Les anneaux de Saturne et l'orbiteur spatial CASSINI

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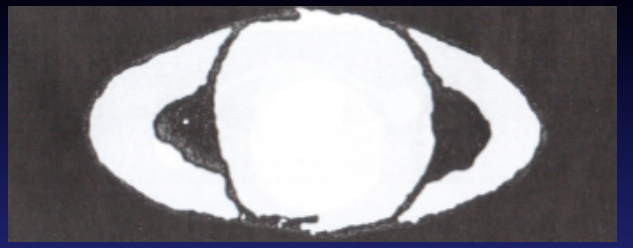
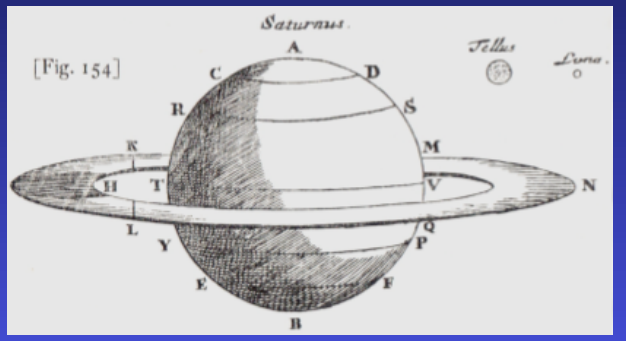
Séminaire LPNHE - Laboratoire de Physique Nucléaire et de Hautes Energies – 5 nov. 2009

1610 Dessin de Galilée

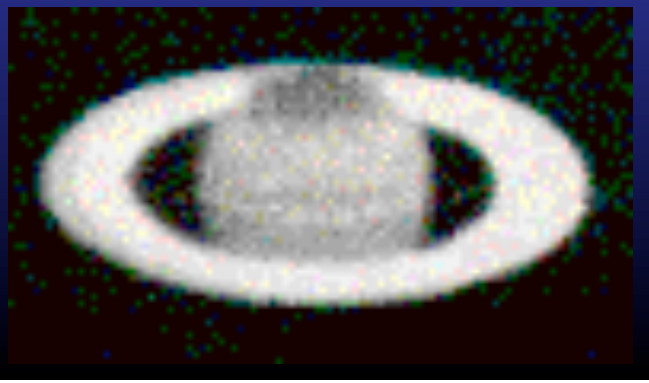


1659 Dessin de Huygens



1676 Dessin de Cassini

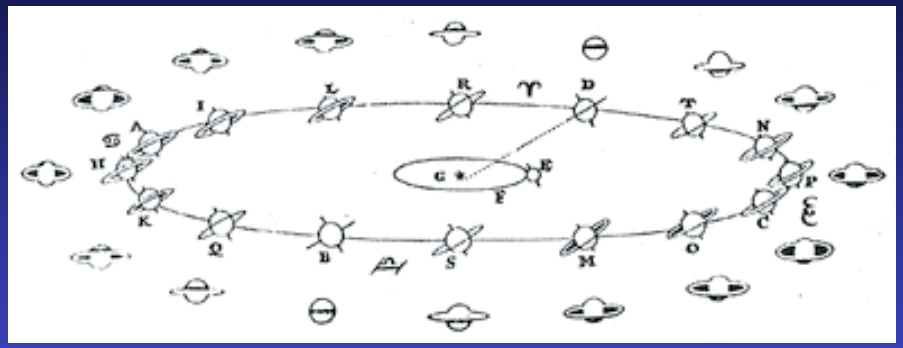
1883 Première photo de Commons



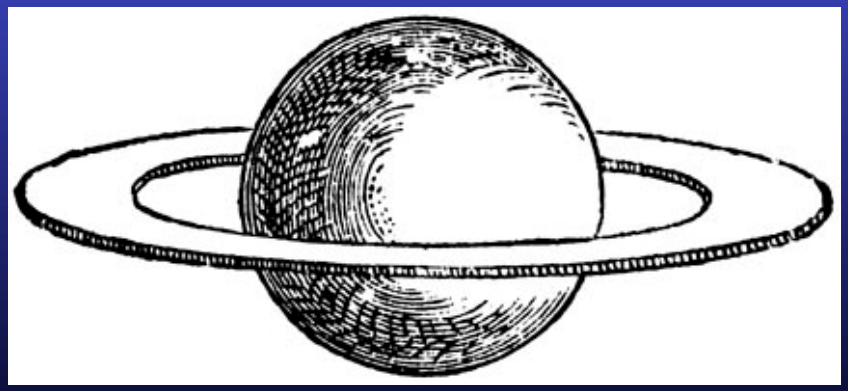
Astronomie --> Astrophysique

Je ne connais aucune application pratique des anneaux de Saturne [...] mais quand on regarde les anneaux d'un point de vue purement scientifique on ne peut pas rester l'esprit au repos.

James C. Maxwell, 1856



Les anneaux de Saturne sont un laboratoire de Physique !



- Rotation différentielle
- Collisions
- Auto-gravité
- Instabilités gravitationnelles

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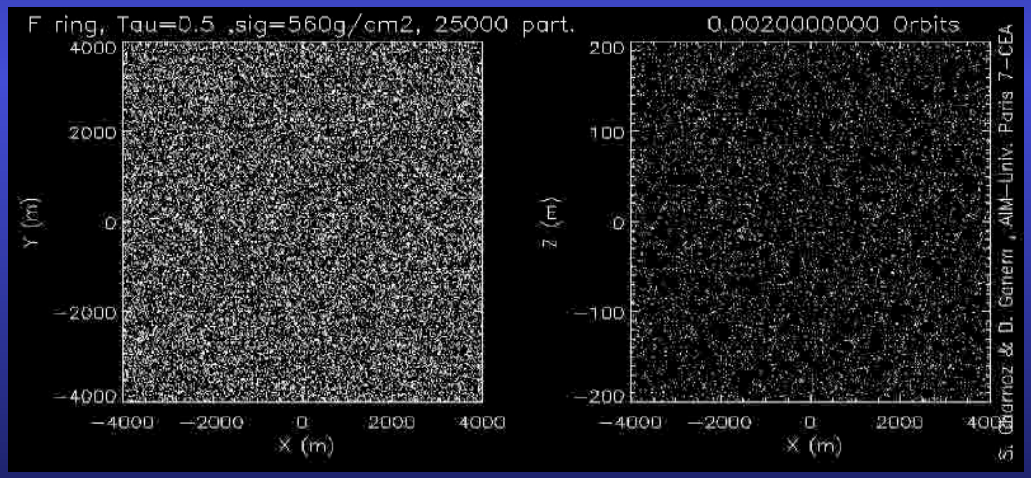
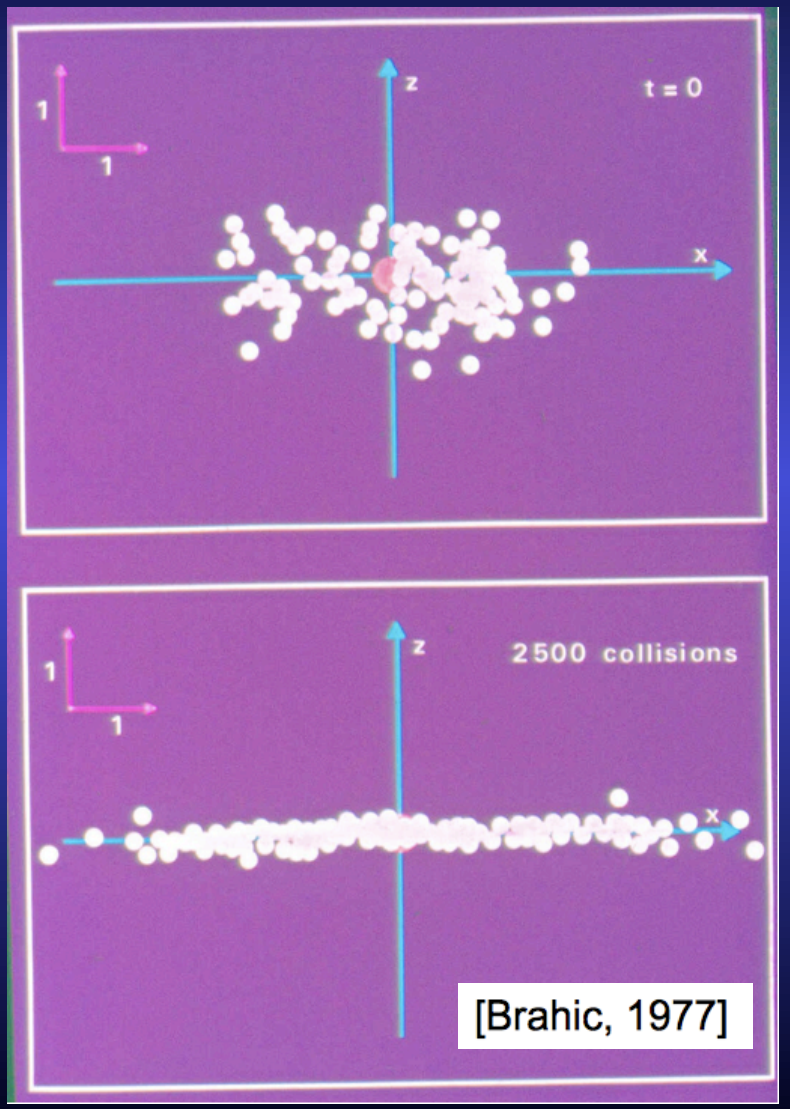


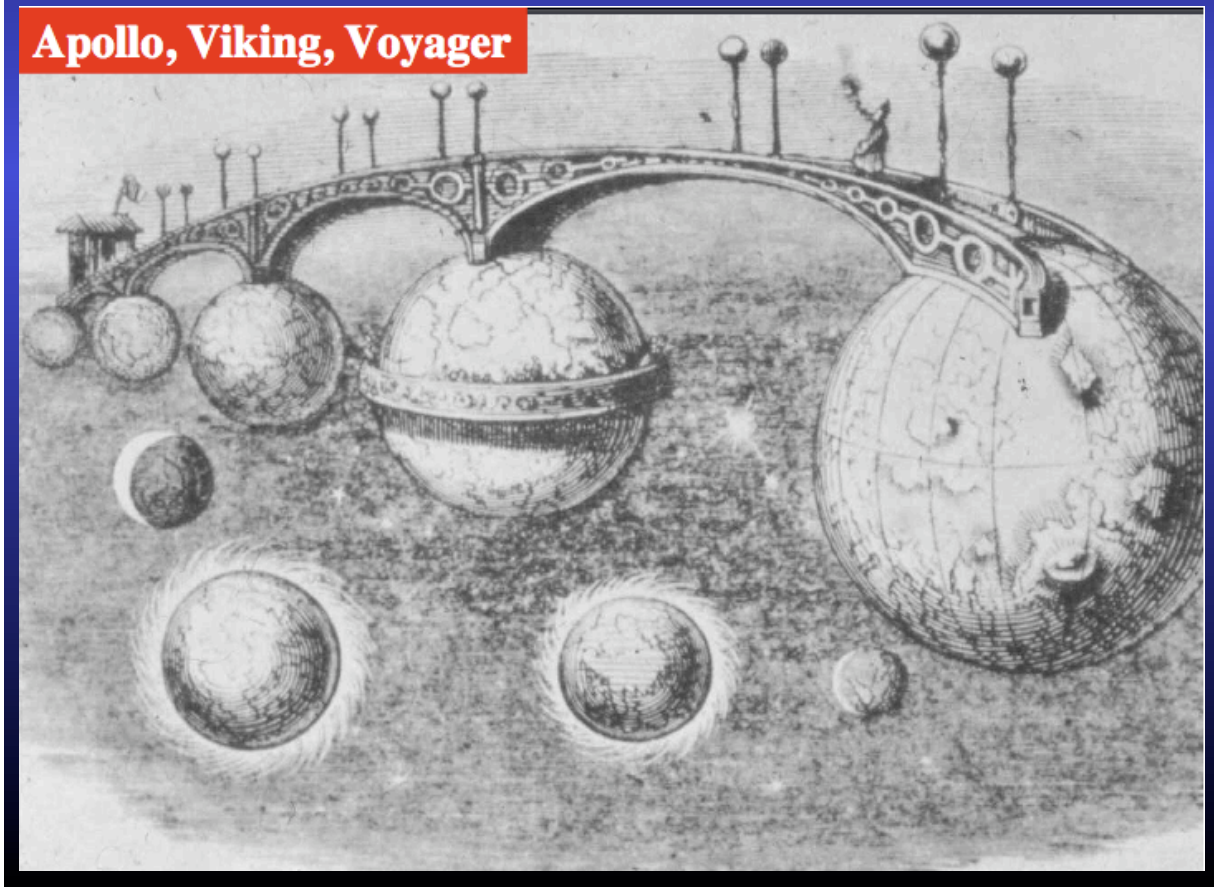
Simulations numériques Charnoz



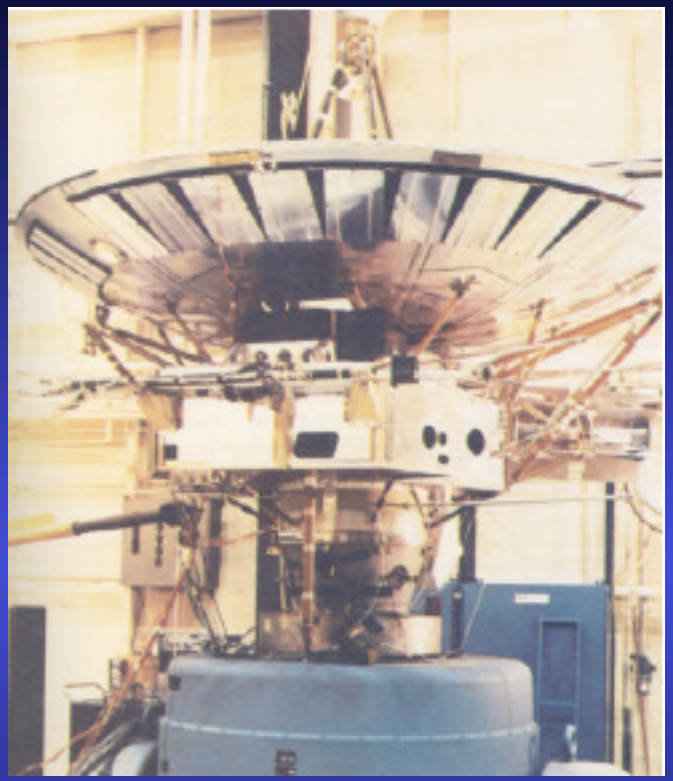
Fin des années 1970

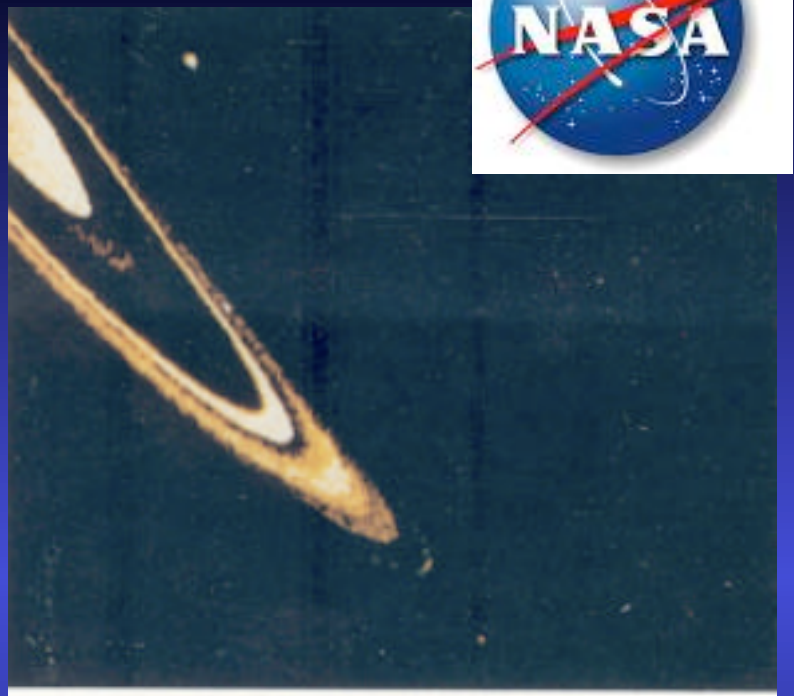
Ère de l'exploration du Système Solaire

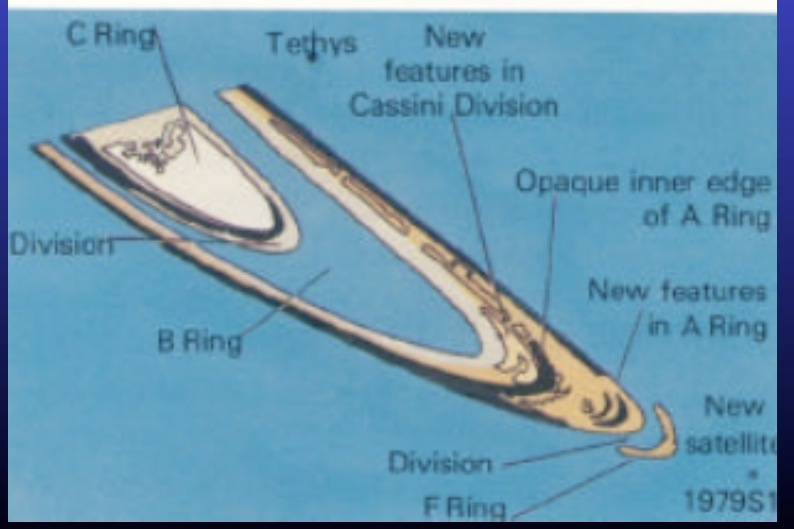
Missions spatiales interplanétaires

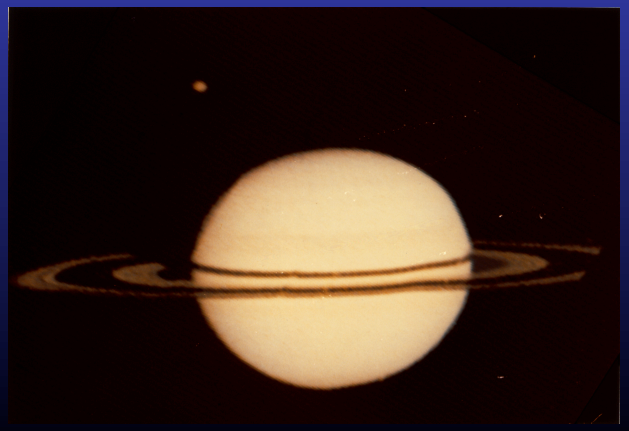


PIONEER 11: survol de Saturne en 1979

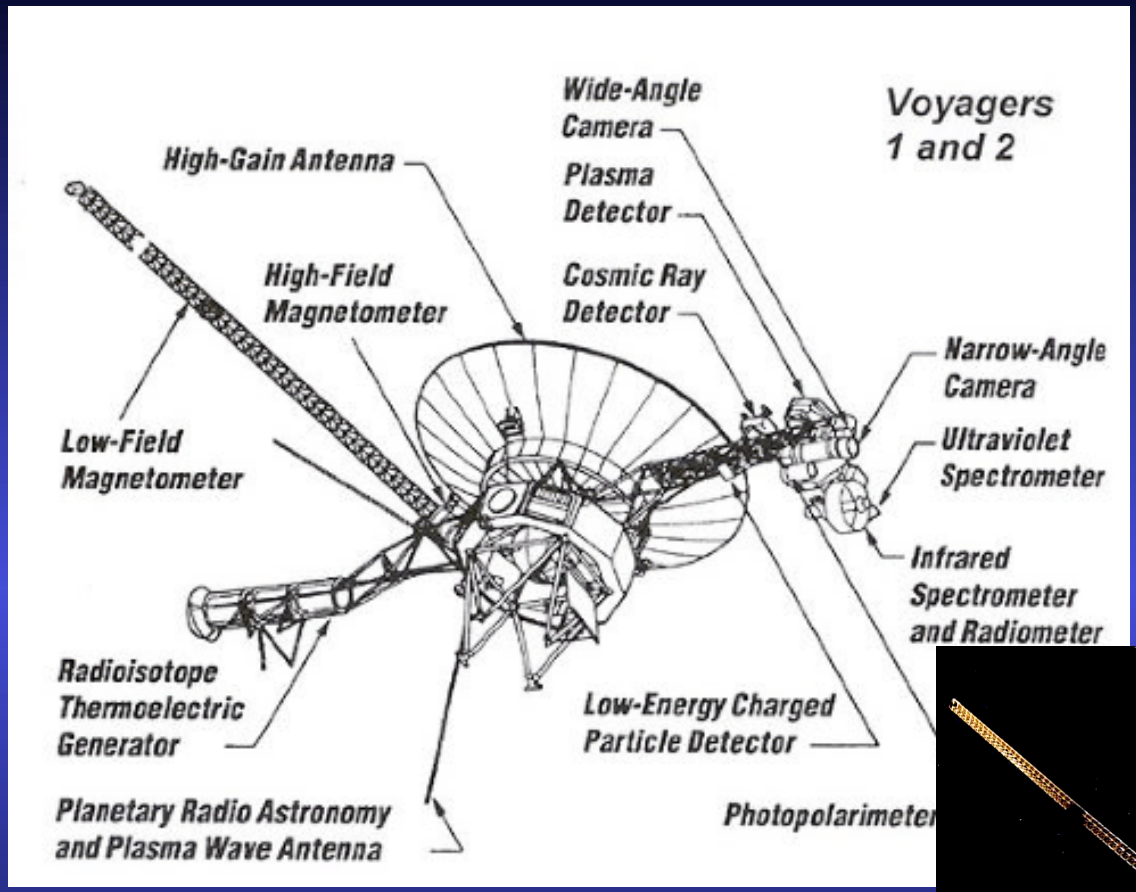






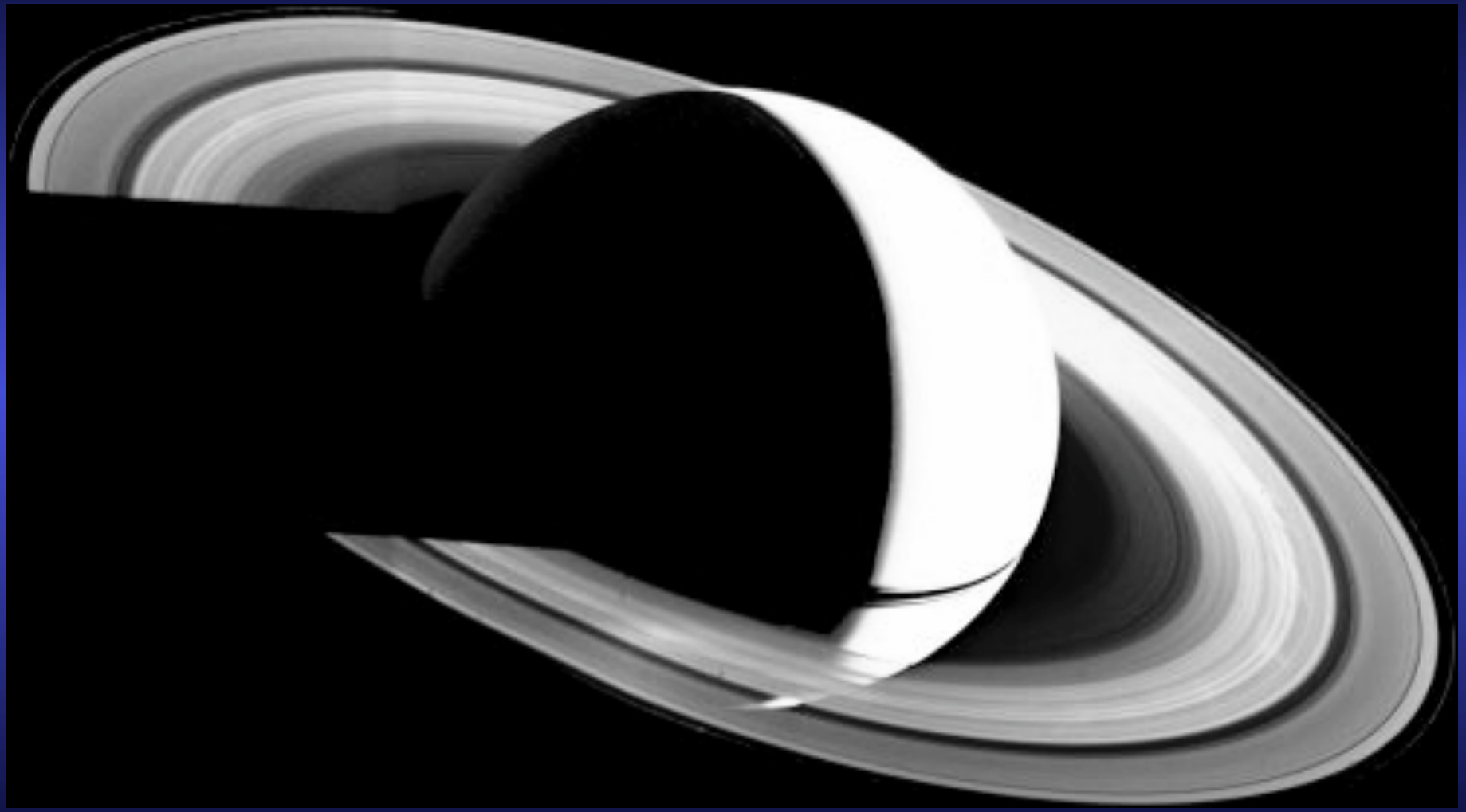


VOYAGER 1 & 2 : survols de Saturne en 1980 et 1981



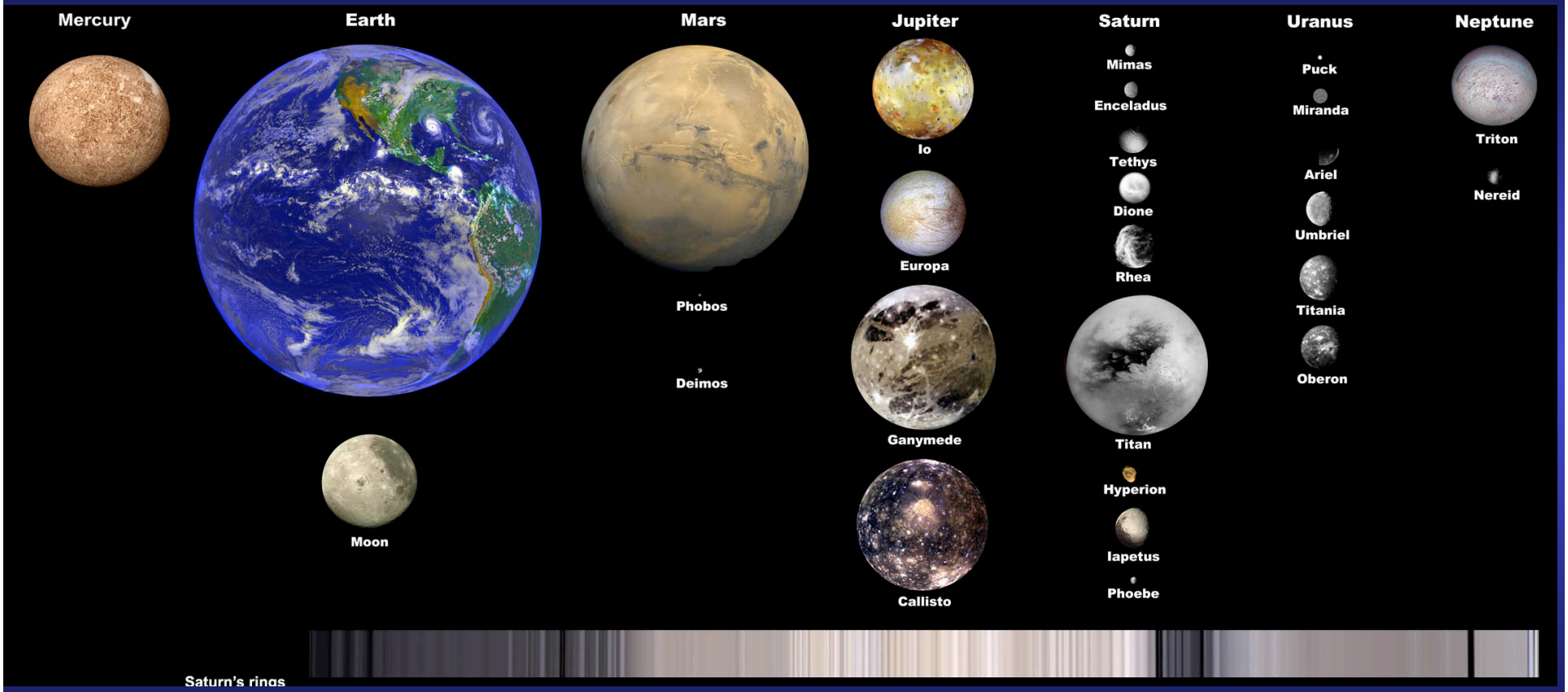
750 millions US$
815 kg
Générateur : 23 W

Les anneaux de Saturne (Voyager 1)



Les anneaux de Saturne

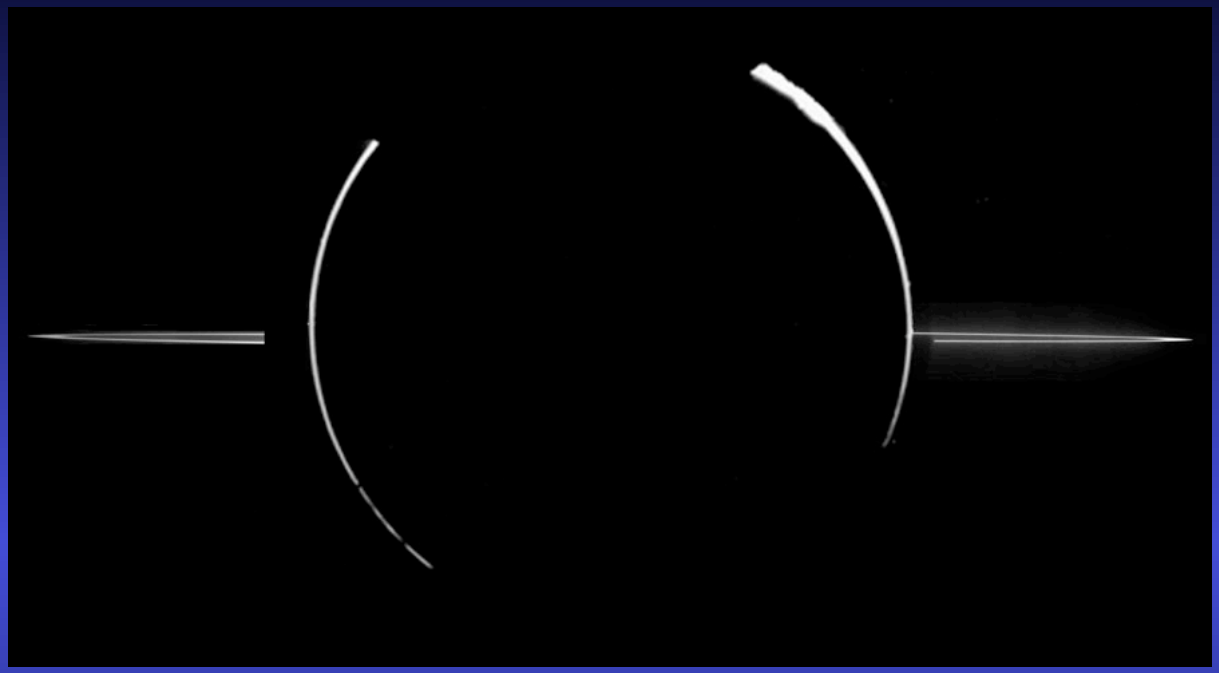
Montage à l'échelle !



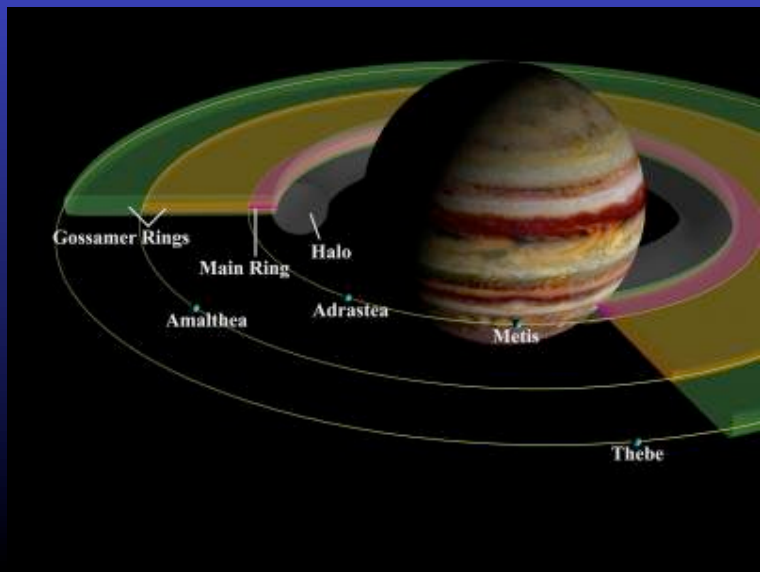
Terre diamètre : 12 700 km
Lune diamètre : 3 500 km

Et les anneaux des autres planètes géantes ?

Jovian rings discovered in 1979 by Voyager 1



Images Galileo
(1995-2003)



Uranian rings discovered in 1977 by Elliot, Dunham & Mink

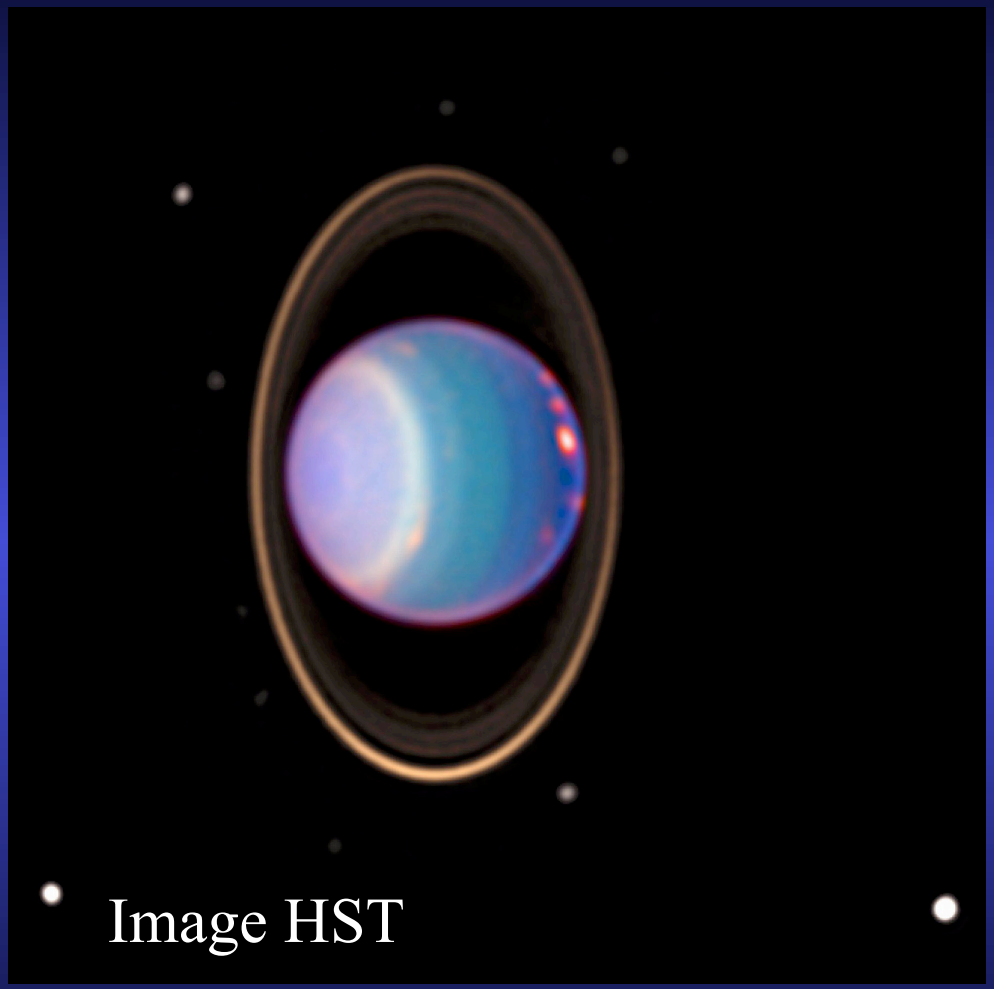


Image HST

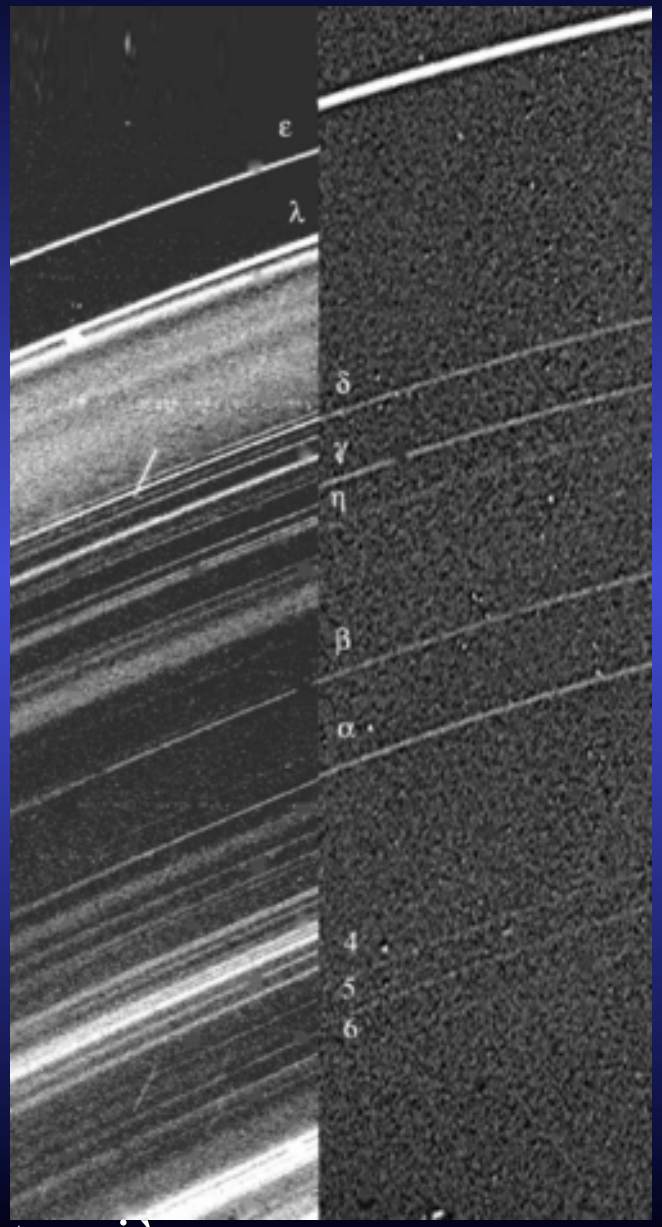


Image Voyager 2
(1986)
Diffusion avant et arrière

Neptunian rings discovered in 1984 by Hubbard & Brahic

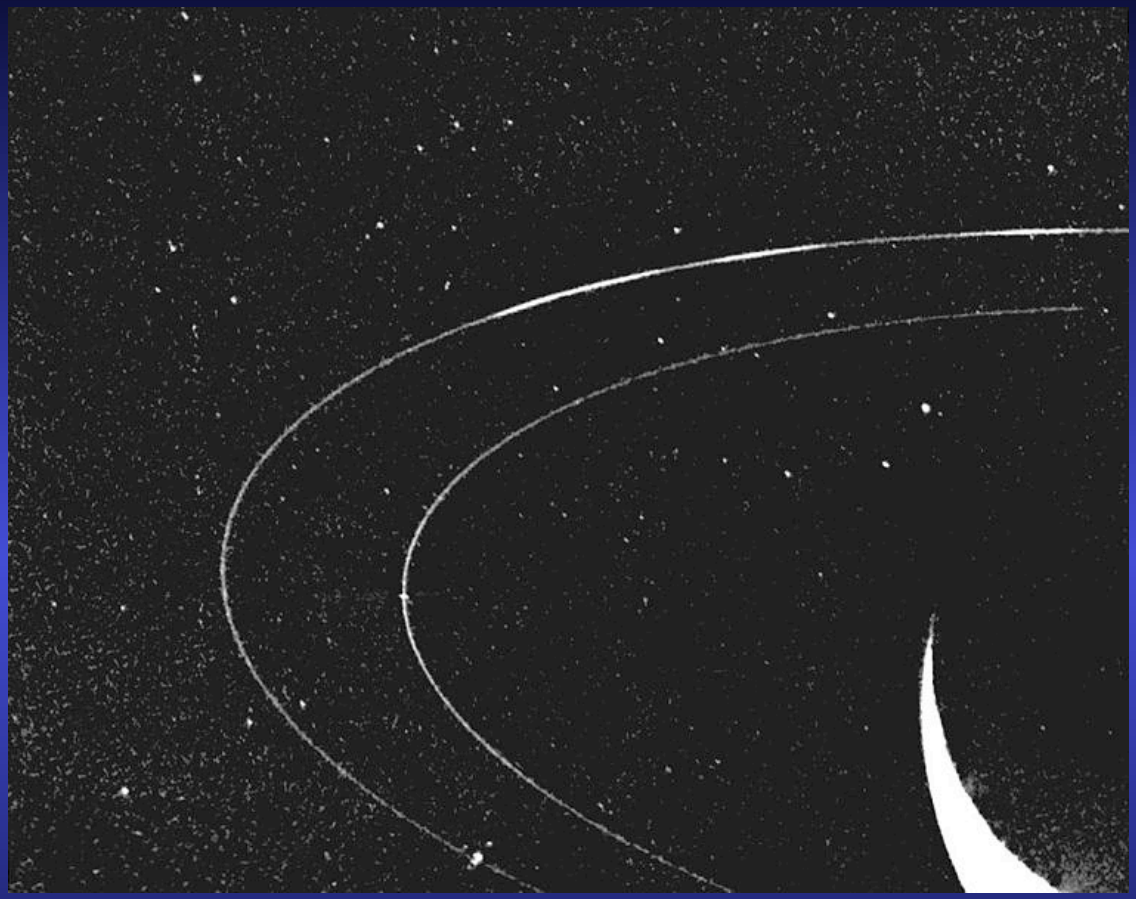
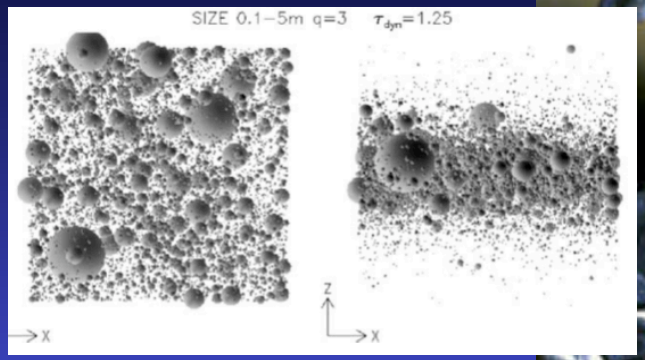
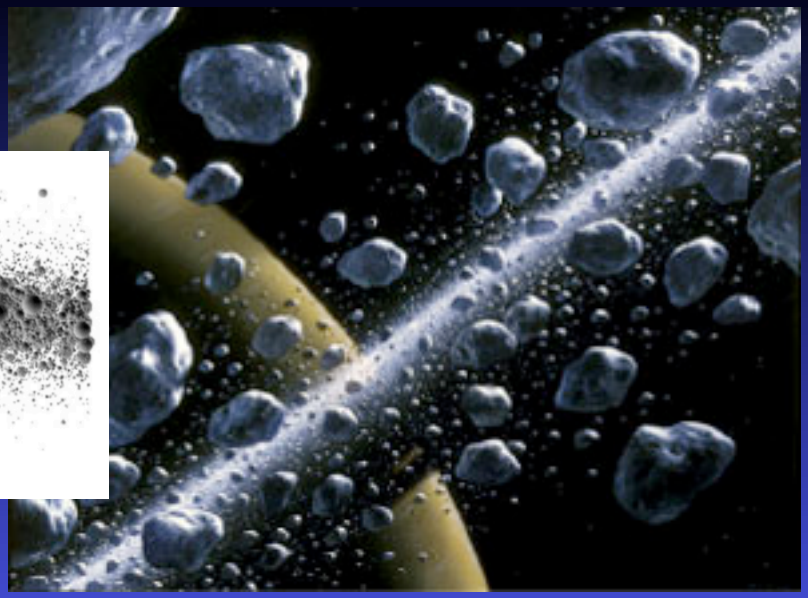


Image Voyager 2
(1989)

Questions ouvertes :

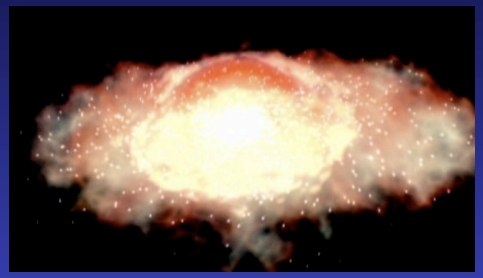
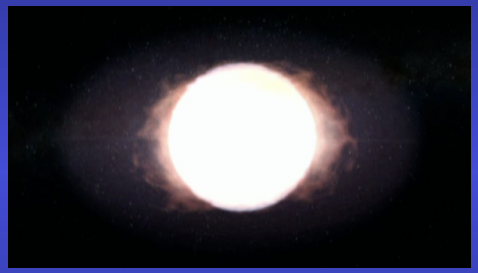
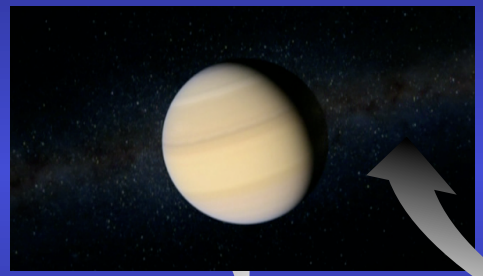
- Origine ?
- Structure ?
- Evolution ?
- Différences ?



