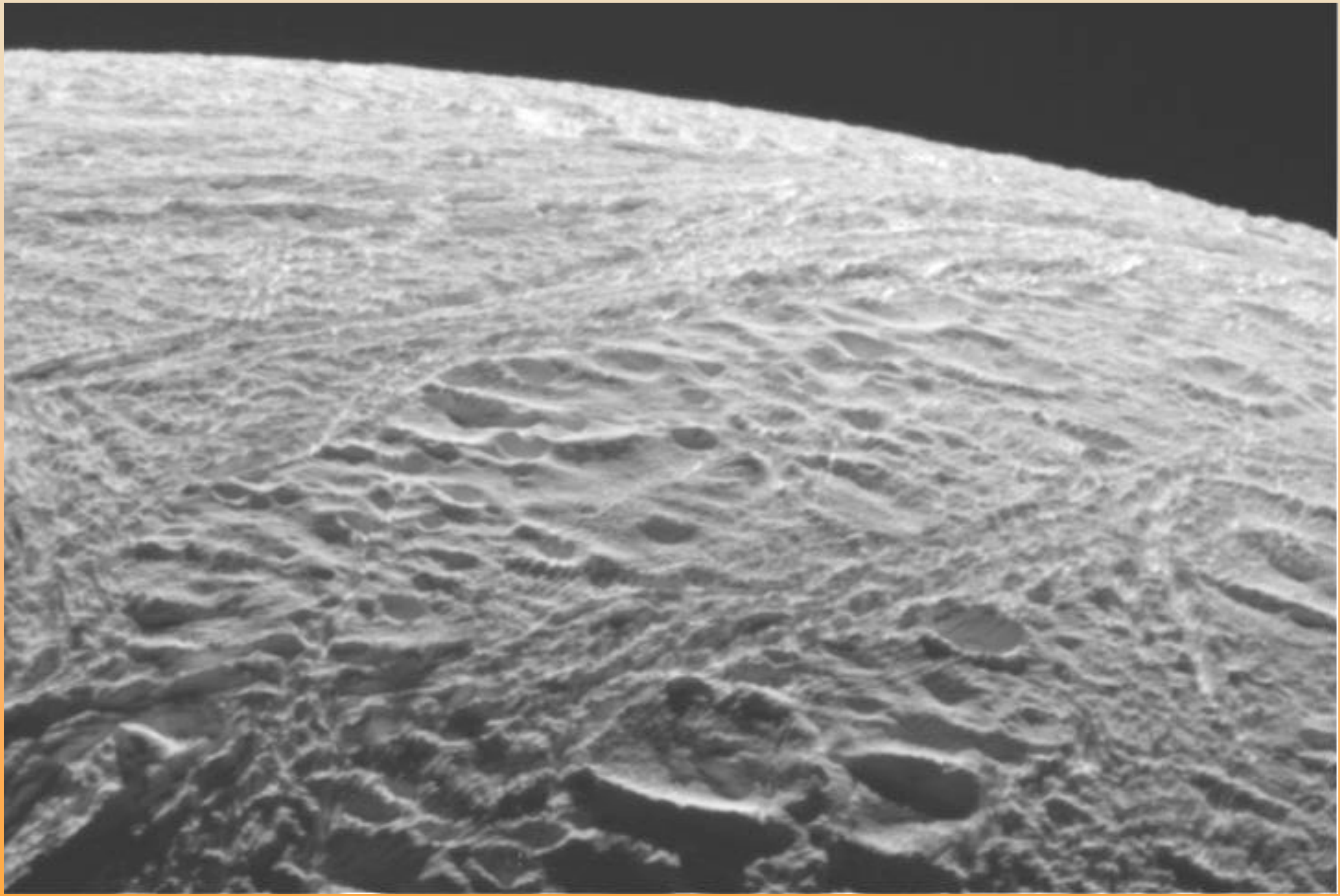


Porco et al. 2006


NASA/JPL/SSI


JPL/NASA/SSI





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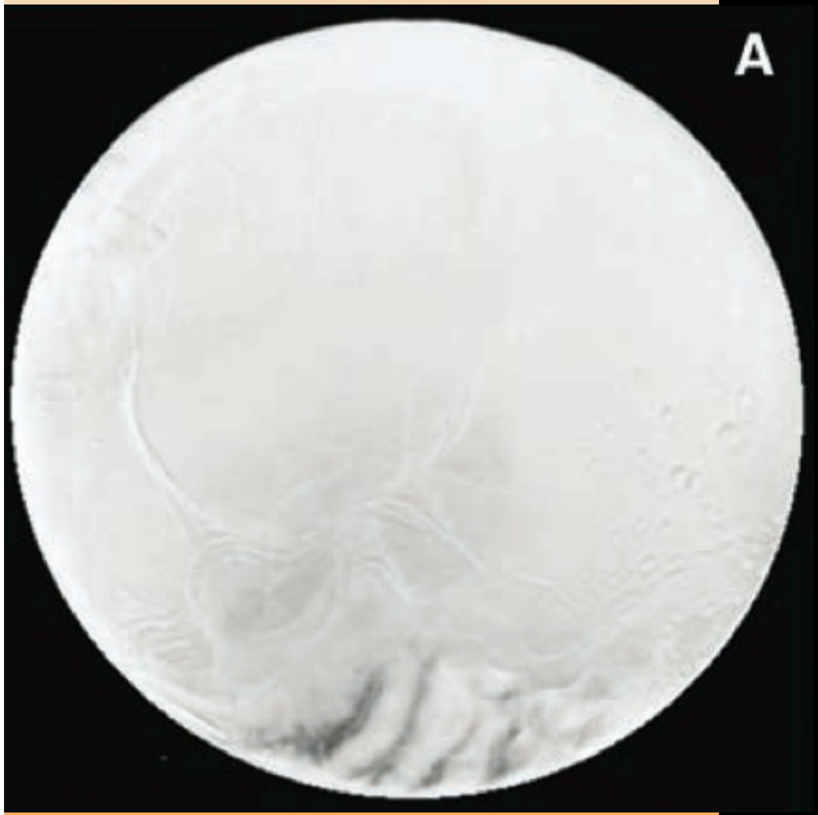
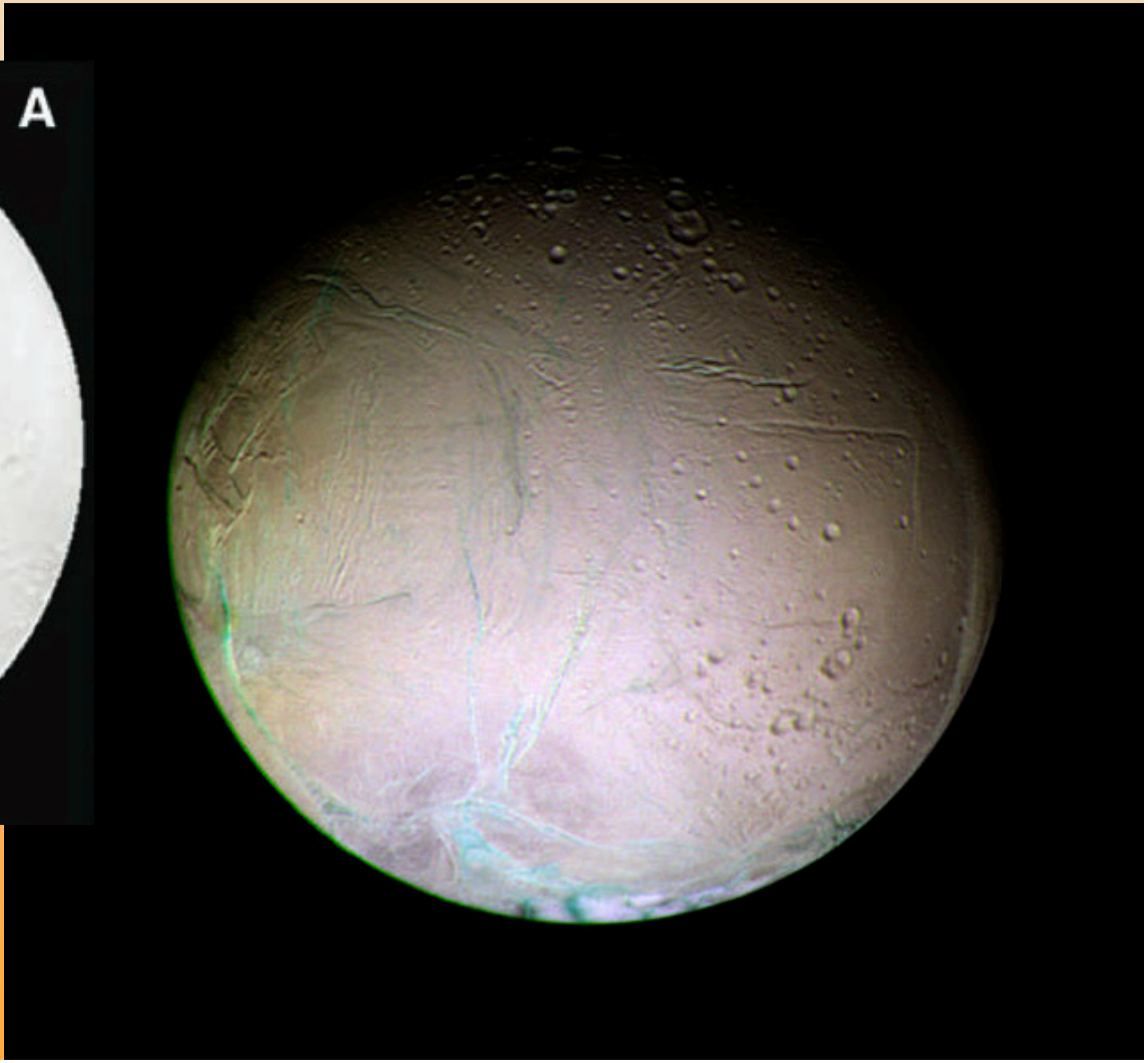
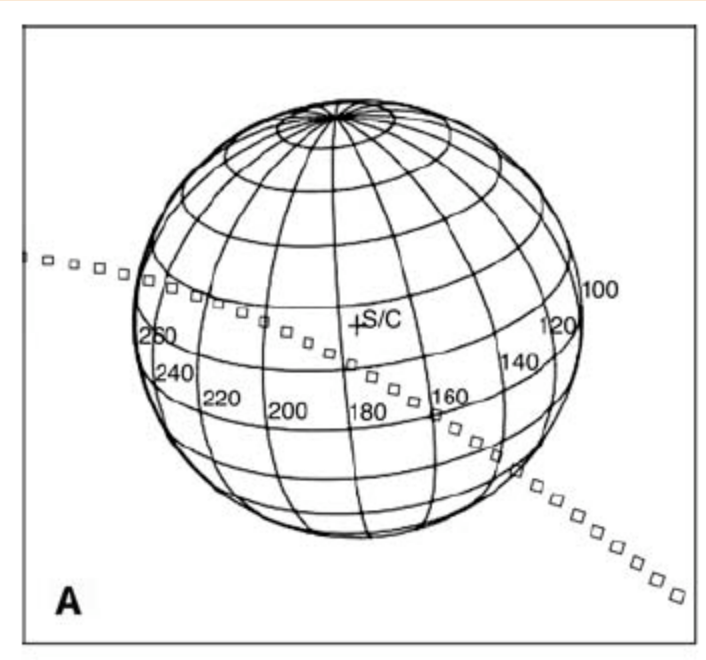
Hints of South Polar Weirdness…

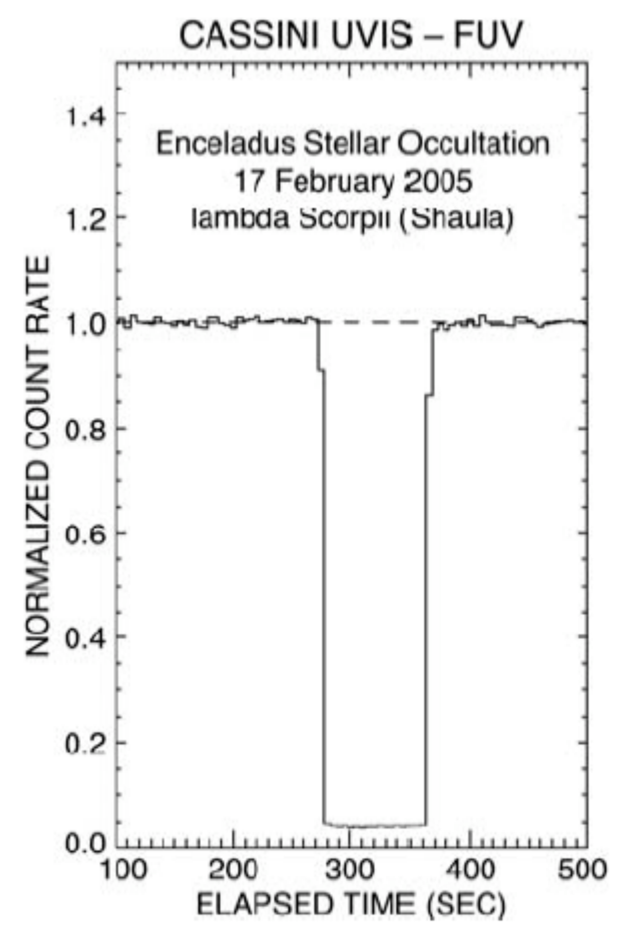




Feb. 2005 UVIS Stellar occultation

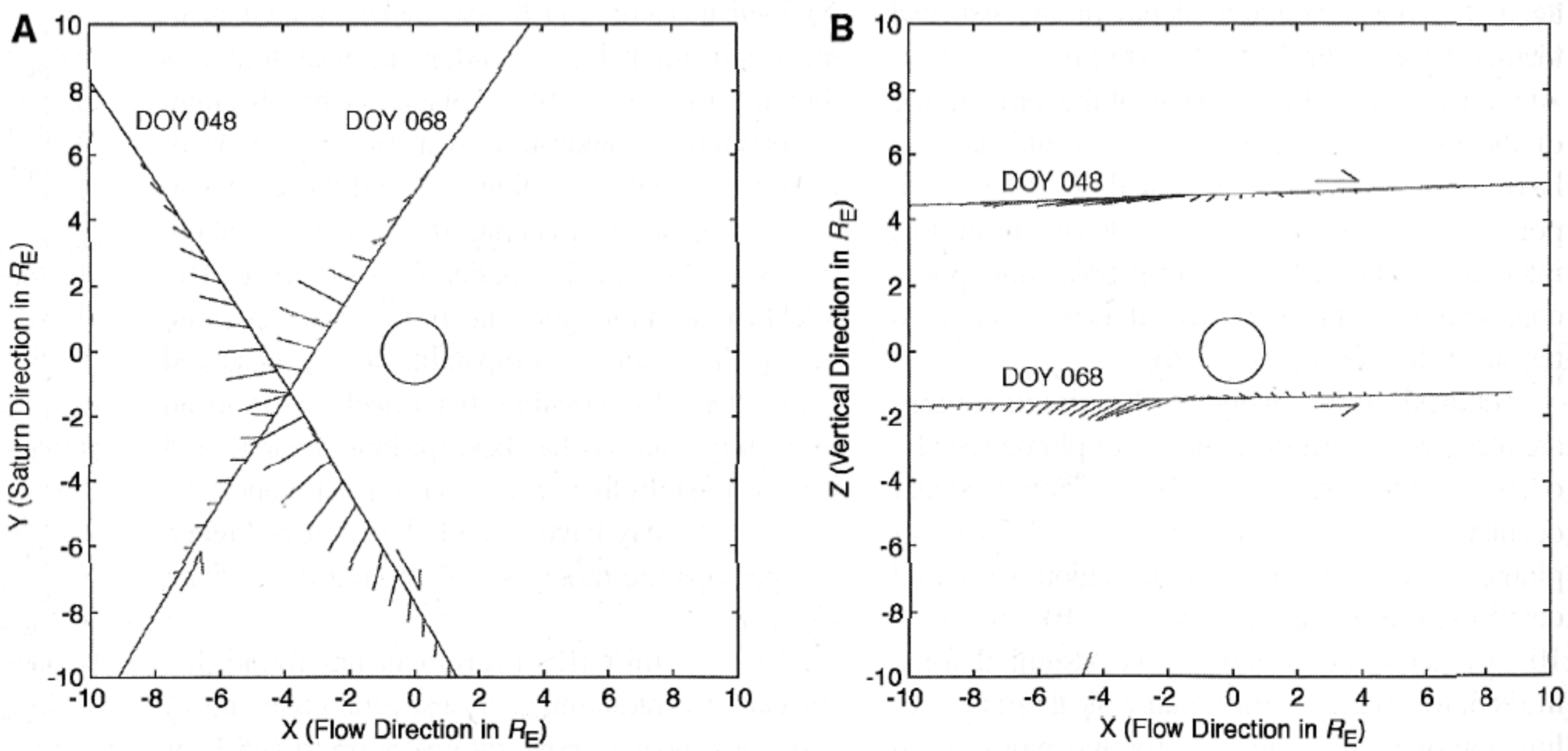
- Low latitudes: No atmospheric signature seen (Hansen et al. 2006)





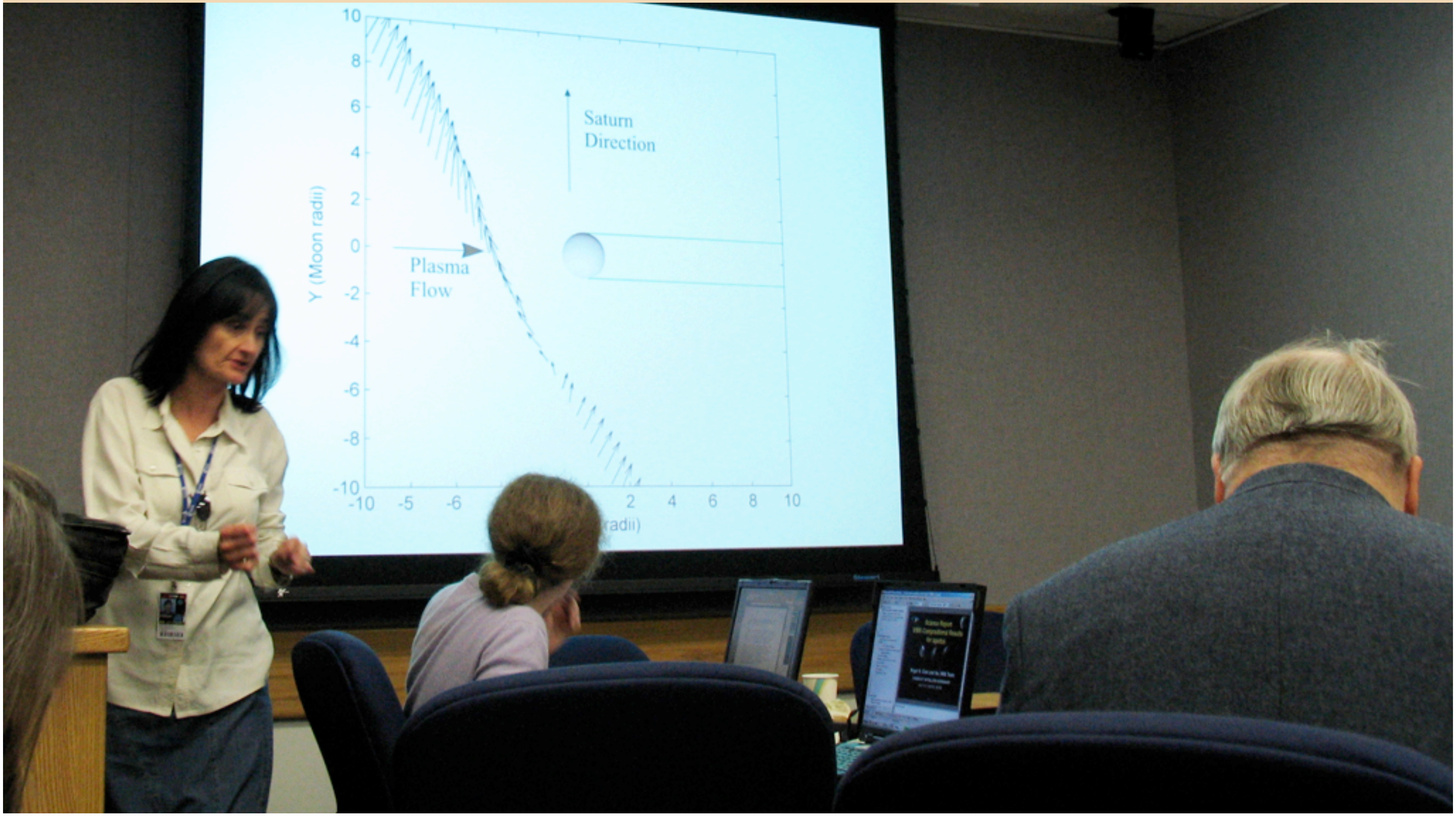
Feb., Mar. 2005 Magnetometer results

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



April 2005: Cassini satellite Workshop,JPL

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



July 14th 2005 (Rev. 11): The Flyby That Changed Everything

- Good view of the south pole on approach
- UV star occultation over the south pole
- 175 km altitude flyby allowing close investigation by the in situ instruments

