Powerhouses to PacPeople: An update on the recent discoveries by Cassini/CIRS on the nature of the icy Saturnian satellite surfaces.

C.J.A. Howett, J.R. Spencer, A. Verbiscer,
T. Hurford, M. Segura, P. Schenk, C. Paranicas,
R. Johnson,

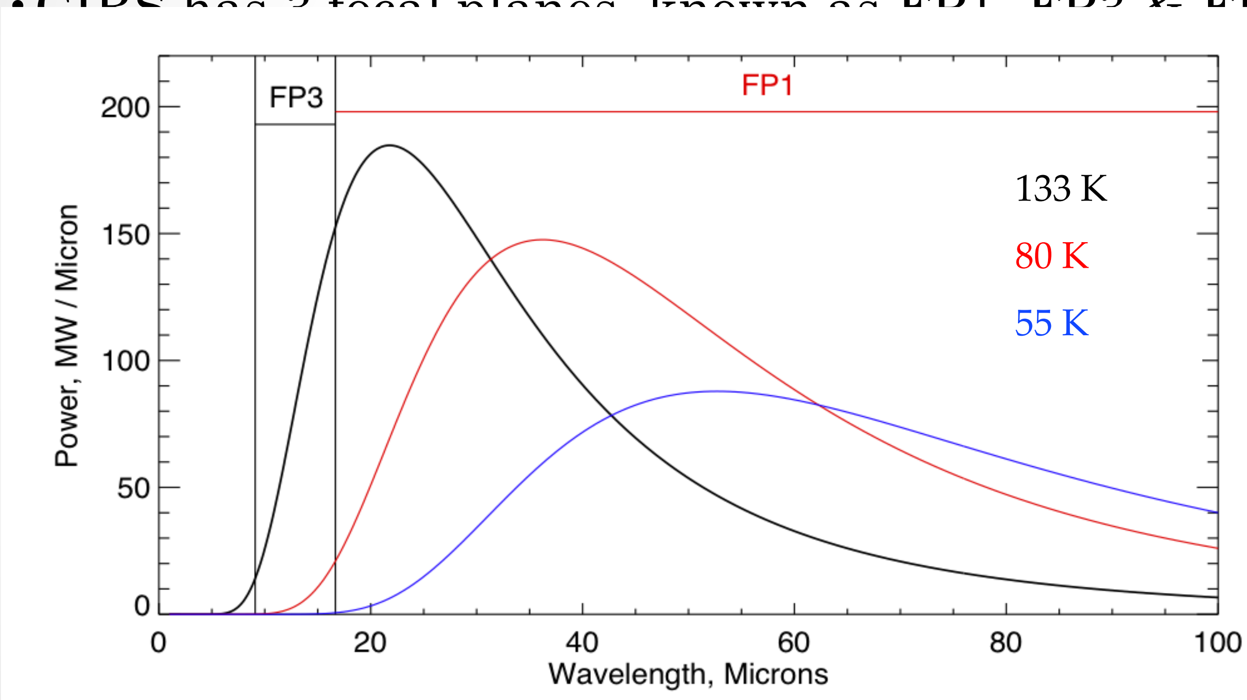
Overview

- Introduction to the Cassini mission and the CIRS instrument
- Icy Saturnian satellites surface thermal properties and variations
- Quantifying Enceladus' heat flow
- The thermal anomalies on Mimas and Tethys

CIRS

• Cassini's Composite Infrared Spectrometer (CIRS) is a dual interferometer covering the far- and near-infrared (10 to 1600 cm^{-1} which is equivalent to 7.16 - 1000 microns)

• CIRS has 3 focal planes, known as FP1, FP3 & FP4

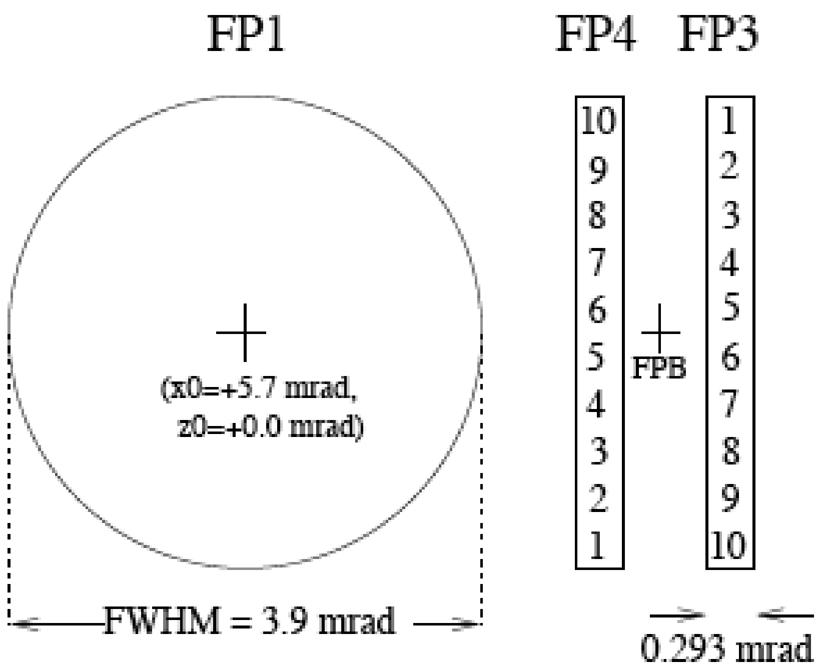


The temperatures of icy Saturnian satellites ranges from ~40 K to 130 K.

So the wavelength range of the CIRS FP3 and FP4 renders them sensitive to only warm (usually daytime) temperatures.

CIRS

However, FP1 has the lowest spatial resolution of the three detectors.

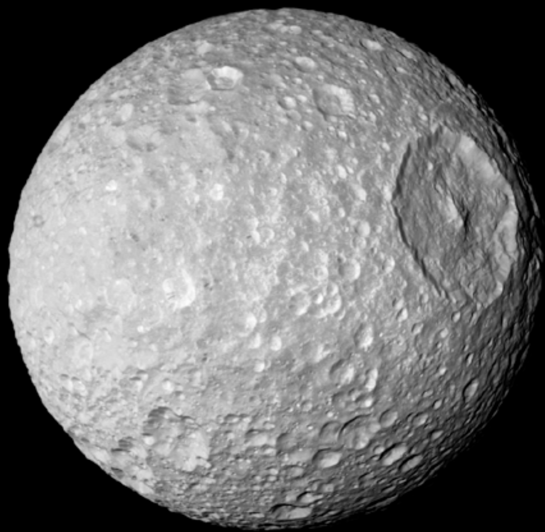


So usually for CIRS observations of icy satellites a mixture of FP1 and FP3 (with FP4 riding) will be used.

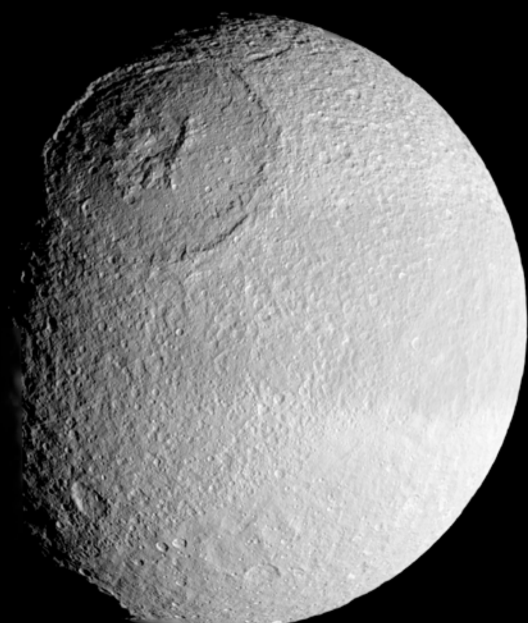
Saturn's Icy Satellites

Iapetus on this scale is ~27 m away (at approximately the elevators!)

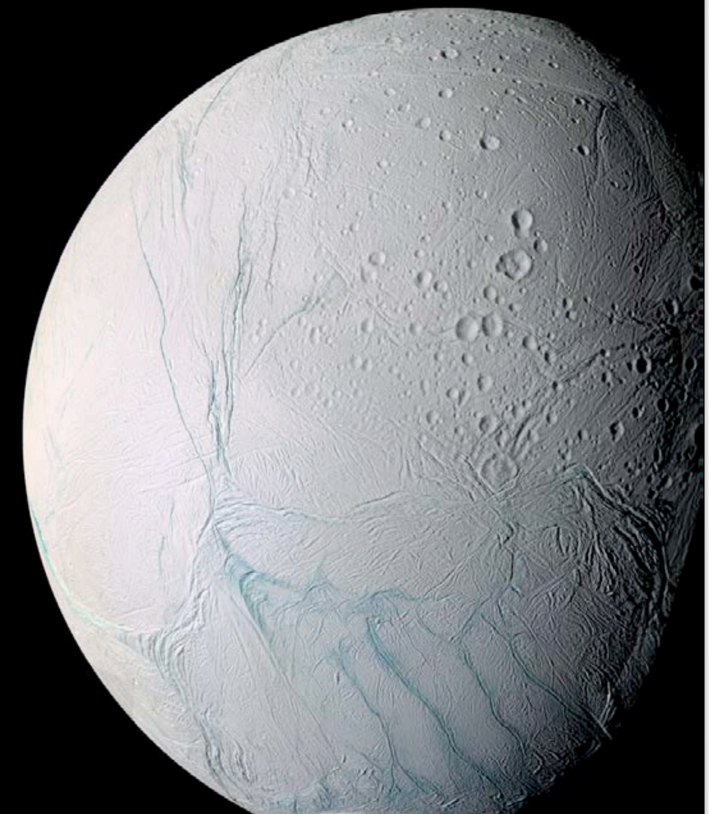
Saturn's Icy Satellites



Mimas



Tethys



Enceladus

Surface Properties

- Albedo – the fraction of sunlight reflected from a surface

Snow

<- High albedo

Low -> albedo

Bare rock

- Thermal inertia – the ability of a surface to store and reradiate thermal energy

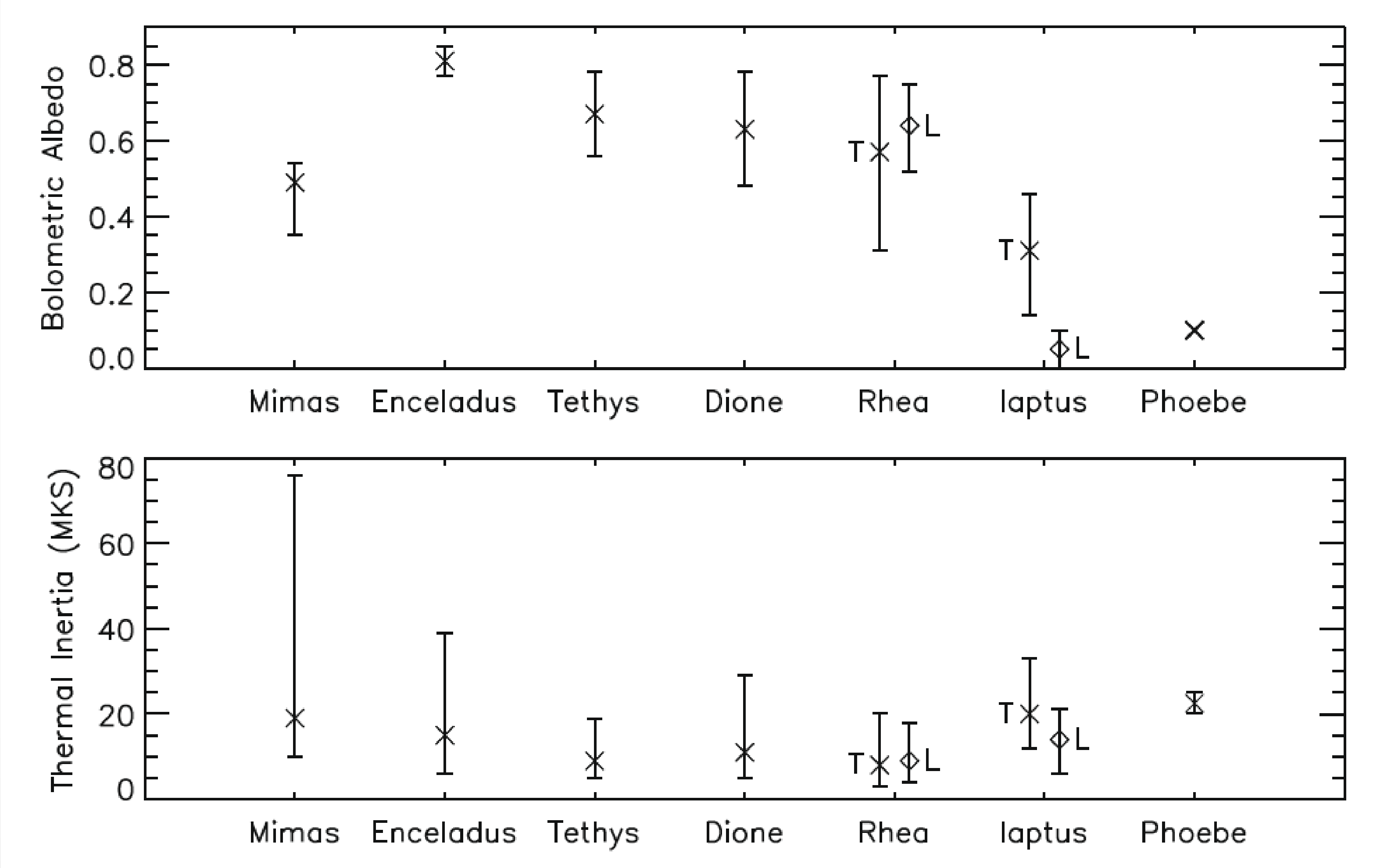
Sandstone Striations on the Colorado Planetau in Utah

<- High thermal inertia

Low -> thermal inertia

Sand Dunes in Mui Ne, Vietnam

Surface thermal property determination of Saturn's icy Satellites



From Howett *et al.* (2010)

Surface thermal property determination of Saturn's icy Satellites

Target	Bolometric albedo	Thermal inertia (MKS)	Skindepth (cm)	References
Jovian satellites				
Io	0.52	70	0.39[c]	Rathbun et al. (2003)
Europa	0.55	70	0.55[c]	Spencer et al. (1999)
		14 ± 5	0.01[d]	Hansen (1973)
Ganymede	0.32 ± 0.04	70 ± 20	0.78[c]	Spencer (1987)
		12 ± 3	0.01[d]	Hansen (1973)
		14 ± 3	0.01[d]	Morrison and Cruikshank (1973)
Callisto	0.2 ± 0.4	50 ± 10	0.86[c]	Spencer (1987)
		10 ± 1	0.01[d]	Morrison and Cruikshank (1973)
Saturnian satellites				
Mimas	$0.49^{+0.05}_{-0.14}$	19^{+57}_{-9}	0.54	
Enceladus	0.81 ± 0.04	15^{+24}_{-9}	0.51	
Tethys	0.67 ± 0.11	9^{+10}_{-4}	0.36	
Dione	0.63 ± 0.15	11^{+18}_{-6}	0.53	
Rhea trailing	$0.57^{+0.20}_{-0.26}$	8^{+12}_{-5}	0.50	
Rhea leading	$0.63^{+0.11}_{-0.12}$	9^{+9}_{-5}	0.56	
Iapetus trailing	$0.31^{+0.15}_{-0.17}$	20^{+13}_{-8}	5.22	
Iapetus leading	0.10[a]	14^{+7a}_{-8}	3.66	
Phoebe	0.1	20/25[b]		

Table 7, Howett *et al.*, (2010)

Table compares the albedo and thermal inertia of the Jovian and Saturnian icy satellites.

Saturnian system satellites tend to have:

- Higher albedo
- Lower thermal inertia

than their Jovian counterparts.

Saturnian vs. Jovian Icy Satellites.

Both have ice surfaces

Grainy snow

↓

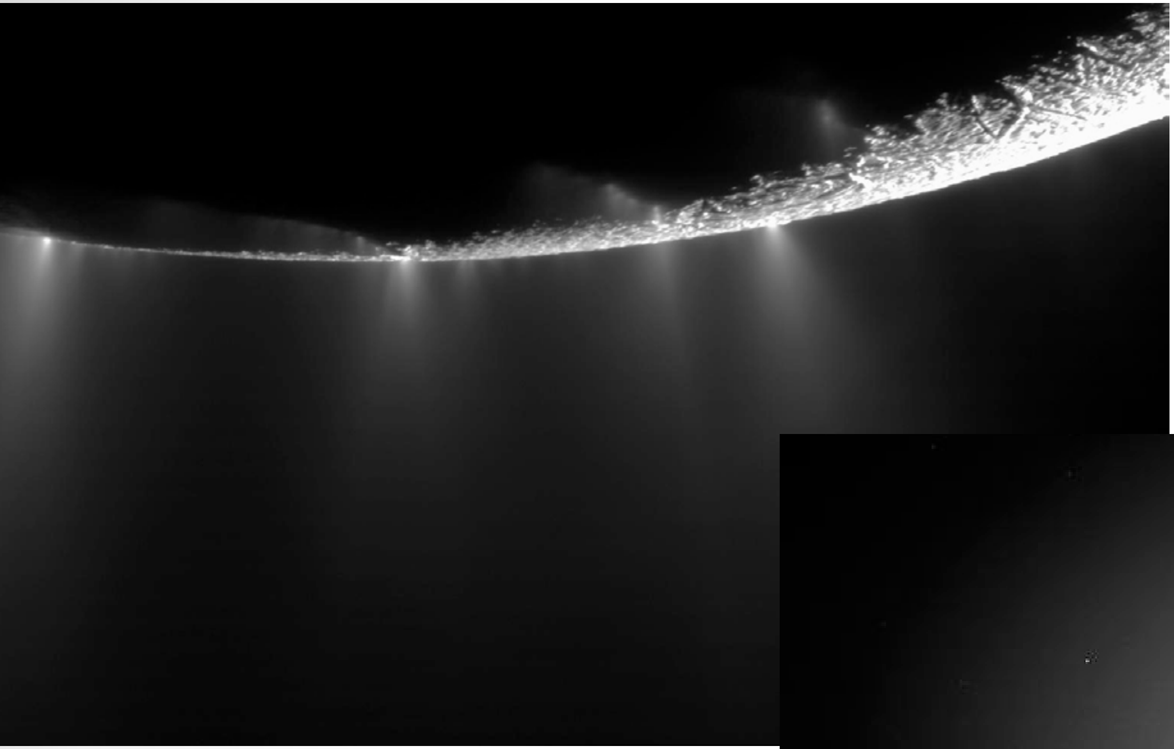
Saturnian Icy Satellites
High albedo
Low thermal inertia