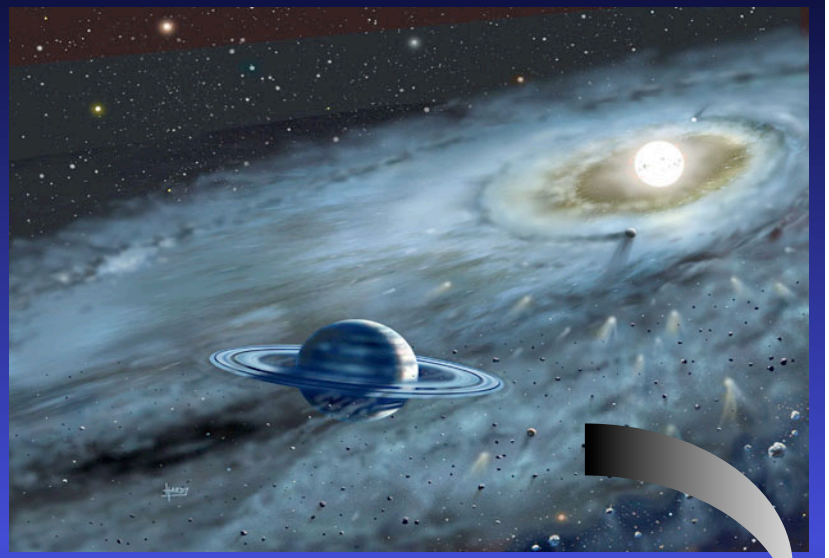


Anneaux jeunes ou vieux ?

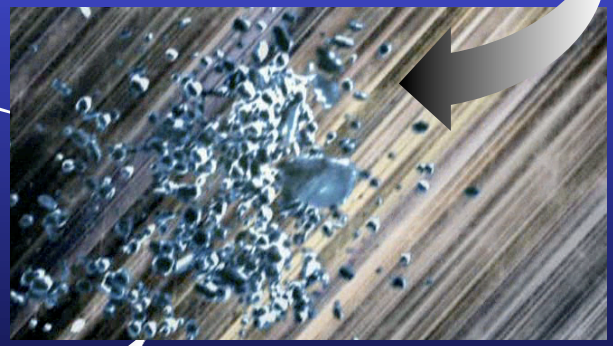
Si anneaux jeunes: Saturne formée seule

Si anneaux vieux: crées en même temps que Saturne



érosion



création

alimentation ?

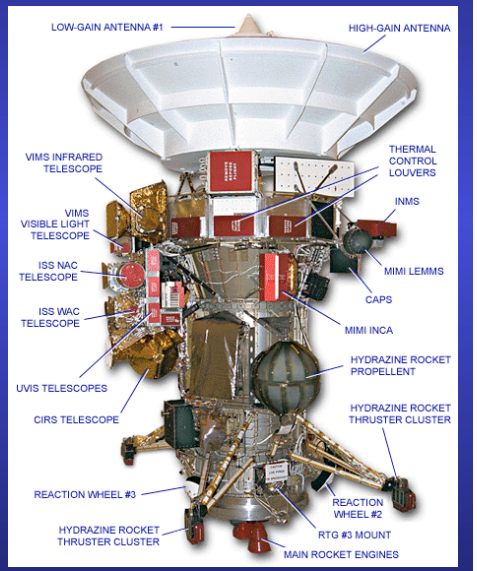
CASSINI-HUYGENS : 4 milliards US$

Cassini :
7m de haut
4m de diamètre
5,7 tonnes

Huygens :
2,7m de diamètre
320 kg

Générateur : 830 W

18 instruments à bord !
12 dans CASSINI
6 dans HUYGENS

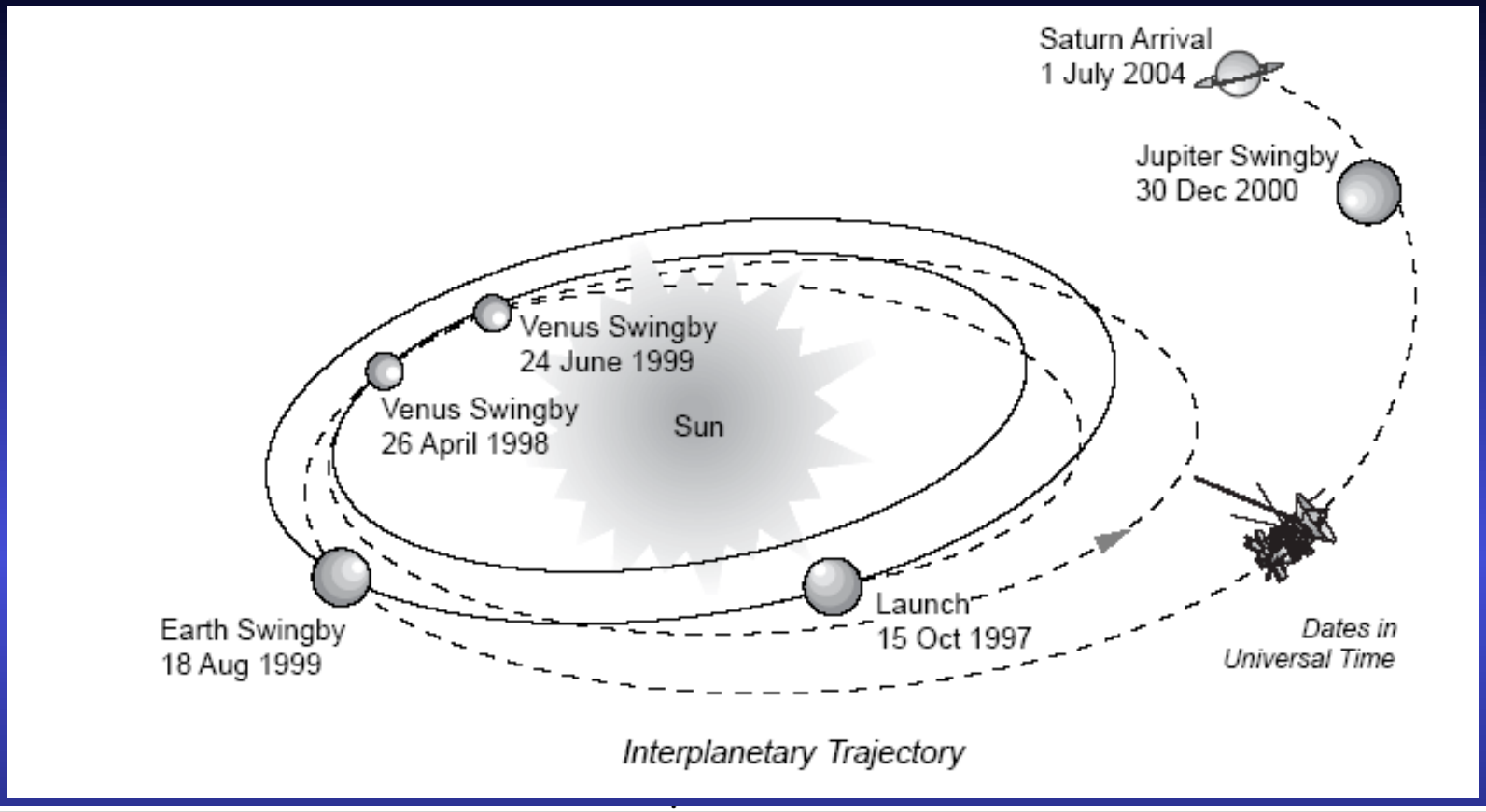


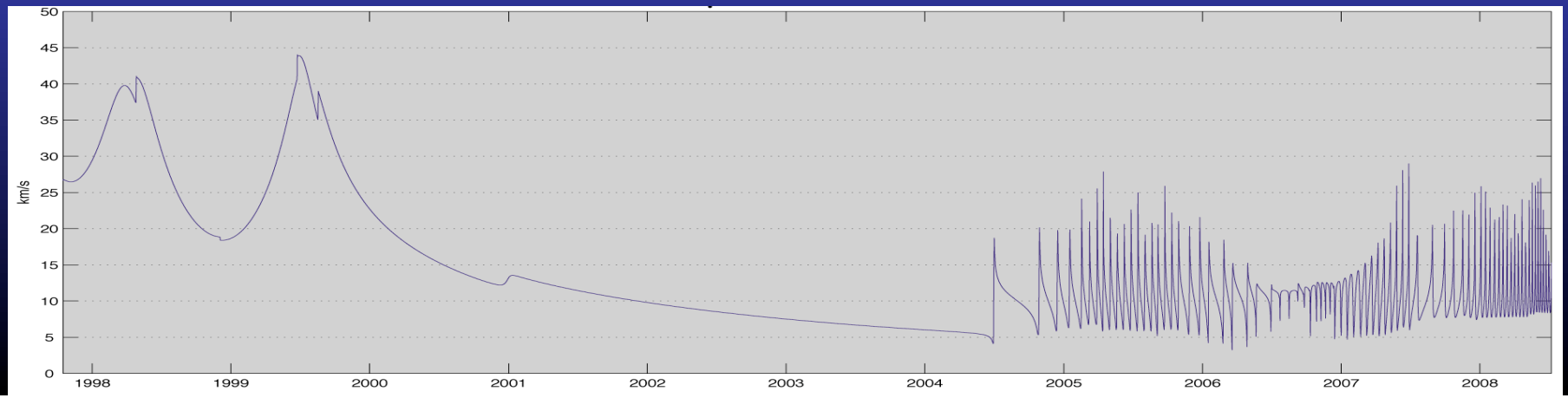
Que faisiez-vous le 15 octobre 1997 ?

6 tonnes à propulser !

Lanceur Titan 4B pas suffisant

Un voyage de 7 ans qui utilise 4 rebonds gravitationnels





Cassini équipé de CCD (Nobel 2009 !)

1970 1980 2000-2010

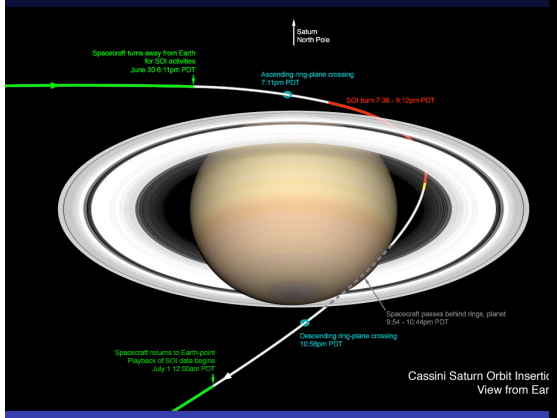
Pioneer 11

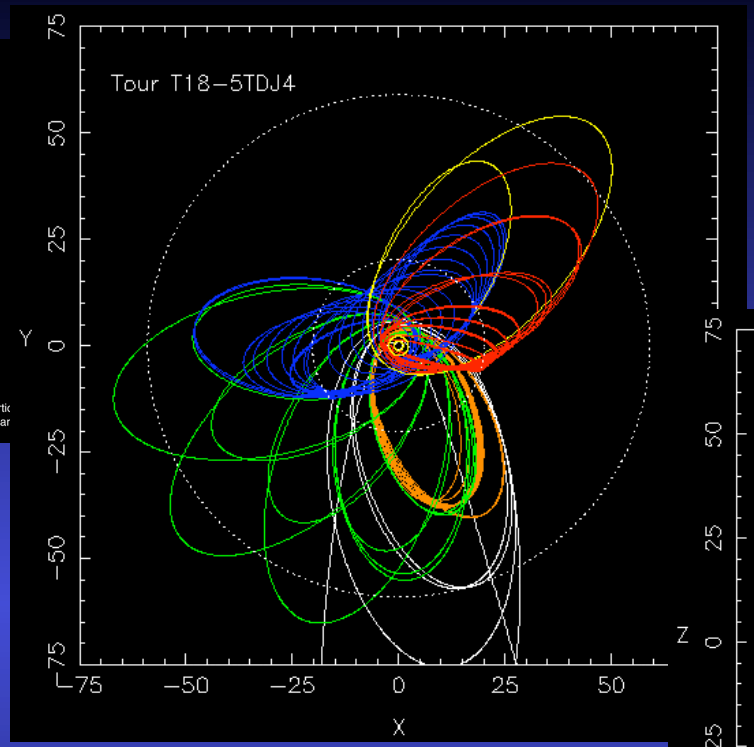
Voyager 1

Cassini

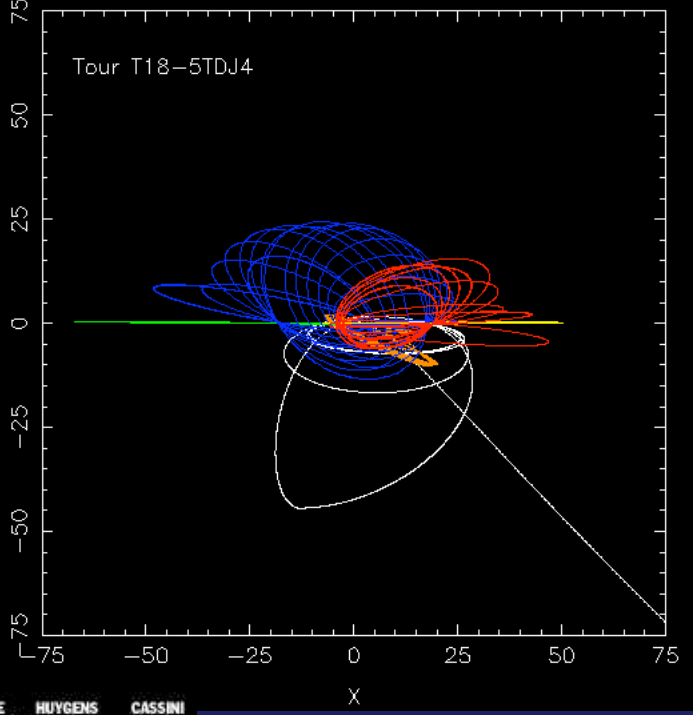
Le système de caméras ISS (Imaging Science Sub-System)
1024x1024 Pixels , Proche IR <-> Proche UV , 21 filtres

Des orbites complexes autour de Saturne et de ses satellites





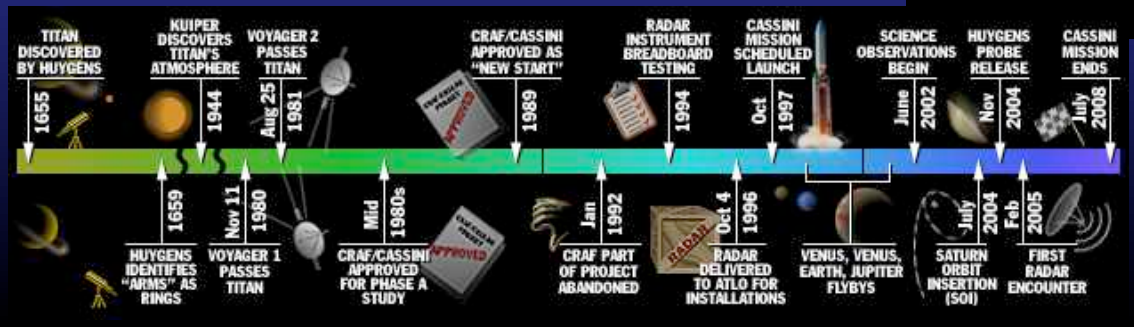
SOI + Huygens (Jul. 04, Jan. 05)
Occultation orbits (Feb 05-Sep05)
Petal rotation (Oct 05 –July 06)
180°transfer (Aug. 06 –Jun 07)
High inclination (Aug 07 –July 08)



Insertion orbitale:
1er Juillet 2004

52 rencontres avec:
Phoebé, Titan, Encelade,
Japet, Rhéa, Théthys

Fin de la mission nominale: 30 Juin 2008



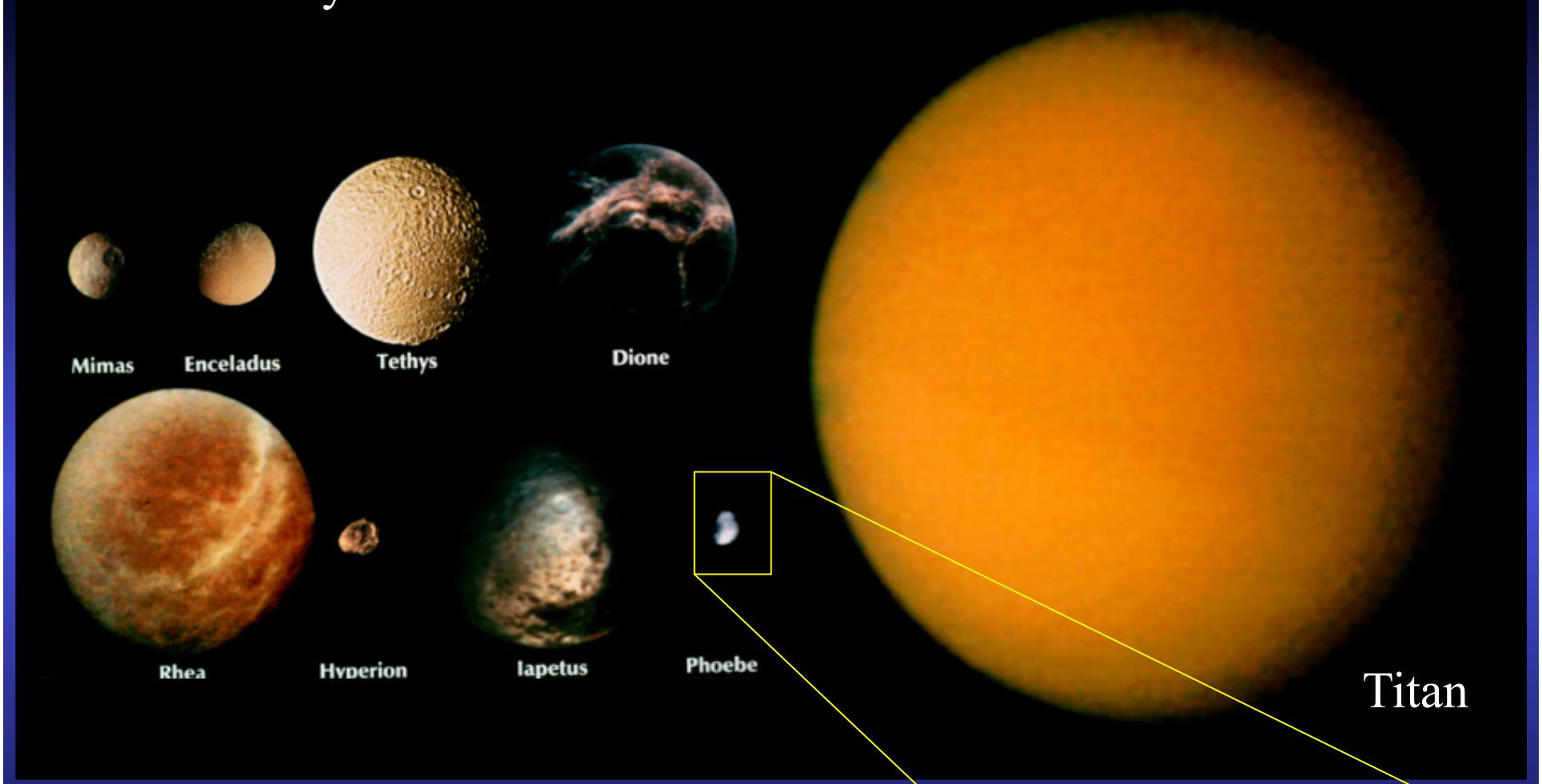
76 orbites autour
de Saturne

Les découvertes Cassini pour les satellites

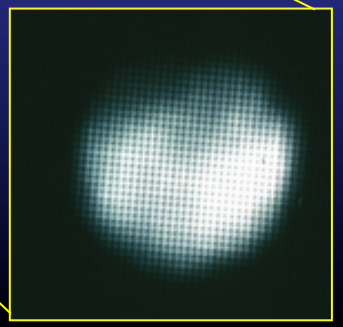
Saturne: un système solaire en miniature …

AVANT : images Voyager

Saturne: un système solaire en miniature …



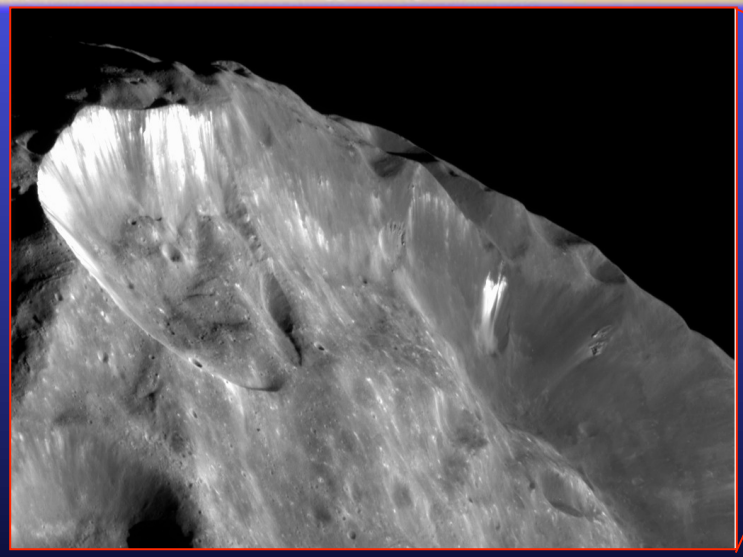
AVANT : images Voyager

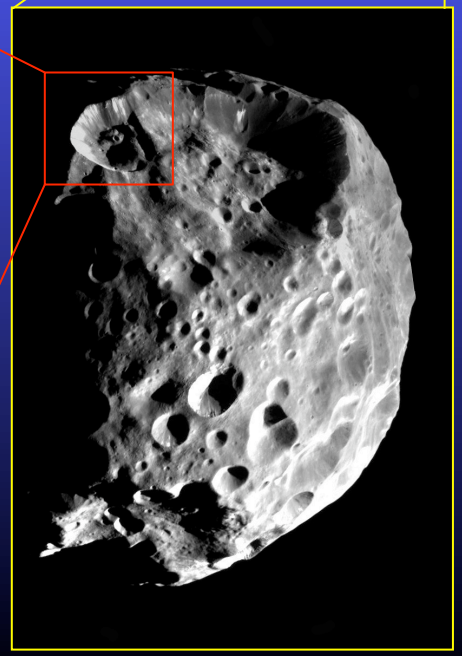


Saturne: un système solaire en miniature …

APRES : images Cassini

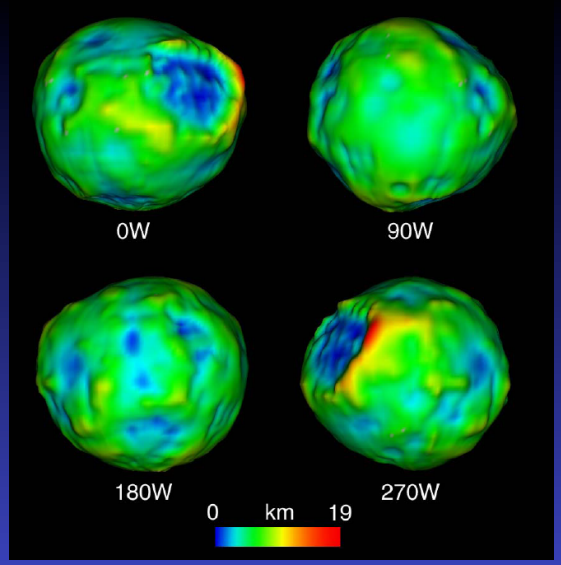
Saturne: un système solaire en miniature …





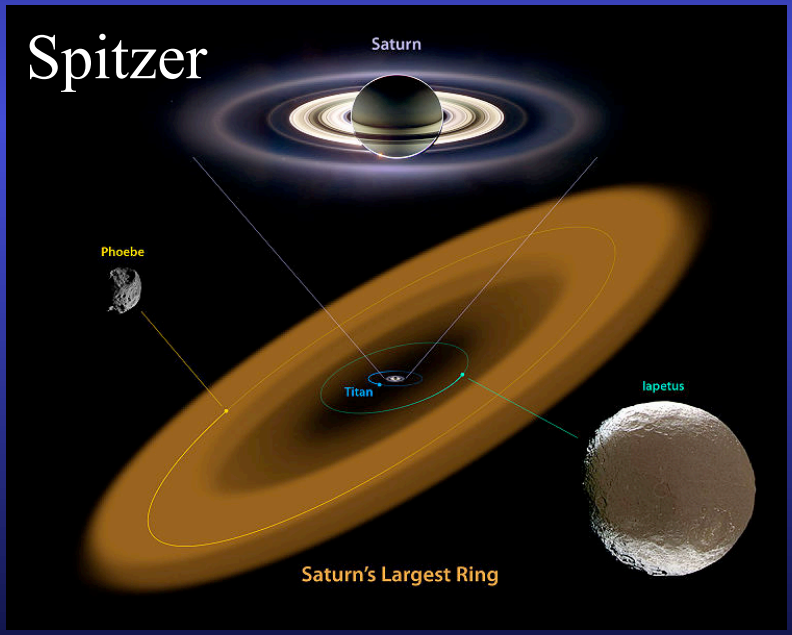
APRES : images Cassini

PHOEBE



Résolution ~ 20 m par pixel !!

Spitzer



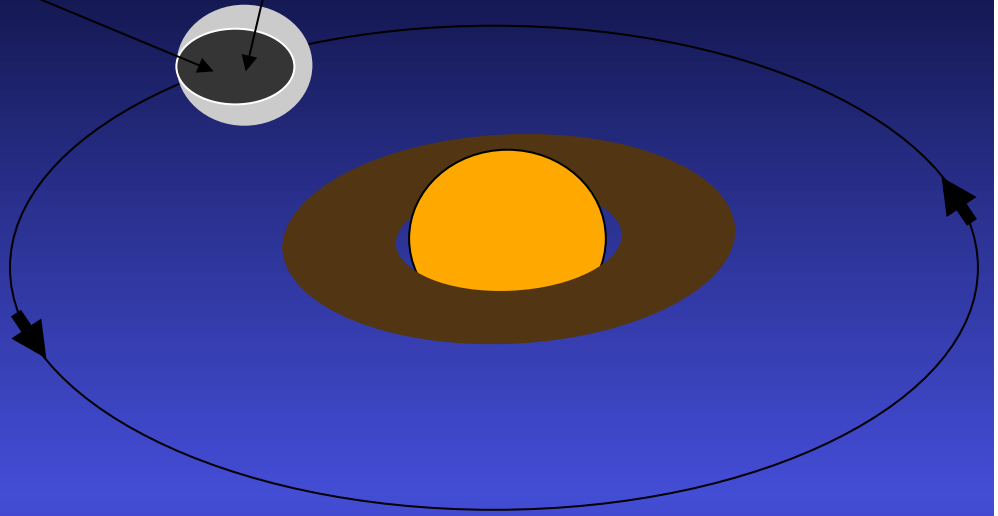
Diamètre moyen : 212 km, non relaxé

Roche + glace + volatils (CO_2) VIMS

Cassini/ISS

JAPET

Cassini Regio

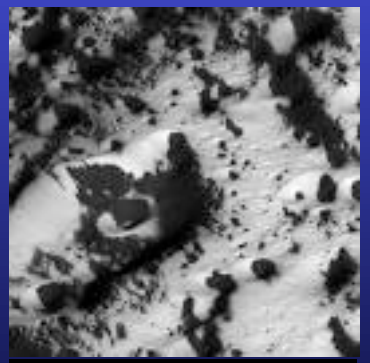


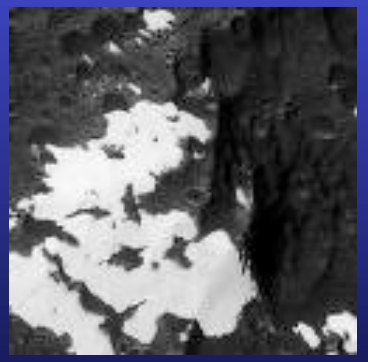
Diamètre : 1 500 km

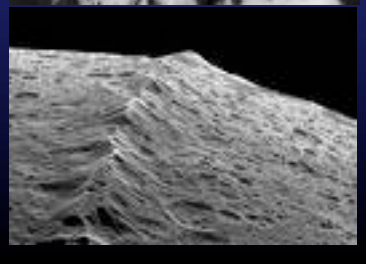
Rotation de Japet bloquée en rotation synchrone par effet de marée (79 j)

Cassini Regio : Région ancienne, bcp de cratères
Pas de signe de volcanisme actif apparent
Dépôt balistique de matière sombre
Couche noire peu épaisse (< 1m) ?

Ceinture coupe au milieu de Cassini Regio : lien ?



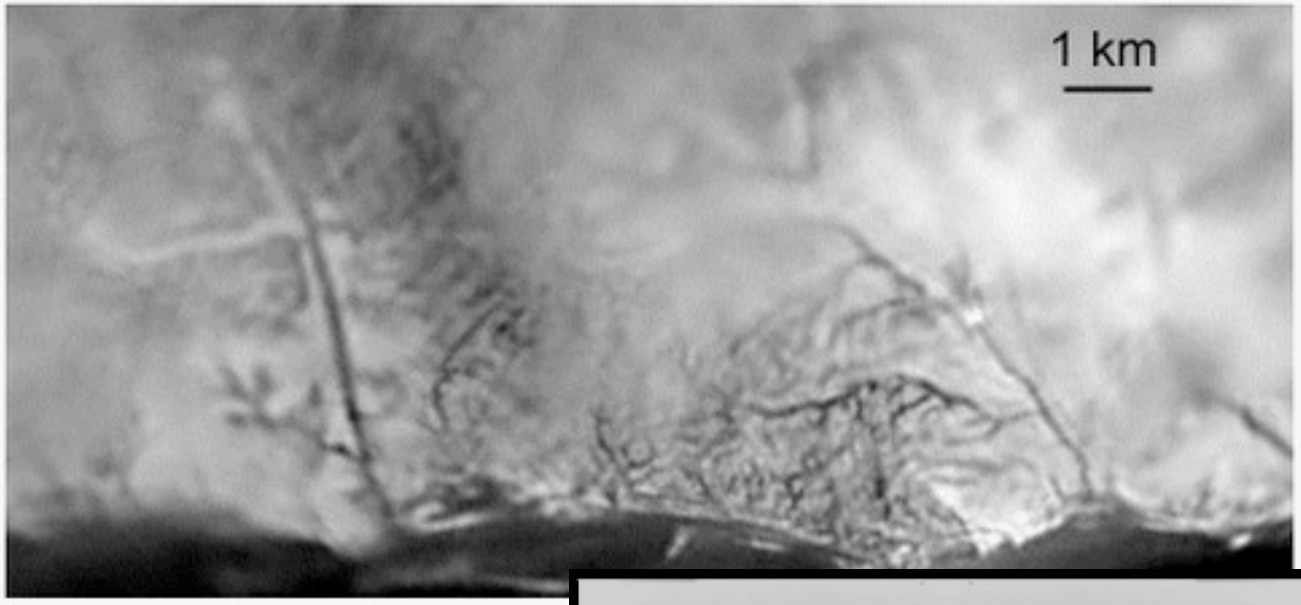


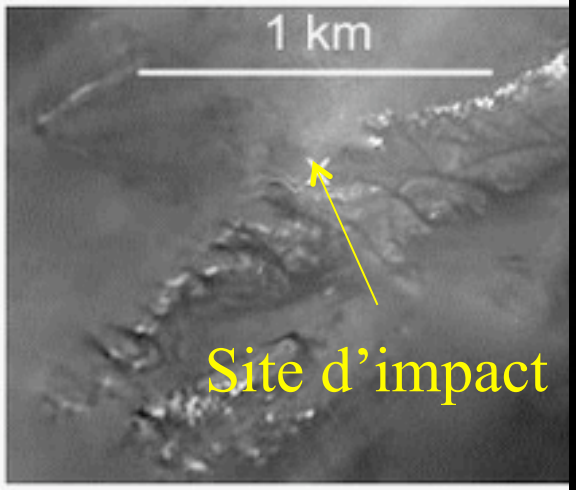


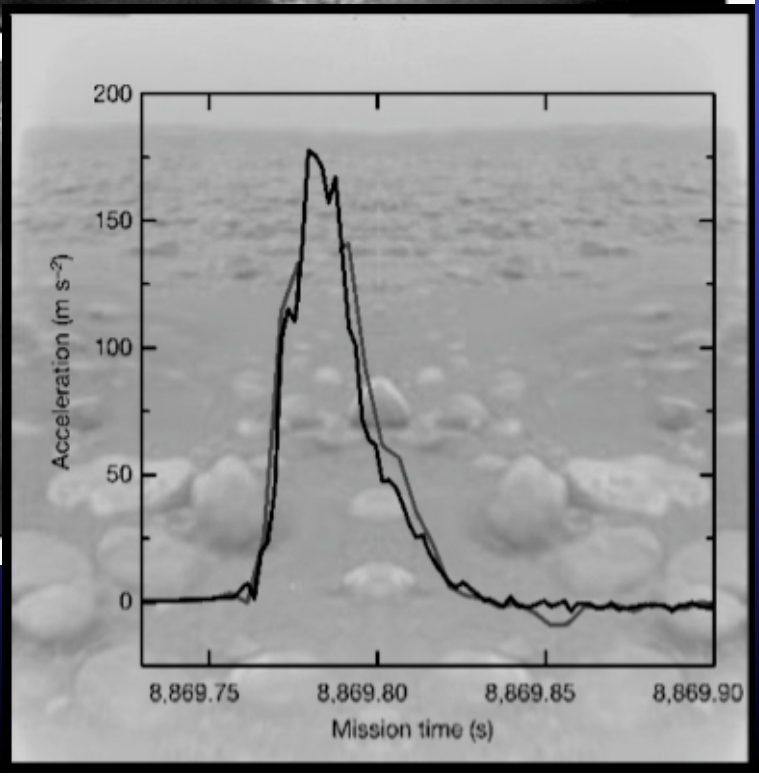
Images ISS

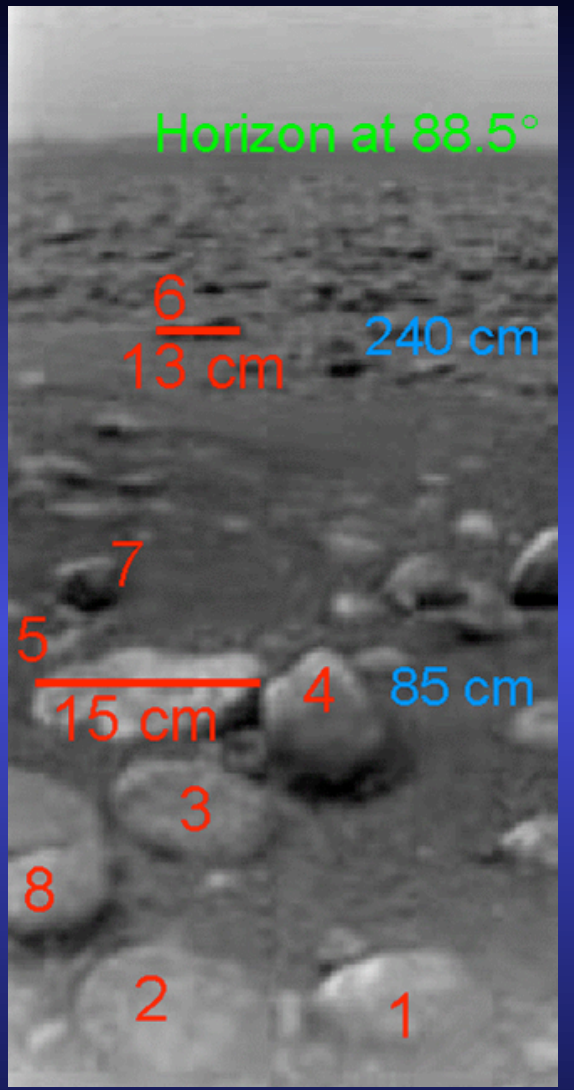
TITAN

Images DISR





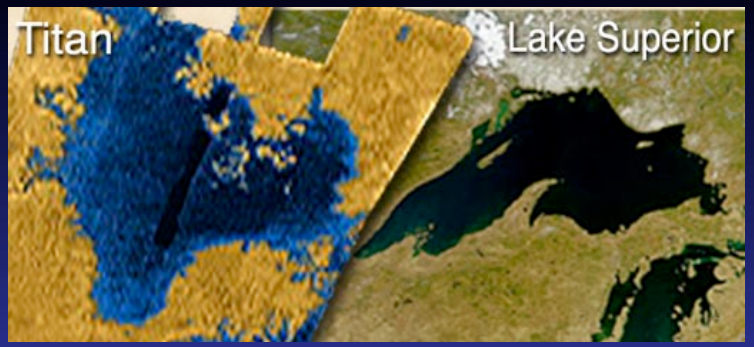




Diamètre : 5 000 km

Accéléromètres
HASI & SSP

TITAN

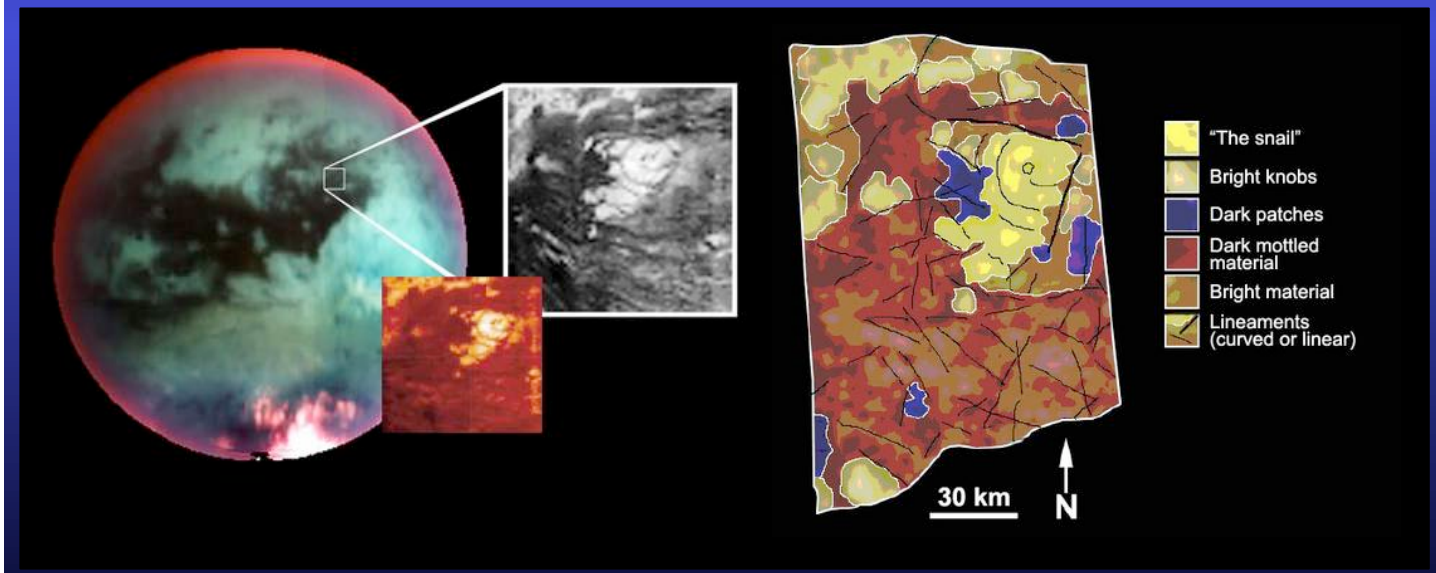


Liquid Lakes !!

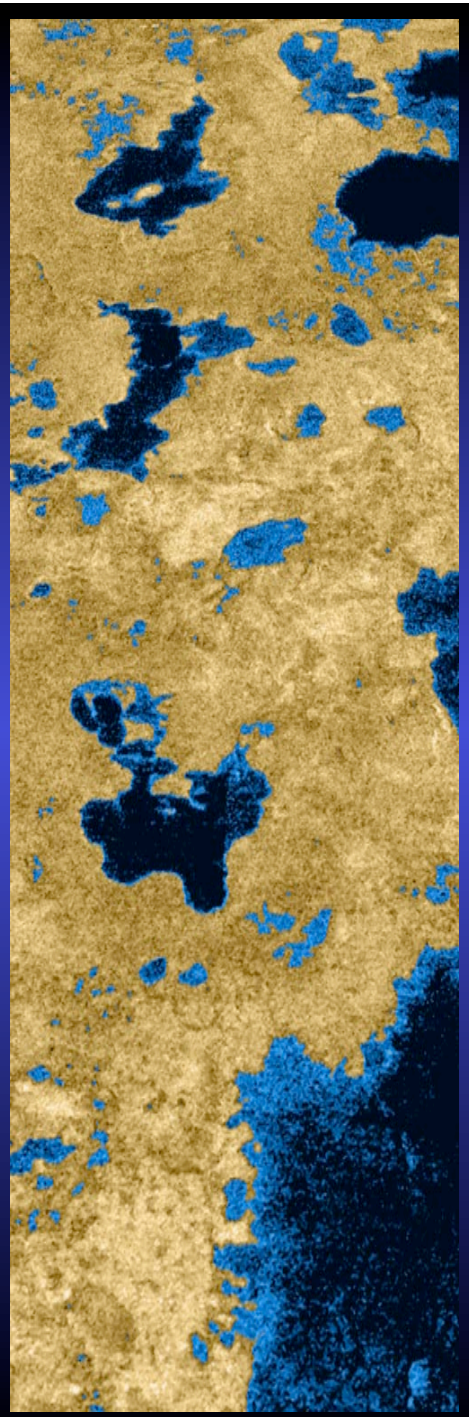
Images RADAR
140 km across
1 pixel ~ 500 m

Titan Lake : 100 000 km^2
Lake Superior : 82 000 km^2

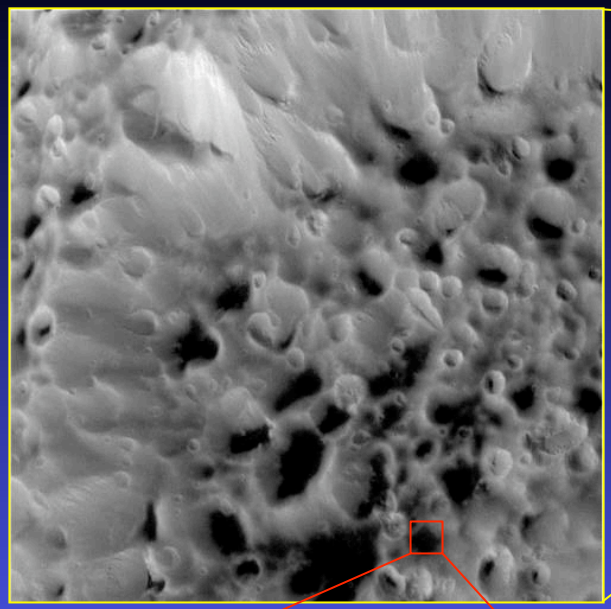
The Black Sea covers 0.085 % of the surface of the Earth;
Titan's Lake covers 0.12 % of the surface of Titan.

