Planétologie: atmosphère, surface, habitabilité

UE M1 Grandes Questions Environnementales

Aymeric SPIGA

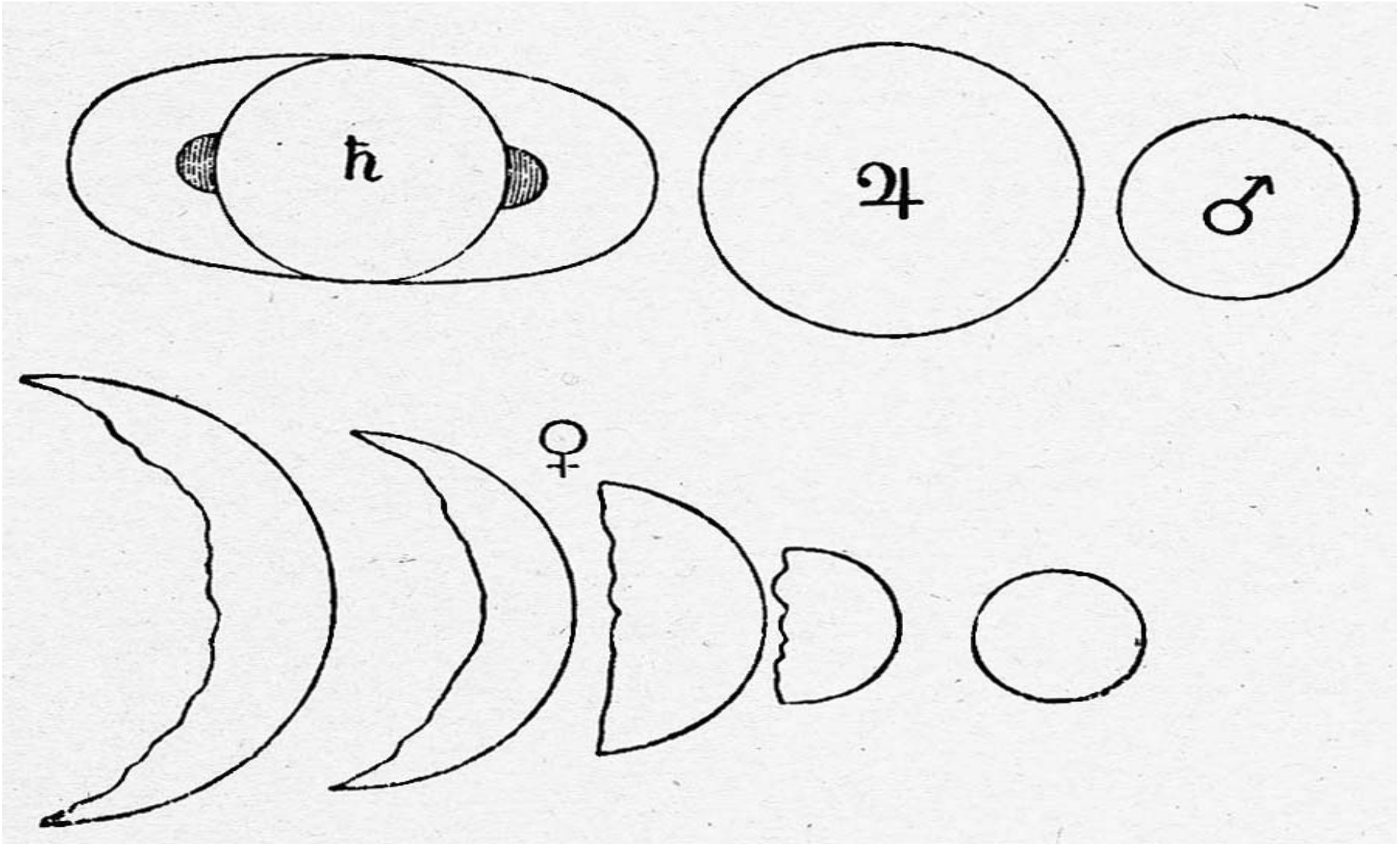
21 octobre 2022

Cours magistral 1 : Une exploration phénoménologique

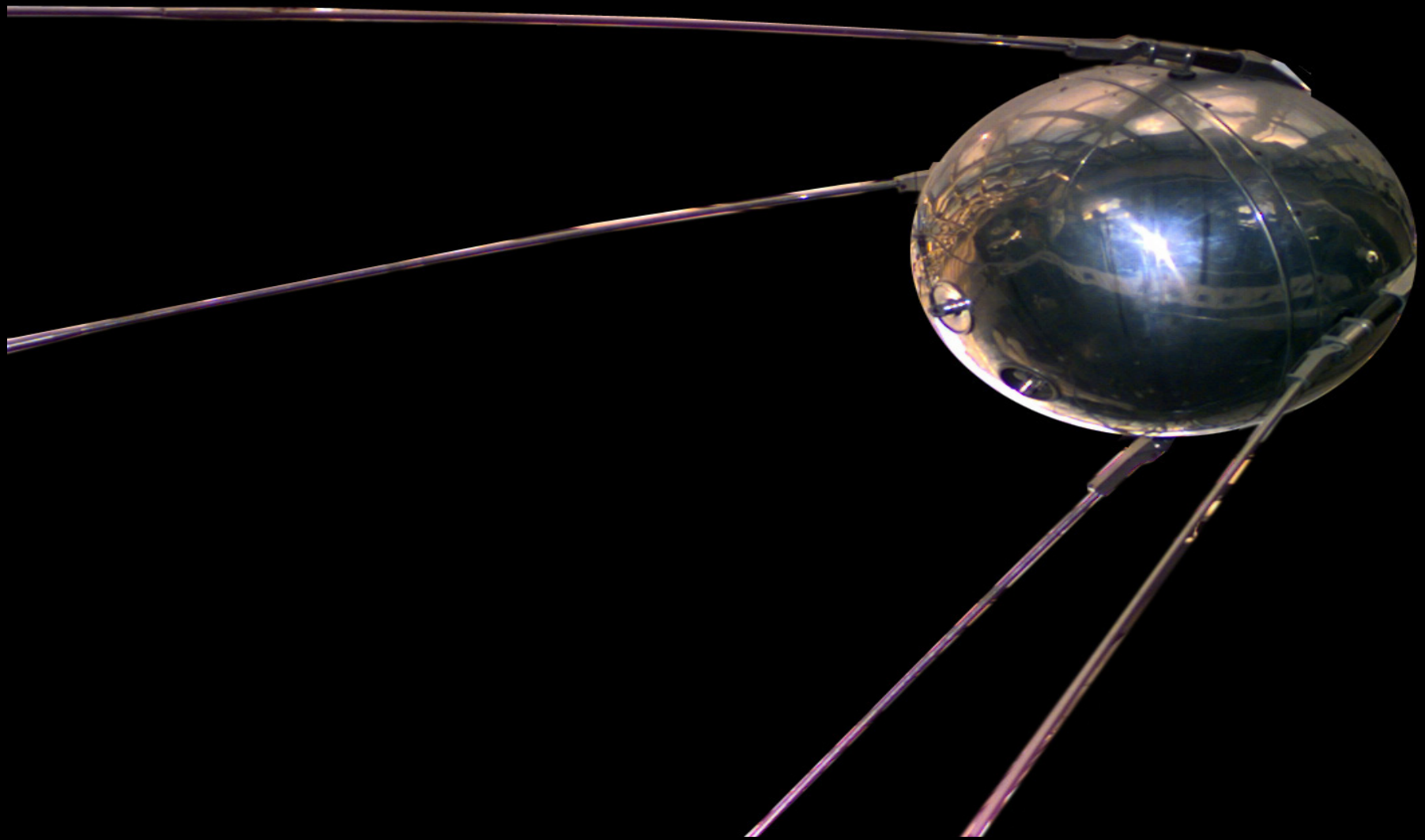
Plan

Les planètes vues par Galilée