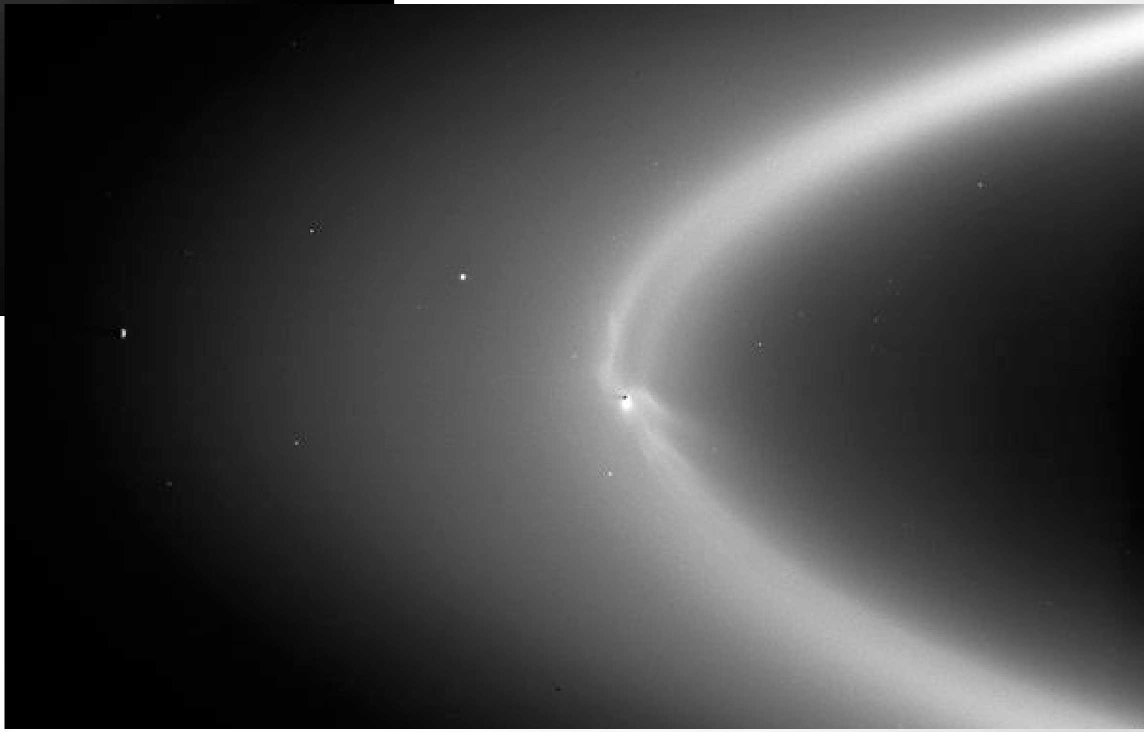
Packed snow

↓

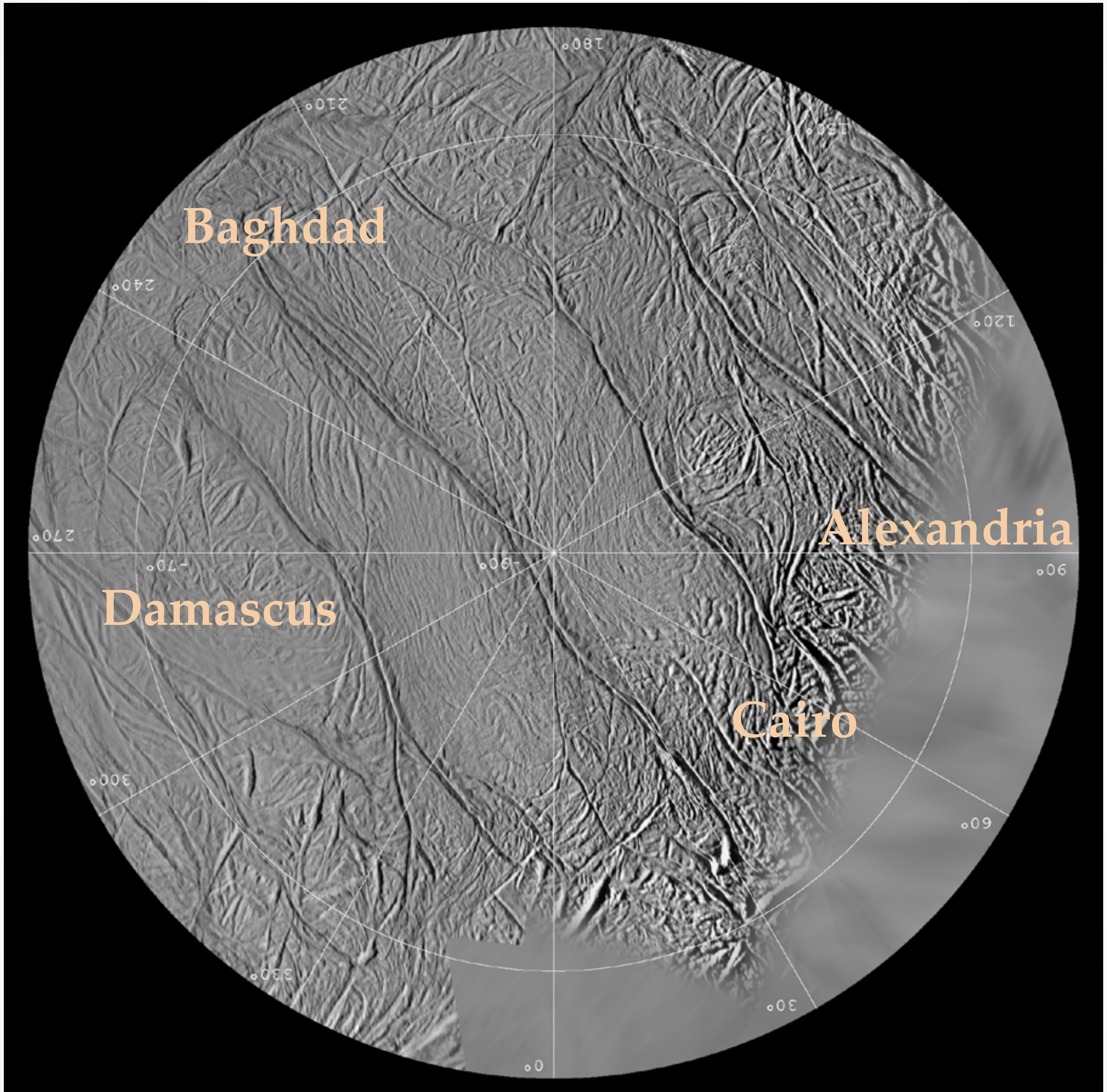
Jovian Icy Satellites
High albedo
High thermal inertia

Enceladus

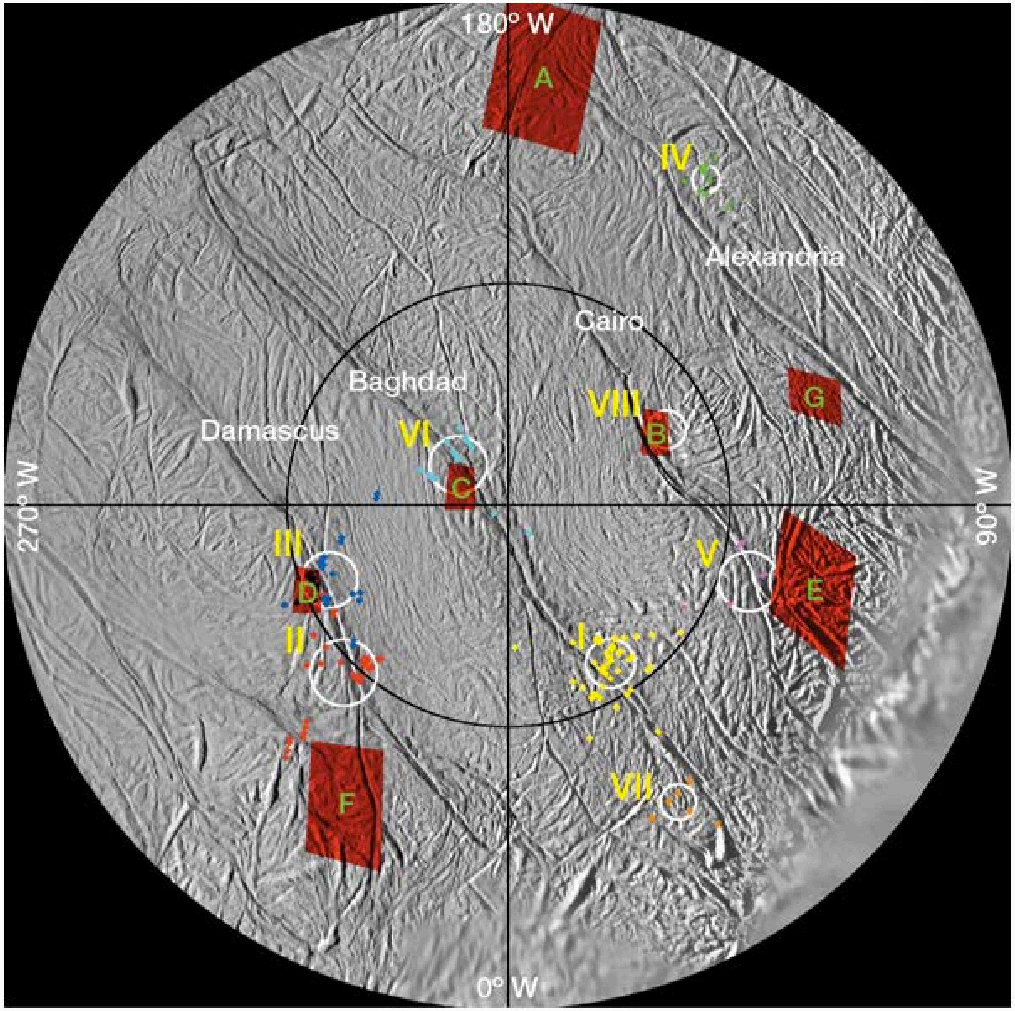




Enceladus – South Polar Terrain



Enceladus - Plumes

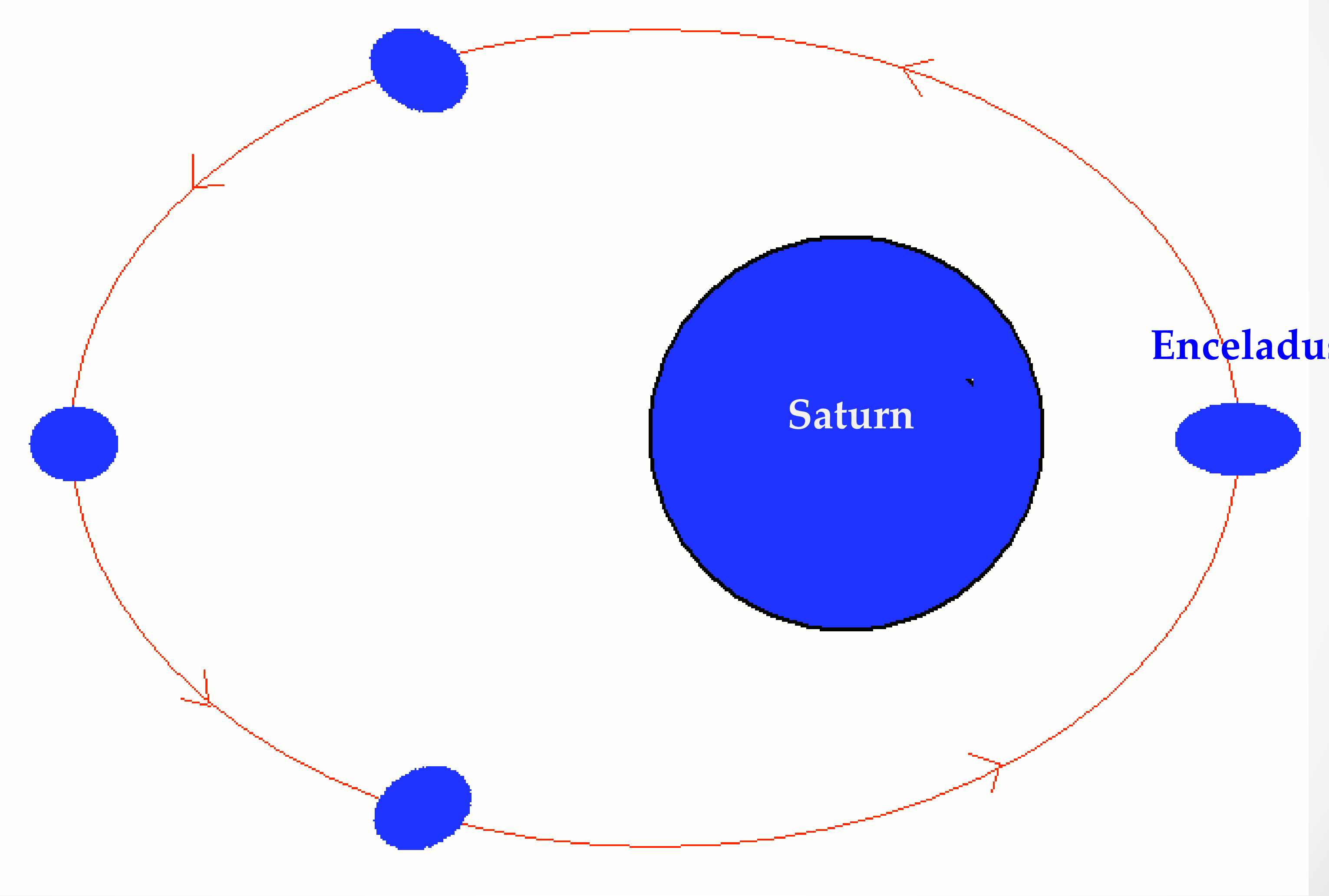


From Spitale and Porco *et al*. (2007) Source locations are labeled with yellow roman numerals; CIRS hotspots (Spencer *et al*., 2006) are labeled with green capital letters.

Enceladus – Heat Flow Previous Estimated Values

Predicted Power	Power
Radiogenically produced (Porco *et al*., 2006)	0.3 GW

Tidal Heating



Enceladus – Heat Flow Previous Estimated Values

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Radiogenically produced (Porco *et al*., 2006)	0.3 GW
Maximum steady-state dissipation of tidal heating (Meyer and Wisdom, 2007)	1.1 GW

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Initial power estimate of the SPT using CIRS FP3 data (Spencer *et al.*, 2006)	5.8 ± 1.9 GW

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But:
0.3 GW
+
1.1 GW
≠
3.9 (5.8-1.9) GW

So, what is going on?

Enceladus – Heat Flow Previous Estimated Values

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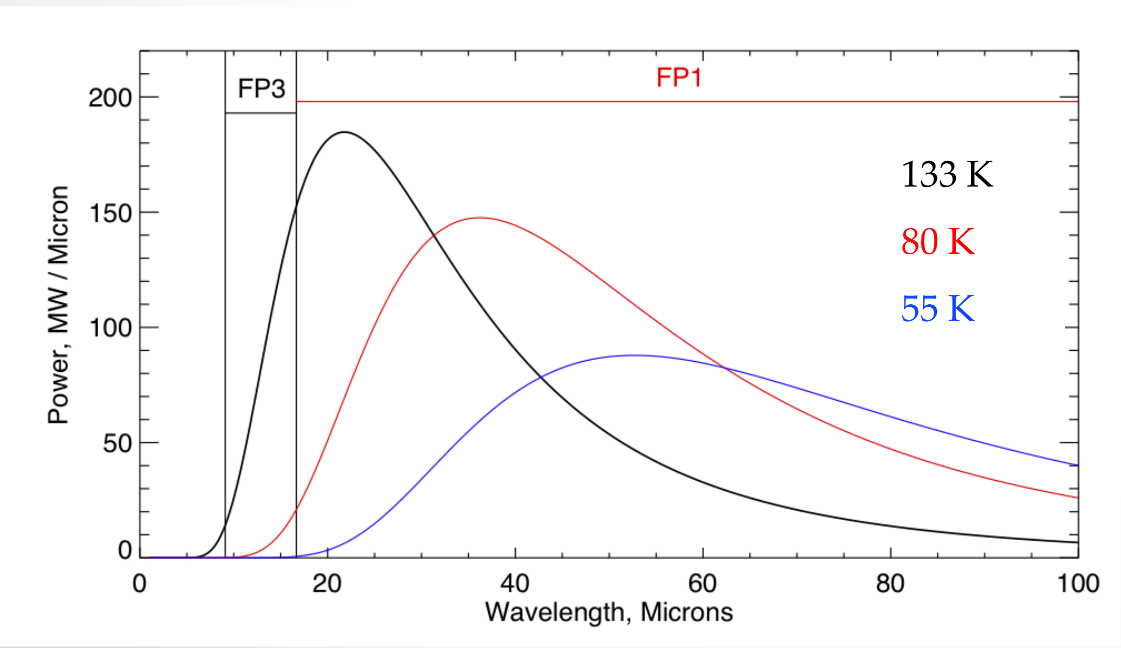
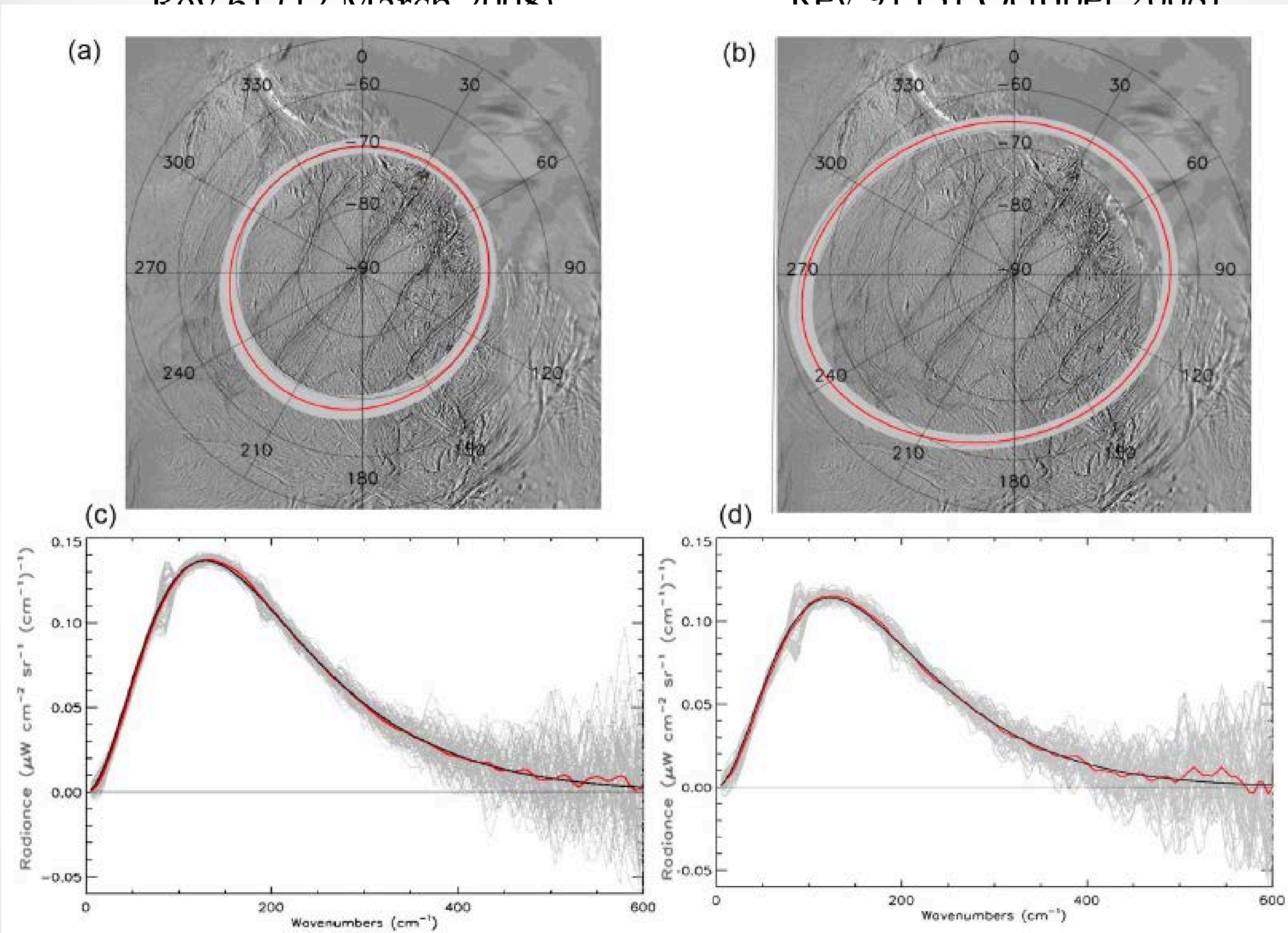


- FP3 is only sensitive to temperatures > 65 K. So any endogenic emission at temperatures below will be missed by FP3.
- The majority of the power curve for cooler temperatures however lies within the FP1 wavelength range……..

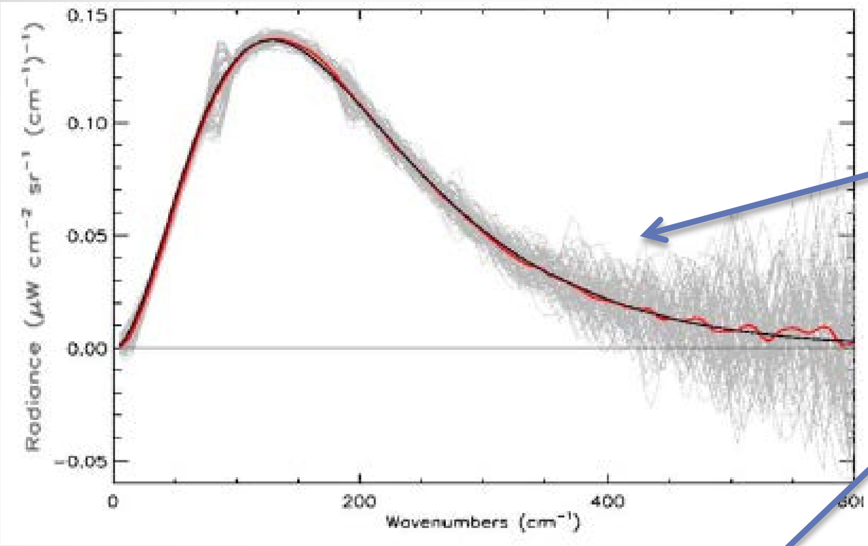
Enceladus – FP1 SPT CIRS observations

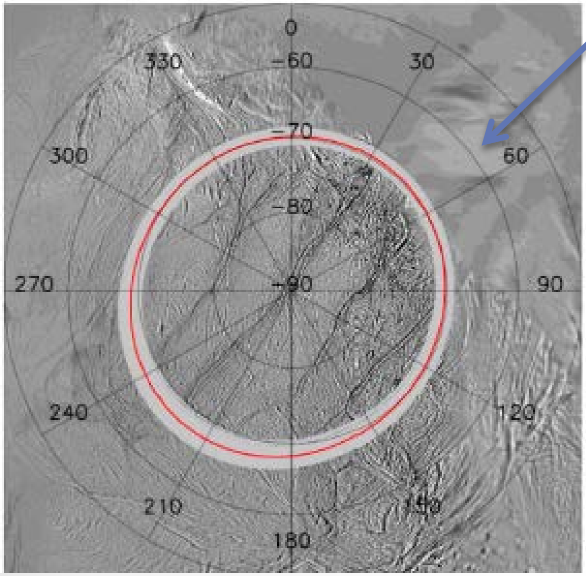
Rev 61 (12 March 2008)

Rev 91 (31 October 2008)



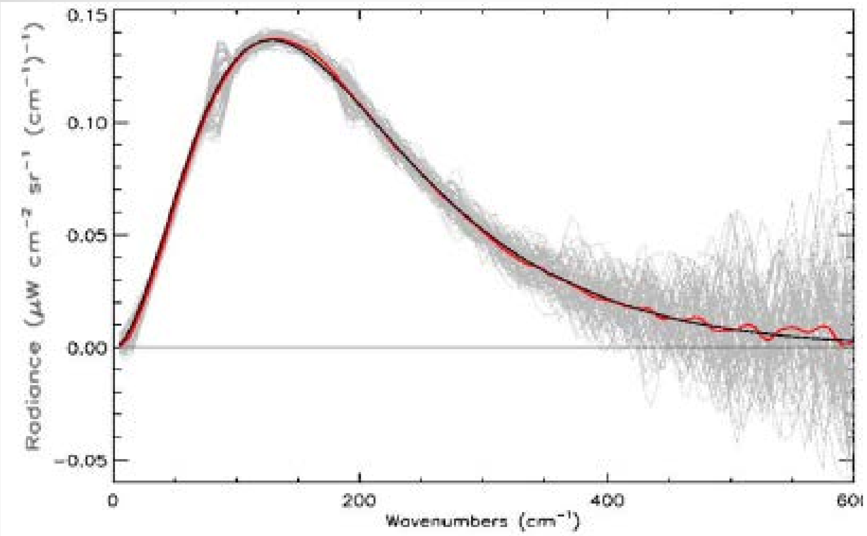
Calculating Enceladus' thermal emission

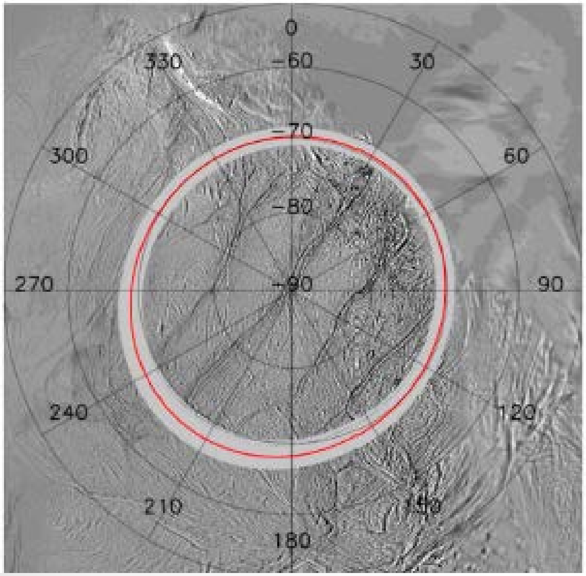




- Getting the power emitted by a surface from a radiance curve is simply achieved by integrating the radiance at all wavelengths over the area observed at all solid angles.