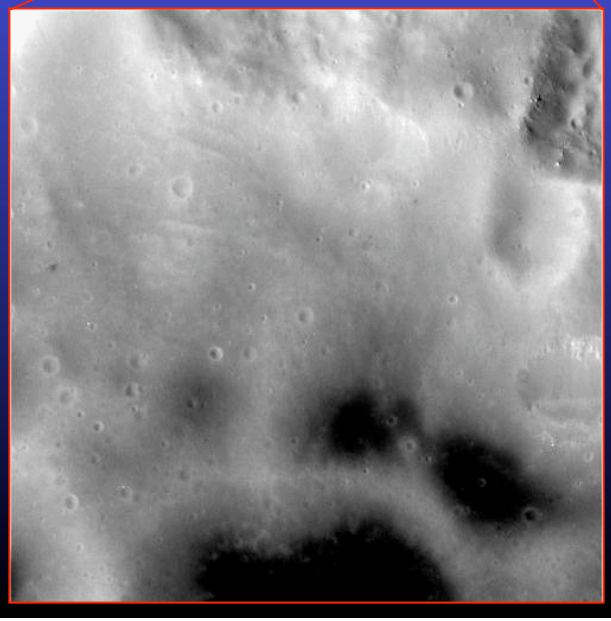


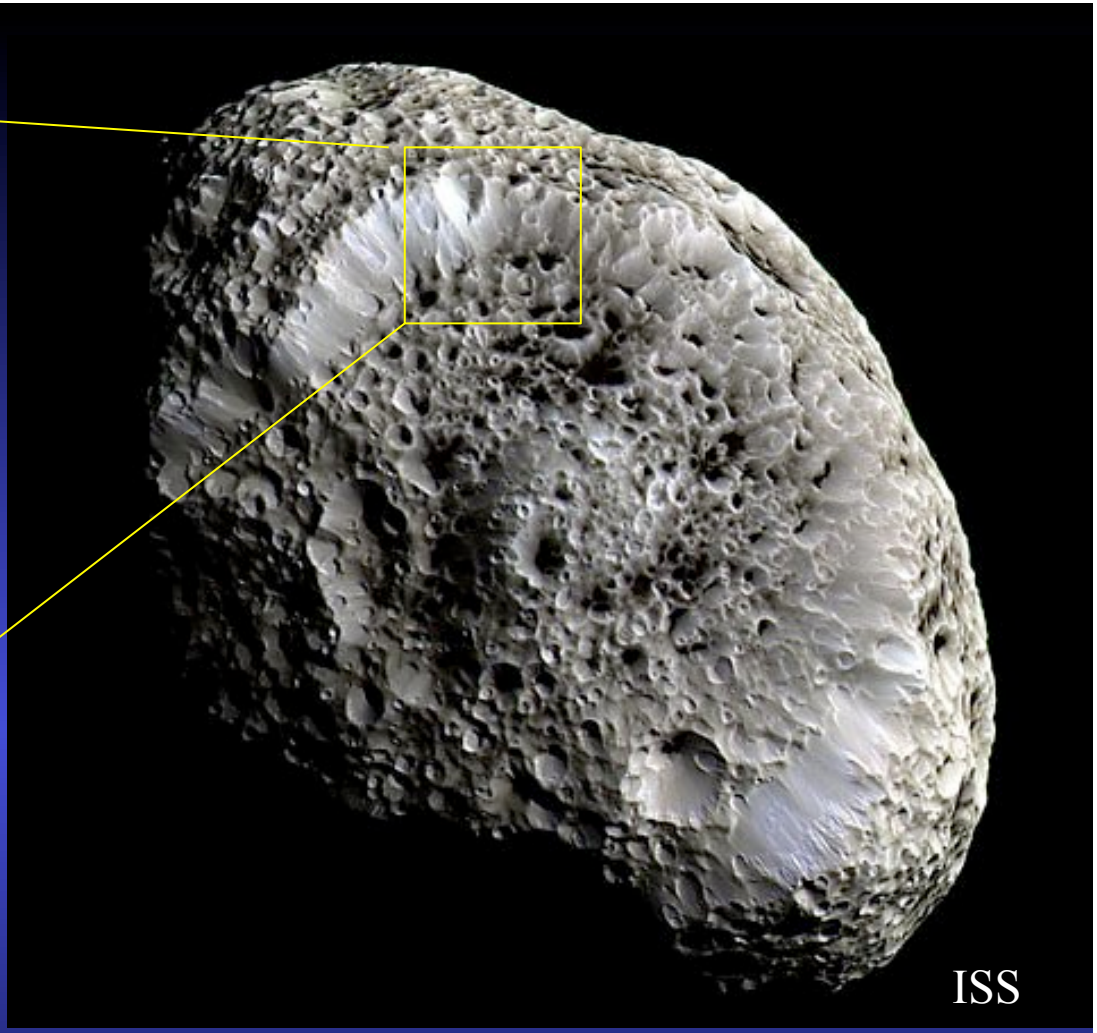
Cryovolcanism
Image VIMS



HYPERION







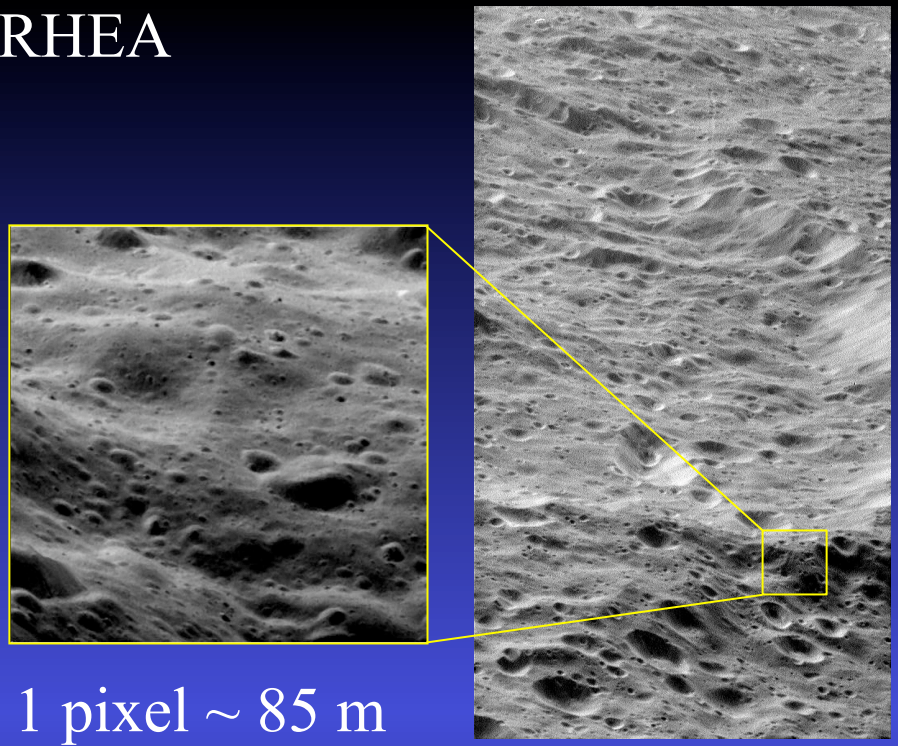
ISS

Diamètre : 286 km

Résolution spatiale : 50 m par pixel

RHEA

Diamètre : 1 530 km

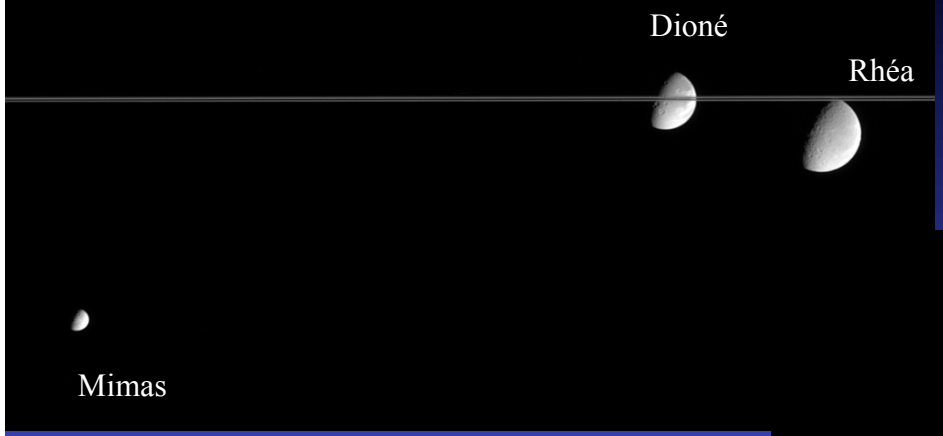


1 pixel ~ 85 m

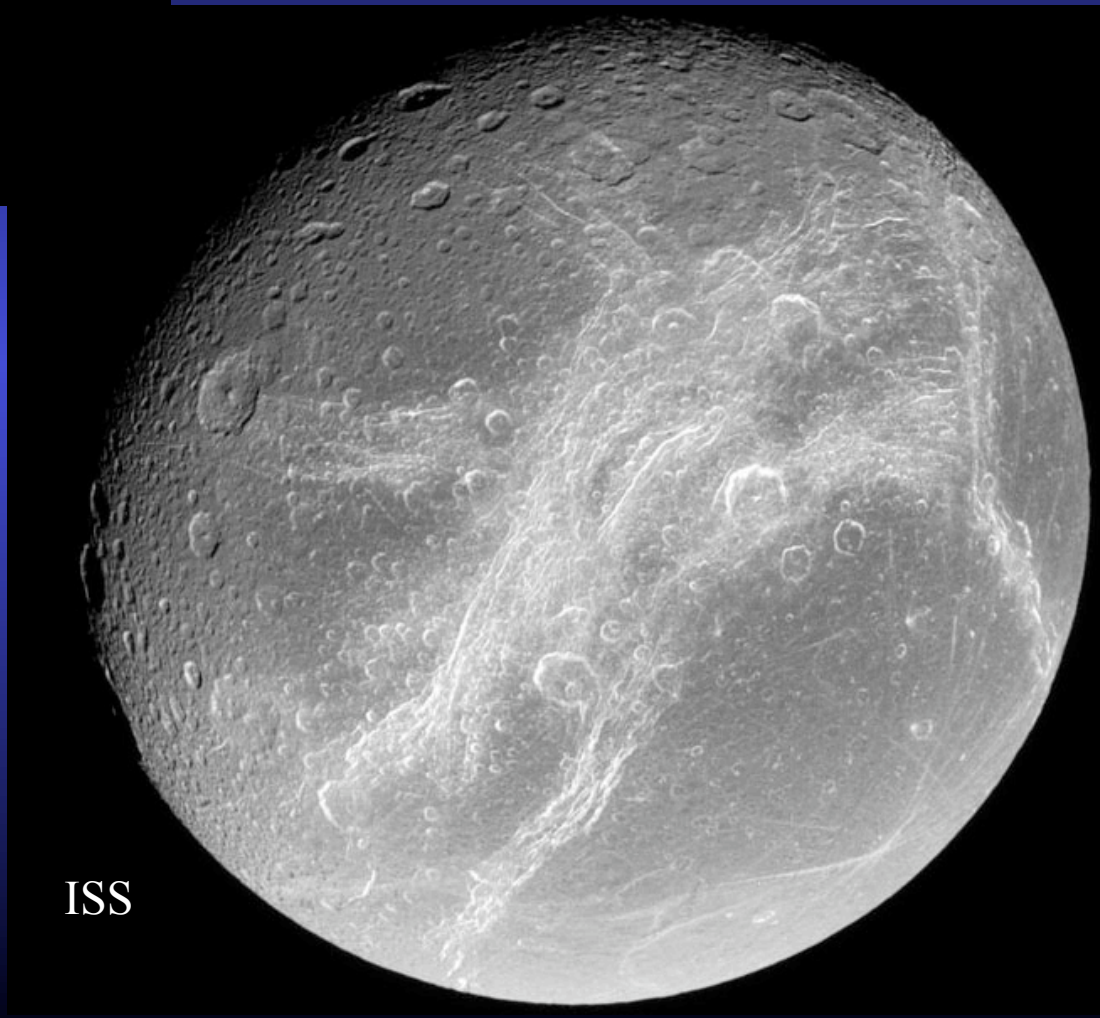
ISS

DIONE

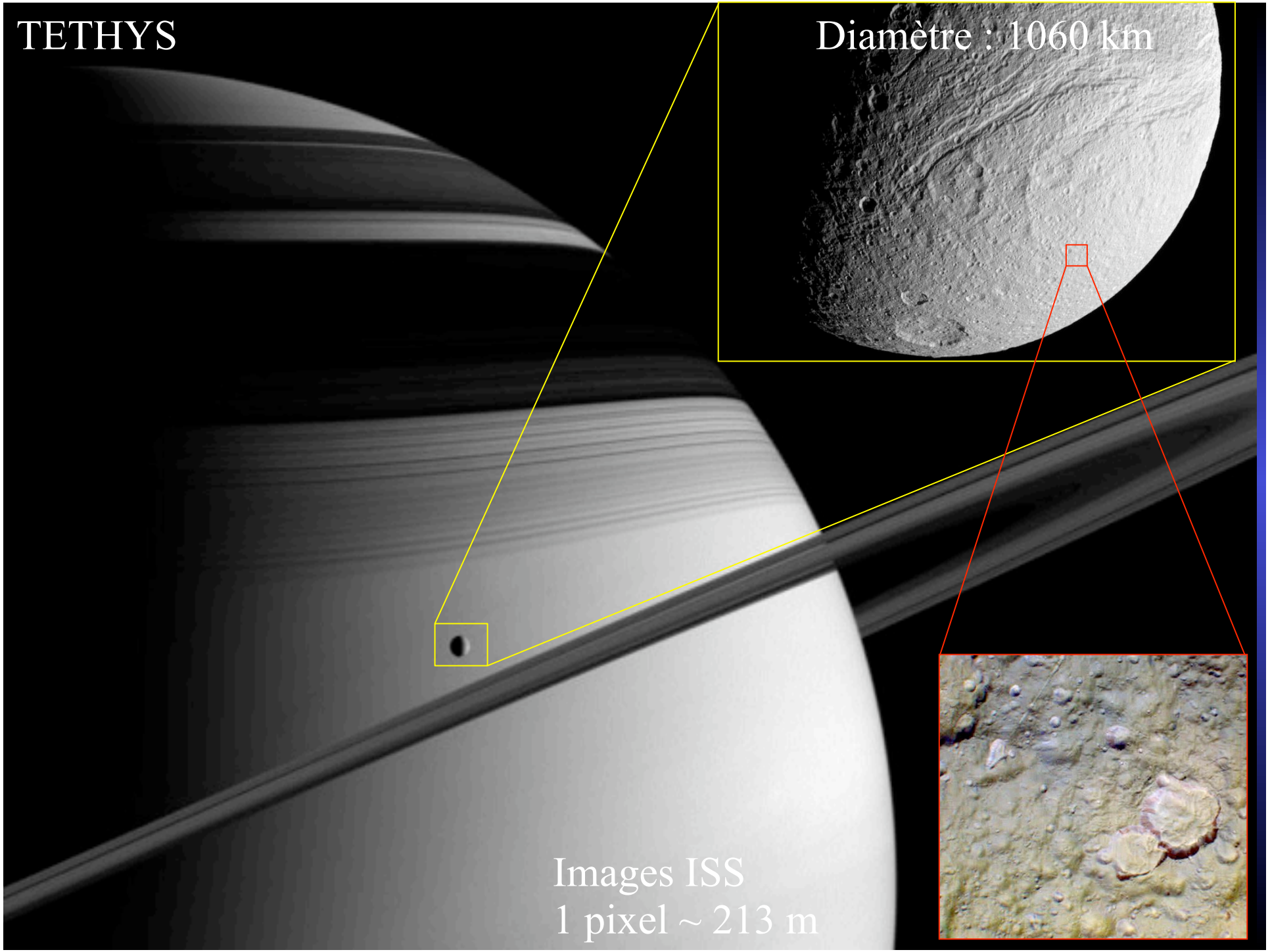
Diamètre : 1 120 km

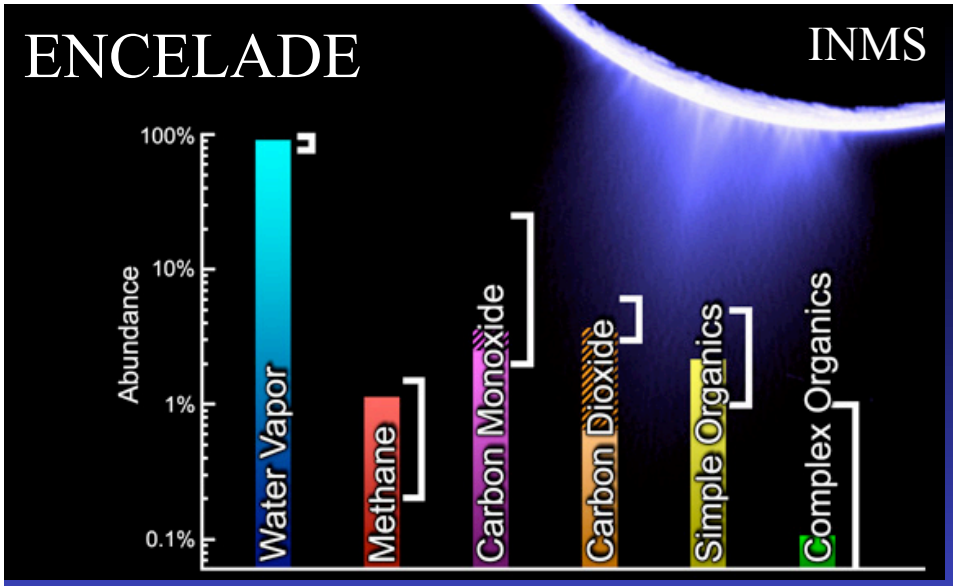


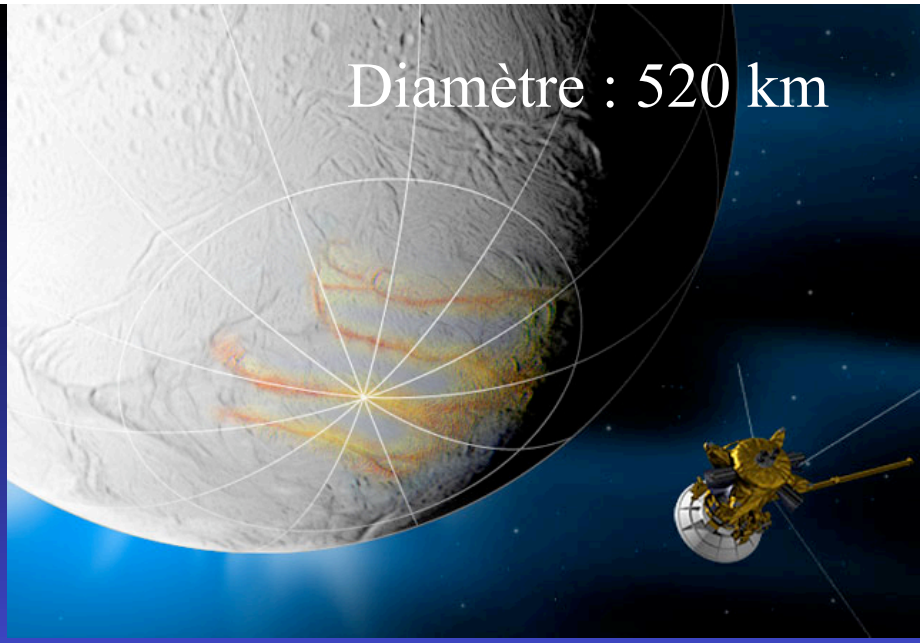
1 pixel ~ 23 m
60 km across

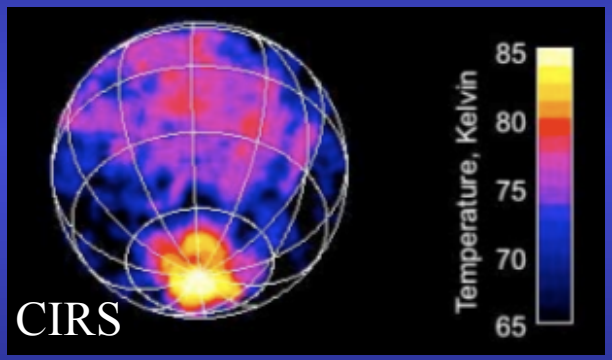


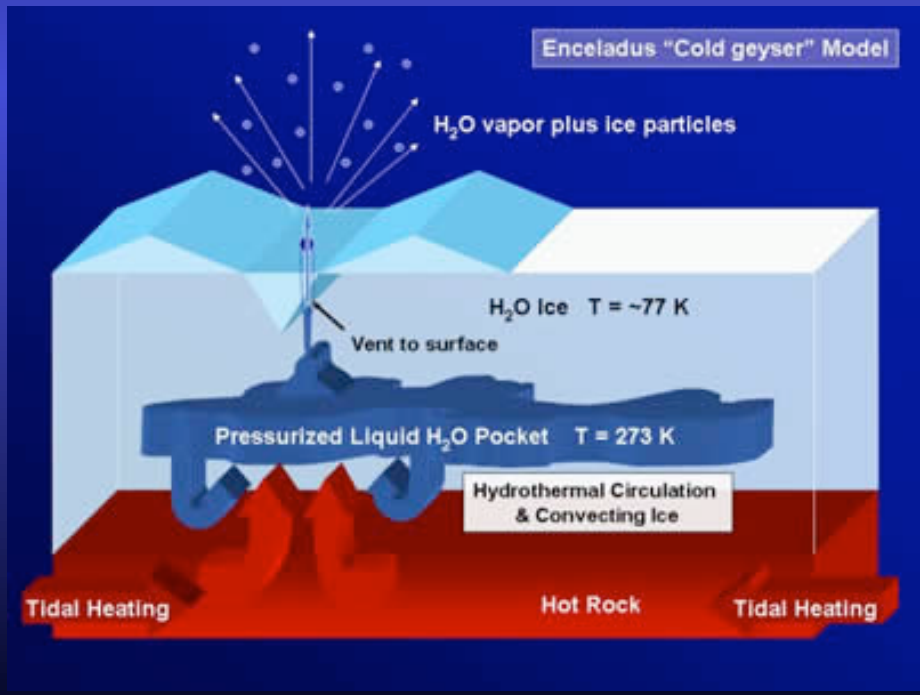
ISS


TETHYS
Diamètre : 1060 km
Images ISS
1 pixel ~ 213 m







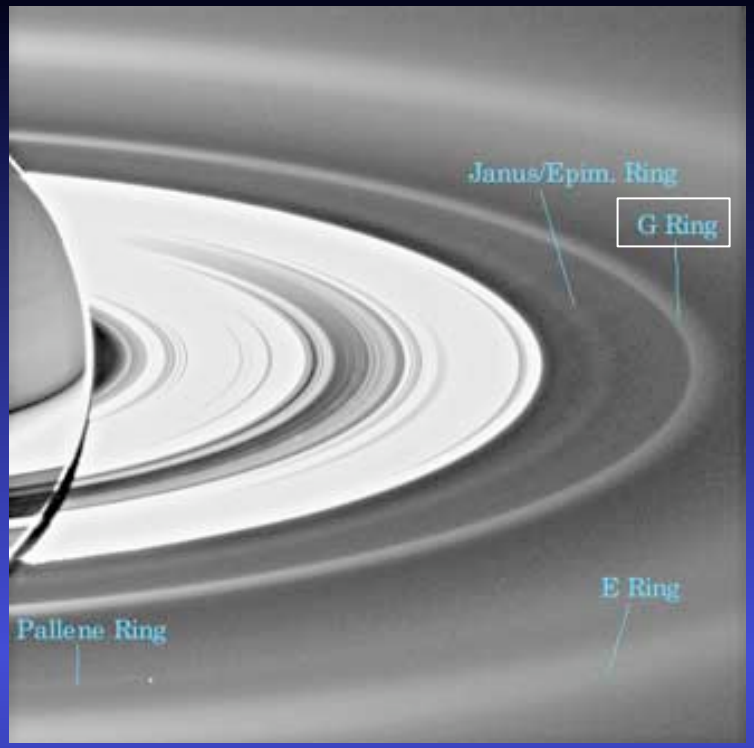


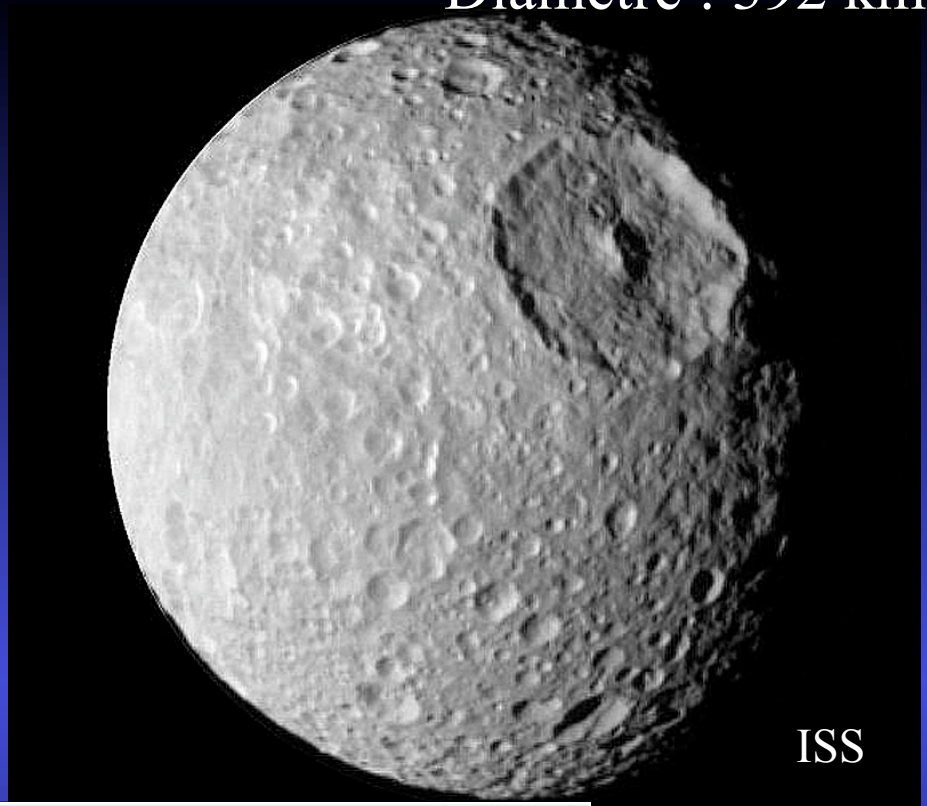
Geysers de vapeur d'eau
Alimentation de l'anneau E

→ Interdisciplinaire !

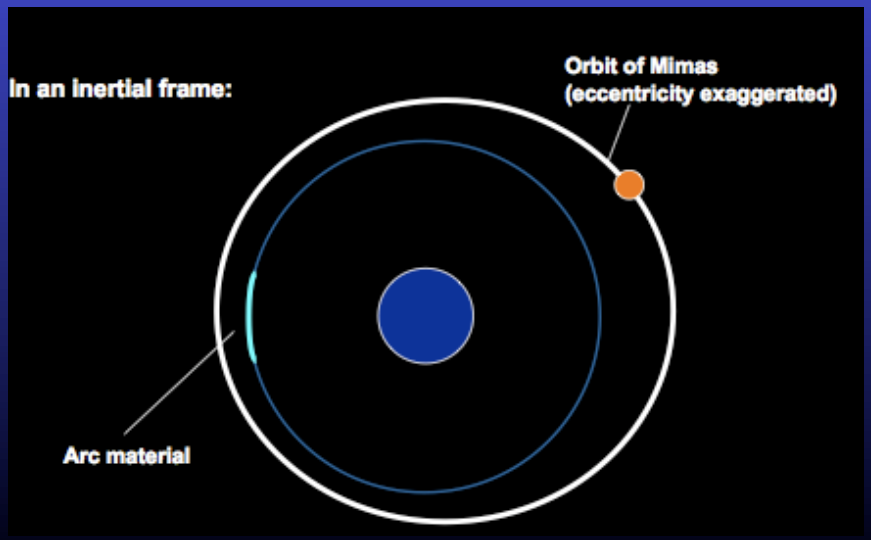
MIMAS

Diamètre : 392 km

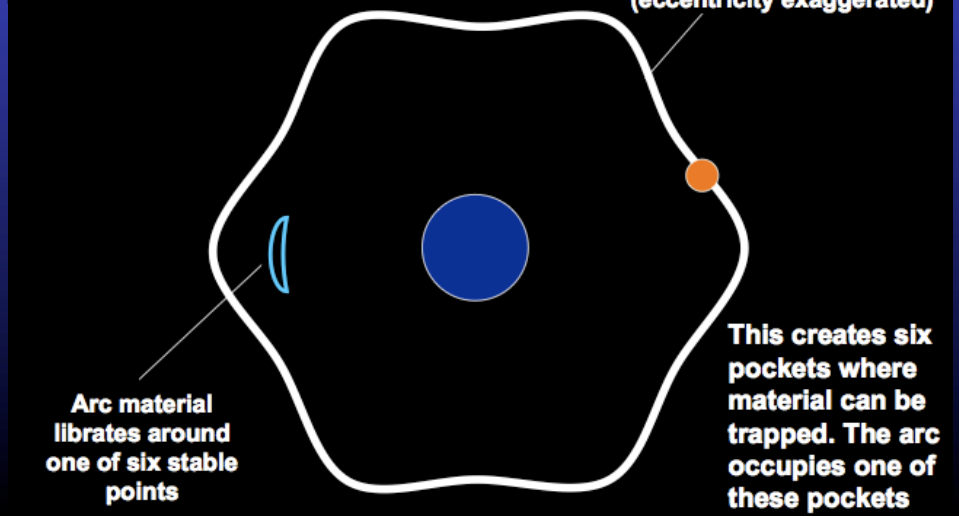




ISS



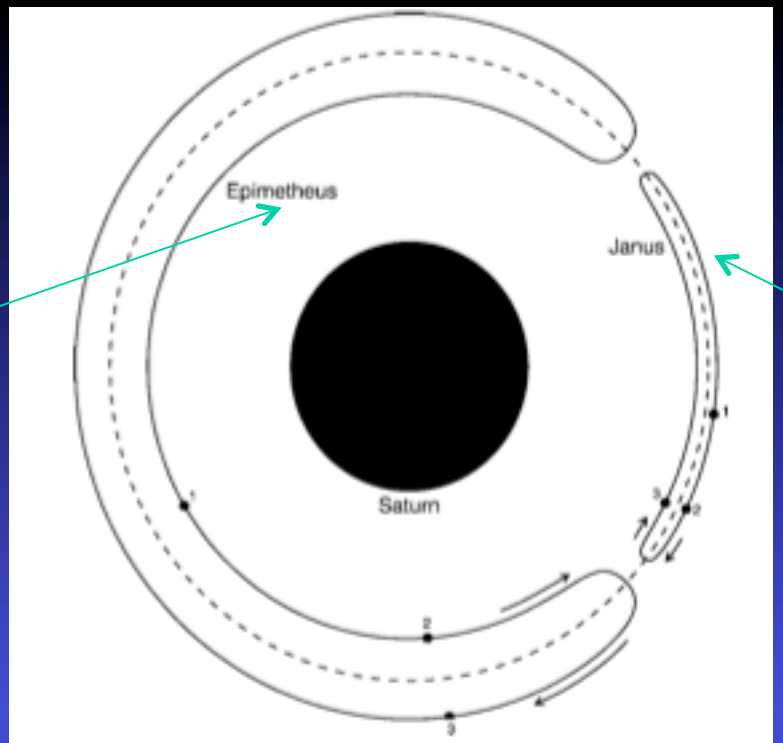
$$6\lambda_{arc} - 7\lambda_{Mimas} + \varpi_{Mimas} = \pi$$

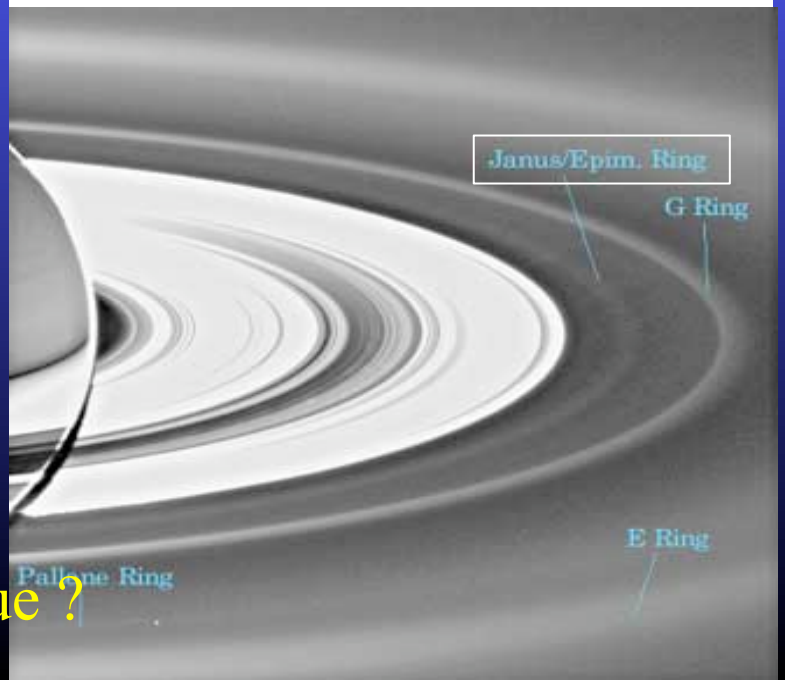


JANUS & EPIMETHEE

Voyager

Images Cassini/ISS





Voyager

Cassini/ISS

Janus: 178 km
Epiméthée: 104 km

Anneau

Destruction d'un corps unique ?

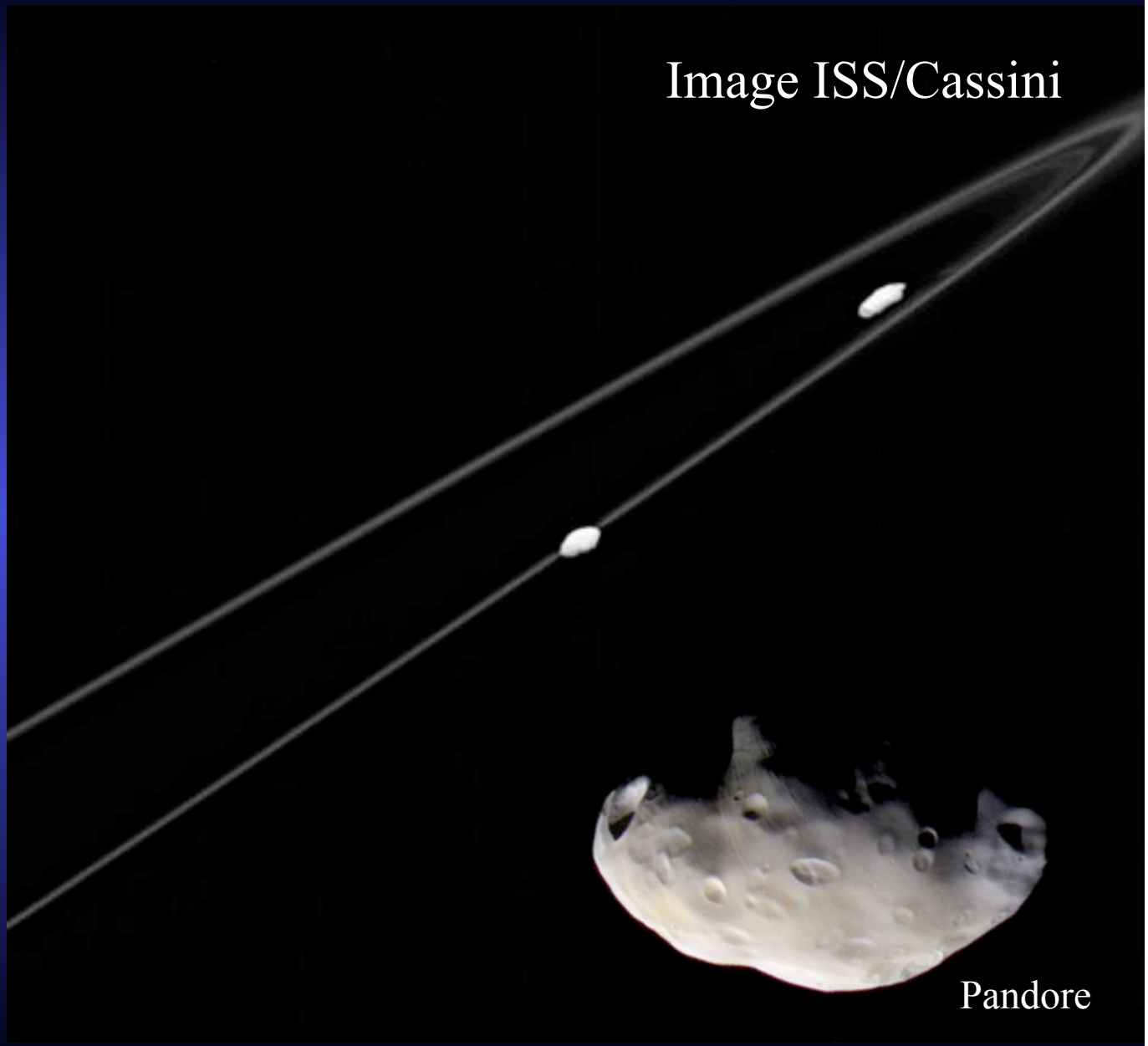
PROMETHEE & PANDORE

Image Voyager

Satellites bergers anneau F
Découverts par Voyager 2
Etalement radial anneau F

Cratères sur Pandore
mais surface lisse …

Pandore: 92 km
Prométhée: 92 km

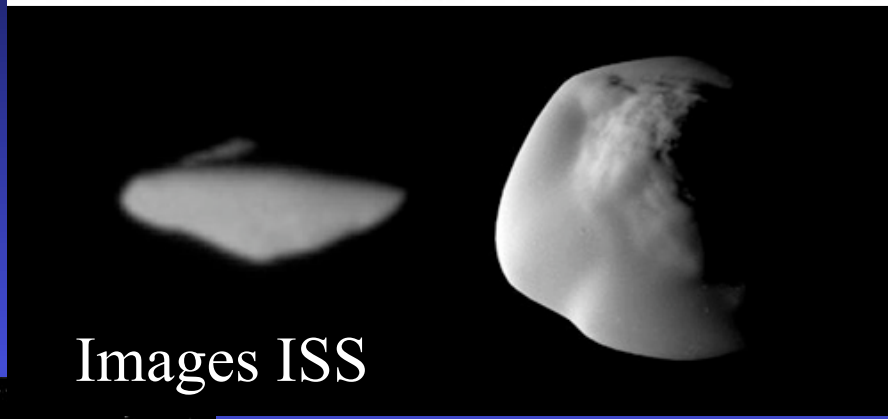


ATLAS

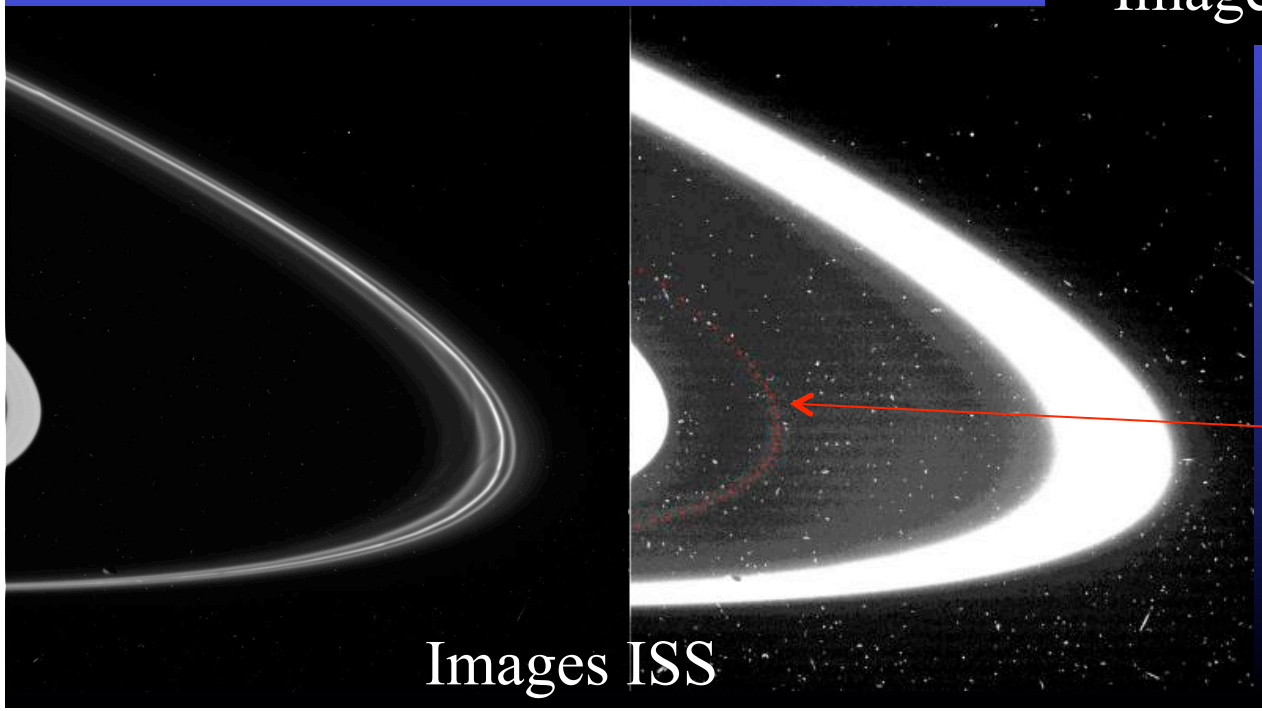
Diamètre: 28 km

Fort renflement équatorial
→ apparence de « soucoupe volante »

Image de synthèse



Images ISS

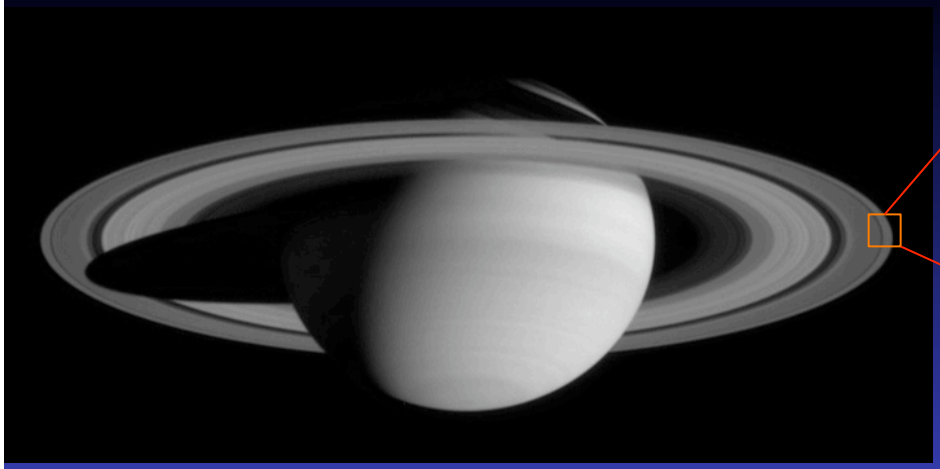


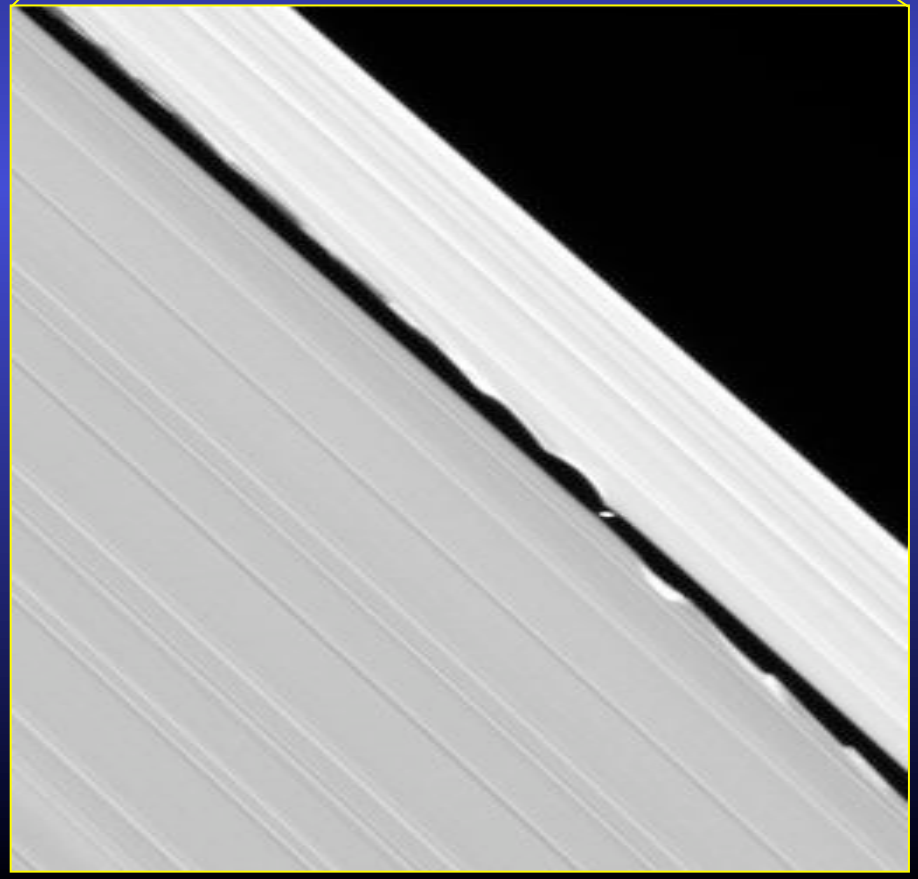
Images ISS

Anneau d'Atlas

DAPHNIS

Images ISS



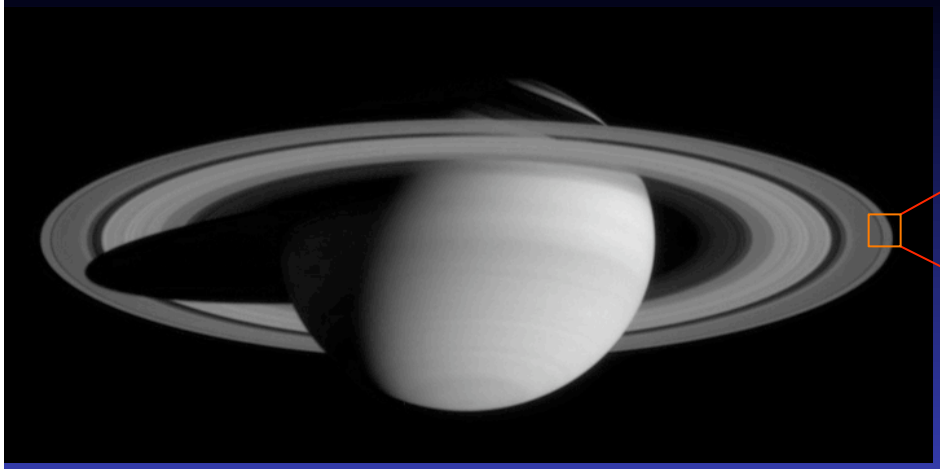


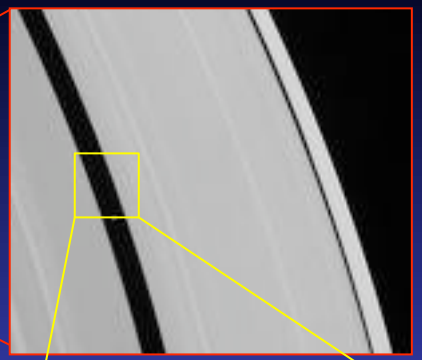
Lacune de Keeler
Ondes cinématiques
Satellite Daphnis découvert en 2005
annelet ?