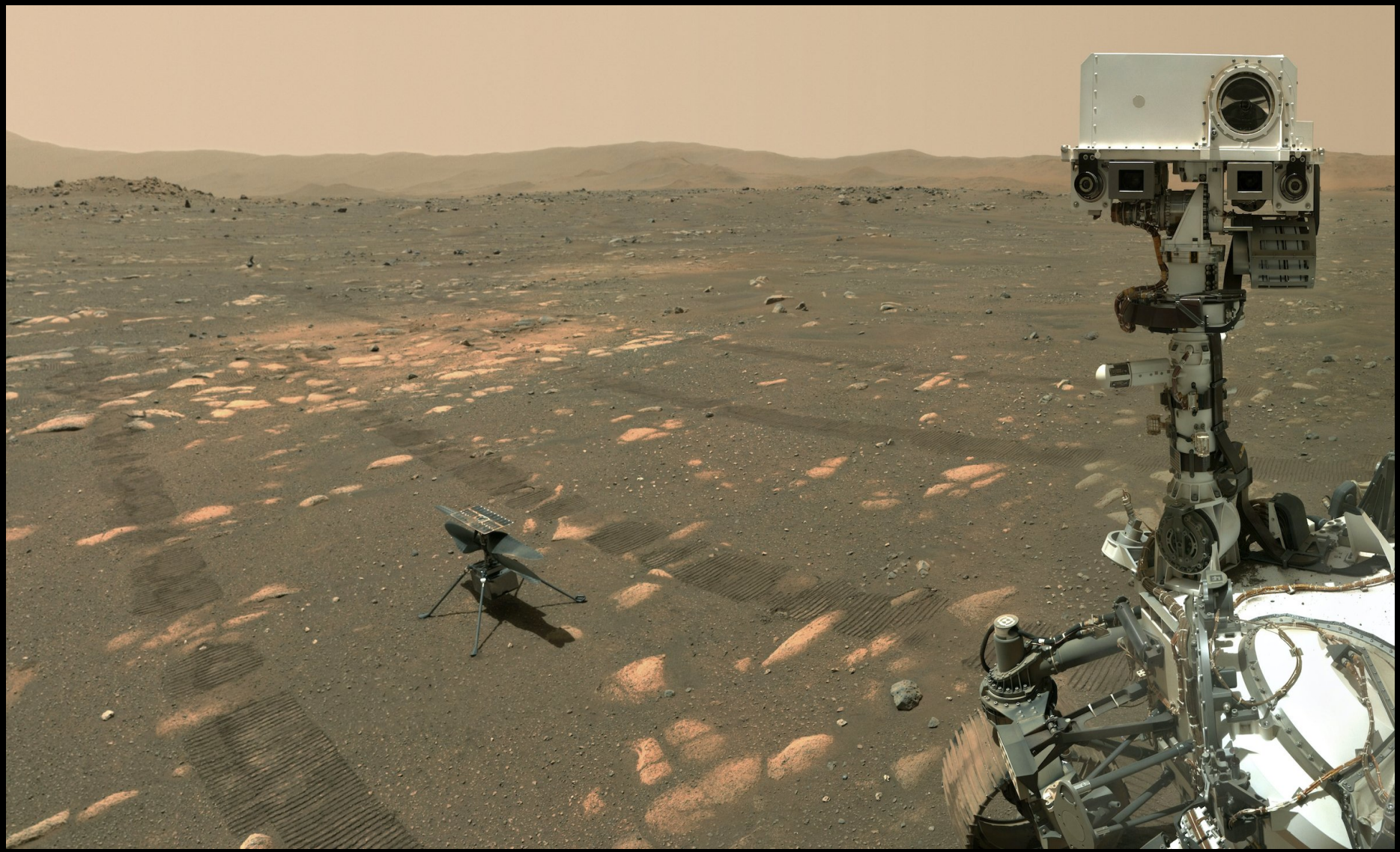
Tiré du Saggiatore 1623 (premières observations 1610)



Sputnik 1957 : début de l'exploration spatiale

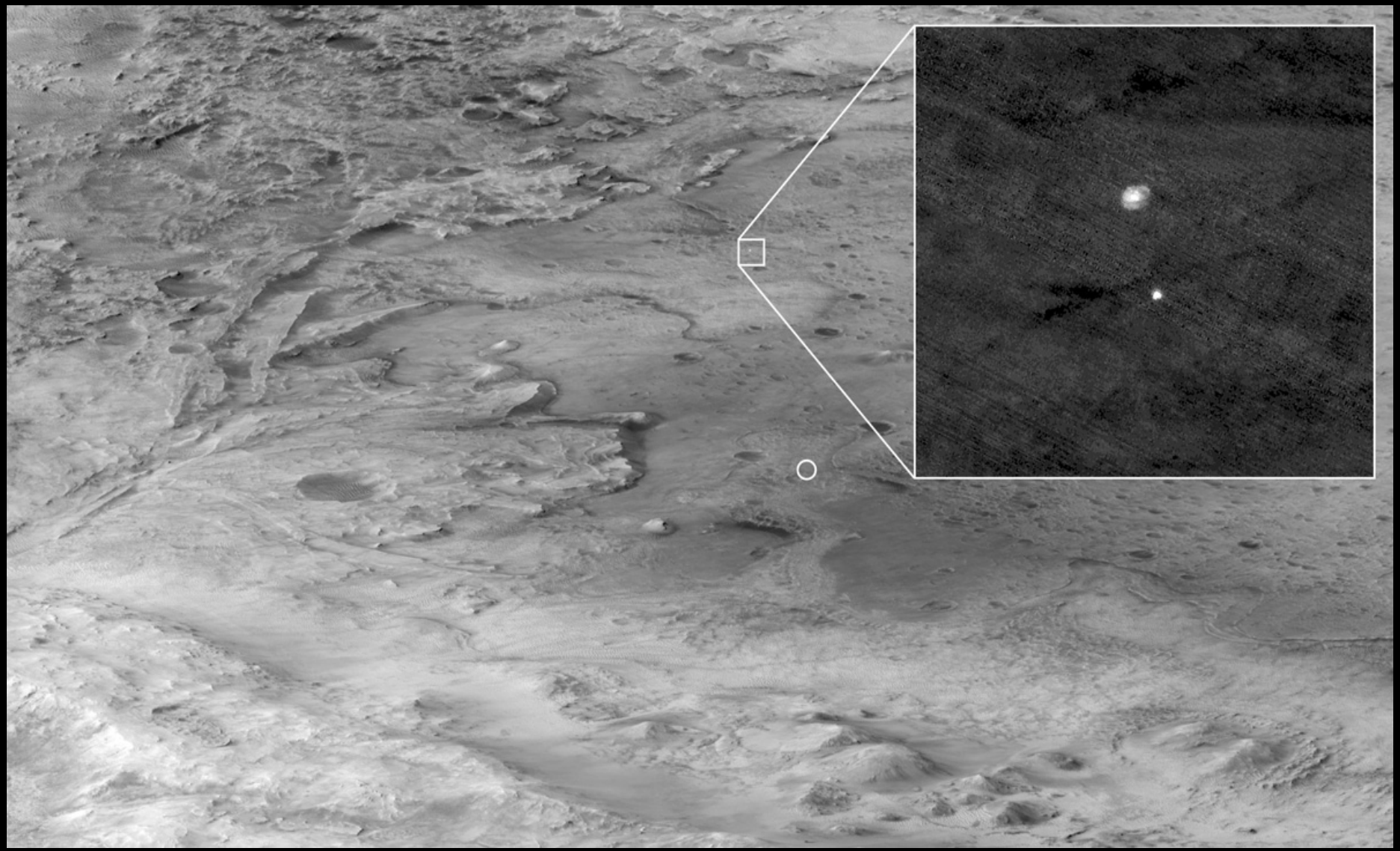


Ingenuity à la surface avec Perseverance (2021)



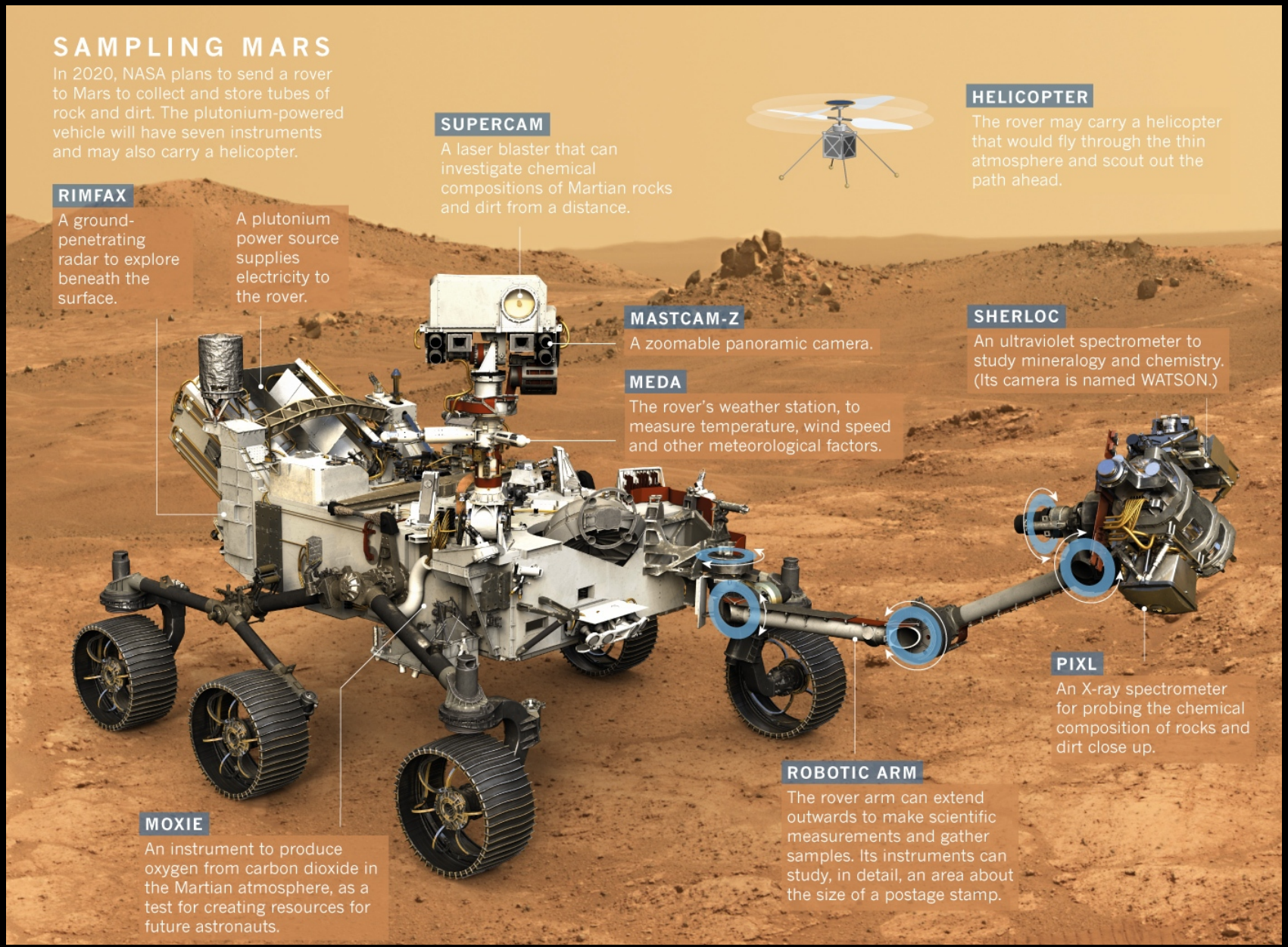
[NASA/JPL/Caltech/ASU]

