

Planétologie: atmosphère, surface, habitabilité

UE M1 Grandes Questions Environnementales

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Cours magistral 1 : Une exploration phénoménologique

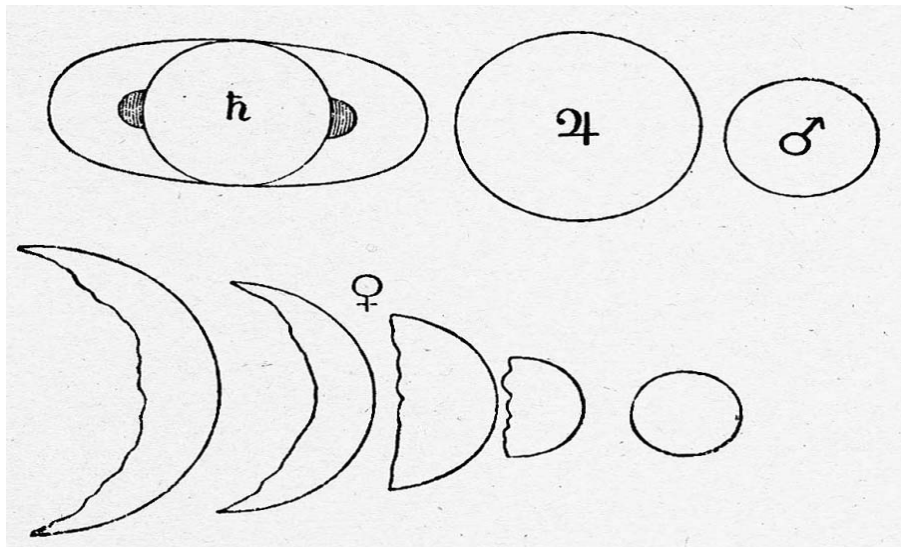
- 1 Avant-propos
- 2 Soleil
- 3 Petits corps
- 4 Planètes telluriques
- 5 Planètes géantes
- 6 Satellites des planètes géantes
- 7 Objets transneptuniens

Plan

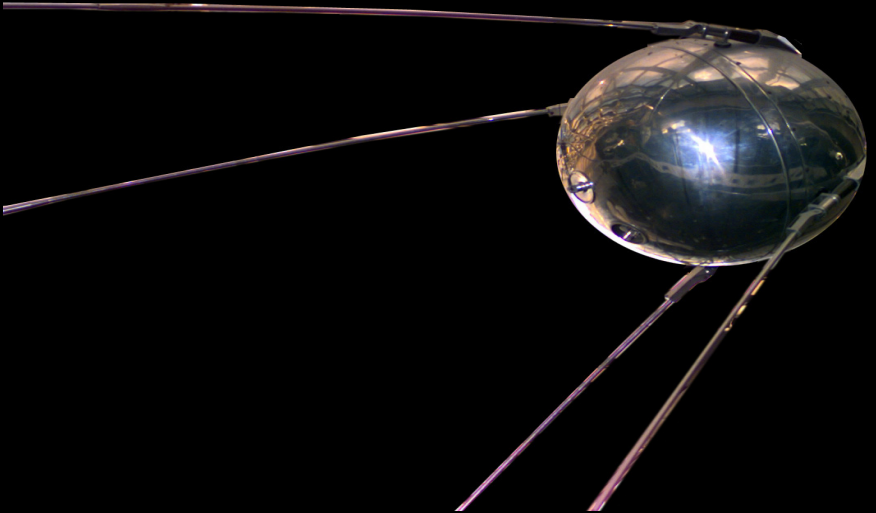
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Les planètes vues par Galilée

Tiré du Saggiatore 1623 (premières observations 1610)



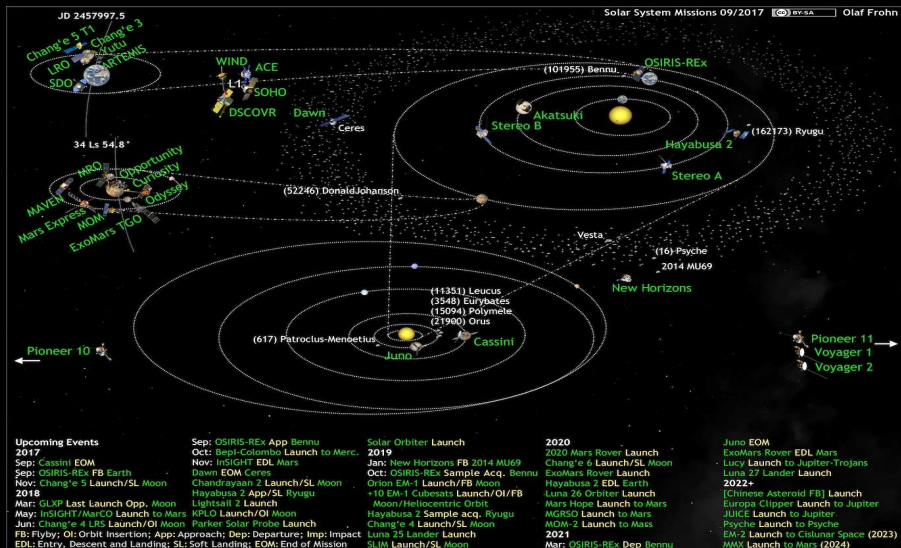
Sputnik 1957: début de l'exploration spatiale



Auto-portrait Curiosity hiver 2013 (“selfie”)



Un état de l'exploration spatiale



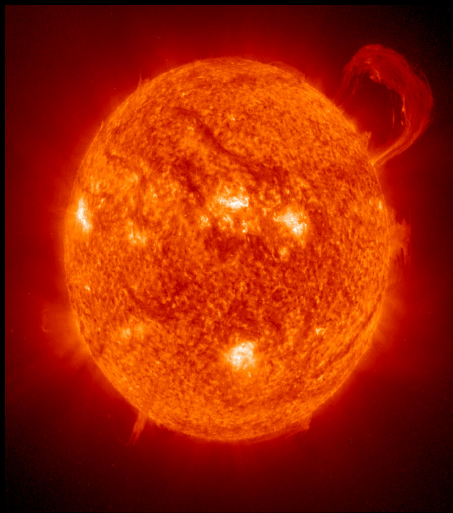
Plan

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Notre étoile: le Soleil

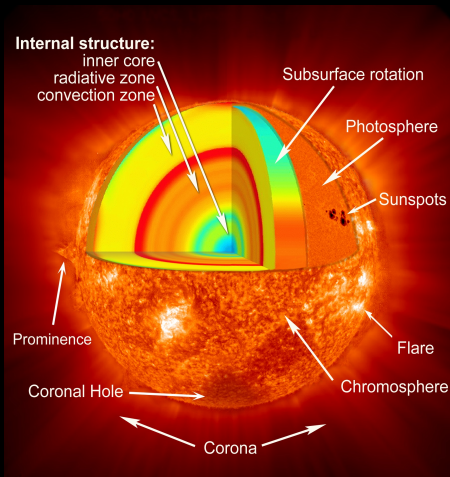
vue par SOHO (en XUV) $\lambda = 30.4 \text{ nm}$, haute chromosphère $T = 60.000 \text{ K}$

- ☞ Étoile de type G (banale) de la séquence principale (de taille et de densité telles qu'elle produit en son coeur de l'énergie par fusion nucléaire)
- ☞ 73.5% H // 24.8% He
- ☞ Principale source d'énergie à la surface des astres du système solaire
- ☞ Création d'un plasma (état de la matière dans lequel les constituants des atomes, noyaux et électrons, sont dissociés) et d'un champ magnétique par effet dynamo



[PIA03149, prise le 14 sept 1999]

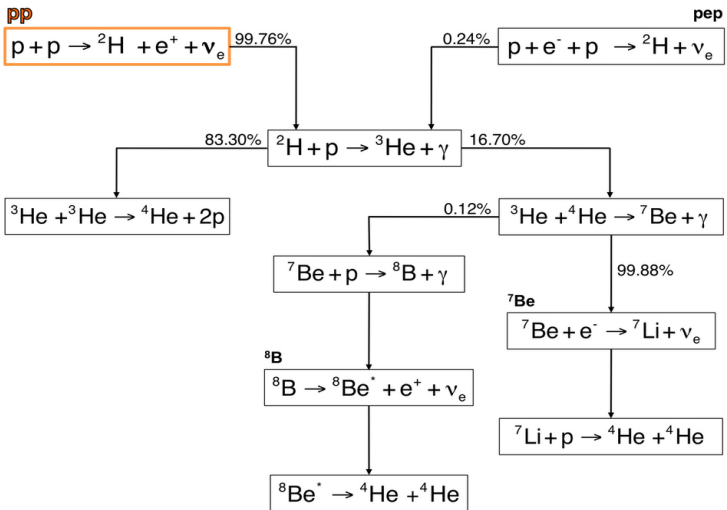
Structure du Soleil



[Image résumé de la mission SOHO <https://sohowww.nascom.nasa.gov/gallery/images/eit006.html>]

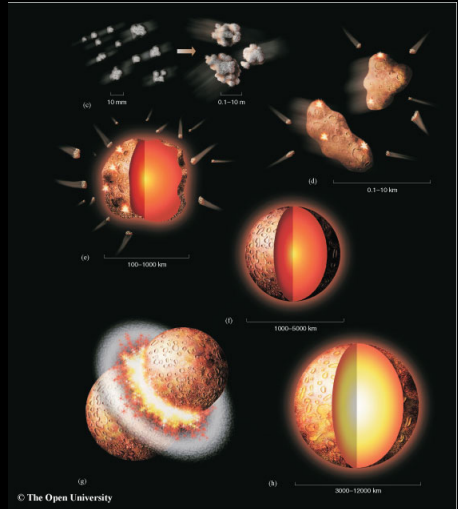
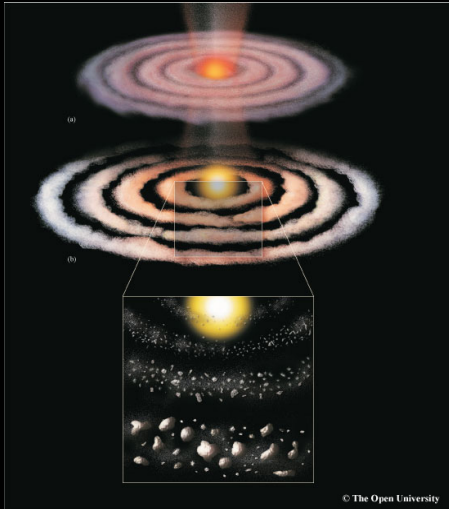
- ☞ Structure interne : variation de c_{son} sondé par mesures héliosismiques. Coeur (bleu) à 15 millions K.
- ☞ Rotation différentielle : rouge=rapide, bleu=lent.
- ☞ Couche des tâches solaires: photosphère, vue en visible ($T = 6.000 \text{ K}$).
- ☞ Couche externe: chromosphère, vue en XUV ($T = 60.000 \text{ K}$).