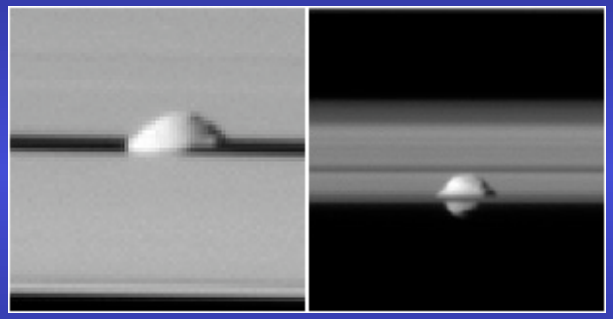
Diamètre < 10 km

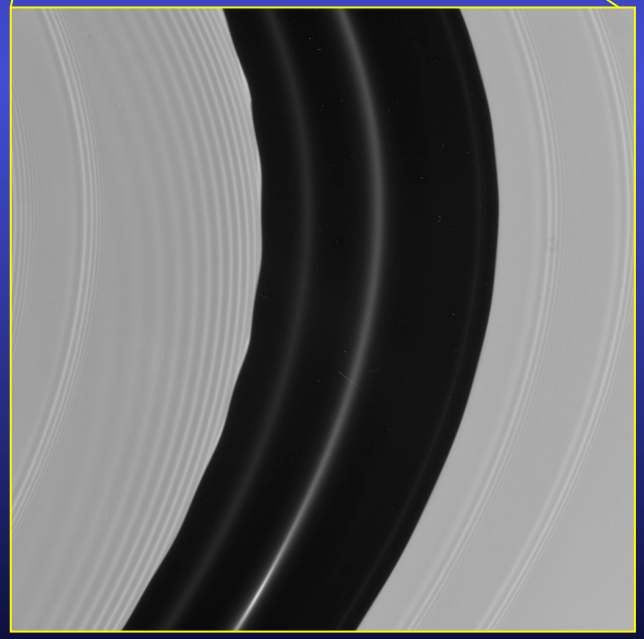
PAN

Images ISS

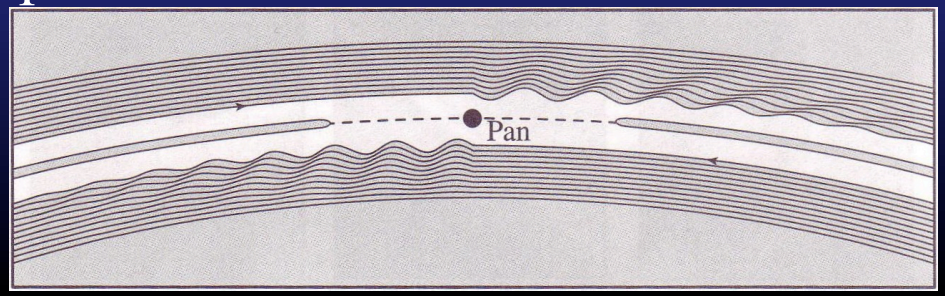








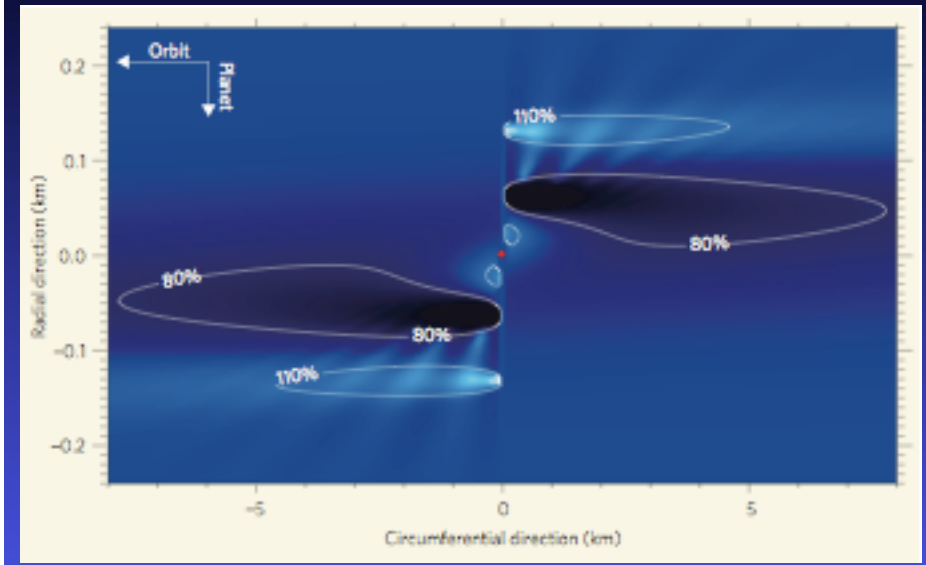
Pan « dépasse » des anneaux !!
Diamètre satellite : 20 km
Hauteur satellite ~ 20 km
Epaisseur anneaux ~ 20 m



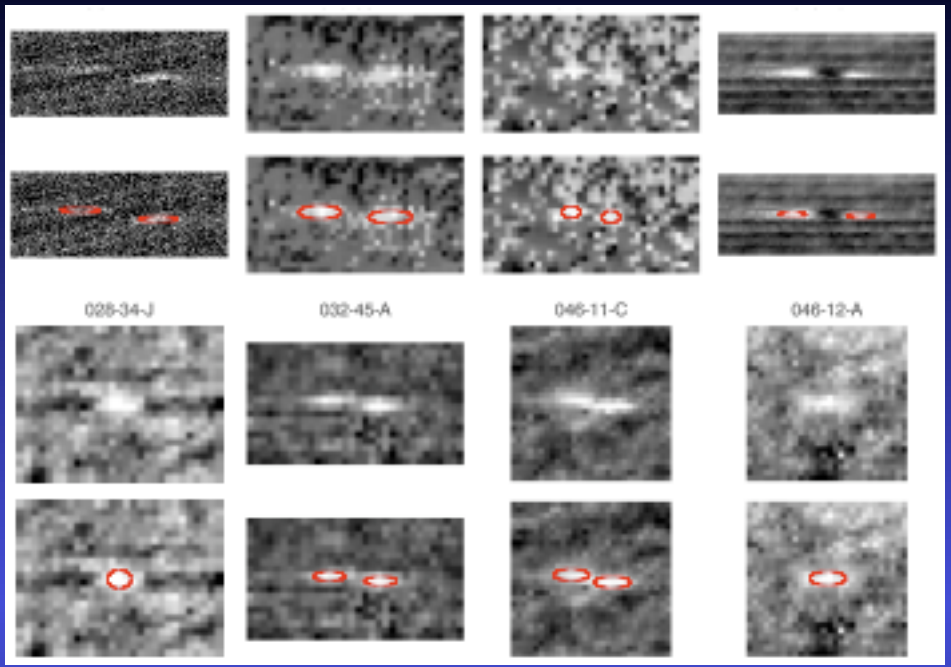
Lacune d'Encke
4 annelets

PROPELLERS (hélices)

Images ISS



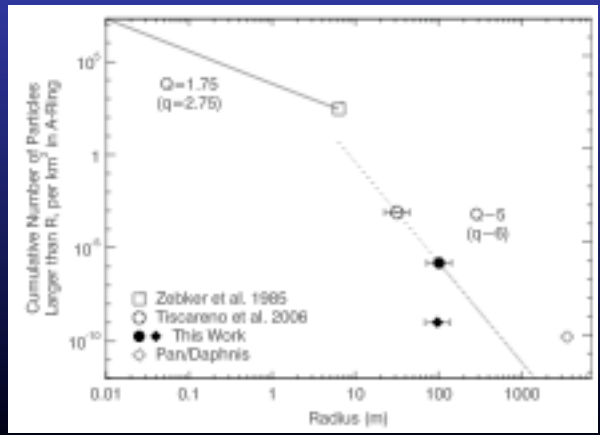
Spahn et al., 2007



Tiscareno et al., 2007

Population de « gros objets »
dans l'anneau A

Pas vraiment des particules d'anneaux…



Résultats majeurs pour les satellites

→ Interactions entre anneaux et satellites

* Erosion satellite / alimentation anneau
* Accrétion satellite / anneau source matière
* Interactions gravitationnelles

Découvertes Cassini pour les anneaux

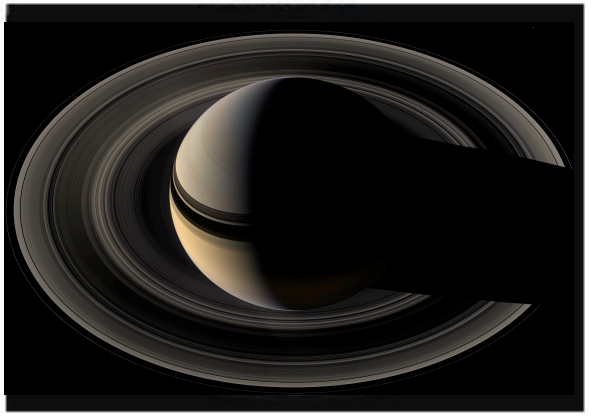
Les anneaux de Saturne

1970 — 1980-1990 — 2000-2010

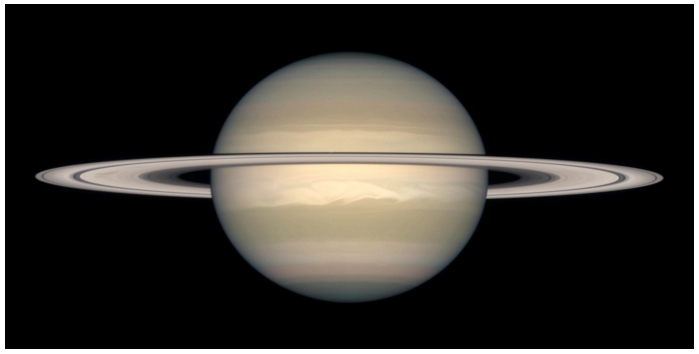
Pioneer 11

Voyager 1

Cassini



Hubble

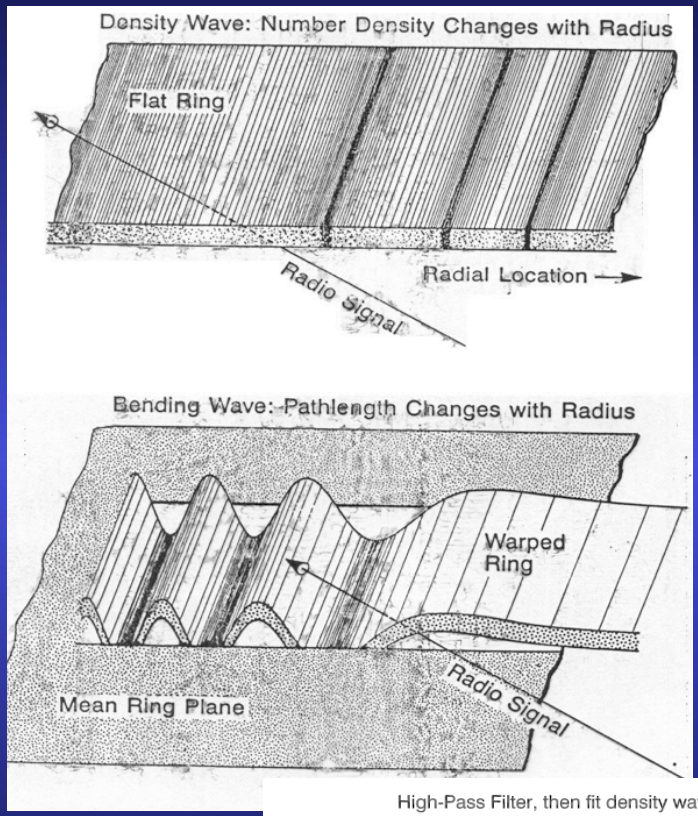


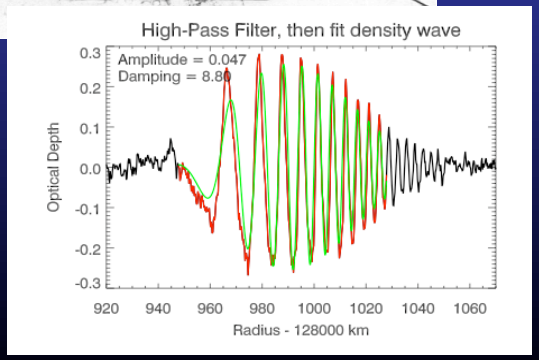
Cassini = Gain en :
- Sensibilité, Résolution, Géométries d'observation
- Suivi temporel

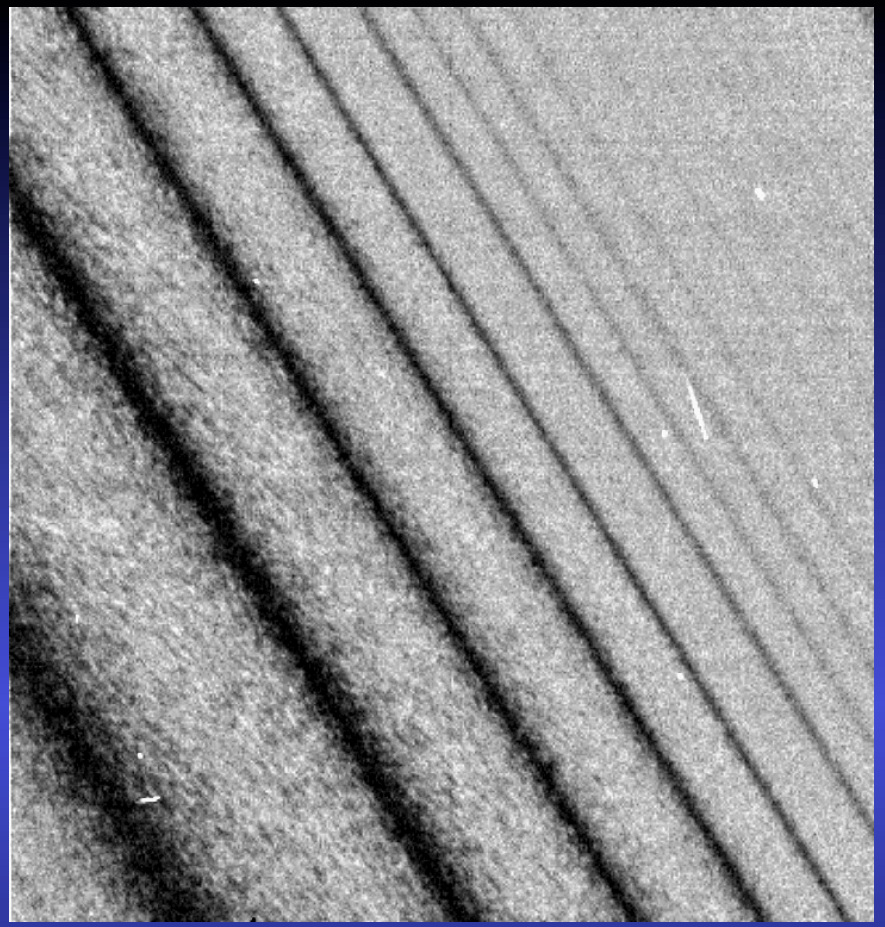
Waves

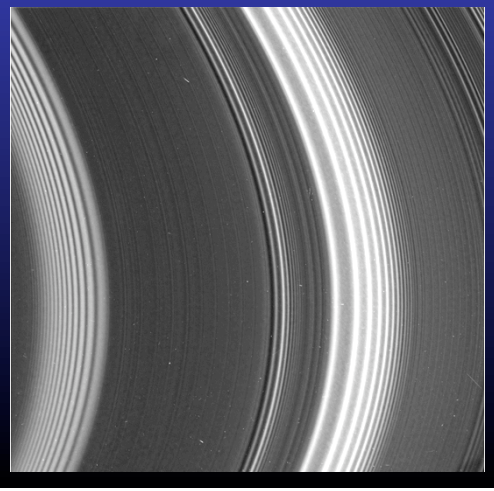
Images ISS

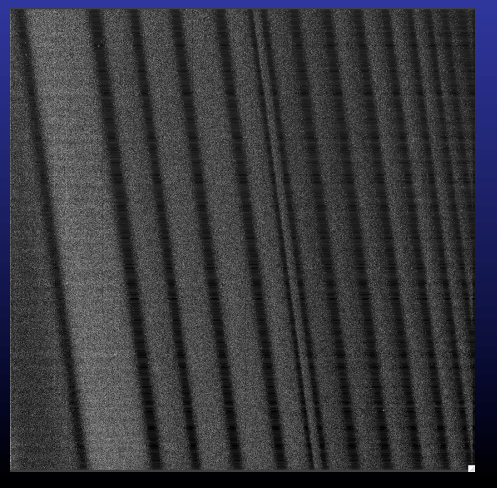
Résolution spatiale ~ 100 m par pixel !!





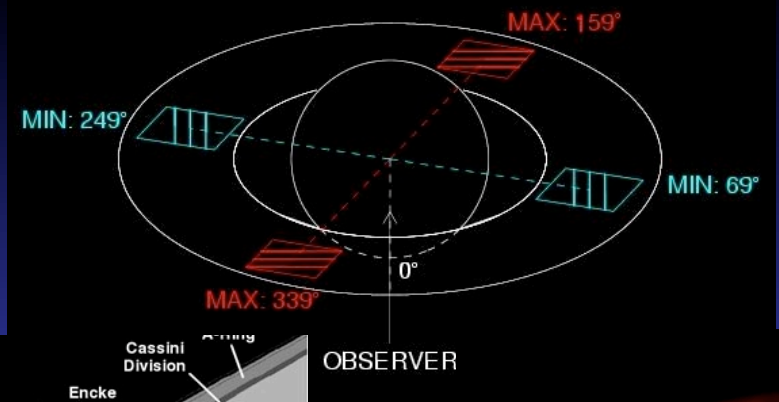






Tiscareno et al., 2007

Wakes



VIMS

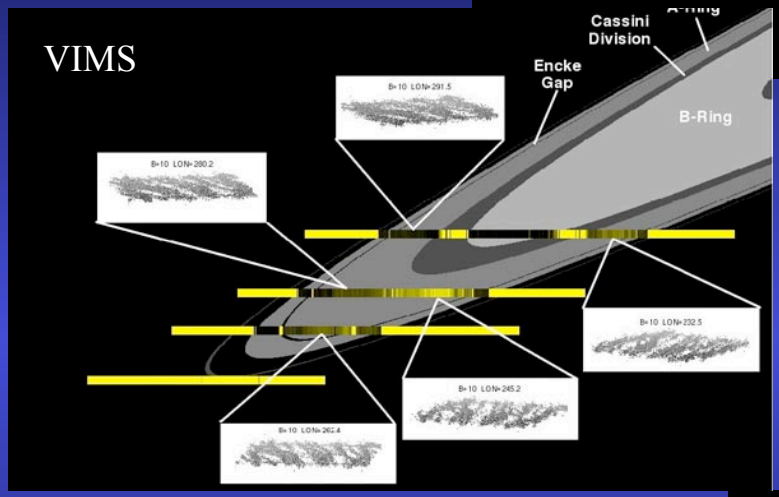
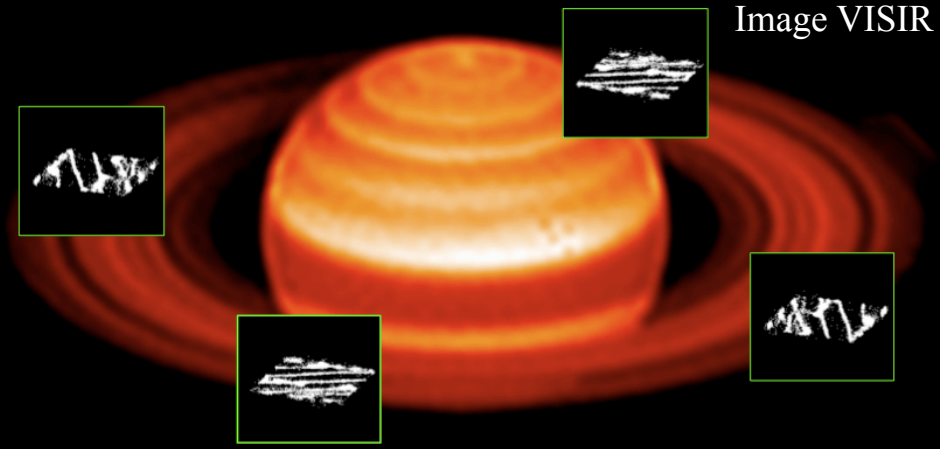
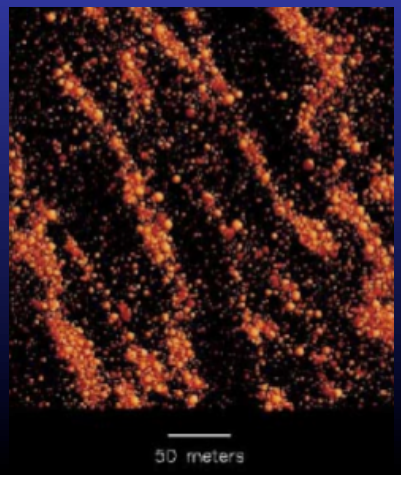


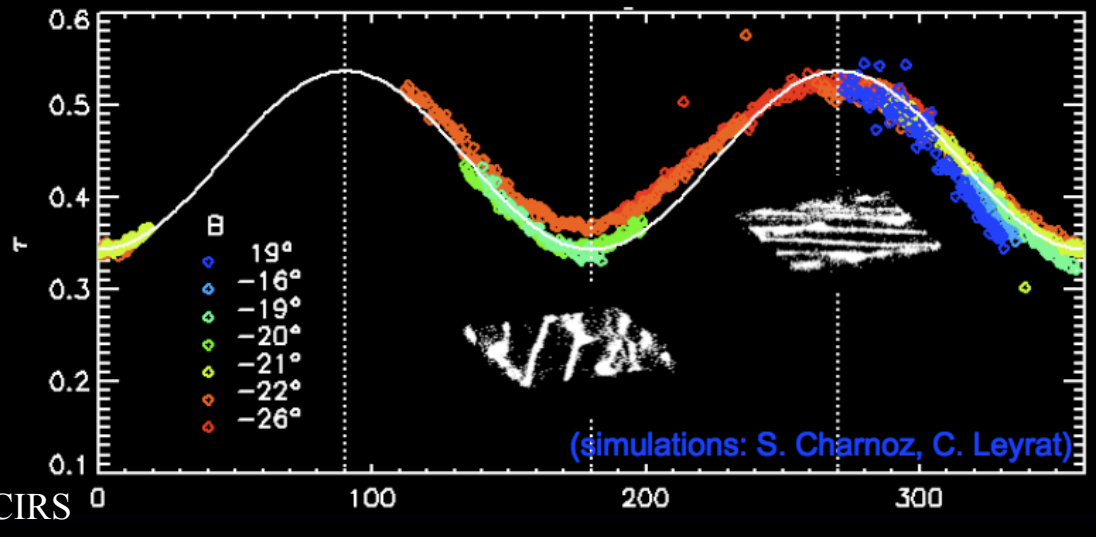
Image VISIR



Instabilités gravitationnelles

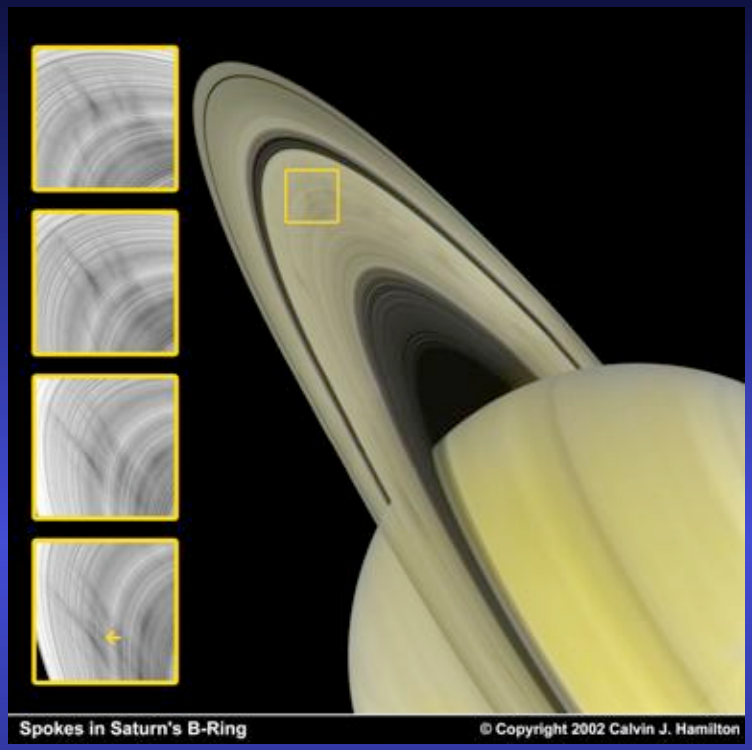


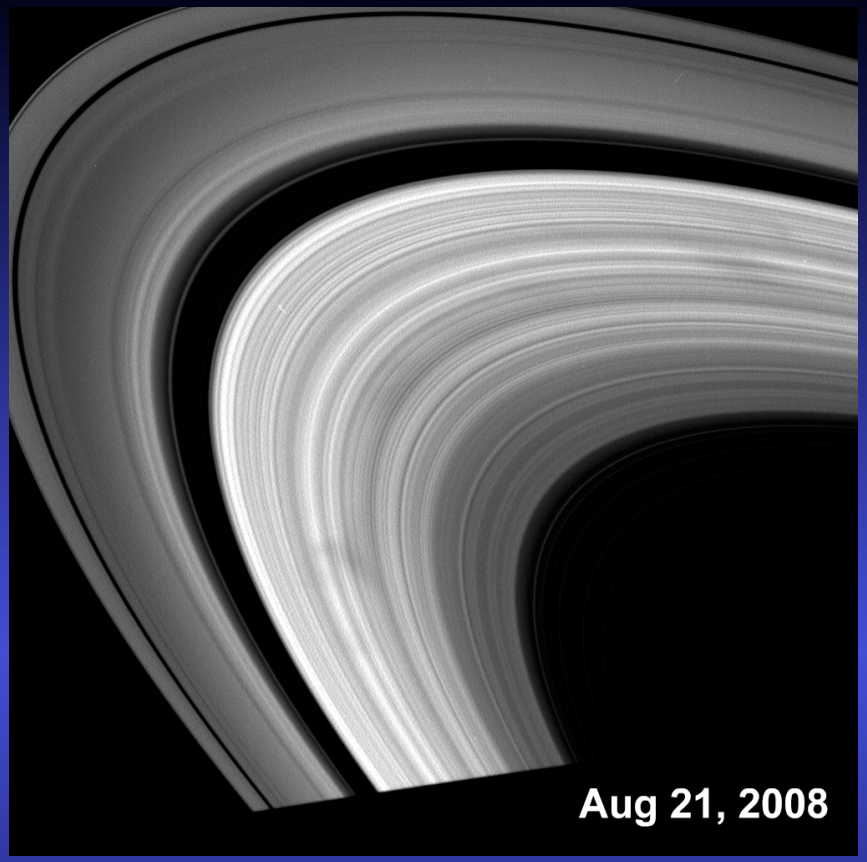
Salo, 1992



CIRS

Spokes



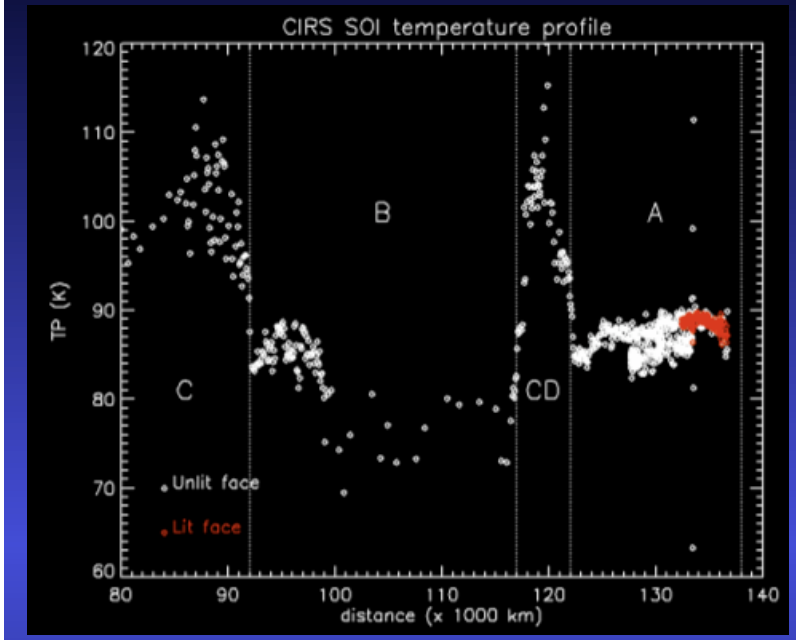


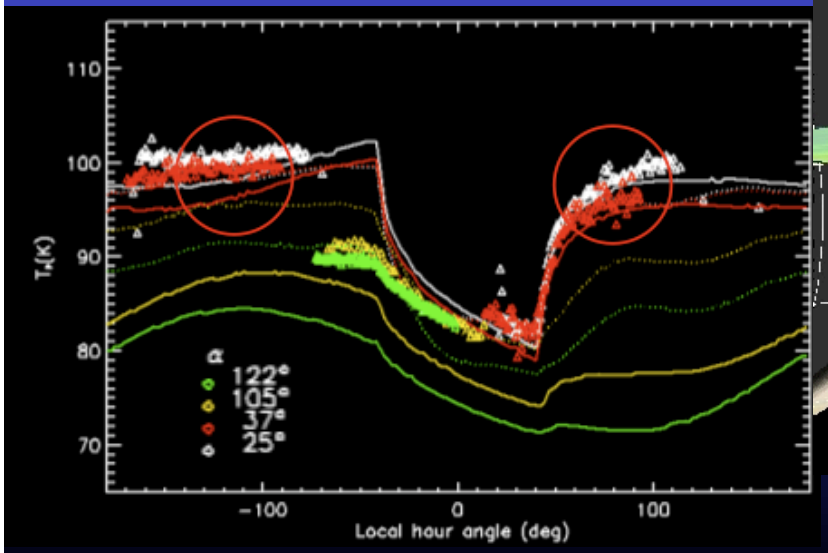
Voyager

Cassini/ISS

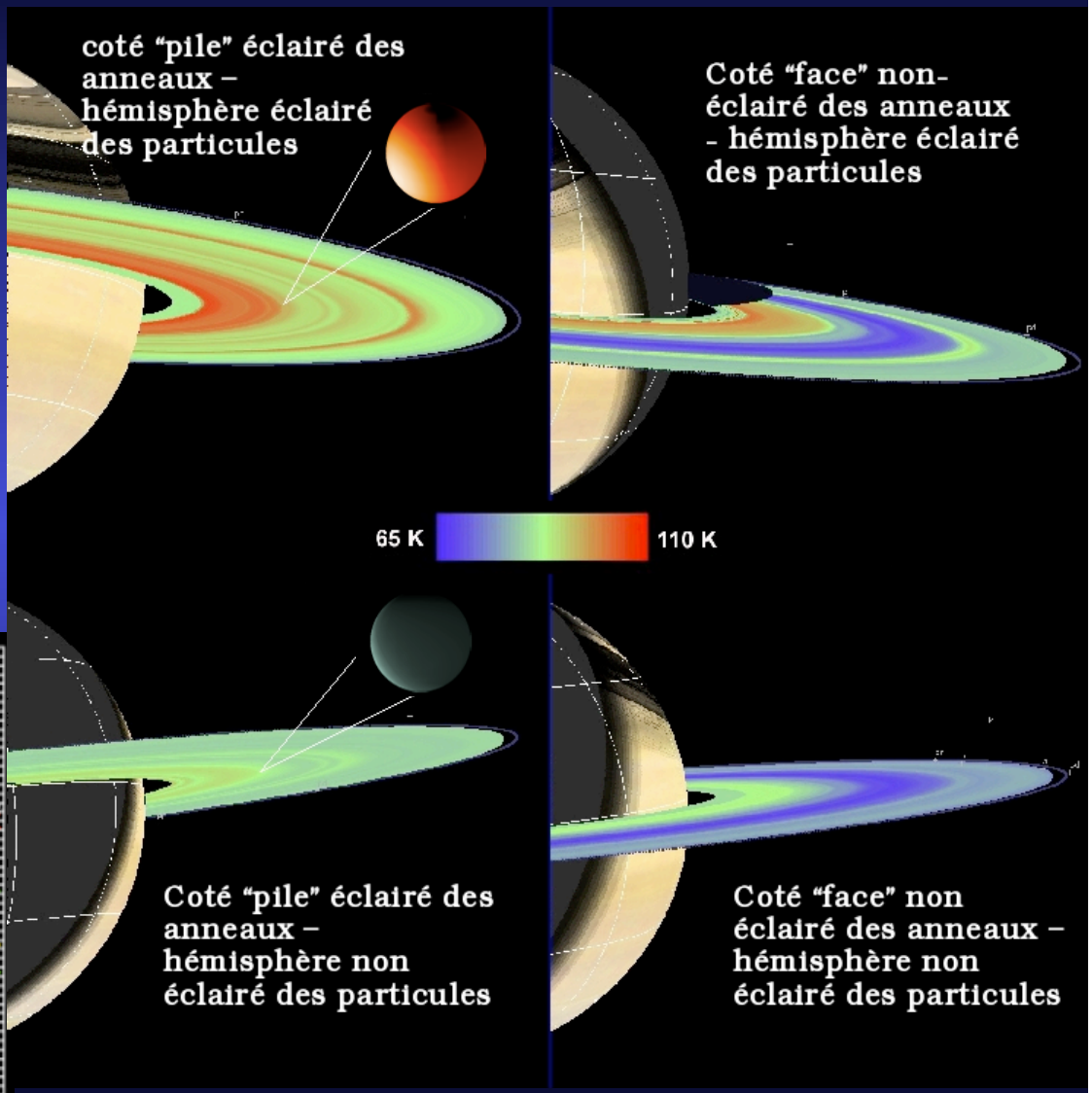
Mc Ghee et al., 2001

Emission thermique





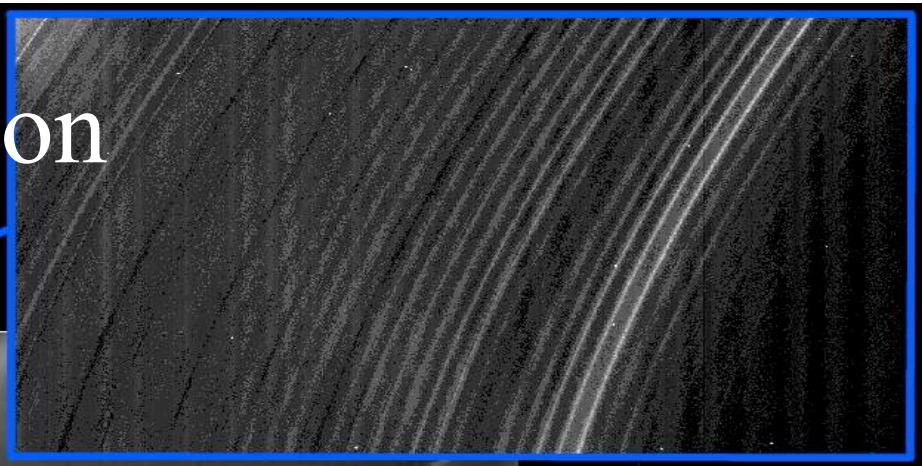
Ferrari et al., 2007



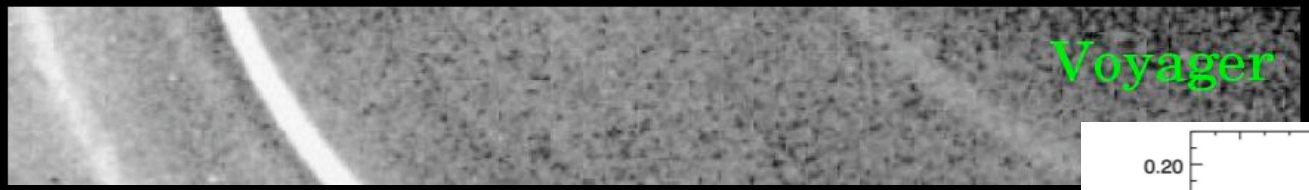
Images CIRS

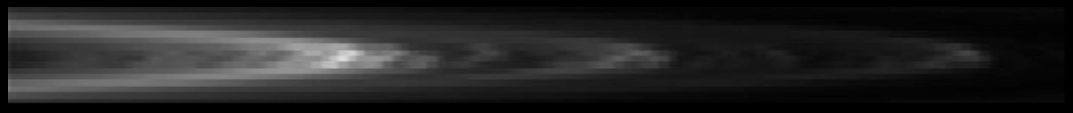
Structure et évolution

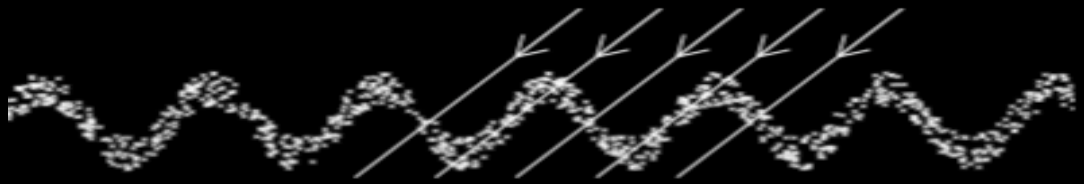
Hedman et al., 2007

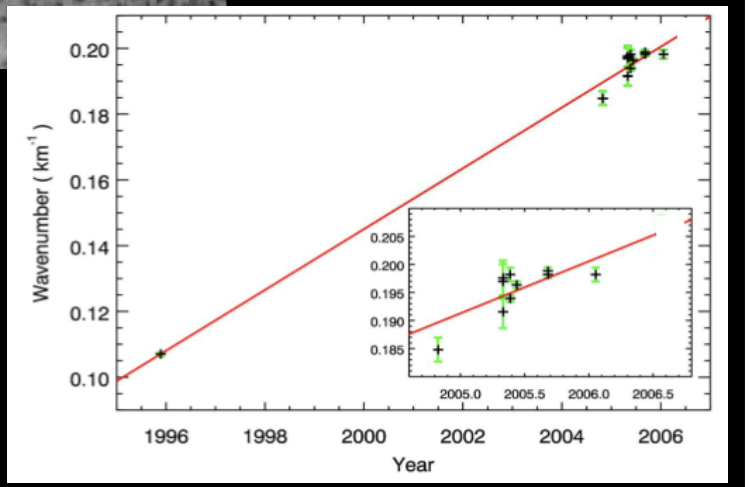


Images Cassini/ISS





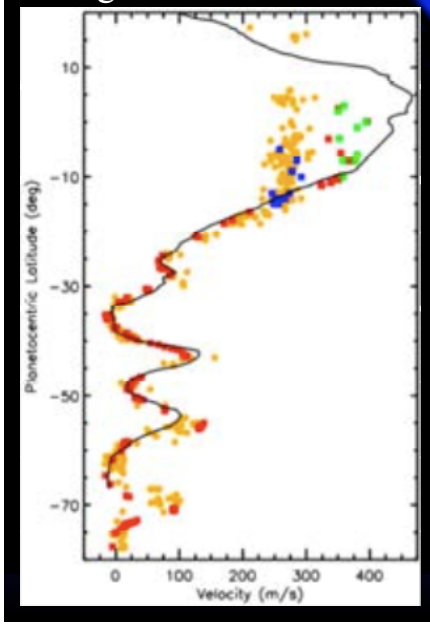




Et Saturne ?!!...