HiRISE image of Perseverance landing

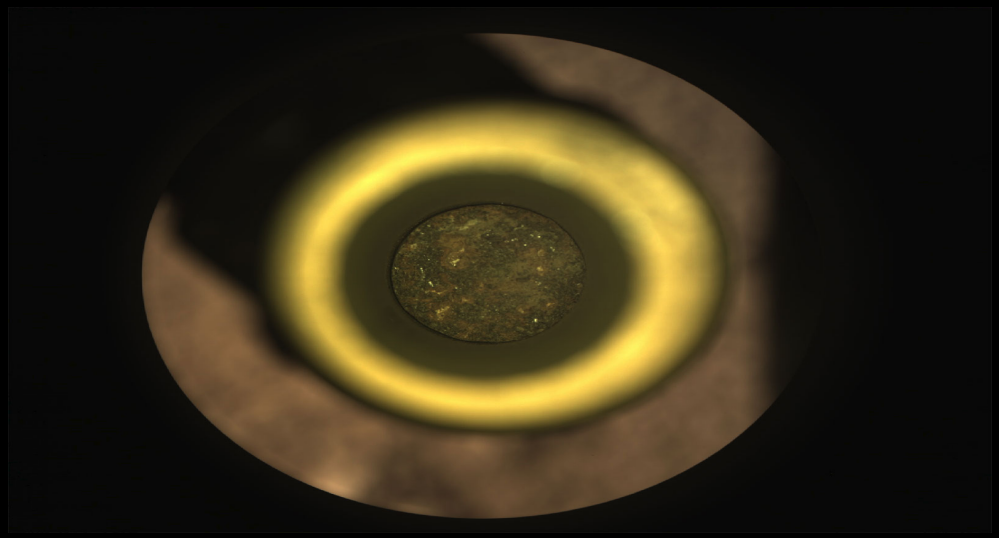


[PIA 24270, NASA/JPL-Caltech/University of Arizona]