Réactions de fusion au sein du Soleil



[Borexino collaboration, Nature 2014]

The formation of planets

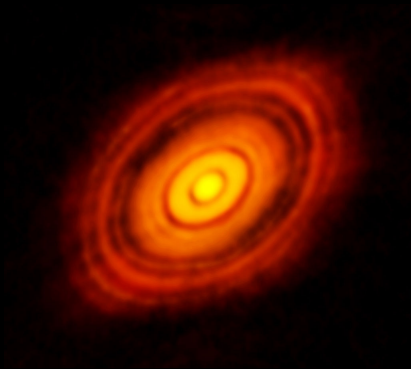


[McBride and Gilmour, An Introduction to the Solar System, 2004]

Young stars and protoplanetary discs

Atacama Large Millimeter Array image

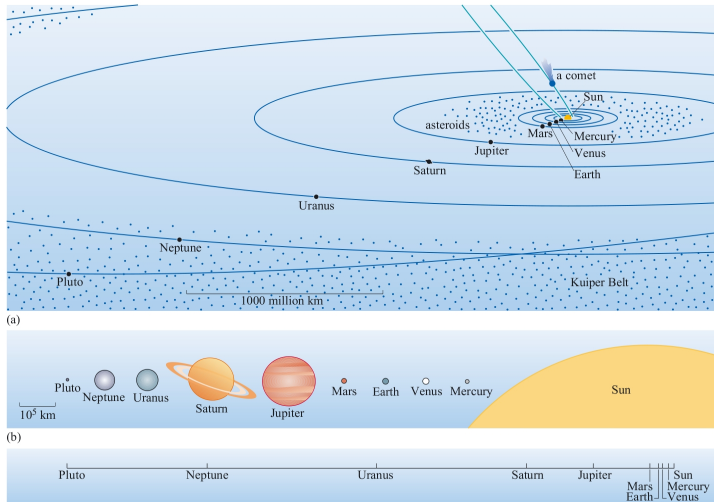
HL Tauri



Elias 2-27



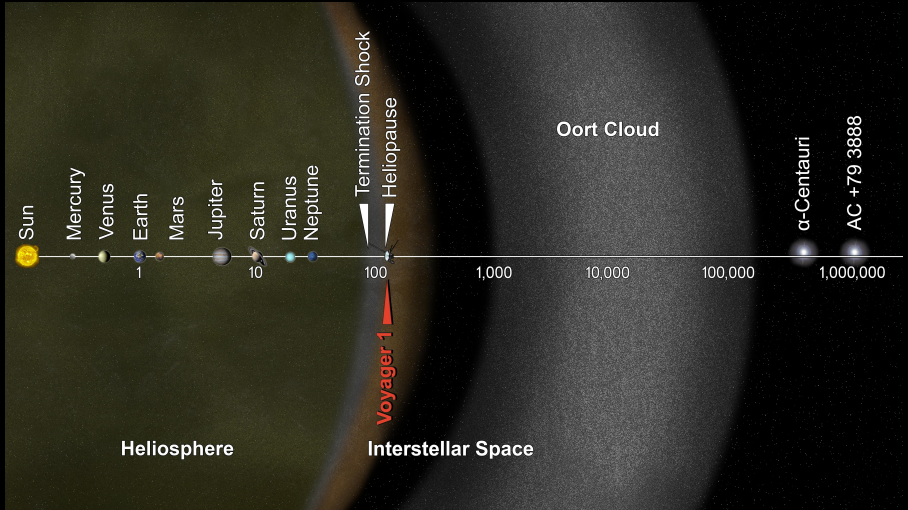
Le Système Solaire



[McBride and Gilmour, An Introduction to the Solar System, 2004]

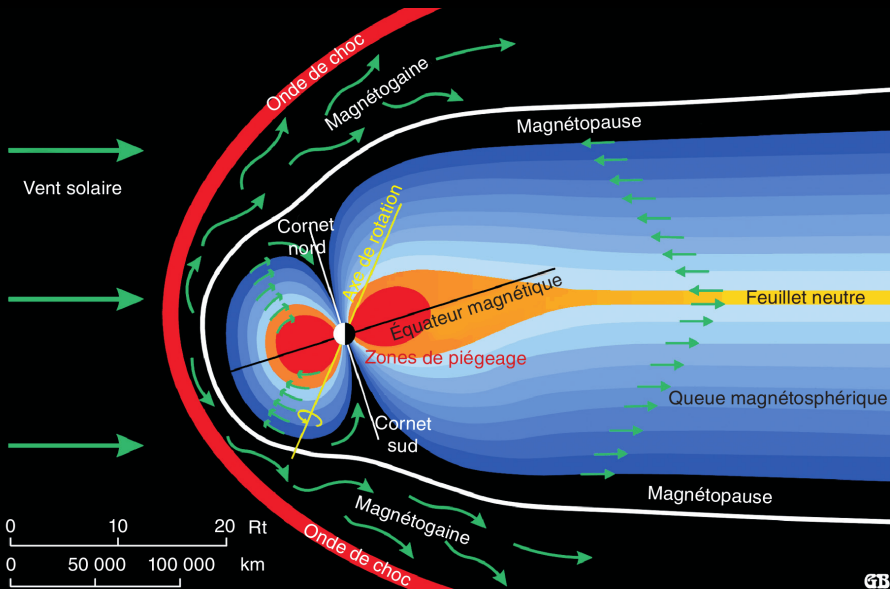
Échelles spatiales du système solaire

Echelle log. 1 UA = 150 millions de kilomètres.



[PIA17046. Image d'artiste NASA/JPL-Caltech.]

Environnement ionisé de la Terre et flux de matière



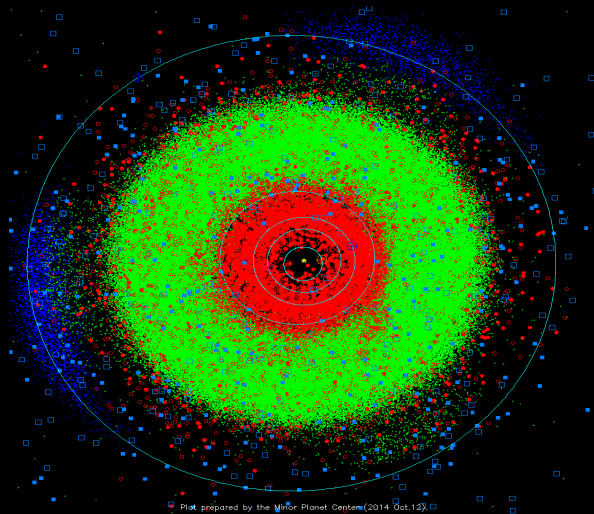
[J. Lilensten et T. Dudok de Wit in *Le Climat à Découvert*, CNRS éditions, 2011]

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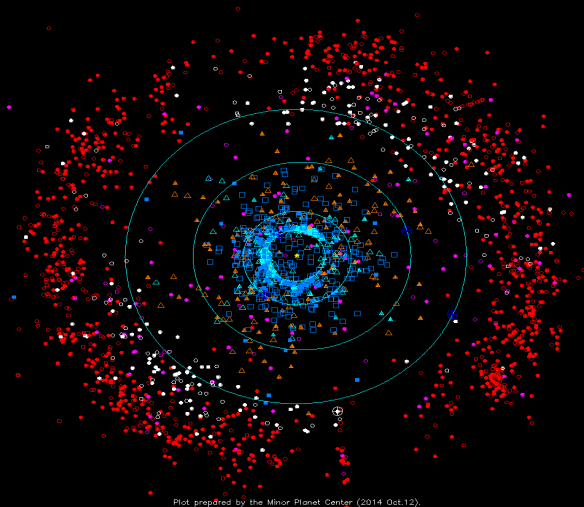
Astéroïdes

Ceinture principale et Troyens joviens



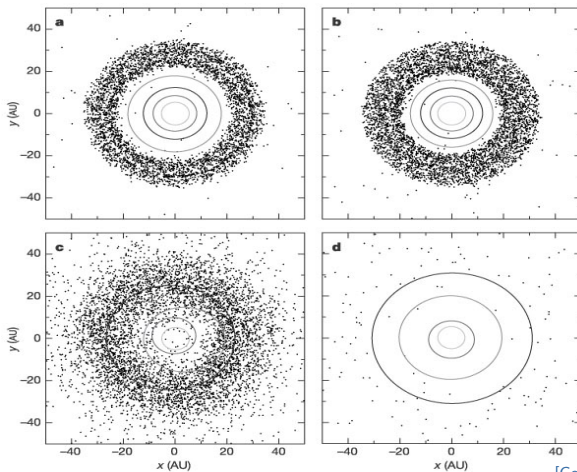
Ceinture de Kuiper

Objets trans-neptuniens



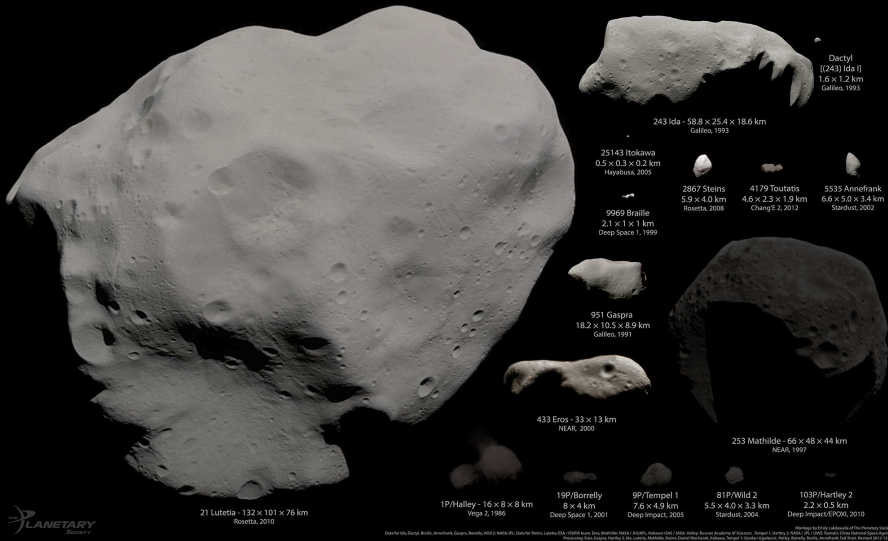
Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets

The LHB was triggered by the rapid migration of the giant planets



[Gomes et al. Nature 2005]

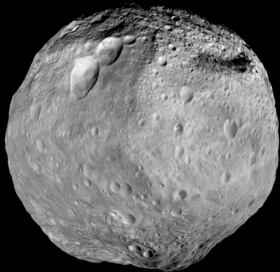
Astéroïdes visités par des sondes spatiales hors Vesta



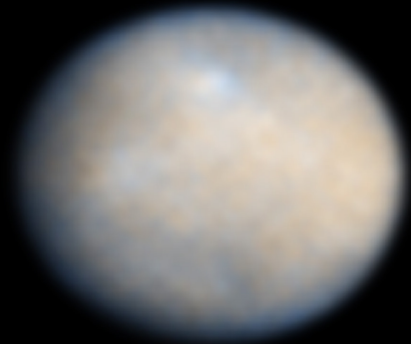
[Montage par E. Laddawalla (décembre 2012)]

Astéroïdes remarquables

Vesta (1807 Olbers, $d=530\text{km}$)

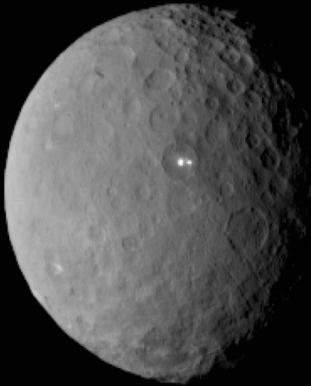


Ceres (1801 Piani, $d=963\text{km}$)



Ceres' bright spots observed by Dawn

February 19th, 2015



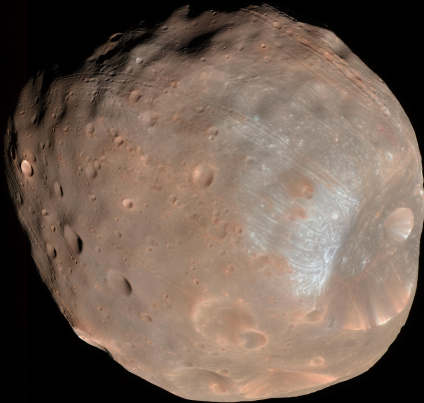
June 9th, 2015



Satellites de Mars

Images HiRISE à bord de Mars Reconnaissance Orbiter (2008-2009)

Phobos (d=21 km)



Deimos (d=12 km)



Météorite de Chelyabinsk (février 2013)



[Photo prise par Uragan TT référencée dans l'article correspondant Wikipedia]

Comète de Halley et tapisserie de Bayeux en 1066

Invasion de l'Angleterre par Guillaume Le Conquérant



[Cité dans de Pater et Lissauer, Planetary Sciences, 2010 d'après Beatty et al. 1999]

Rosetta in front of 67P-Churyumov-Gerassimenko

Image by CIVA on board Philae on board Rosetta!