Calculating Enceladus' thermal emission



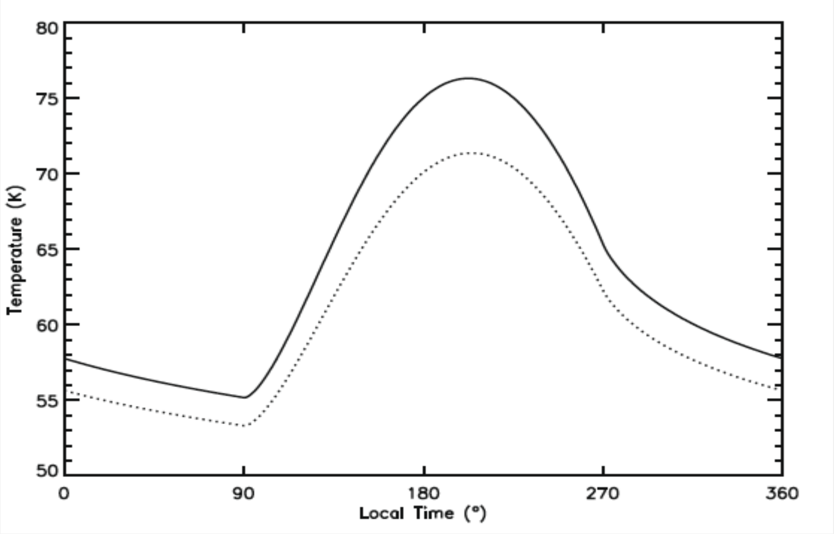


- Getting the power emitted by a surface from a radiance curve is simply achieved by integrating the radiance at all wavelengths over the area observed at all solid angles.
- However…….
  - Since FP1 is sensitive to low temperatures it is also sensitive to Enceladus' passive emission (reradiated sunlight).
  - Thus, this component must be removed before we can determine the power
    - So **all** we need to estimate Enceladus' passive emission component.

Easy, right?………

Modeling the thermal emission

- We use a model to predict surface temperature, it accounts for:
  - o Heliocentric distance
  - o Saturn's orbital eccentricity
  - o Rotation period
  - o Sub-solar latitude
  - o Latitude
  - o Local Time
  - o Eclipses
  - o Saturnshine
  - o Surface properties:
    - Bolometric albedo
    - Thermal inertia
    - Spatial distribution of endogenic emission

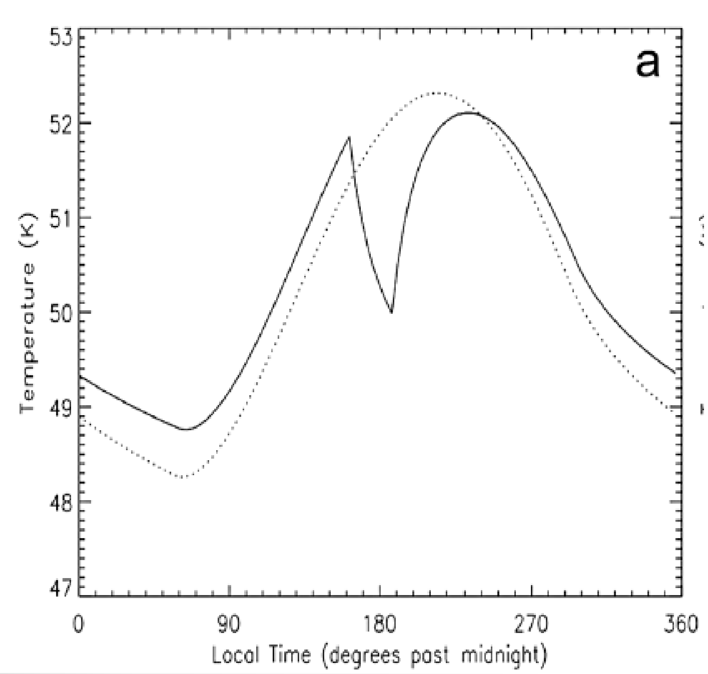


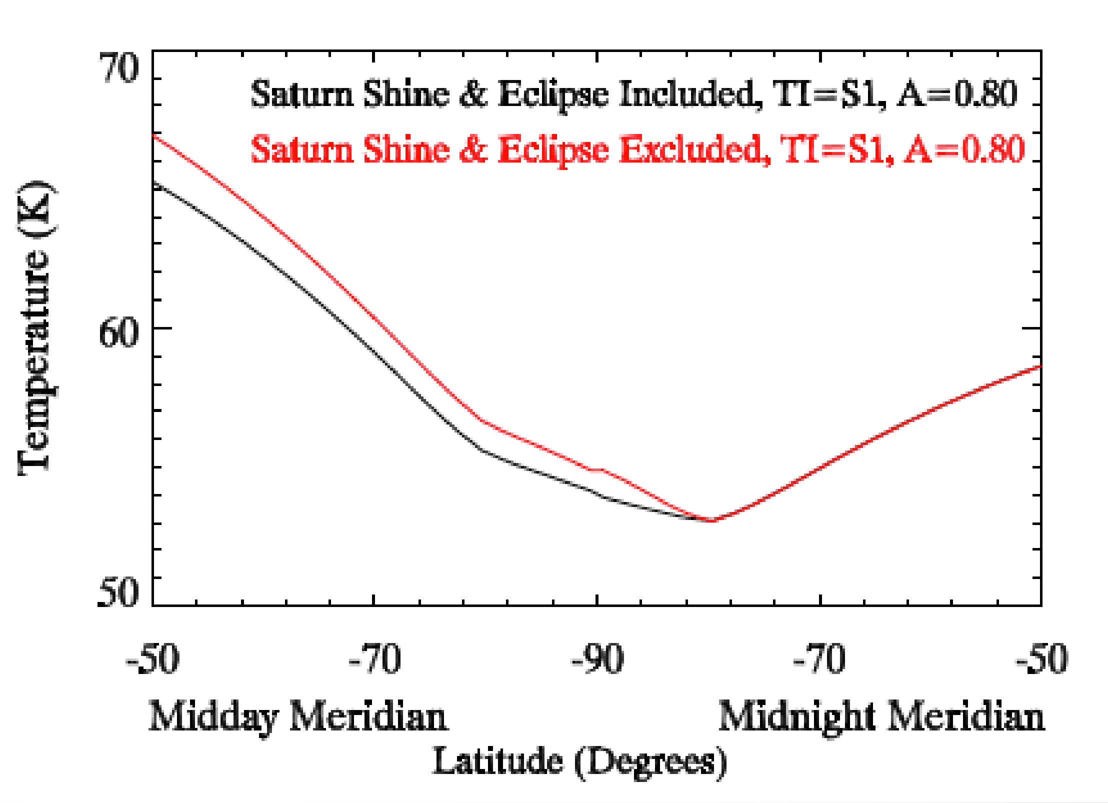
Typical diurnal curve model output for Enceladus at perihelion (solid lime) and aphelion (dashed line) at equatorial latitudes. Assumed albedo and thermal inertia are: 0.81 and 15 MKS respectively.

Estimating Enceladus' passive emission

Effects to "worry about":

- Saturnshine
- Eclipse Effects



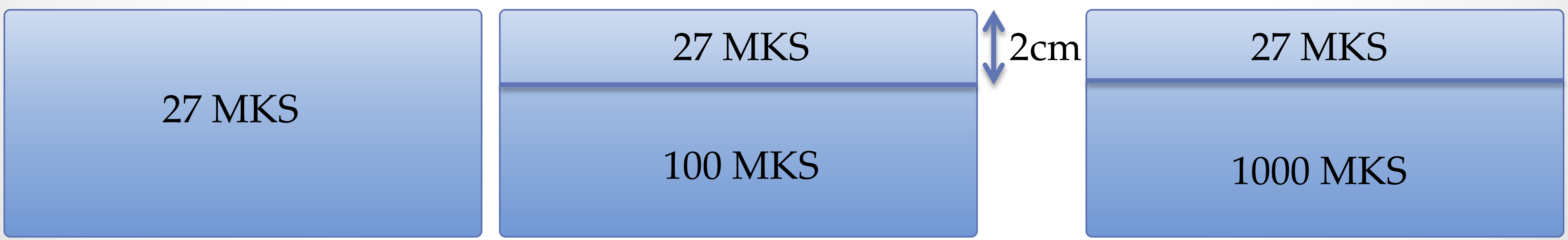


Estimating Enceladus' passive emission

Effects to "worry about":

- Saturnshine
- Eclipse Effects
- Thermal inertia variations (spatial/depth variations)

Thermal Inertia Scenarios Considered:



Scenario 1

27 MKS is the closest thermal inertia value previously derived to the south polar terrain (Howett *et al.*, 2010).

Scenario 2

100 MKS is the upper limit of thermal inertia at Enceladus' north pole at depths of < 1m (Spencer *et al.*, 2006)

Scenario 3

1000 MKS is approximately the value of pure water ice (Paige *et al.*, 1994)

Estimating Enceladus' passive emission

Effects to "worry about":

- Saturnshine
- Eclipse Effects
- Thermal inertia variations (spatial/depth variations)
- Assumed Albedo (and spatial variations)

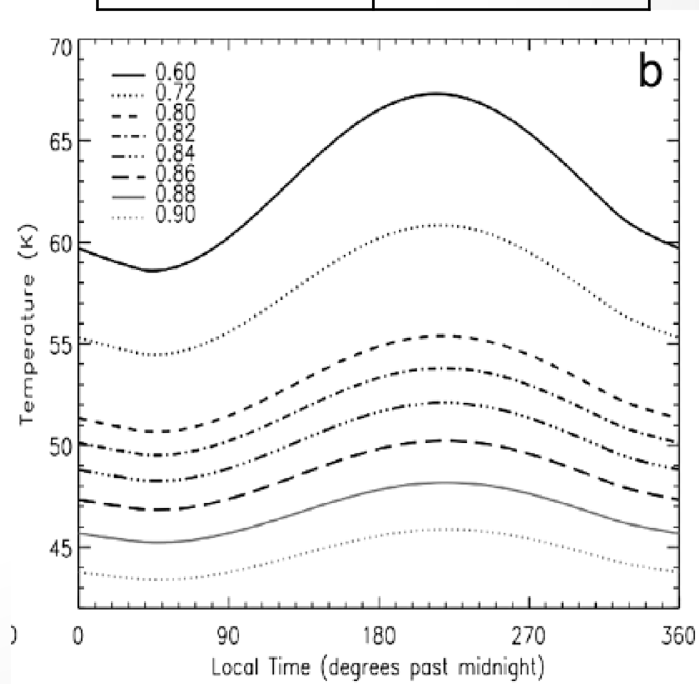
Latitude bin	Bolometric Bond albedo	Thermal inertia (MKS)
60°N to 70°N	0.76 ± 0.06	16^{+17}_{-13}
40°N to 50°N	$0.74^{+0.06}_{-0.04}$	9^{+5}_{-4}
30°N to 40°N	0.77 ± 0.05	10^{+10}_{-6}
20°N to 30°N	$0.78^{+0.05}_{-0.04}$	12^{+15}_{-7}
10°N to 20°N	0.75 ± 0.03	17^{+10}_{-7}
0° to 10°N	$0.79^{+0.04}_{-0.05}$	25^{+25}_{-14}
10°S to 0°	$0.78^{+0.03}_{-0.02}$	25^{+22}_{-12}
20°S to 10°S	$0.81^{+0.03}_{-0.05}$	18^{+21}_{-9}
30°S to 20°S	$0.81^{+0.05}_{-0.06}$	20^{+19}_{-12}
40°S to 30°S	$0.82^{+0.02}_{-0.03}$	26^{+12}_{-13}
50°S to 40°S	$0.79^{+0.02}_{-0.01}$	40^{+10}_{-18}
60°S to 50°S	$0.80^{+0.03}_{-0.04}$	27^{+13}_{-20}

Table 8 from Howett *et al.* (2010)

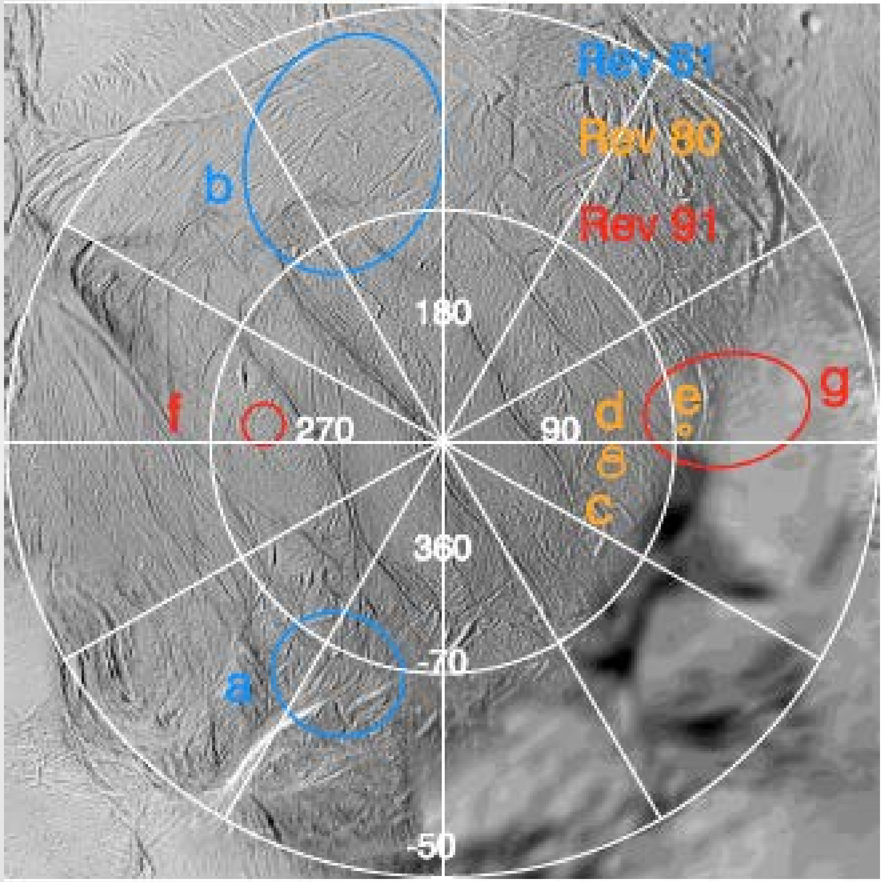
Three bolometric Bond albedo values are selected for use: 0.60, 0.72 and 0.80.

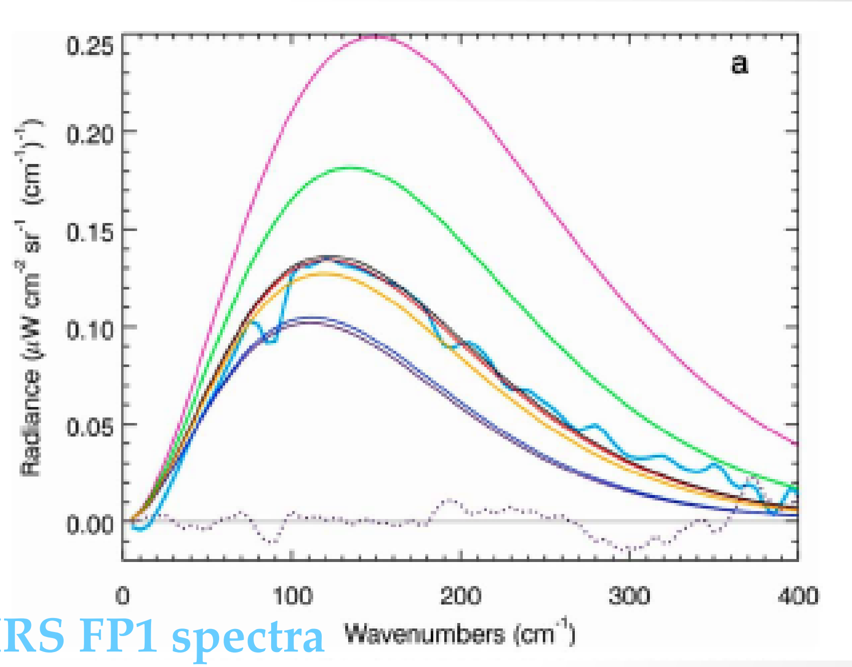
Thermal Surface Property values of Enceladus' Southern Hemisphere

Albedo	Thermal Inertia (MKS)
0.75 - 0.84	9 – 50



Estimating Enceladus' passive emission - Verification





CIRS FP1 spectra

All models don't include: Saturn heating or eclipses

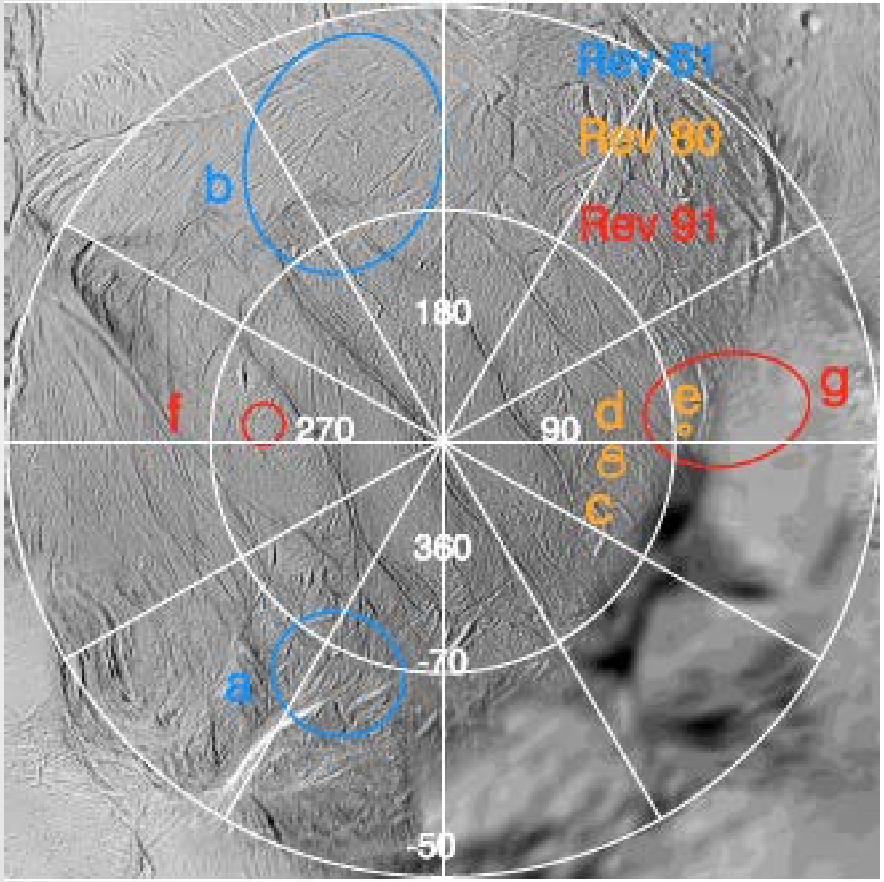
0.60, 0.72, **0.80** albedo values using thermal inertia scenario