2.3 microns (shown in blue) : icy ring particles are highly reflecting while methane gas absorbs
3.0 microns (shown in green) : rings water ice is absorbing while sunlit hemisphere is bright
5.1 microns (shown in red) : reflected sunlight weak → thermal radiation

Images VIMS/Cassini



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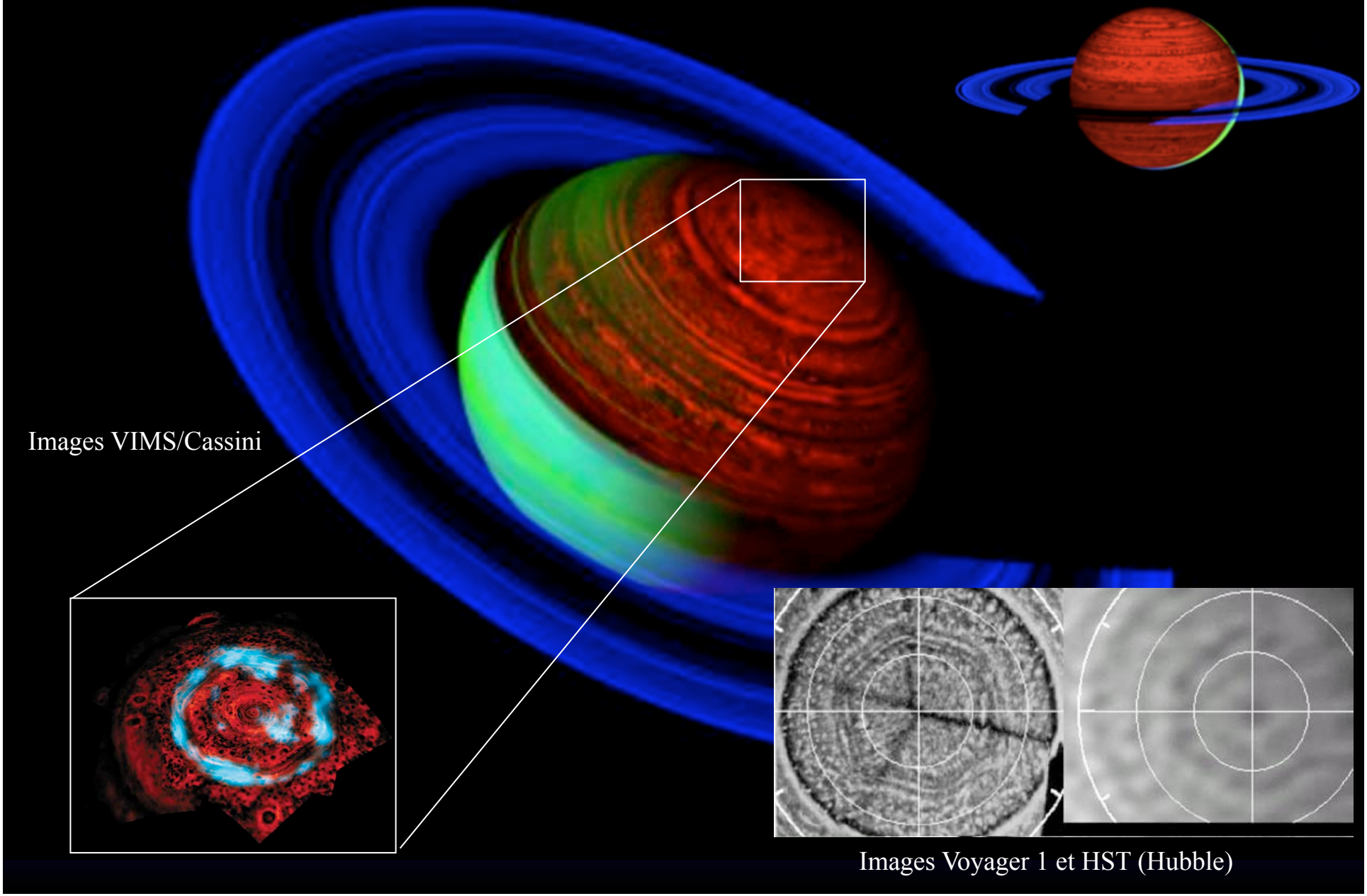
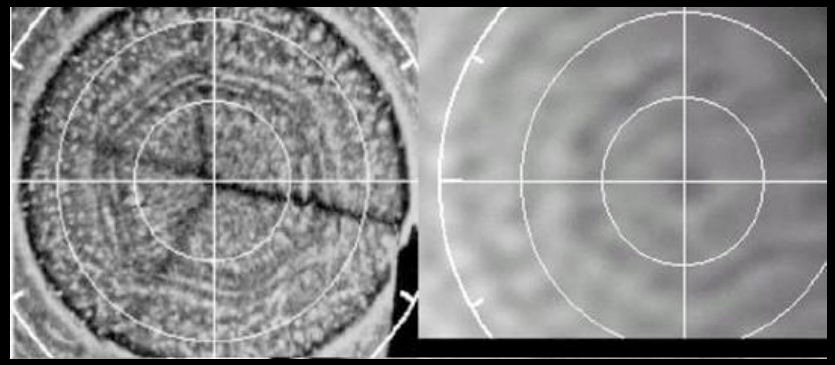


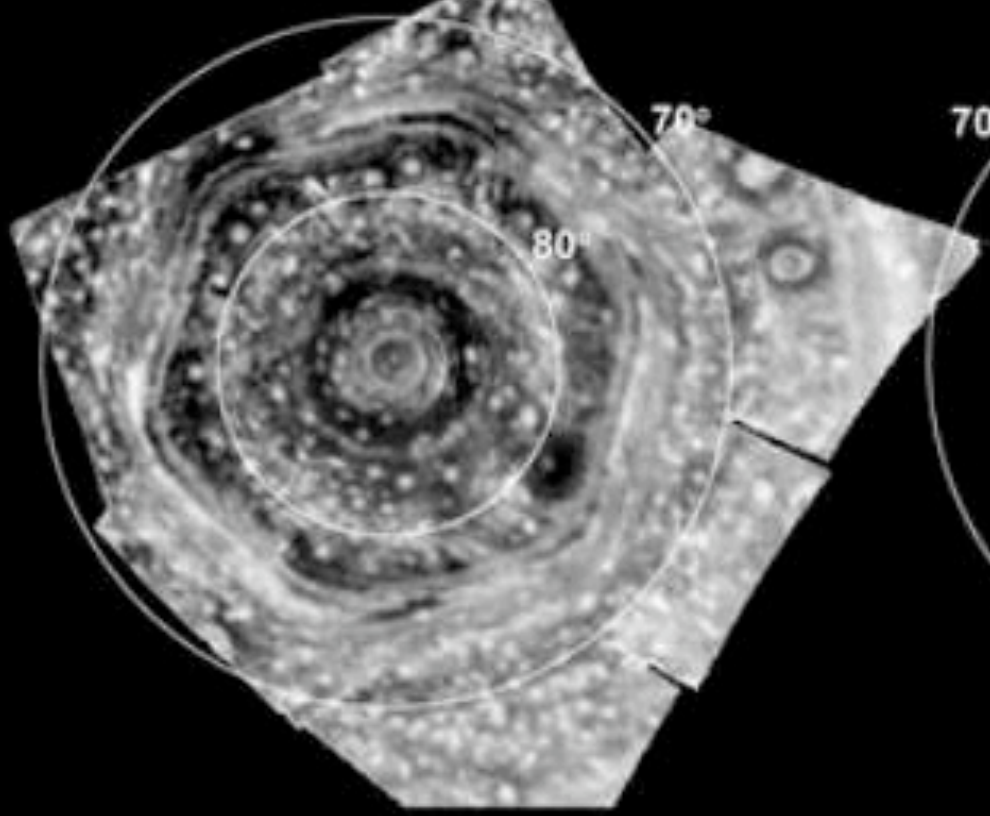
Images VIMS/Cassini

Images Voyager 1 et HST (Hubble)

Saturn's North Pole



Images Voyager 1 et HST (Hubble)



Images VIMS

Saturn's South Pole

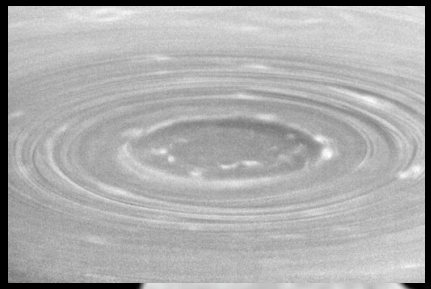
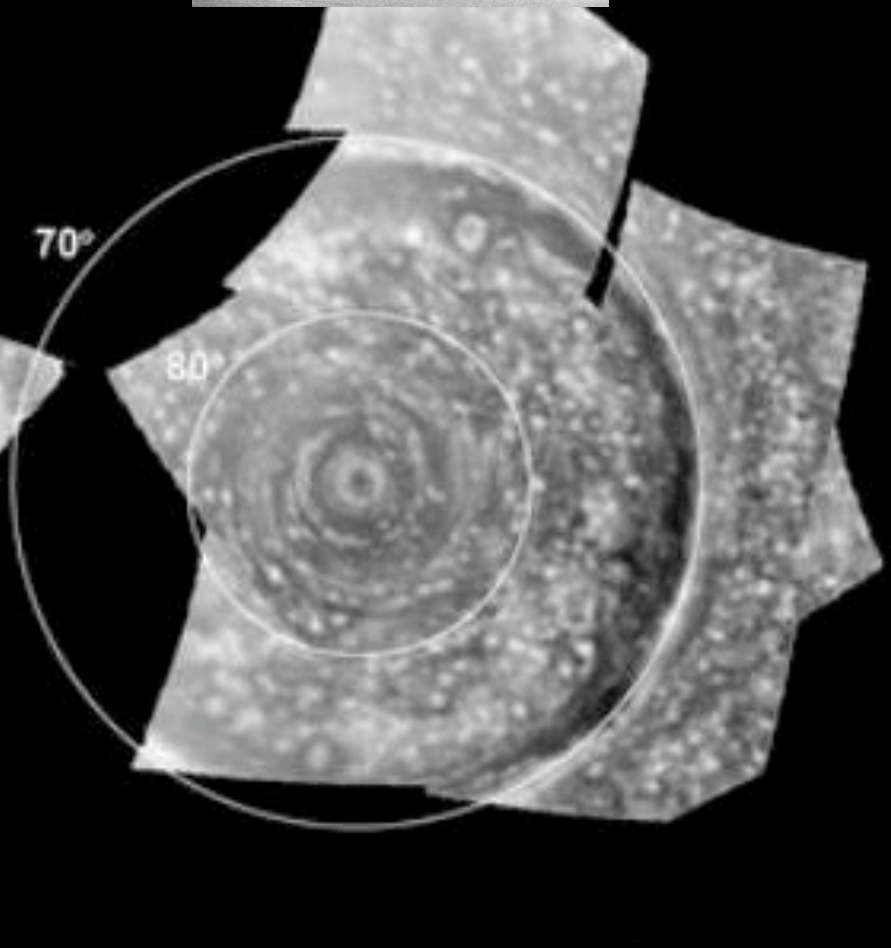
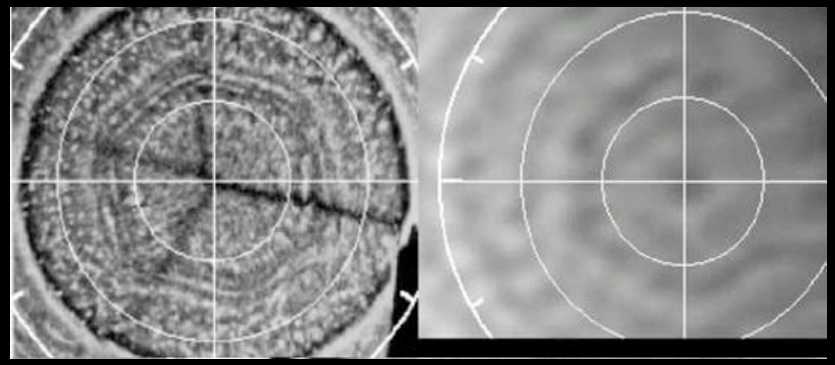


Image ISS

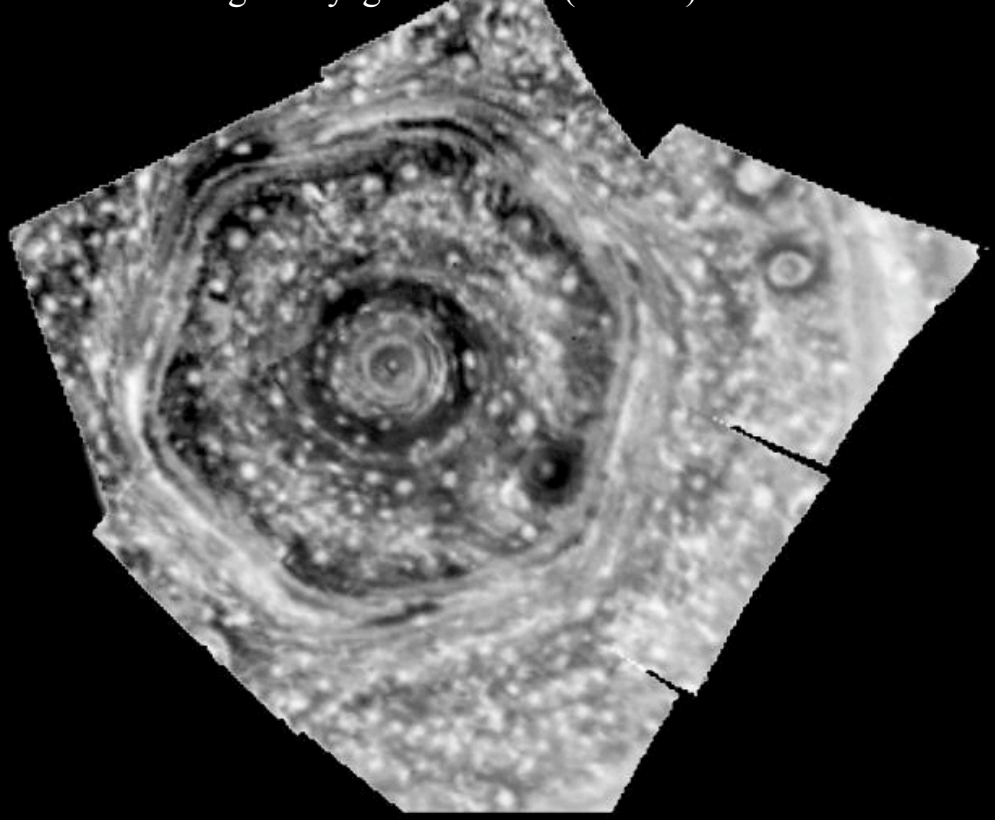


Images VIMS

Saturn's North Pole



Images Voyager 1 et HST (Hubble)



Images VIMS

Saturn's South Pole

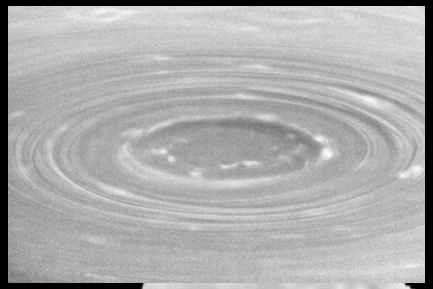
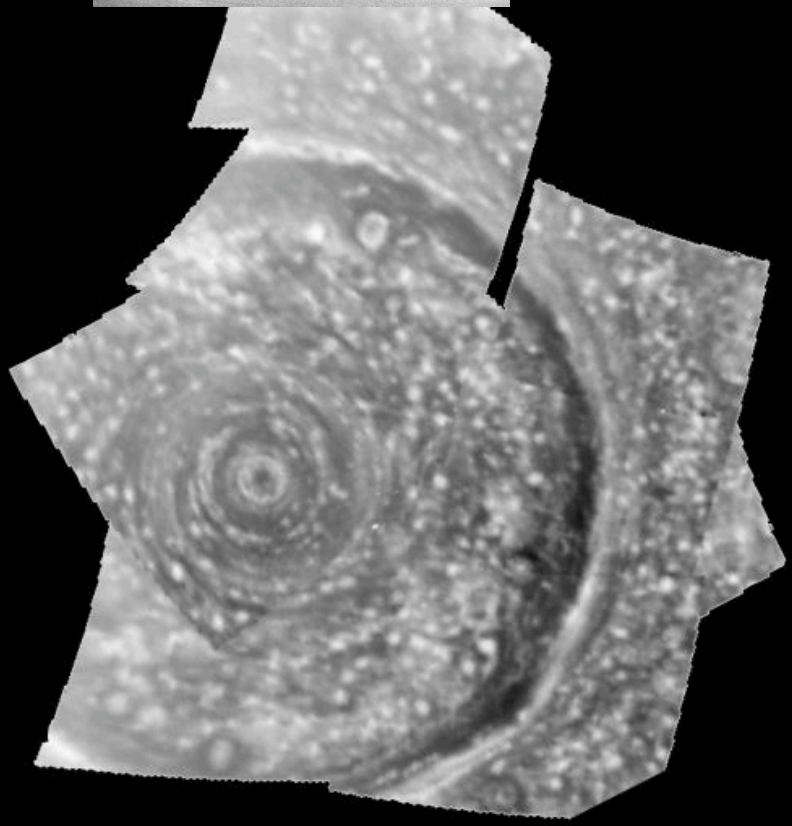
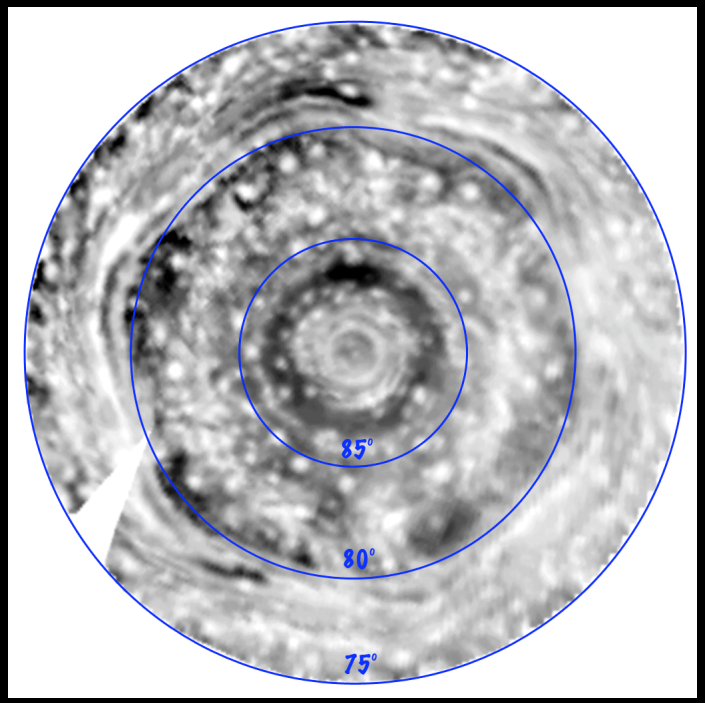


Image ISS



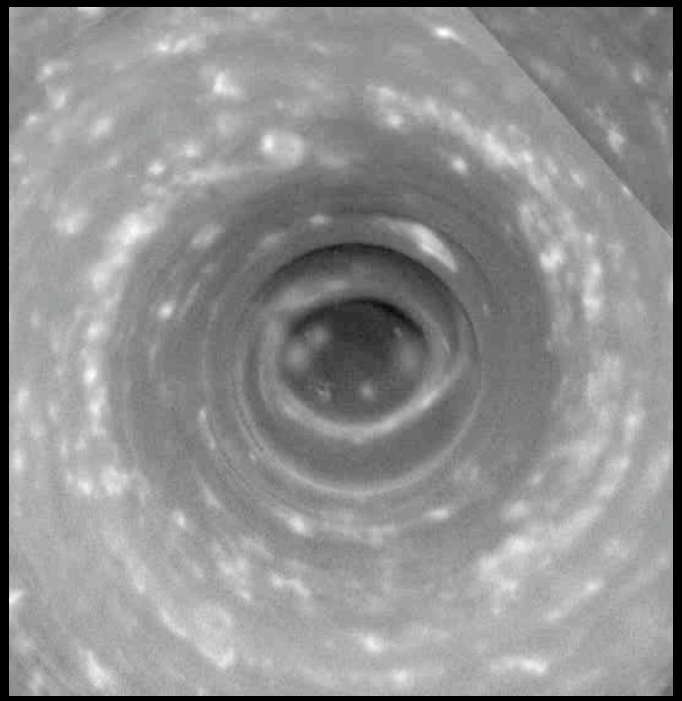
Images VIMS

Saturn's North Pole



Images VIMS

Saturn's South Pole



Images ISS

Dynamique des anneaux (1/2)

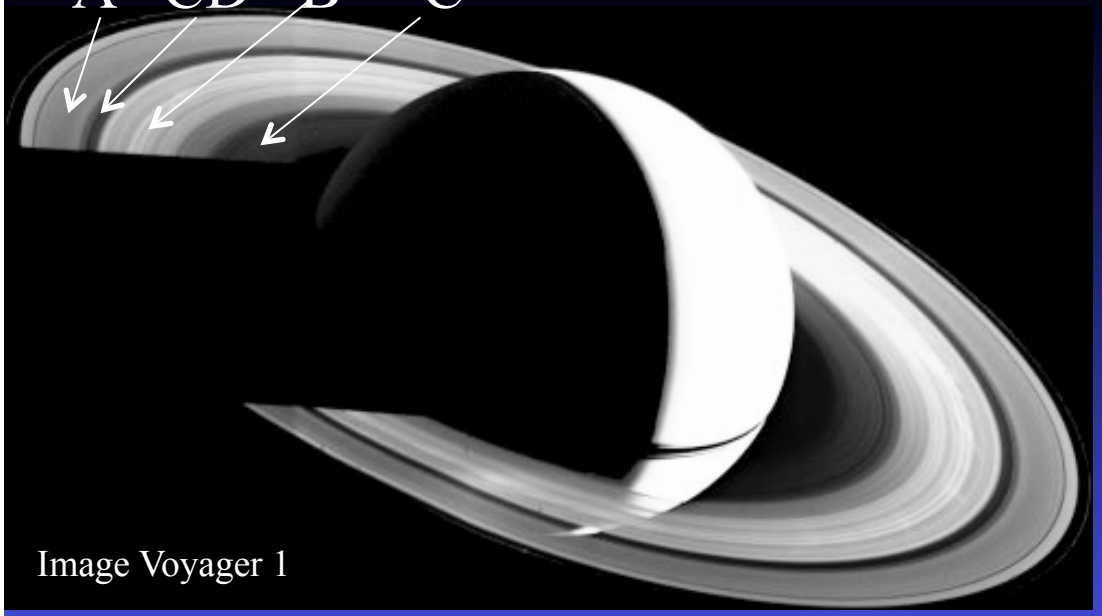
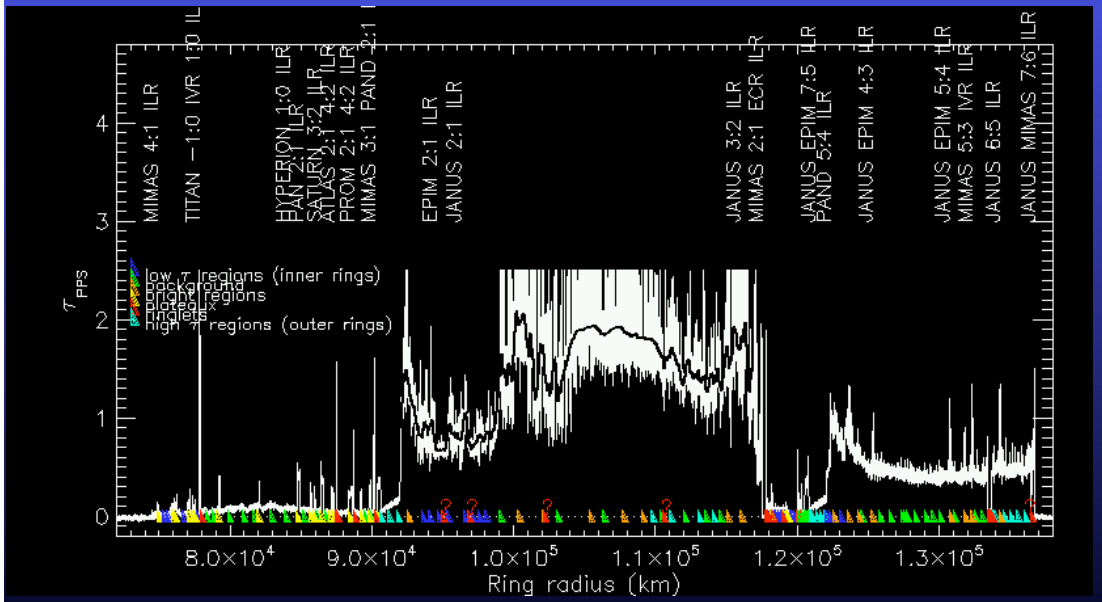


Image Voyager 1



Anneaux principaux

* Vitesse de rotation autour de Saturne: 30 000 à 60 000 km.h^{-1}

* T_{orbit} = 10 à 15h

* 70 000 km extension radiale

* ~100 résonances identifiées avec satellites distants

* Masse de Mimas

* Variations de profondeur optique ($10^{-3}<\tau<5$): composition, compacité, rugosité, taille des particules (1 μm à 10 m)

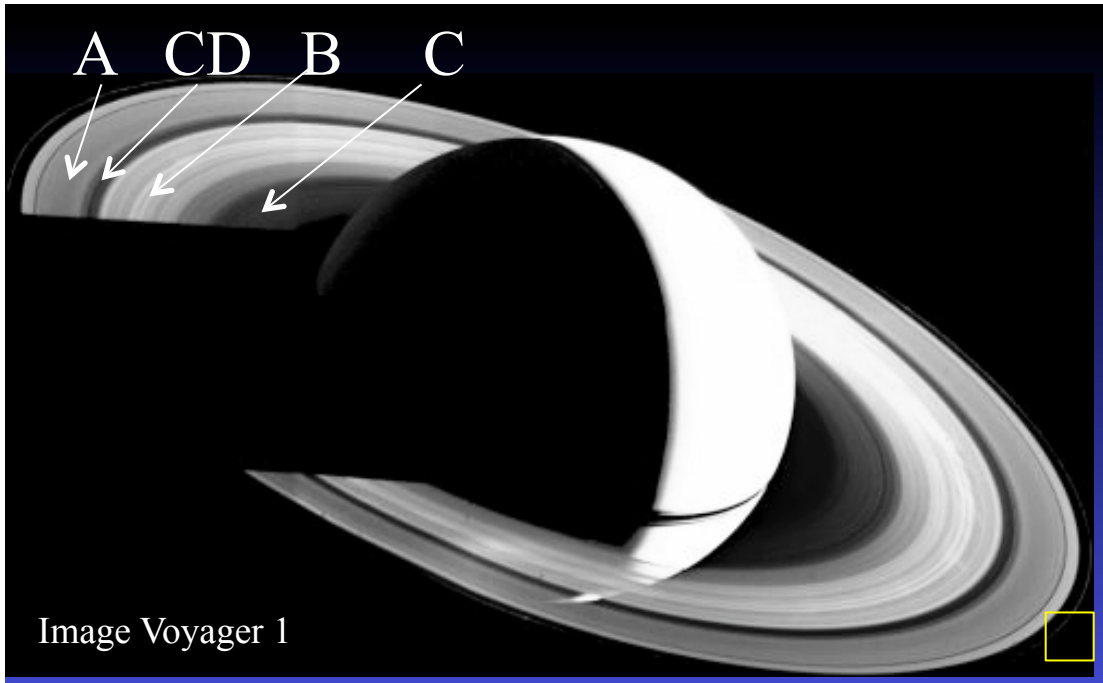


Image Voyager 1

Anneaux principaux

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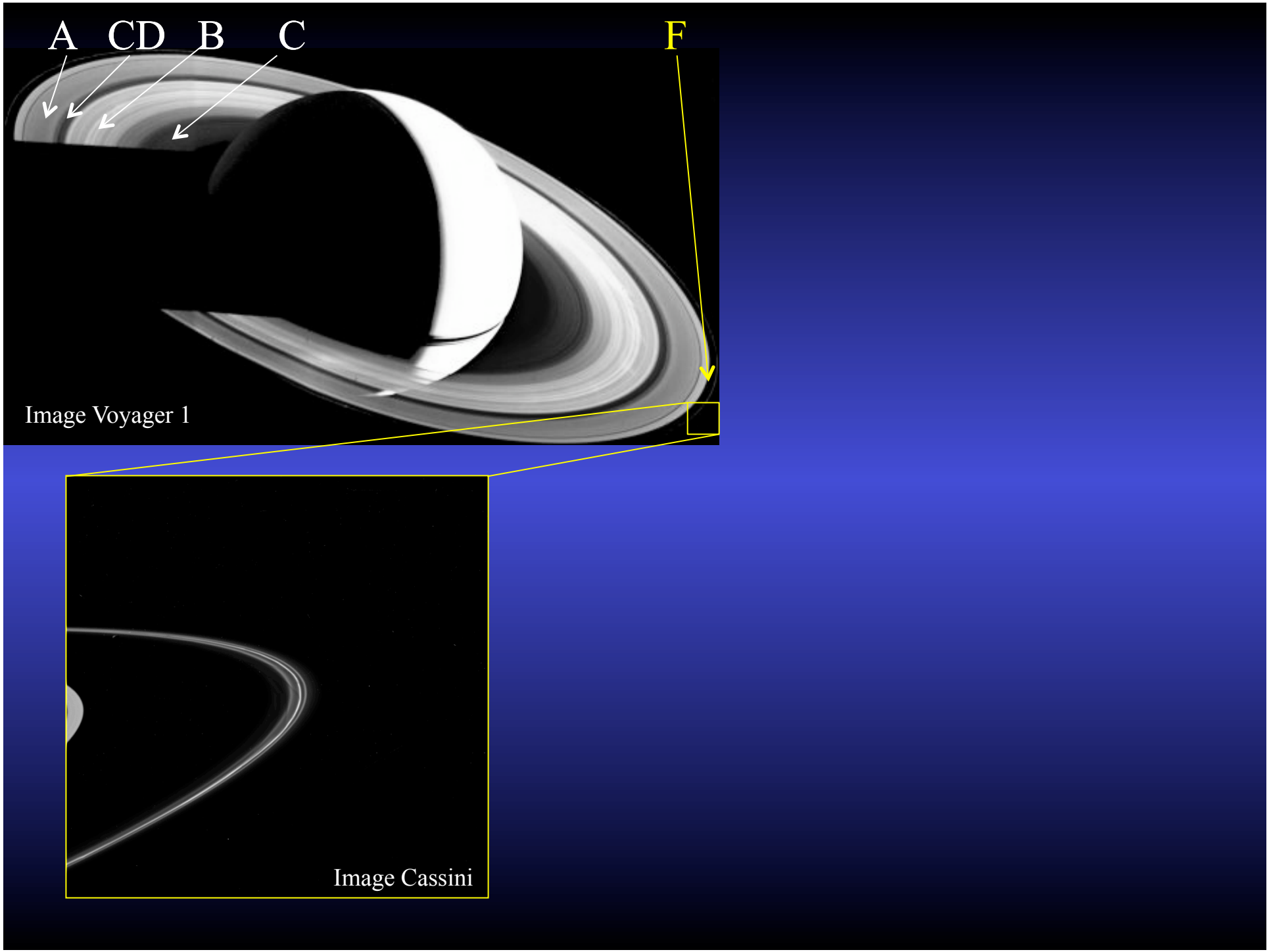
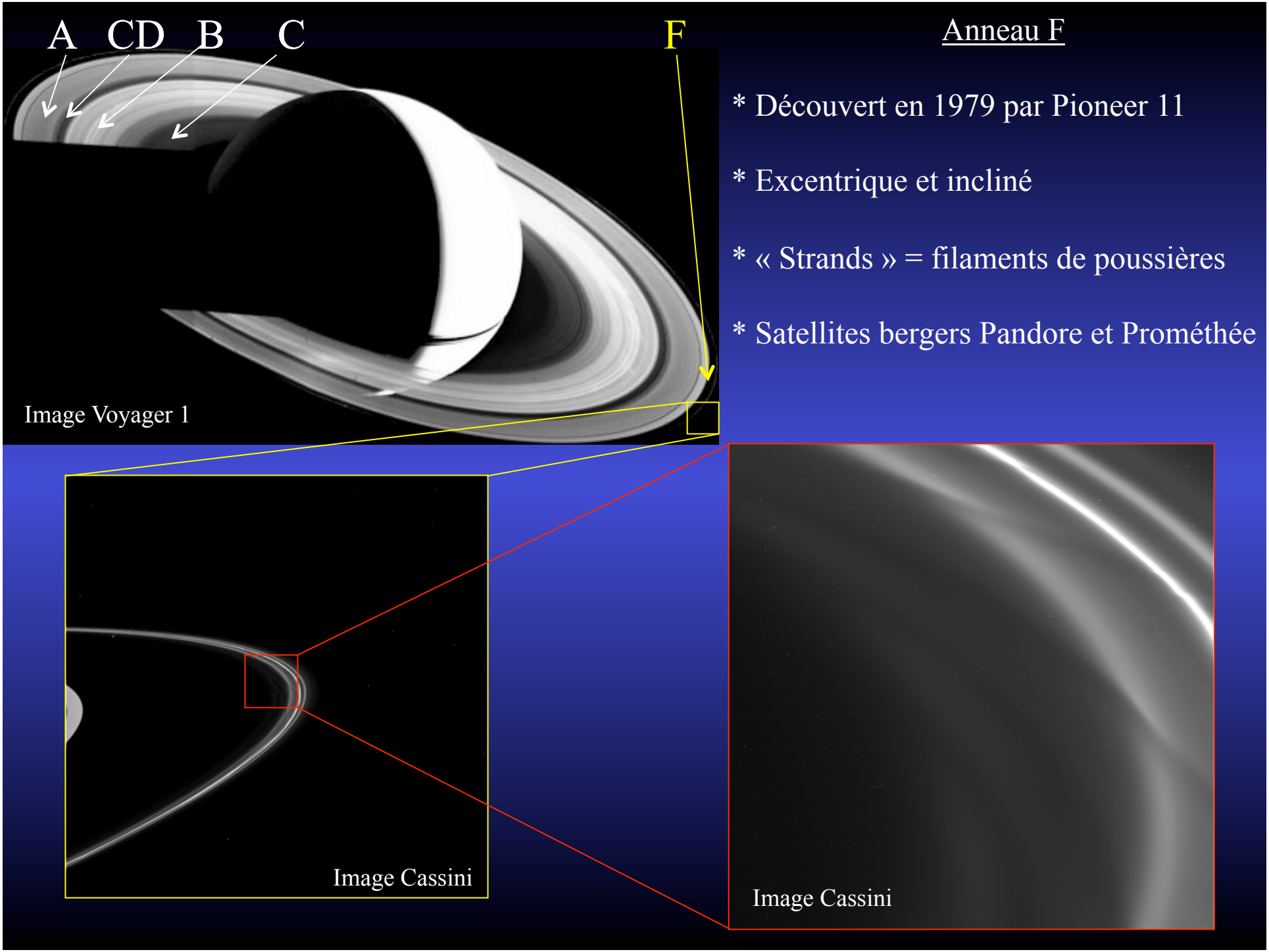
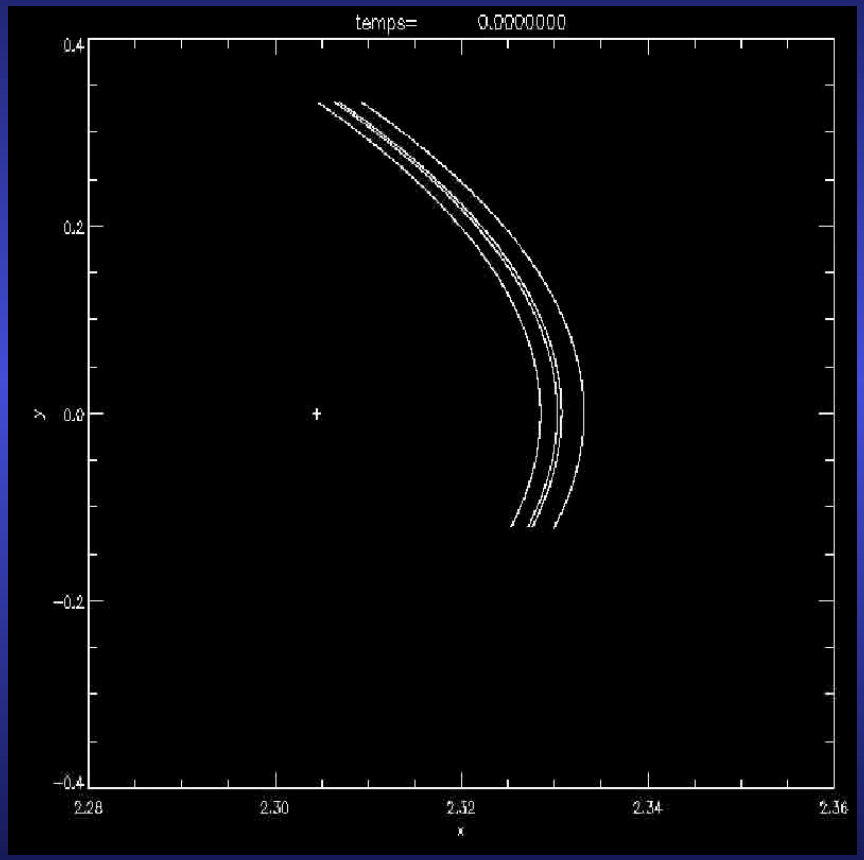

A
CD
B
C
F
Image Voyager 1
Image Cassini



Anneau F

* Découvert en 1979 par Pioneer 11
* Excentrique et incliné
* « Strands » = filaments de poussières
* Satellites bergers Pandore et Prométhée

Simulations numériques F + Prométhée



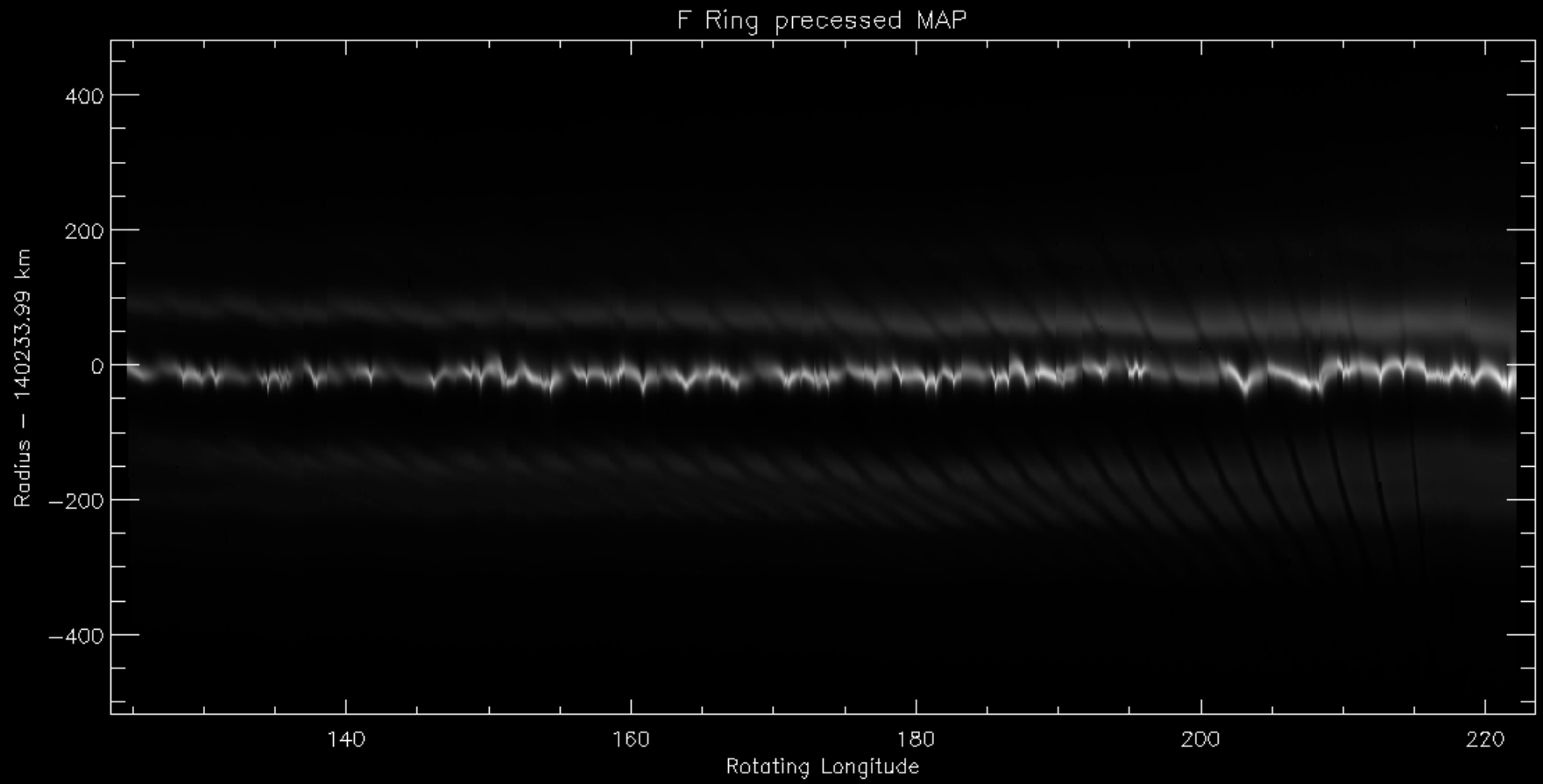
Murray, Juliatti-Winter, Charnoz ….