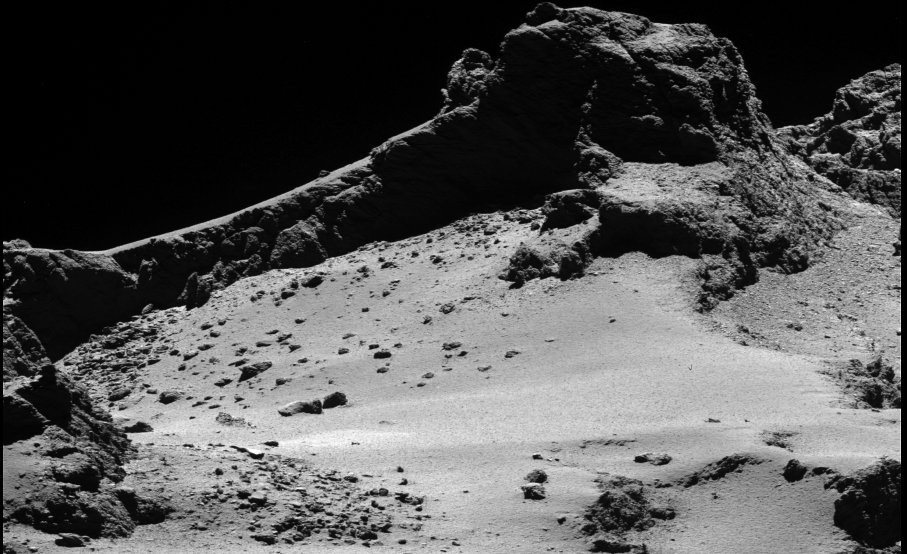


2 months of 67P-Churyumov-Gerasimenko

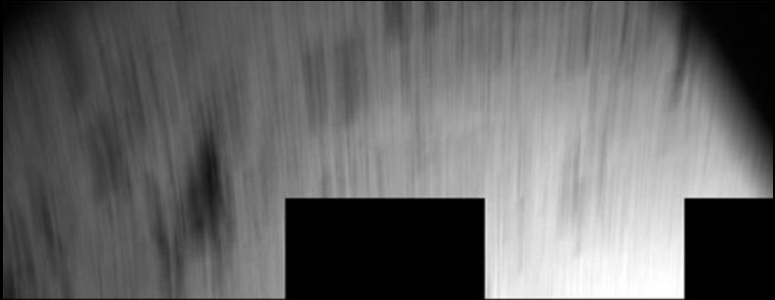


Activity of comet Churyumov-Gerasimenko - 28 March to 5 June 2015
ESA/Rosetta/NAVCAM/Thomas Appéré - CC BY-SA IGO 3.0

A view of 67P's smaller lobe at 8km from surface

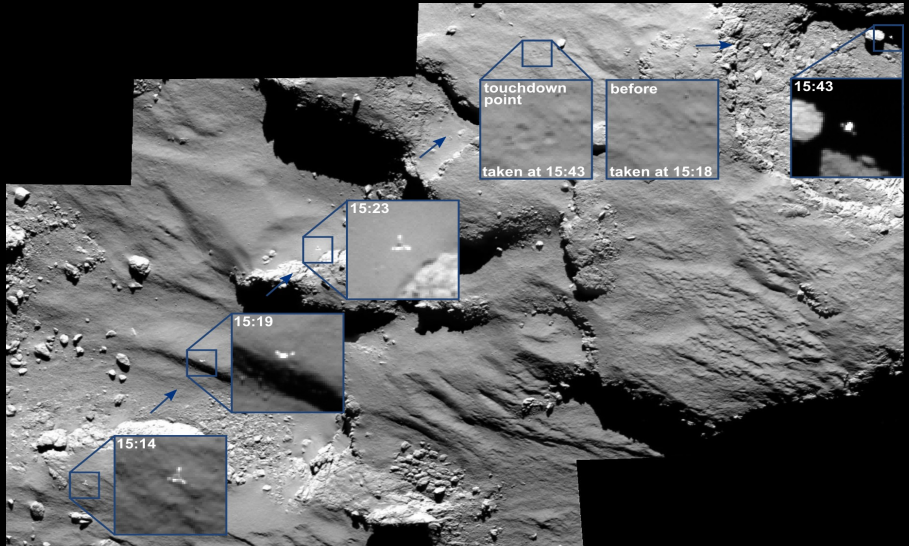


Philae's first CIVA picture when supposedly landed



ESA/PHILAE/CIVA

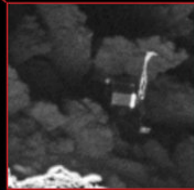
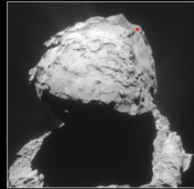
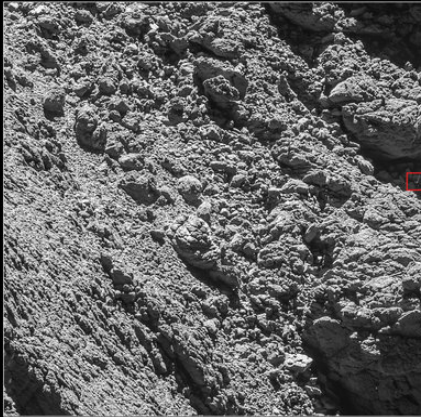
Philae's bumps seen from Rosetta



Philae on his final landing site (Nov 12th, 2015)



Philae found! (Sep 2th, 2016)

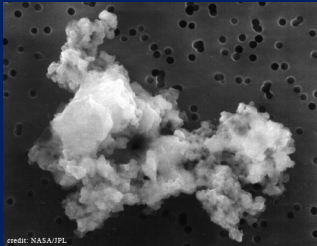


[OSIRIS narrow-angle camera, 5cm/pixel, ESA/Rosetta]

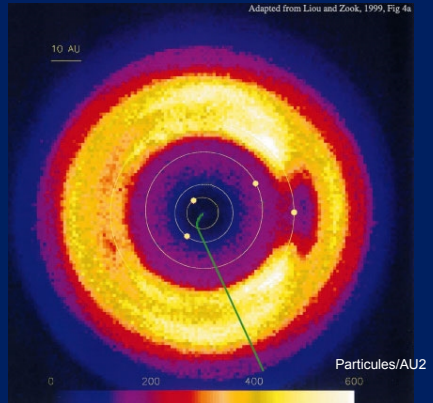
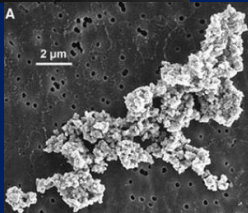
Les poussières interplanétaires

Les poussières interplanétaires sont des grains de poussière qui voyagent dans le système solaire. Leur source peut être :

- le système solaire et ses objets
- l'environnement interstellaire



credit: NASA/JPL



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Définition de l'IAU en 2006

Planète

Une planète est un objet céleste qui :

- ☞ est en orbite autour du Soleil (n'est pas un satellite)
- ☞ possède une masse suffisante pour que sa gravité surpasse les forces des corps rigides pour que sa forme corresponde à un équilibre hydrostatique (forme quasiment sphérique)
- ☞ a nettoyé le voisinage de son orbite (accrétion par gravité)

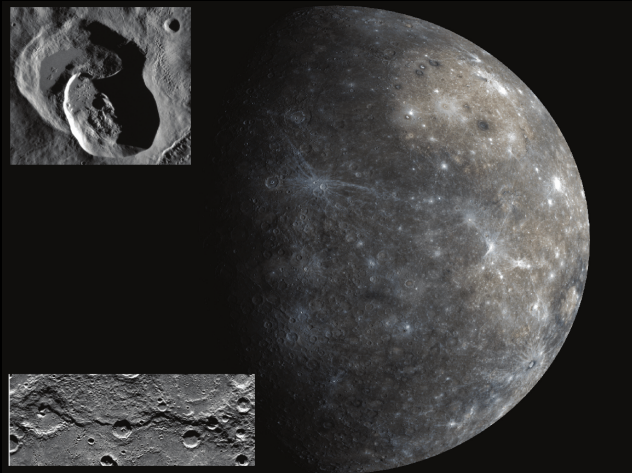
Planète naine

Une planète naine est un corps céleste qui :

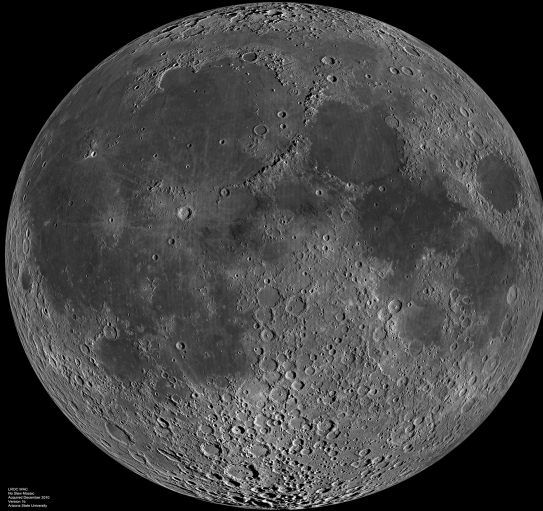
- ☞ est une planète SAUF
- ☞ qu'elle n'a pas nettoyé le voisinage de son orbite (accrétion par gravité)

Mercure

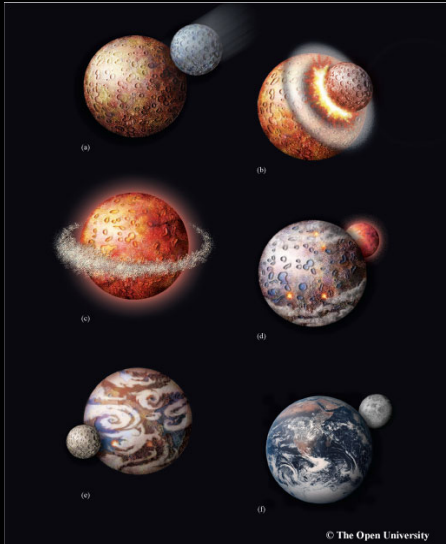
moisson de découvertes de la sonde MESSENGER



Near-side Moon imaged by LRO in 2010

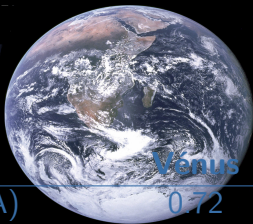


The formation of the Moon

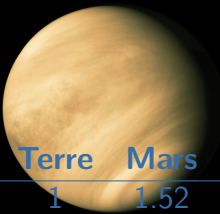


Science Magazine, October 2013
Where did the moon come from? For 3 decades, planetary scientists have agreed that it happened something like this: While the solar system was still forming, a body the size of Mars struck Earth a glancing blow that reduced both to rubble. The cloud of debris reformed itself into the modern Earth and moon. This "giant impact" theory neatly explained why the rocks Apollo astronauts brought back from the moon closely resembled rocks on Earth—or so it seemed at first. Actually, recent computer models show, such a collision wouldn't have scrambled the two bodies together enough to explain the similarity. Meeting last month in London to discuss the problem, scientists agreed that the origin of the moon must have been messier and more complicated than anyone had assumed.