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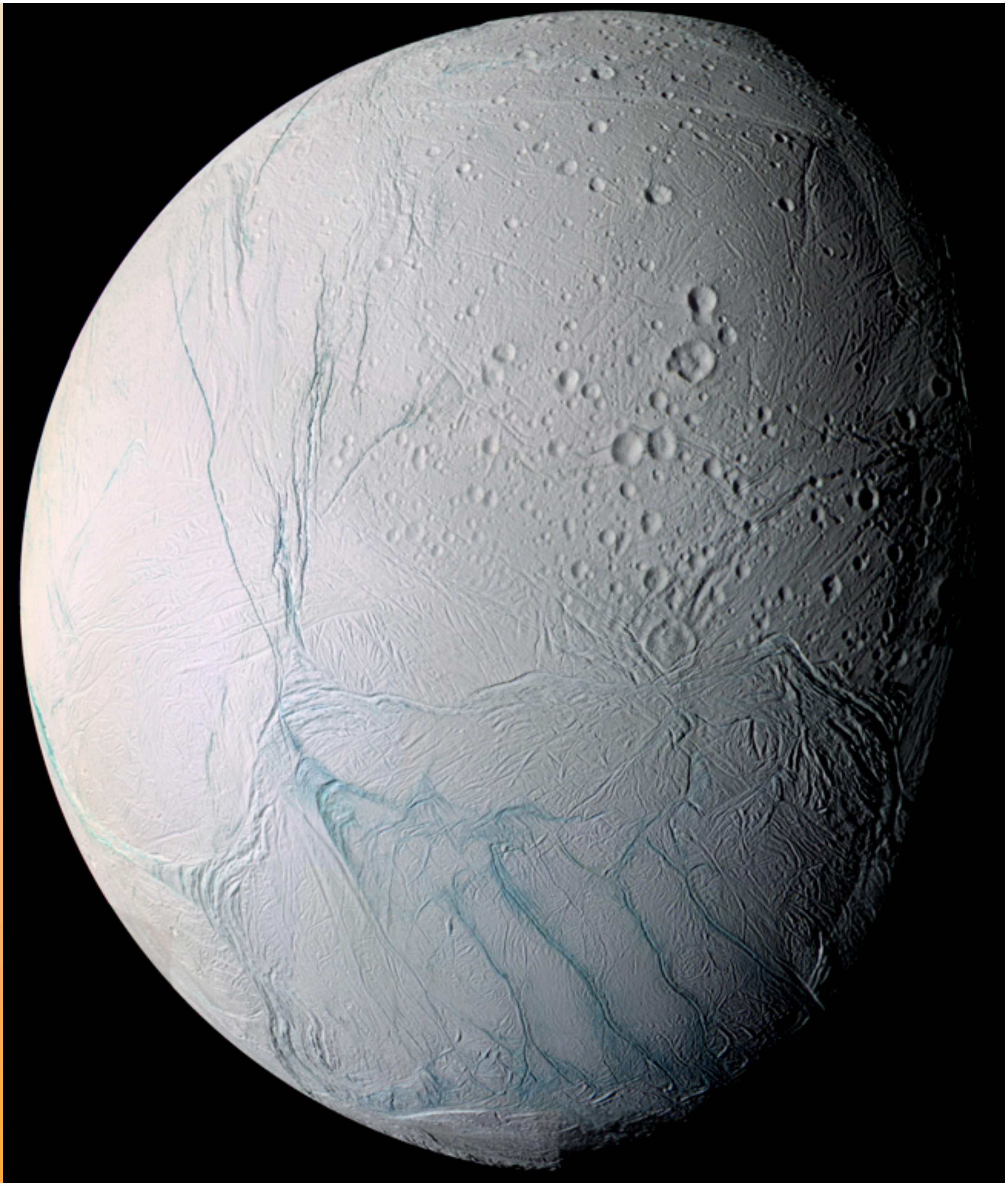
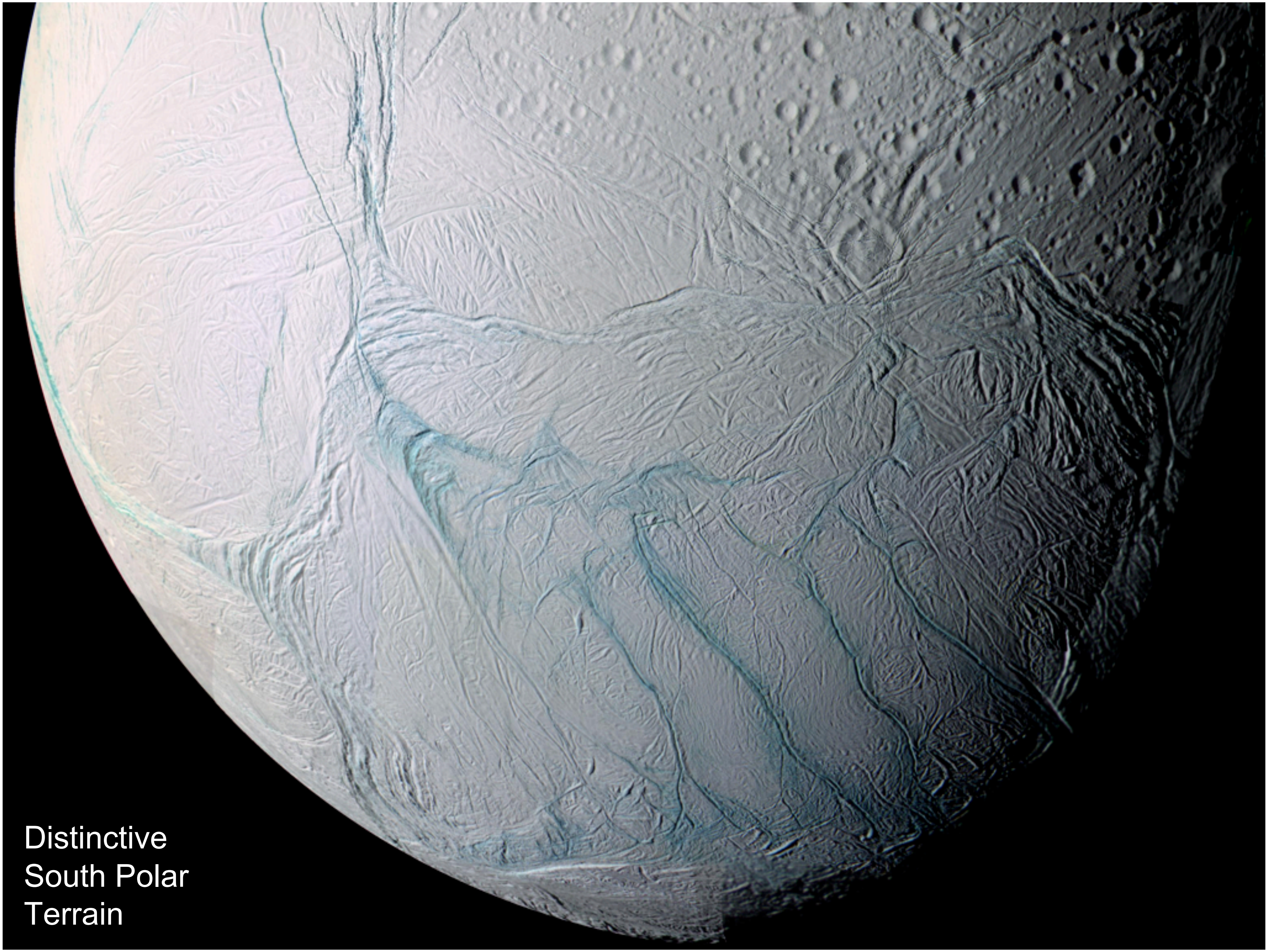
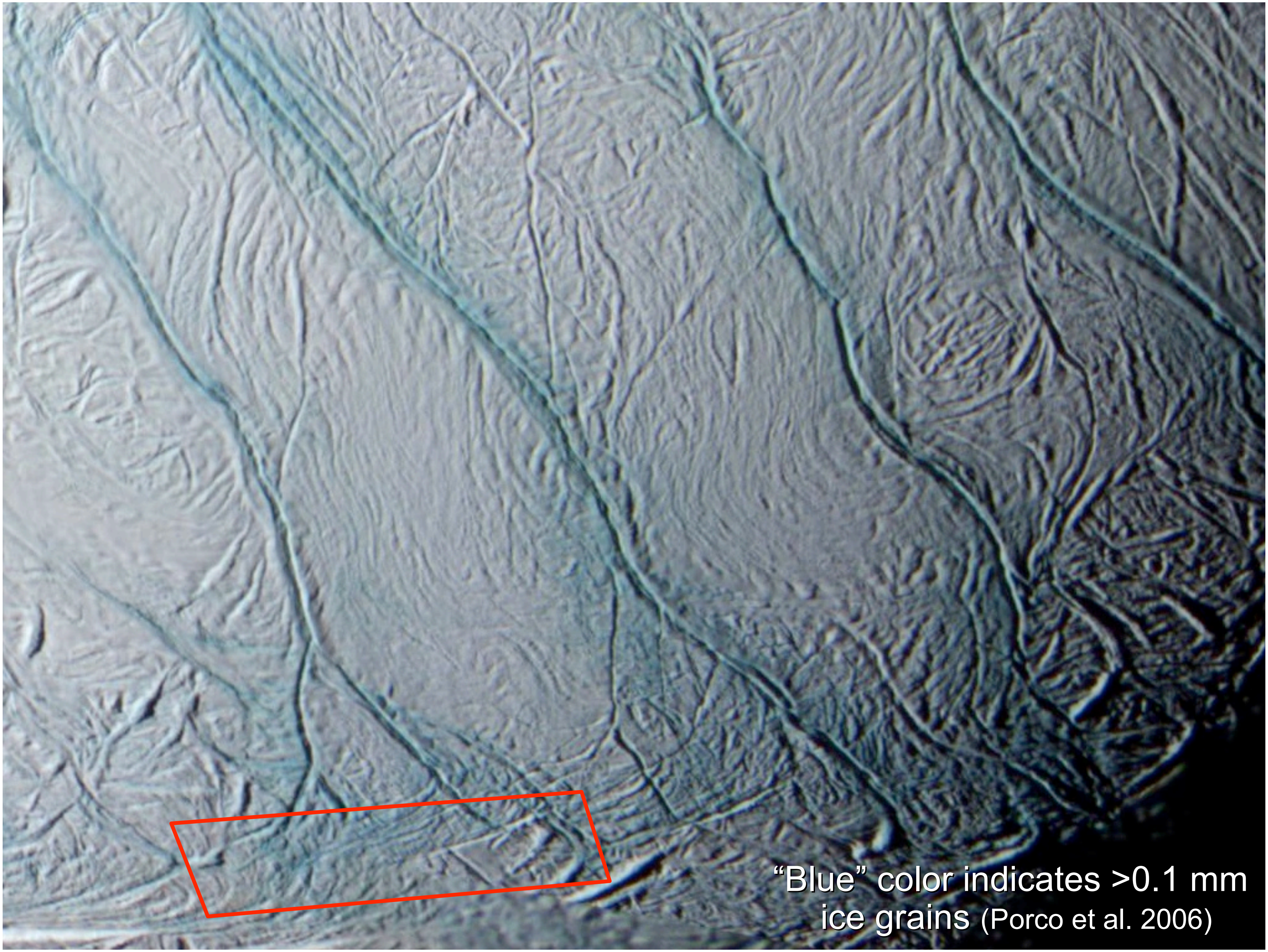
Imaging on Approach

- First good view of south polar “tiger stripes”



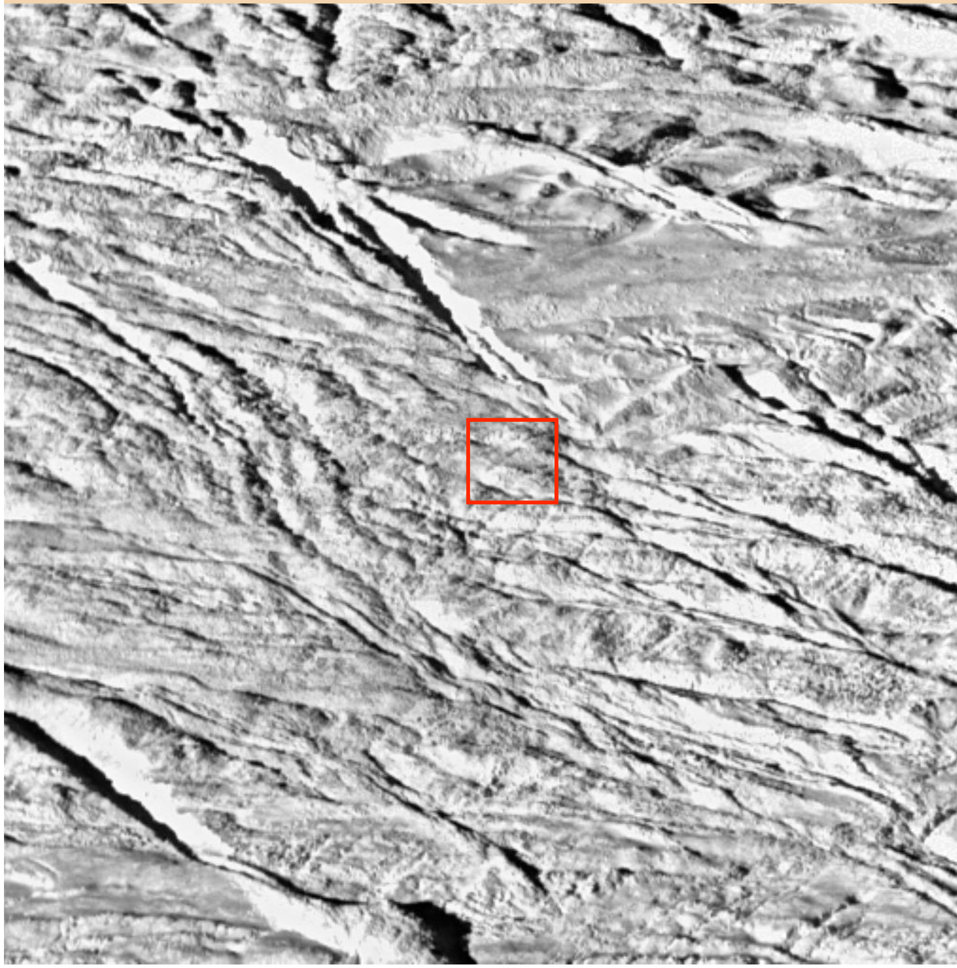
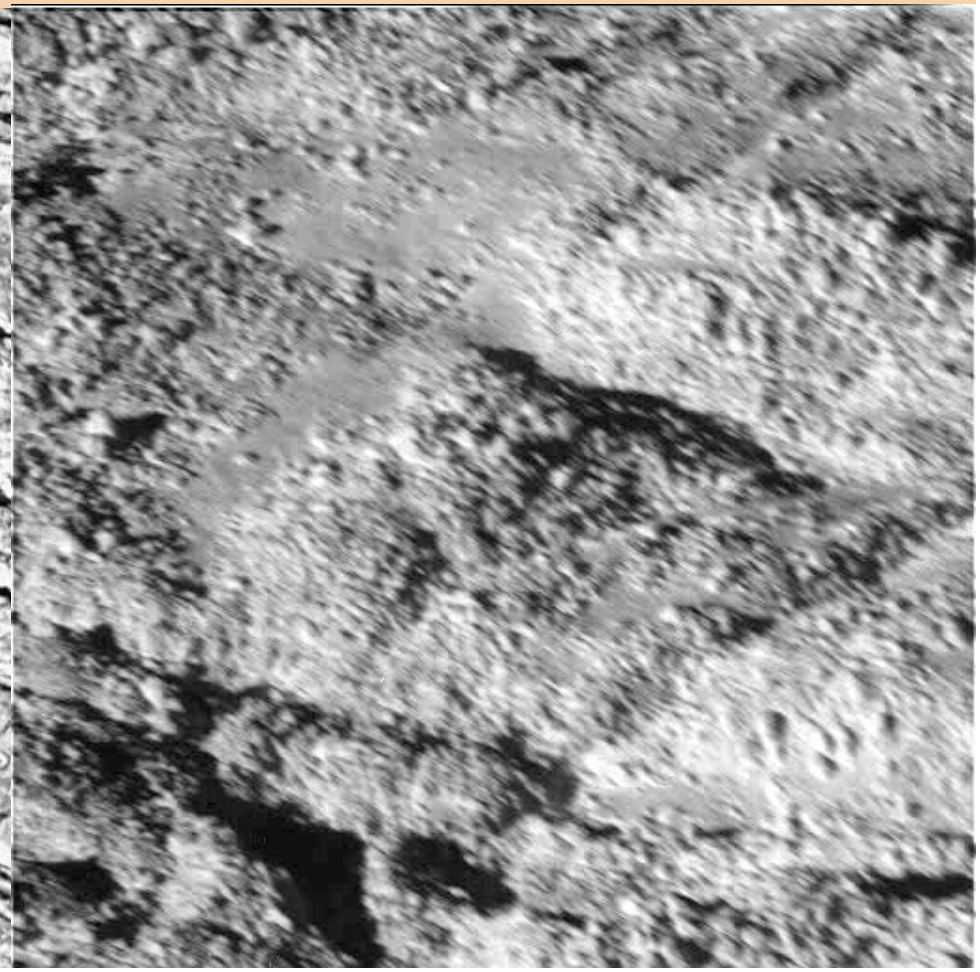
NASA/JPL/SSI


Distinctive
South Polar
Terrain

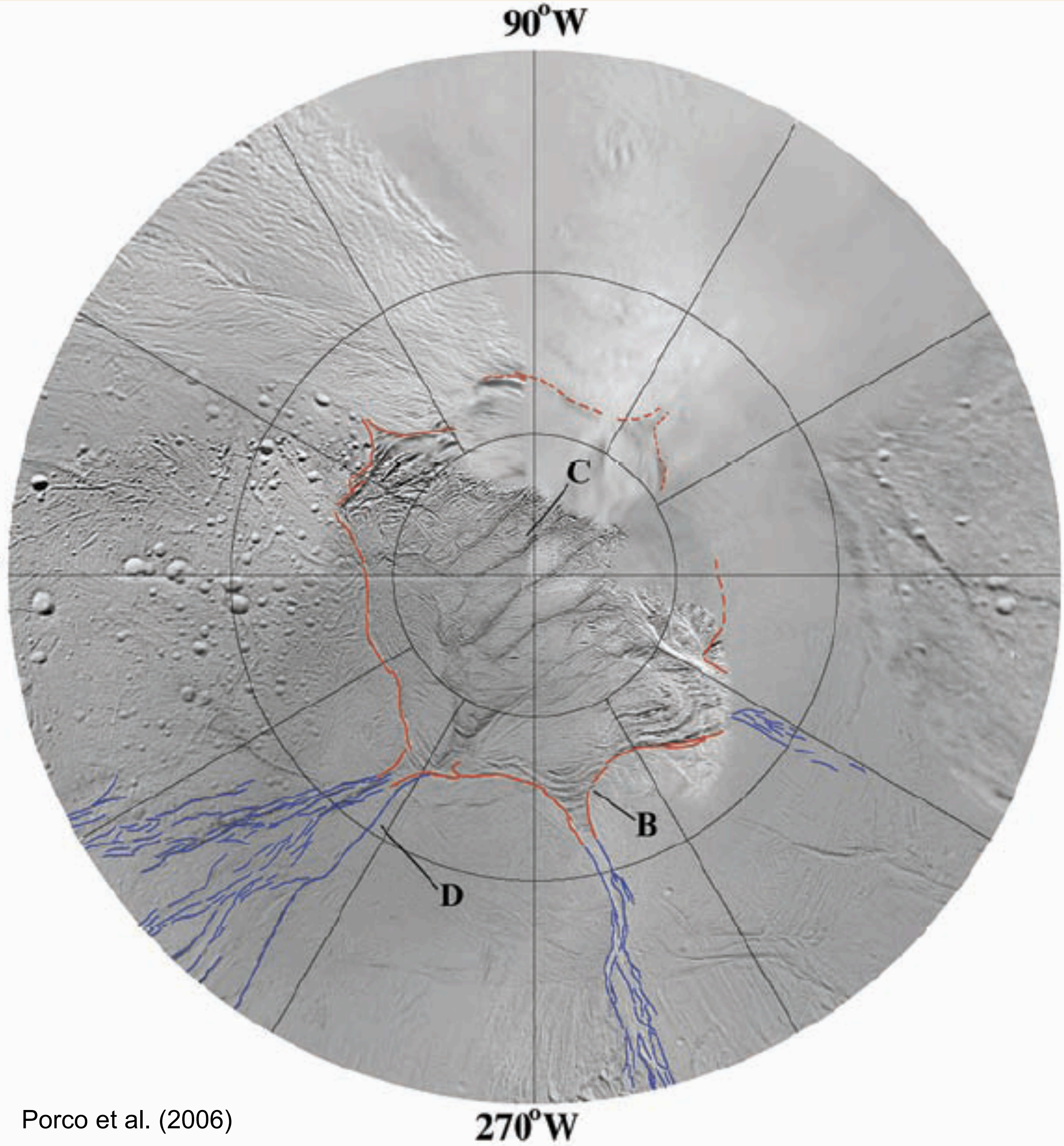

"Blue" color indicates >0.1 mm
ice grains (Porco et al. 2006)

High Resolution Imaging

- 37 m/pixel, 4 m/pixel

- 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)

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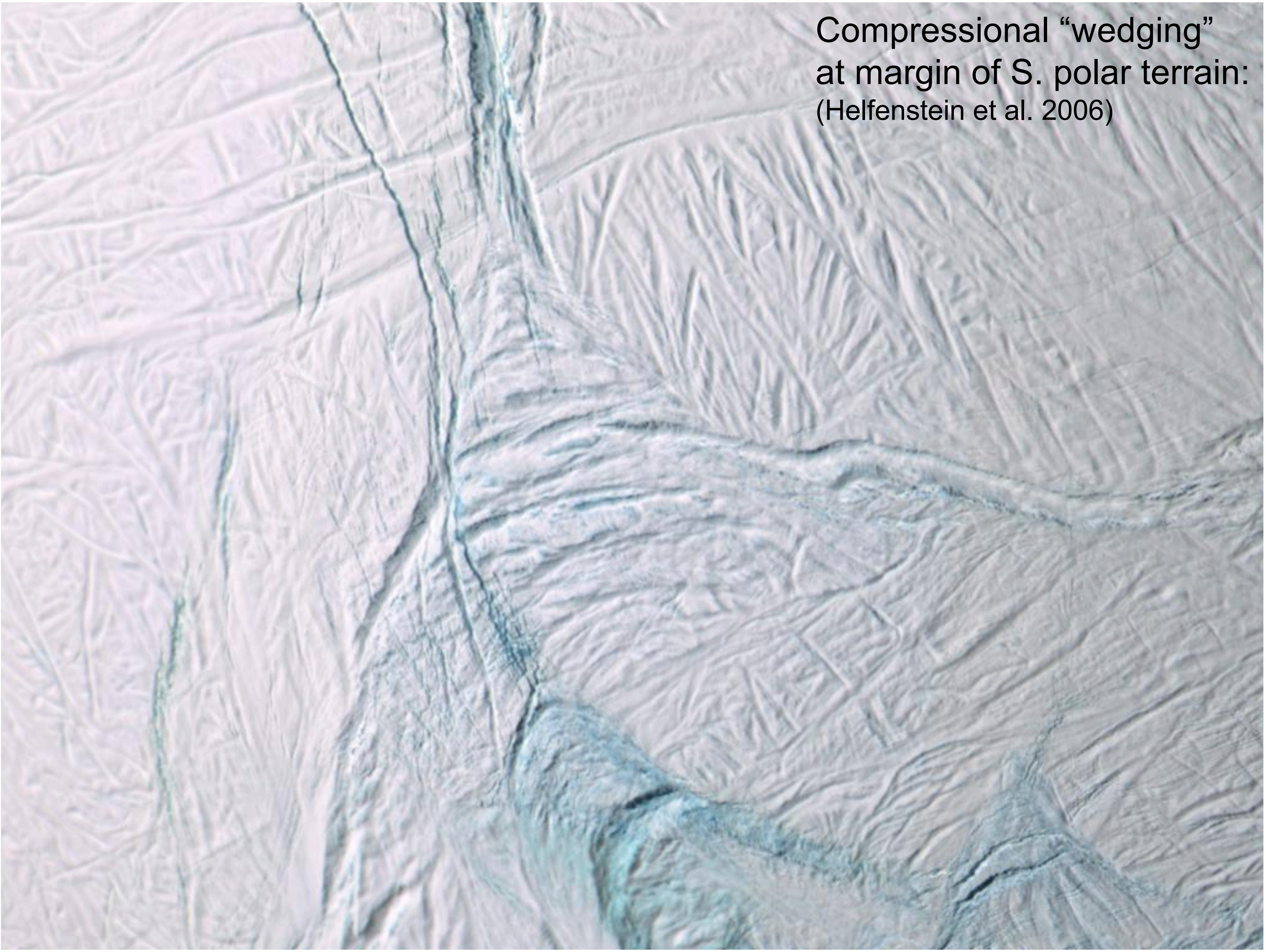
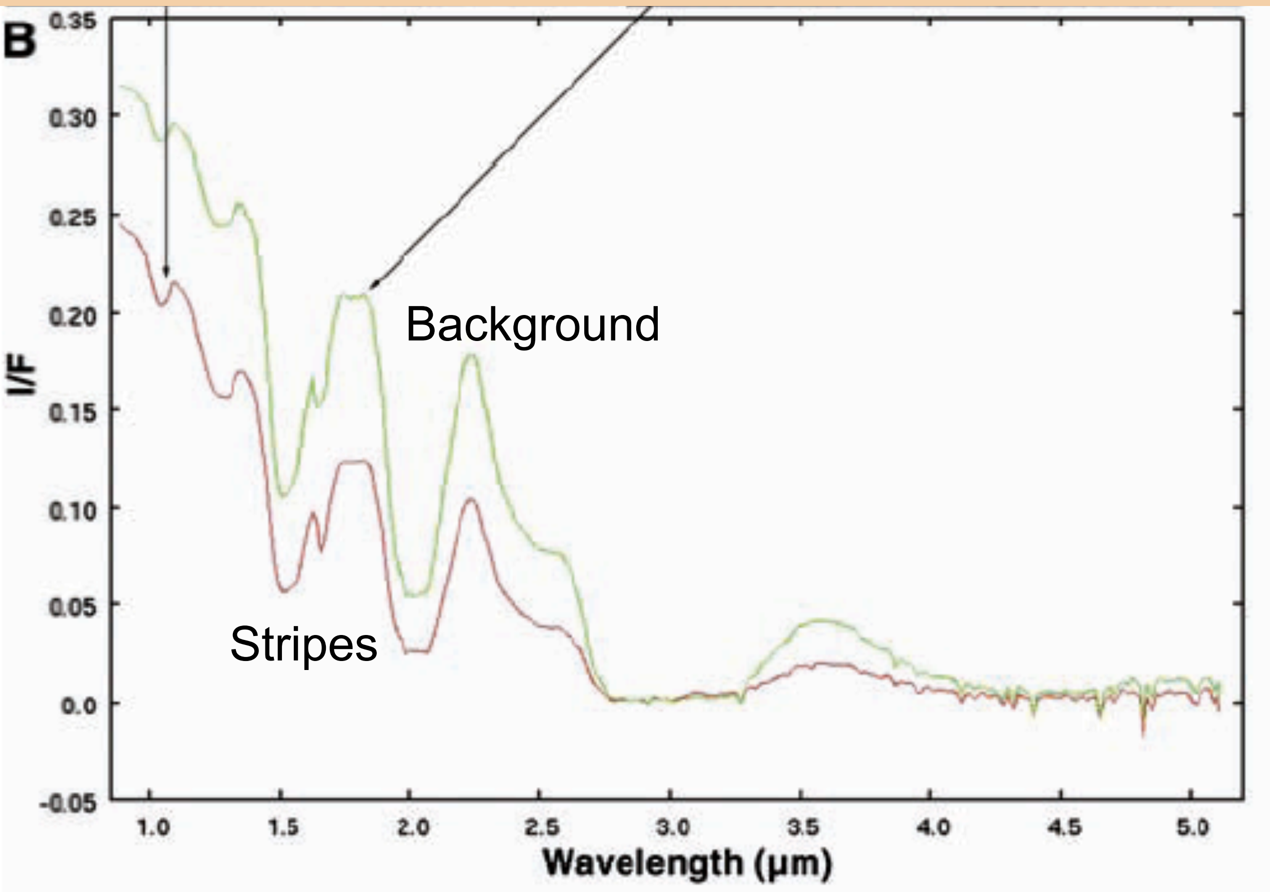
Compressional “wedging”
at margin of S. polar terrain:
(Helfenstein et al. 2006)