Mars 2020 NASA mission

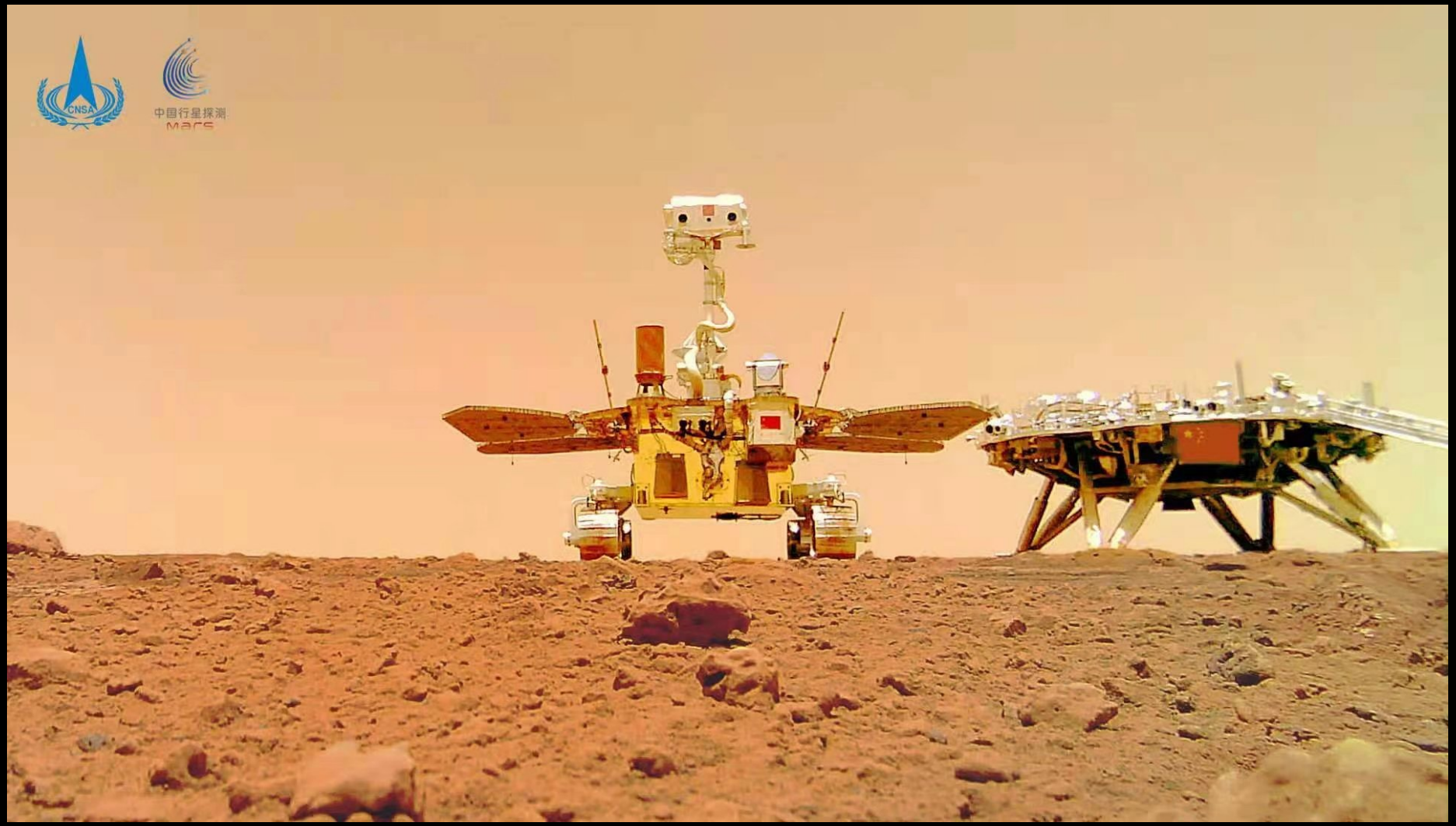


First cored sample of Mars rock by Perseverance

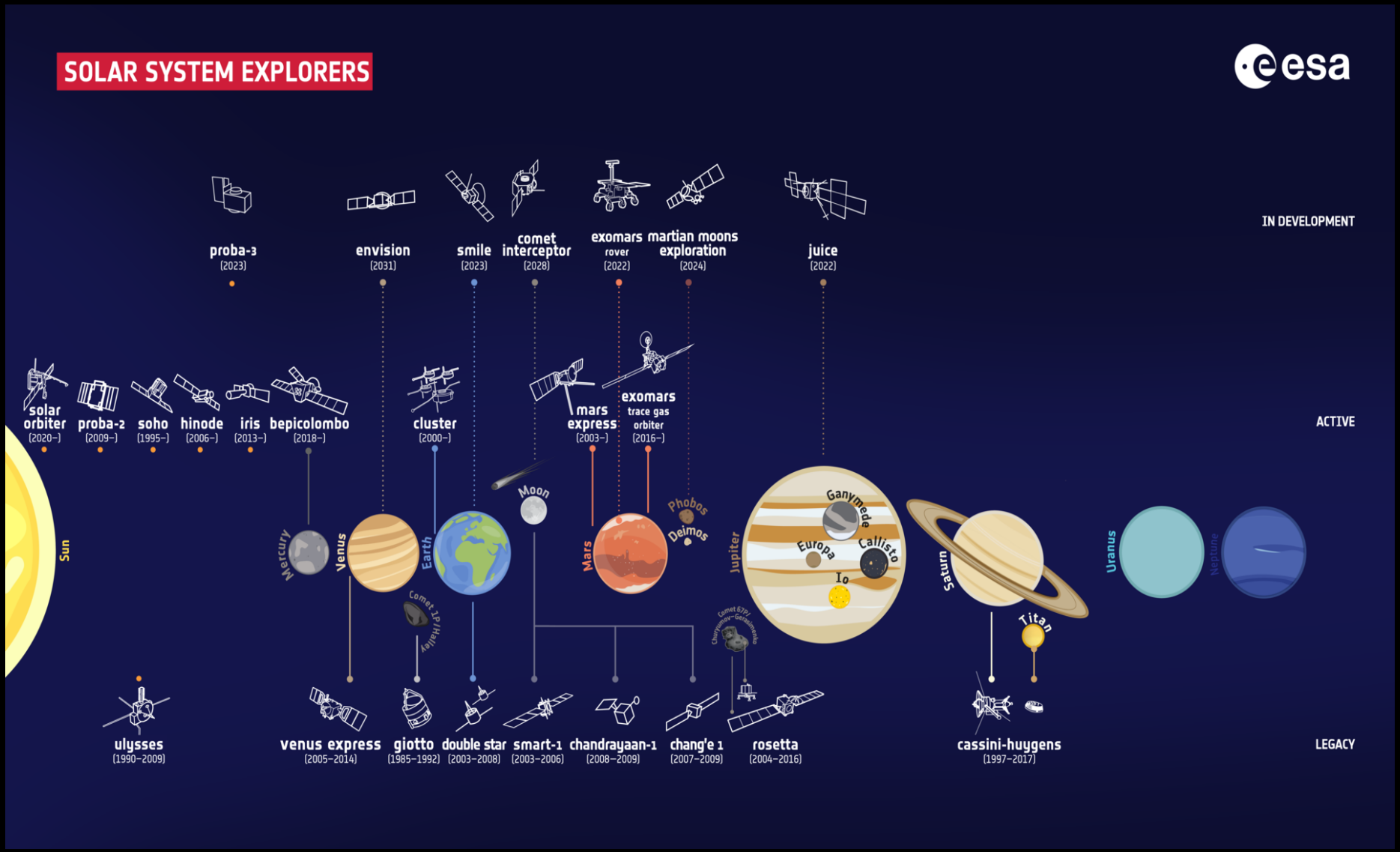


[Images sol 194 [Fall 2021]. PIA 24805 24806 24808. Credits : NASA/JPL-Caltech]

Zhurong, the first Chinese rover on Mars (2021)



ESA missions in the Solar system



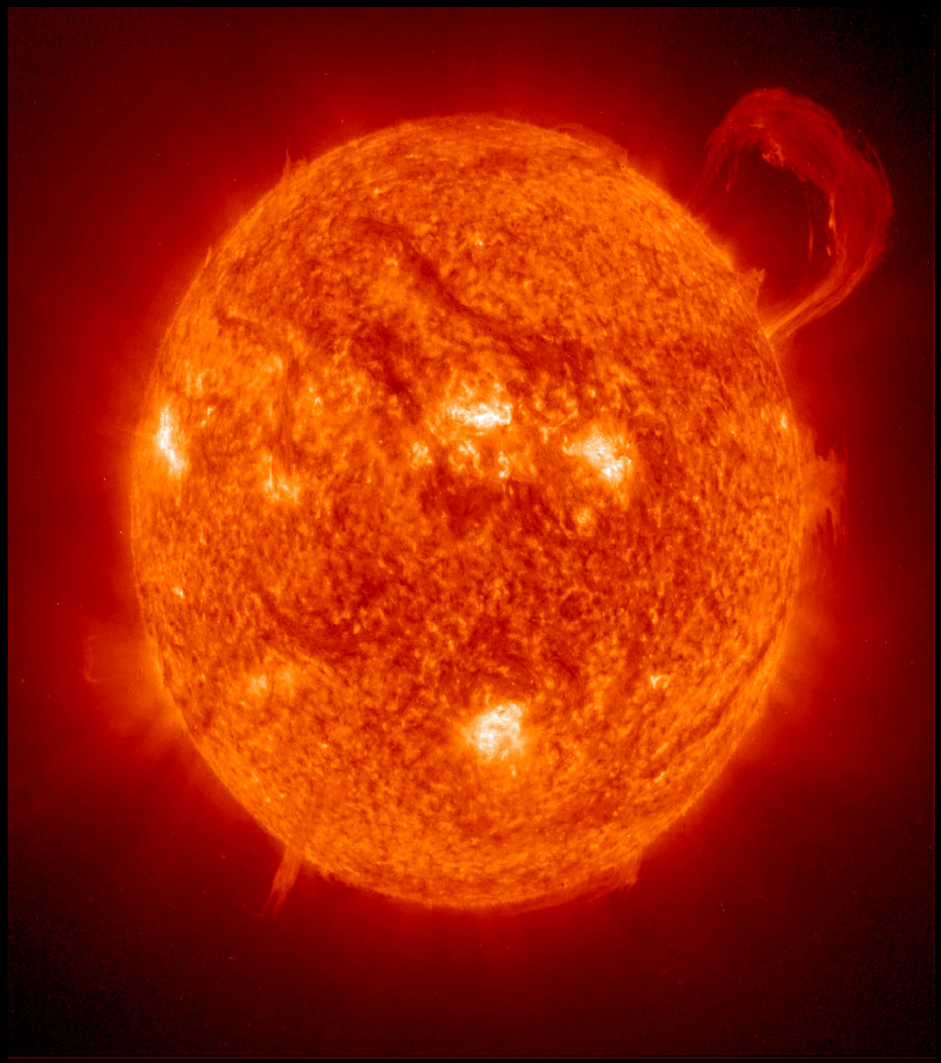
[Updated on June 2021]

Plan

Notre étoile : le Soleil

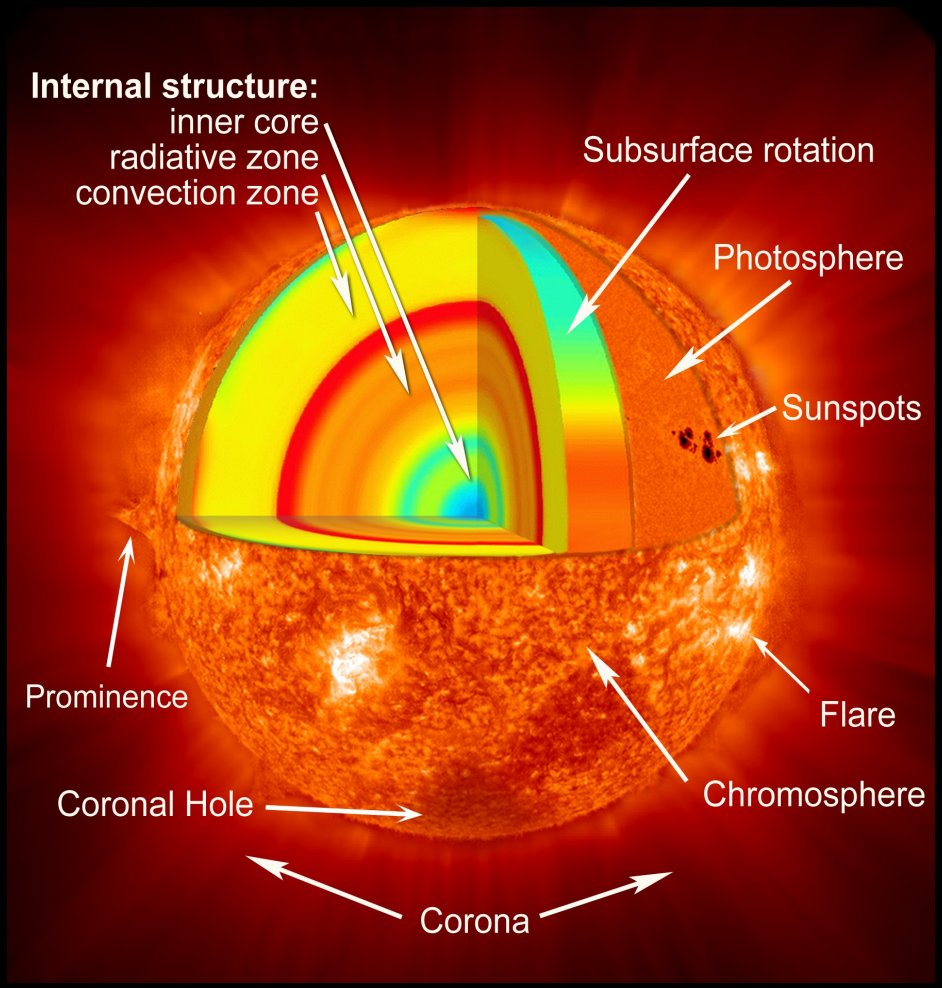
vue par SOHO (en XUV) $\lambda = 30.4$ nm, haute chromosphère $T = 60.000$ K

- ☞ 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, 14 sept 1999]