Planètes telluriques (ayant une atmosphère substantielle)



Vénus



Terre



Mars

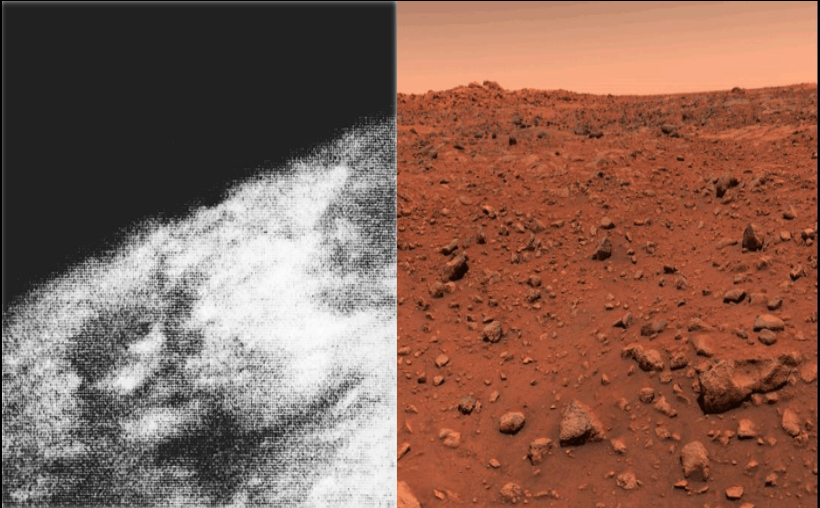


Titan

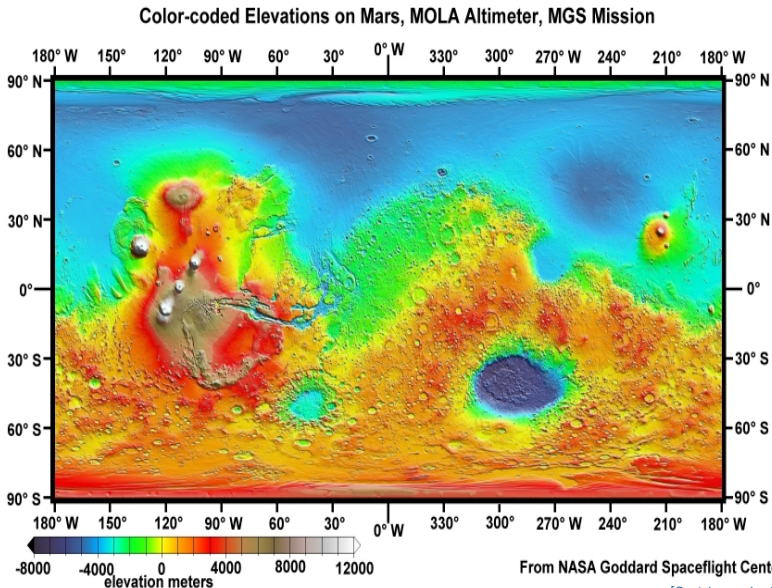
	Vénus	Terre	Mars	Titan
d (UA)	0.72	1	1.52	9.55
a (km)	6052	6378	3394	2575
g_{surface} (m s^{-2})	8.86	9.81	3.72	1.35
T_{surface} (K)	730	288	220	95
Ω (10^{-5} s^{-1})	0.03	7.3	7.1	0.46
μ (g mol^{-1})	43.4	28.9	43.3	27.8
c_p ($\text{J K}^{-1} \text{ g}^{-1}$)	0.85	1.00	0.84	1.04

Exploration de Mars

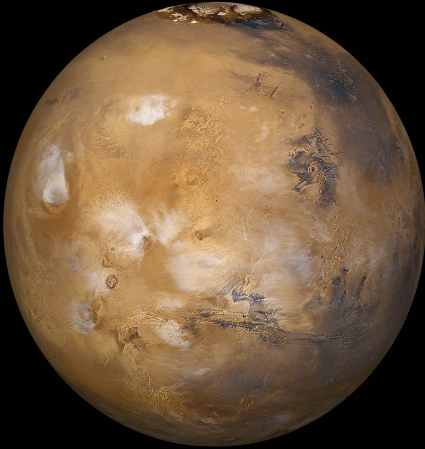
Mariner 4 flyby (july 1965) ... Viking lander (july 1976)



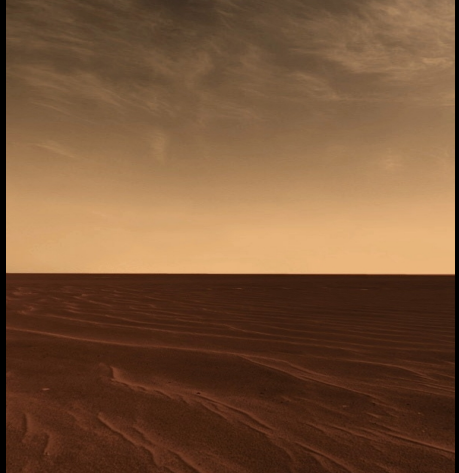
Mars' topography by the MOLA altimeter



Mars

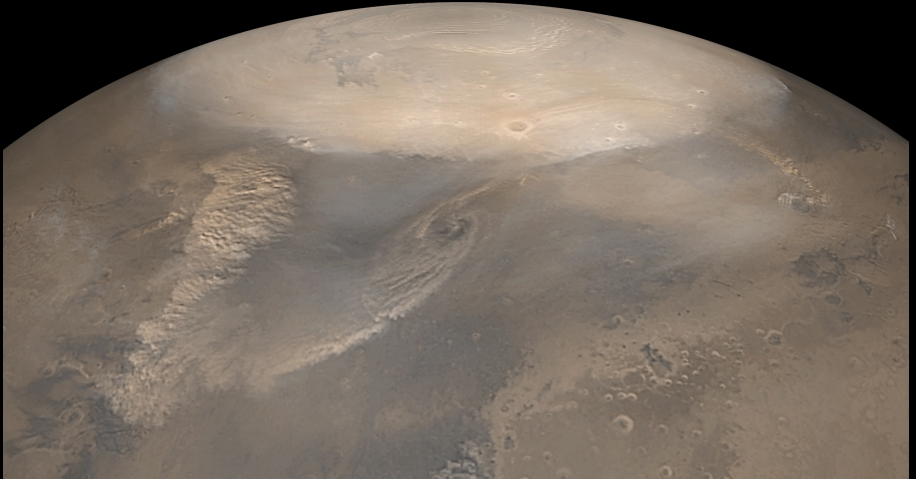


[Mars Global Surveyor, 2002]



[Mars Opportunity panorama, 2006]

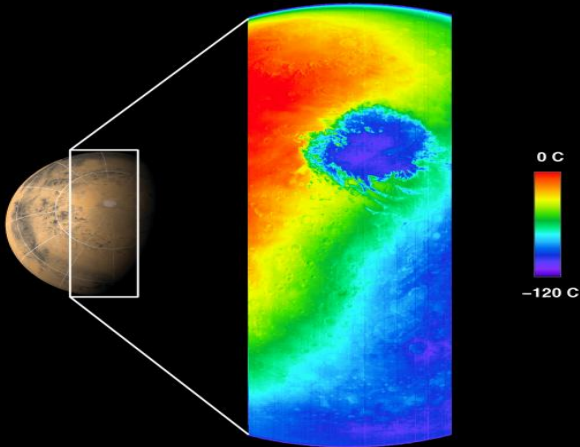
Fronts poussérieux et ondes baroclines



[Image MOC sur Mars Global Surveyor 2002 (printemps nord martien)]

Le cycle du CO₂ sur Mars

Illustration: calotte polaire saisonnière sud de CO₂ à la fin du printemps

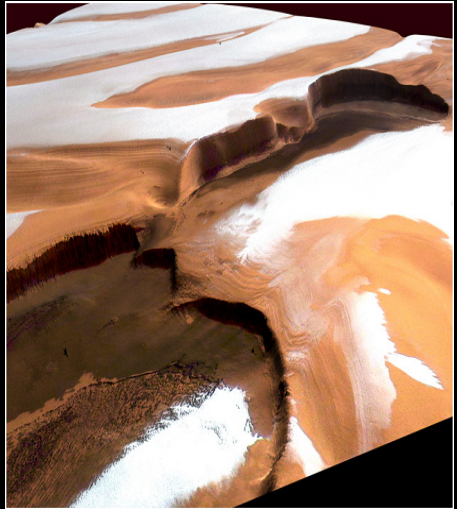


[First THEMIS image on board Mars Odyssey 2001 reference PIA03459]

Martian northern polar cap

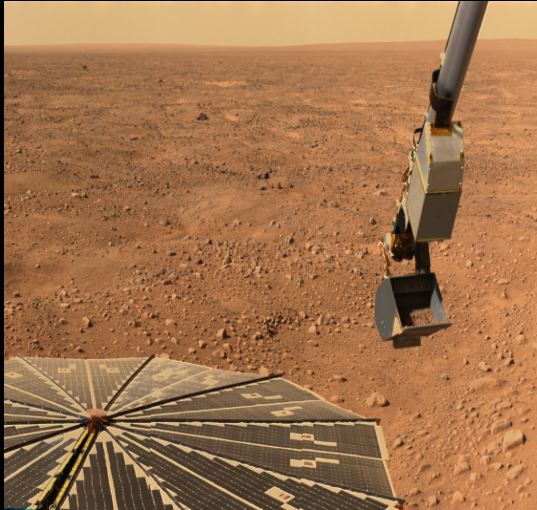


[MGS/MOC visible image]



[HRSC visible image (3D-projected)]