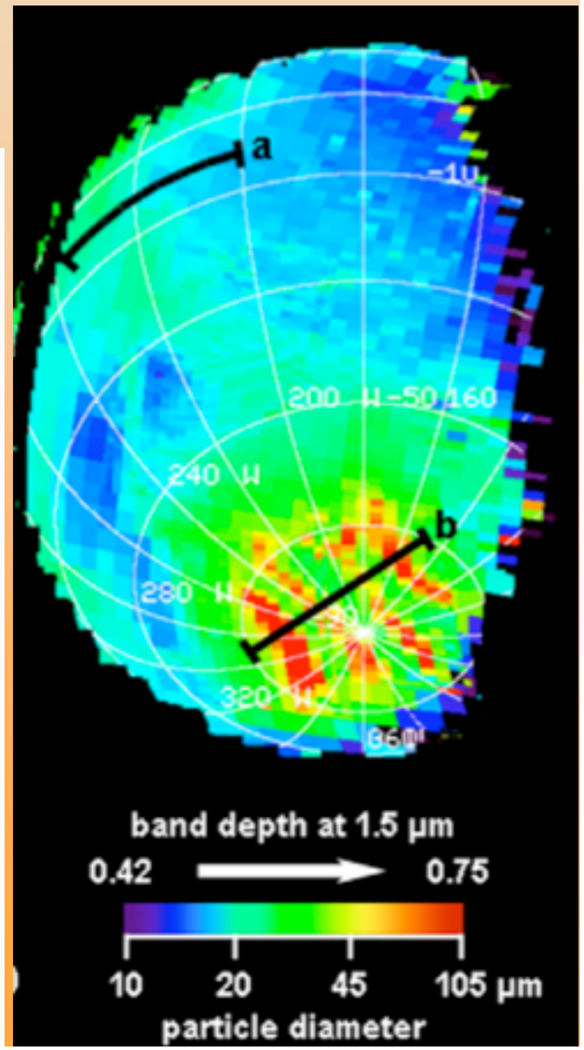


Tiger Stripe Infrared Spectrum

VIMS (Brown et al. 2006, Jaumann et al. 2008, Newman et al 2008):

- Coarser ice grains ~0.1 mm in tiger stripes
- Crystalline ice at the tiger stripes, more amorphous ice between the stripes





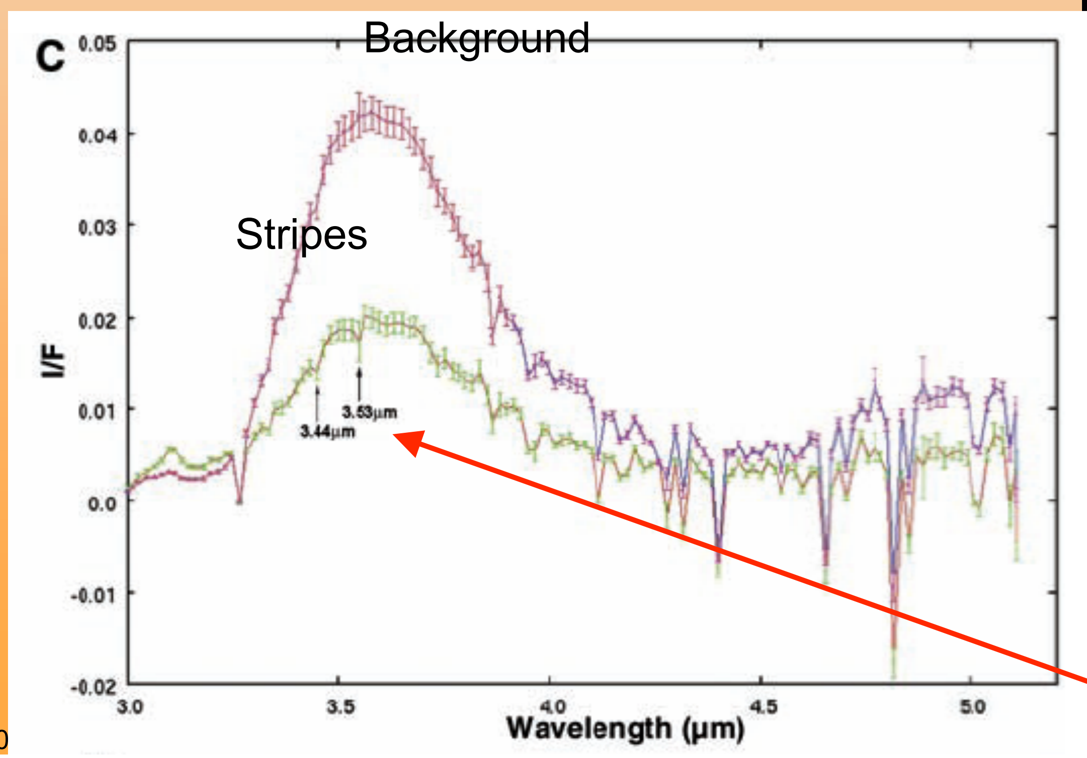
Tiger Stripe IR Spectrum, contd.

Stripes are also enriched in

- CO_2
- Organics

NH_3 frost not seen

(Brown et al. 2006)

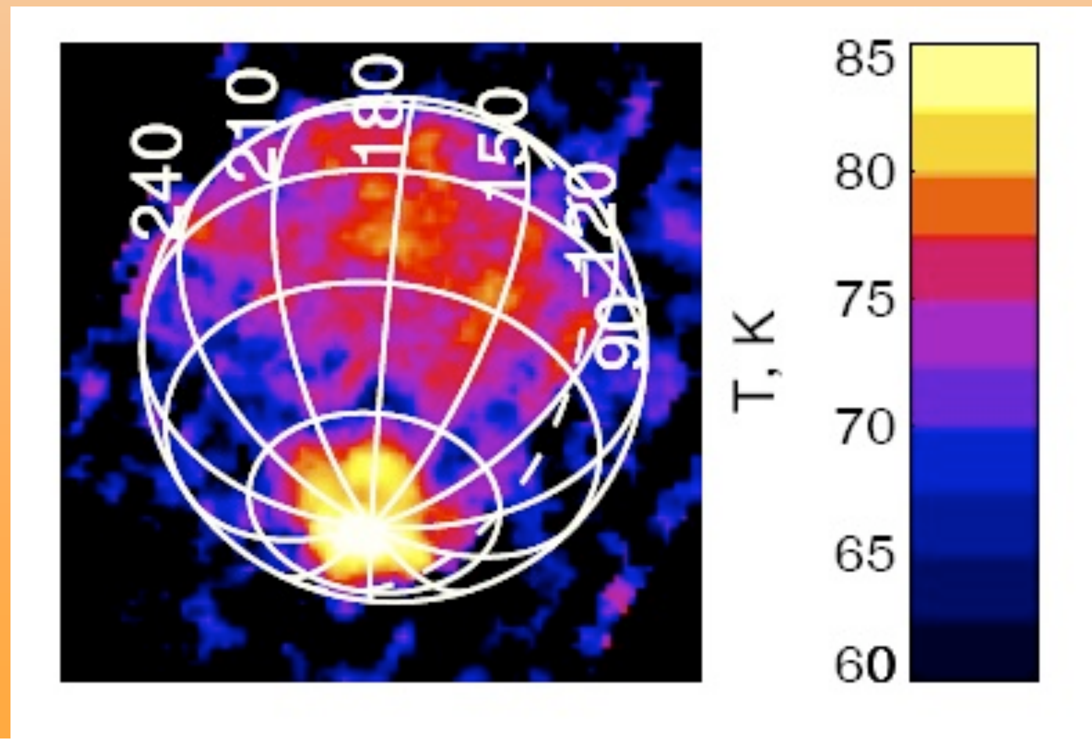


Thermal Infrared Observations

CIRS instrument: Map heat radiation from Enceladus' surface Spencer et al. (2006)

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

South polar hot spot



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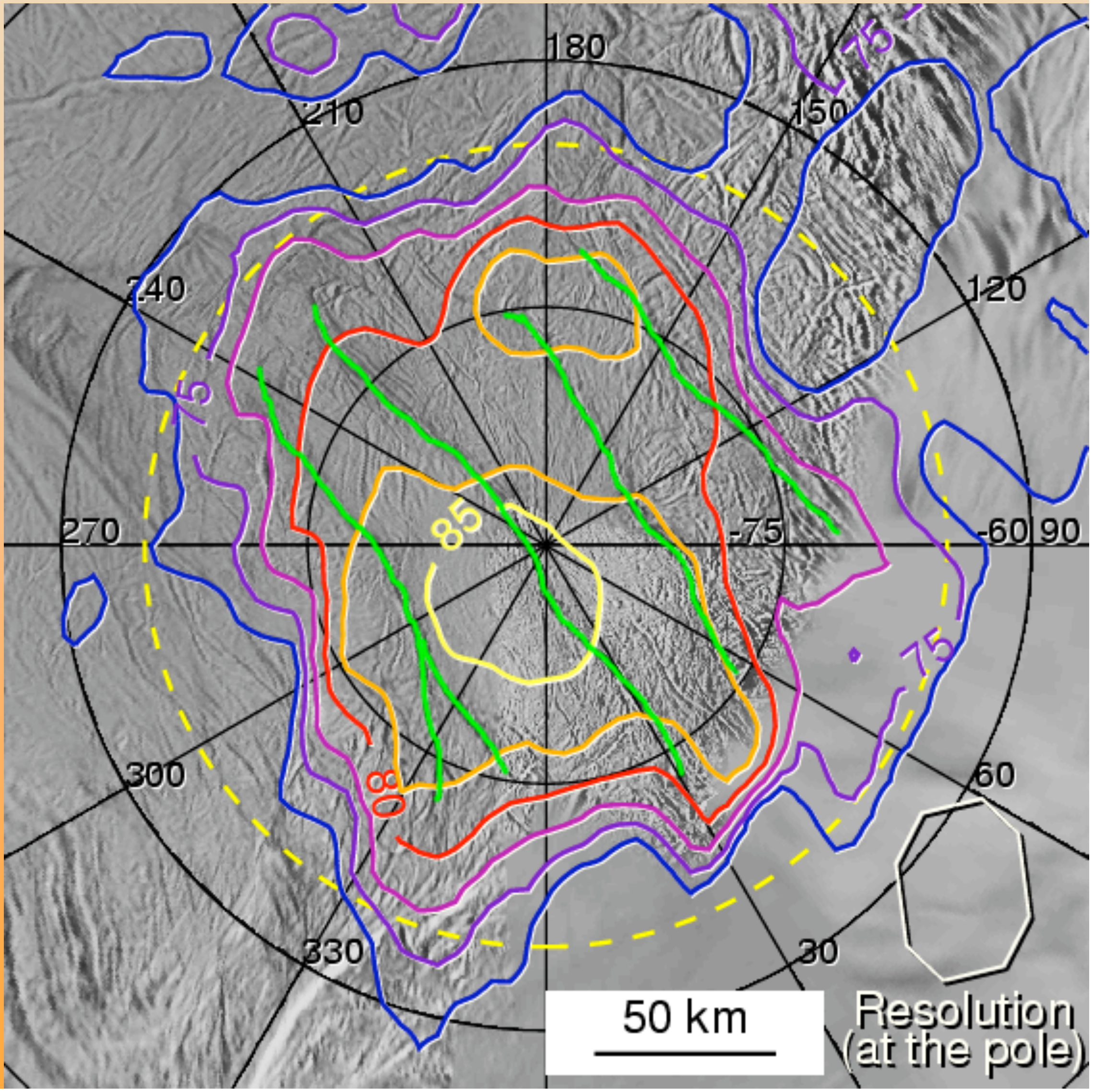
Location of Warm Region

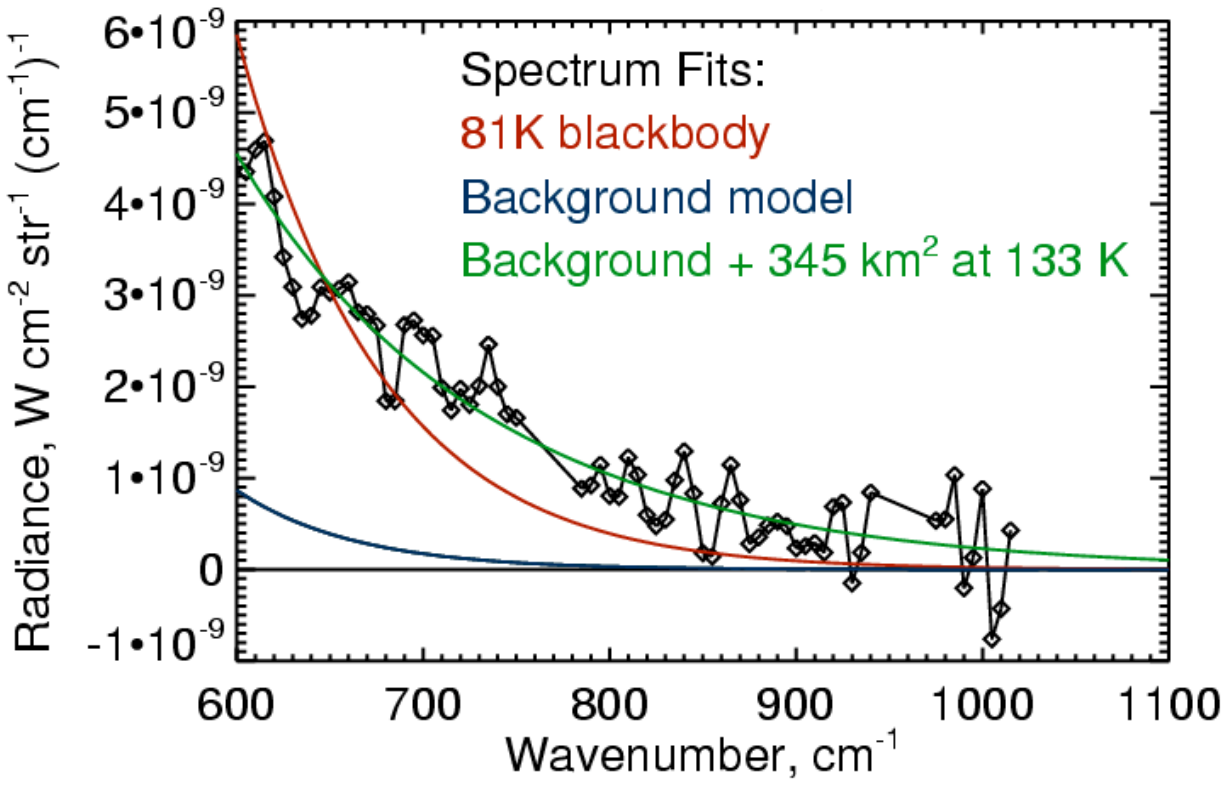
- Corresponds closely to the "tiger stripe" fractures



Brightness Temperature Contours
(Spencer et al. 2006)

Spectrum of South Polar Warm Region

- ~345 km^2 (~1% of the surface) at ~133 K
  - Remainder of surface is much colder, <75 K
- E.g., ~660 m width of warm material along the tiger stripes
- Total radiated power: at least 5.8 ± 1.9 GW

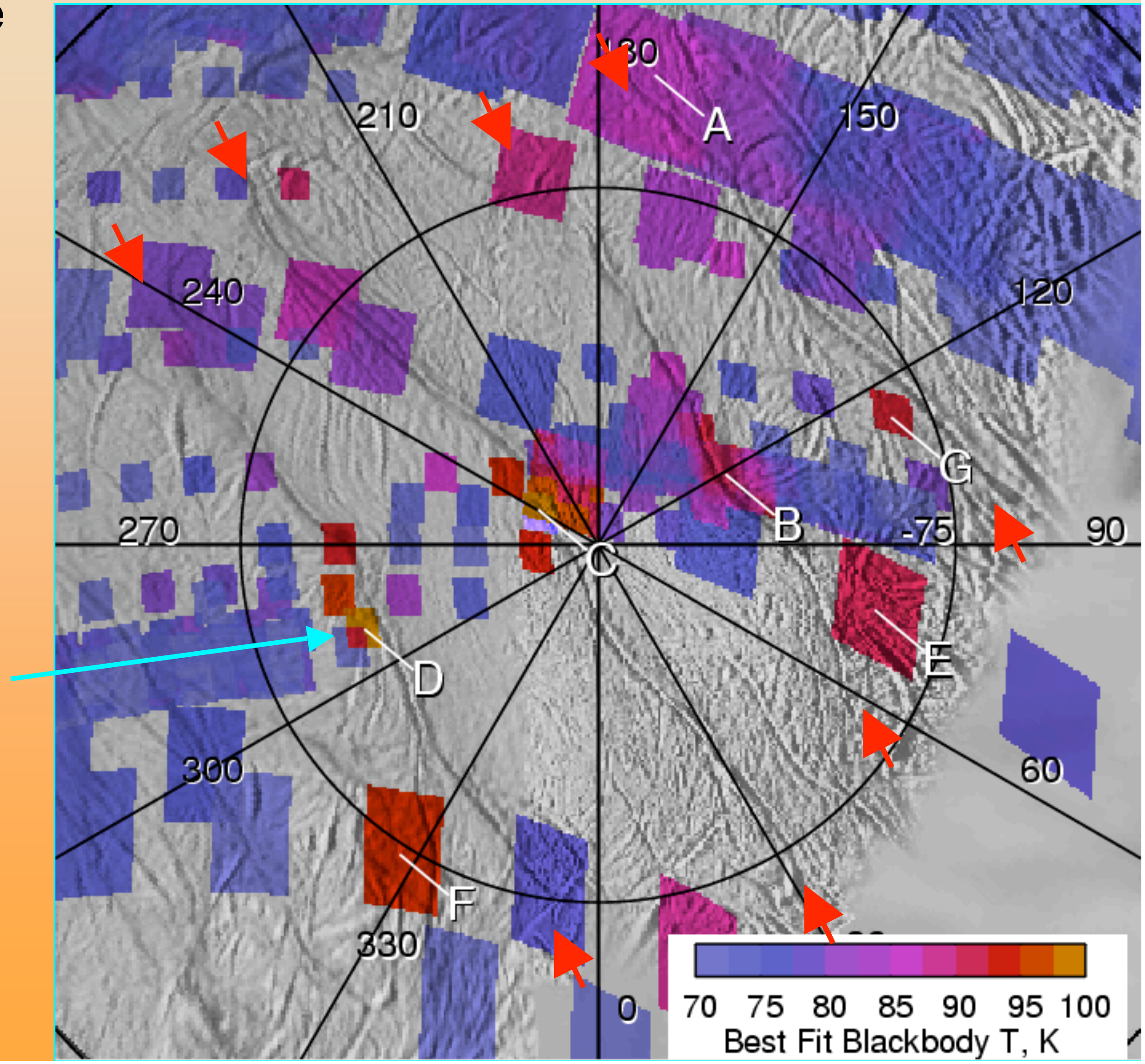


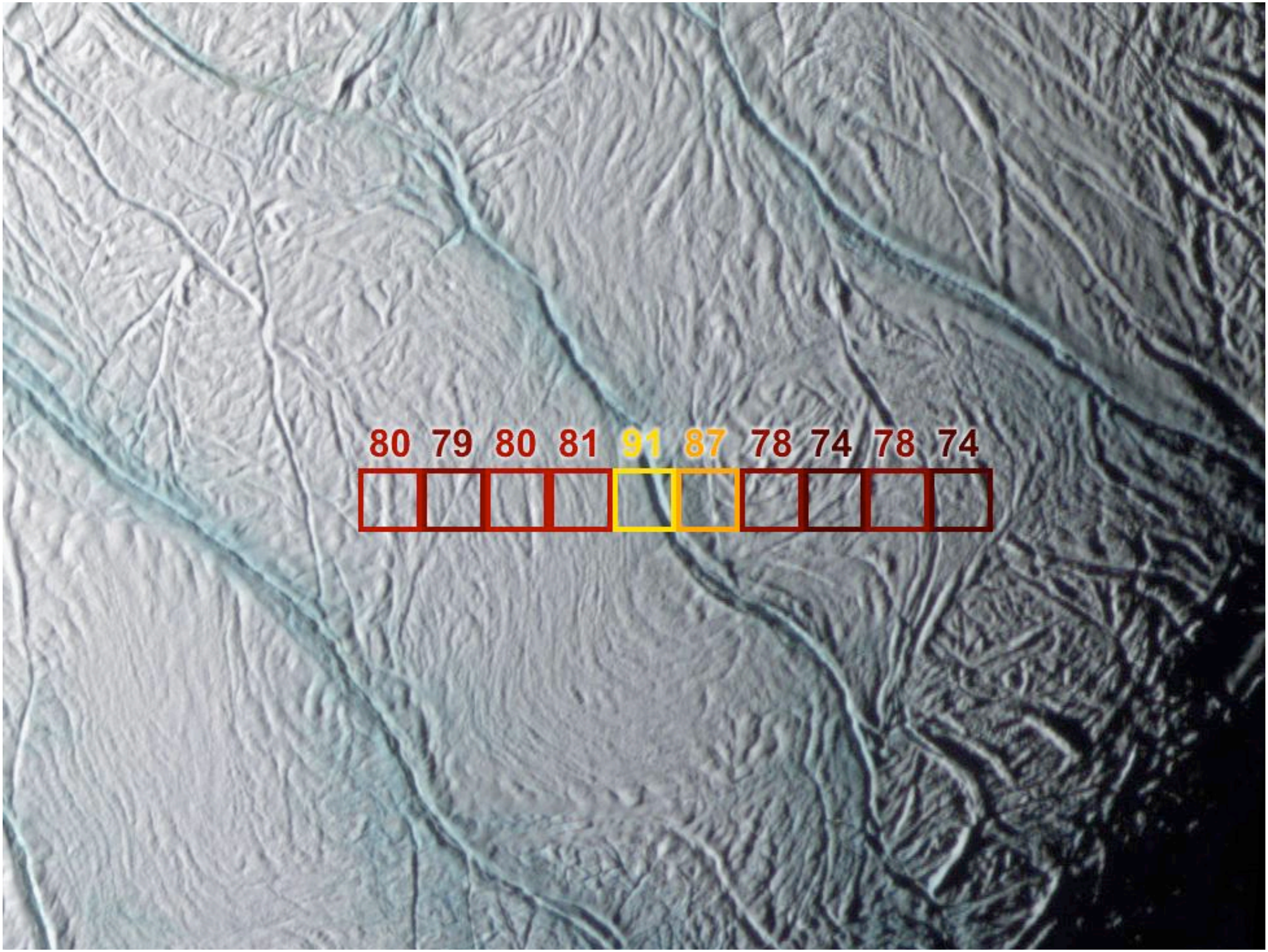
Spencer et al. (2006)

High Resolution CIRS Observations

- Warm material concentrated along the tiger stripes
- Temperatures up to at least 145 K