Structure du Soleil

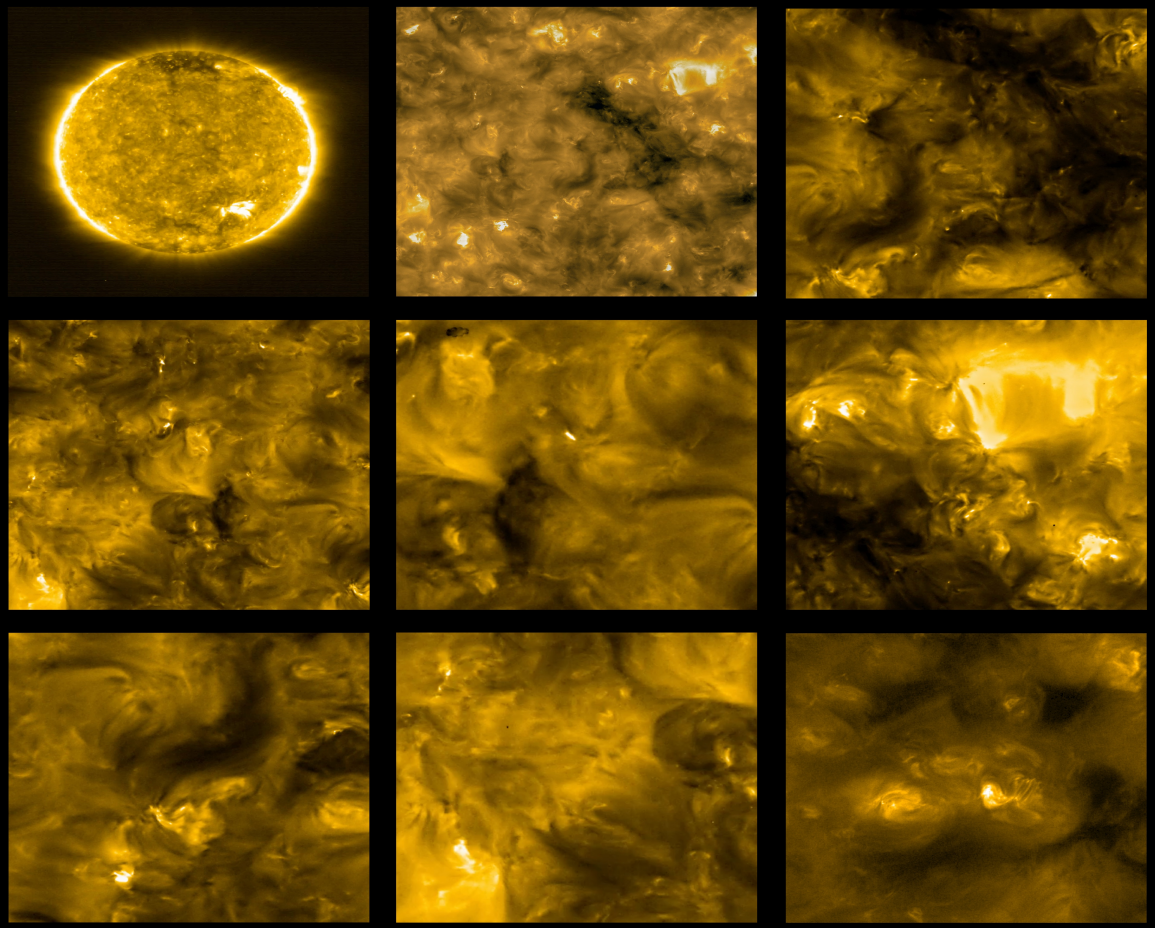


[SOHO mission https://sohowww.nascom.nasa.gov/gallery/images/eit006.html]

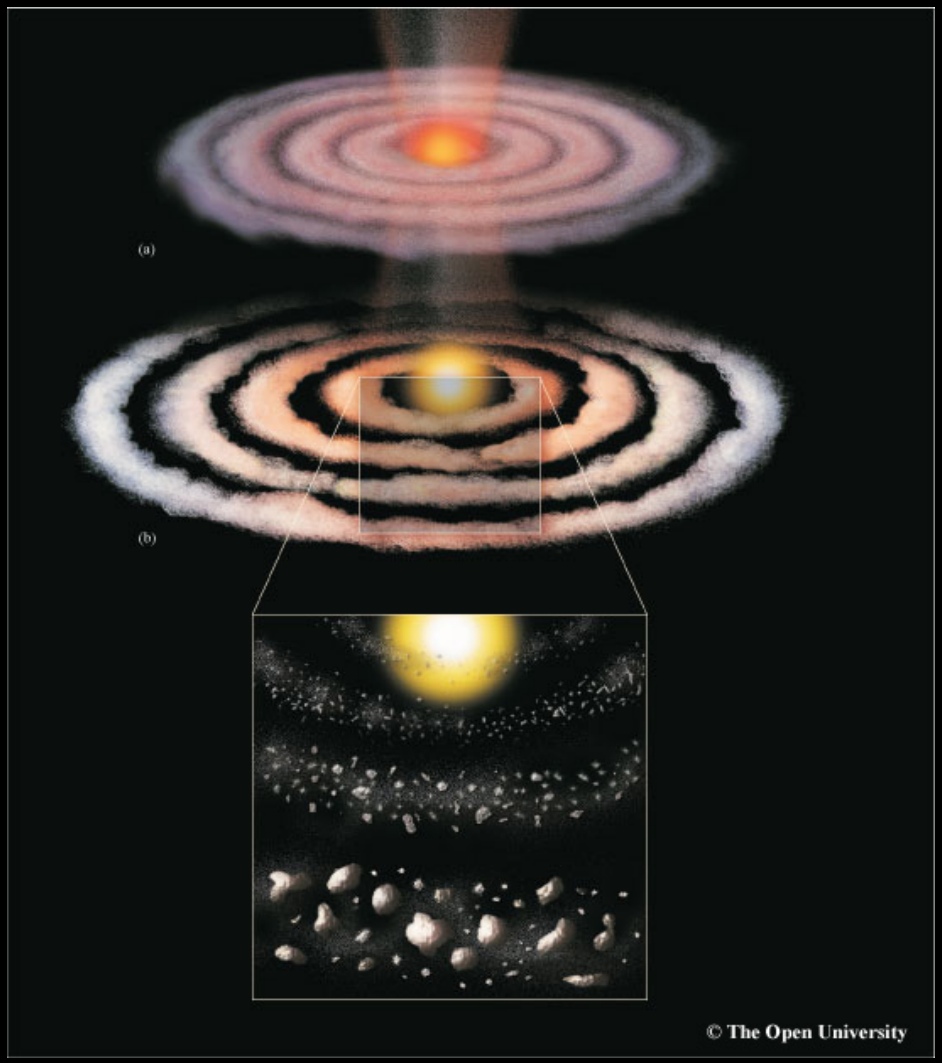
- ☞ Structure interne : variation de $c_{\rm son}$ sondé par mesures héliosismiques. Coeur (bleu) à 15 millions K.
- ☞ Rotation différentielle : rouge=rapide, bleu=lent.
- ☞ Couche des tâches solaires : photosphère, vue en visible ($T = 6.000$ K).
- ☞ Couche externe : chromosphère, vue en XUV ($T = 60.000$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

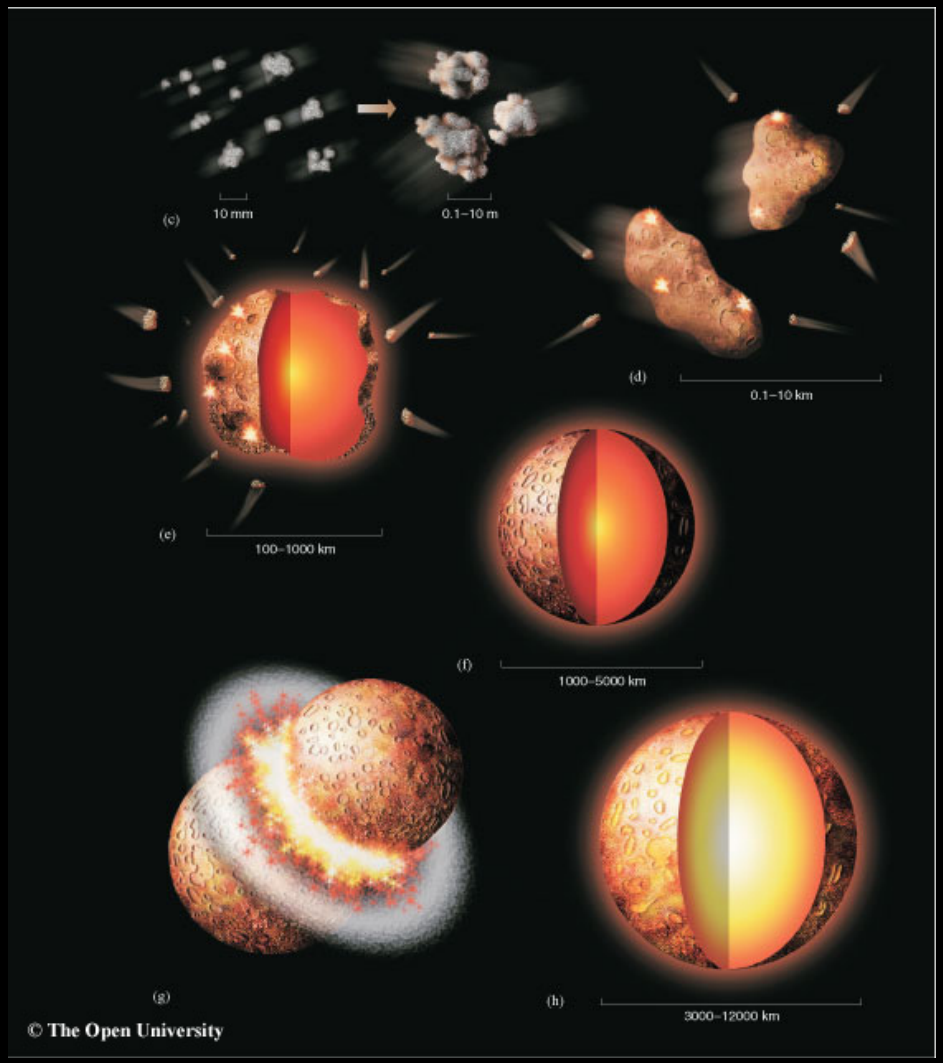
ESA Solar Orbiter mission

Taking the closest ever images of the Sun, observing the solar wind and the Sun's polar regions like never before, unravelling the mysteries of the solar cycle