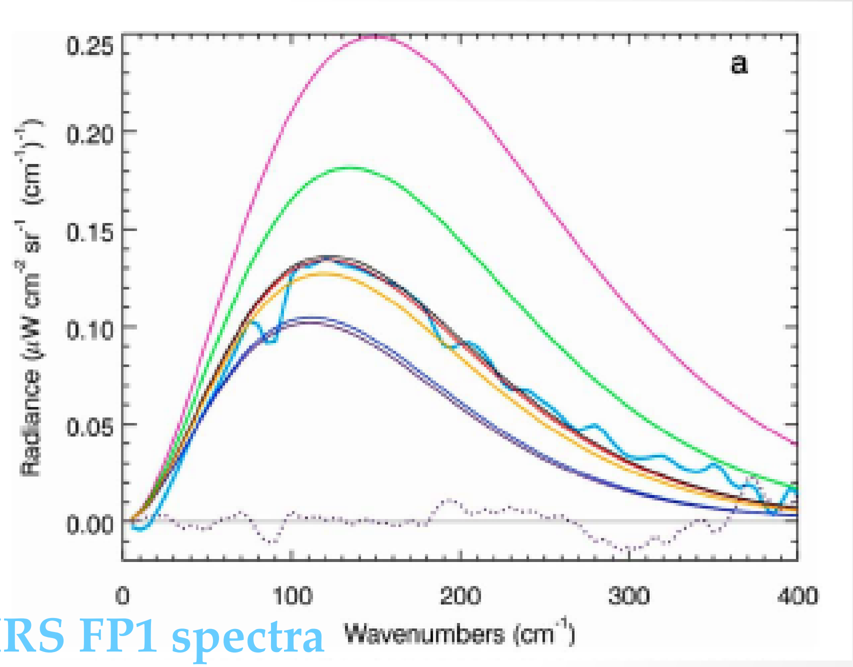
Thermal inertia scenarios 1, **2**, 3 (albedo 0.80)

A(i) (thermal inertia scenario 1) and A(i) (thermal inertia scenario 2)

Dotted line is nearest deep space spectra

Estimating Enceladus' passive emission - Verification





CIRS FP1 spectra

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~~0.60, 0.72~~, **0.80** albedo values using thermal inertia scenario

Thermal inertia scenarios **1, 2,** 3 (albedo 0.80)

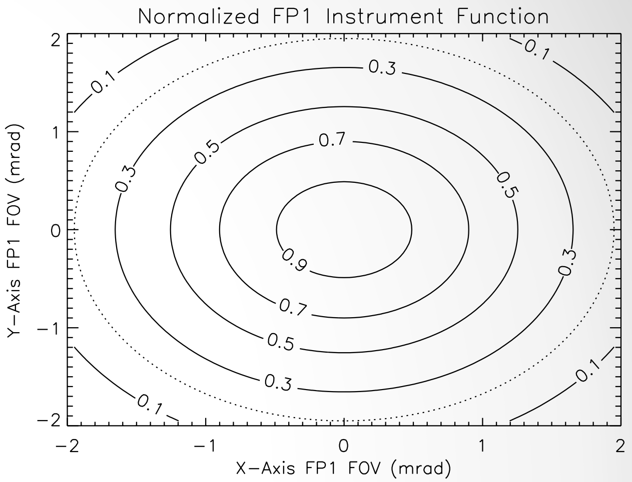
~~A(i) (thermal inertia scenario 1) and A(i) (thermal inertia scenario 2)~~

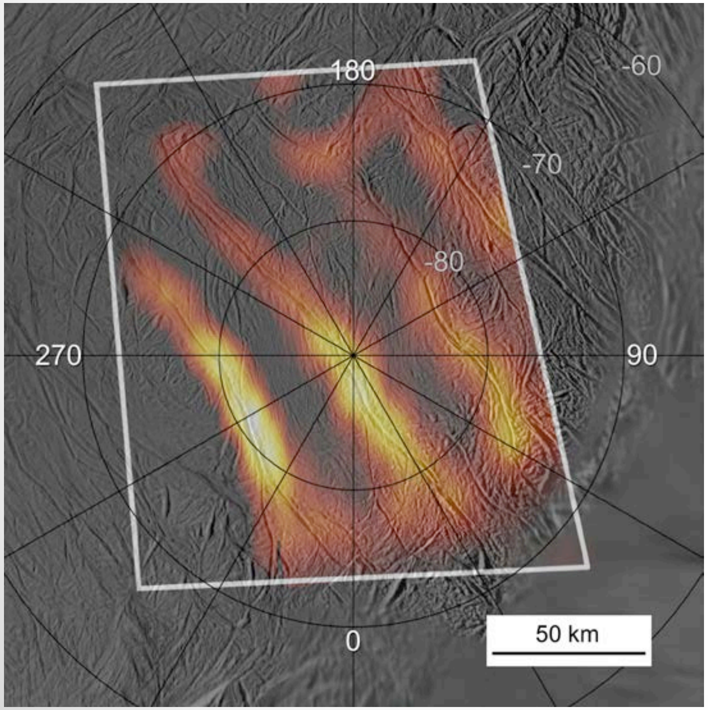
Dotted line is nearest deep space spectra

Estimating Enceladus' passive emission

Effects to "worry about":

- Saturnshine
- Eclipse Effects
- Thermal inertia variations (spatial/depth variations)
- Assumed Albedo
- Spatial distribution of endogenic emission

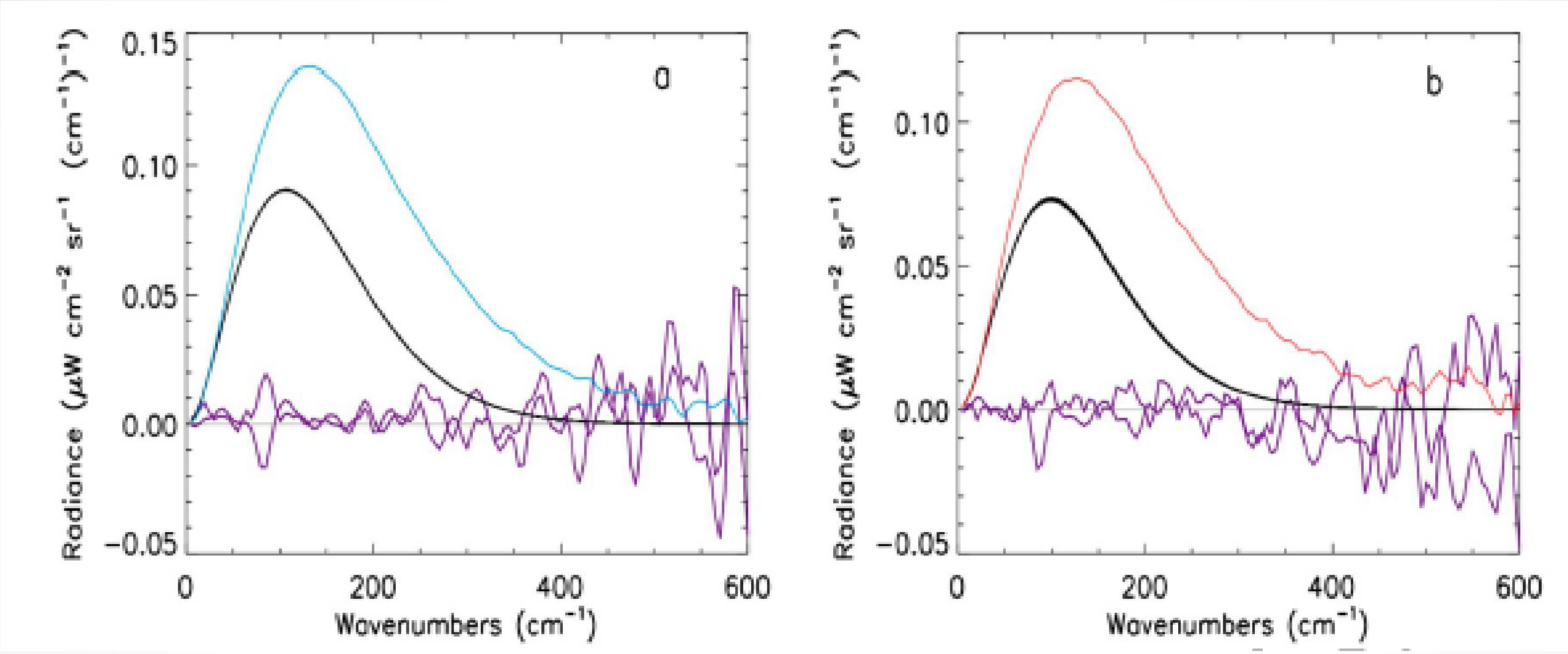




Three spatial distributions considered for the emission of the tiger stripes:

- uniform emission along length of each of the stripes
- emission intensity varies along each stripe according to shorter wavelength FP3 observations
- emission is independent of the tiger stripes but arises instead from an area within the most sensitive central 10% of the FP1 field of view

Calculating Enceladus' thermal emission



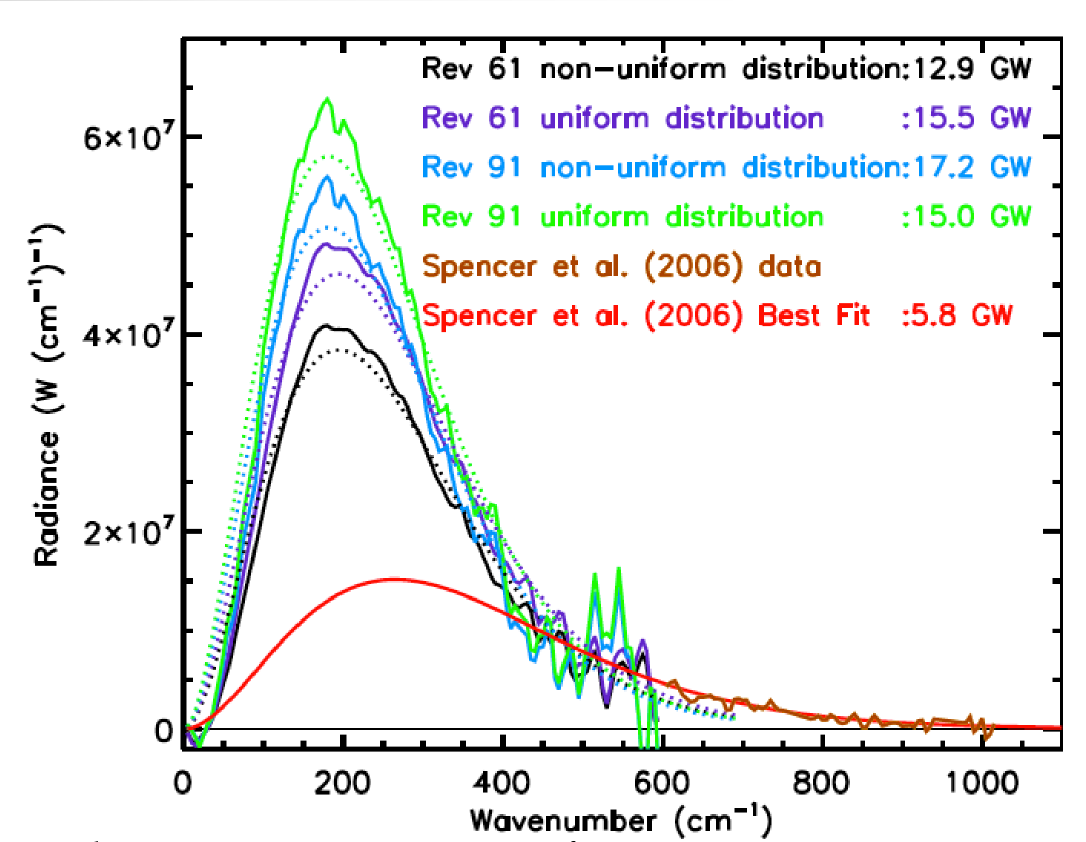
Model passive emission (black line) is shown for a model using thermal inertia scenario 2 and a constant bolometric Bond albedo of 0.80.

Mean observed FP1 spectra for rev 61 and **rev 91** south polar stares

Remove black line from the colored line to finally get the **endogenic component, but the shape of the black line depends on the model assumed.**

(**Deep space spectra** taken closest to each of the observations.)

Calculating Enceladus' thermal emission



Endogenic emission spectra for various passive emission models

Enceladus' Endogenic Emission: 15.8 ± 3.1 GW

Assumed Subsurface Conditions for Thermal Model	Rev 61 Endogenic Power Uniform Spatial Distribution (GW)	Rev 61 Endogenic Power FP3-Like Spatial Distribution (GW)	Rev 61 Endogenic Power Central Spatial Distribution (GW)	Rev 91 Endogenic Power Uniform Spatial Distribution (GW)	Rev 91 Endogenic Power FP3-Like Spatial Distribution (GW)	Rev 91 Endogenic Power Central Spatial Distribution (GW)
Scenario 1	16.6	13.8	8.2	19.3	16.9	11.9
Scenario 2	15.5	12.9	7.6	17.2	15.0	10.6
Scenario 3	16.6	13.8	8.1	16.6	14.5	10.2

Calculating Enceladus' thermal emission

Predicted Power	Power
Radiogenically produced (Porco *et al.*, 2006)	0.3 GW
Maximum steady-state dissipation of tidal heating (Meyer and Wisdom, 2007)	1.1 GW
Initial estimate using CIRS FP3 data (Spencer *et al.*, 2006)	5.8 ± 1.9 GW
Final estimate of this work (Howett *et al.*, 2011a)	**15.8 ± 3.1 GW**

But:
0.3 GW
+
1.1 GW
≠
3.9 (5.8-1.9) GW
≠
12.7 GW

So, what is going on?

Enceladus' thermal emission

So, why the high heat flow at Enceladus' SPT?.....

- Episodic release?
  - Rate of tidal heating is stable but the heat is released episodically.

- Orbital/tidal non-equilibrium?
  - Current activity is a result of recent changes to Enceladus' orbital eccentricity.

- Current tidal model problem?
  - The models rely on assumptions, one of which is how Saturn is able to dissipate its tidal heat. If the assumed value is too high then the heating we see maybe stable.

Enceladus’ thermal emission

So, what are implication of the high heat flow at Enceladus’ SPT?....

Liquid water!

- It’s ‘easier’ to generate the observed power if Enceladus’ core and ice shell were decoupled.
- Could be a global ocean, local south polar sea or more localized pockets of water.

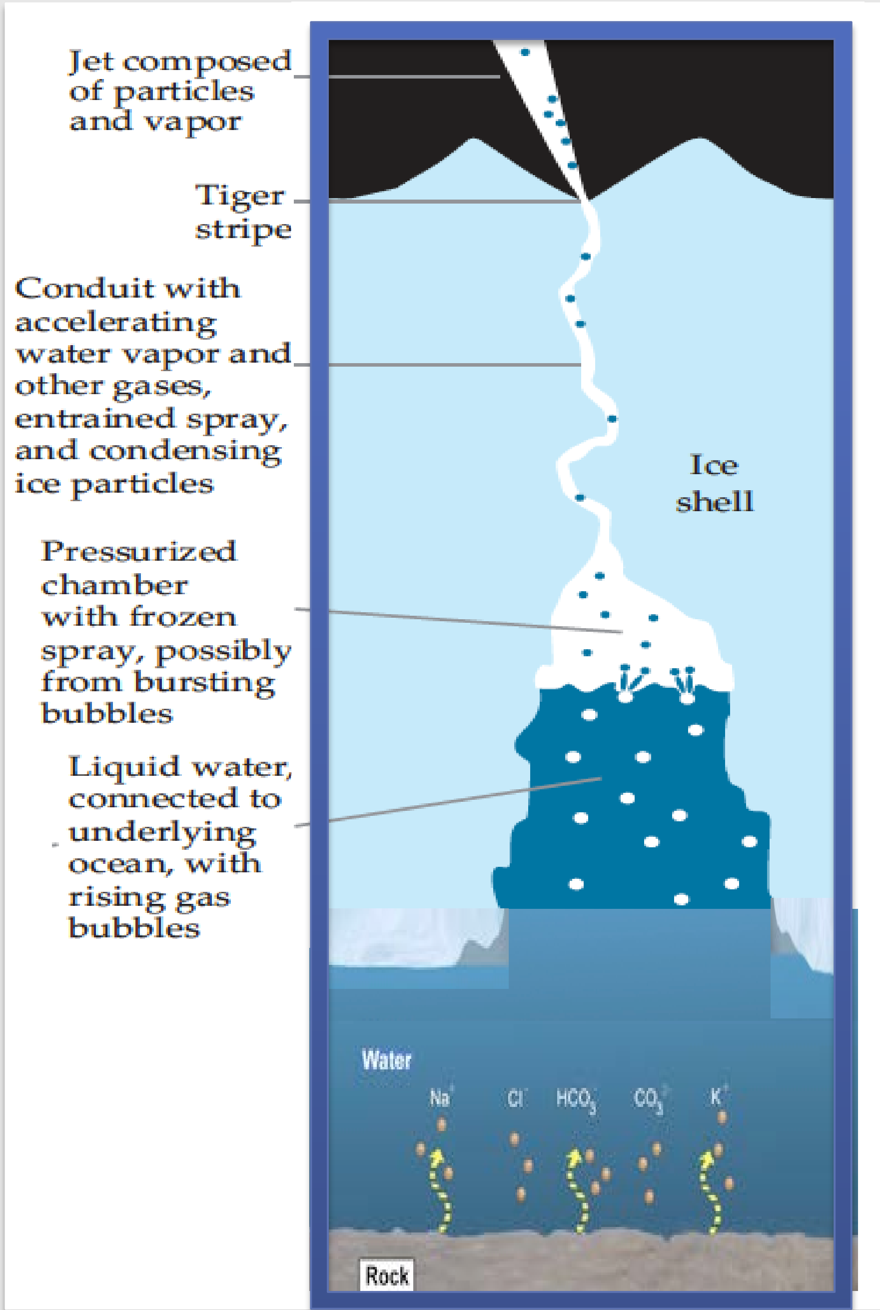
Enceladus' thermal emission: production

What else do we know?