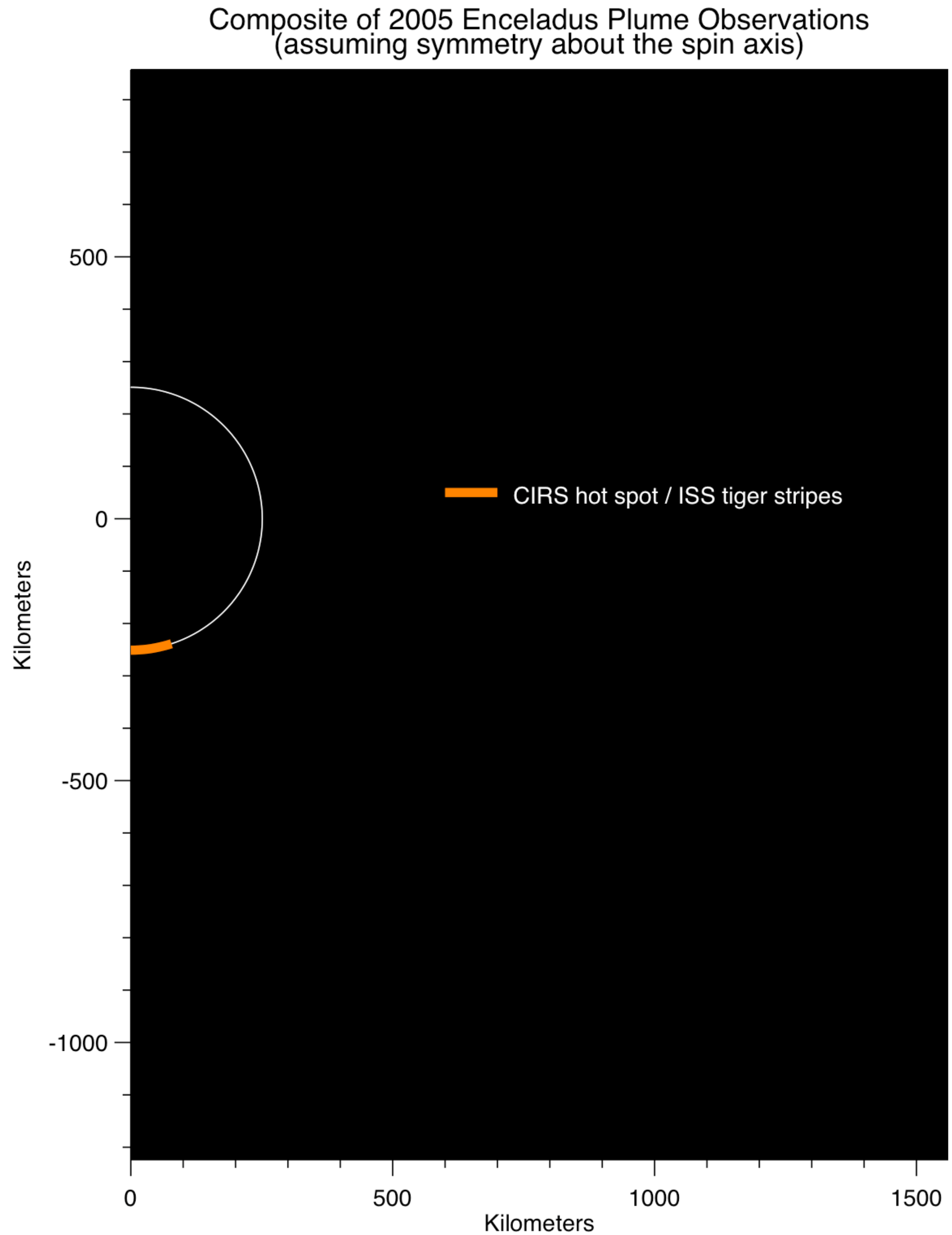
Spencer et al. (2006)




80 79 80 81 91 87 78 74 78 74

Putting Together the Big Picture

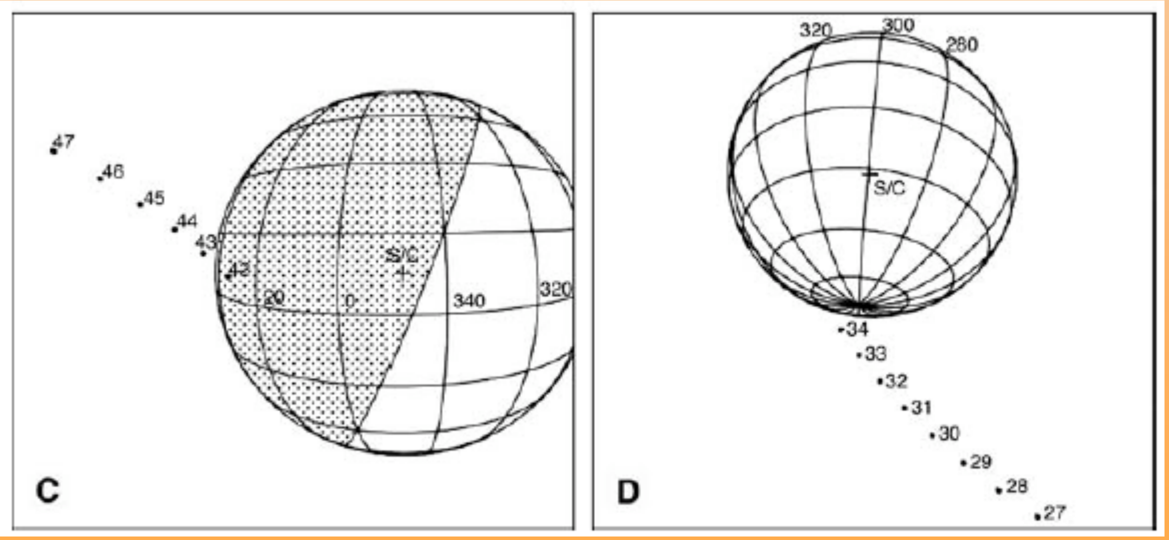
- Assume everything is symmetrical about the south pole

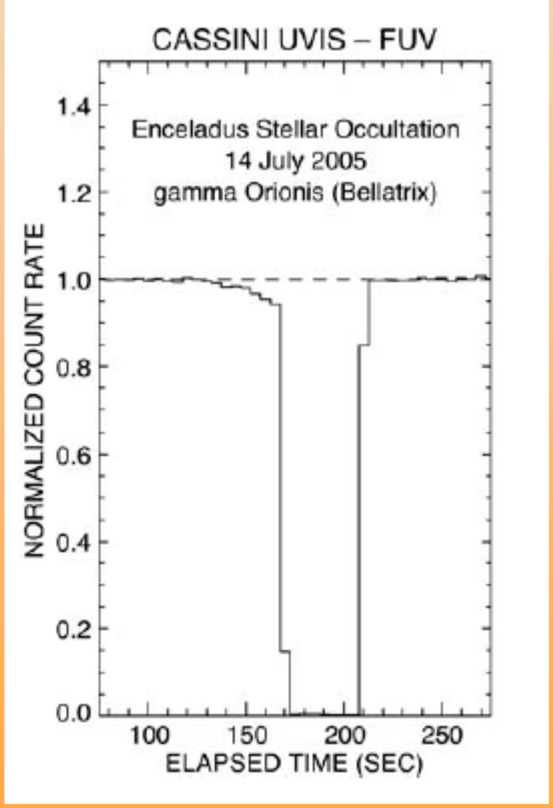


July 2005 UVIS Stellar Occultation

Hansen et al. (2006):

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

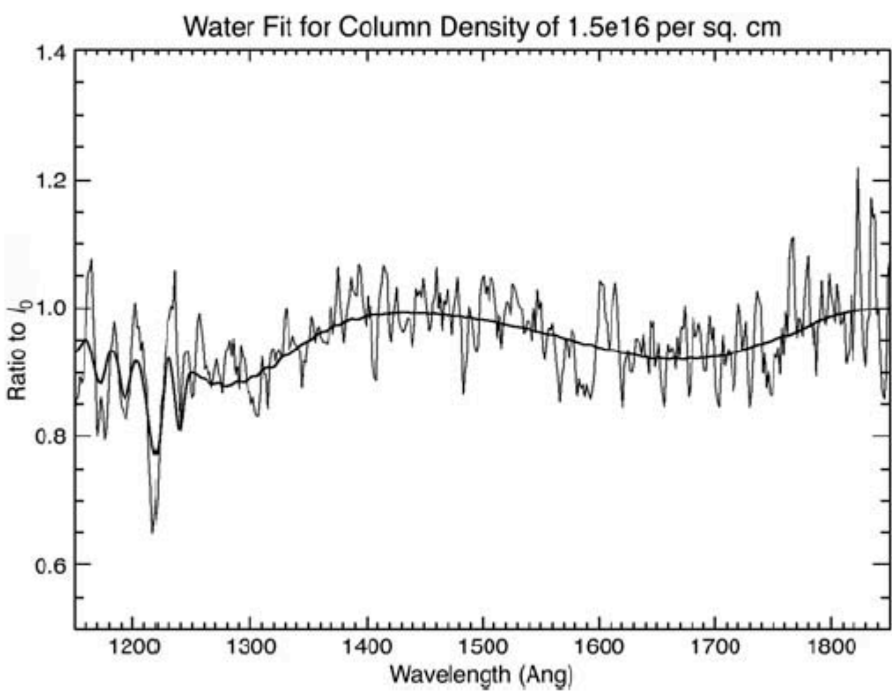


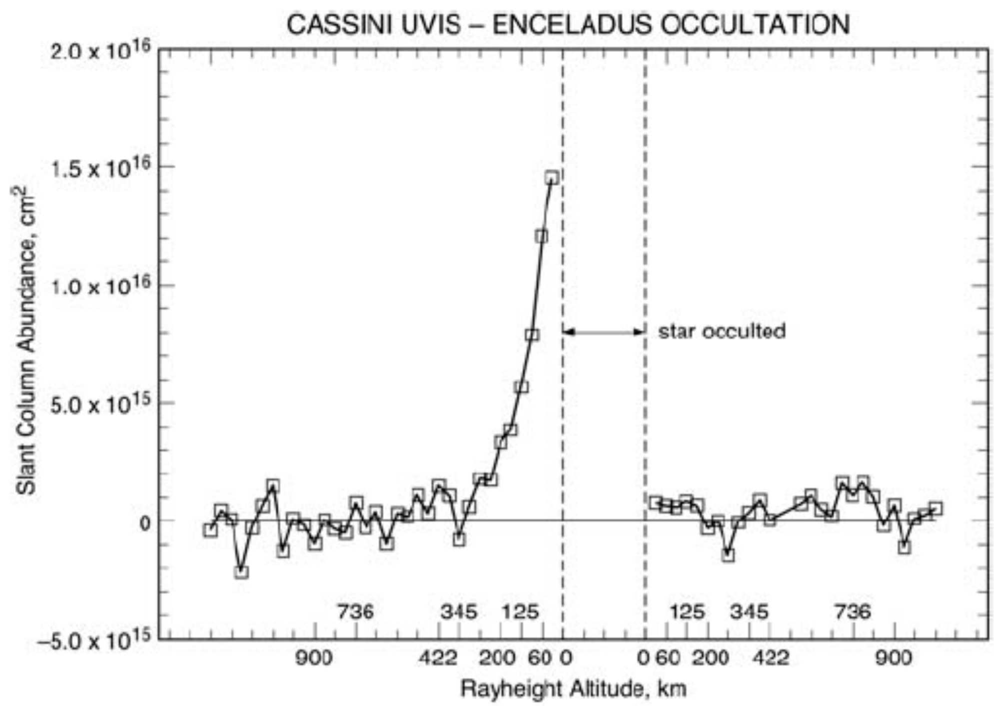


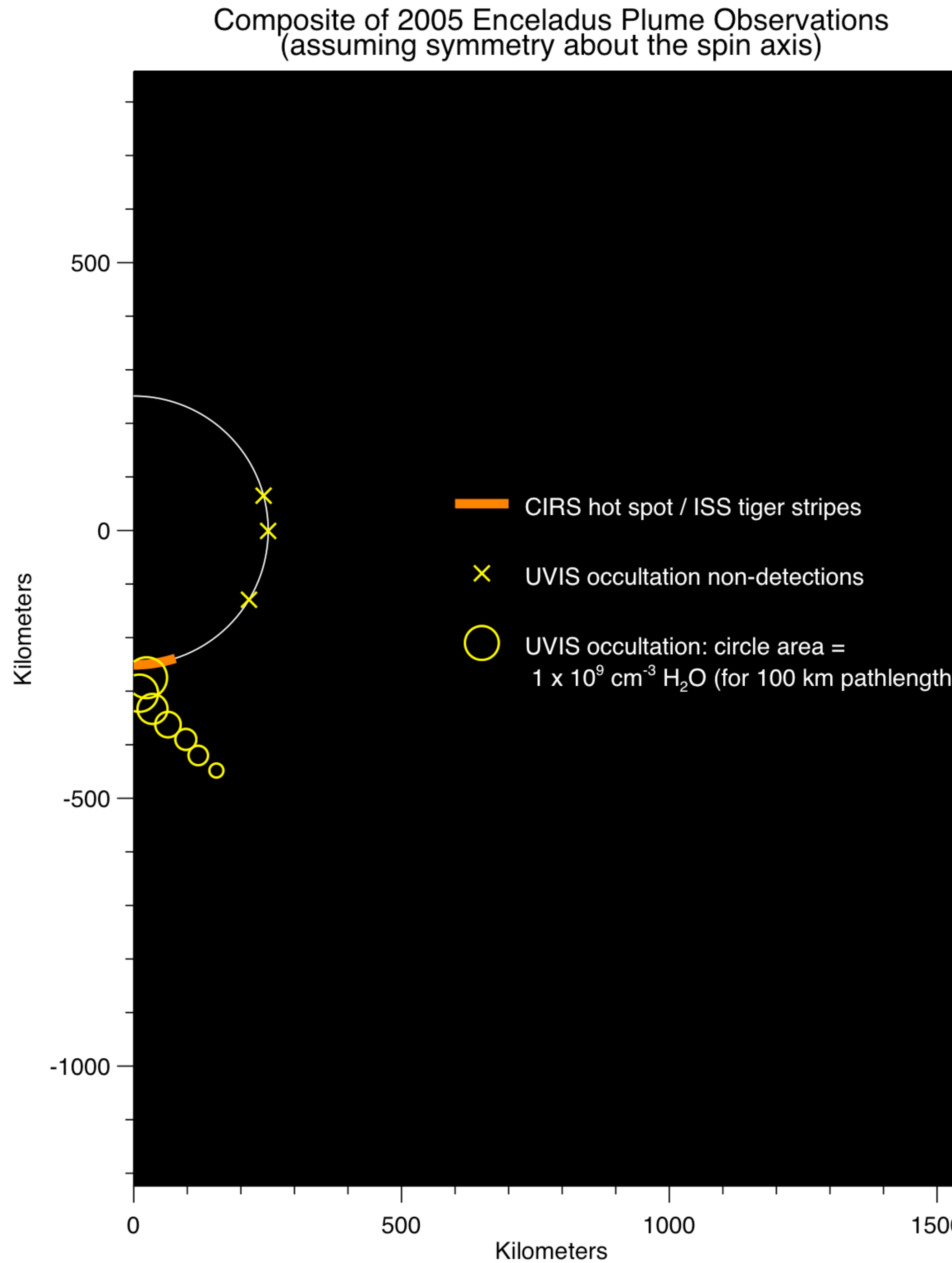
UVIS Stellar Occultation, contd.

- 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)







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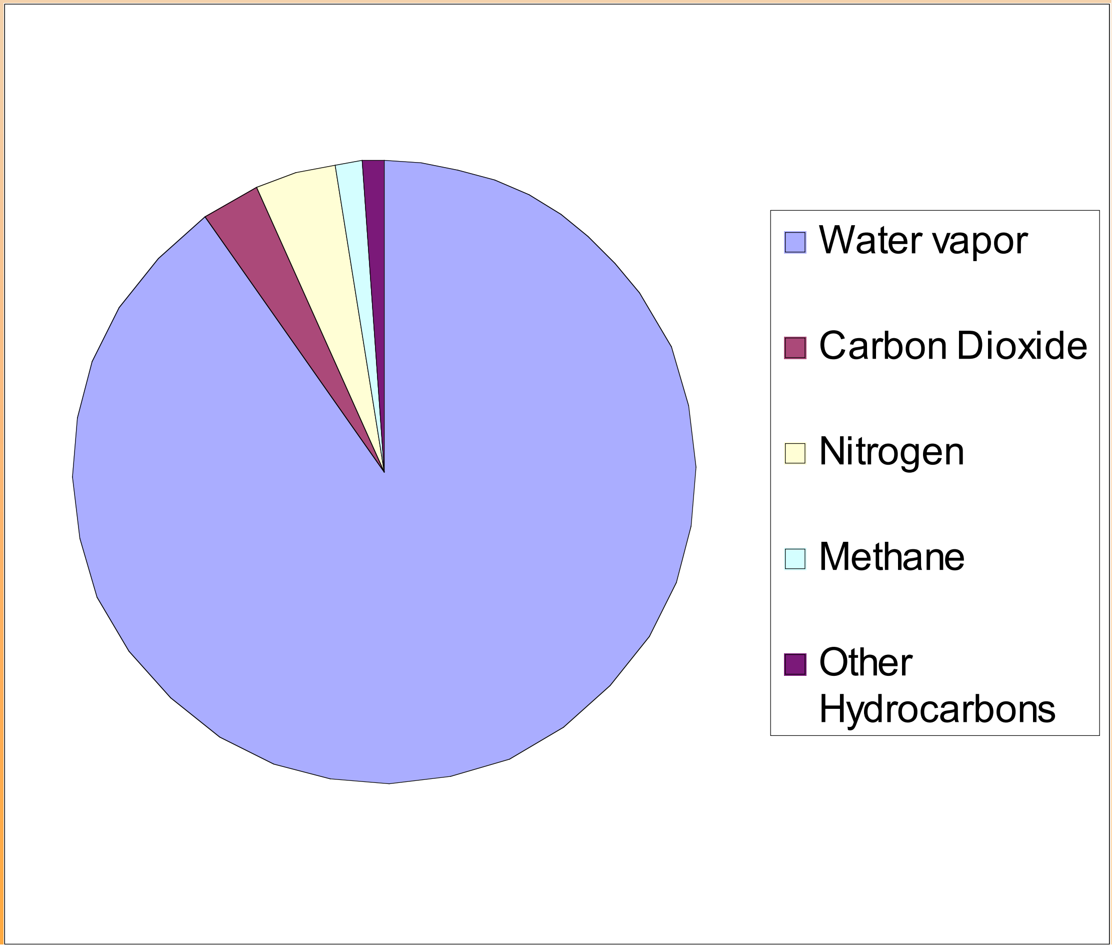
July 2005 INMS Observations

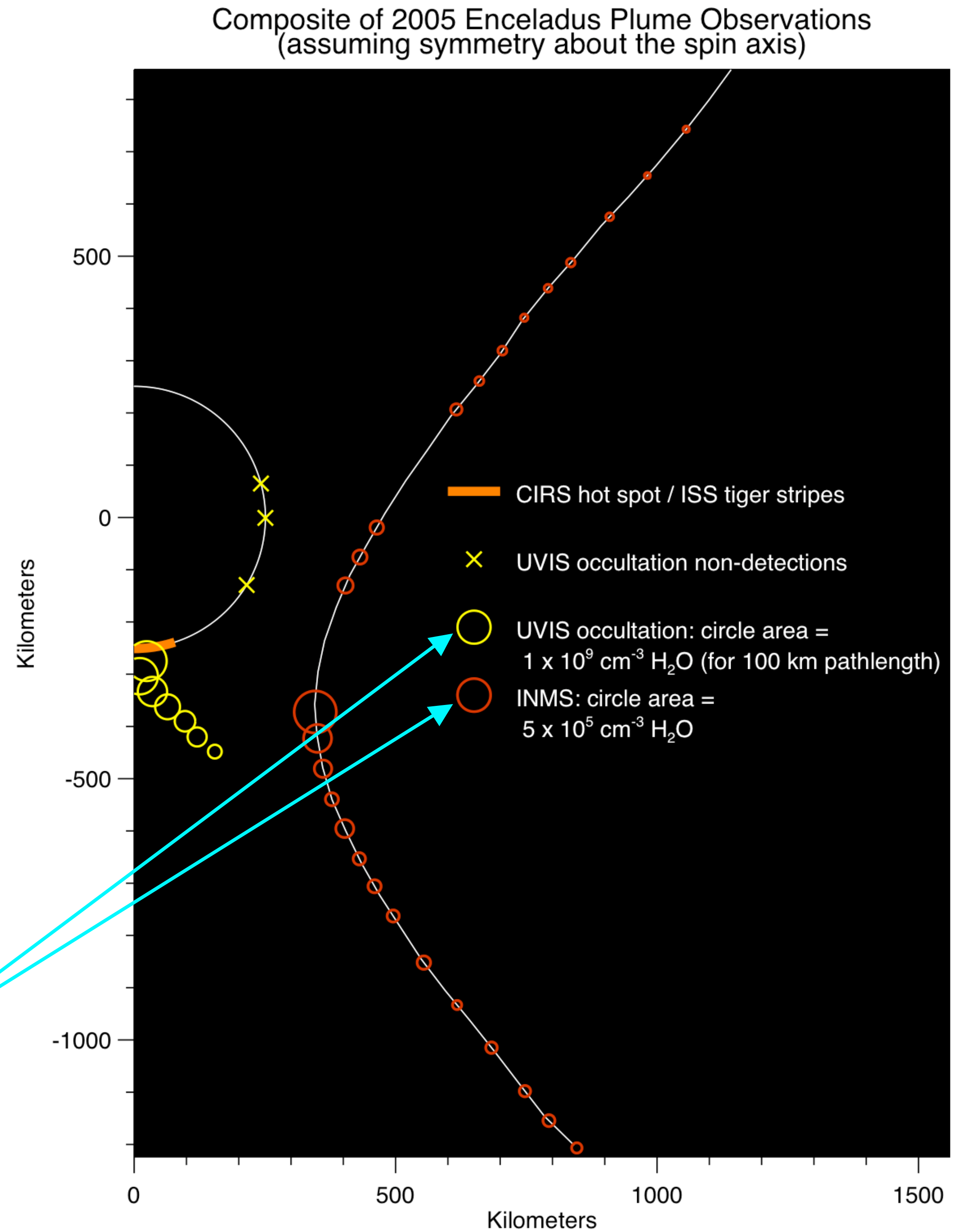
Ion & Neutral Mass Spectrometer: *in situ* measurements of the gas cloud (Waite et al. 2006)

- Gas composition:
  - 91% H_2O, plus
  - CO_2
  - N_2
  - CH_4
  - C_2H_2, C_3H_8 ??
- Ammonia not seen…



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

2000x scale difference

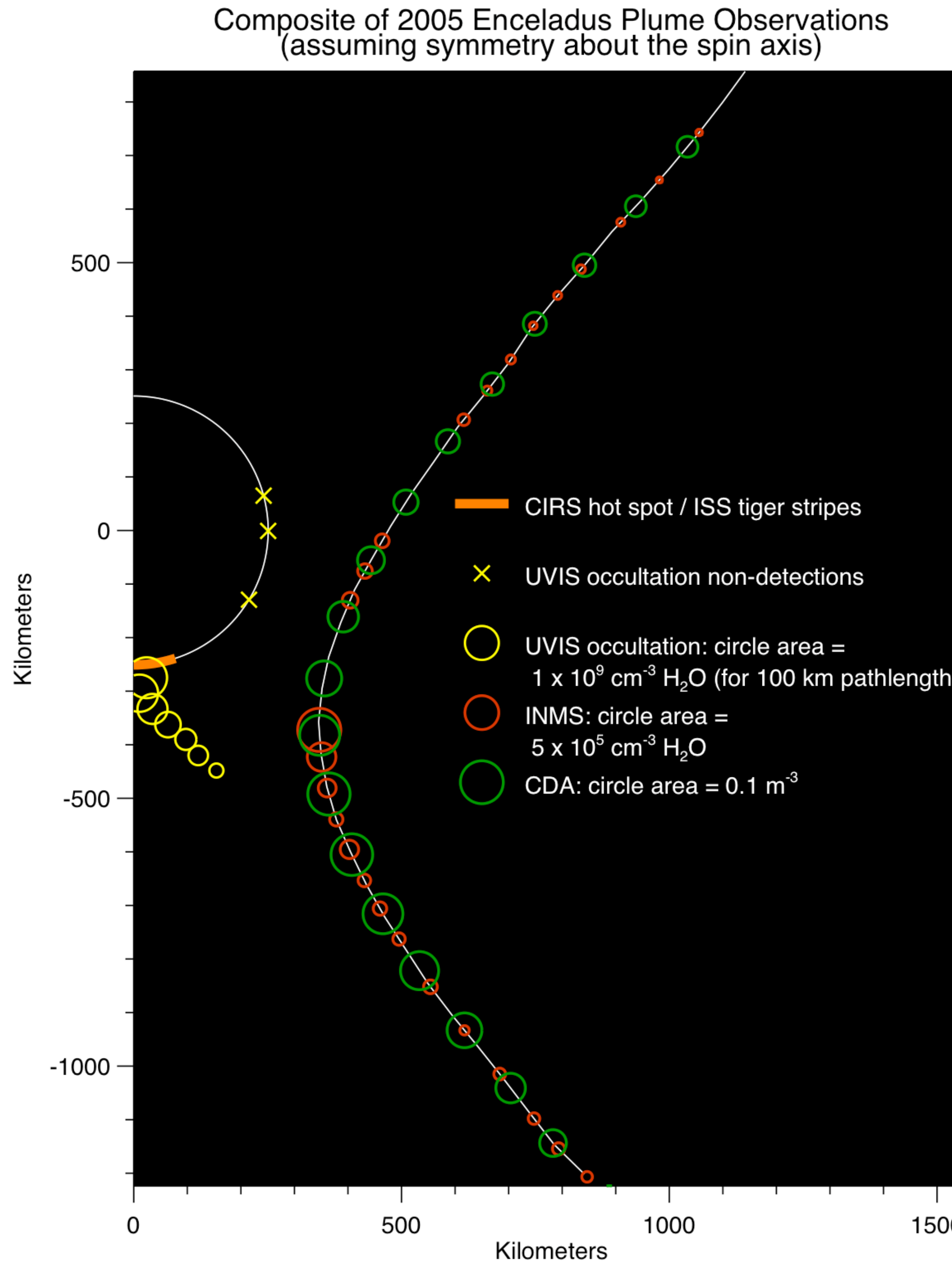


CDA Dust Observations

Cosmic Dust Analyzer: Spahn et al. (2006)