The formation of planets



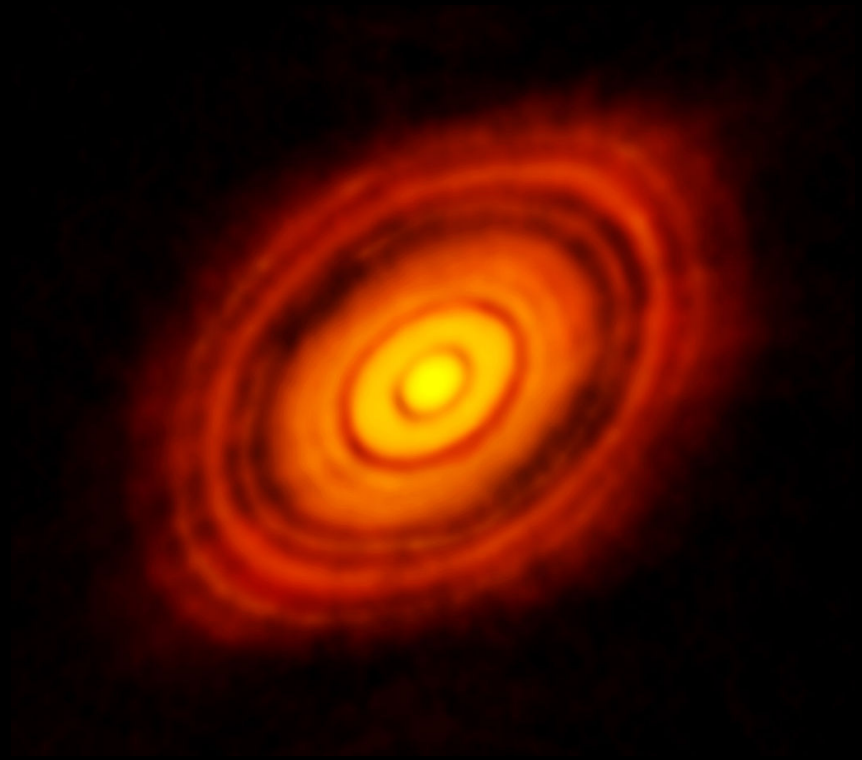


[McBride and Gilmour, An Introduction to the Solar System, 2004]

Young stars and protoplanetary discs

Atacama Large Millimeter Array (ALMA interferometer) image

HL Tauri



Elias 2-27

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)

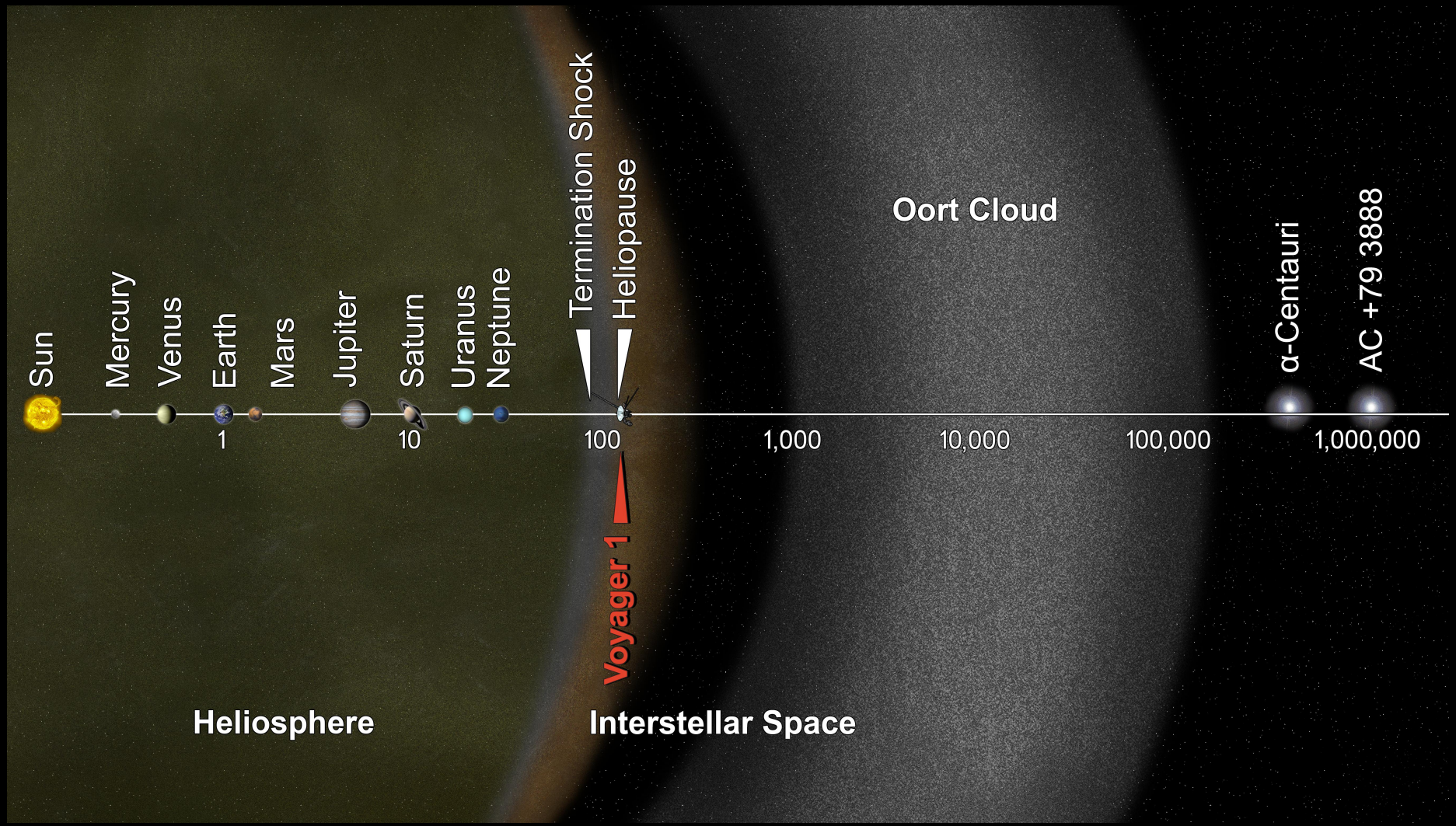
Planète naine

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)