- Ammonia was observed in the plumes
  - Anti-freeze properties, so liquid water could exist at cooler temperatures (176 K, -143 F)

- Salt-rich particles are in the plume
  - The water reservoir from which the plumes are produced must have contact with Enceladus' bedrock

Enceladus' thermal emission: plumes



Not to scale

Adapted from figures by Spencer (2011) (November Physics Today) and Sascha Kempf

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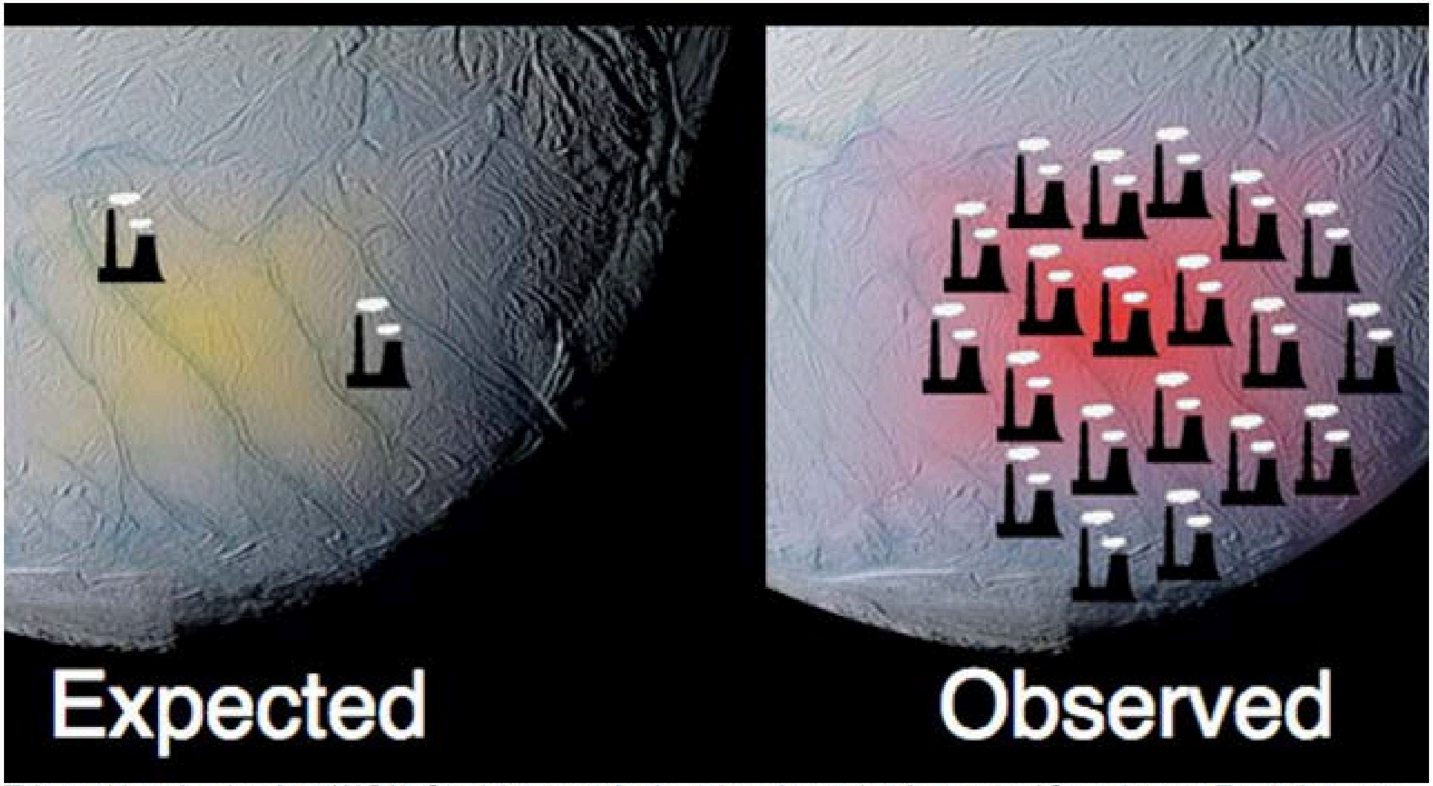
Cassini Finds Enceladus is a Powerhouse



This graphic, using data from NASA's Cassini spacecraft, shows how the south polar terrain of Saturn's moon Enceladus emits much more power than scientists had originally predicted. Images credit: NASA/JPL/SWRI/SSI

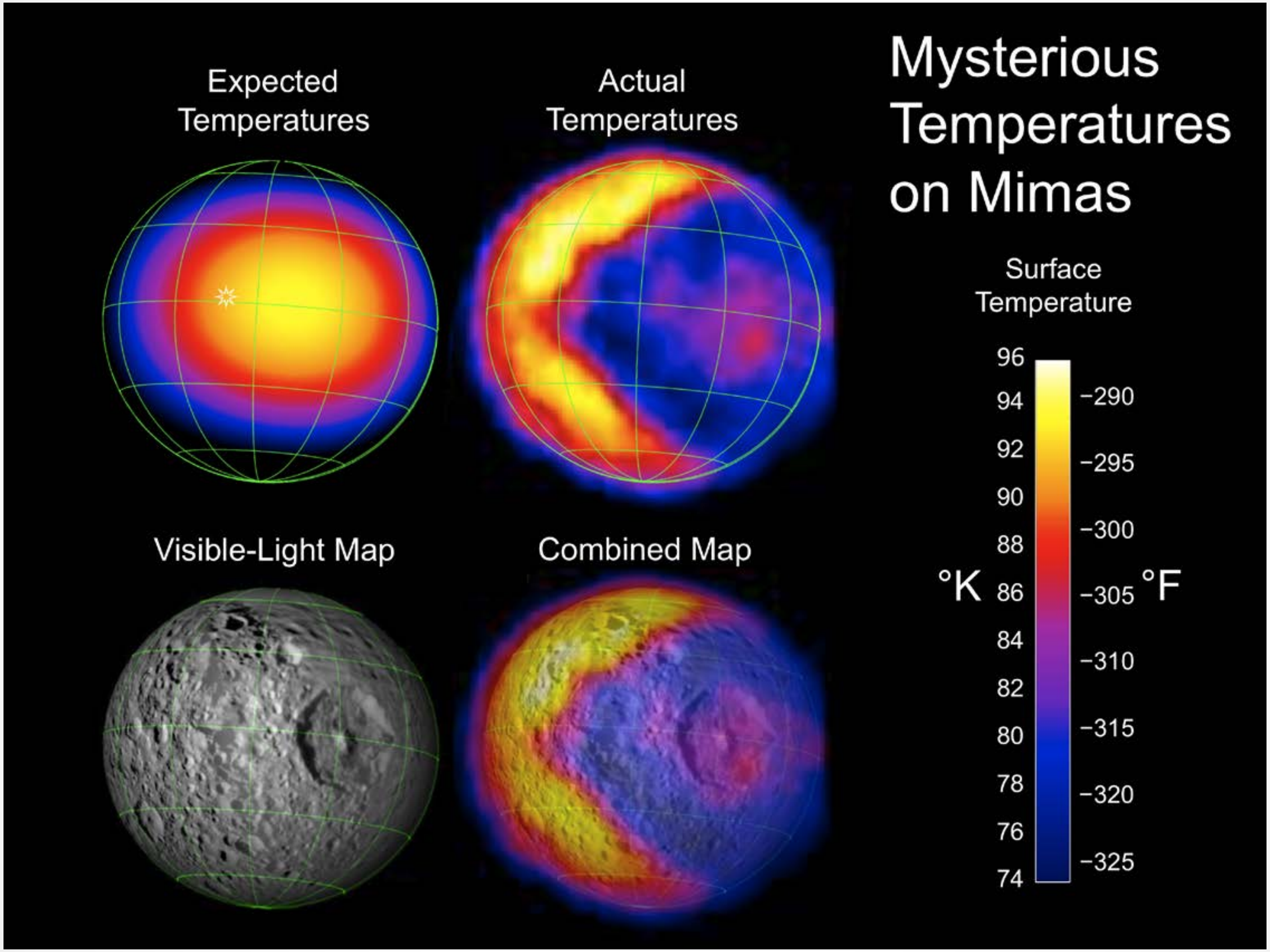
› Full image and caption

March 07, 2011

C.J

PASADENA, Calif. – Heat output from the south polar region of Saturn's moon Enceladus is much greater than

Thermal anomaly on Mimas



JPL/SwRI Press Release March 29 2010

THE PAC-MAN MOON: MIMAS GOES WOCKA-WOCKA-WOCKA

Analysis by Jennifer Ouellette
Wed Mar 31, 2010 01:59 PM ET
(9) Comments | Leave a Comment

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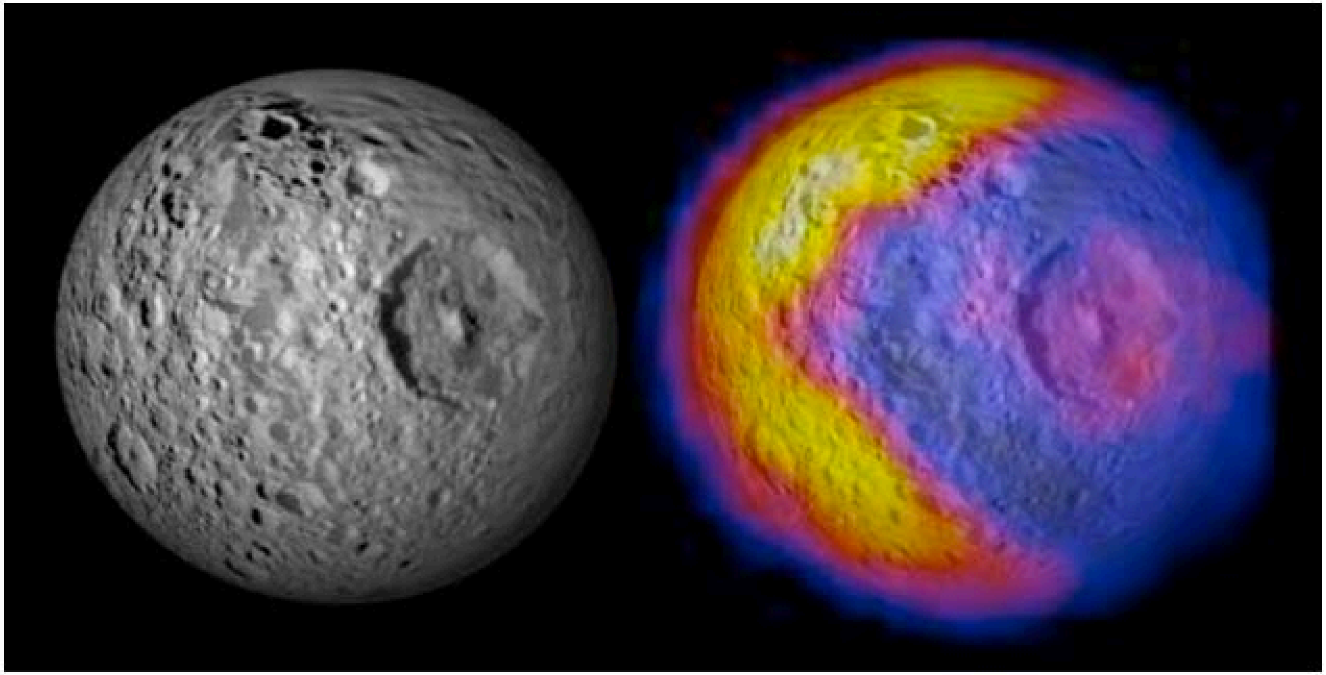


Thermal inertia Variations on Mimas

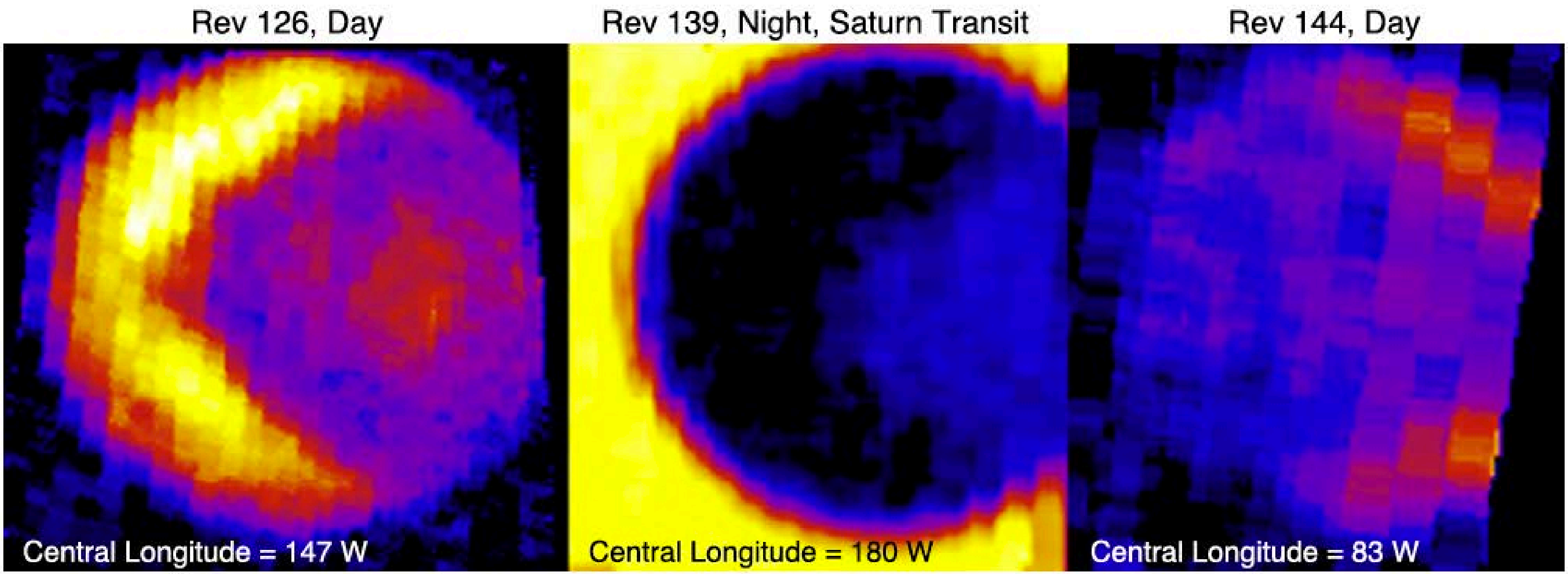


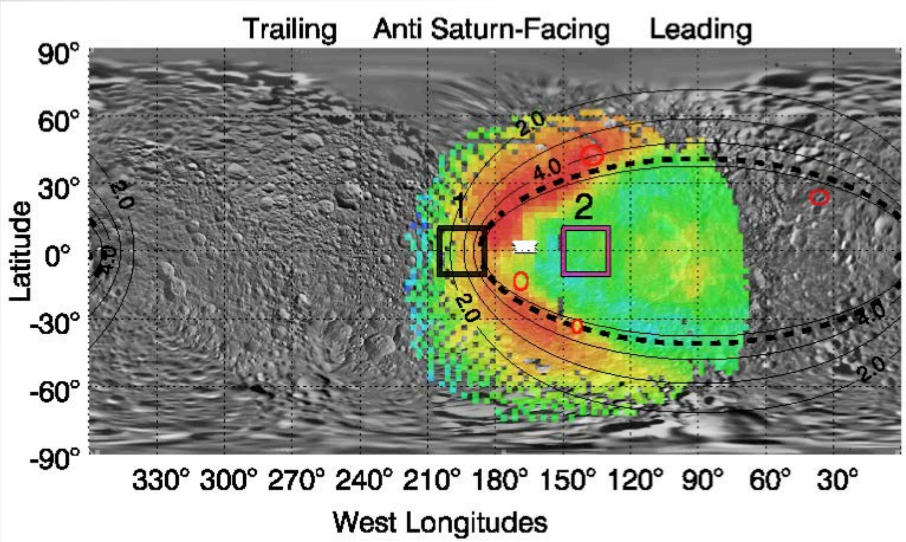
Table 1
Details of the CIRS FP3 observations used in this analysis. Local time is defined as the angular rotation of the body, in degrees, since local midnight.

Orbit	Date	Time (UT)	Sub-solar longitude (°)	Local time coverage between ±20° latitude (°)	Range (km)	Average spatial resolution (km/pixel)
126	13 February 2010	19:10–20:30	164–170	127–264	37,510–65,826	9.0
139	16 October 2010	14:27–16:53	85–90	4–130	73,167–101,071	16.0
144	31 January 2011	01:30–03:05	34–53	70–207	138,88–141,011	42.2

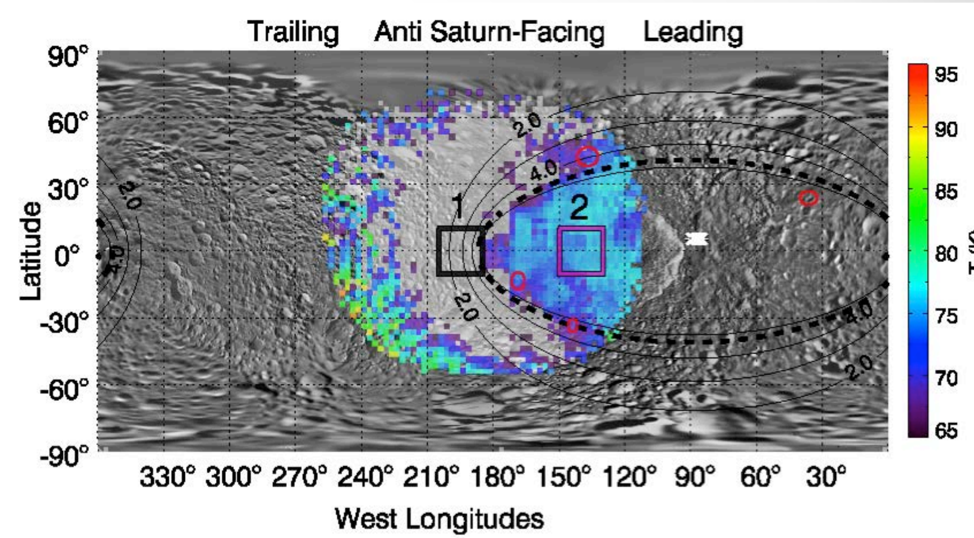
Howett *et al.* (2011b)

CIRS Results

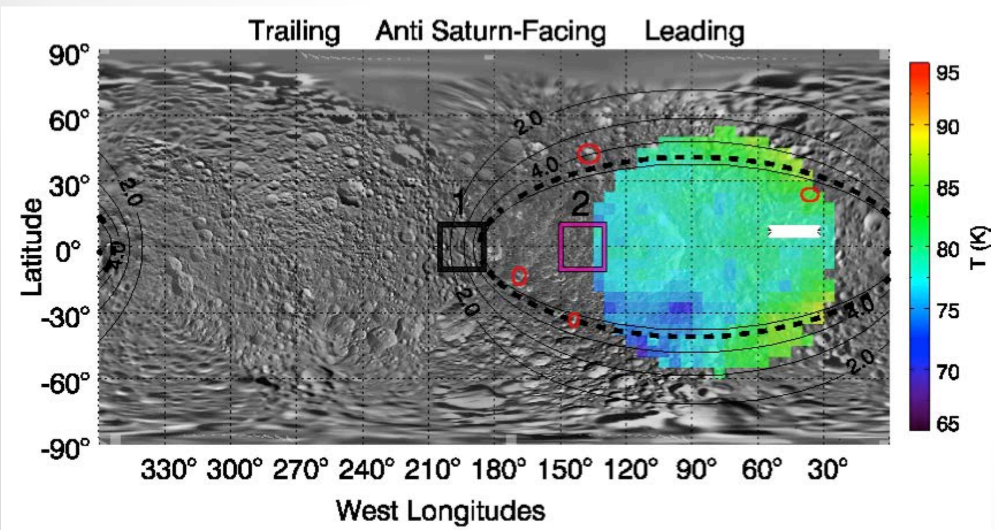
Feb 2010



Oct 2010



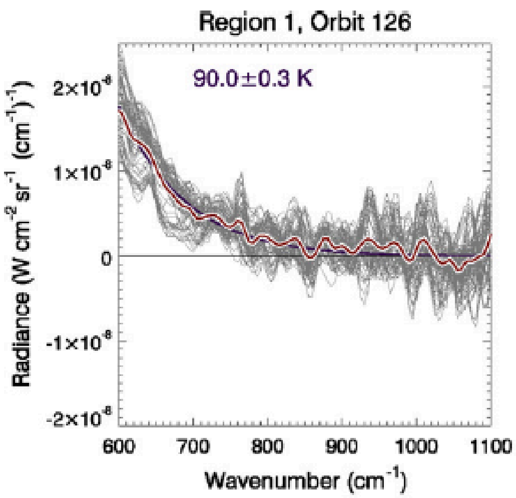
Jan 2011



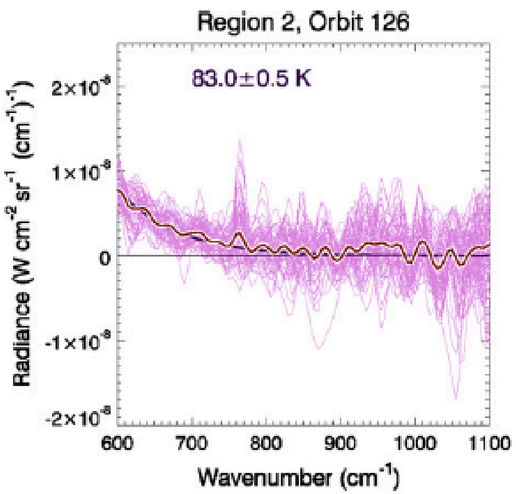
- The presence of a thermal anomaly on Mimas' leading hemisphere was confirmed in the results from all three recent encounters with Mimas.