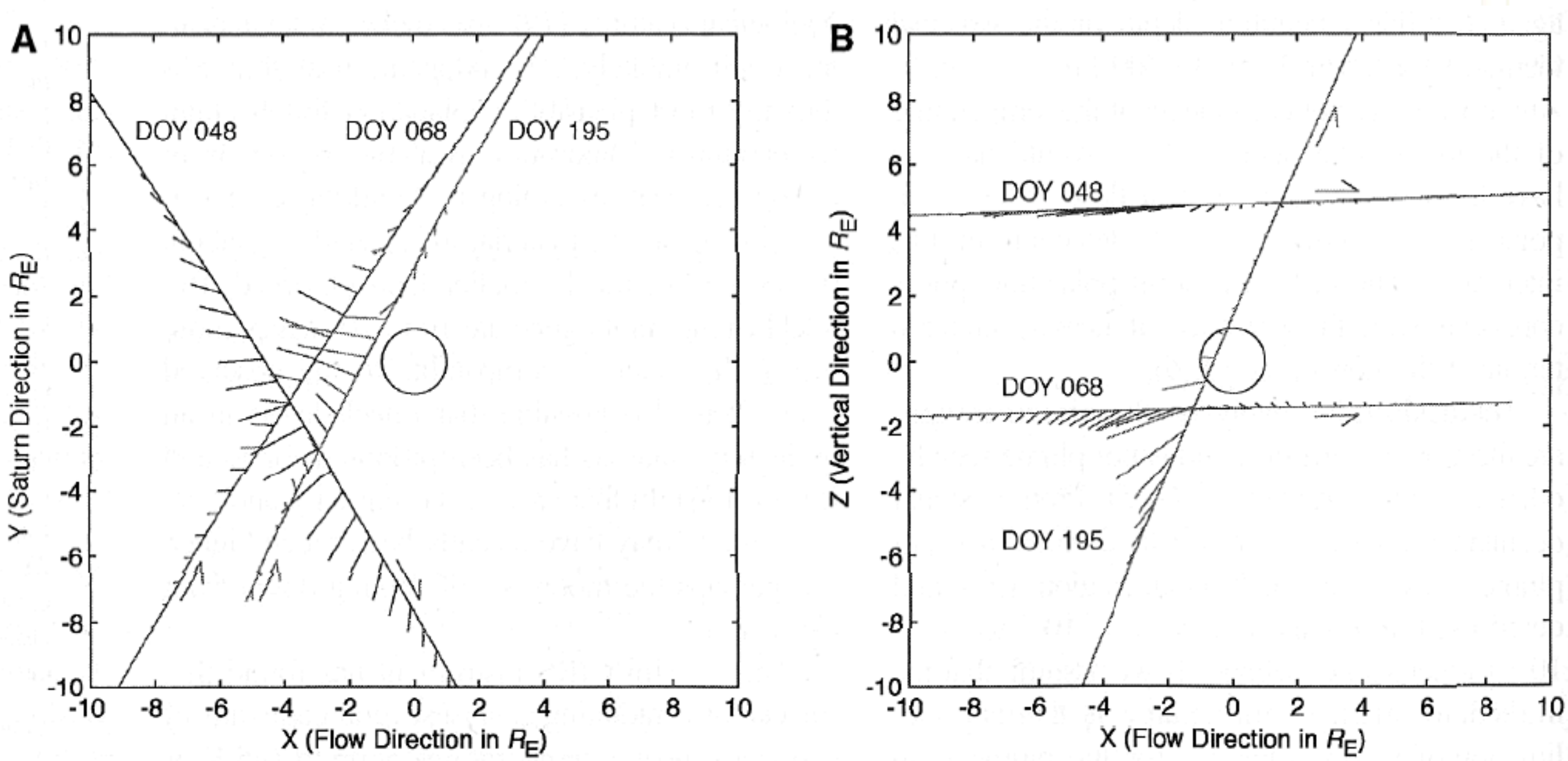
- Peak dust ~1 minute before C/A
- Modeled dust production rate > 0.2 kg s^{-1}
  - Could be much higher, depending on size distribution

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)

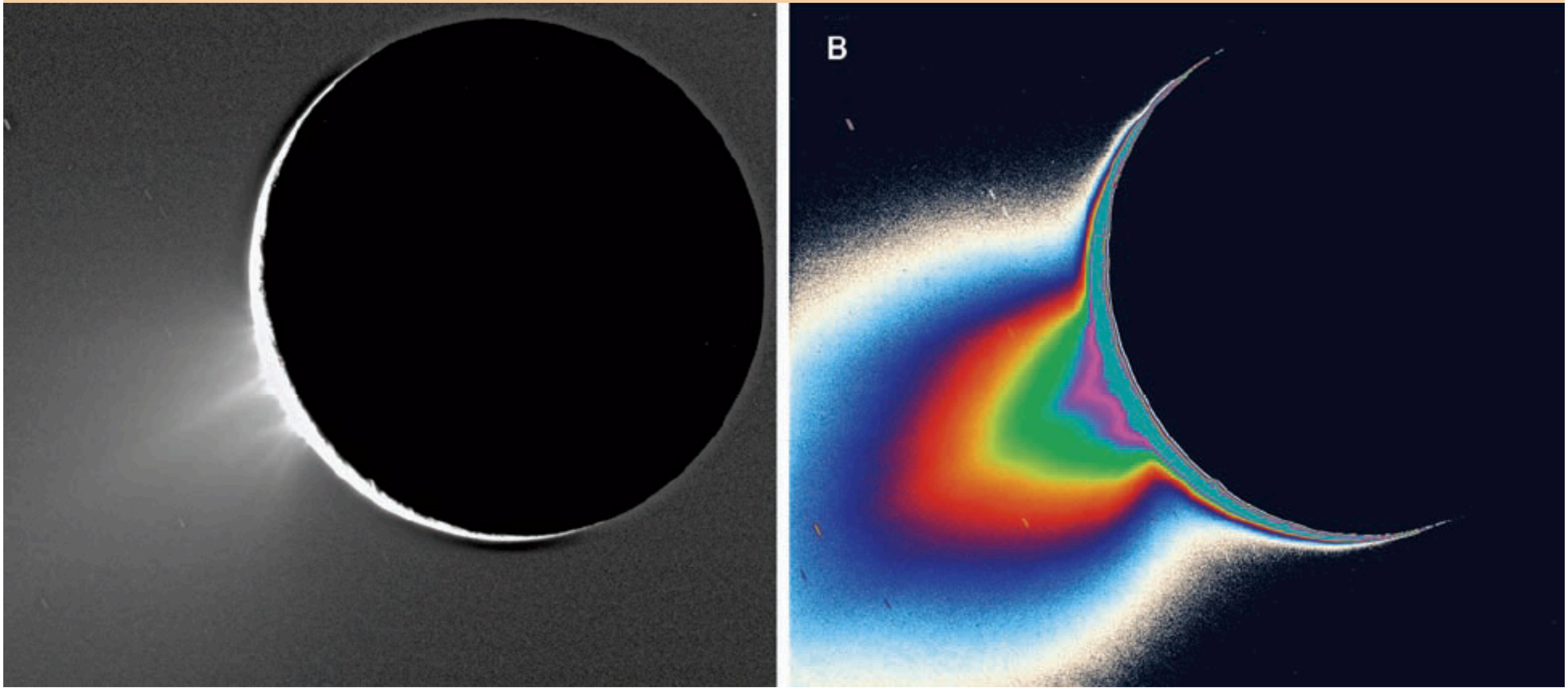


Cassini plume images

Higher-resolution images taken in November 2005

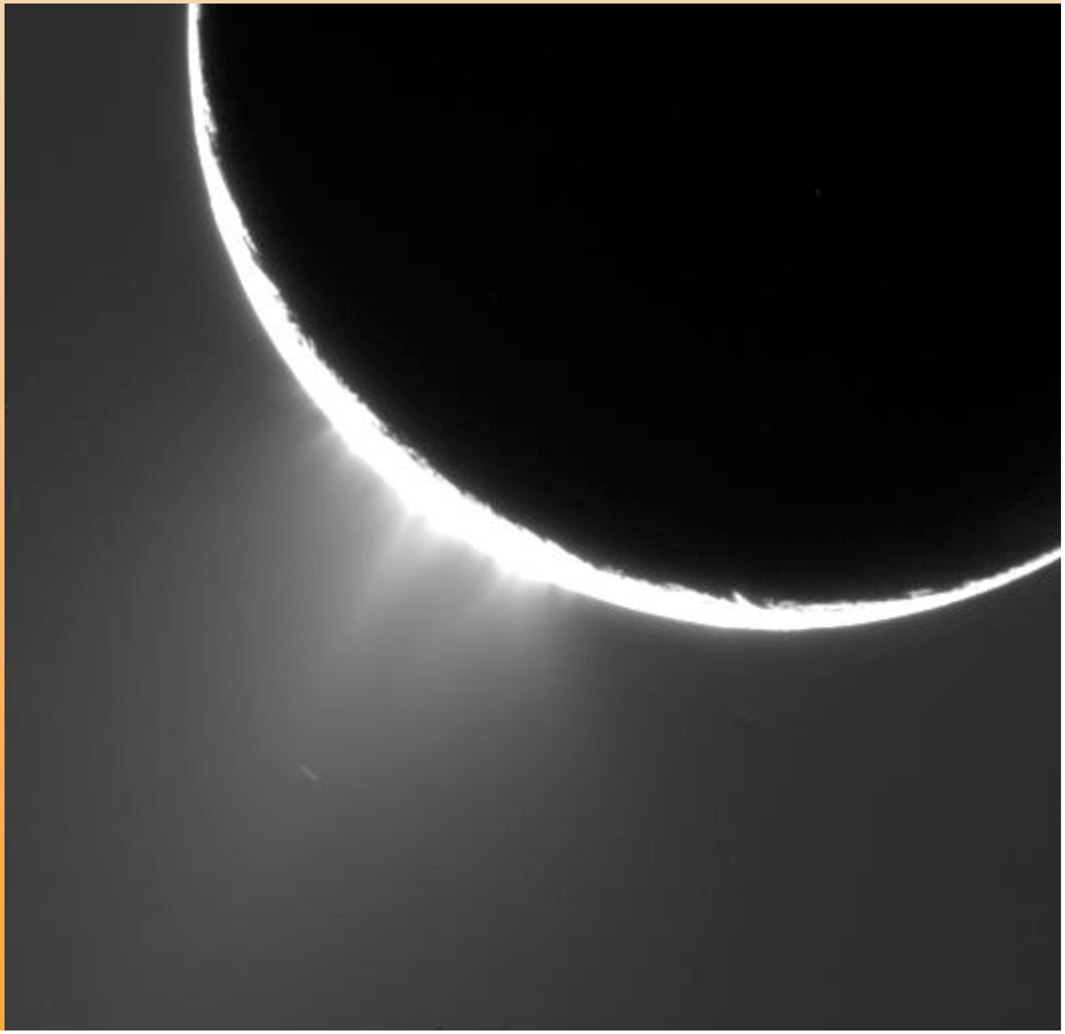
- Confirm reality of Feb., Mar. 2006 plume detection
- Multiple plume sources
- Source locations are consistent with the tiger stripes

Porco et al. (2006)

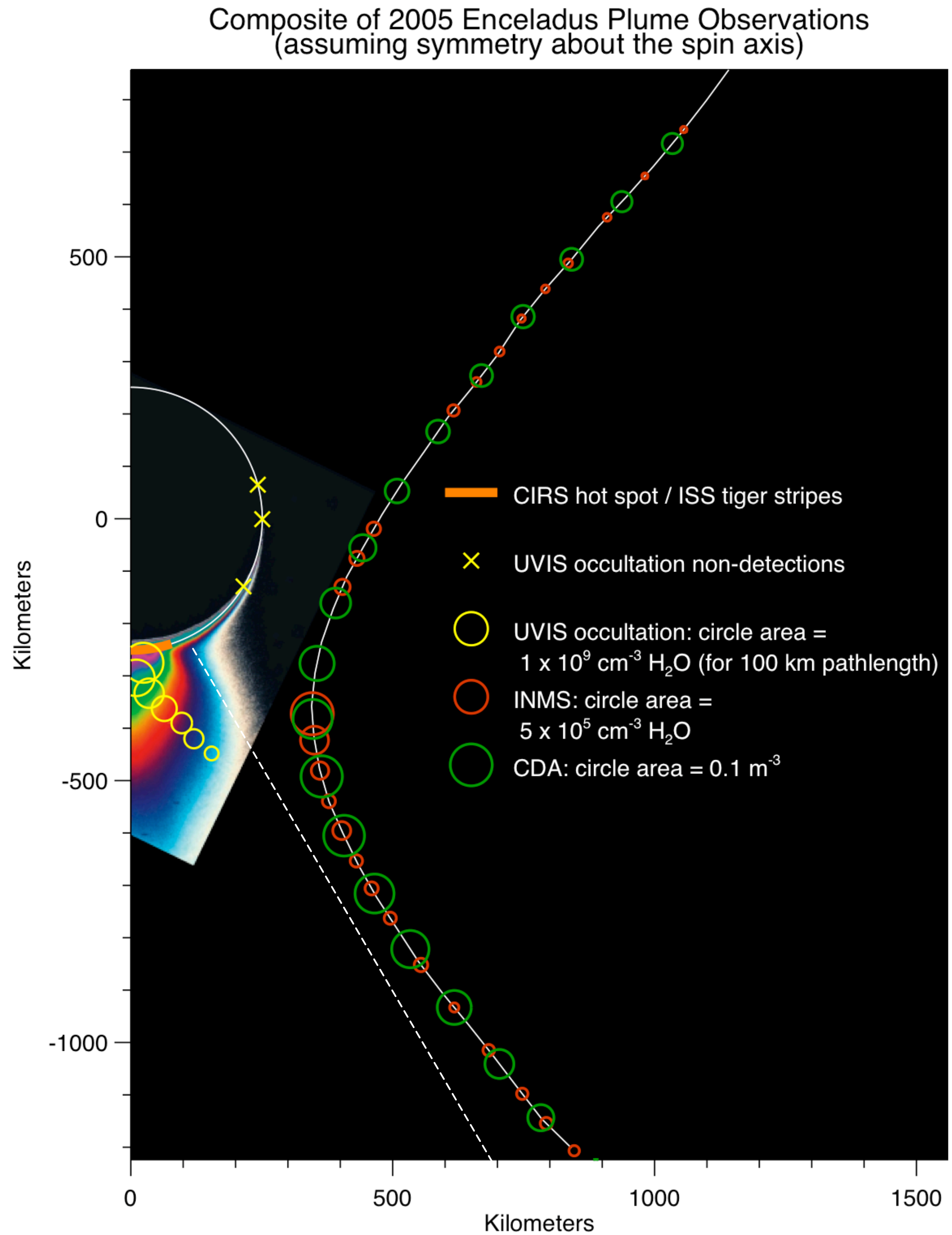


ISS Camera Plume Observations, contd.

- Dust concentrated near the surface:
  - Mean vertical speed ~ 60 m s^{-1}
    - Much less than escape velocity, 240 m s^{-1}
    - Much less than gas velocity
  - Most particles re-impact the surface!
  - ~1% of particles escape



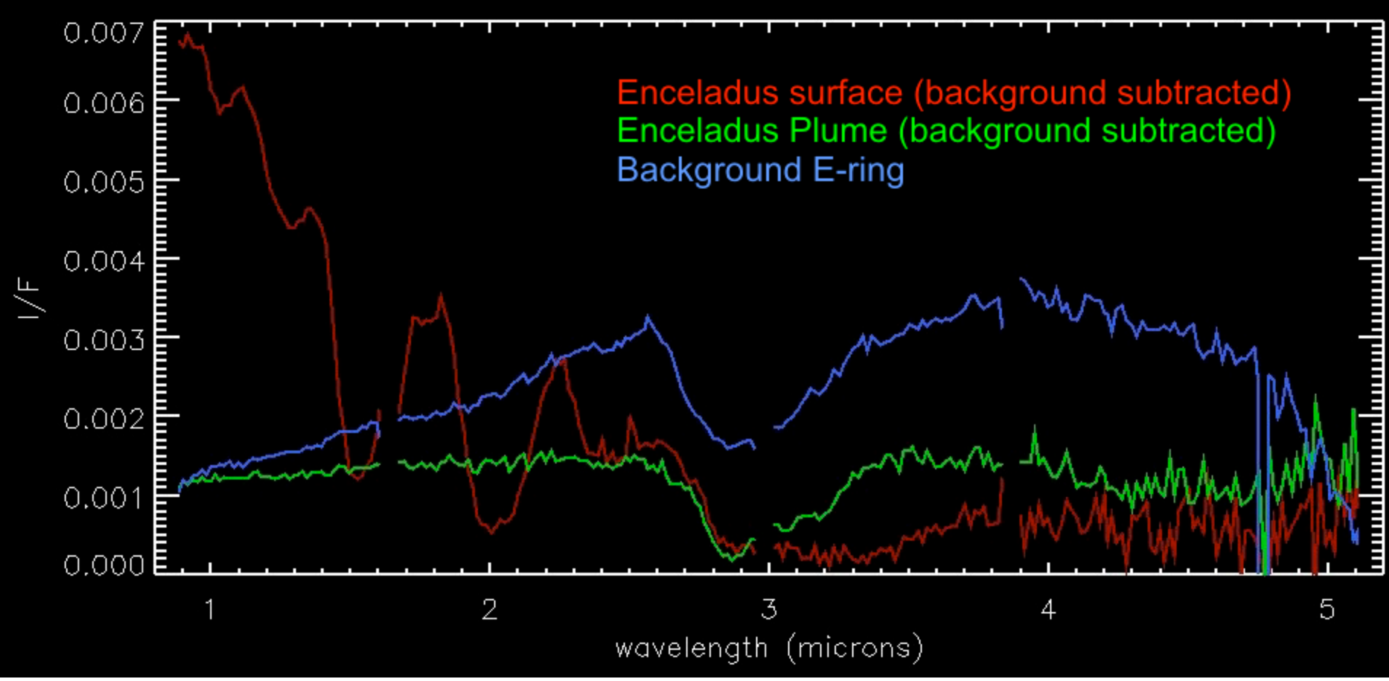
- Cassini trajectory skirted the edge of the plume seen by the Cassini cameras



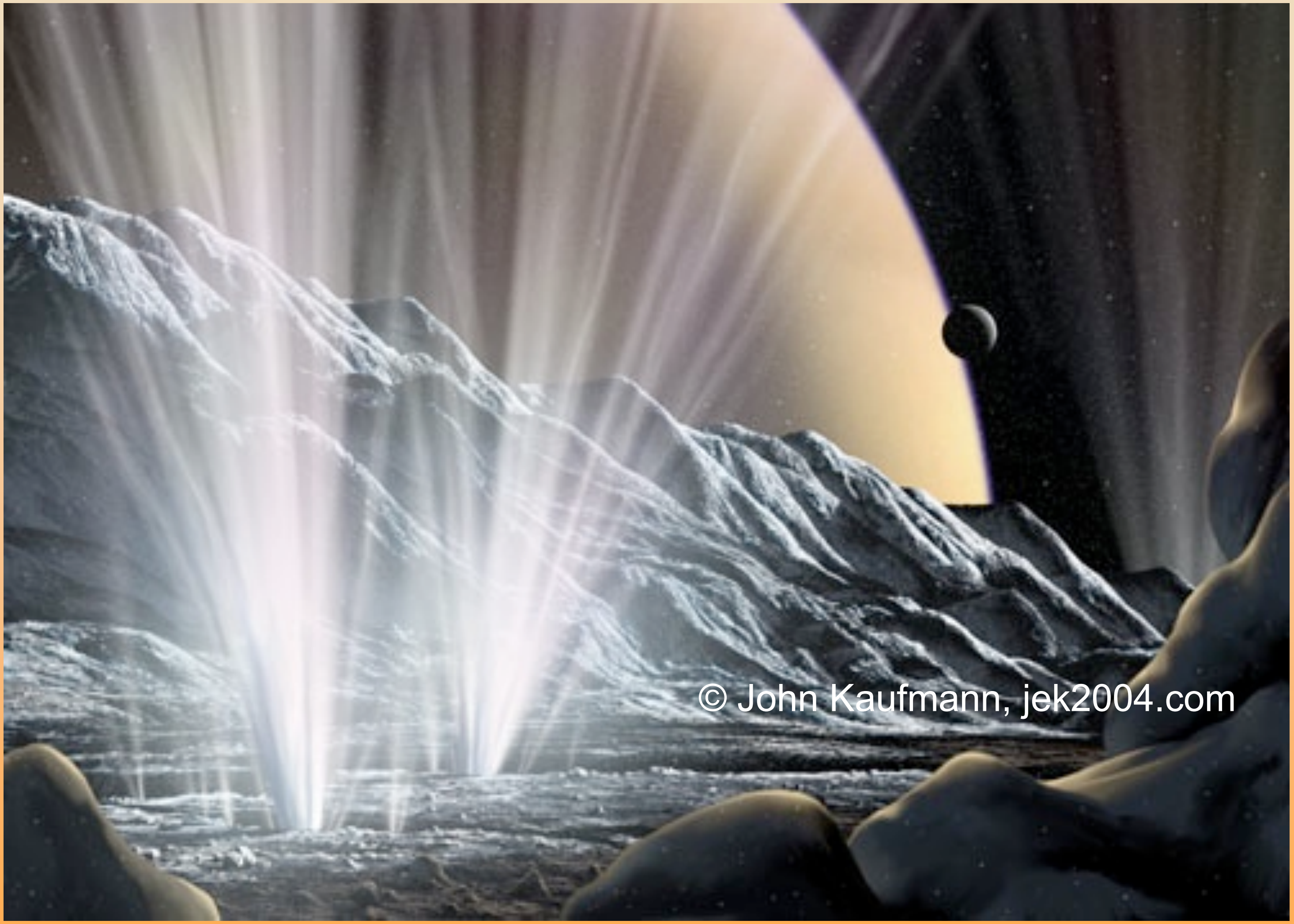
VIMS Plume Spectrum

Simultaneous with November ISS images

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



NASA/JPL/U. Arizona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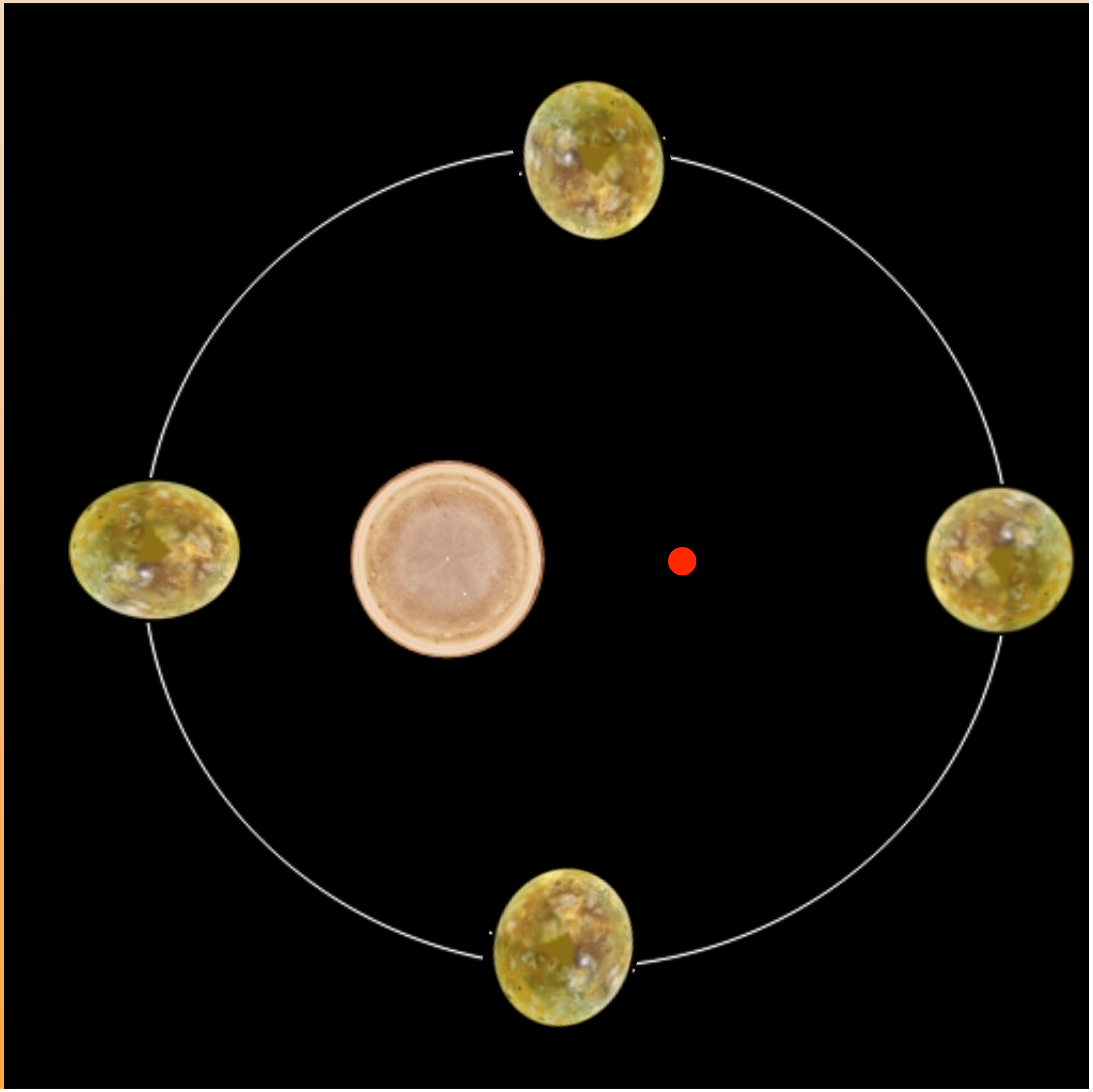
What’s Going On?