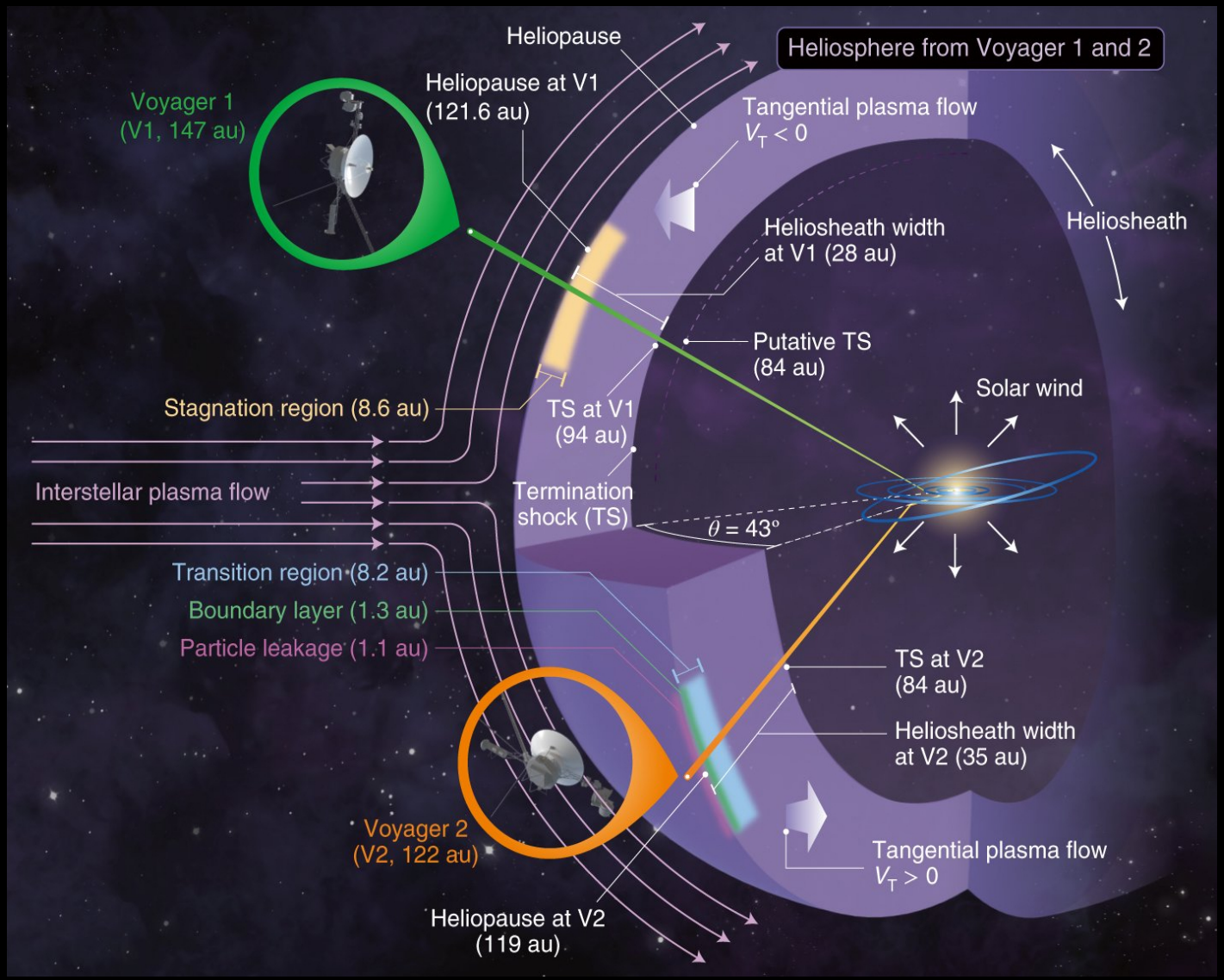
Les échelles du système solaire (et au-delà)

Échelle logarithmique. 1 UA = 150 millions de kilomètres.



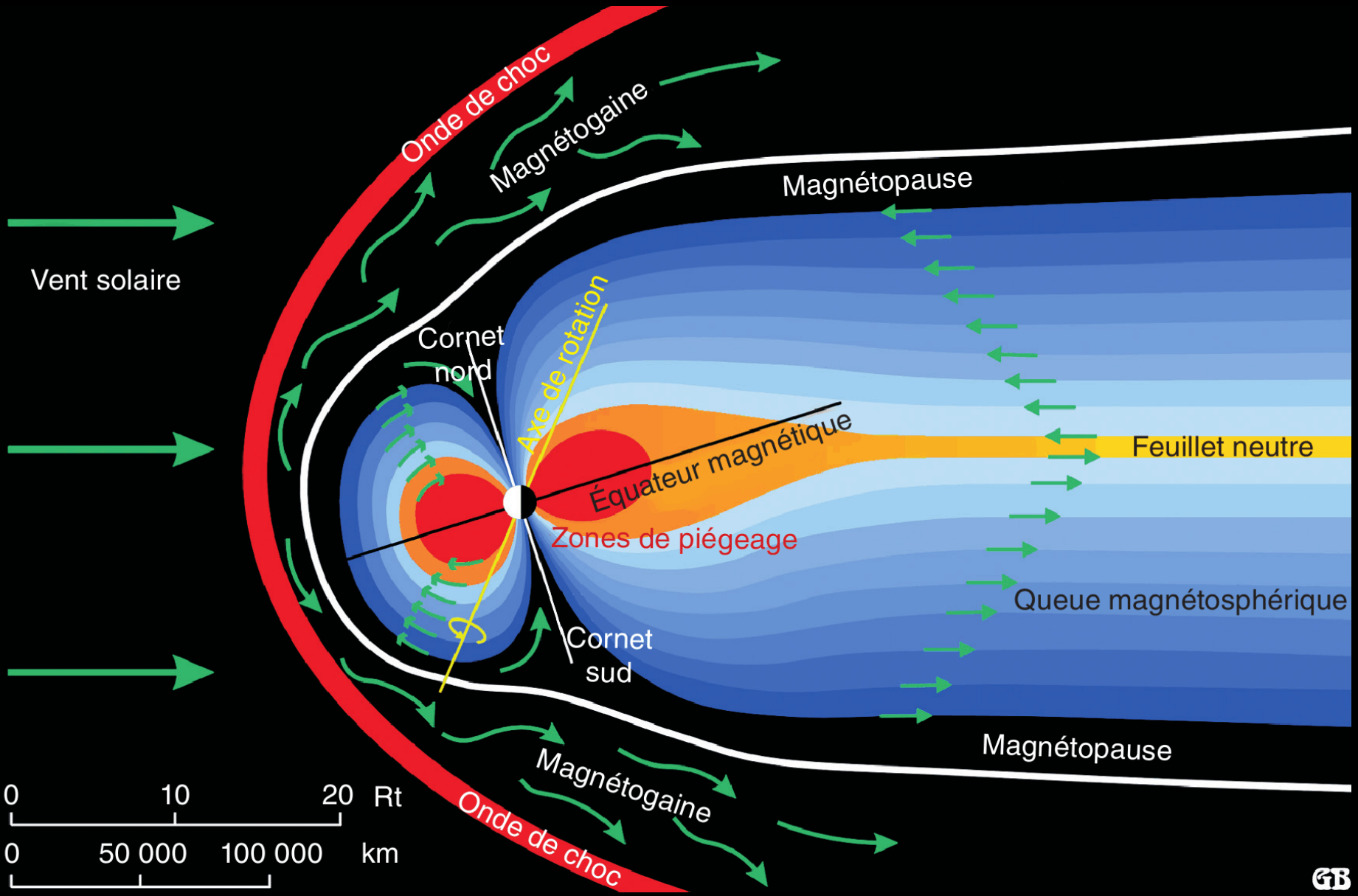
[PIA17046. Artist impression, credits NASA/JPL-Caltech.]

Voyager 1&2 probes status in November 2019



[Illustration from the Science special issue 2019]