Écart Prométhée-Trou : 2°

Anneau F très perturbé radialement et azimutalement

Écart Prométhée-Trou : 2°

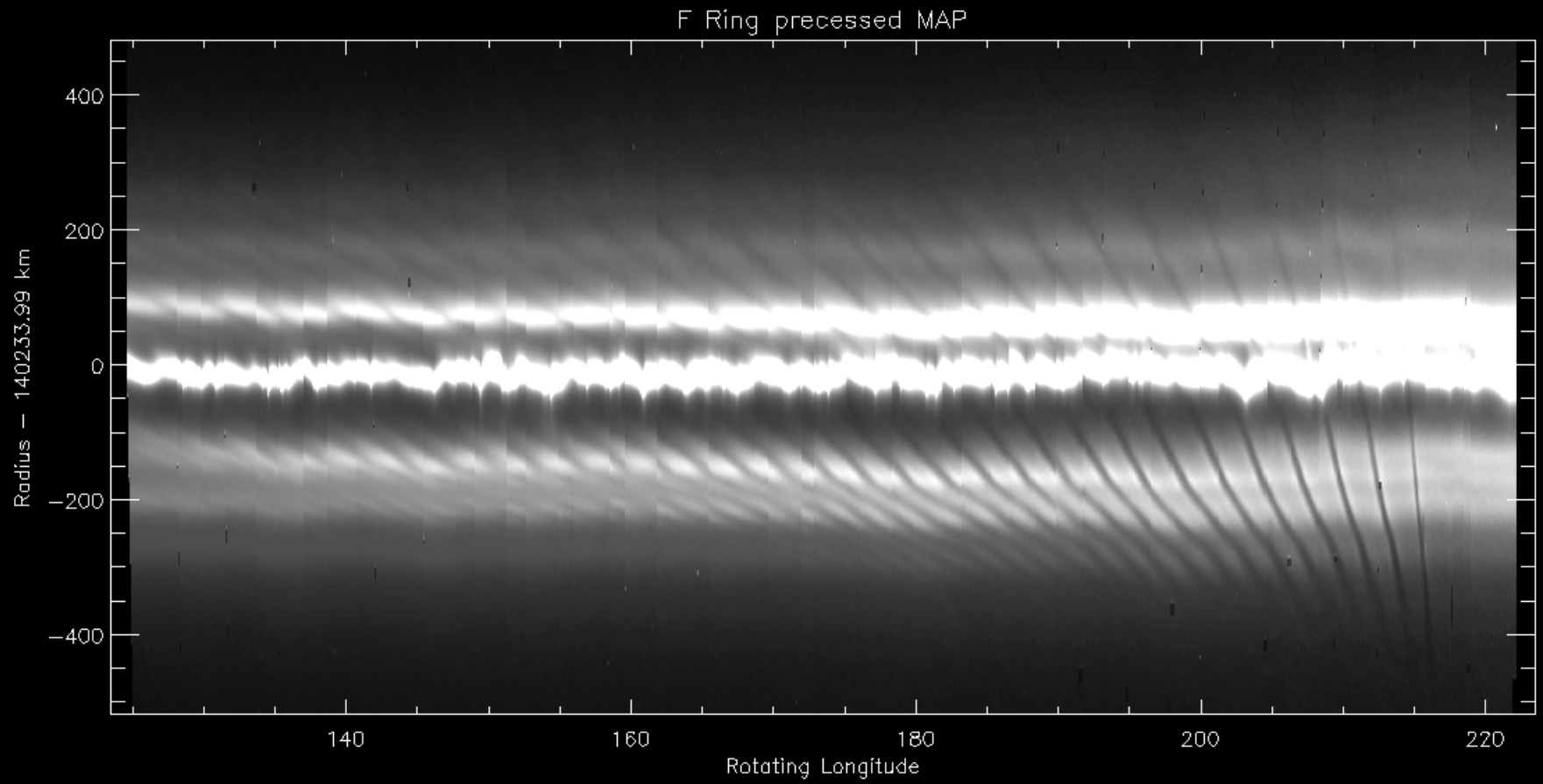
Mosaïque Cassini/ISS



Rencontre toutes les 14,7h
Anneau F garde traces précédentes rencontres

Écart Prométhée-Trou : 2°

Mosaïque Cassini/ISS



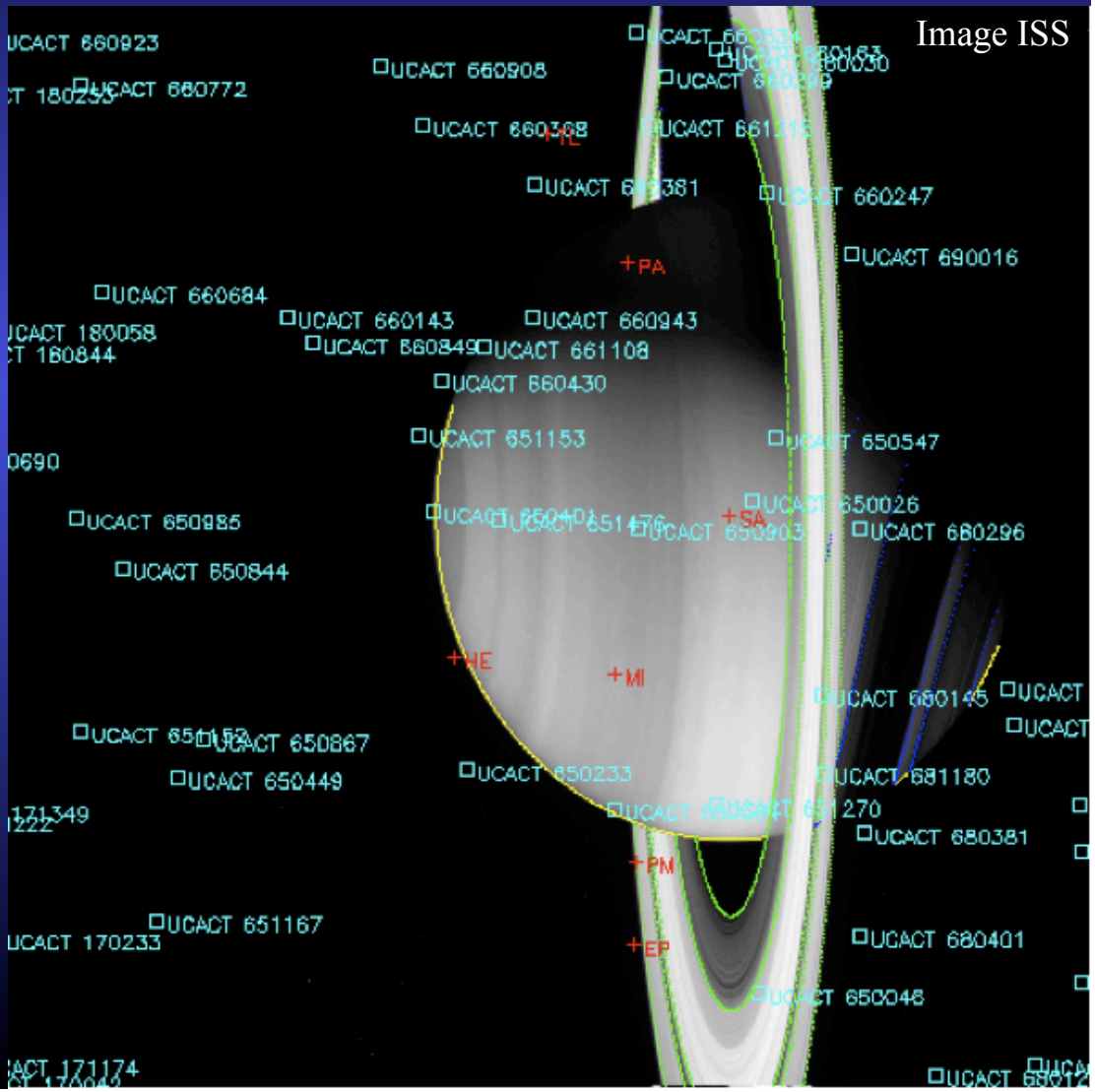
Rencontre toutes les 14,7h
Anneau F garde traces précédentes rencontres

Écart Prométhée-Trou : 2°

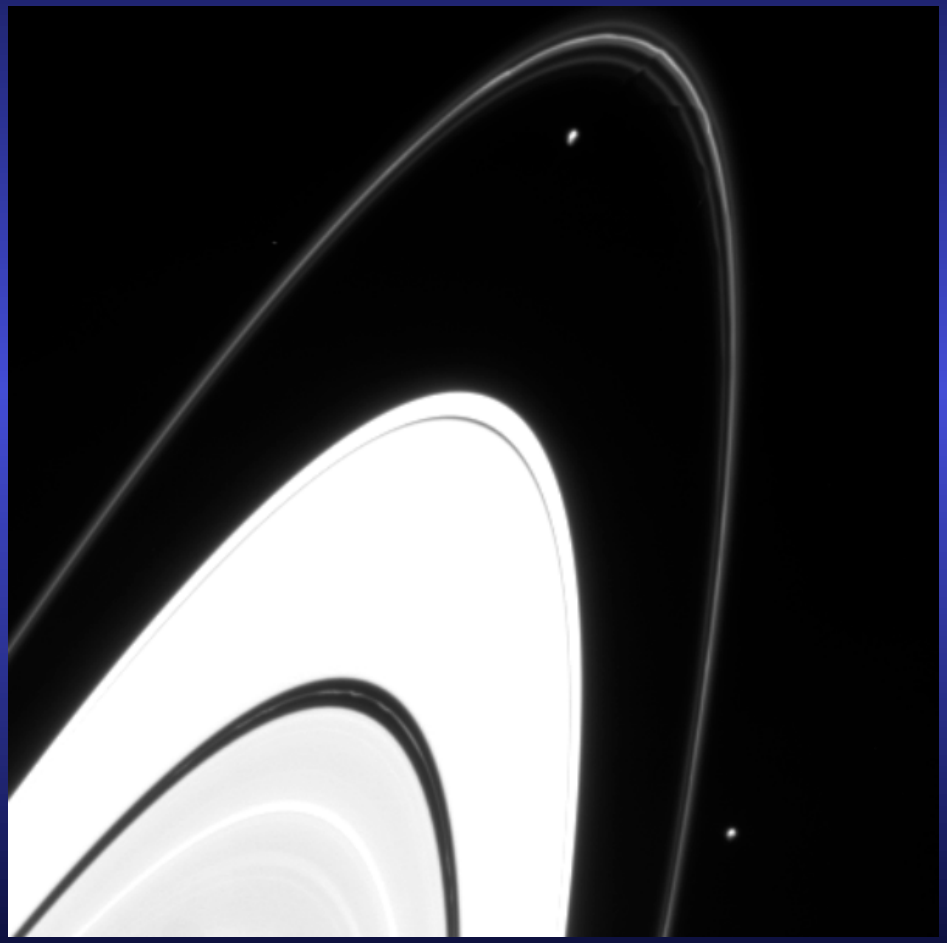
Traitement d'images

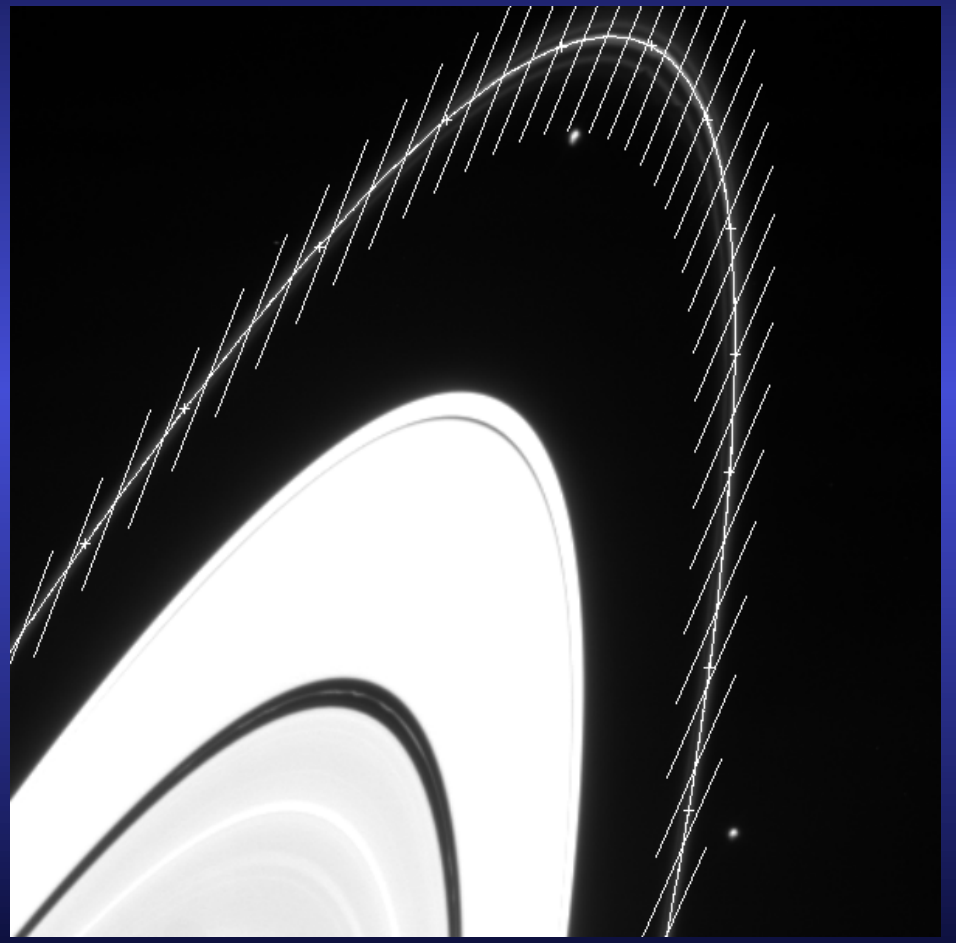
Ingrédients:

* Bonne astrométrie
* Bonne résolution spatiale
* Défilement sur fenêtre de longitudes
* Temps défilement >= T_{orb}



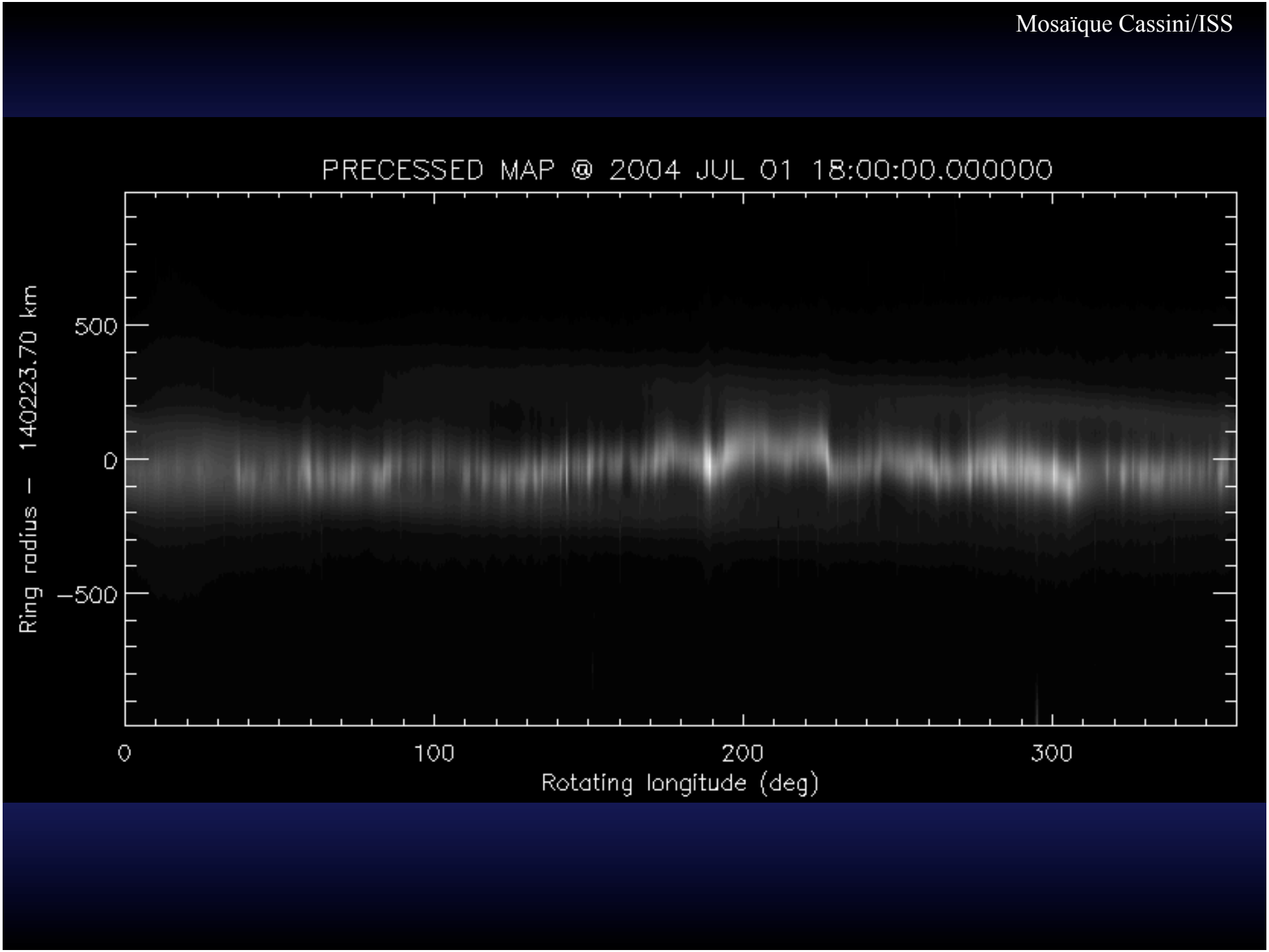
Traitement d'images



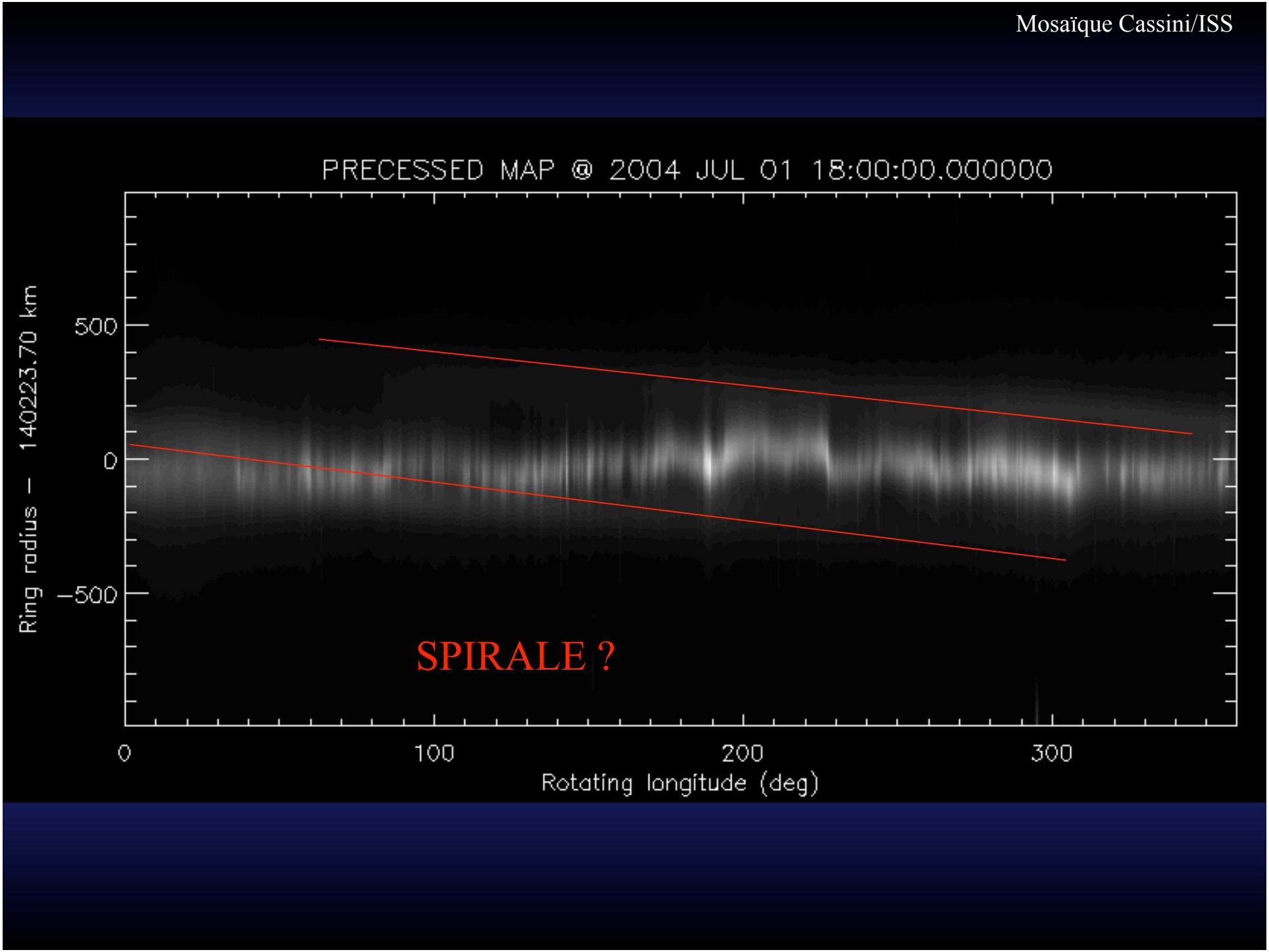


Images Cassini/ISS

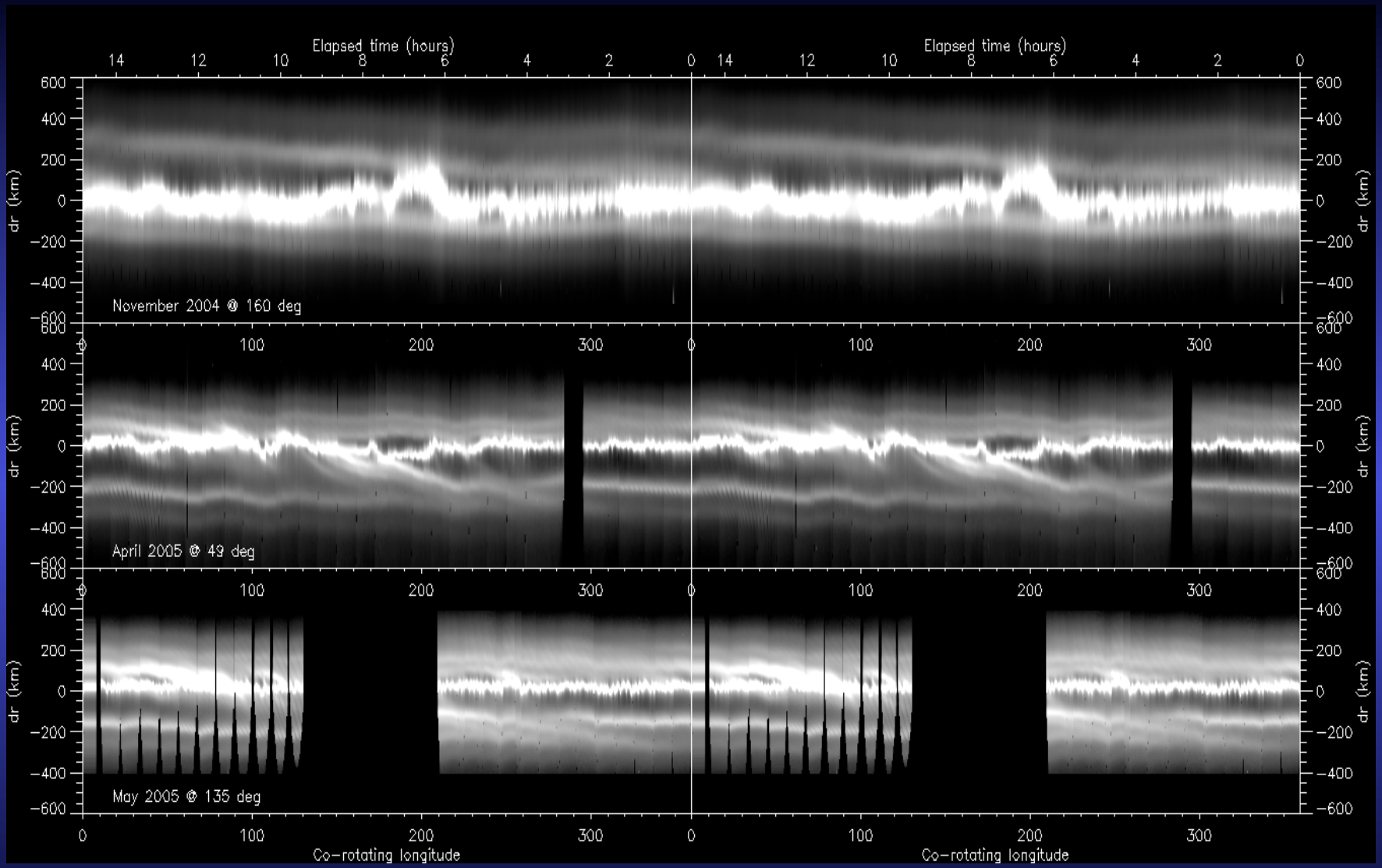
Mosaïque Cassini/ISS



Mosaïque Cassini/ISS



Mosaïques Cassini/ISS

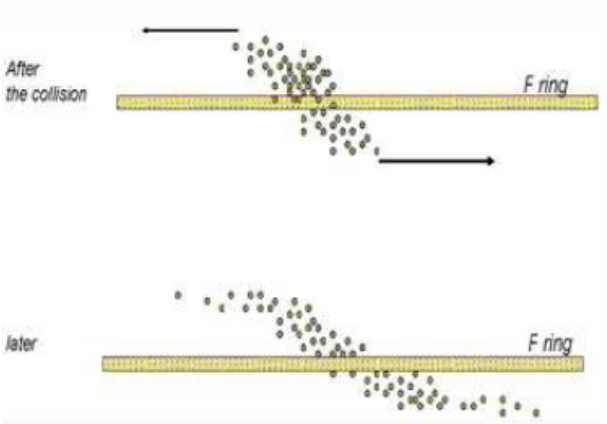


fort gradient radial
(≠ filament circulaire)

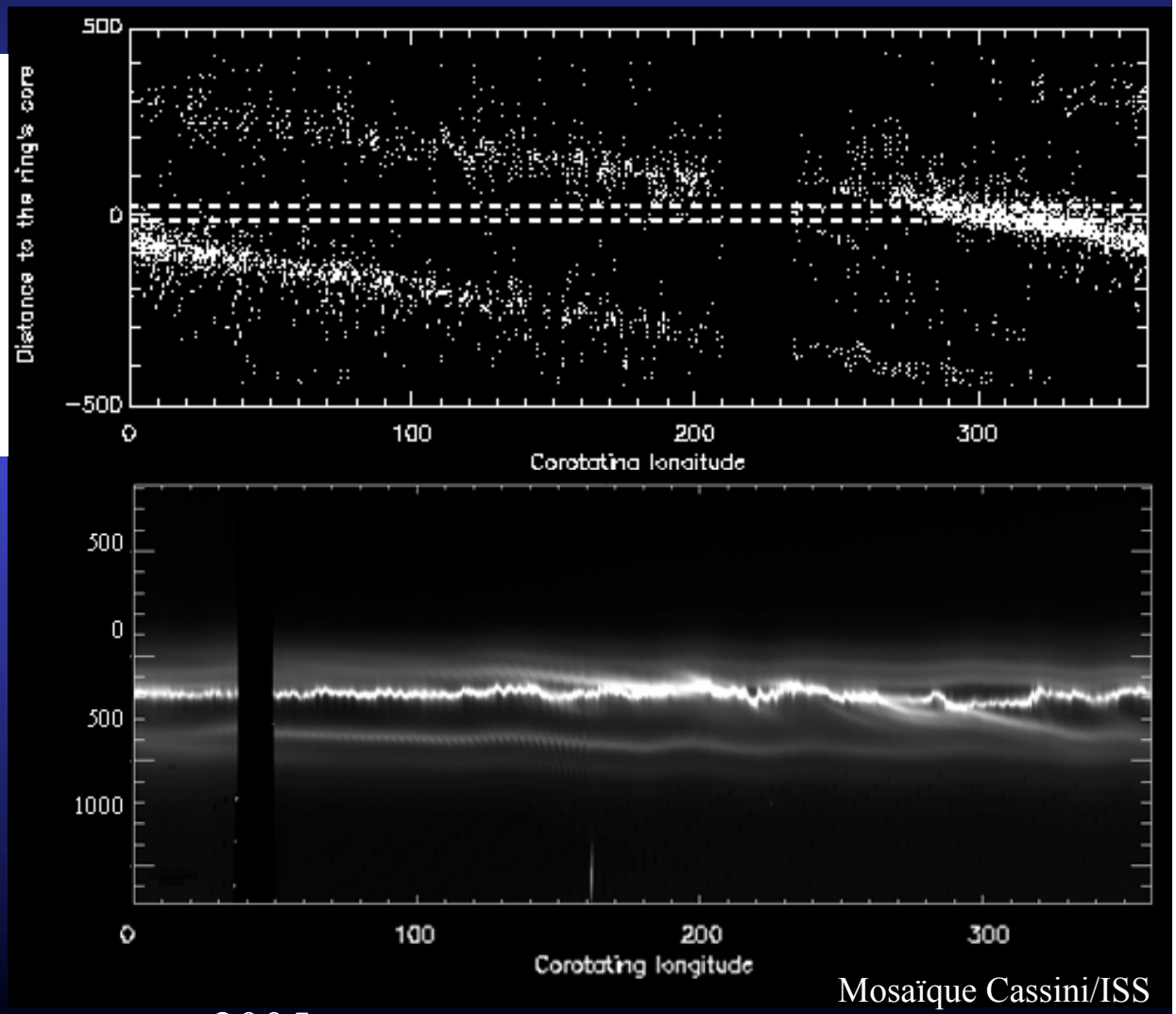
Solution : SPIRALE

Simulations numériques / Observations

Modèle : satellite rentre dans l'anneau F



Observations

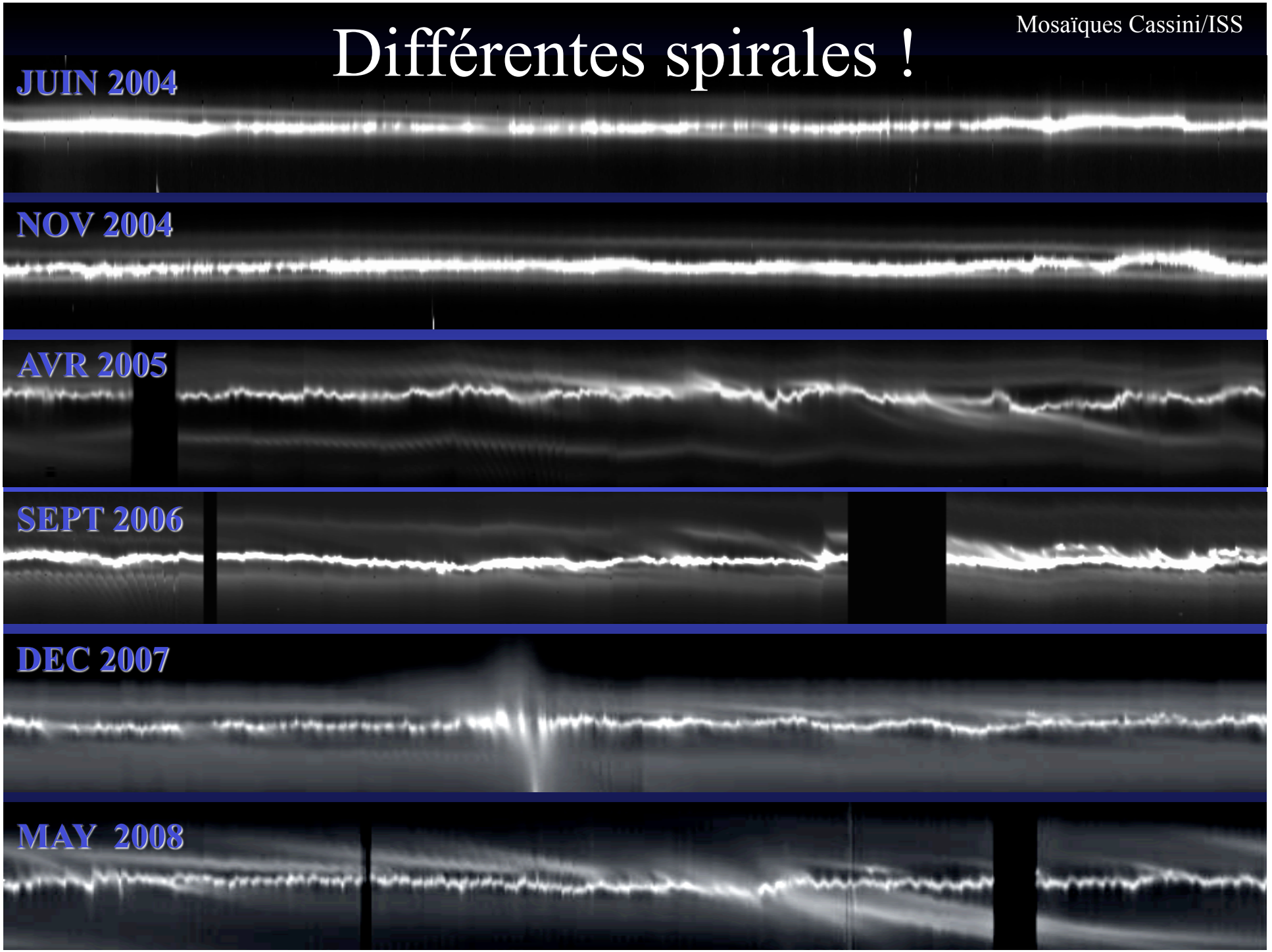


Mosaïque Cassini/ISS

Publication dans la revue *Science* nov. 2005

Différentes spirales !

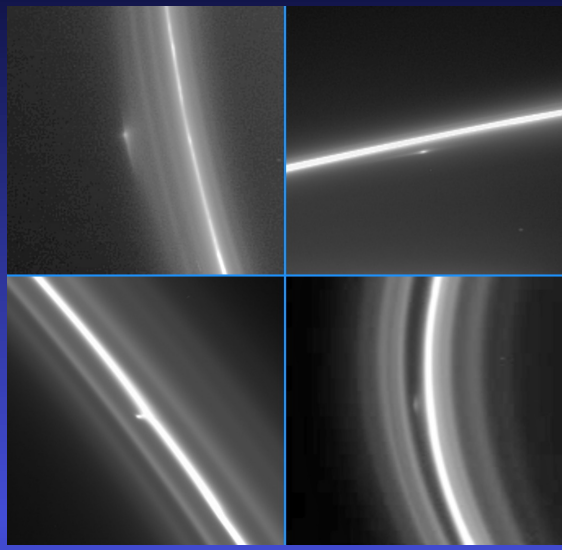
Mosaïques Cassini/ISS



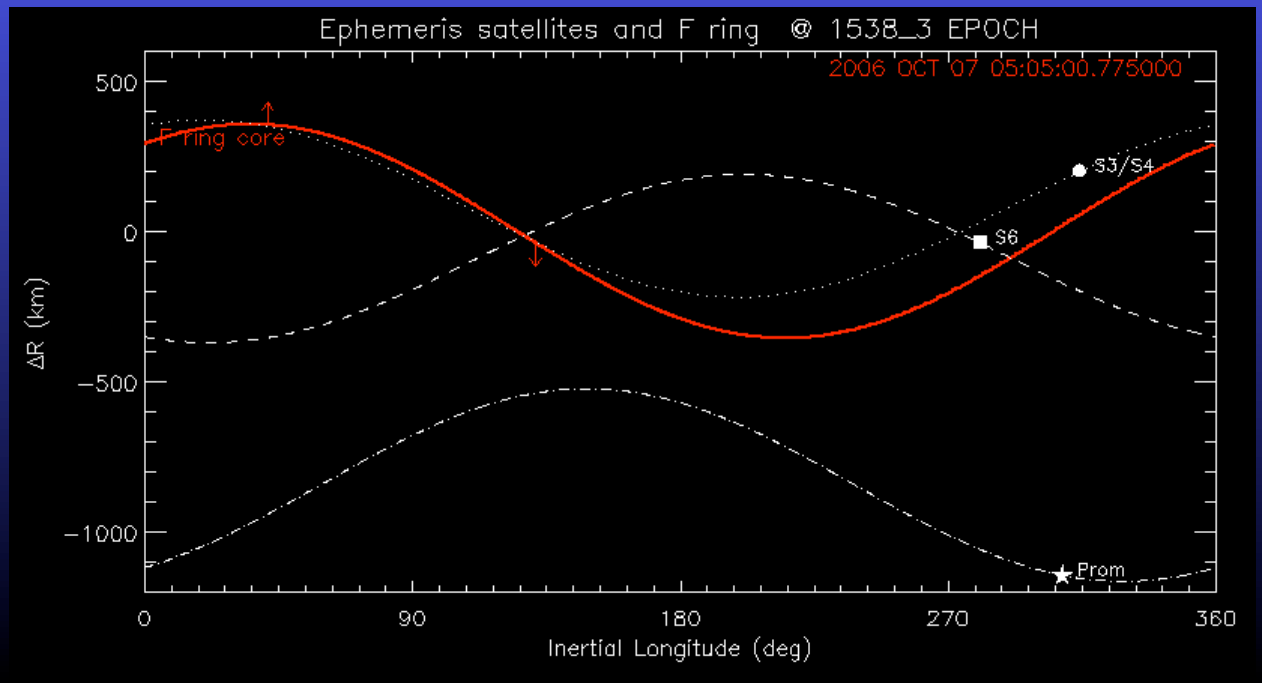
L'anneau F : conclusions…

- Satellites éphémères croisent l'orbite du cœur

- Multiplicité et complexité des spirales
  → ≠ croisements



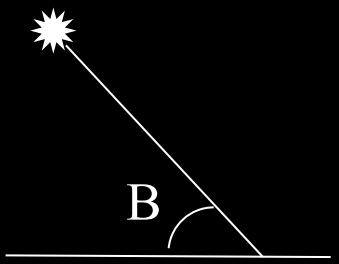
Images Cassini/ISS

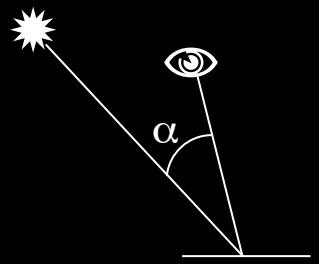


Photométrie des anneaux (2/2)

Hubble

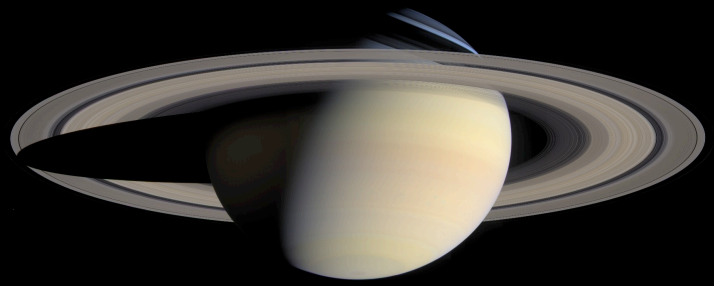
1 pixel ~ 4000 km
Surtout élévation du Soleil
Angles de phase restreints : 0°-6°

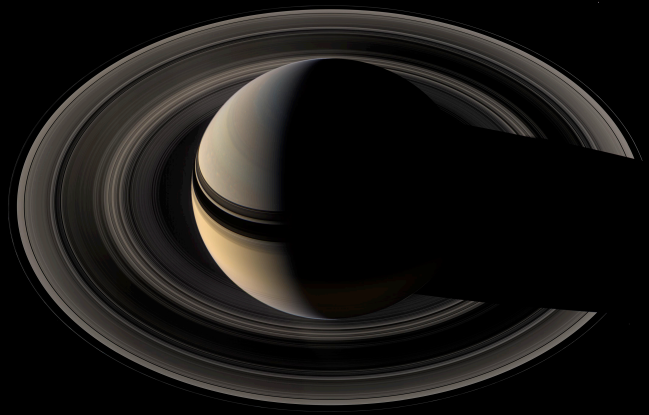


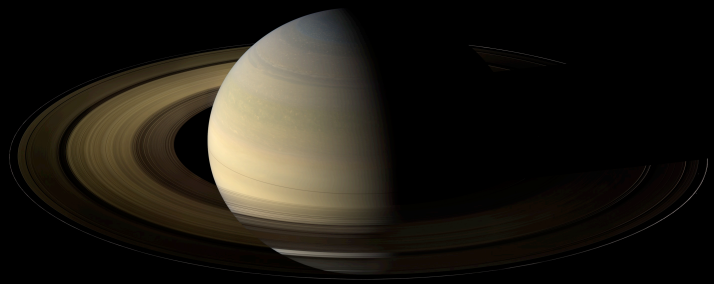


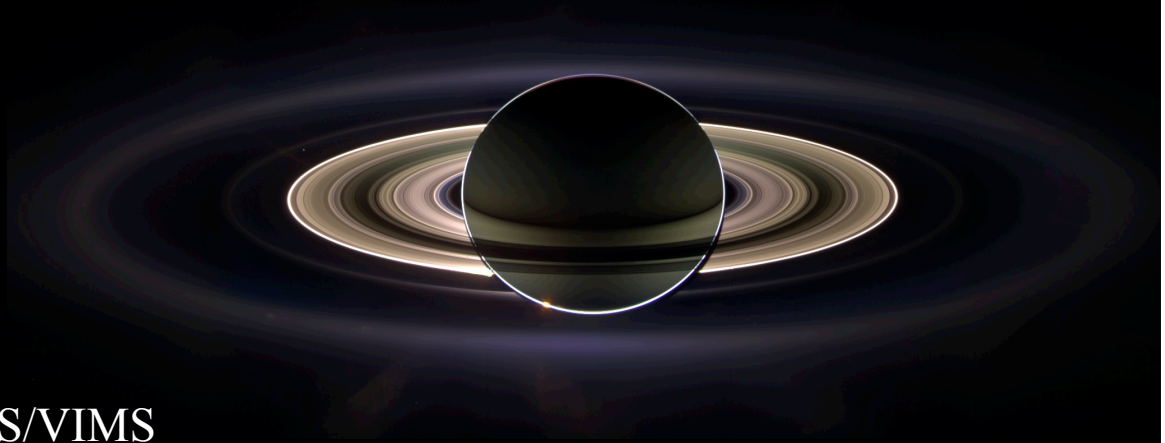
Cassini

1 pixel ~ 10-100 km
Variété inégalée des géométries d'illumination
Gamme complète des angles de phase (0°-180°)



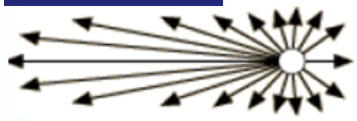


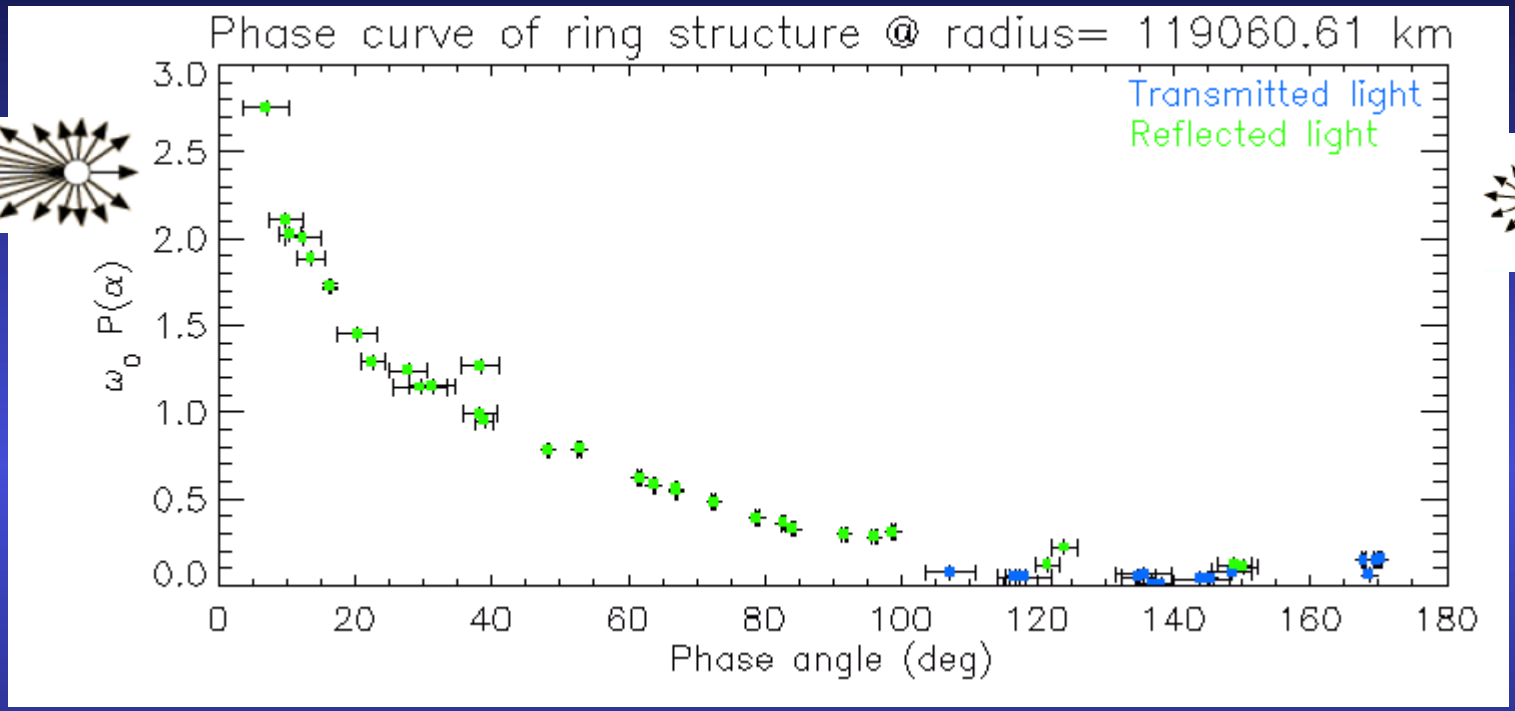


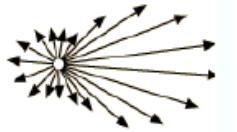


Images ISS/VIMS

Photométrie: Fonction de phase

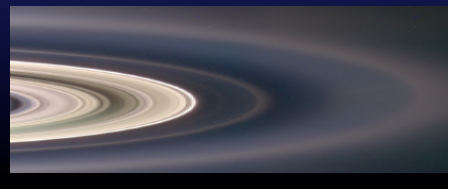




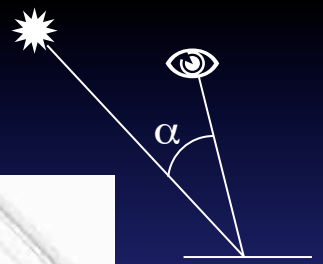


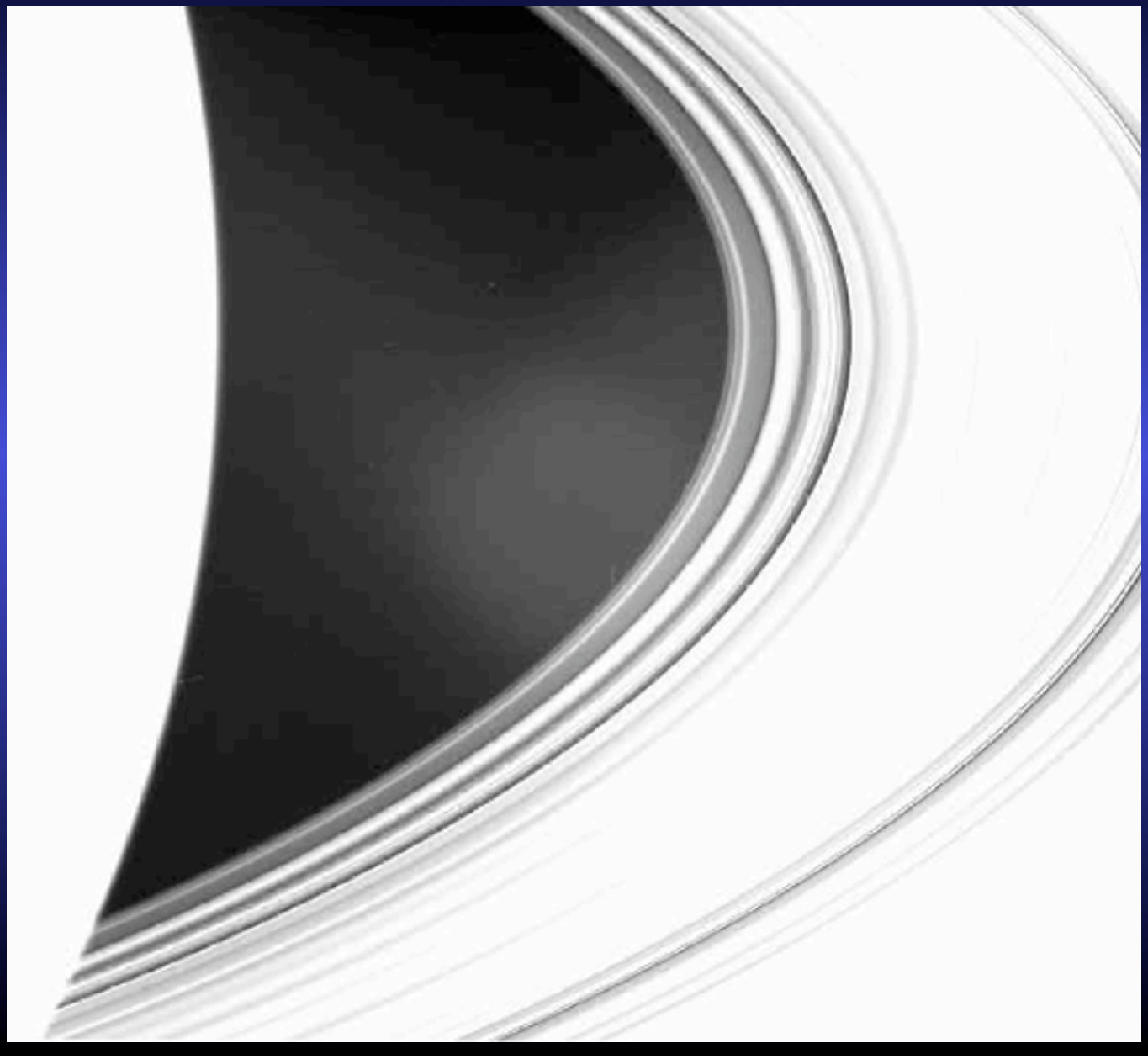
Diffusion
vers l'arrière
($\alpha < 90°$)