- Large amounts of heat and intense crustal deformation
  - What’s the power source?
- Jets of gas and ice emerging from south polar fractures
  - What’s the jet source?
- Why only at the south pole?
- Why only on Enceladus?

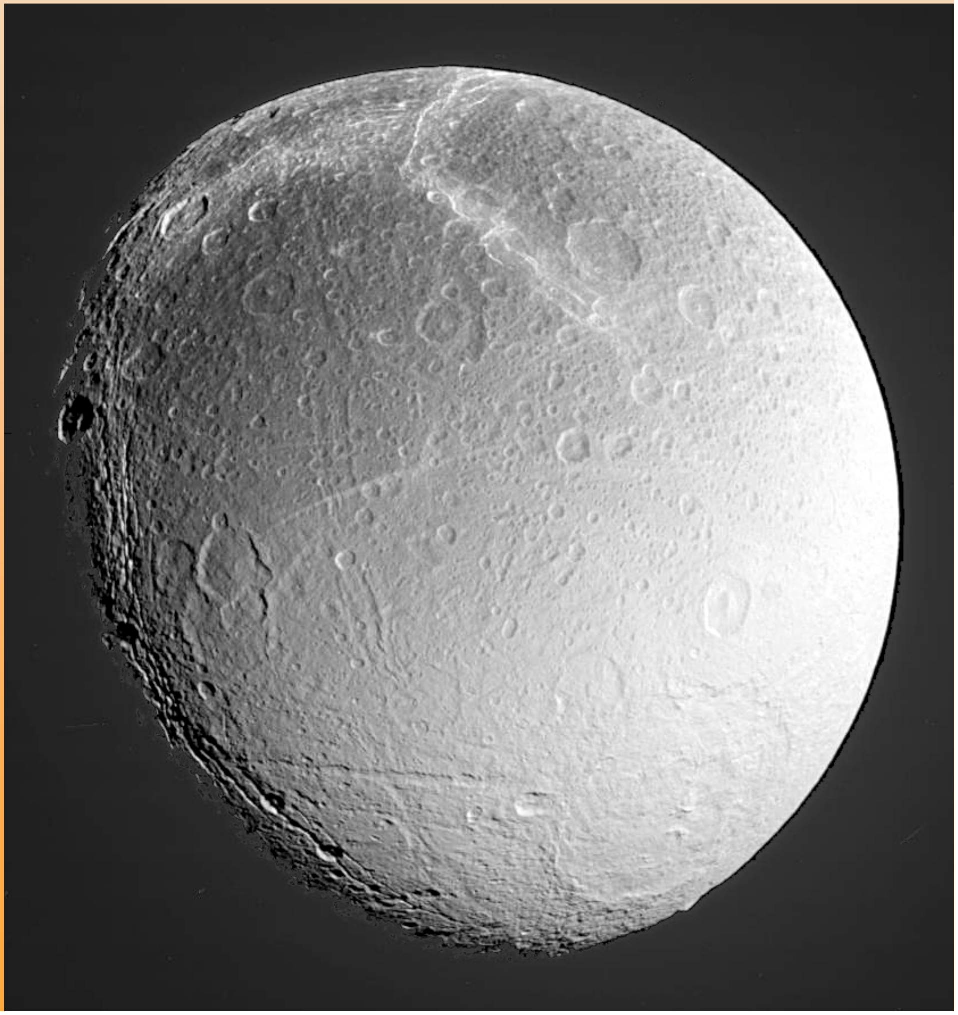
Tidal Heating

- Satellite in eccentric orbit
- Tidal bulge is larger when closer to primary
- Apparent direction of primary varies around the orbit (satellite faces empty focus of ellipse)
- Distortion generates frictional heat
- Poster child: Io



Maintaining Eccentric Orbit?

- For Io, 2:1 orbital resonance with Europa
- For Enceladus, 2:1 resonance with Dione
  - Hints of activity on Dione too



Dione from Cassini

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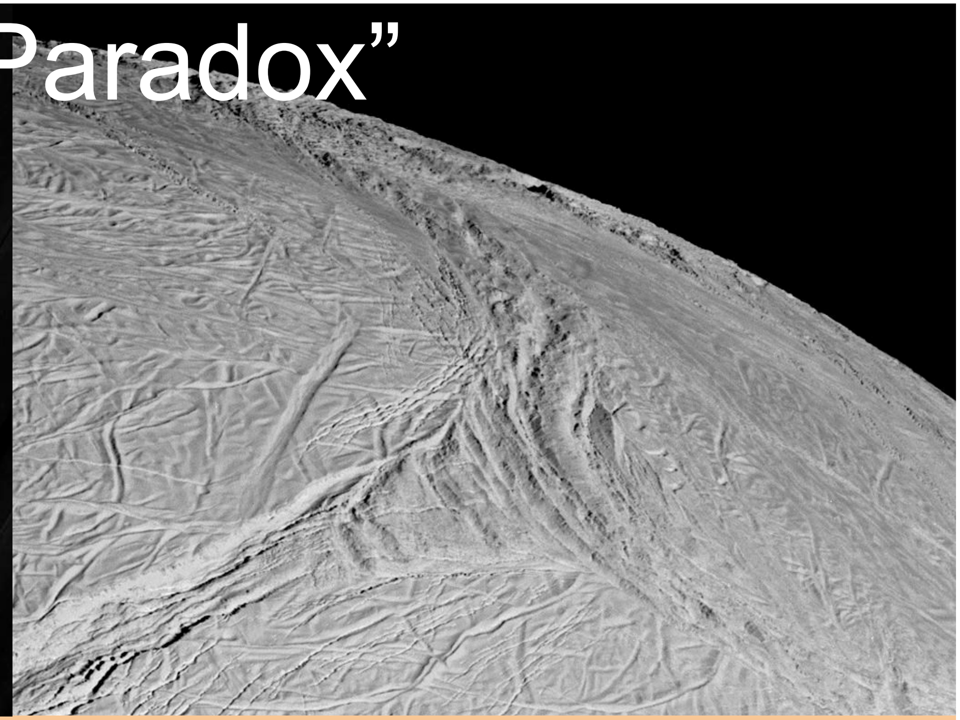
“Mimas Paradox”



- Mimas is closer to Saturn than Enceladus, and its orbit is much more eccentric
  - Should have 10x the tidal heating of Enceladus
- But, Mimas’ ancient surface shows no sign of tidal heating
- Bistable tidal heating?
  - Enceladus is warm, soft, readily distorted by tides, stays warm.
  - Mimas is cold, rigid, stays cold.
- Need a way to “kick start” Enceladus initially
  - Aluminum 26 very early? (Matson et al. 2007)
  - “Normal” tidal heating plus insulation? (Schubert et al. 2007)

How Much Tidal Heat?

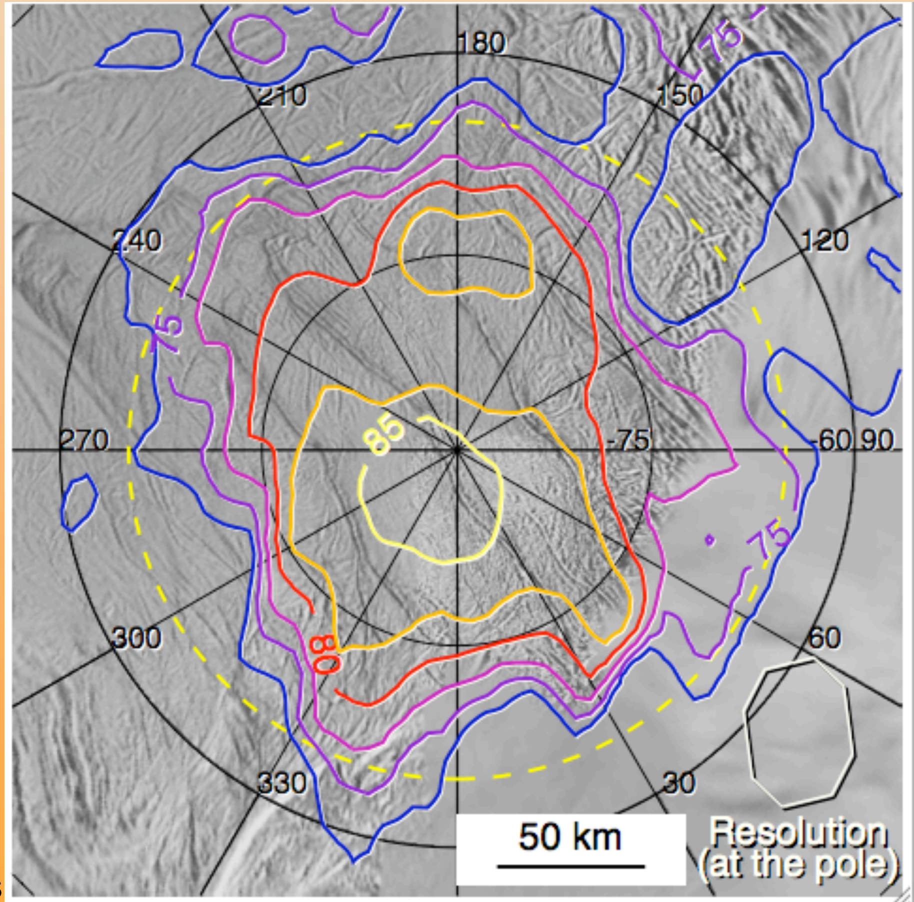
- Pre-Cassini estimates: 0.1 GW - 4 GW
- But orbit stability implies < 1 GW of power if system is in equilibrium (Meyer and Wisdom 2007)
- Observed power at least ~6 GW!
  - Not in equilibrium?
  - Recent impact??
- Heating by spin/orbit resonance ("wobble") also possible?
  - But no wobble seen by Cassini

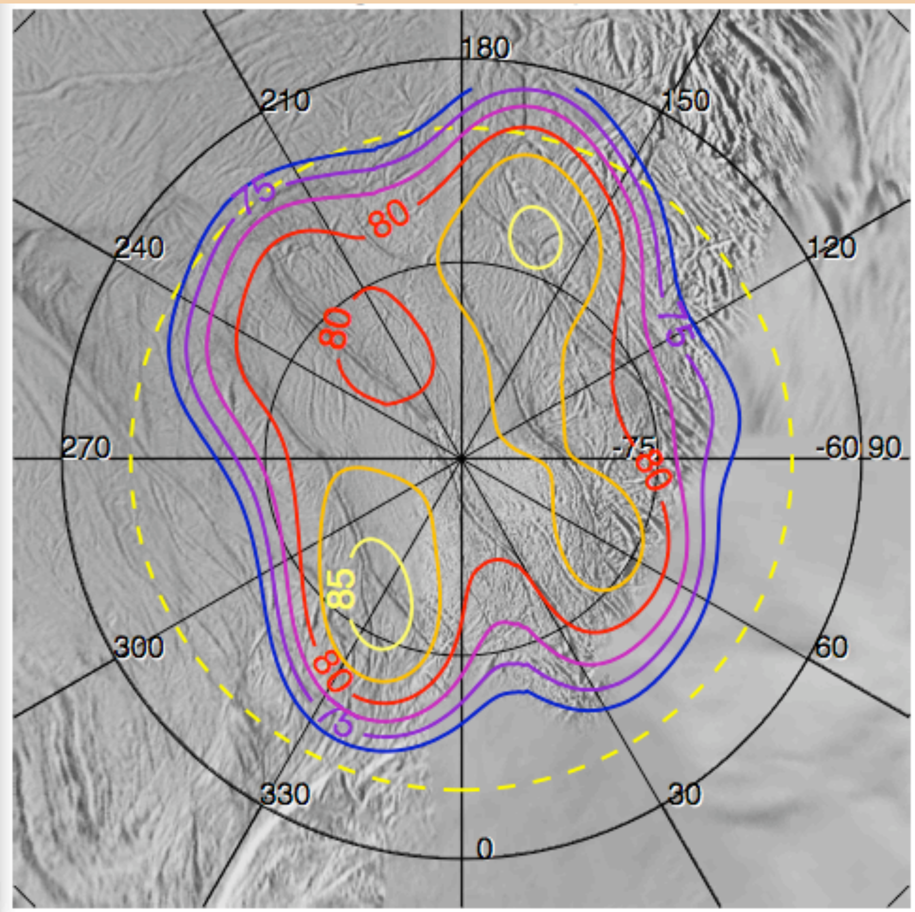
Plume Source?

- Boiling of near-surface liquid water ? (Porco et al. 2006)
  - Easy way to make ice particles
  - Why near-surface liquid?
- Warm vapor from frictionally-heated ice? (Nimmo et al. 2007)
  - Can give right numbers for heat flow, vapor production
  - Requires ocean at depth
- Decomposing clathrates? (Keiffer et al. 2007)
  - Explains other gases in the plume
  - Hard to explain water vapor
- Dense condensing vapor from deep H_2O reservoir? (Schmidt et al. 2008)
  - Explains number and speed of ice particles

Comparison to Observations

- E.g., Nimmo et al. (2007) shear heating model
- Polar stripe (Baghdad) is more active than predicted by this model





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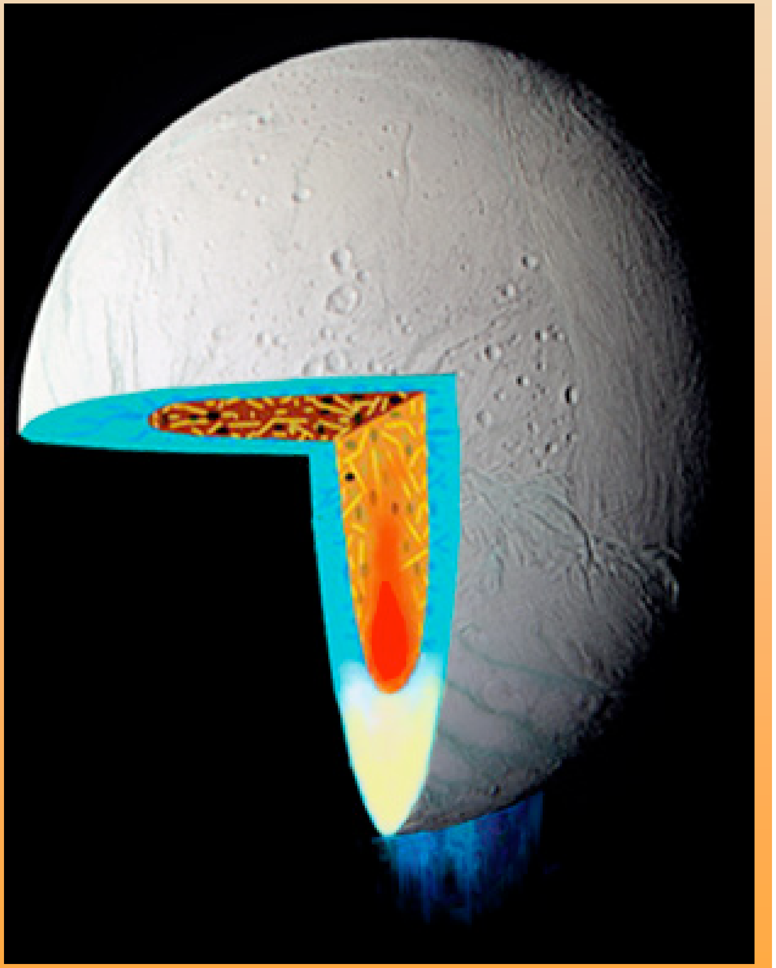
Why the South Pole?

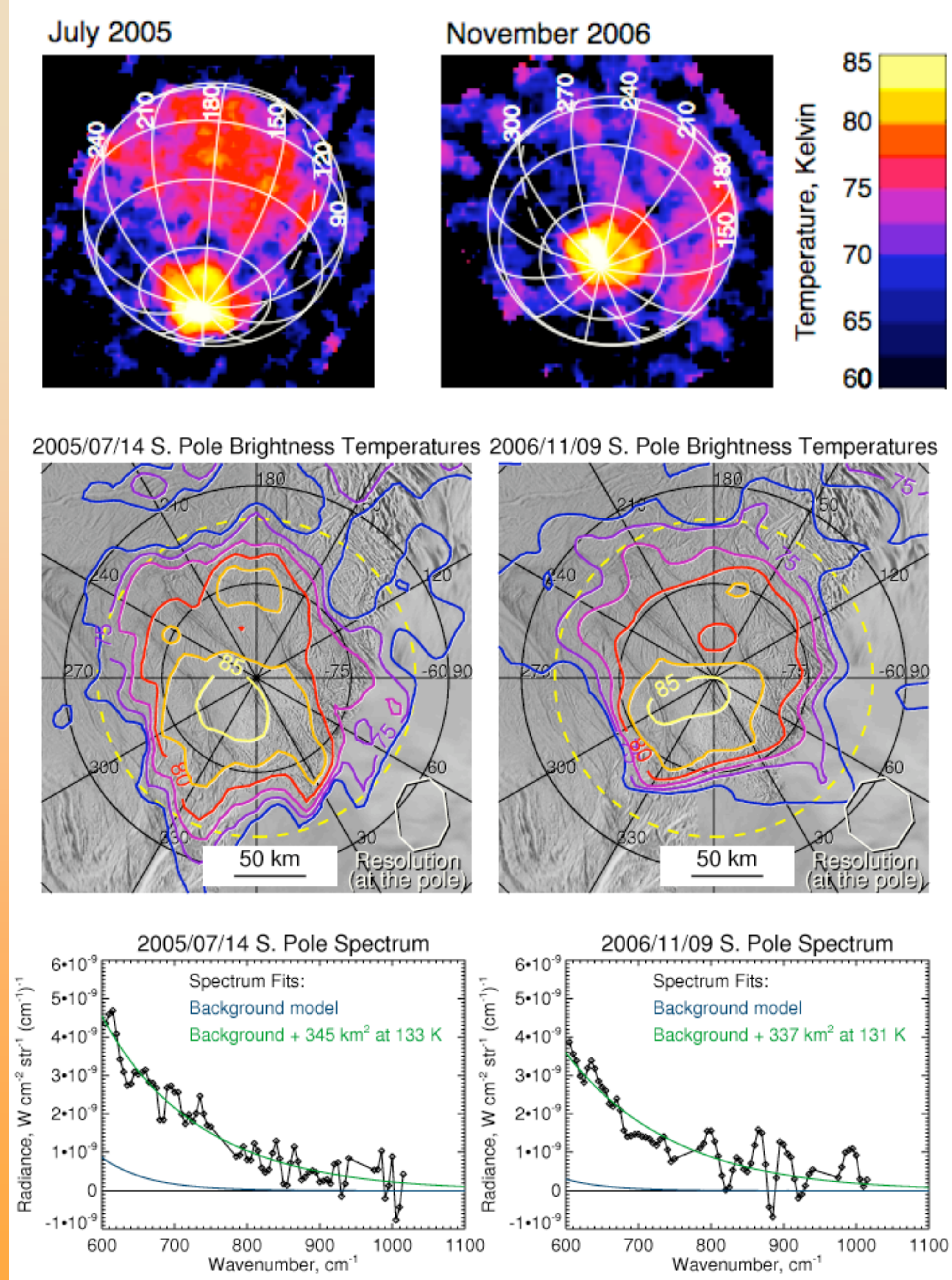
Nimmo and Pappalardo (2006)

- Low-density silicate or ice diapir can reorient Enceladus
- Resulting stresses may be consistent with the observed tectonic patterns
- Gravity anomaly might be detectable by Cassini?



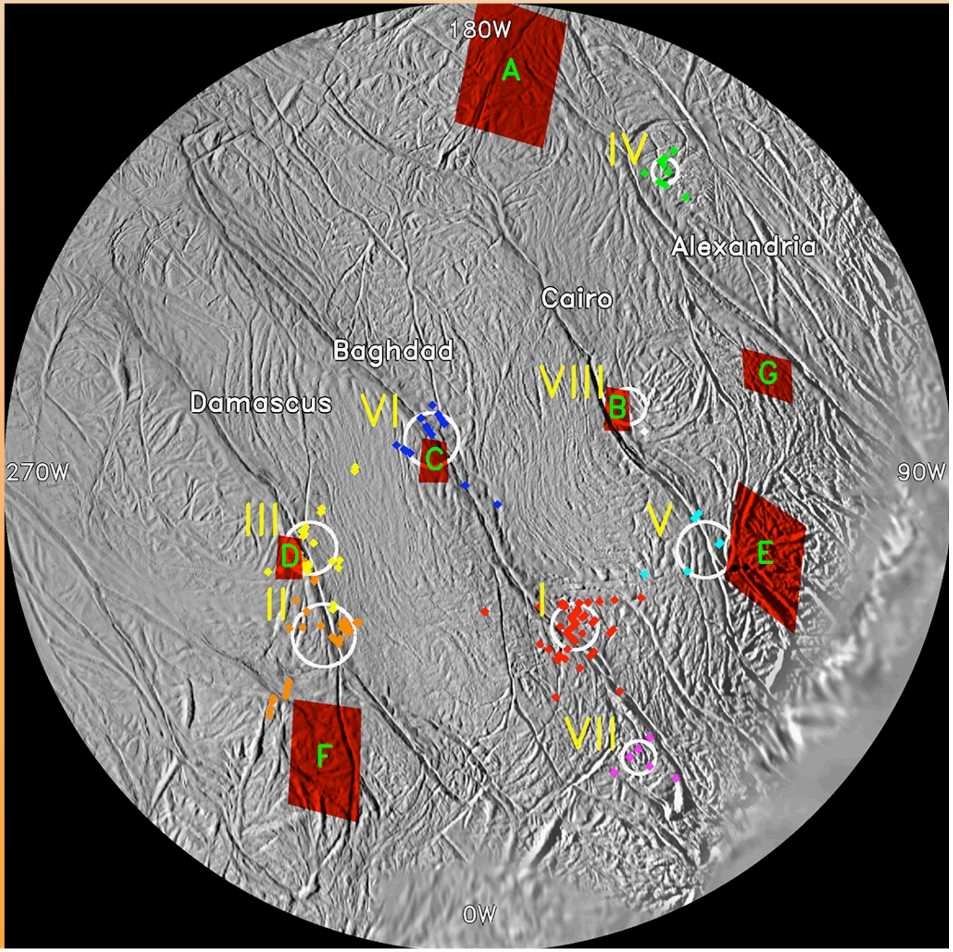
2006 CIRS Observations

- November 2006: first view of the south polar terrain since July 2005 (Abramov and Spencer 2008)
- Same power as 2005, despite more vertical view
    - Most hot material not in cracks?