Determining Mimas' Surface Thermal Properties

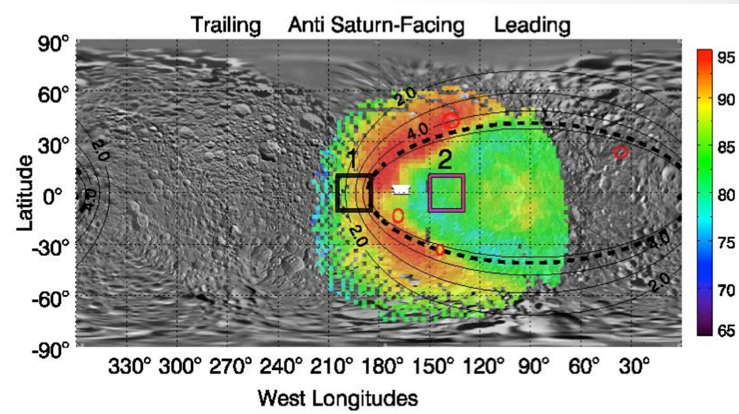
CIRS FP3 Spectra for each observation taken in each Region

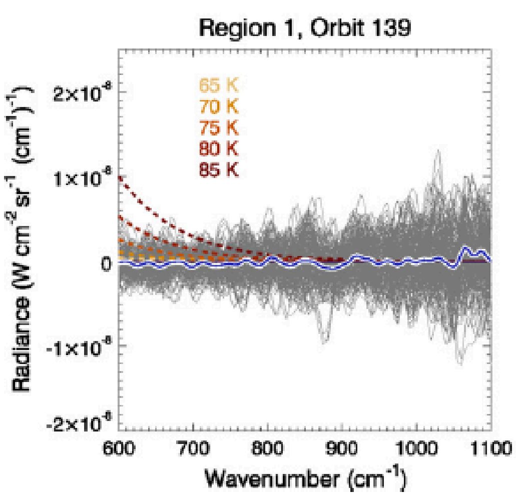


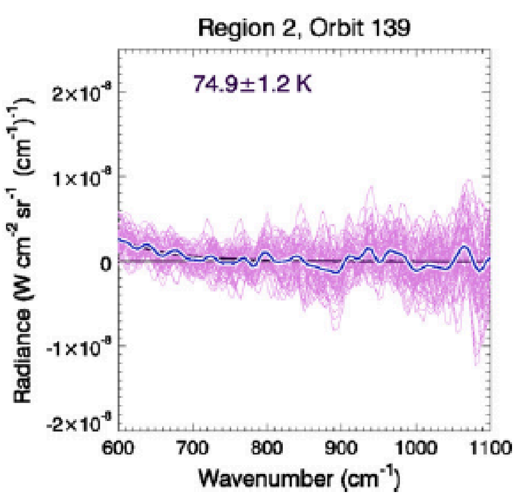
(a) Region 1

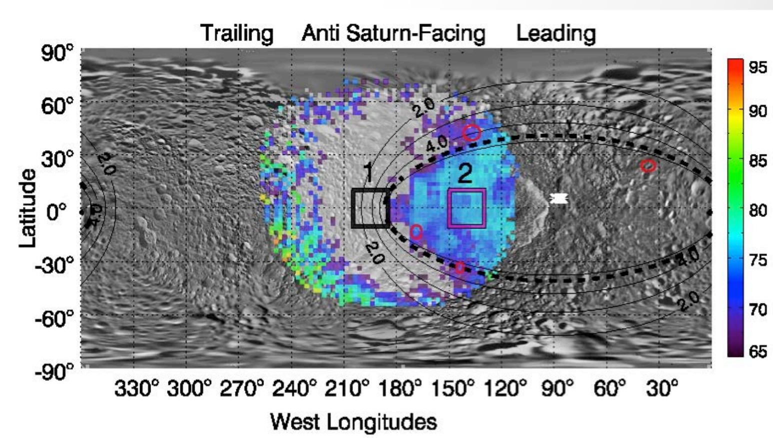


(b) Region 2



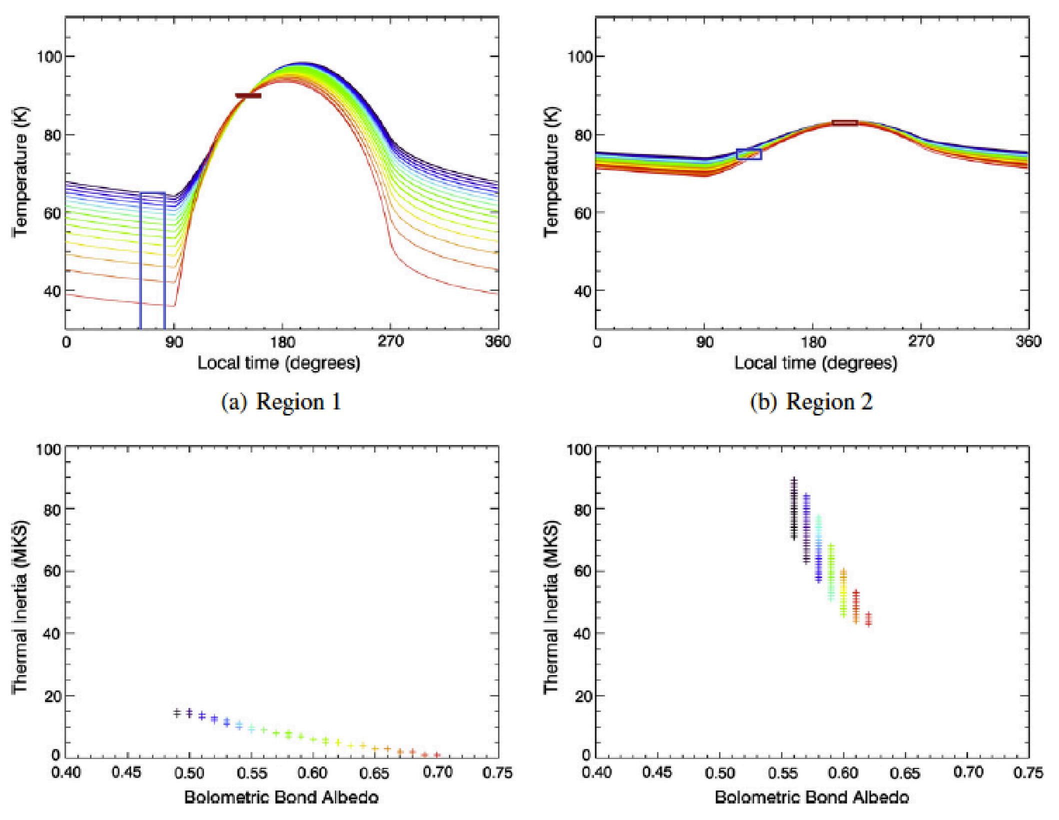


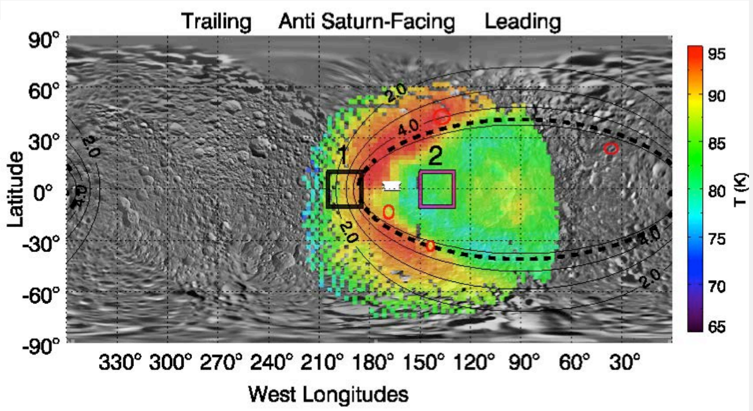


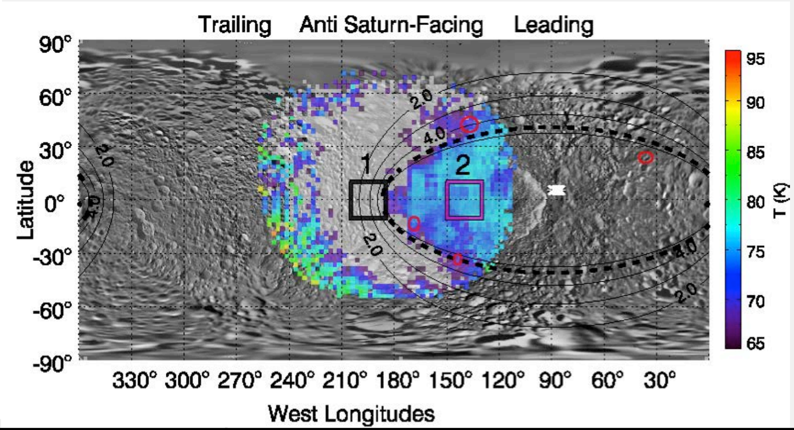


Determining Mimas' Surface Thermal Properties

Diurnal curves and their corresponding thermal physical properties that are able to fit Mimas' observed temperatures







Box	Albedo	Thermal Inertia
1 (outside the anomaly)	**0.60±0.11**	**<16 MKS**
2 (inside the anomaly)	0.59±0.03	66±23 MKS

Mimas' Surface Thermal Properties

Target	Bolometric albedo	Thermal inertia (MKS)	Skindepth (cm)	References
Jovian satellites				
Io	0.52	70	0.39[c]	Rathbun et al. (2003)
Europa	0.55	70	0.55[c]	Spencer et al. (1999)
		14 ± 5	0.01[d]	Hansen (1973)
Ganymede	0.32 ± 0.04	70 ± 20	0.78[c]	Spencer (1987)
		12 ± 3	0.01[d]	Hansen (1973)
		14 ± 3	0.01[d]	Morrison and Cruikshank (1973)
Callisto	0.2 ± 0.4	50 ± 10	0.86[c]	Spencer (1987)
		10 ± 1	0.01[d]	Morrison and Cruikshank (1973)
Saturnian satellites				
Mimas	$0.49^{+0.05}_{-0.14}$	19^{+57}_{-9}	0.54	
Enceladus	0.81 ± 0.04	15^{+24}_{-9}	0.51	
Tethys	0.67 ± 0.11	9^{+10}_{-4}	0.36	
Dione	0.63 ± 0.15	11^{+18}_{-6}	0.53	
Rhea trailing	$0.57^{+0.20}_{-0.26}$	8^{+12}_{-5}	0.50	
Rhea leading	$0.63^{+0.11}_{-0.12}$	9^{+9}_{-5}	0.56	
Iapetus trailing	$0.31^{+0.15}_{-0.17}$	20^{+13}_{-8}	5.22	
Iapetus leading	0.10[a]	14^{+7}_{-8}[a]	3.66	
Phoebe	0.1	20/25[b]		

Table 7, Howett *et al.*, (2010)

New Mimas Thermophysical Values

Box	Albedo	Thermal Inertia
1 (outside anomaly)	**0.60±0.11**	**<16 MKS**
2 (inside anomaly)	**0.59±0.03**	**66±23 MKS**

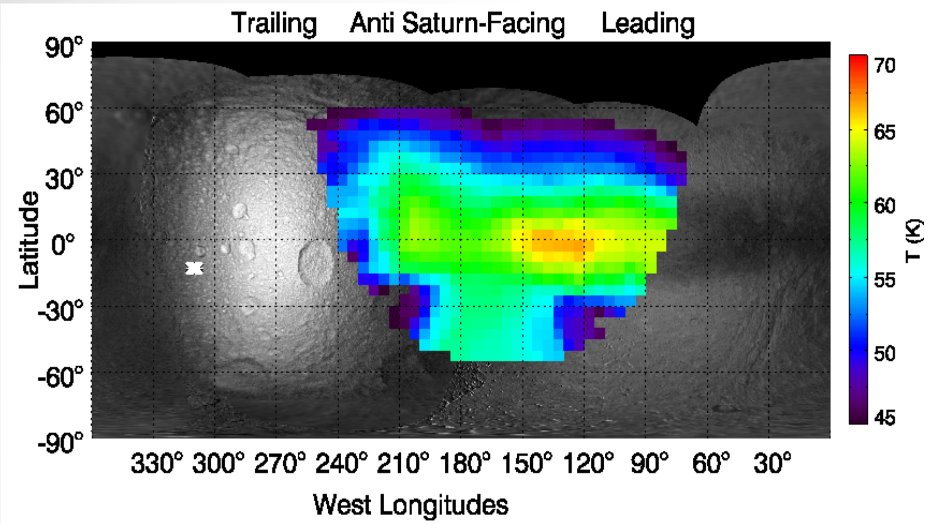
- The thermal inertia inside of the anomalous region is much higher than seen elsewhere in the Saturnian system.
- The thermal inertia outside of the anomalous region is consistent with the other Saturnian icy satellites.
- Albedos across Mimas' surface are comparable with Saturnian icy satellite values

Are there more Pac-People?

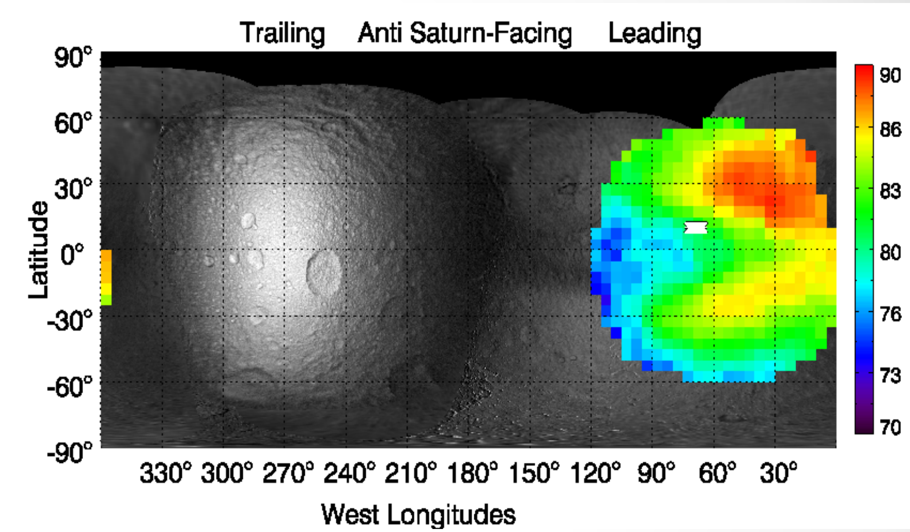
Tethys?

Tethys CIRS observed temperatures during

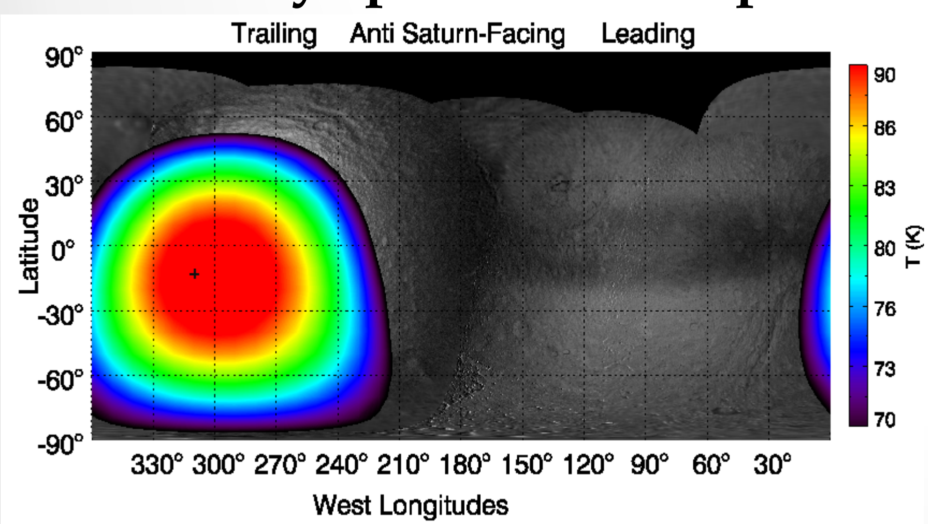
June 2007 (nighttime)

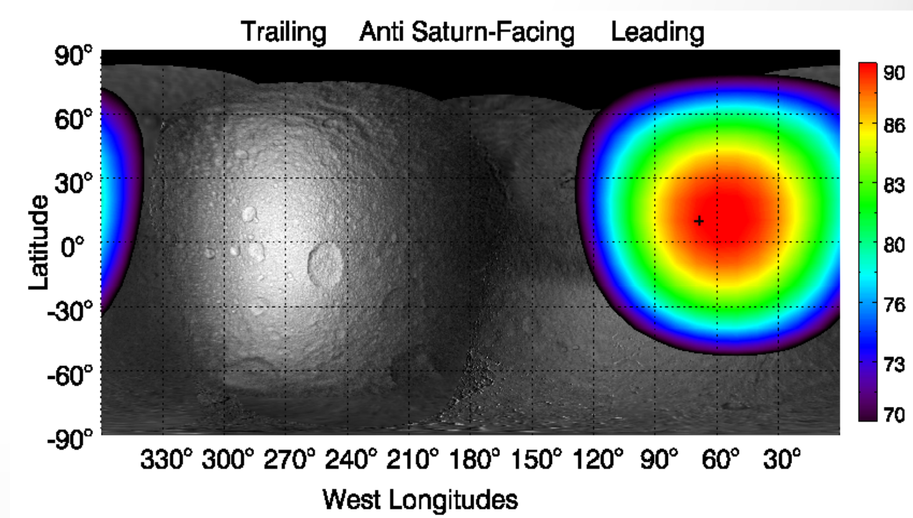


Sept 2011 (daytime)



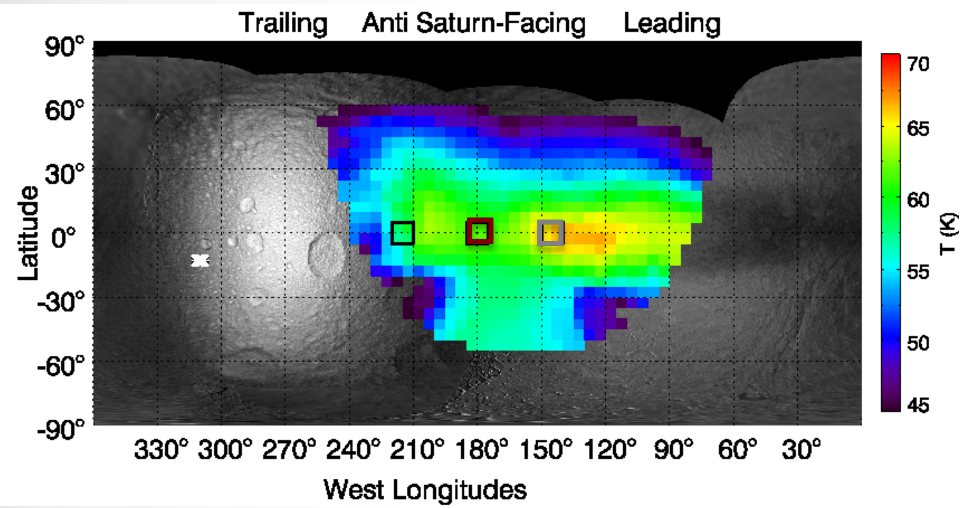
Tethys predicted temperatures

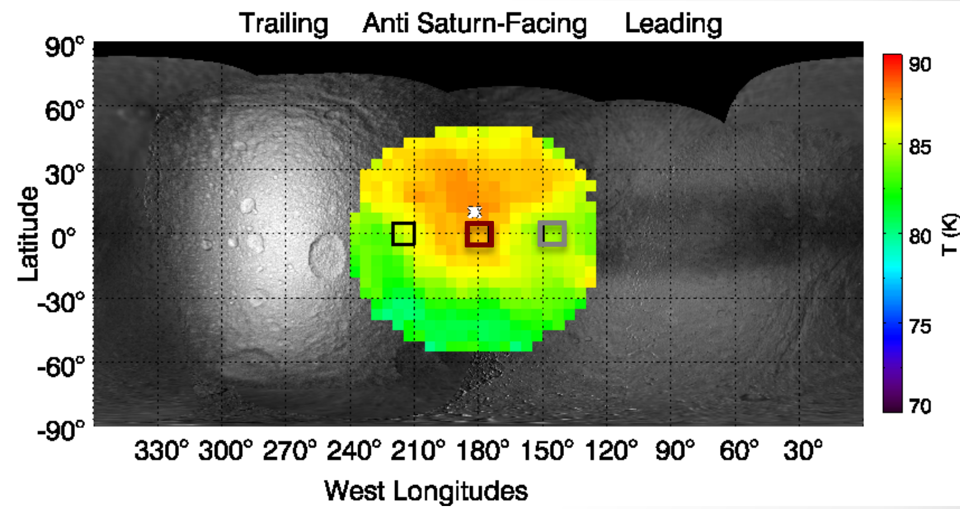




Tethys' thermophysical surface properties

Tethys CIRS observed temperatures during June 2007 (nighttime) | **Sept 2011 (daytime)**

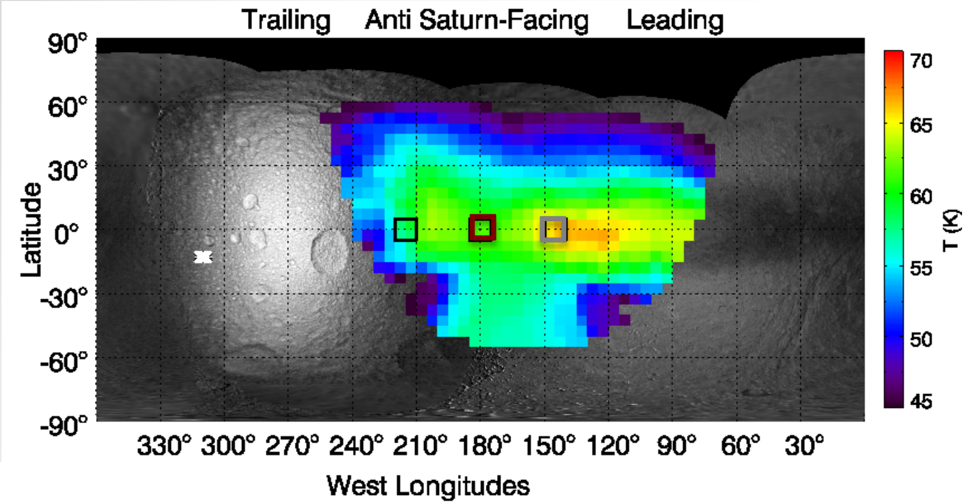


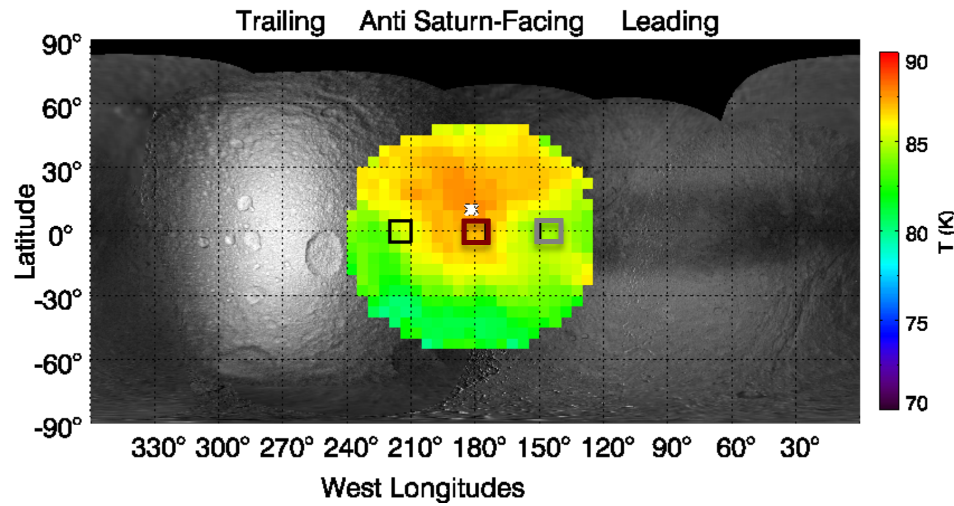


	Box 1	Box 2	Box 3
Longitude	210° -> 220° W	175° -> 185° W	140° -> 150° W
Latitude	5° S -> 5° N	5° S -> 5° N	5° S -> 5° N