Mission Phoenix sur Mars 2009



Sol 20

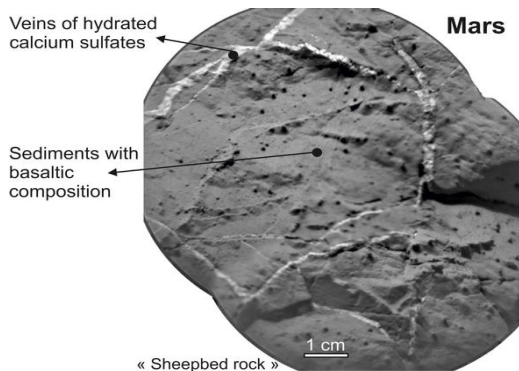


Sol 24



Veines de gypse découvertes par Curiosity en 2014

Apport régulier sur longue durée d'une eau tiède, sels minéraux, peu acide

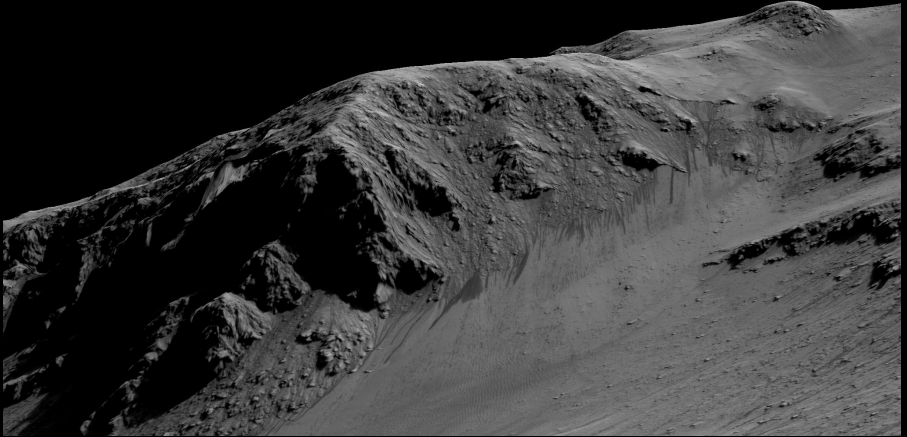


Earth



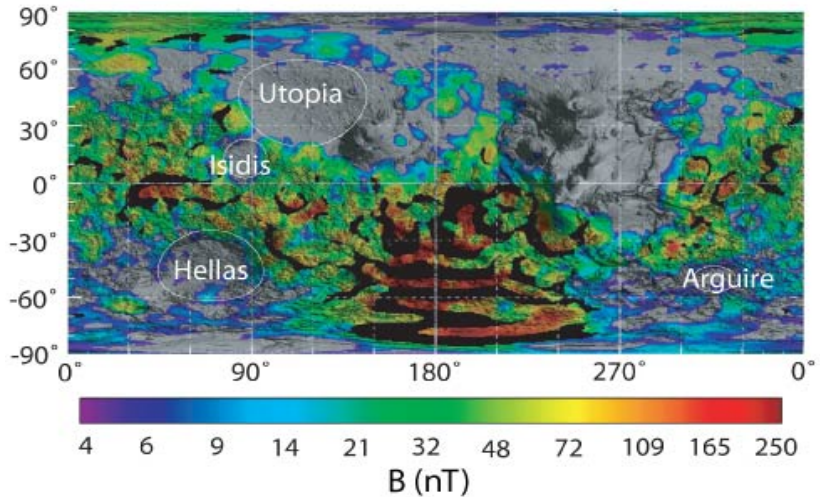
[PIA16617 NASA / Université Nantes]

Recurring Slope Lineae sur Mars



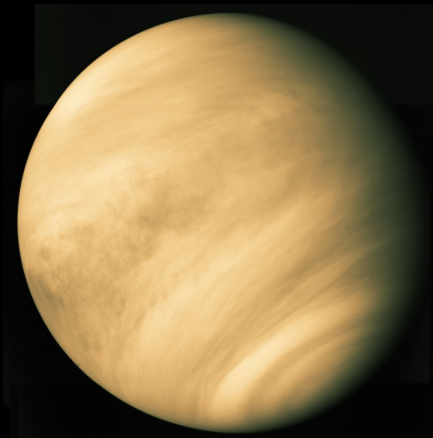
[Caméra HIRISE à bord de Mars Reconnaissance Orbiter]

Mars crustal magnetic field

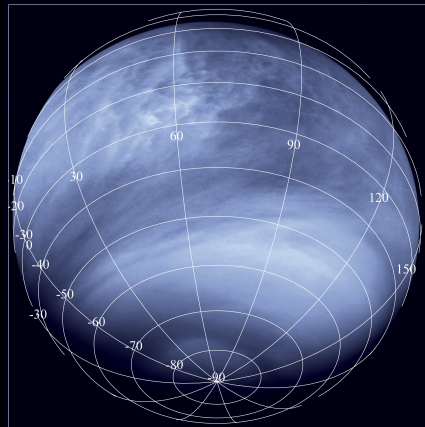


[Lillis et al. 2008. MGS Electron Reflectometer data]

Vénus



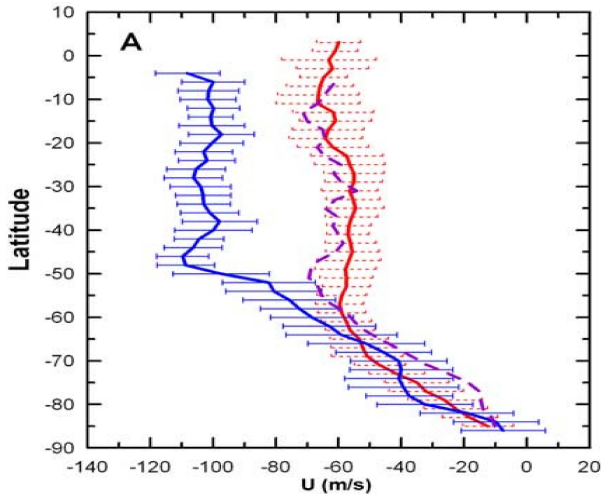
[Pioneer Venus, 1979]



[Venus Express, 2006]

Vents en super-rotation sur Vénus

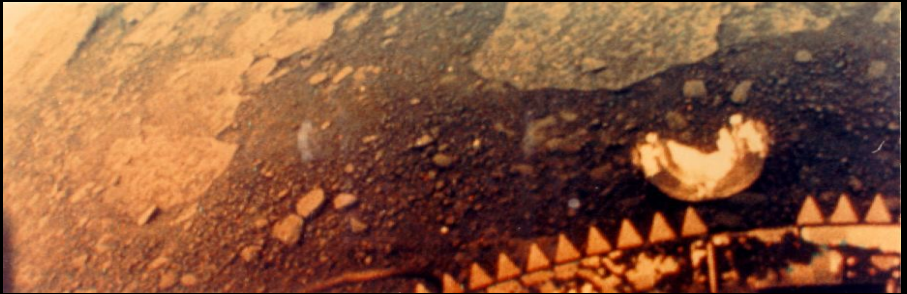
Récentes observations Venus Express / VIRTIS cloud tracking



[Sanchez-Lavega et al., 2008]

A la surface de Vénus

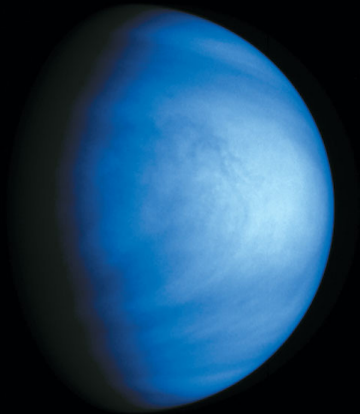
$p = 90$ bars et $T = 450^{\circ}\text{C}$



[Image capturée par Venera 13 en 1982]

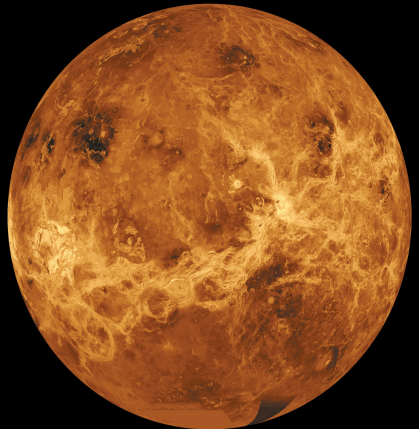
Vénus

vue par Galileo (image visible
fausses couleurs)



Courtesy of NASA

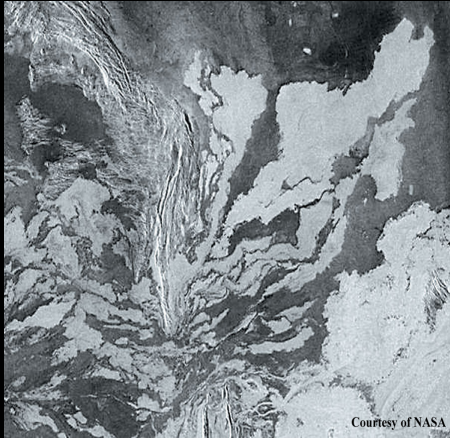
vue par Magellan
(cloud-penetrating radar)



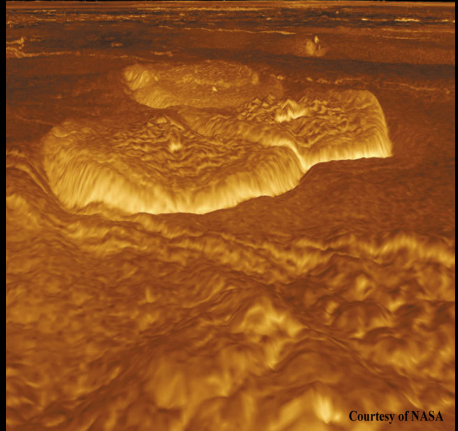
Courtesy of NASA

Traces de volcanisme sur Vénus

Lava flows (400 km)



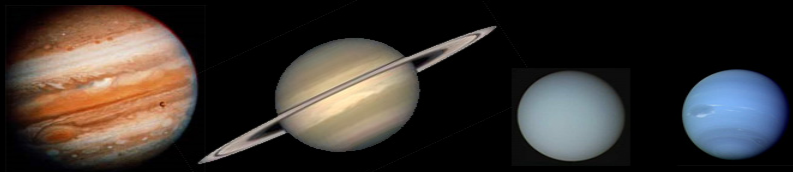
Pancake domes (25 km, 750m)



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Planètes géantes (absence de surface)



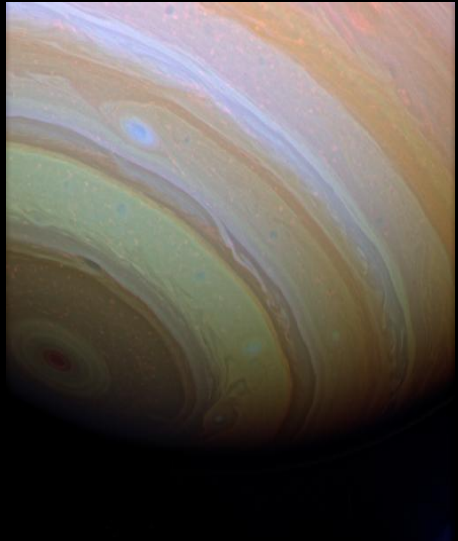
	Jupiter	Saturne	Uranus	Neptune
d (UA)	5.2	9.55	19.22	30.11
a (km)	71492	60271	25559	24766
g (m s^{-2})	23.1	9.1	8.7	10.9
$T_{\text{equivalente}}$ (K)	109.5	82.3	58.2	45.9
$T_{\text{effective}}$ (K)	124.4	95.0	59.1	59.3
Ω (10^{-5} s^{-1})	17.6	16.4	10.1	10.8
c_p ($\text{J K}^{-1} \text{ g}^{-1}$)	12.6	14.1	11.0	11.2