More Plume Observations

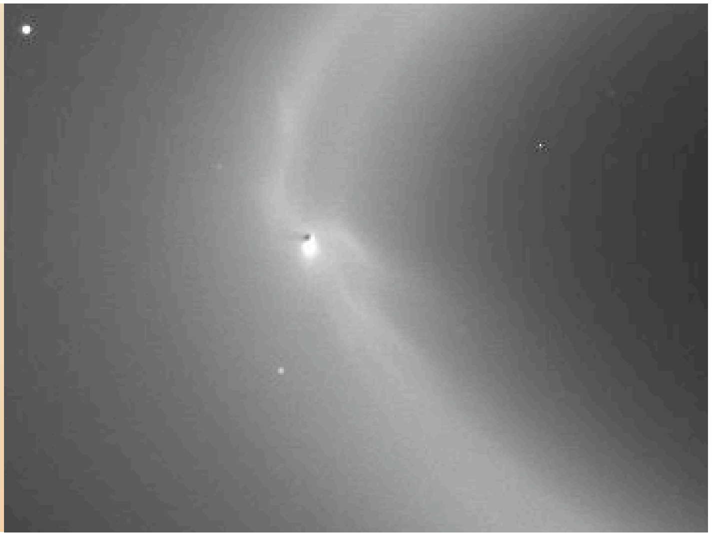
- Triangulation allows determination of plume source locations (Spitale and Porco 2007)
- Plume sources are along the tiger stripes
- Correlate with CIRS hot spots



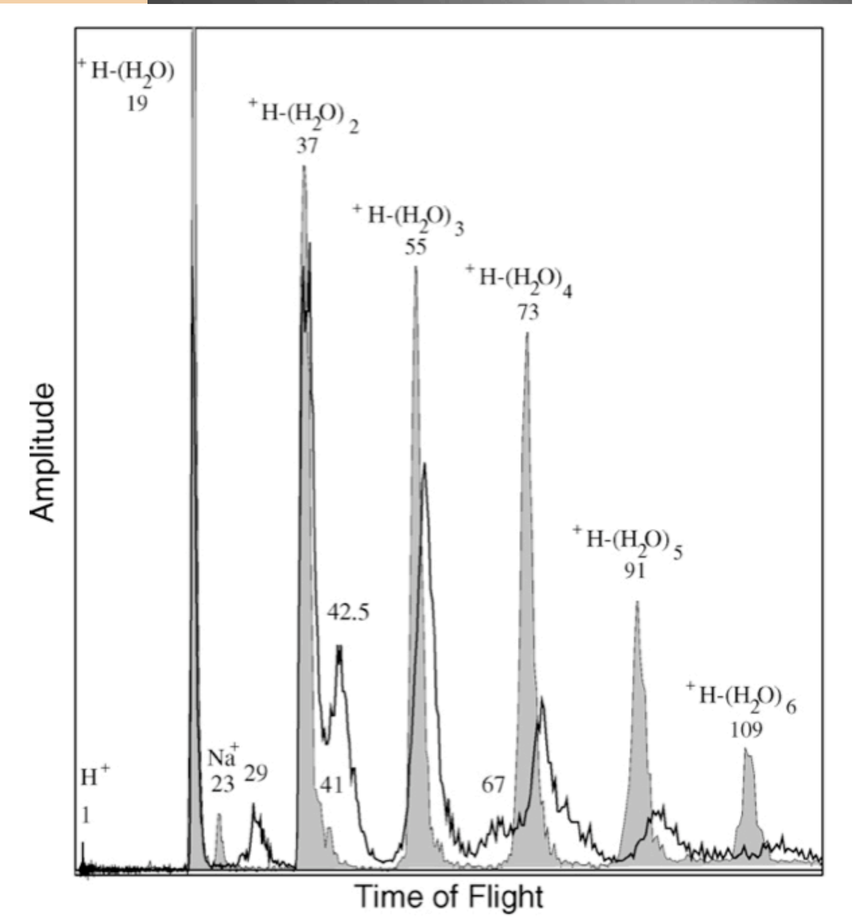
John Spencer,

September 2006 High-Phase Imaging

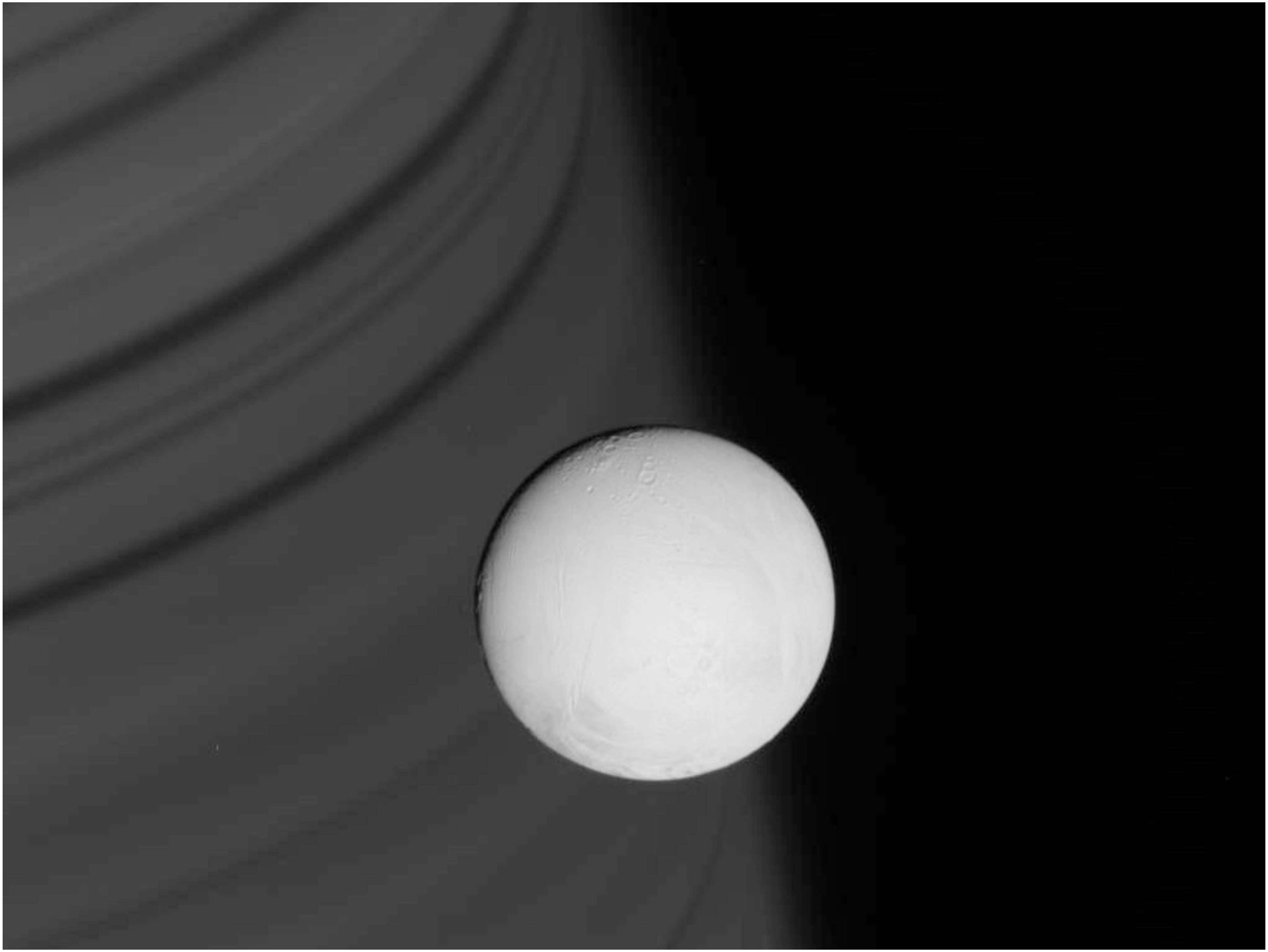
Sampling the E-Ring

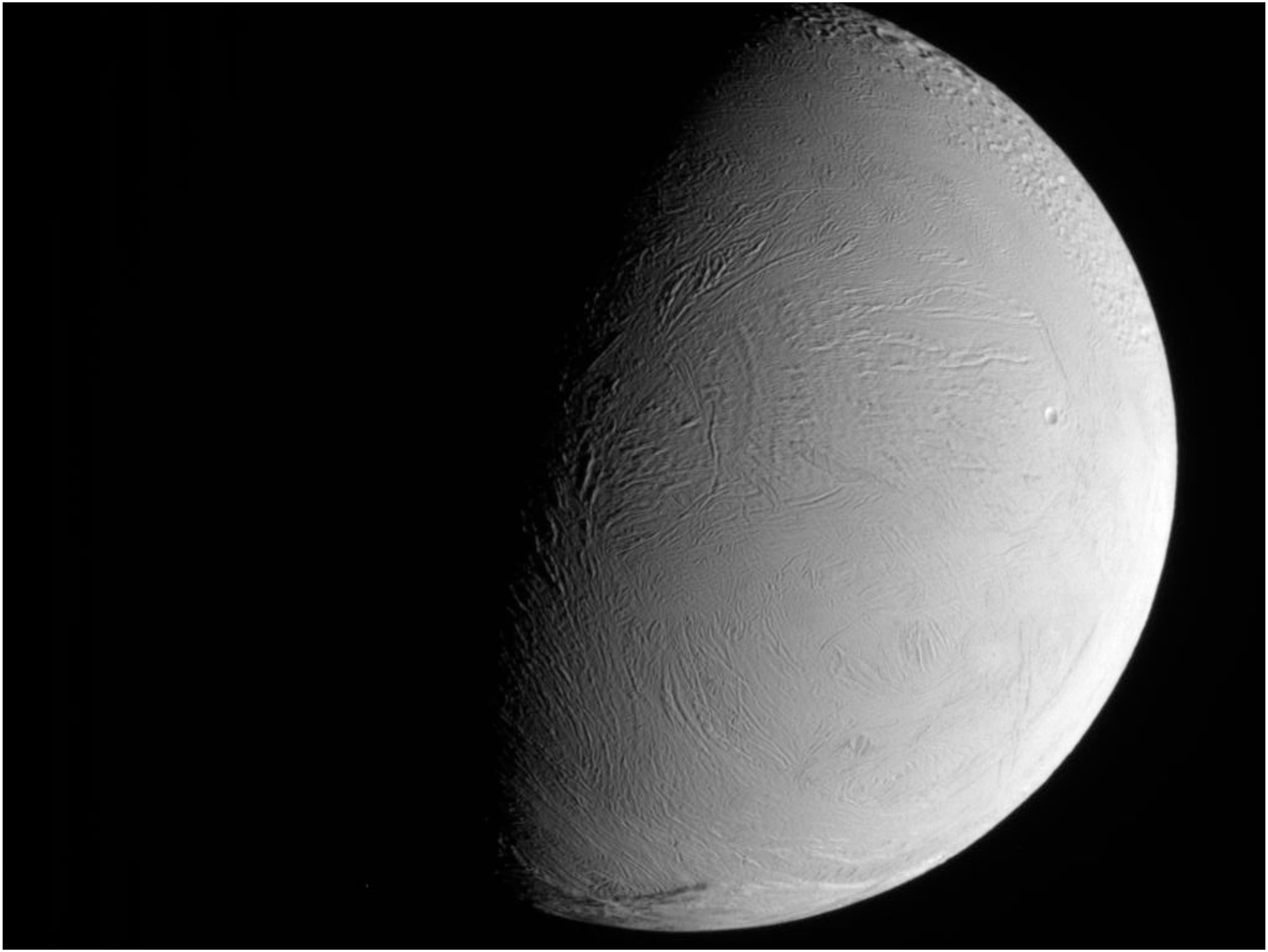


- CDA: Cassini dust analyzer (Postberg et al. 2008)
- Two main particle types
  - ~Pure ice
    - Knocked of Enceladus' surface?
  - Dirty ice
    - From the plumes?



John Spencer, JPL, Feb. 25 2008



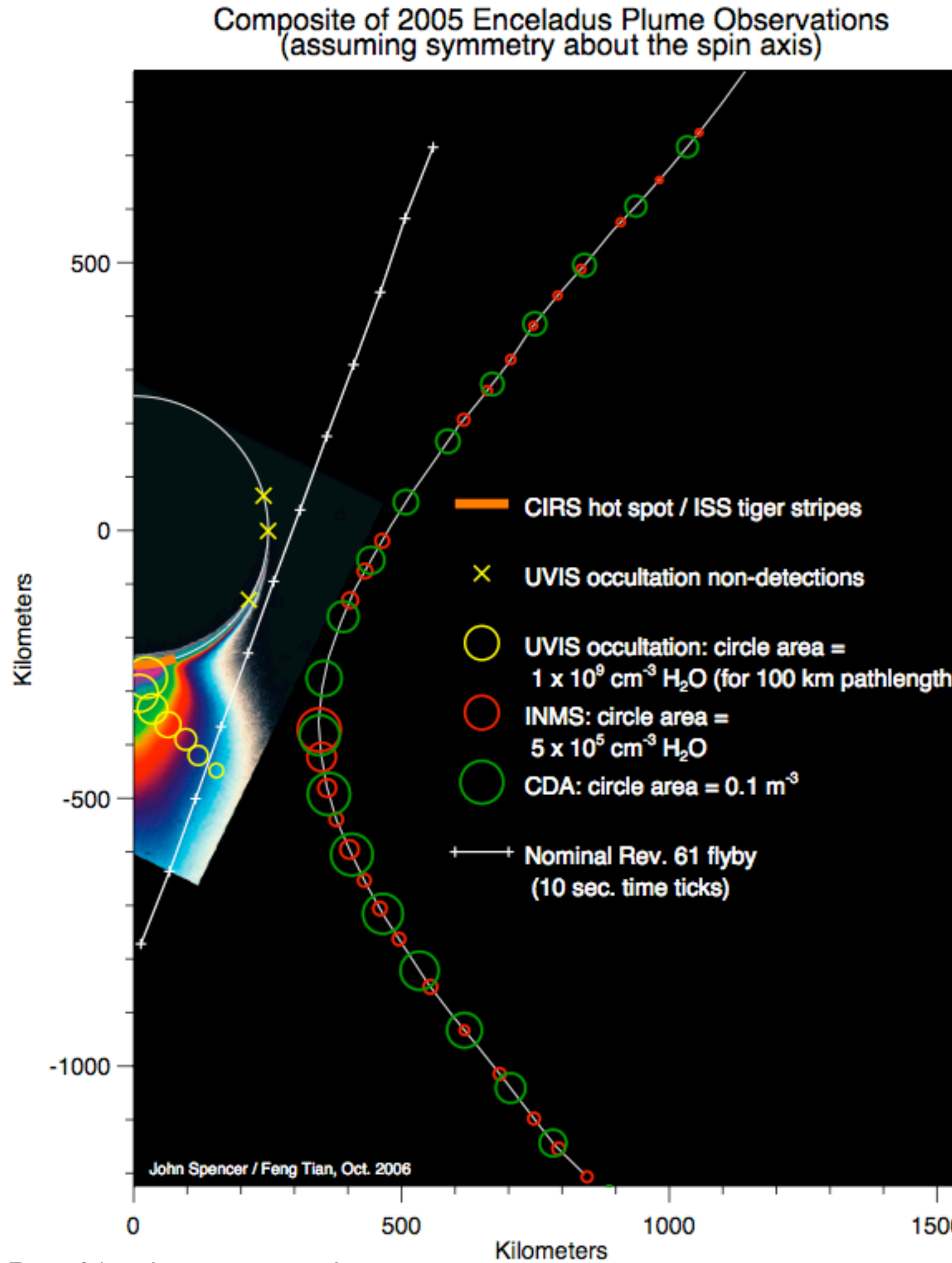


Earth-Based Contributions

- Search for sodium from Enceladus (Schneider et al. 2007)
- Sodium is very bright: detectable in very small quantities
- Also very soluble- should be in any Enceladus ocean
- No sodium found
  - Plume source not connected to an ocean?
  - Or sodium distilled out of the plume?

Next Up: March 12th 2008 (Rev. 61) flyby

- Fly over low latitudes at 50 km altitude
- Fly over south pole at 580 km altitude 55 seconds later
- Much deeper penetration of the plume
  - ~10x better precision on plume composition
  - Plume particle compositions: distinguish impact and plume sources of ice particles?
  - Plasma: measure rate of mass loss from Enceladus?

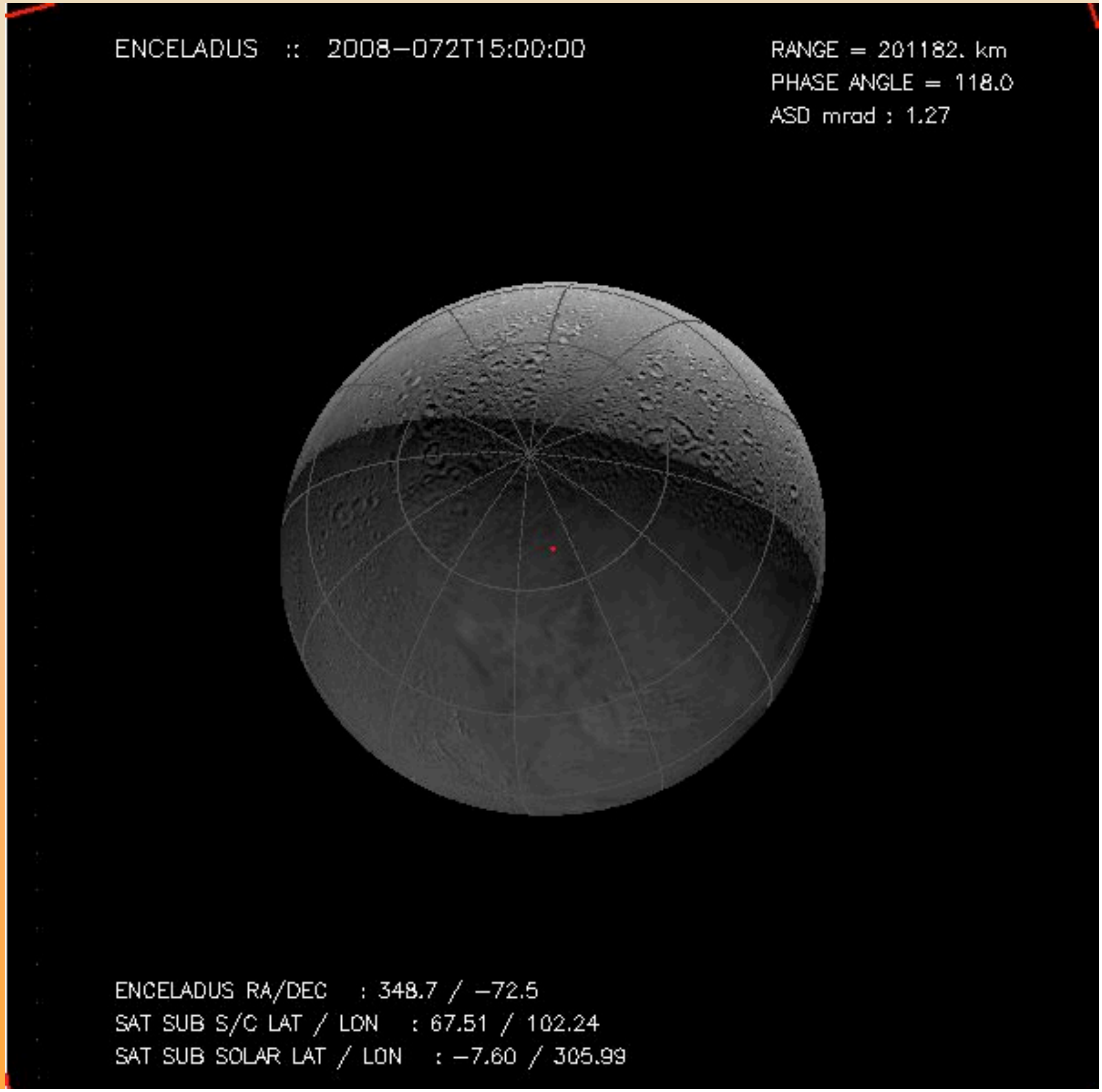


Rev. 61 trajectory approximate

John Spencer, JPL, Feb. 25 2008

Rev. 61 Encounter Movie

- -4 hours → +4 hours
- Red square = ISS camera field of view



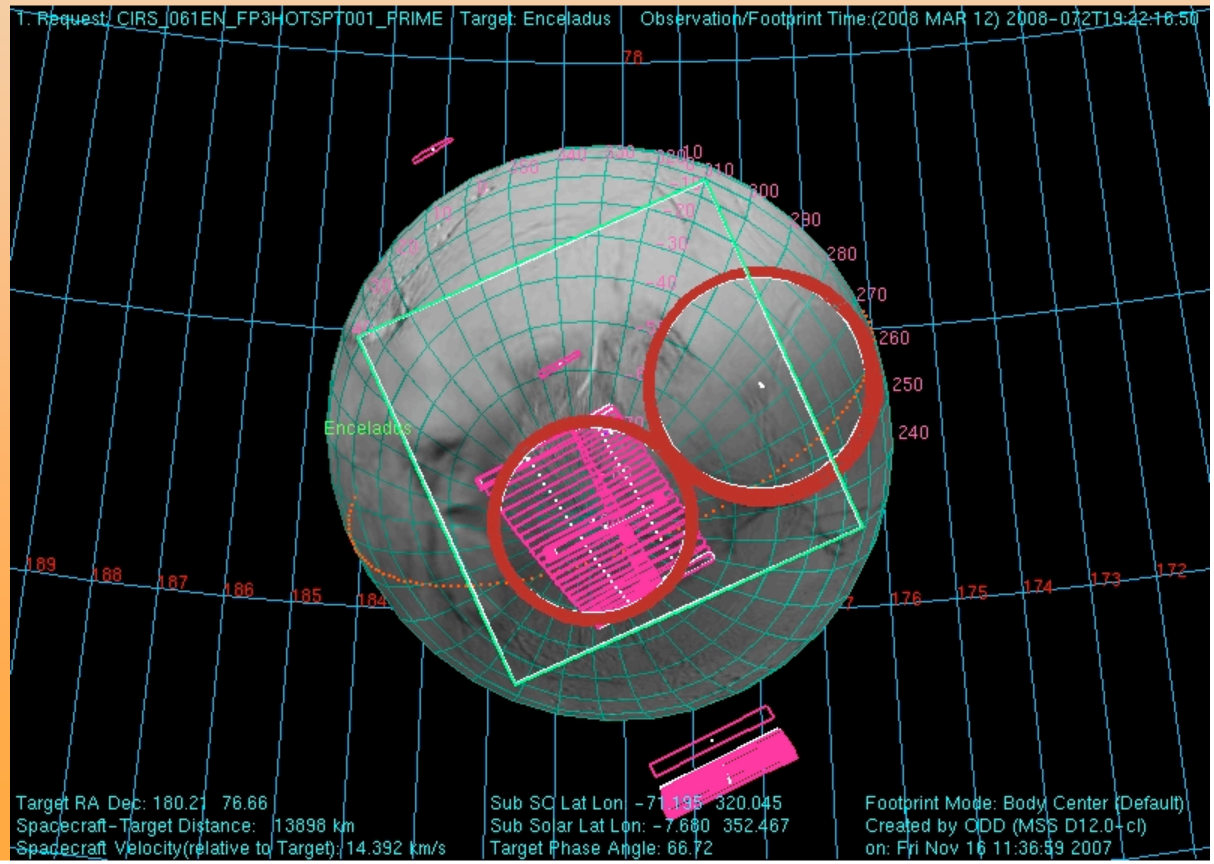
John Spencer, JPL, Feb. 25 2008

Rev . 61 CIRS South Polar Mapping, Part 1

Looking back after closest approach

Saturn eclipse cools surface, makes internal heat easier to measure (and eliminates competition…)