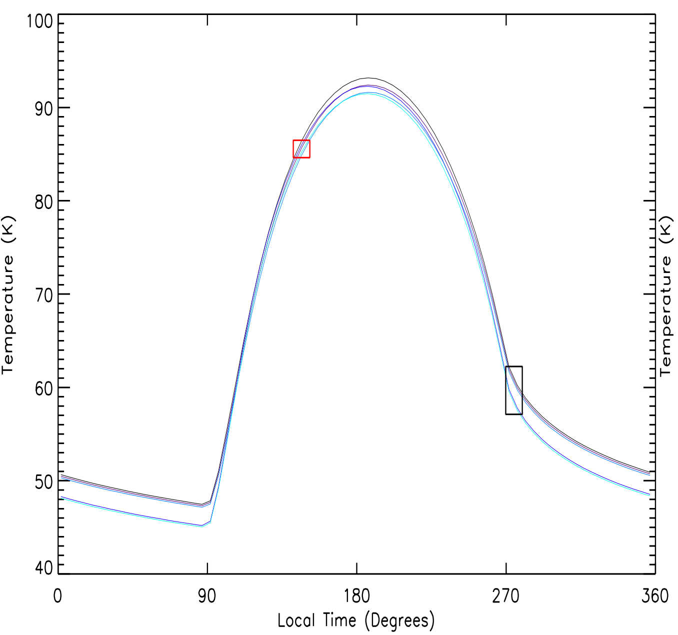
Tethys CIRS observed temperatures during

June 2007 (nighttime) Sept 2011 (daytime)

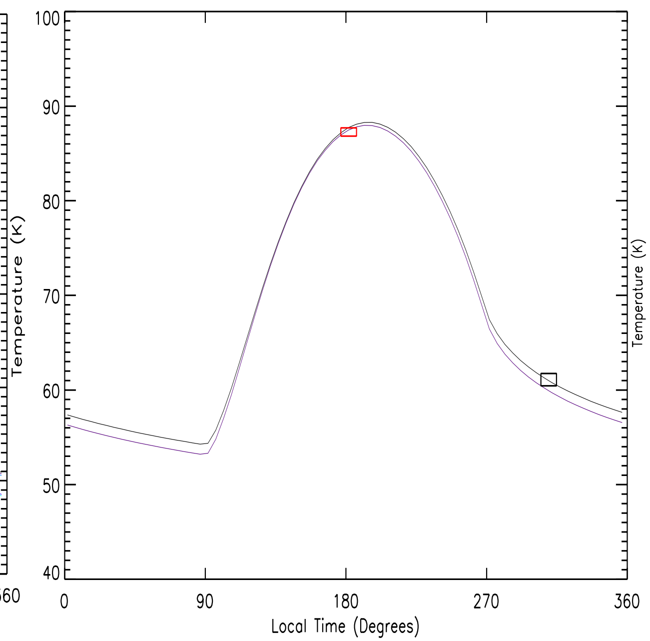




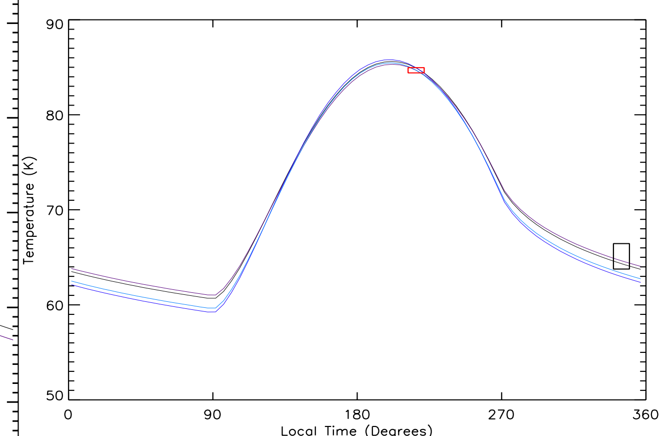
Diurnal curves able to fit the daytime and temperatures observed in the above boxes



Box 1



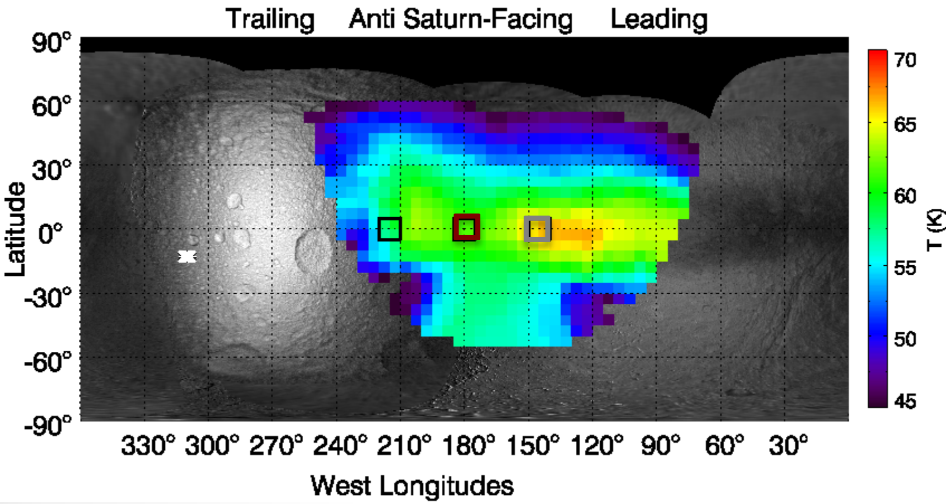
Box 2



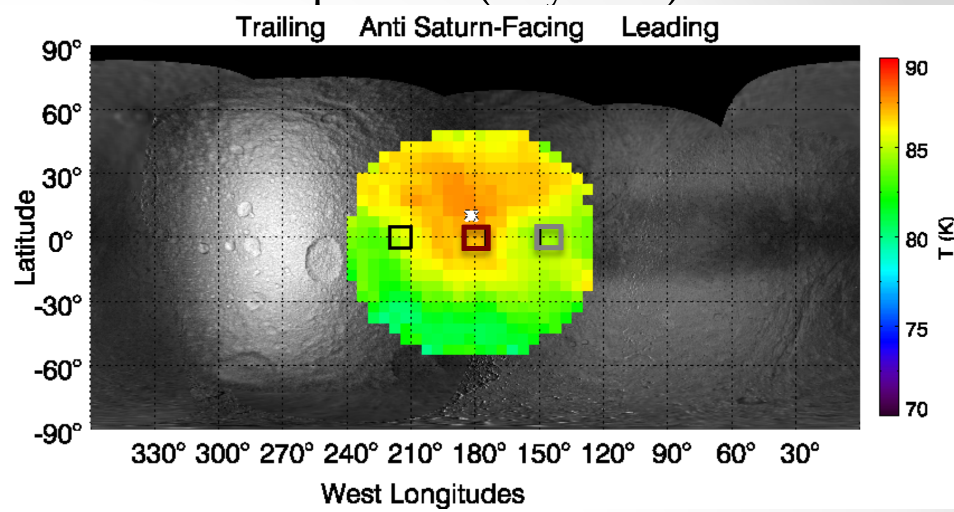
Box 3

Tethys CIRS observed temperatures during

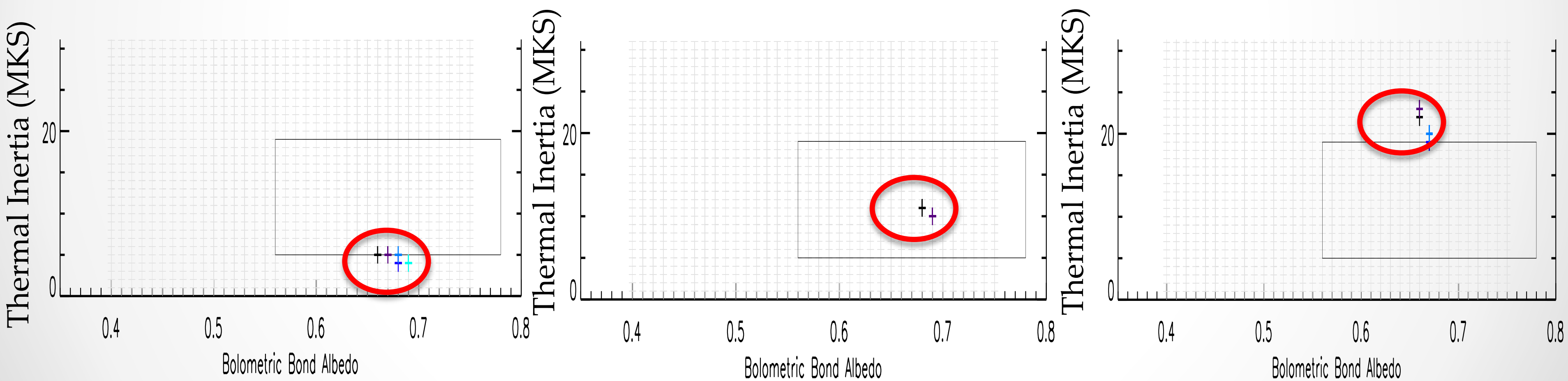
June 2007 (nighttime)



Sept 2011 (daytime)

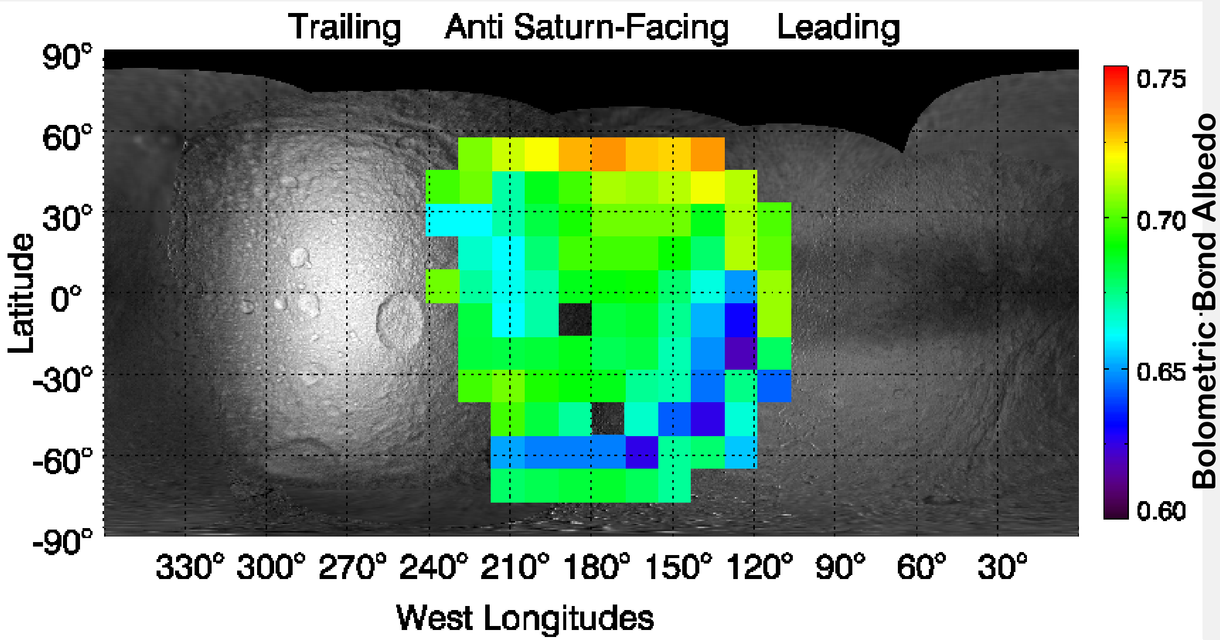


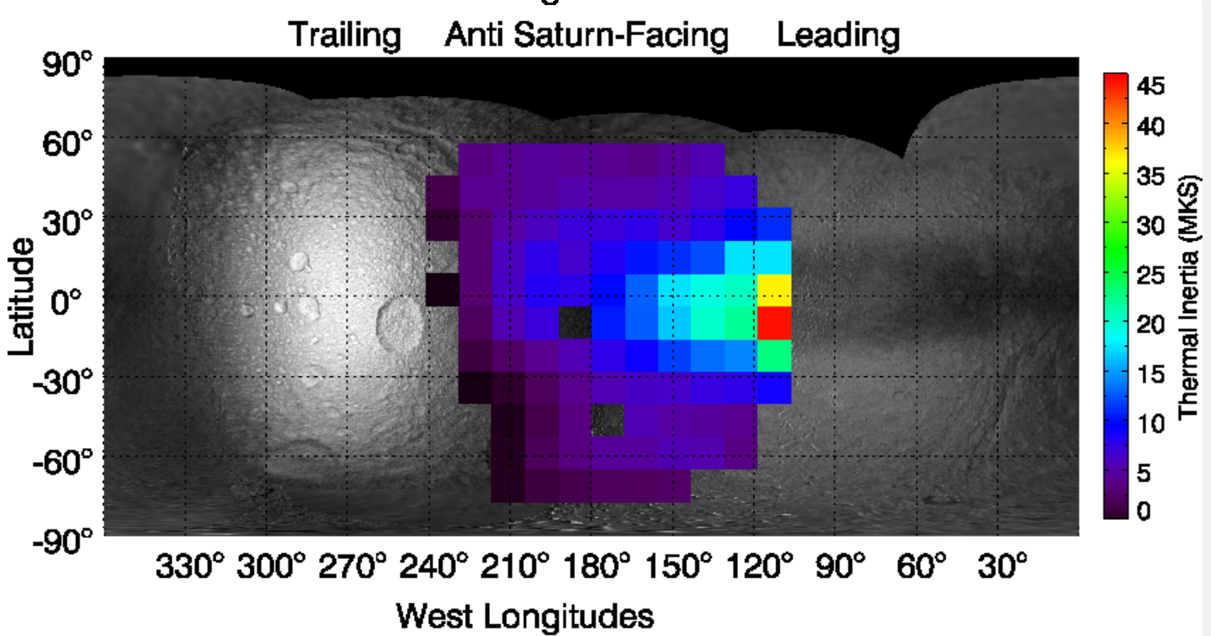
Plausible Albedo and Thermal Inertia Combinations for each Box



	Box 1	Box 2	Box 3
Albedo	0.68±0.02	0.68±0.01	0.67±0.01
Thermal Inertia	5±1 MKS	11±1 MKS	21±2 MKS

Tethys' thermophysical surface properties





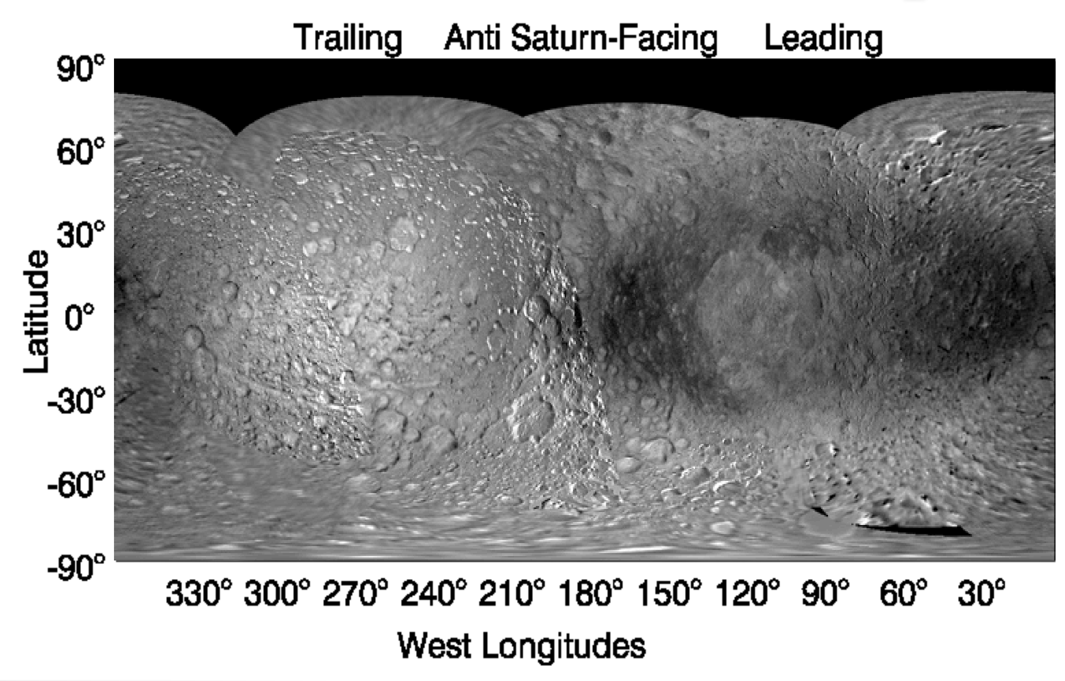
Tethys Thermal Inertia and Bolometric Bond Albedo maps

Albedo is fairly stable around 0.70

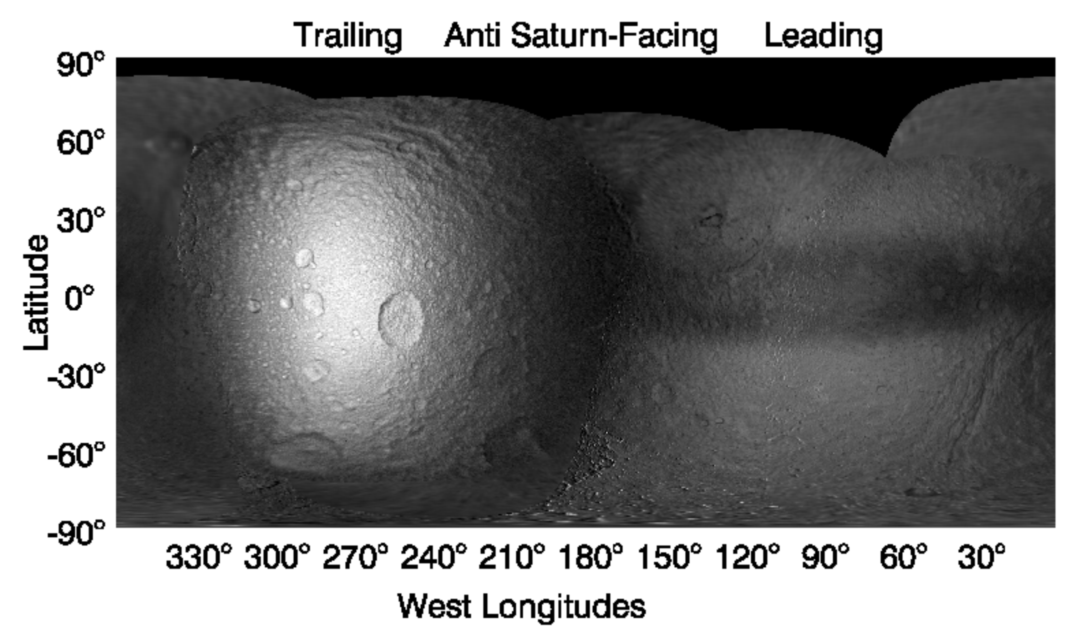
Thermal inertia is:
<10 MKS outside of the anomalous region
>35 MKS inside of the anomaly

How are these thermal anomalies being formed?