Les géantes gazeuses: courants-jets et tourbillons

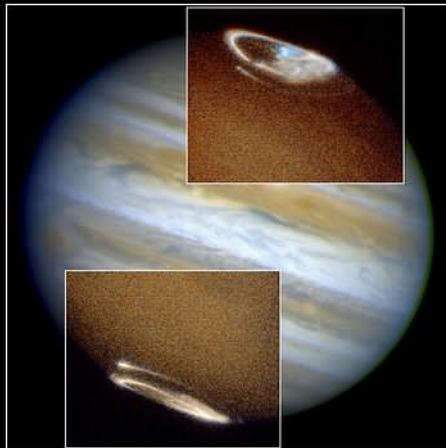
Jupiter



Saturne



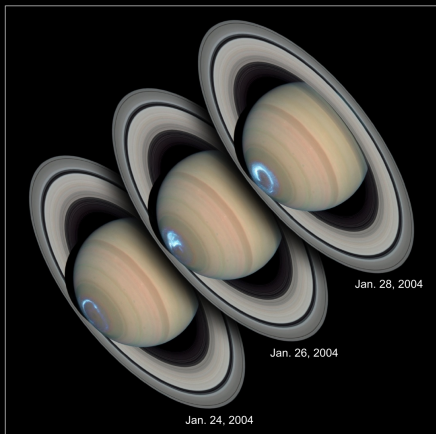
Aurores boréales sur les planètes géantes



Jupiter Aurora

PRC98-04 • ST ScI OPO • January 7, 1998
J. Clarke (University of Michigan) and NASA

HST • STIS • WFPC2



Saturn Aurora

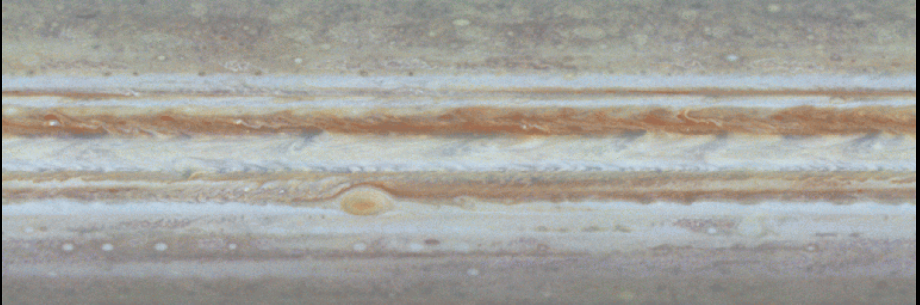
Hubble Space Telescope • ACS • STIS

NASA, ESA and J. Clarke (Boston University)

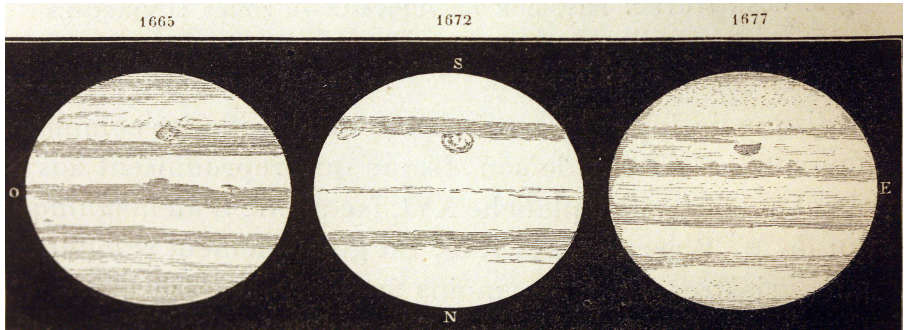
STScI-PRC05-06a

[Image composite HST visible et UV]

Jupiter zonal jets seen by Cassini



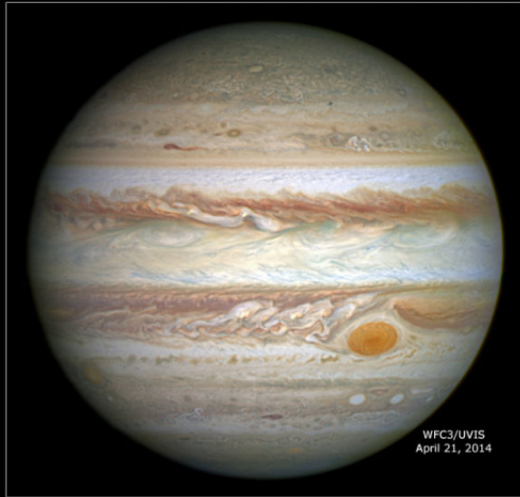
Cassini's drawings of Red Spot



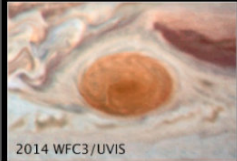
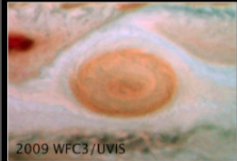
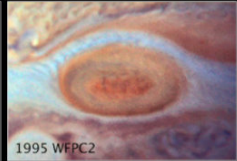
[Excerpts from Amedee Guillemin's "Le Ciel" 1877]

Shrinking of the Great Red Spot

Jupiter and the Great Red Spot ■ *HST* ■ WFC3/UVIS ■ WFC2



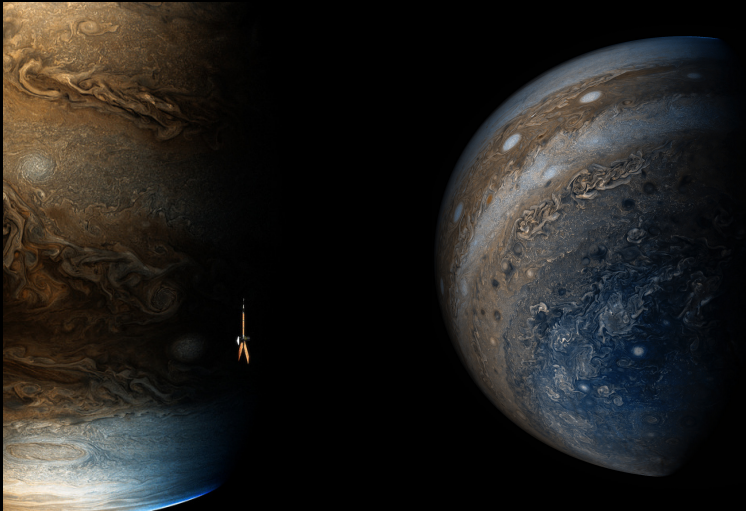
NASA and ESA



STScI-PRC14-24a

[Simon-Miller et al.]

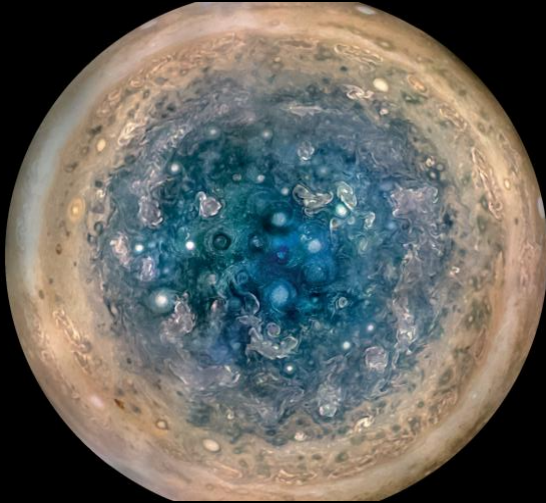
Juno at Jupiter



[NASA / SwRI / MSSS / Gerald Eichstädt / Seán Doran, Model by NASA/JPL-Caltech]

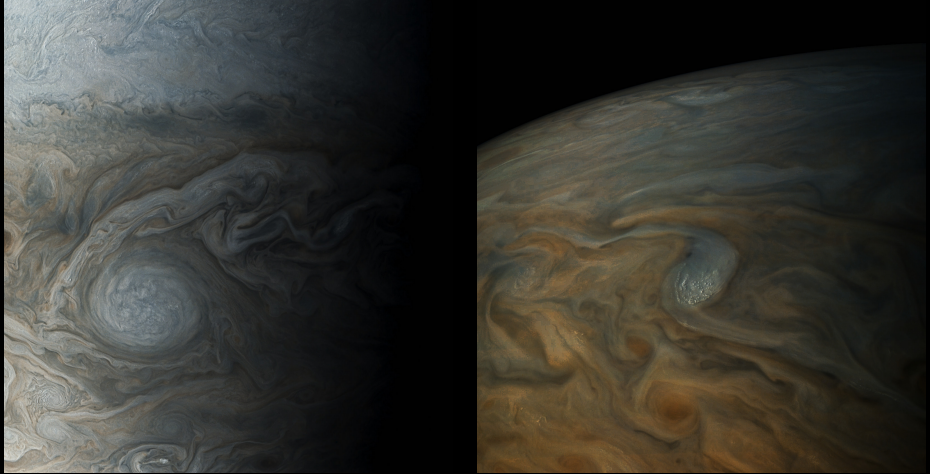
Jupiter's south pole seen by Juno

Junocam daylight images (3 orbits) // $d_{\text{cyclones}} \sim 1000 \text{ km}$



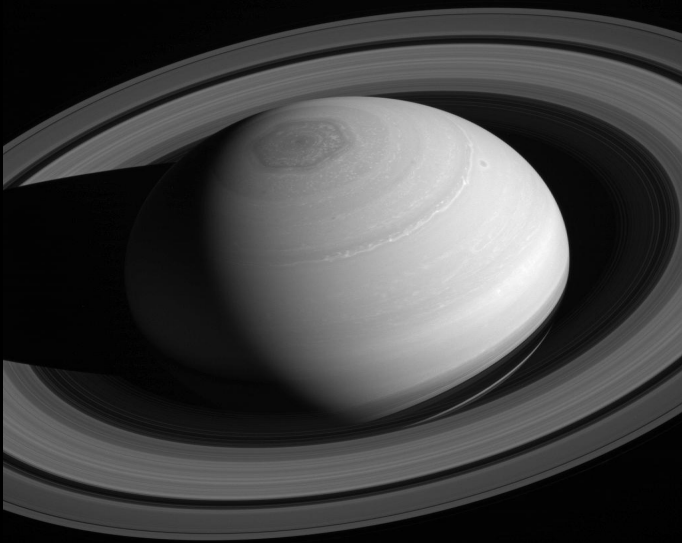
[PIA21641, NASA/JPL-Caltech/SwRI/MSSS/Betsy Asher Hall/Gervasio Robles]

Fine-scale dynamics witnessed by Junocam



[Sean Doran flickr, credits: NASA/SWRI/MSSS/Gerald Eichstadt/Sean Doran]

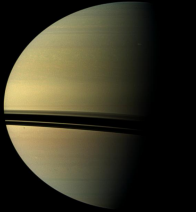
Saturn's hexagon



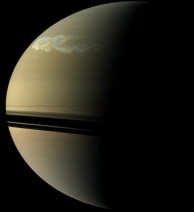
[PIA18278]