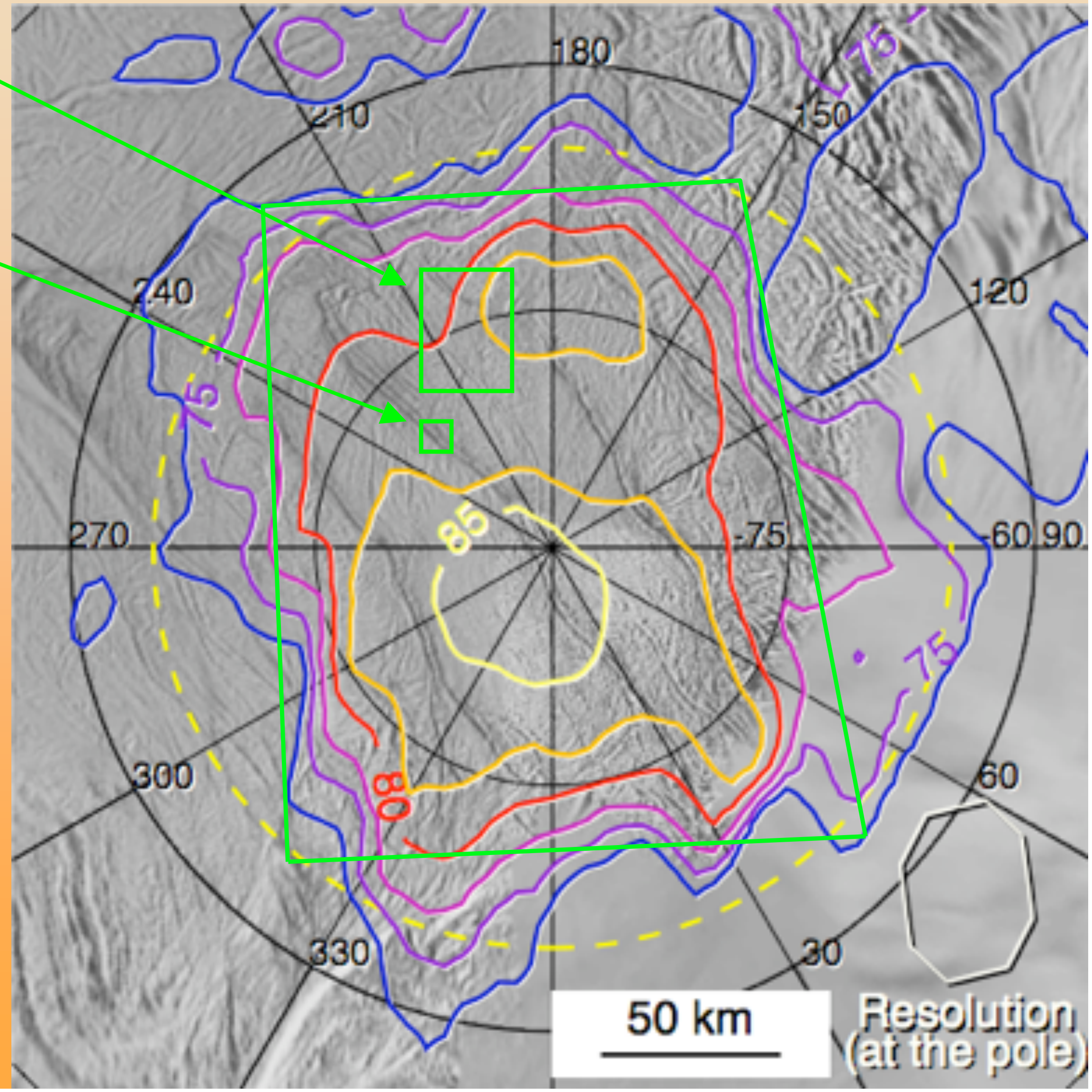
- C/A +00:05 Begin turn back to Enceladus
- C/A +00:16 Begin tiger stripe map (range 13,800 km, resolution 4.1 km)
- C/A +00:37 End tiger stripe map (range 32,000 km, resolution 9.6 km)



John Spencer, JPL, Feb. 25 2008

CIRS South Polar Mapping, Part 1

- Previous best full map had 25 km resolution…
- Typical 10 km resolution of Rev. 61 map
- Easily resolve the tiger stripes, map temperatures along them

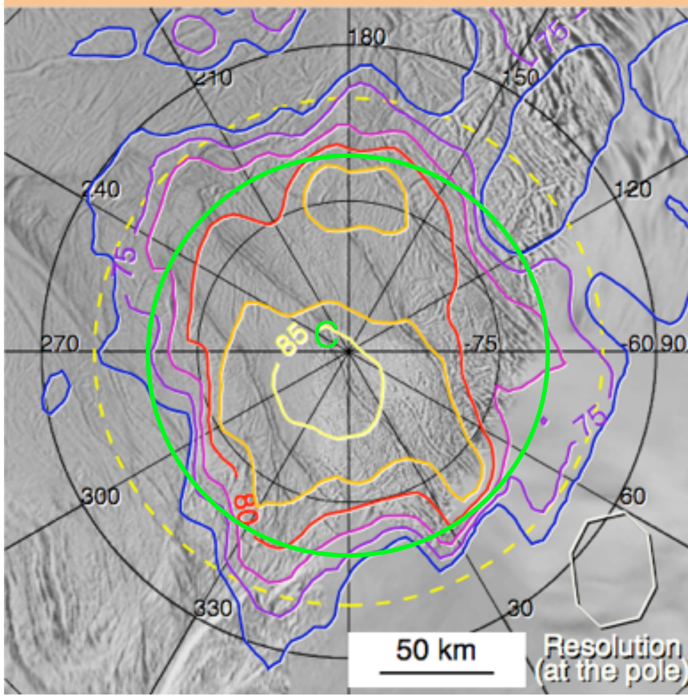


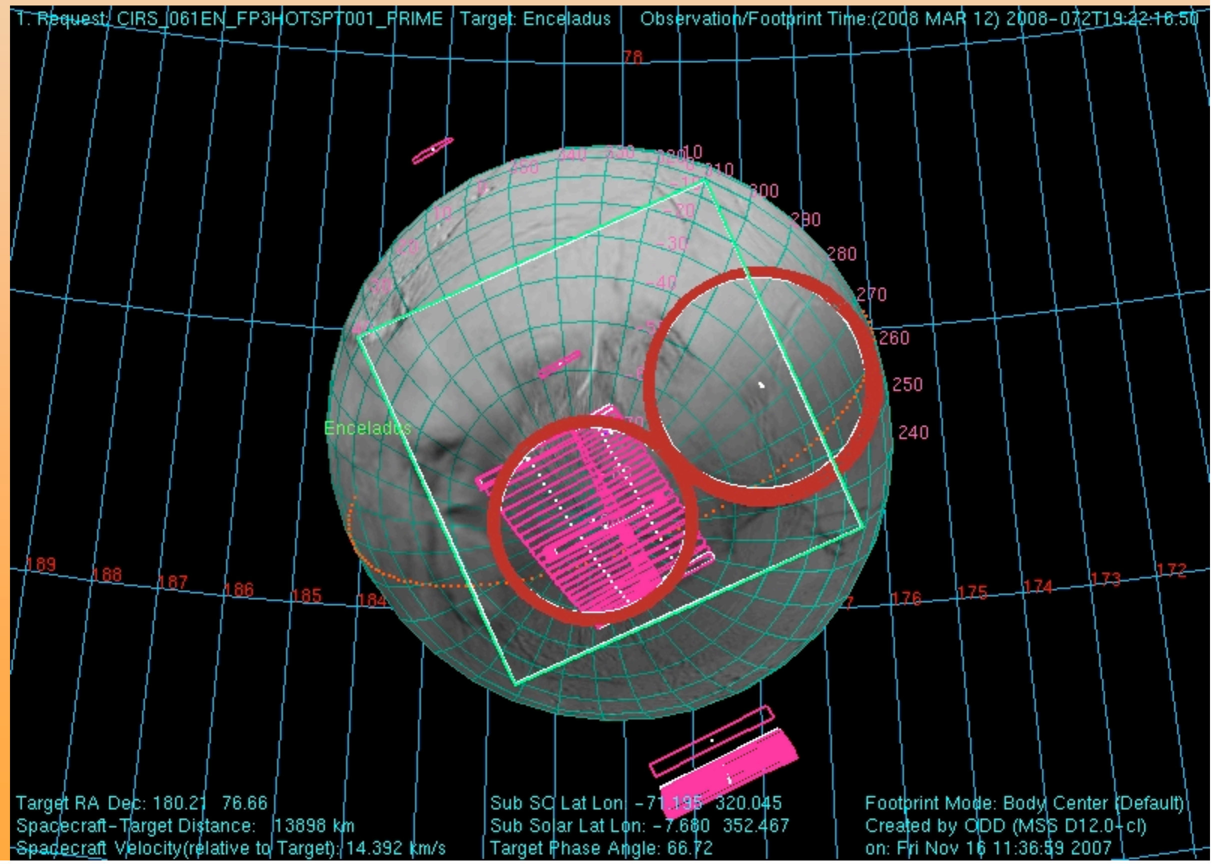
John Spencer, JPL, Feb. 25 2008

CIRS South Polar Mapping, Part 2

- C/A +00:38 Begin 6-minute integration on plume source “VI”, hot spot “C” (resn. 9.8 km) measure hot spot temperatures
- C/A +00:44 Long-wavelength measurements of south pole and nearby, for heat flow
- C/A +01:03 End observation

Spot “C” location, FP1 south polar FOV





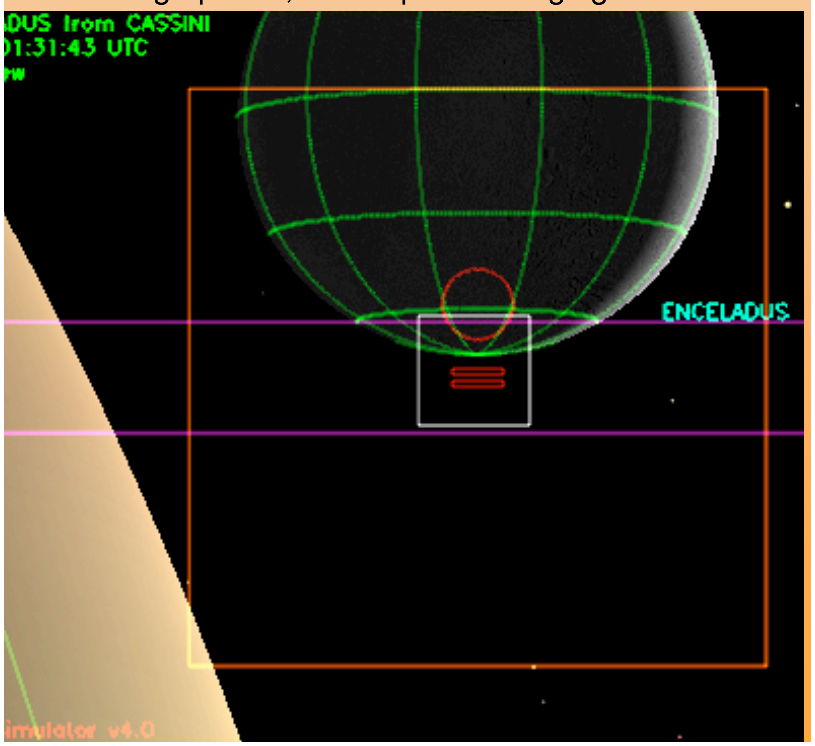
Upcoming Enceladus Flyby Summary

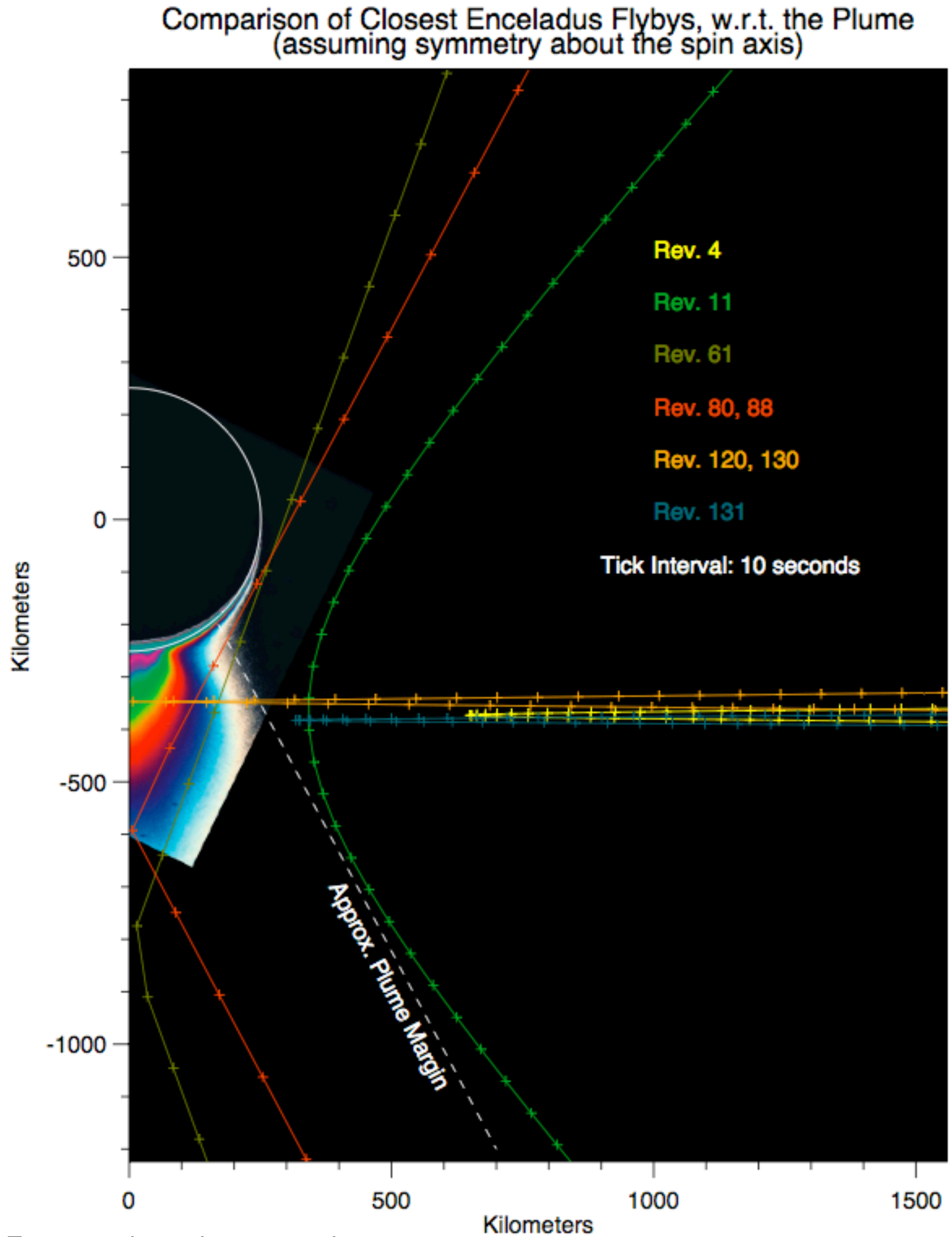
Date	Orbit	Speed, km/s	Altitude, km	Orbit Inclination	C/A science emphasis
12-Mar-2008	61	14.3	50	High	Plume sampling
11-Aug-2008	80	17.7	50	High	S. pole remote sensing
9-Oct-2008	88	17.7	21	High	Plume sampling
31-Oct-2008	91	17.7	196	High	S. pole remote sensing
2-Nov-2009	120	7.7	96	Low	Plume sampling
21-Nov-2009	121	7.7	1560	Low	S. pole remote sensing
28-Apr-2010	130	6.5	96	Low	S. pole gravity
18-May-2010	131	7	246	Low	Plume solar occultation

Extended Mission Plume Observations

Much improved in situ and remote sensing

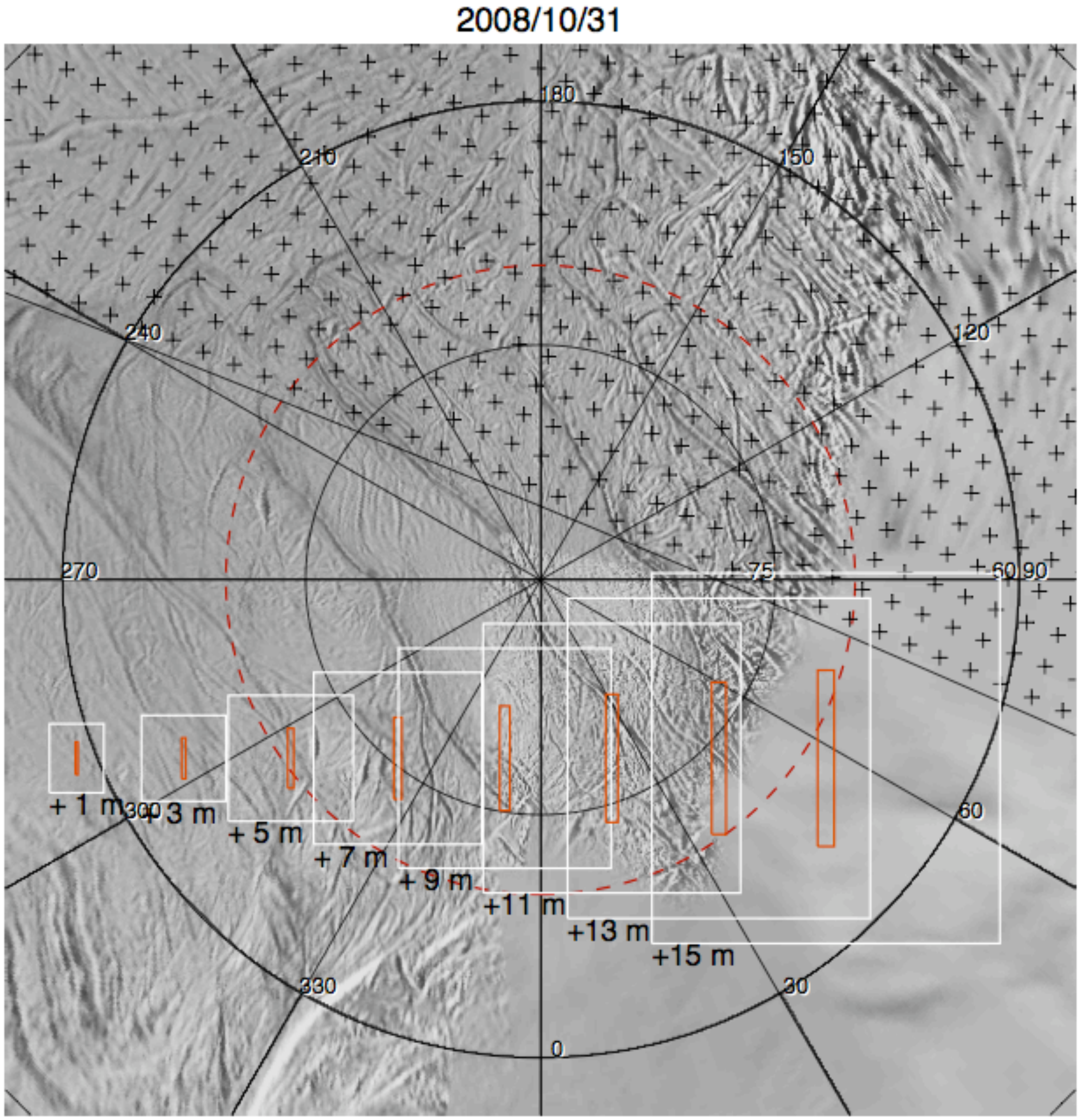
High phase, hi-res plume imaging





Future trajectories approximate

Extended Mission Remote Sensing

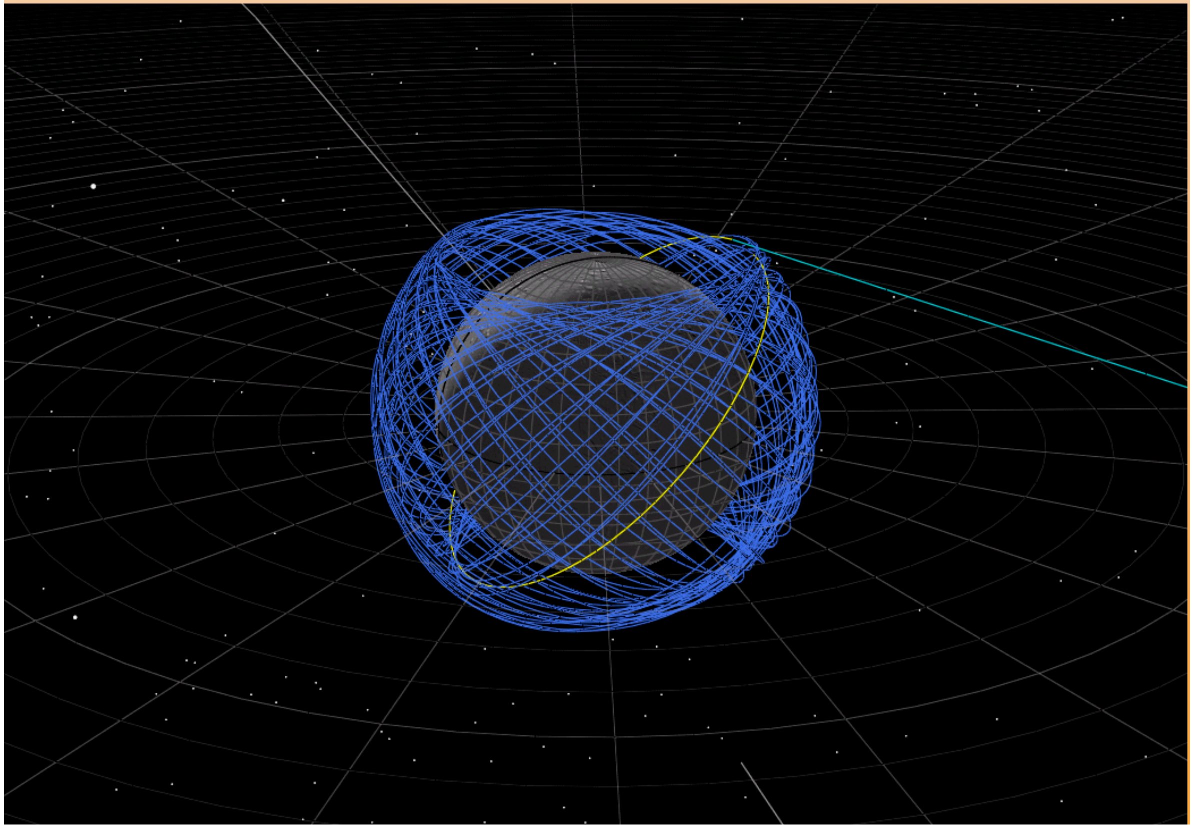


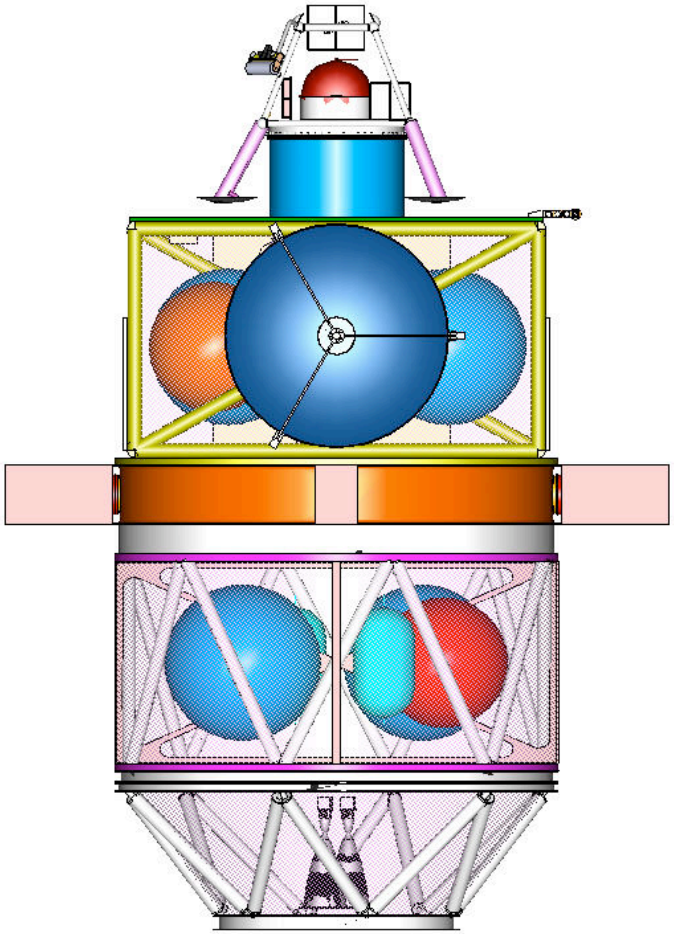
- 3 flybys optimized for hi-res remote sensing
- Coverage is limited:
  - Color imaging at > 6 m/pix
  - VIMS compositional maps at >500 m/pix
  - CIRS 1x10 pixel temperature profiles at >500 m/pix

Enceladus at 16 m/pix

Future Missions to Enceladus?

- 2007 NASA study
- Orbiter + Lander feasible for $3B?
- NASA, ESA now pursuing possible Enceladus flyby science on a Titan flagship mission





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…