Diffusion
vers l'avant
($\alpha \sim 180°$)



Effet d'opposition





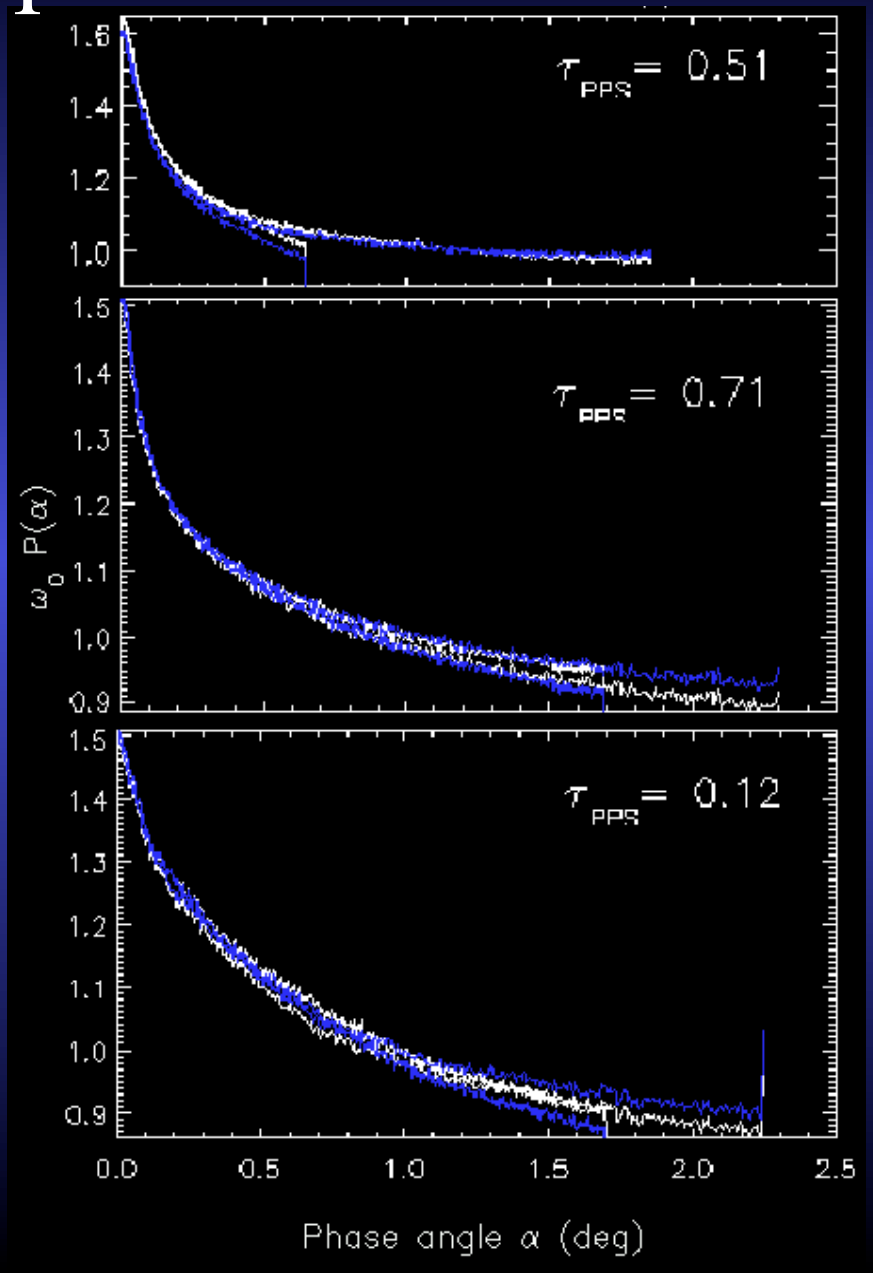
Images ISS

Effet d'opposition

Anneau A

Anneau B

Anneau C

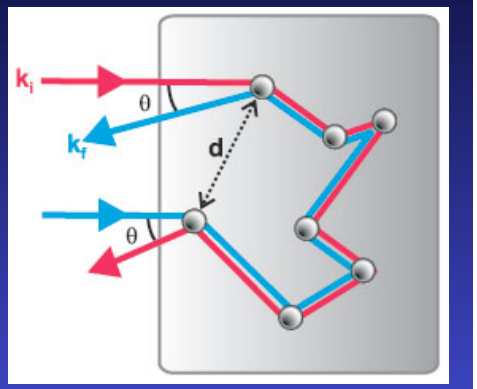


Variation de la morphologie du pic avec la profondeur optique

$10^{-3} < \alpha < 2.5°$

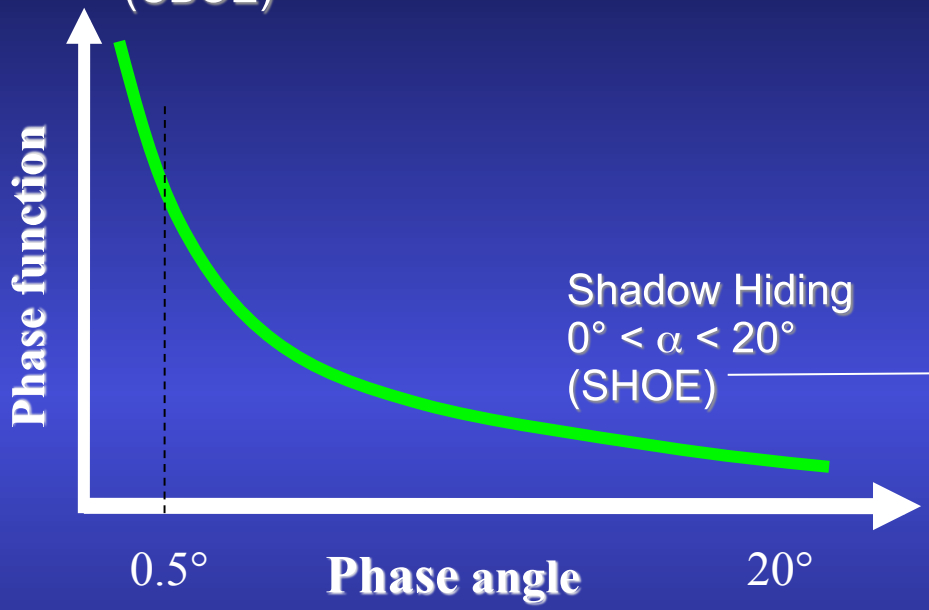
Effet d'opposition

grains

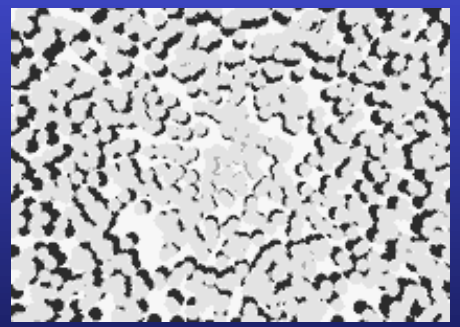


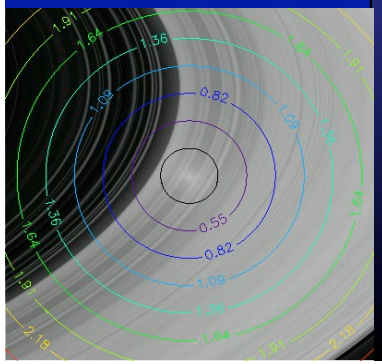
Coherent Backscattering $\alpha < 5°$ (CBOE)

Shadow Hiding $0° < \alpha < 20°$ (SHOE)



densité volumique

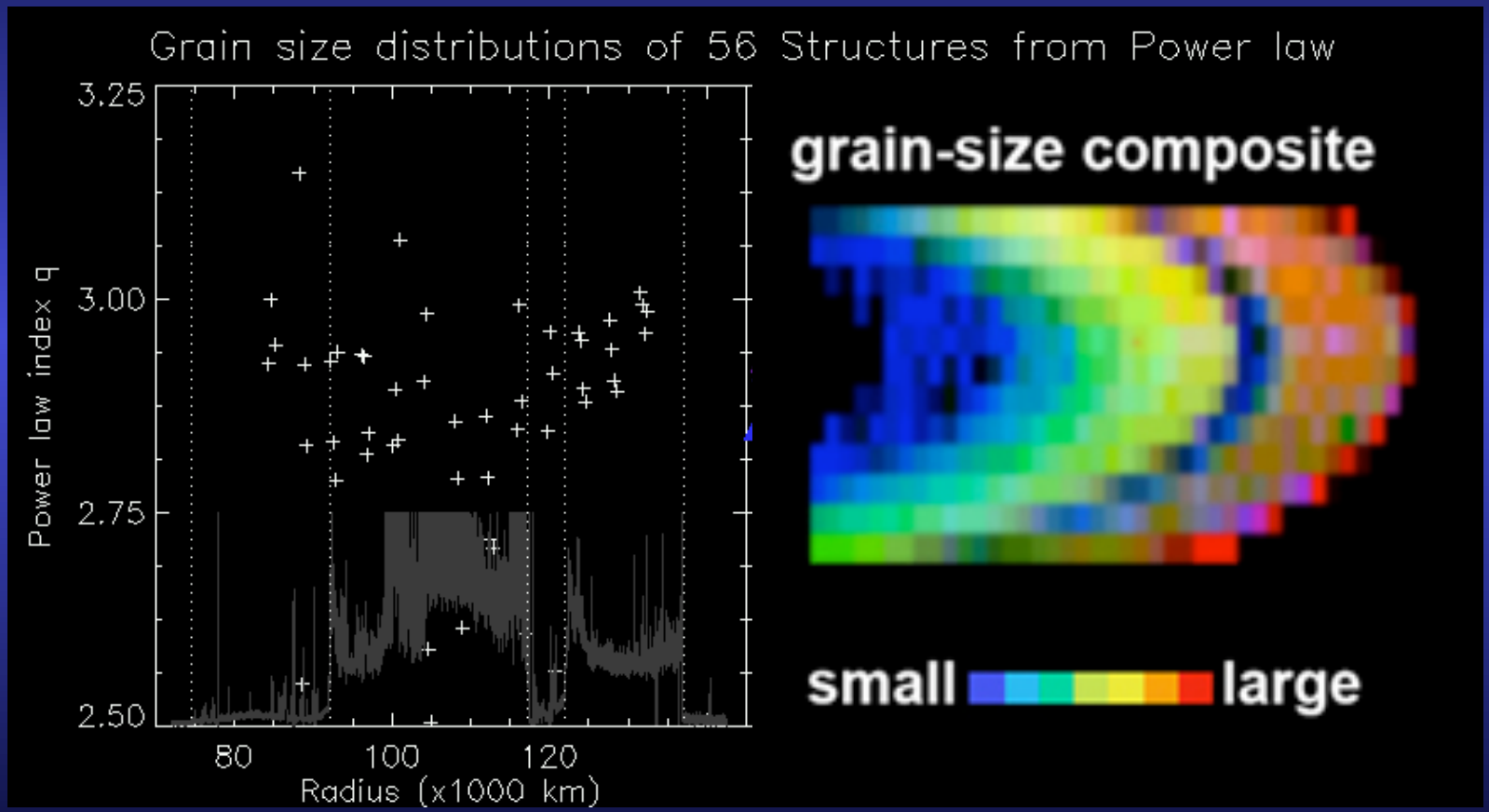




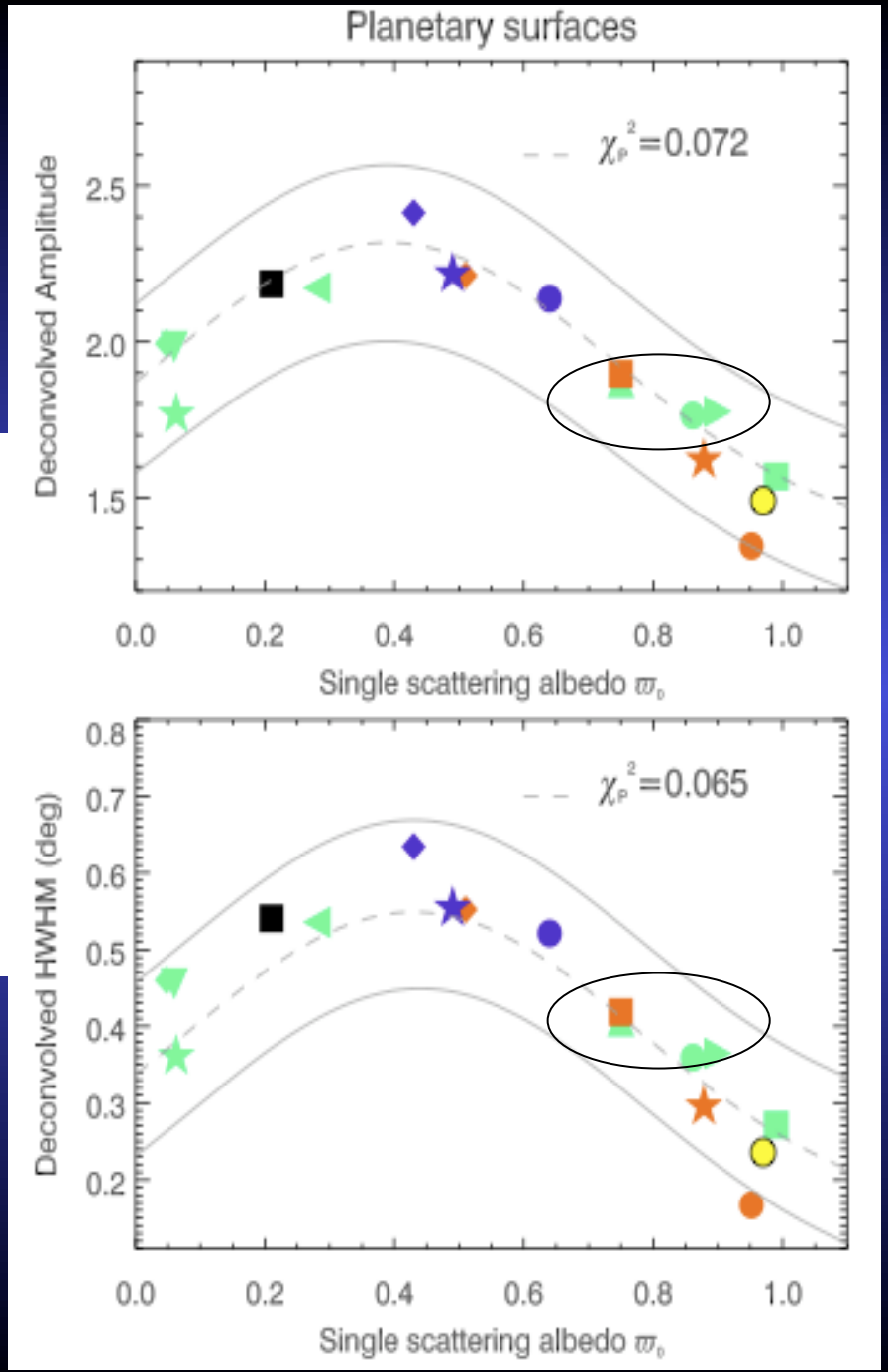
Effet :
-observé sur Terre
-observé sur les surfaces planétaires granulaires
-peu contraint théoriquement

Effet d'opposition

→ distribution de taille des grains de la régolite à la surface des particules

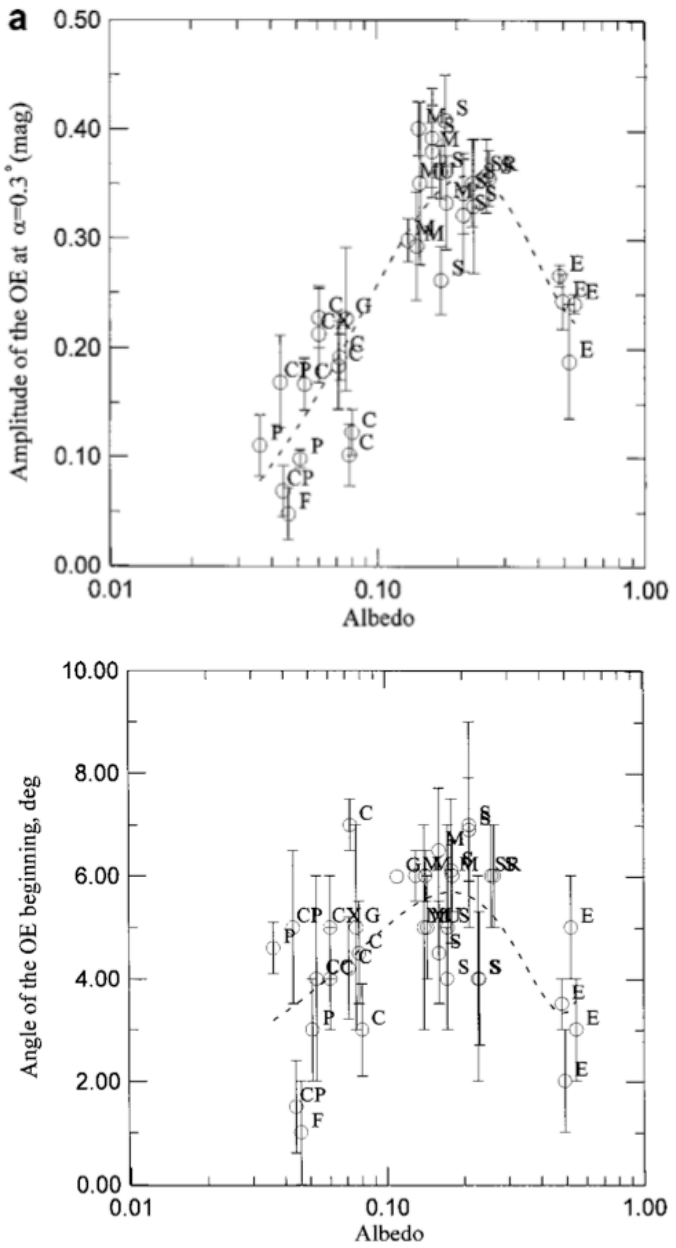


Déau,
in prep.



PLANETARY SURFACES
- Moon
- Io
- Europa
- Ganymede
- Callisto
- Enceladus
- Rhea
- Iapetus
- Phoebe
- A ring
- B ring
- C ring
- E ring
- Ariel
- Titania
- Oberon
- Triton

Asteroids

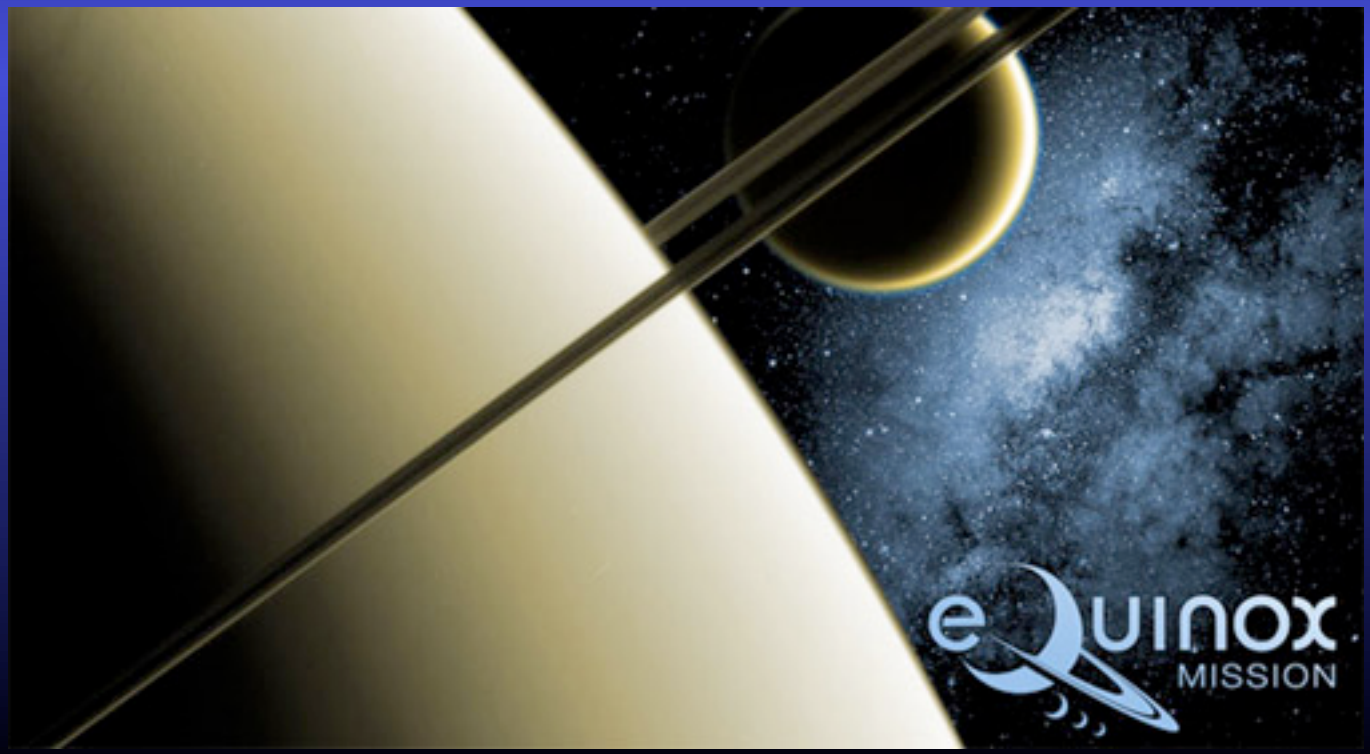


BELSKAYA AND SHEVCHENKO

Fin de la mission nominale : 2008

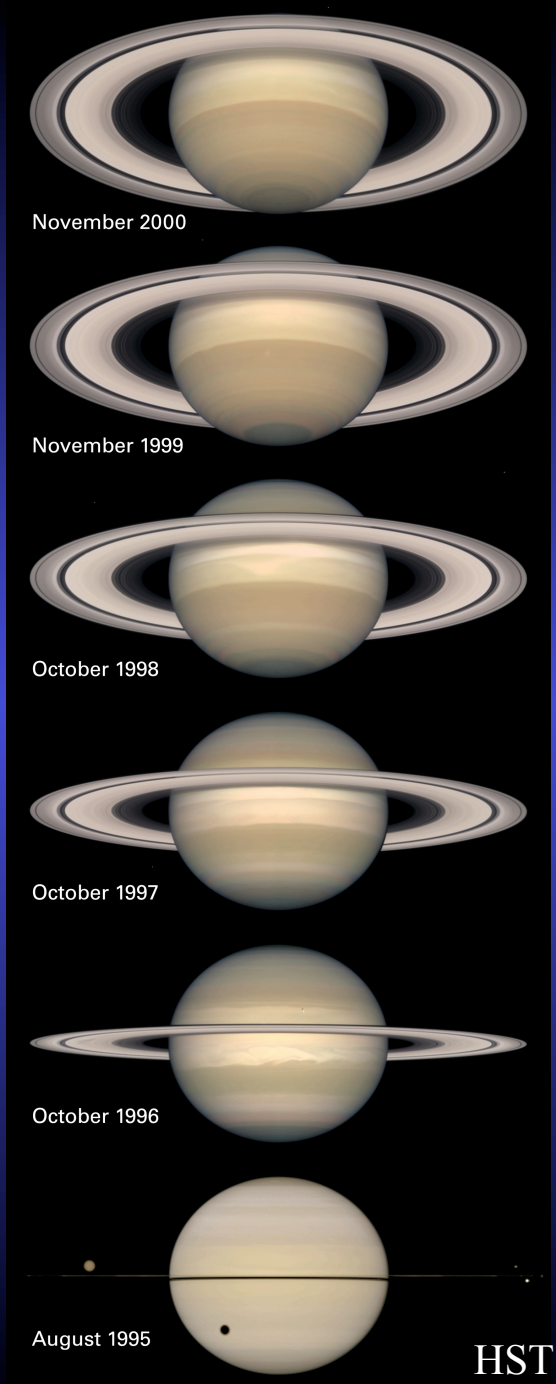
Instruments OK

Extended mission (2008-2010)

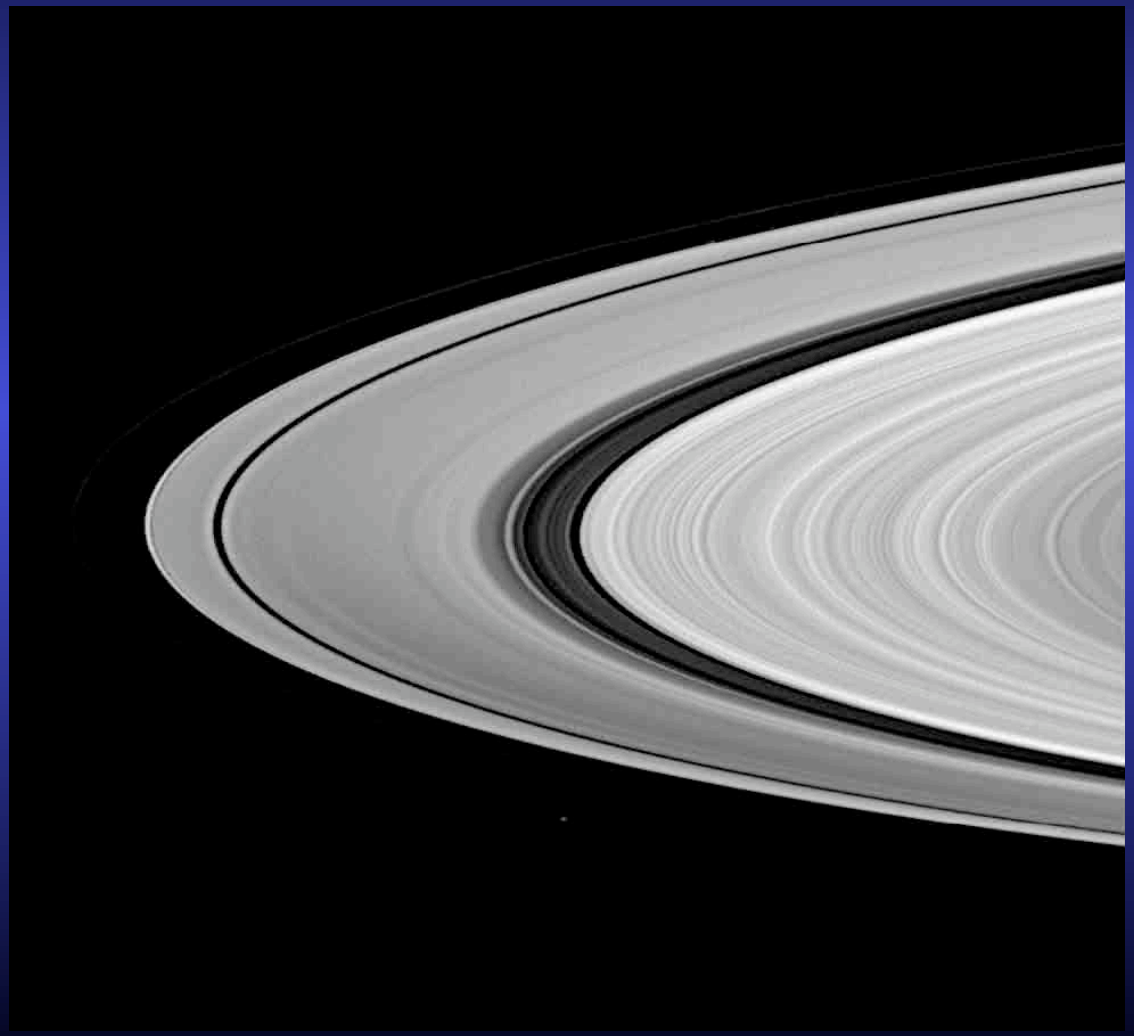


Equinoxe : élévation du Soleil nulle

occasion compléter géométries d'illumination

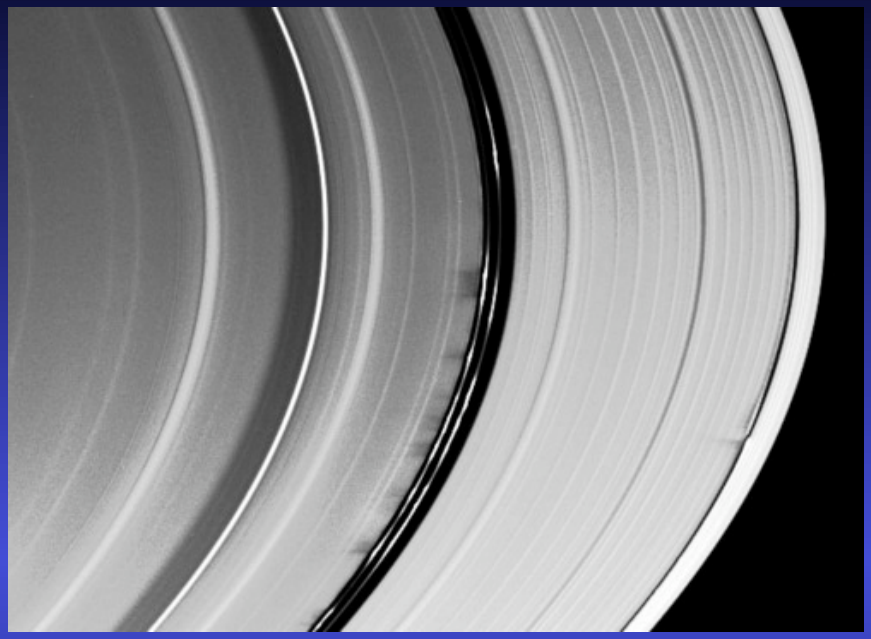


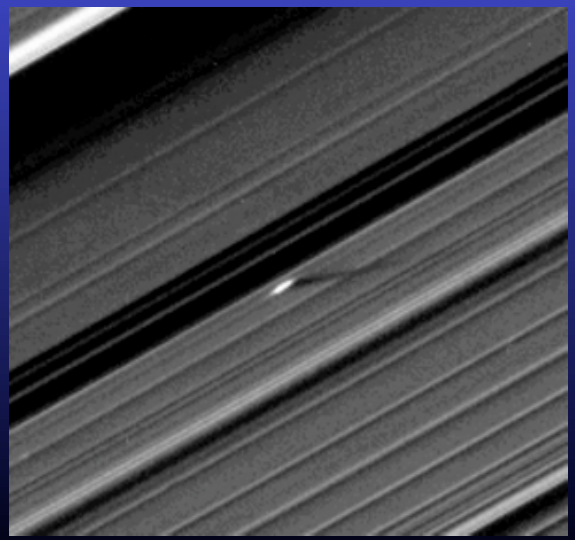
HST

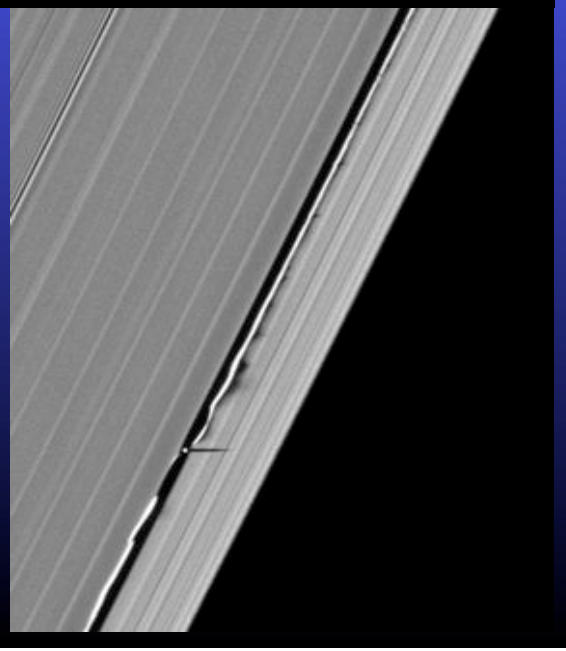


Cassini/ISS

Shadows …

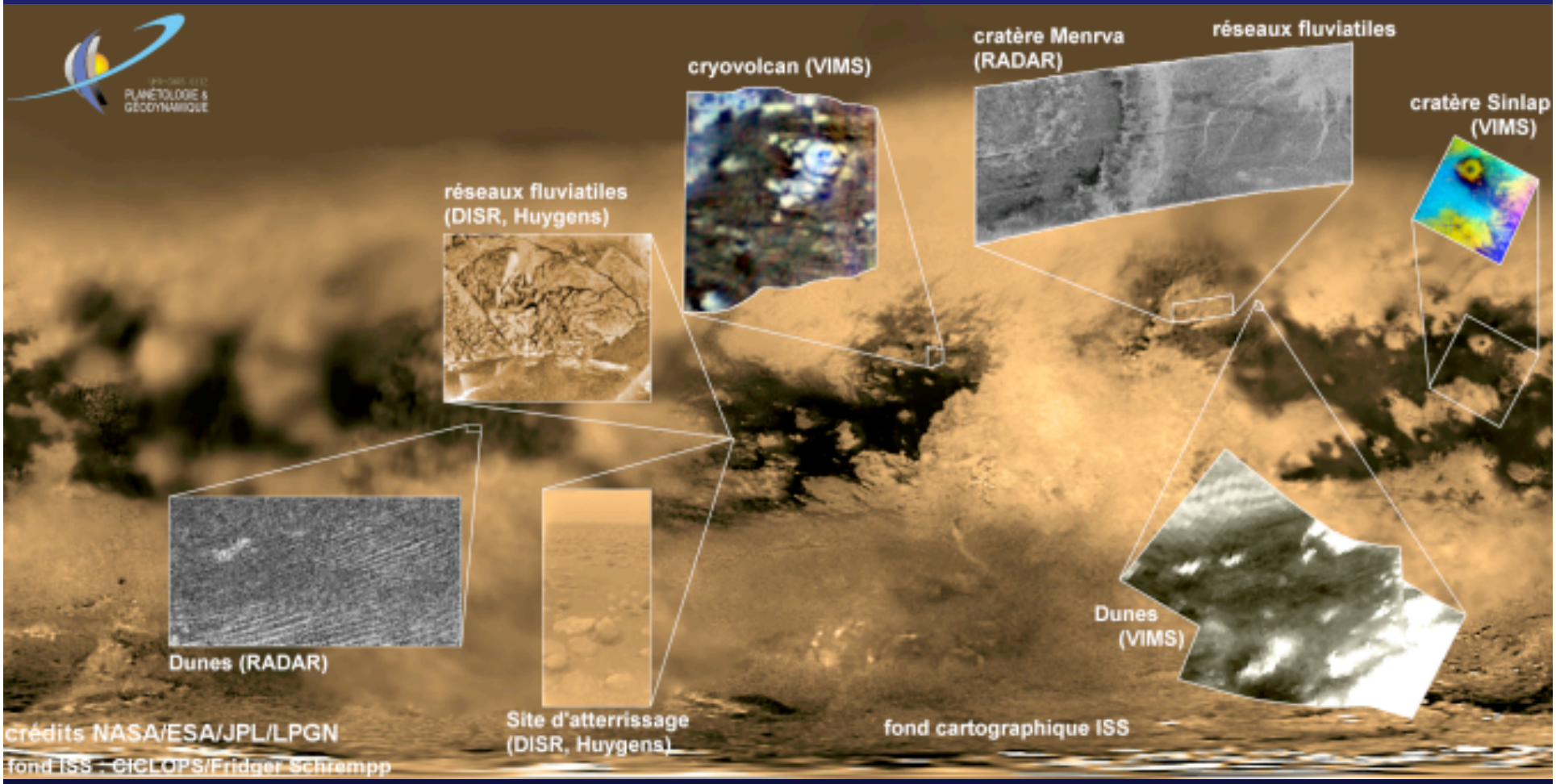






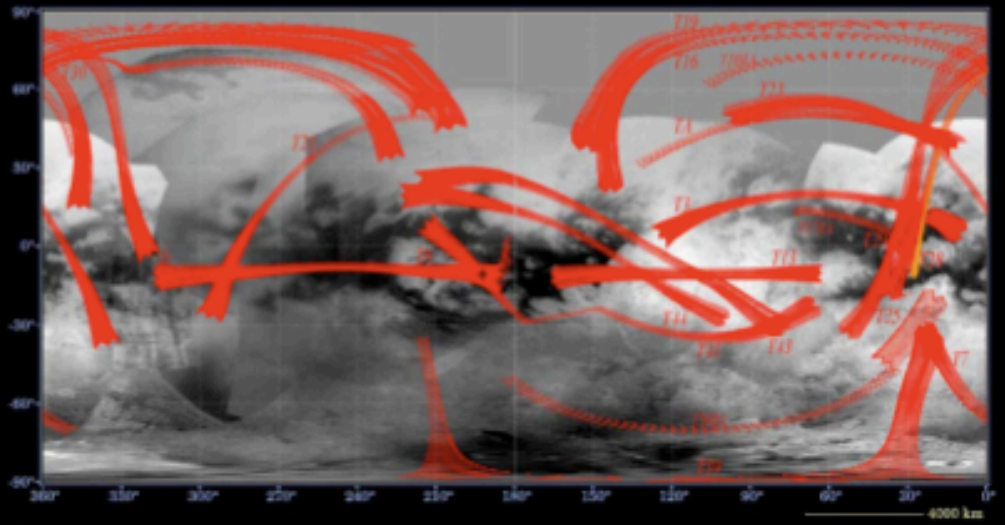
Images ISS

Diversité des terrains sur Titan !