Les orages géants sur Saturne *Great White Spots*

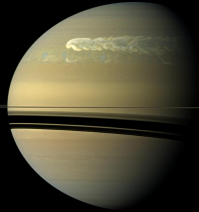
Dec 5, 2010



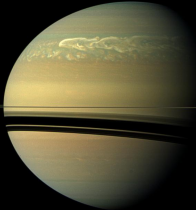
Jan 2, 2011



Feb 25, 2011



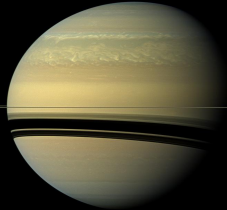
Apr 22, 2011



May 18, 2011

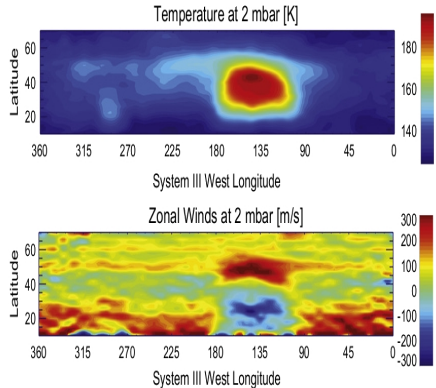
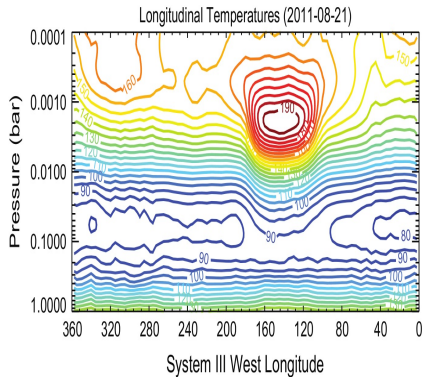


Aug 12, 2011



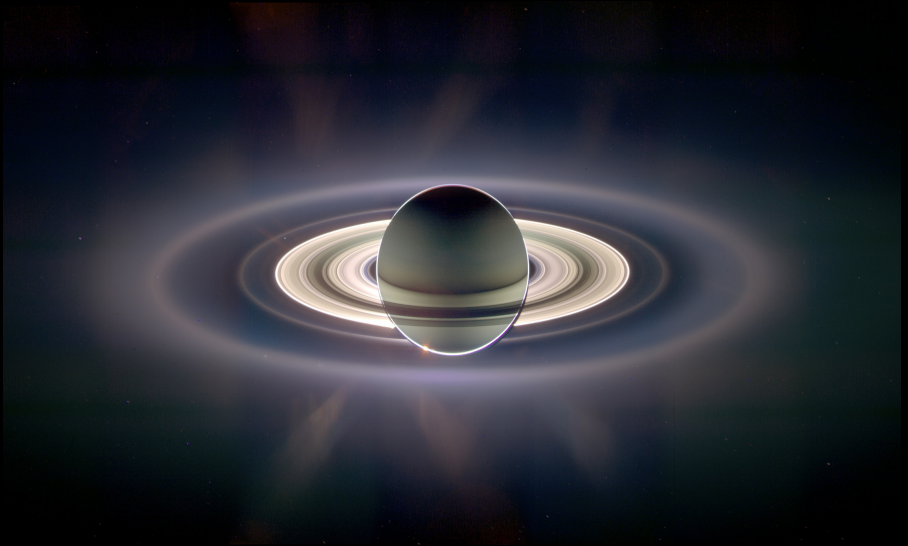
[Images Cassini-Huygens PIA14905]

Warm stratosphere after 2010 Great White Spot

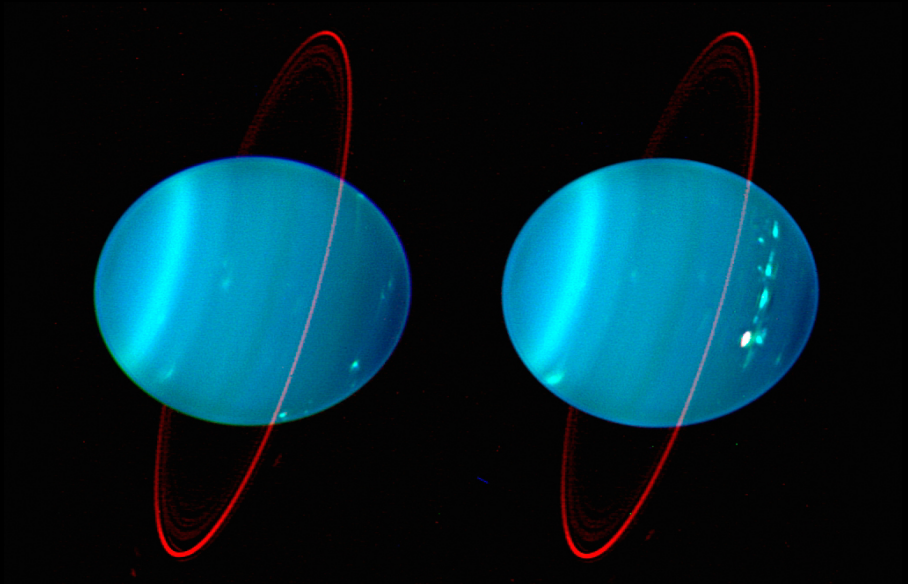


[CIRS measurements: Fletcher et al. Icarus 2012]

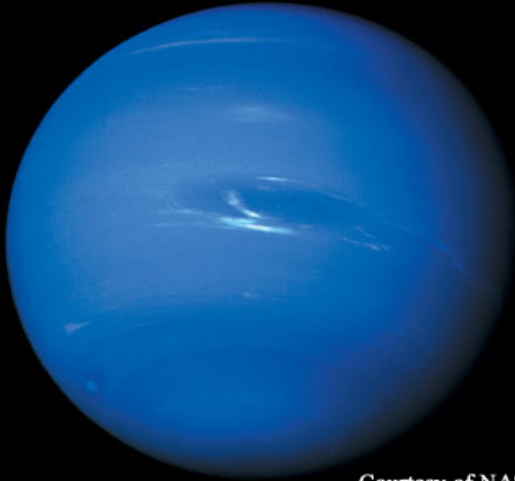
Saturne et ses anneaux (vue en éclipse par Cassini)



Uranus et ses nuages orageux



Neptune et son *Great Dark Spot* (image Voyager 2)

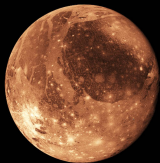


Courtesy of NASA

Plan

- 1 Avant-propos
- 2 Soleil
- 3 Petits corps
- 4 Planètes telluriques
- 5 Planètes géantes
- 6 Satellites des planètes géantes**
- 7 Objets transneptuniens

Les plus grandes lunes et les plus petites planètes



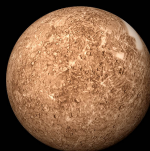
Ganymede

5262 km



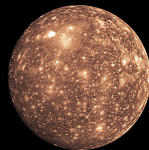
Titan

5150 km



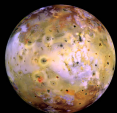
Mercury

4880 km



Callisto

4806 km



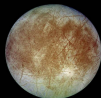
Io

3642 km



Moon

3476 km



Europa

3138 km



Triton

2706 km



Pluto

2300 km



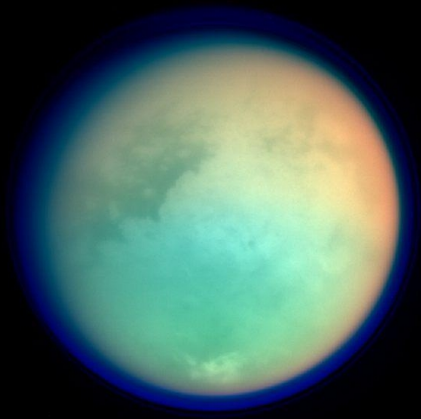
Titania

1580 km

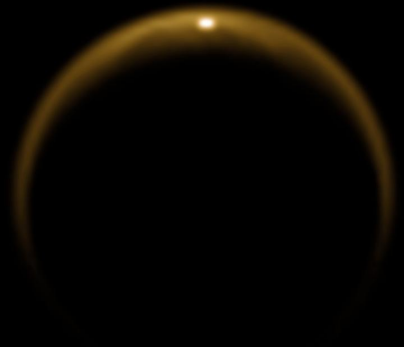
The Largest Moons and Smallest Planets

© Copyright 1999 by Calvin J. Hamilton

Titan



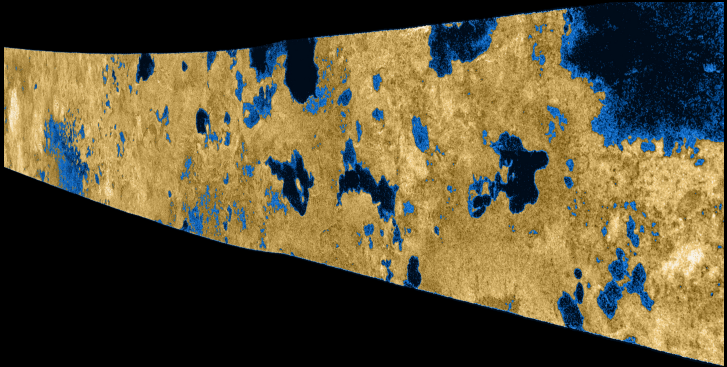
[Cassini-Huygens, 2004]



[Cassini-Huygens, 2009; Stephan et al., 2010]

Des lacs d'hydrocarbures sur Titan

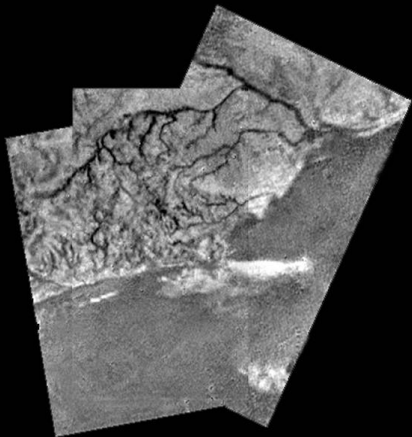
Image radar Cassini. Les lacs sont sombres car rétrodiffusion limitée



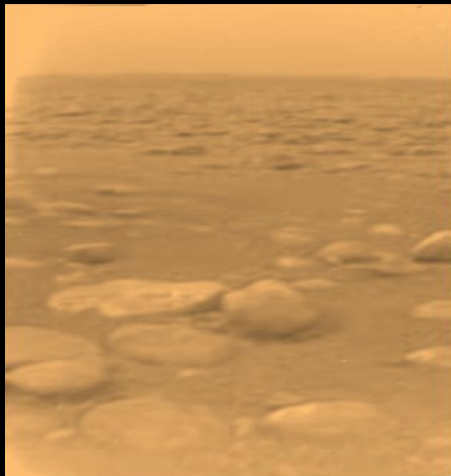
[référence PIA09102]

Titan: imagerie DISR de la sonde Huygens

Vallées fluviales (scène 15 km)