IR/UV color ratio maps (Schenk *et al.*, 2011)



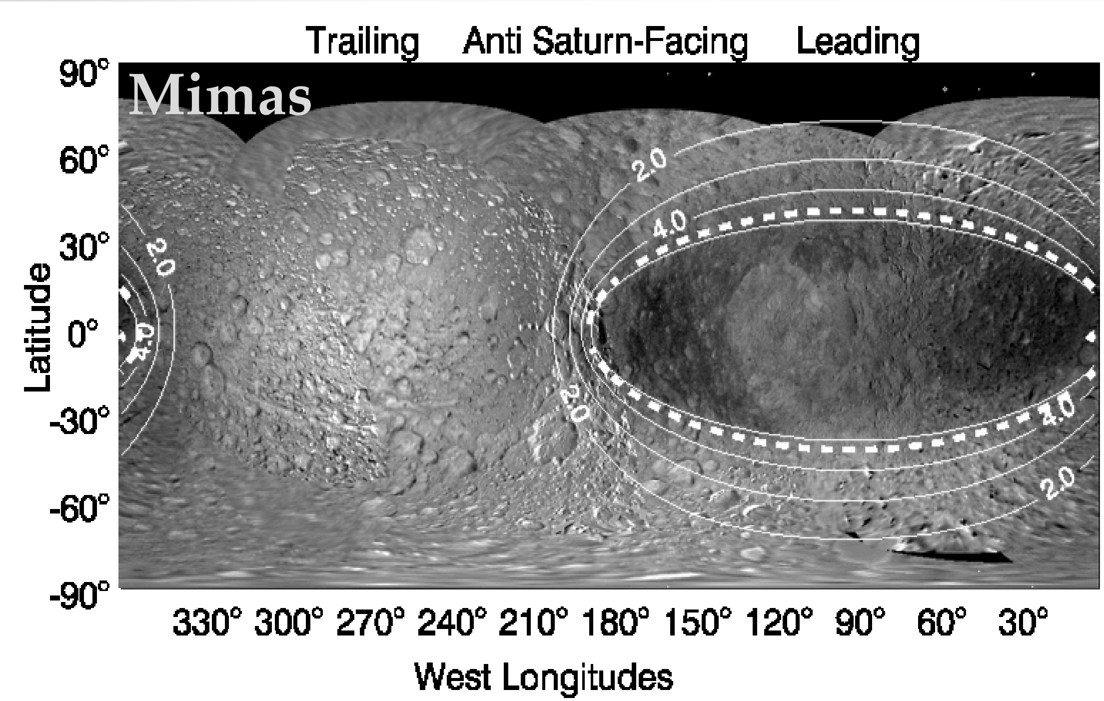
Mimas

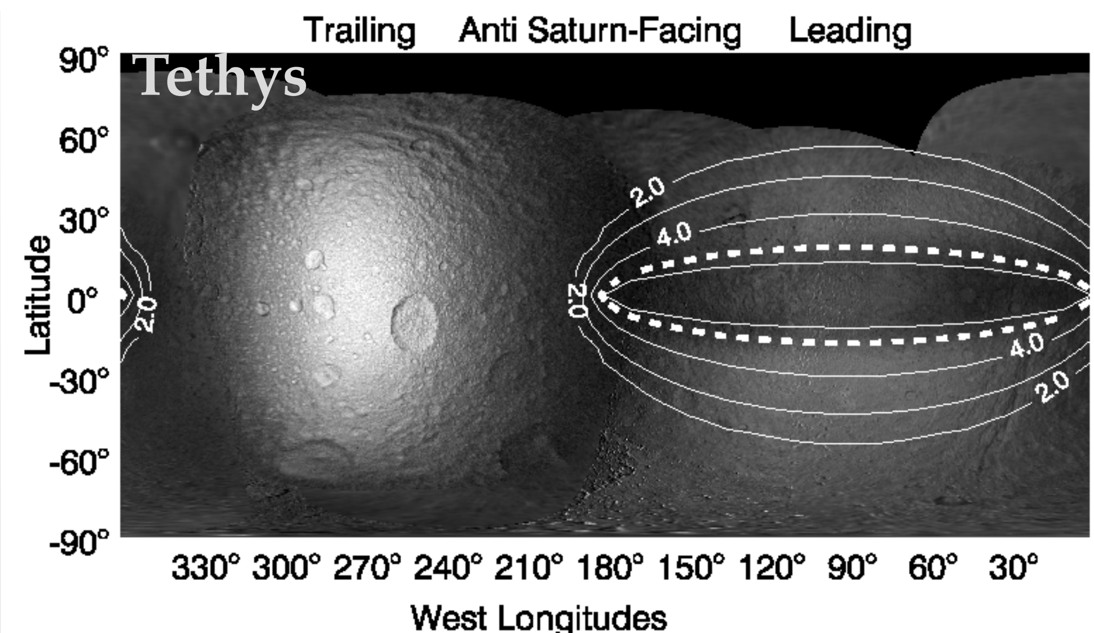


Tethys

A lens-shaped feature on the leading hemisphere is also seen on Mimas' and Tethys' surface in the IR/UV color ratio maps.

IR/UV color ratio maps (Schenk *et al.*, 2011)



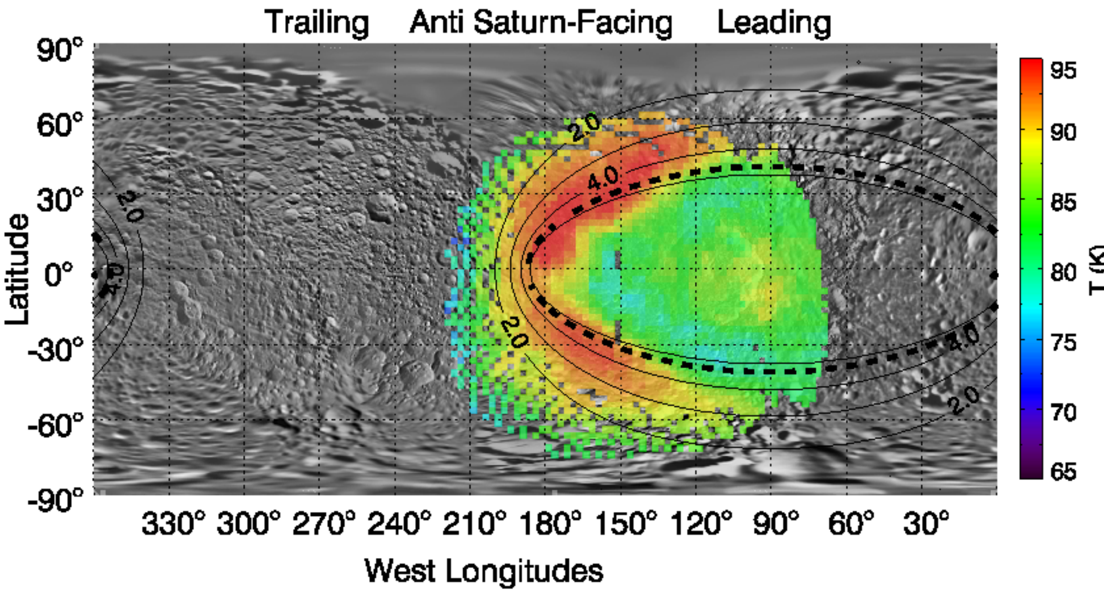


IR/UV color ratio maps with white lines showing contours of electron flux in 10^x MeV cm^{-2} s^{-1}.
(Schenk *et al.*, 2011)

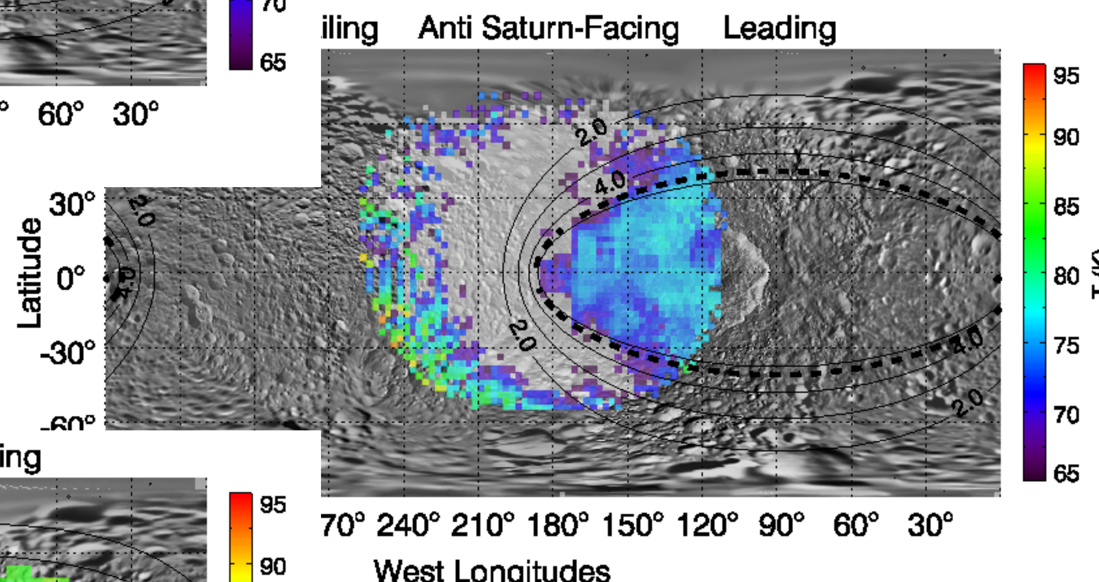
The dark IR/UV regions appear to be spatially well correlated with the regions preferentially bombarded by high-energy electrons.

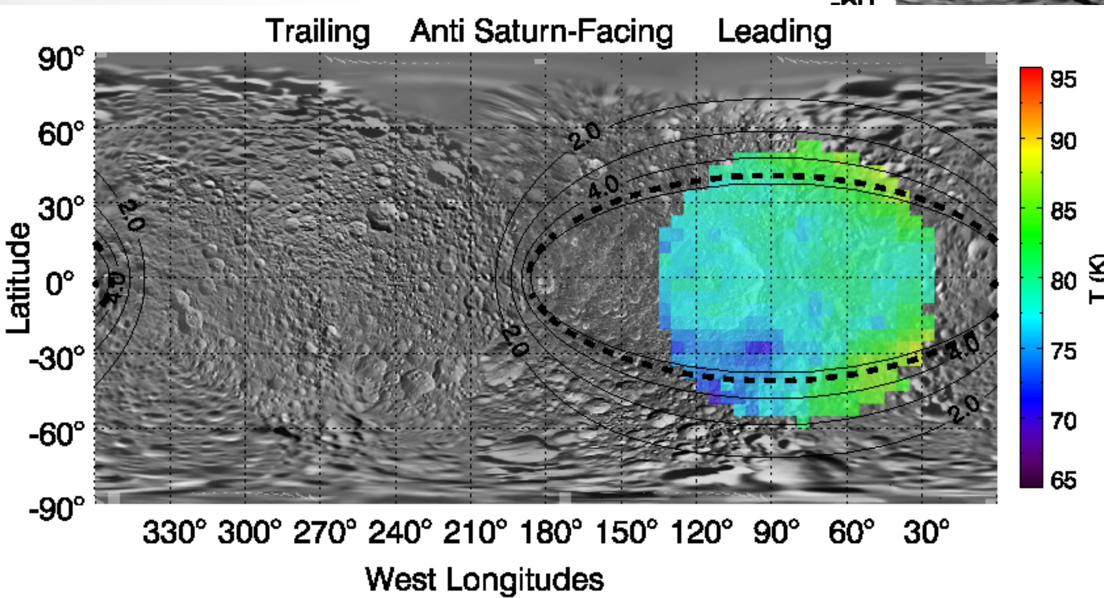
Dotted contours show those that best match the boundary of the dark IR/UV region at $10^{4.75}$ MeV cm^{-2} s^{-1} for Mimas and $10^{4.25}$ MeV cm^{-2} s^{-1} for Tethys. Equivalent to:
56 GeV cm^{-2} s^{-1} (Mimas)
18 GeV cm^{-2} s^{-1} (Tethys)

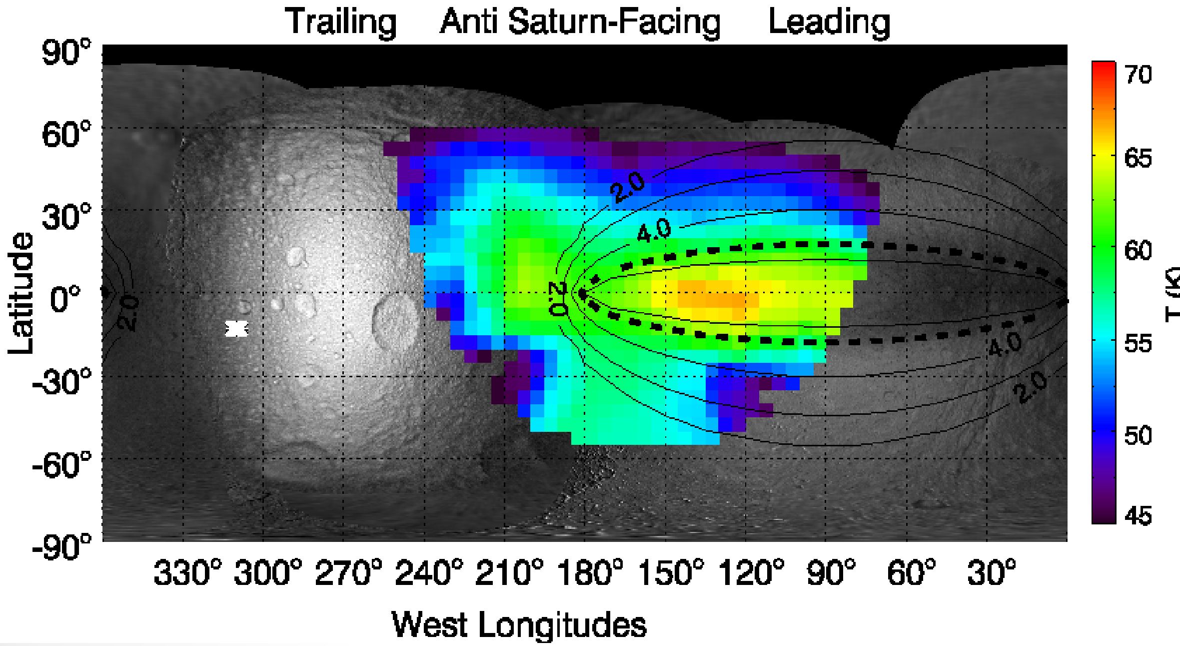
Spatial correlation between regions preferentially bombarded by high-energy electrons and the thermal anomaly



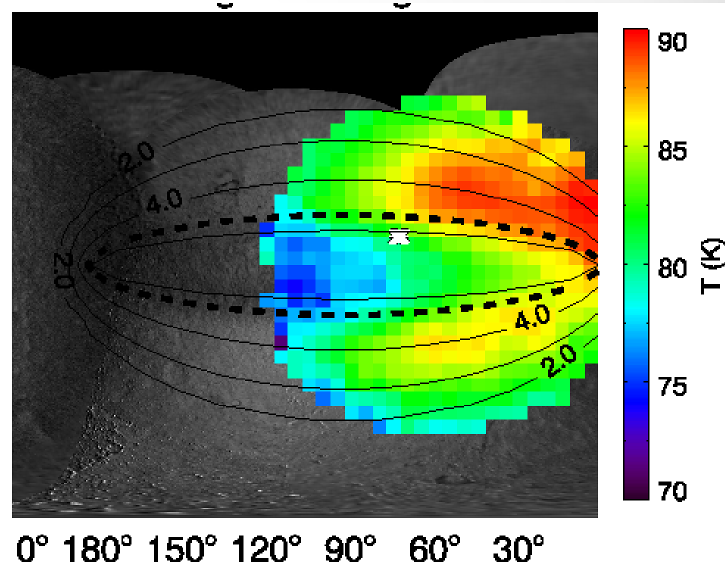
Mimas



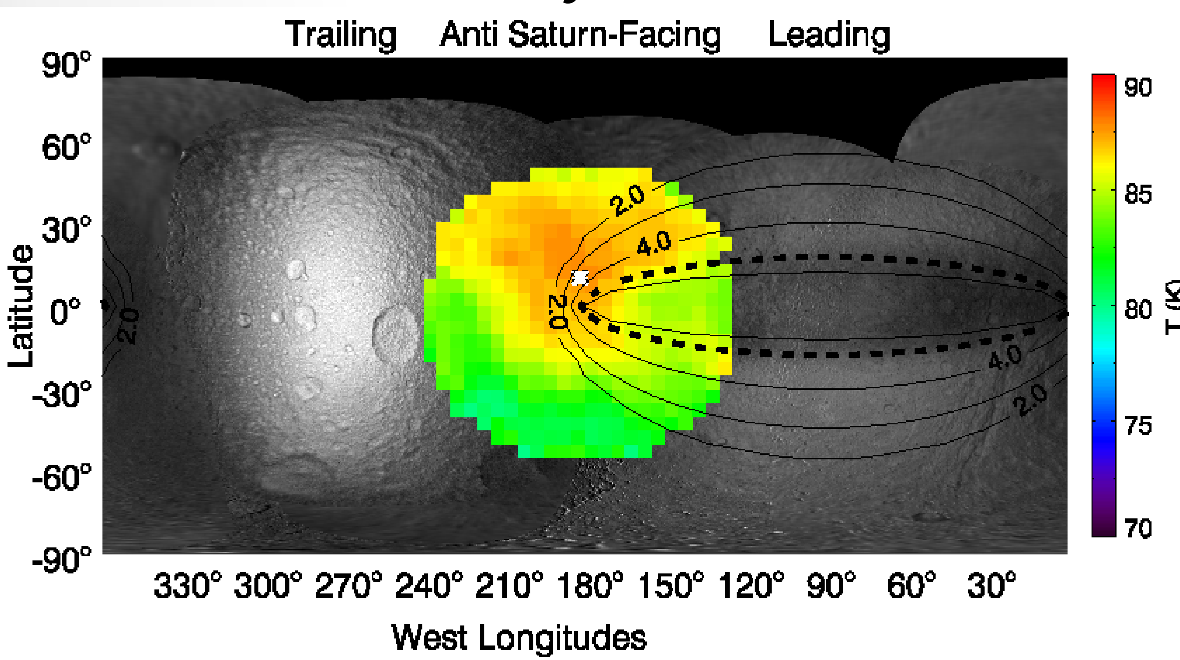




Spatial correlation between regions preferentially bombarded by high-energy electrons and the thermal anomaly

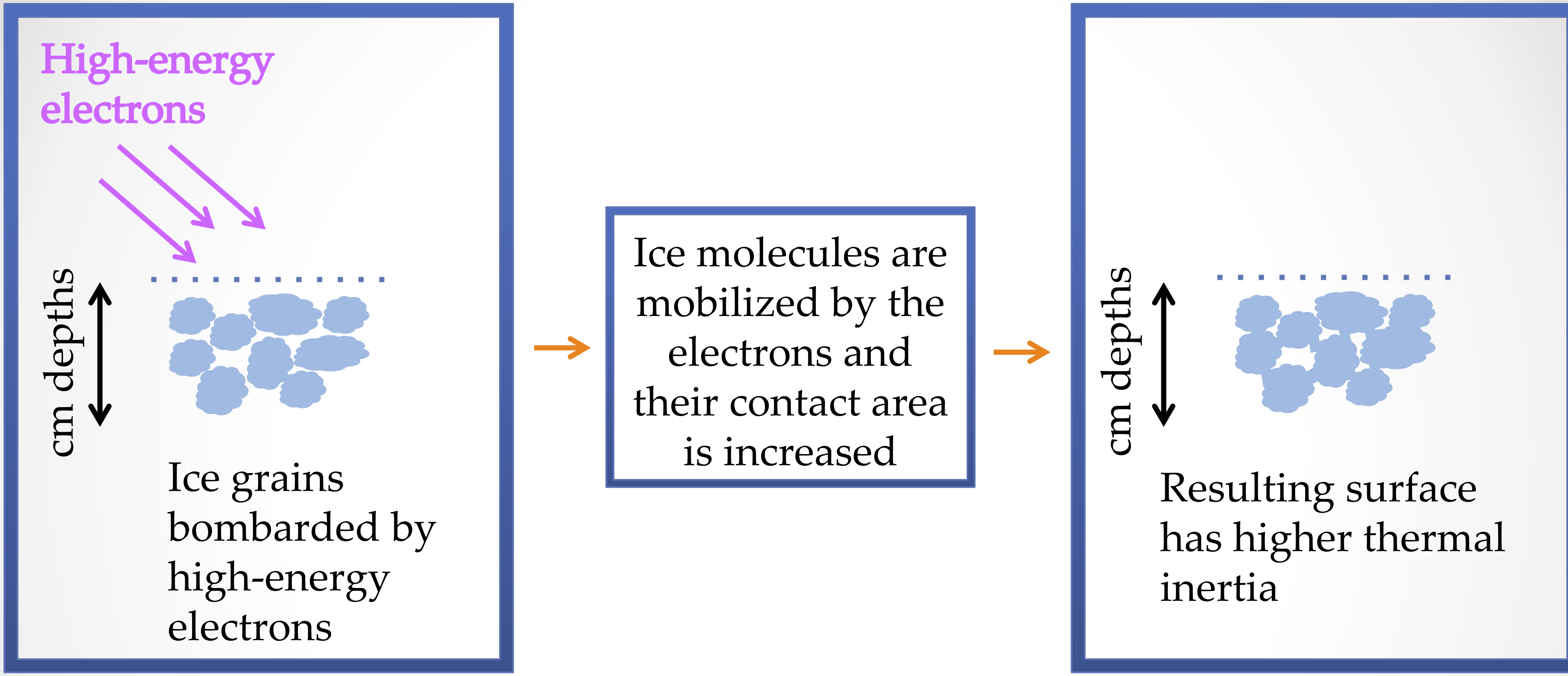


Tethys



Conclusion: there's a clear correlation here too.

How is the surface thermal inertia on Mimas and Tethys being modified by high-energy electrons



- High-energy electrons are able to penetrate the top few surface cms of Mimas' and Tethys' surface.
- Diurnal temperatures probe thermophysical properties over a depth range given by the thermal skin depth.
- For Mimas and Tethys the estimated skin depth is 0.5 to 3 cm (depending on the assumed surface properties)

Conclusion

- Enceladus' heat-flow is much higher than previously estimated
  - It is still not understood how such high heat flows are being produced
  - Such high heat flows would be difficult to produce without sub-surface liquid water
- Thermal anomalous regions are present on Mimas' and Tethys' leading hemispheres.
  - The thermal anomalies are located in regions of high IR/UV albedo and preferential high-energy electron bombardment.
  - High-energy electrons mobilize ice-grains, essentially gluing them together, increasing the surface's thermal inertia.