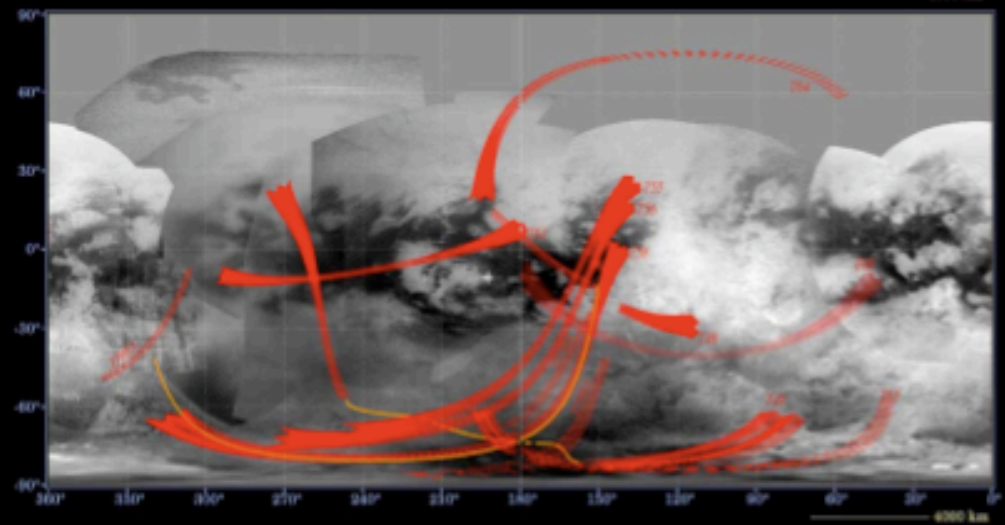
Radar coverage of Titan surface

Prime 22%



XM 8%

(30% total)

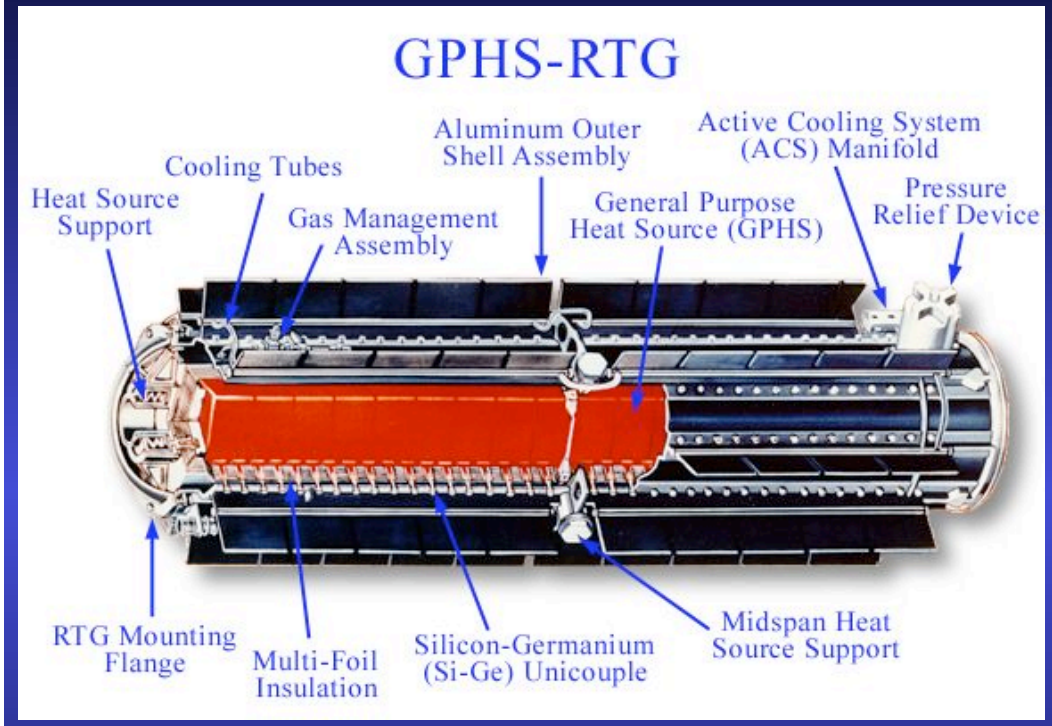


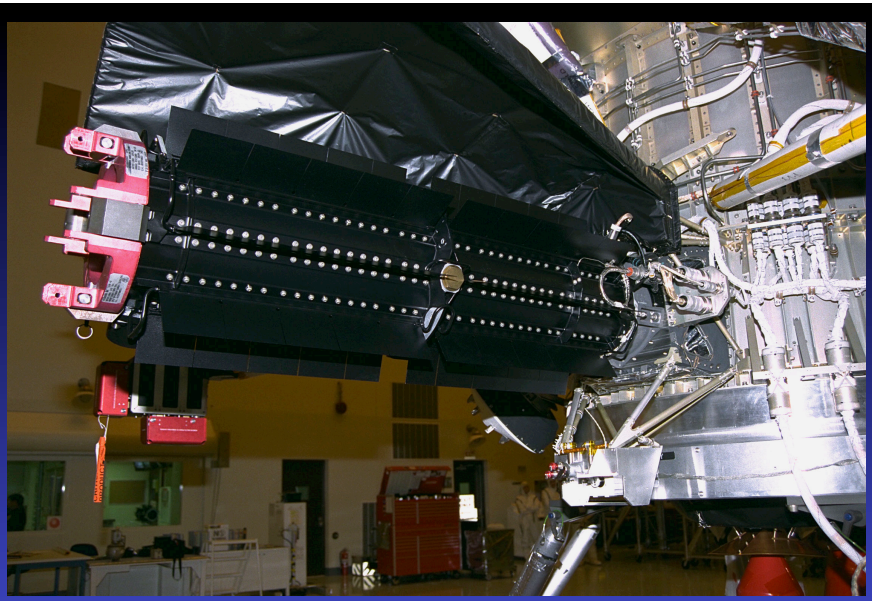
New types of terrain still being uncovered


Cassini Mission Overview
Four-Year Prime Tour + Two-Year Extended Mission (Proposed), July 2004 - July 2010
Extended Mission
Year of Tour
1
2
3
4
5
6
Orbits
11
15
22
27
39
21
Titan
*Huygens
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Rhea
Helene
Dione


Fin de la mission étendue: 2010
Extended^2 mission: 2010-2017 ?
(XXM)
Cassini's Adventure Ends,
and Begins Anew

Power



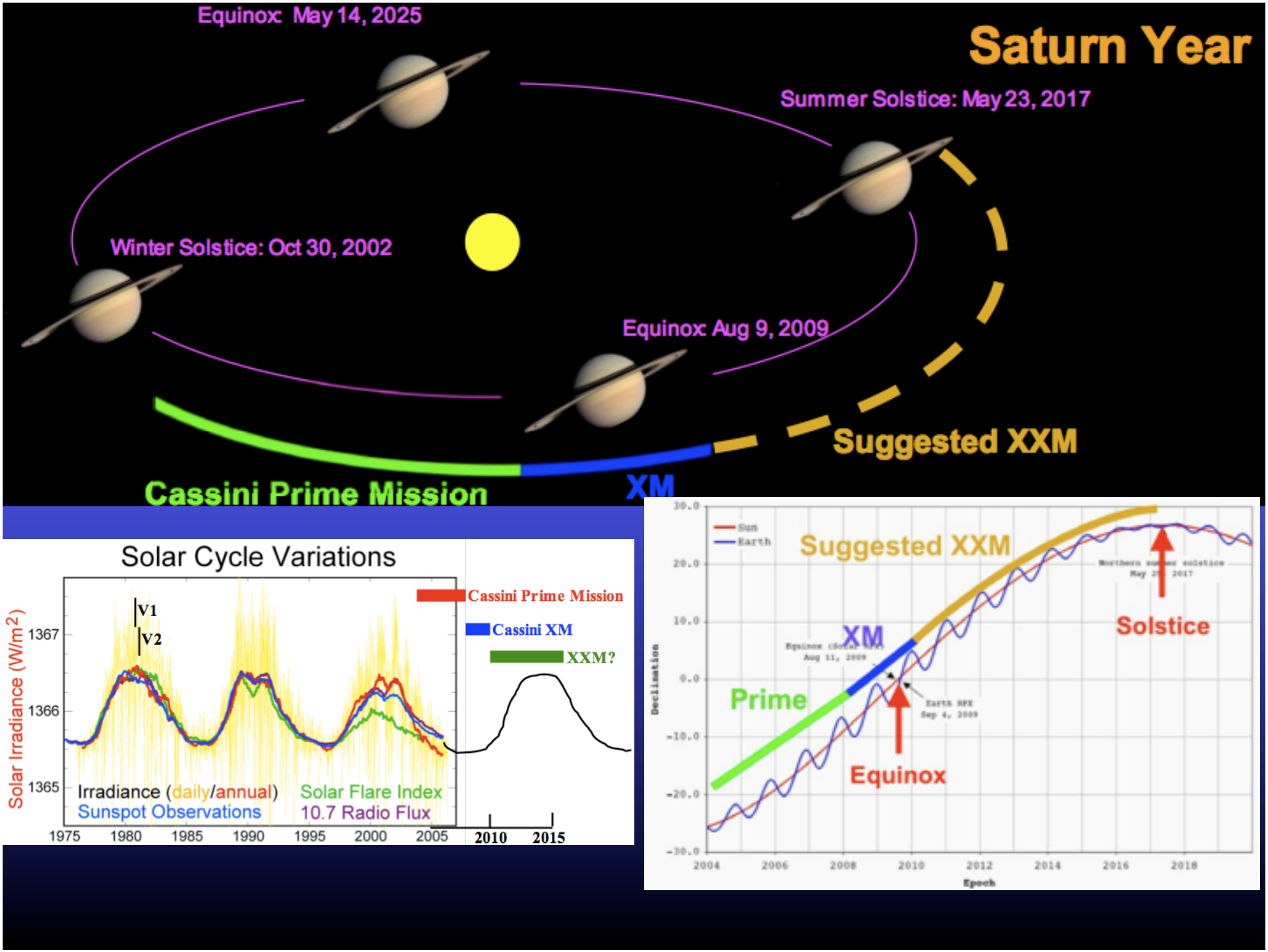


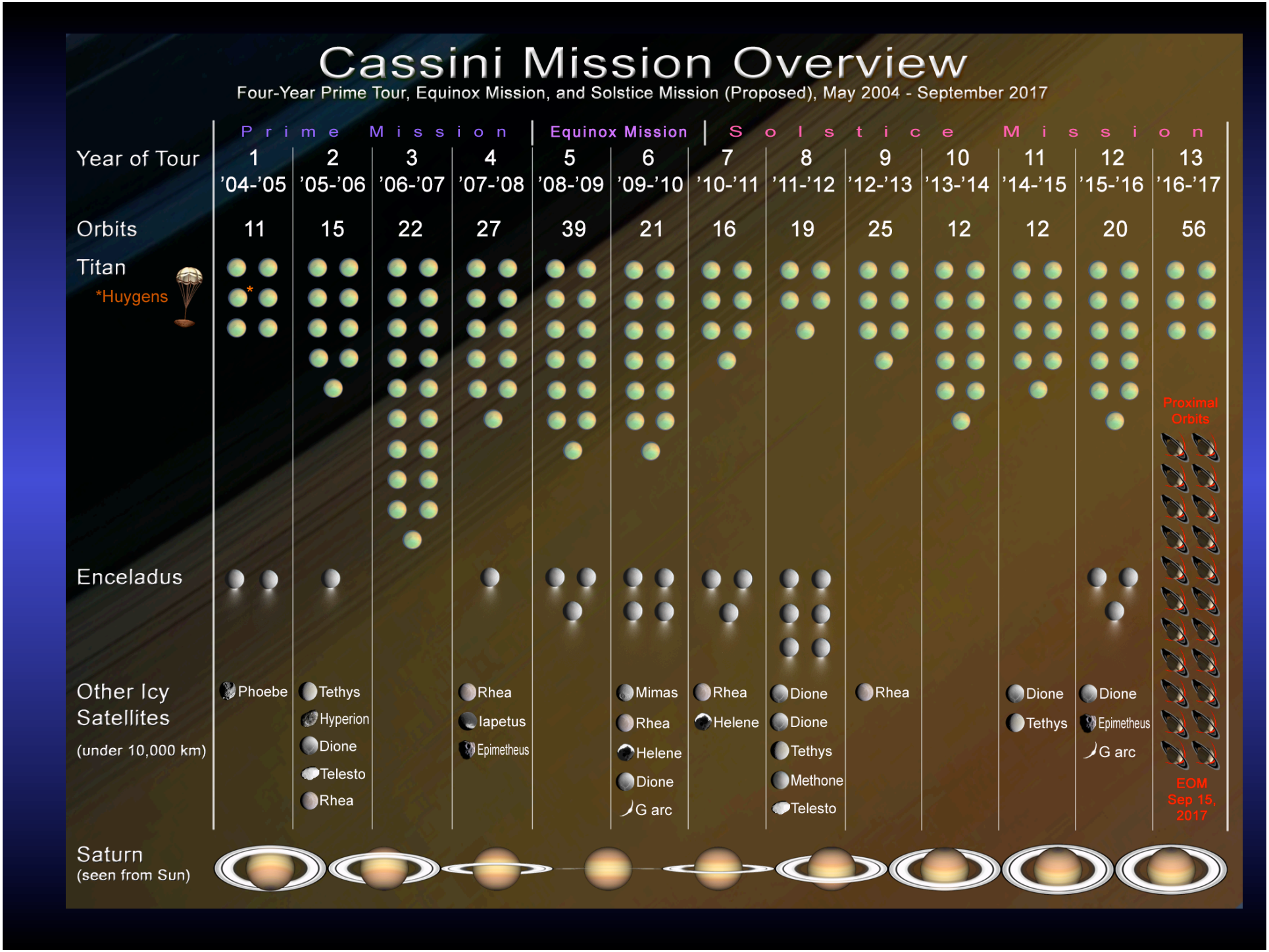
30 kg de
dioxide plutonium à 75% ^{238}Pu

½ vie ^{238}Pu: 87,74 ans

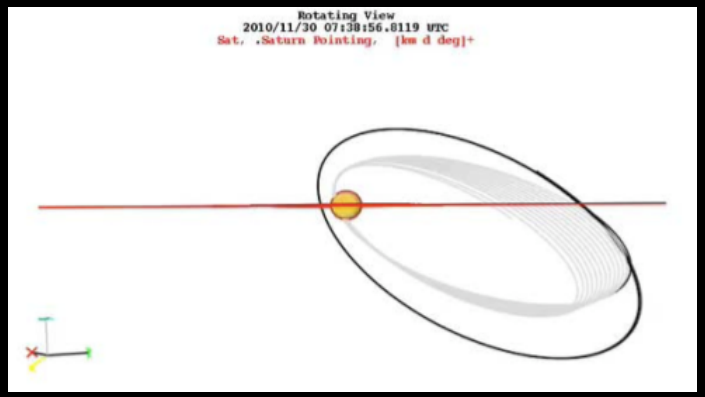
RTG (Radio-isotope Thermoelectric Generators)

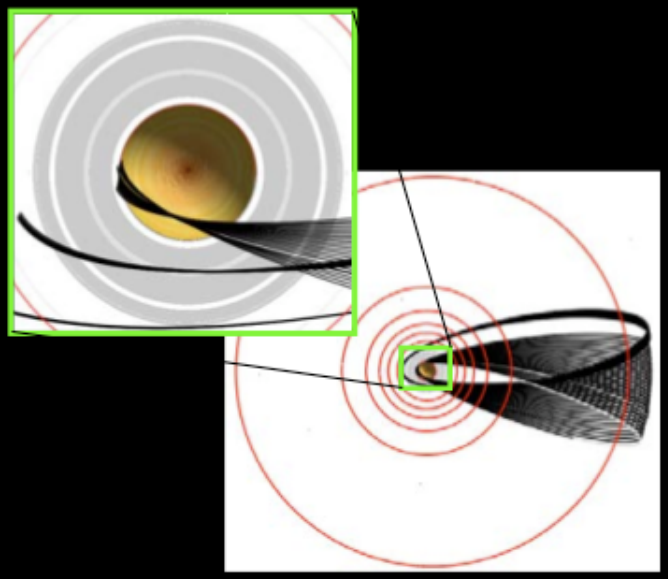
Début mission ~3x300 W
Après 10 ans ~3x250 W
Après 20 ans ~3x210 W (mais efficacité thermocouples diminue)

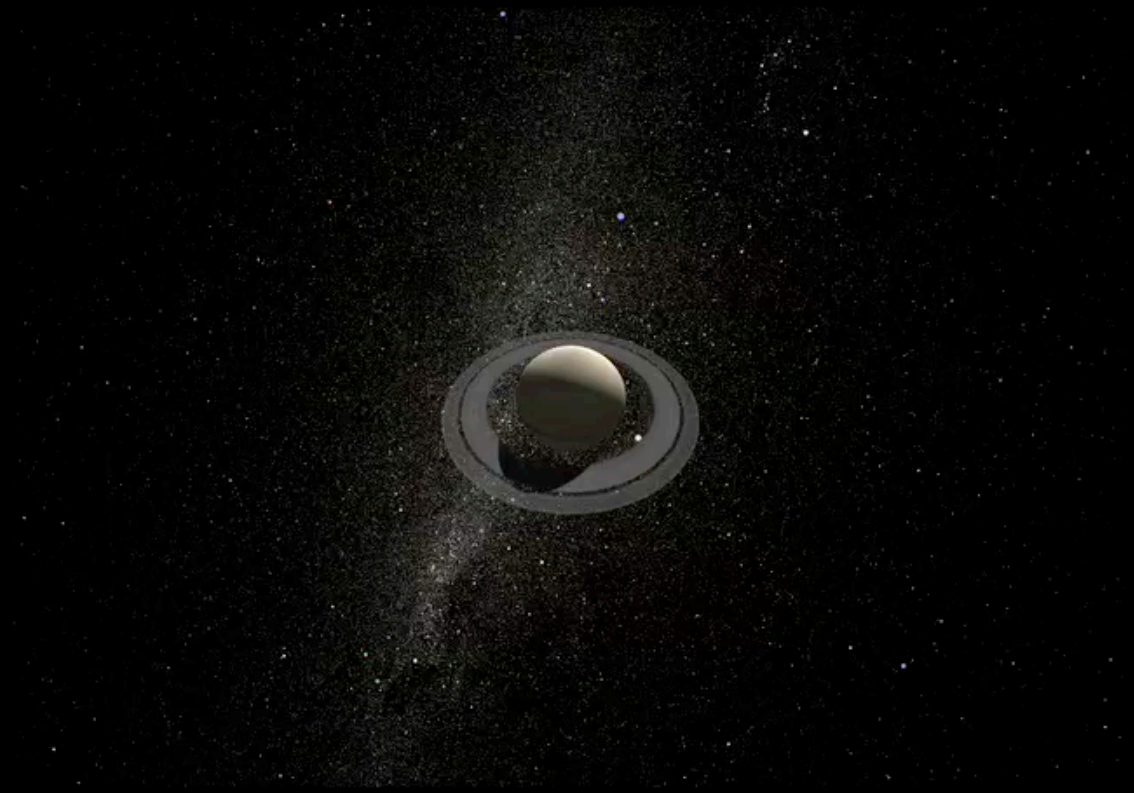

Saturn Year
Equinox: May 14, 2025
Summer Solstice: May 23, 2017
Winter Solstice: Oct 30, 2002
Equinox: Aug 9, 2009
Suggested XXM
Cassini Prime Mission
XM
Solar Cycle Variations
Solar Irradiance (W/m2)
1367
1366
1365
V1
V2
Irradiance (daily/annual)
Sunspot Observations
Solar Flare Index
10.7 Radio Flux
1975
1980
1985
1990
1995
2000
2005
2010
2015
Cassini Prime Mission
Cassini XM
XXM?
Sun
Earth
Suggested XXM
XM
Prime
Equinox
Solstice
Declination
Epoch
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
2004
2006
2008
2010
2012
2014
2016
2018


Cassini Mission Overview
Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), May 2004 - September 2017
Prime Mission
Equinox Mission
Solstice Mission
Year of Tour
1 '04-'05
2 '05-'06
3 '06-'07
4 '07-'08
5 '08-'09
6 '09-'10
7 '10-'11
8 '11-'12
9 '12-'13
10 '13-'14
11 '14-'15
12 '15-'16
13 '16-'17
Orbits
11
15
22
27
39
21
16
19
25
12
12
20
56
Titan
*Huygens
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Mimas
Rhea
Helene
Dione
G arc
Rhea
Helene
Dione
Dione
Tethys
Methone
Telesto
Rhea
Dione
Tethys
Dione
Epimetheus
G arc
Proximal Orbits
EOM Sep 15, 2017
Saturn
(seen from Sun)

Proximal Orbits

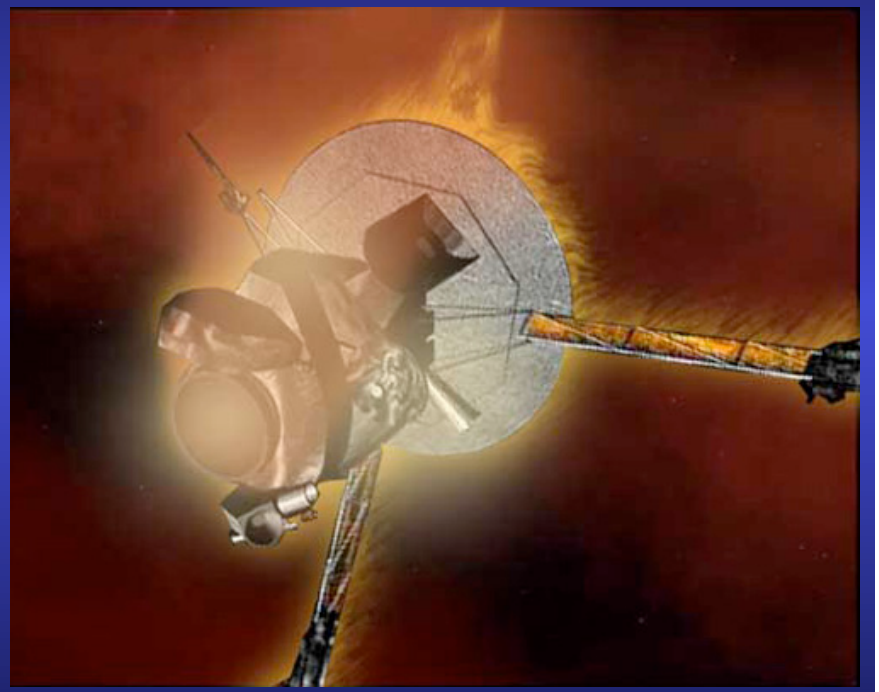






Très certainement l’apothéose de la mission Cassini !!

Fin de Cassini comme Galileo ou Juno
Poubelle = Atmosphère



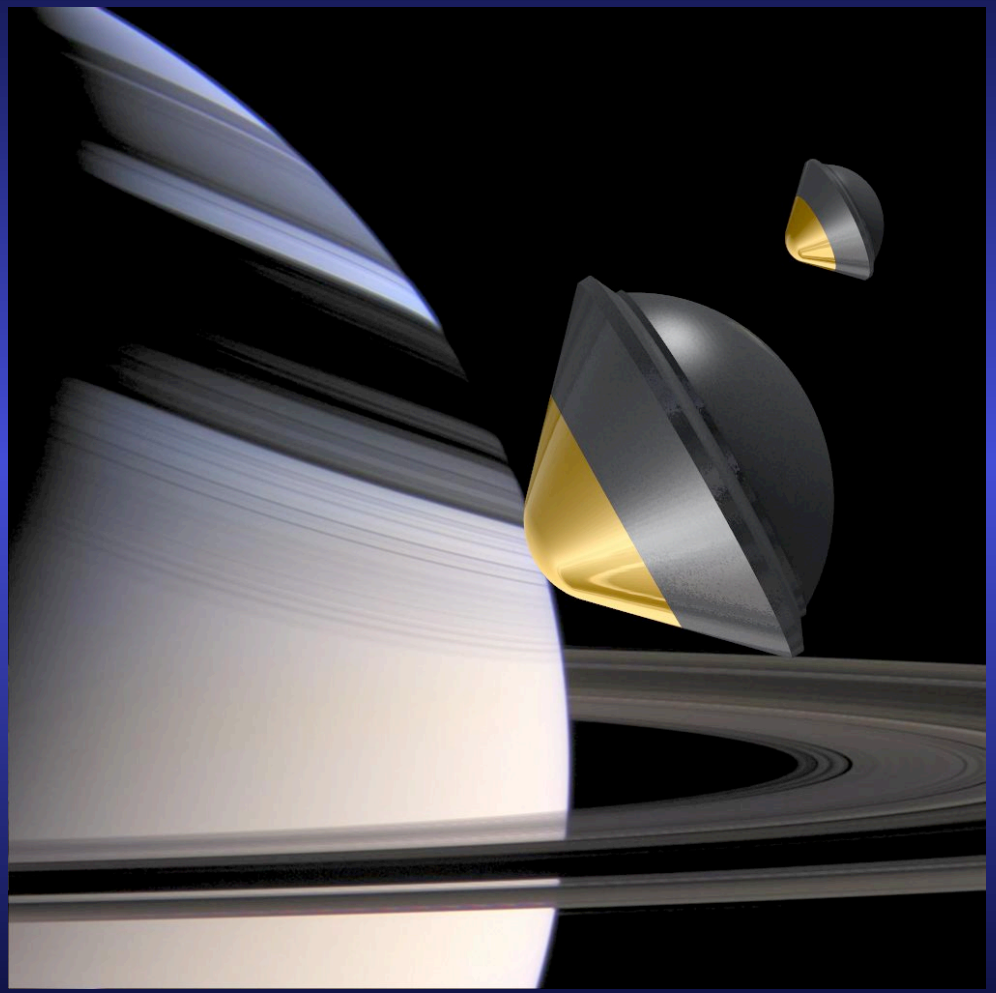
Missions Futures

Concepts

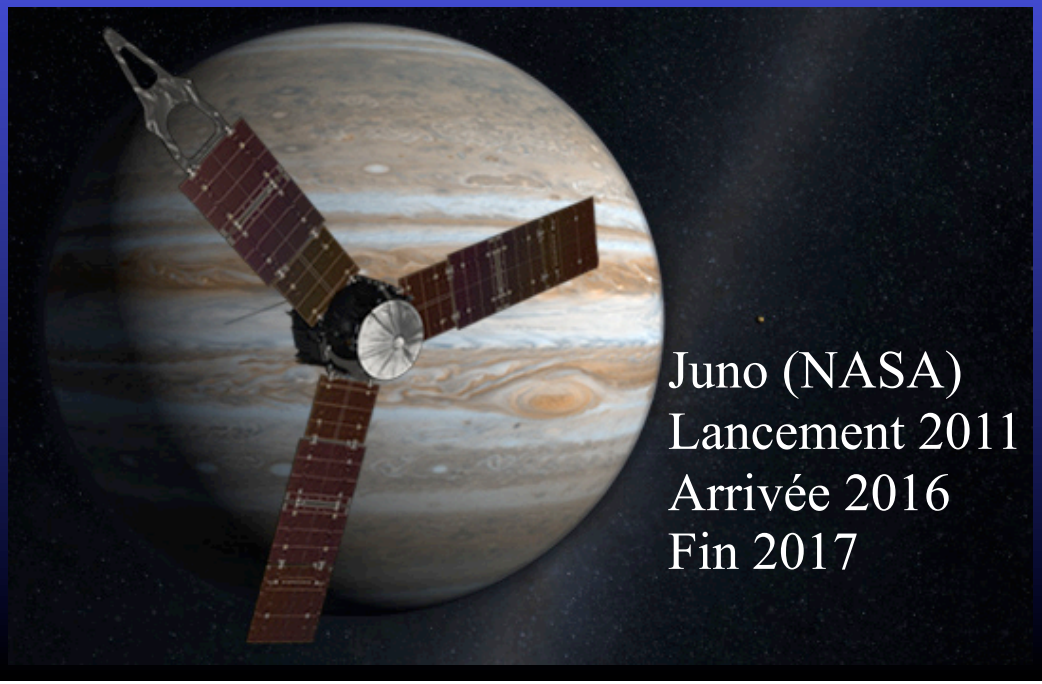
Saturn Flyby with Probes

This mission will send a sciencecraft to flyby Saturn and release probes into the Saturnian atmosphere.

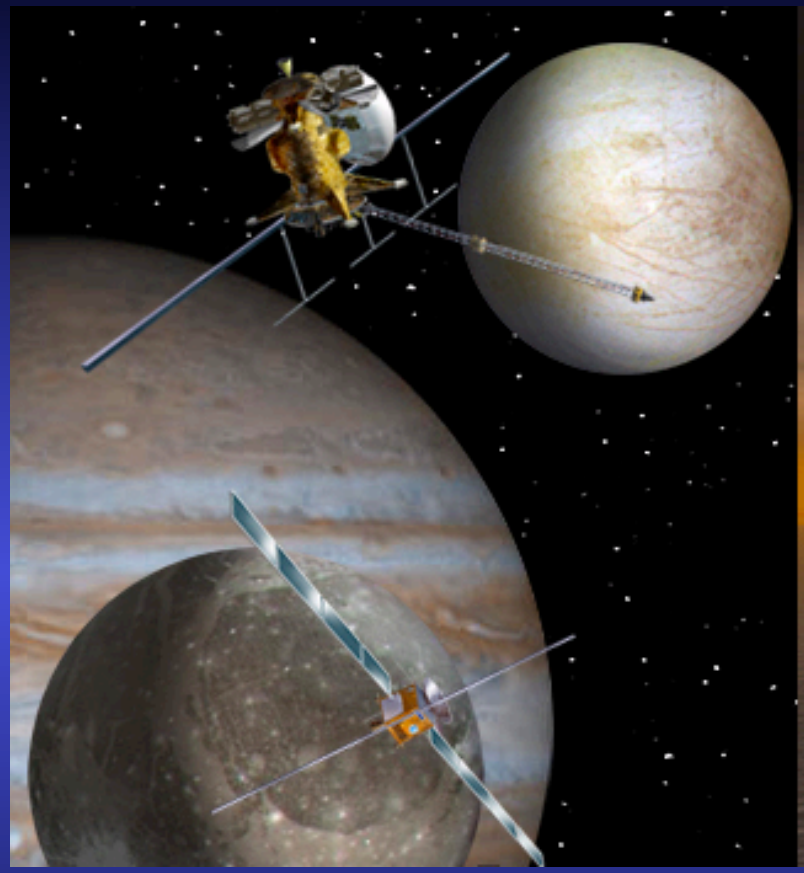
Launch: 2015 ?



Missions à court terme

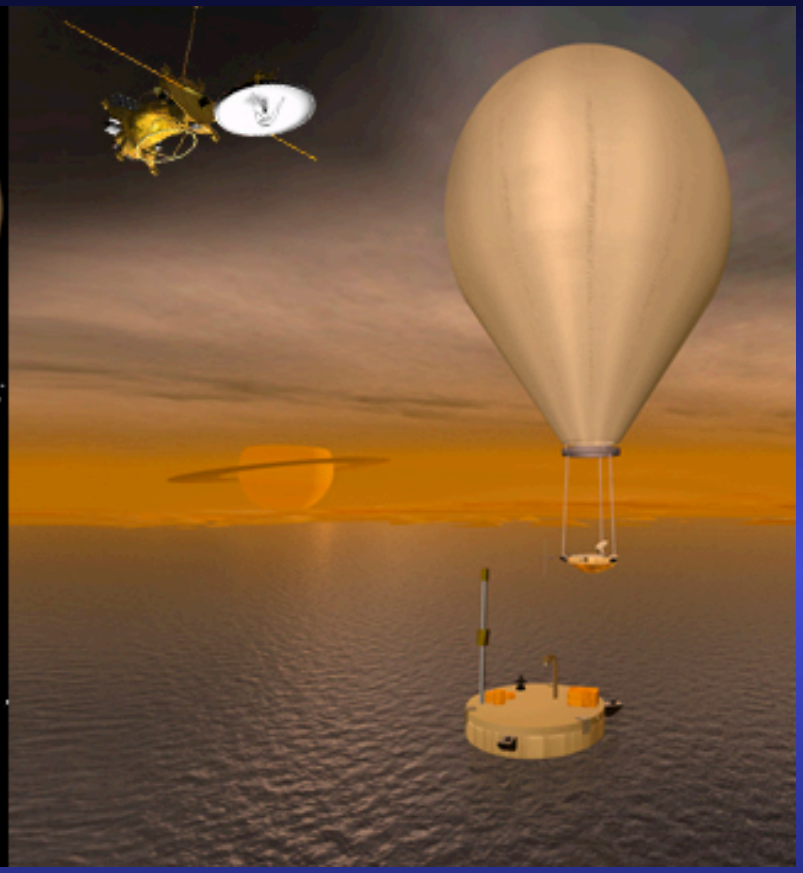


Missions à long terme



EJSM (NASA): Europa Orbiter
GJSM (ESA) : Ganymede Orbiter

Lancement 2020
Arrivée 2025 – Fin 2029



TSSM (NASA/ESA) : Titan Orbiter-Ballon-Lander

Lancement 2020
Arrivée 2029 – Fin 2033

NASA: 1.6-tonne orbiter
ESA: balloon and lake lander

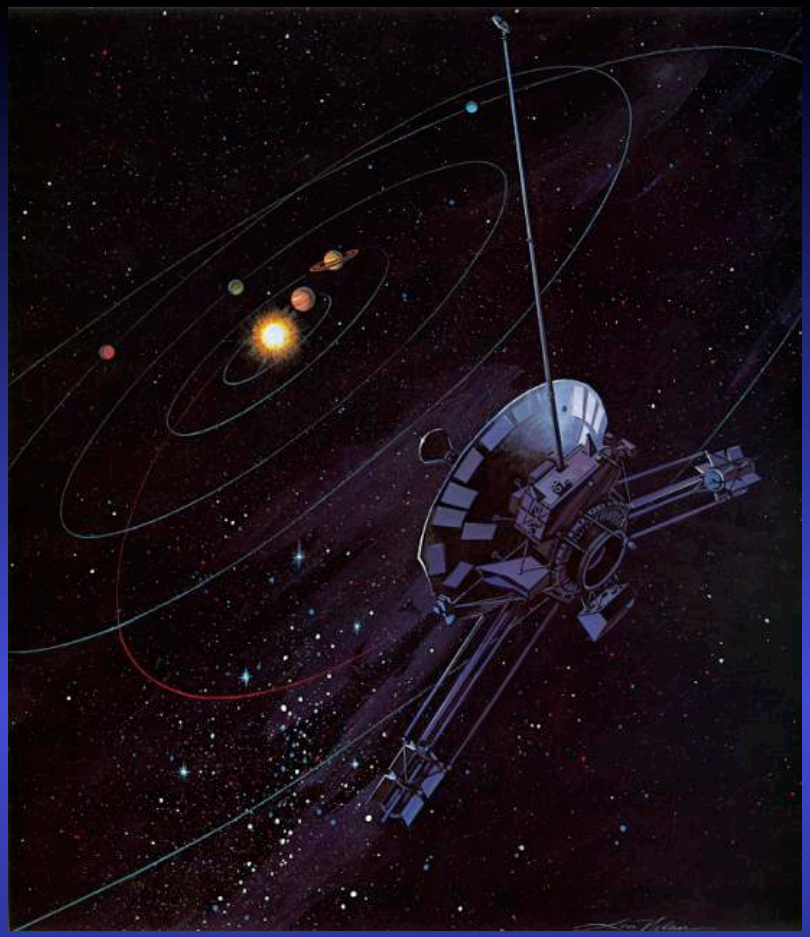
Missions à long terme

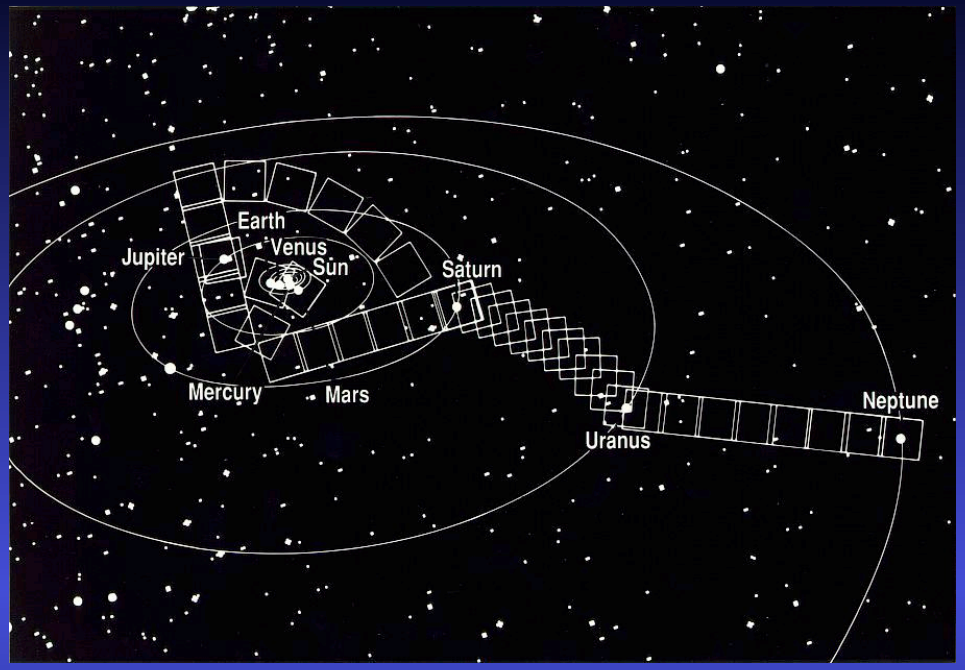
JIMO - Neptune Triton (NASA)

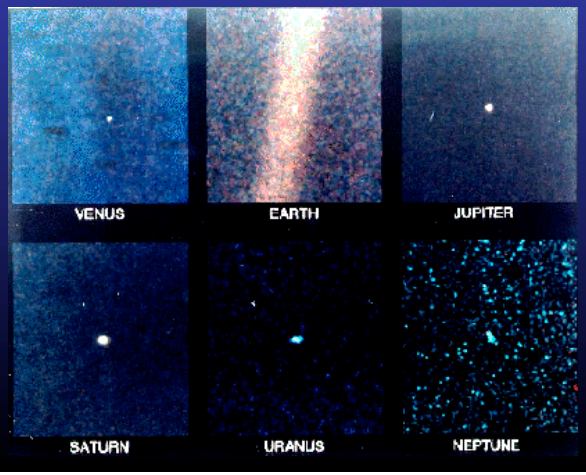
Lancement 2016-2018
Arrivée 2035
Fin 2040 ?

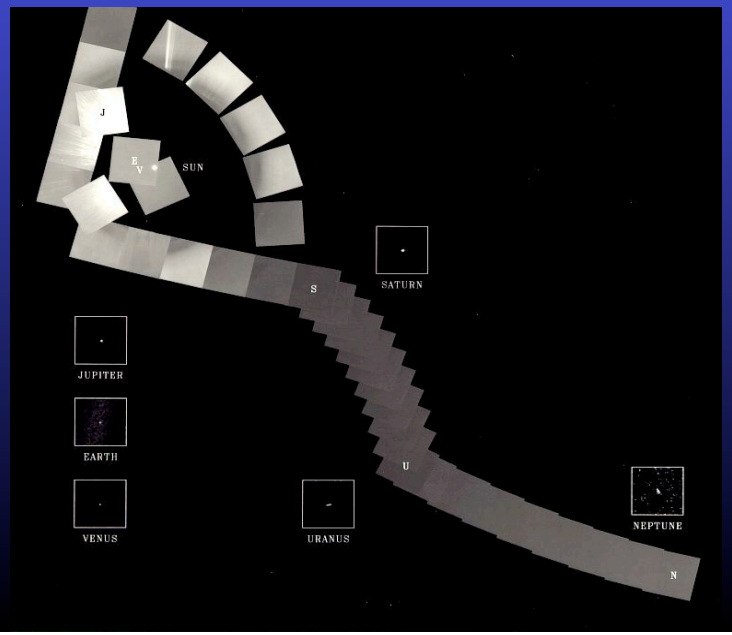
1 orbiter
3 landers (N, Eq and S)

Au-delà



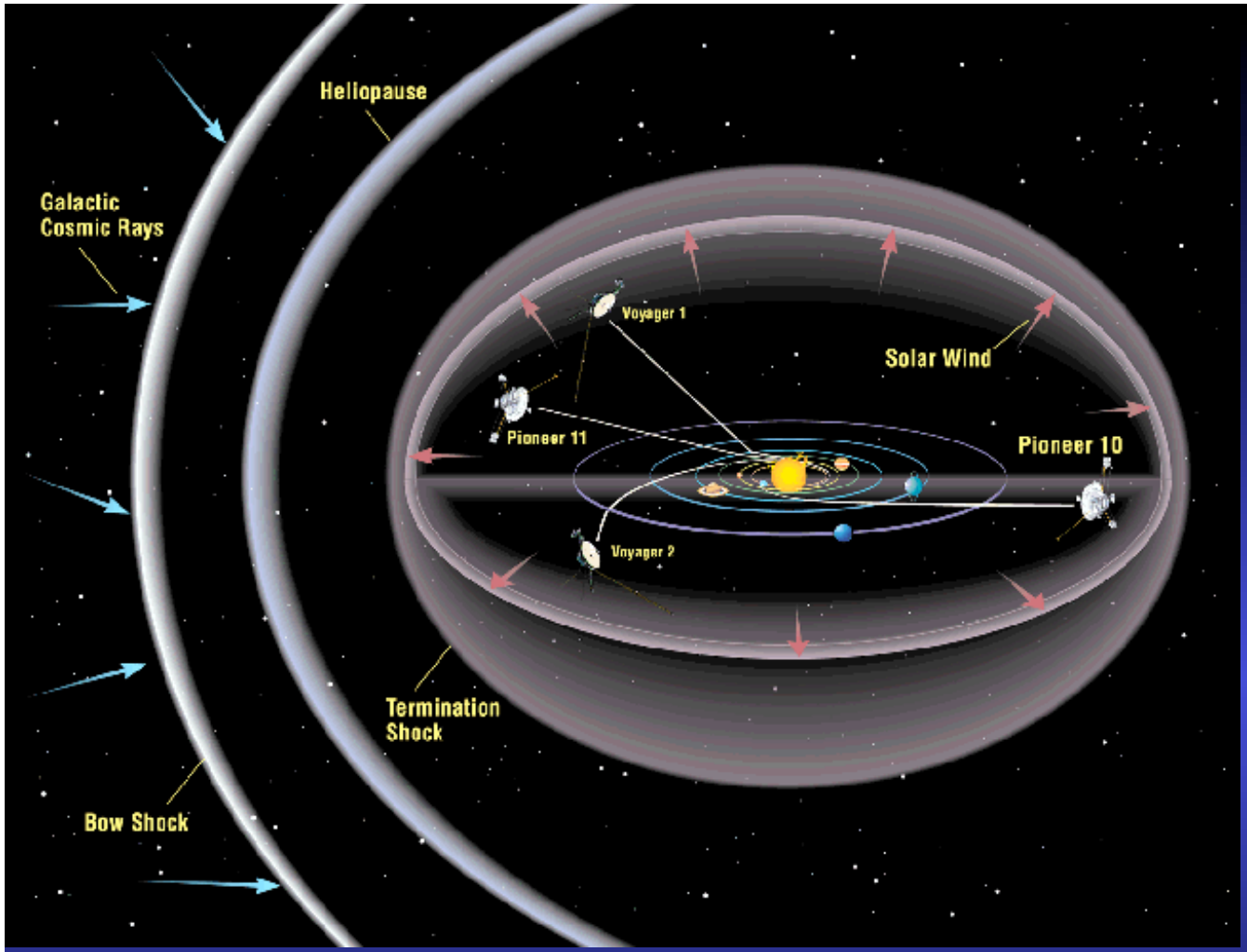


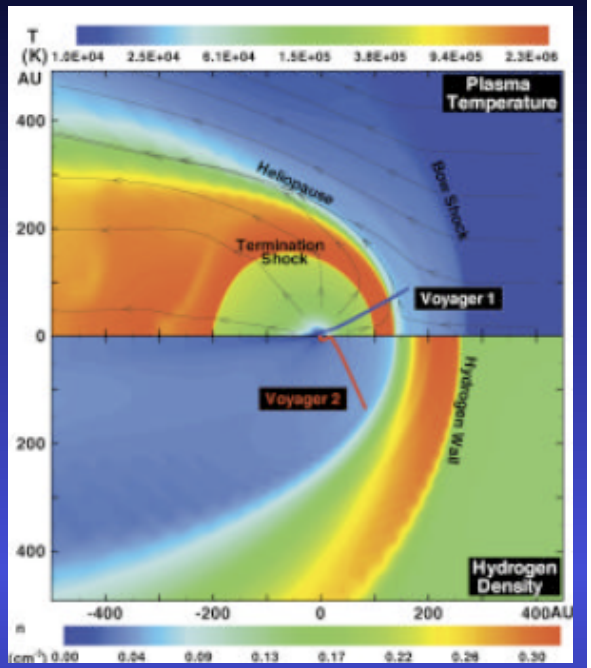




Voyager 1

Au-delà

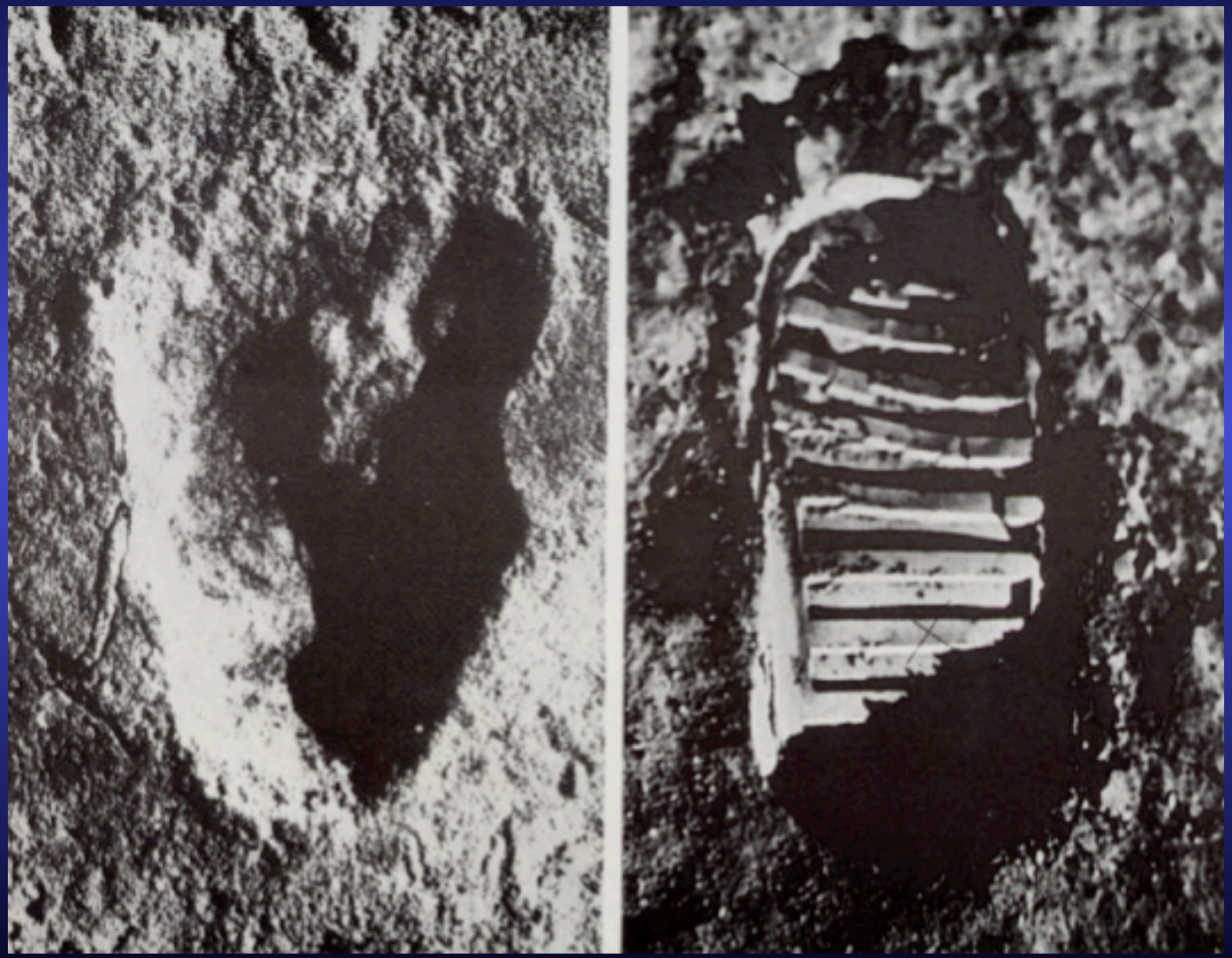




Voyager 1 & 2 : Solar System bounds
New Horizons : Solar System bounds (2029)
Pioneer 10 : Direction Aldebaran (2 My)
Pionerr 11 : Constellation de l'aigle (4My)

Au-delà

20 000 ans



A suivre…