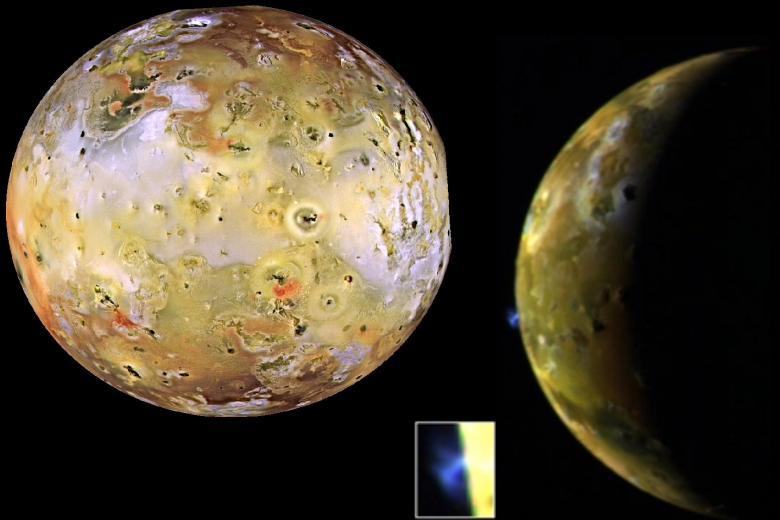


Surface (galets 5-10 cm)

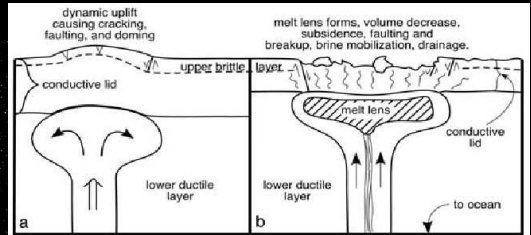
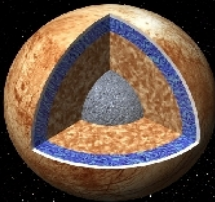
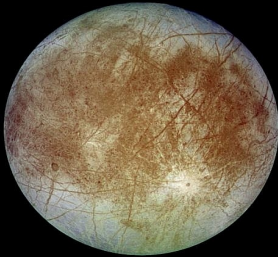


[gauche: PIA07236, droite: PIA07232]

Io et son volcanisme intense (images Galileo)



Europe



Sotin et al. 2002

Structure interne des satellites

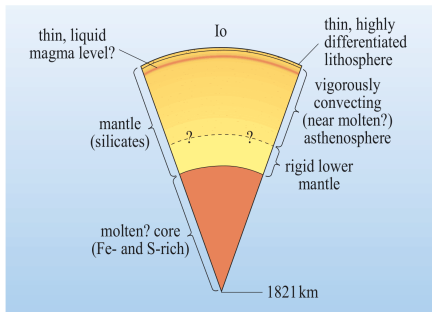


Figure 2.26 Schematic model for the internal structure of Io. The planetary layering within Io is assumed to be highly differentiated because of continual partial melting resulting from the tidally generated high heat flow.

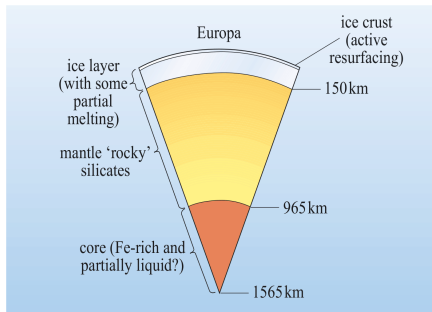


Figure 2.27 Schematic model for the internal structure of Europa.

[McBride and Gilmour, An Introduction to the Solar System, 2004]

Autres satellites de Jupiter

Ganymède



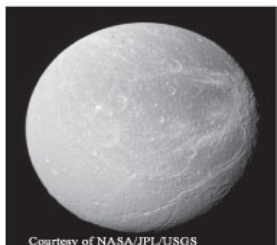
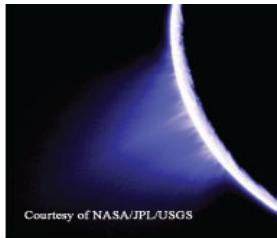
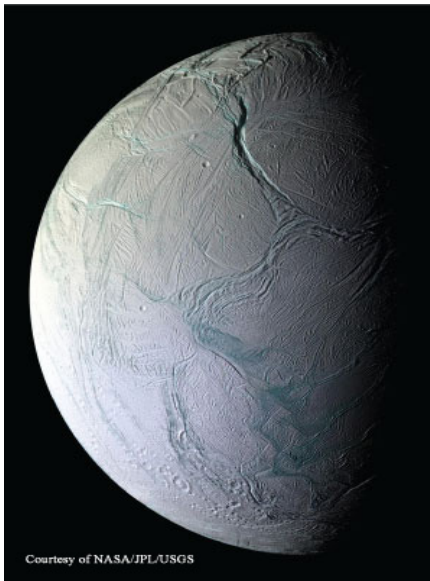
Courtesy of NASA

Callisto



Courtesy of NASA

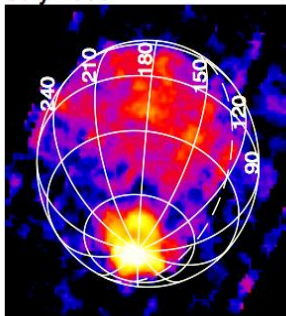
Cryo-volcanisme sur Encelade et Dione



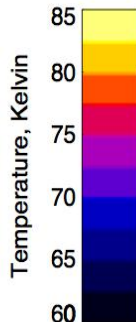
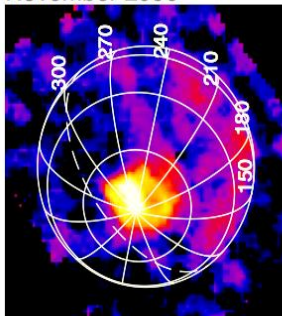
Tidal forcing on Enceladus' south pole

Surface temperature 15 K than expected

July 2005



November 2006



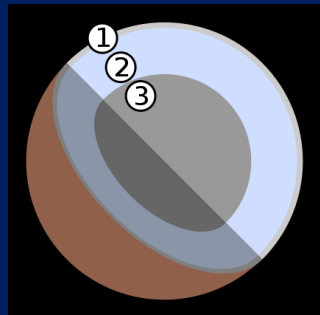
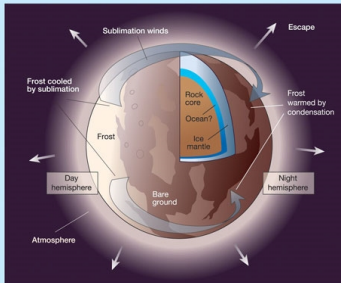
[Cassini Composite InfraRed Spectrometer map PIA09037]

Plan

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Pluton

Pluton possède une atmosphère très ténue (0,3 Pa au sol; $T=43\text{K}$) composée de N_2 et CH_4



Structure interne théorique de Pluton

1. Glace d'azote
2. Glace d'eau (+eau liquide ?)
3. Roche

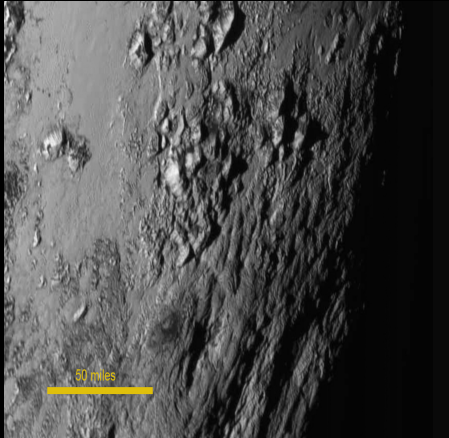
Survol de Pluton+Charon par New Horizons

14 juillet 2015

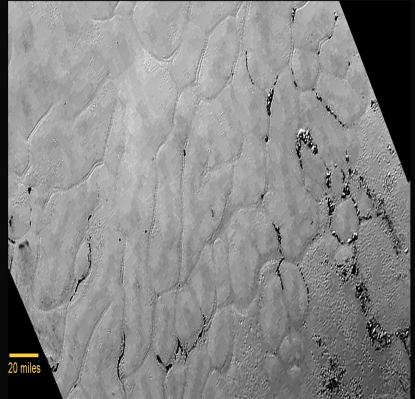


Au coeur de Tombaugh Regio

Montagnes glacées (H_2O)

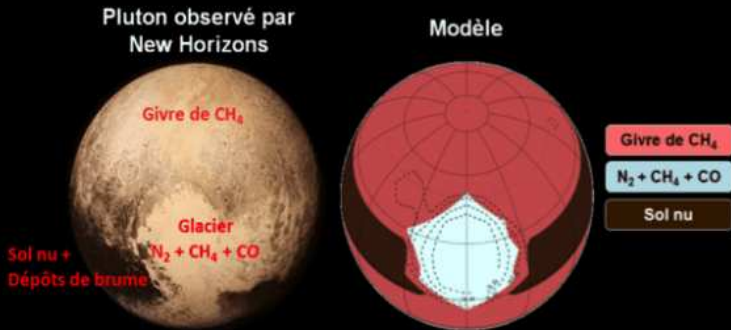


Glaciers Sputnik (N_2, CO)



[Images New Horizons]

Composition des glaces de Pluton



[Bertrand and Forget Nature 2016]

Distant Horizons - Different Surfaces

Comet 67P/C-G



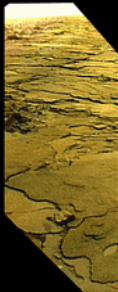
Asteroid Itokawa



Moon



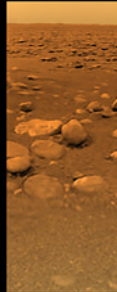
Venus



Mars



Titan



Earth



Image Credits:

Comet 67P/C-G [Rosetta/Philae]: ESA / Rosetta / Philae / CIVA / Michiel Straathof

Asteroid Itokawa [Hayabusa]: ISAS / JAXA / Gordan Ugarkovic

Moon [Apollo 17]: NASA

Venus [Venera 14]: IKI / Don Mitchell / Ted Stryk / Mike Malaska

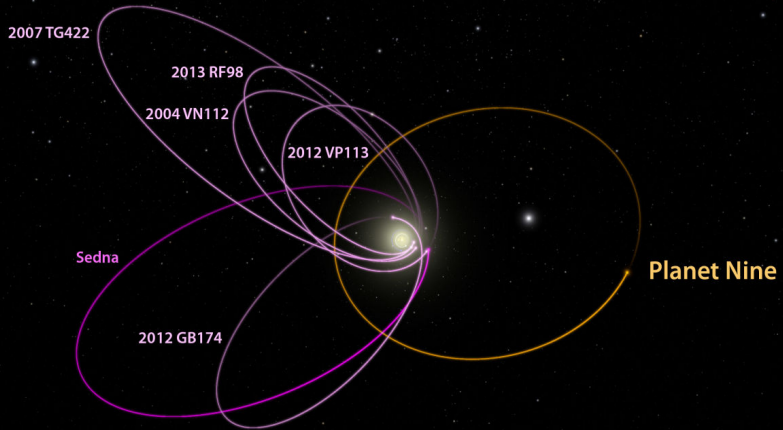
Mars [Mars Exploration Rover Spirit]: NASA / JPL / Cornell / Mike Malaska

Titan [Cassini Huygens]: ESA / NASA / JPL / University of Arizona

Earth: Mike Malaska

Composition by Mike Malaska
updated by Michiel Straathof

Planet Nine?



[Adapted from Batygin and Brown The Astronomical Journal 2016, Arxiv 1601.05438]