Environnement ionisé de la Terre et flux de matière

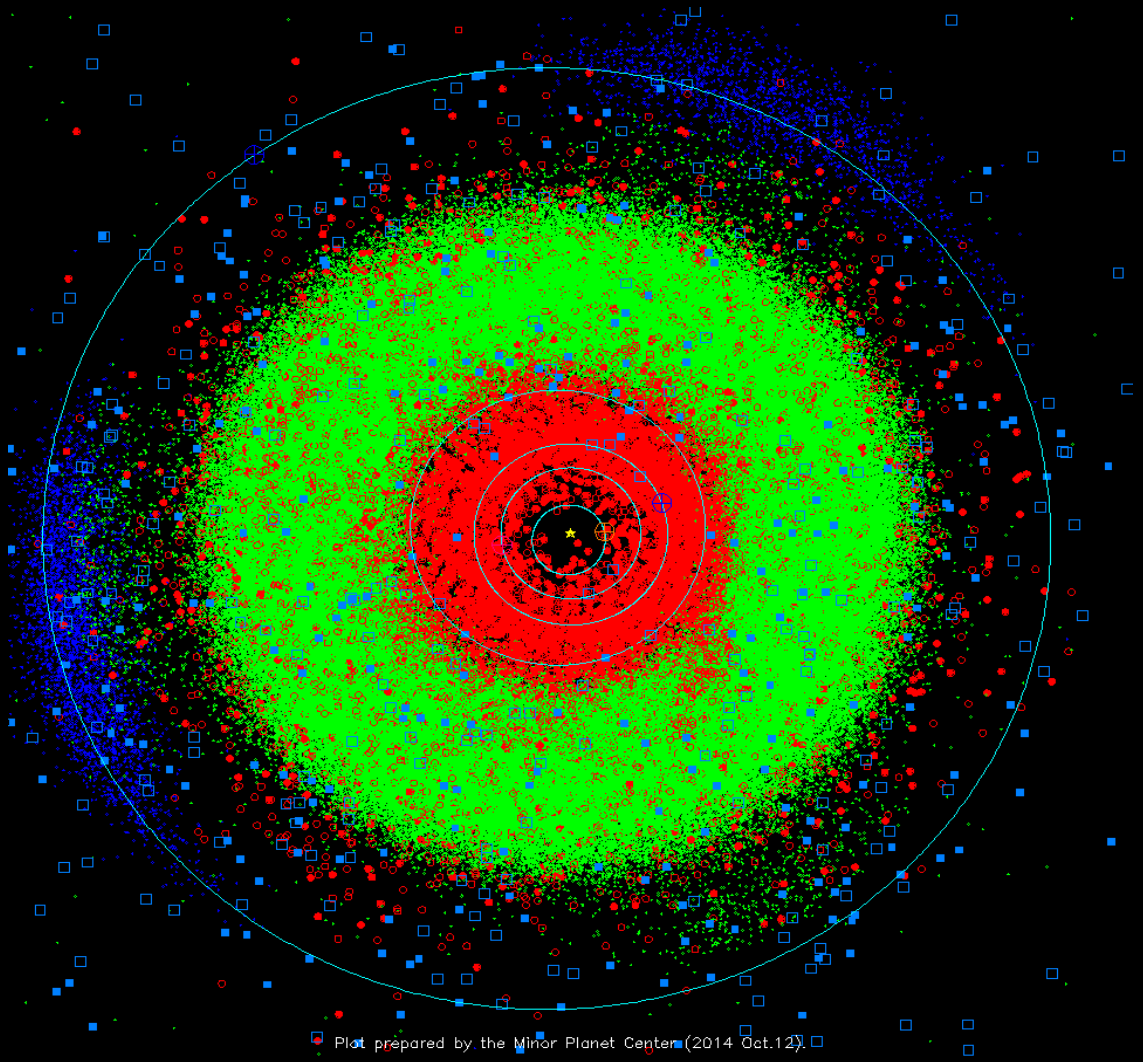


[J. Lilensten et T. Dudok de Wit *in* Le Climat à Découvert, CNRS éditions, 2011]

Plan

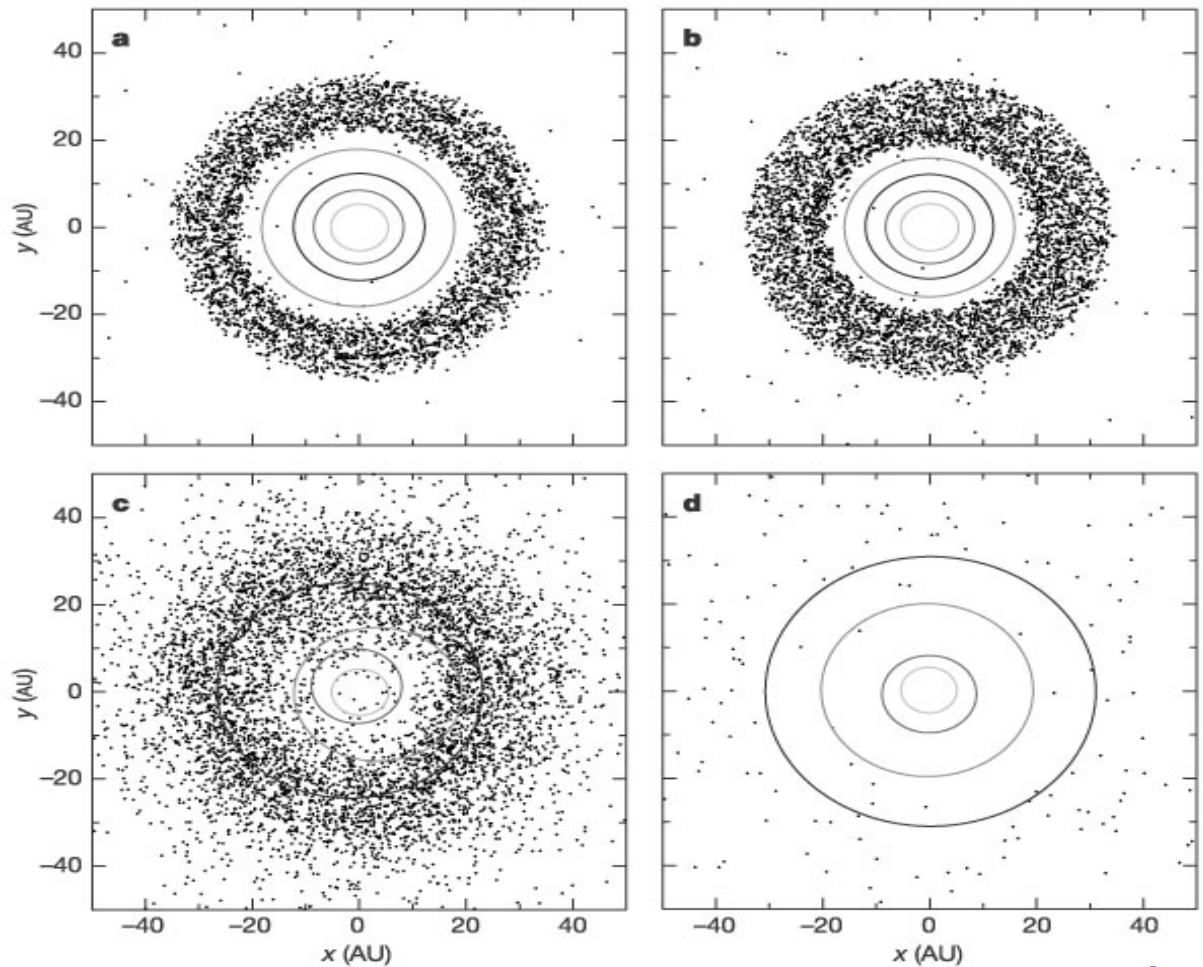
Astéroïdes

Ceinture principale et Troyens joviens



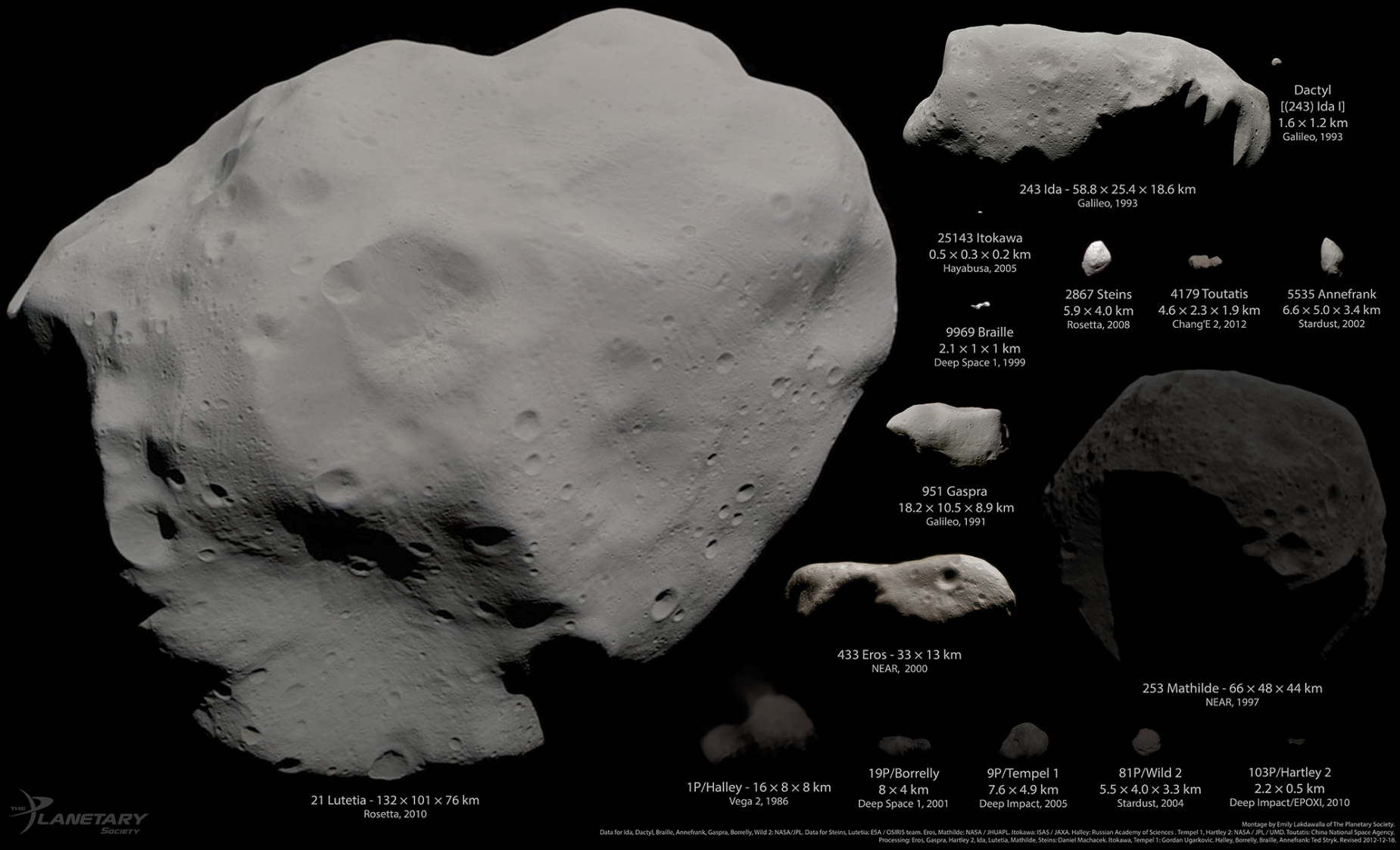
Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets

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



[Gomes et al. Nature 2005]

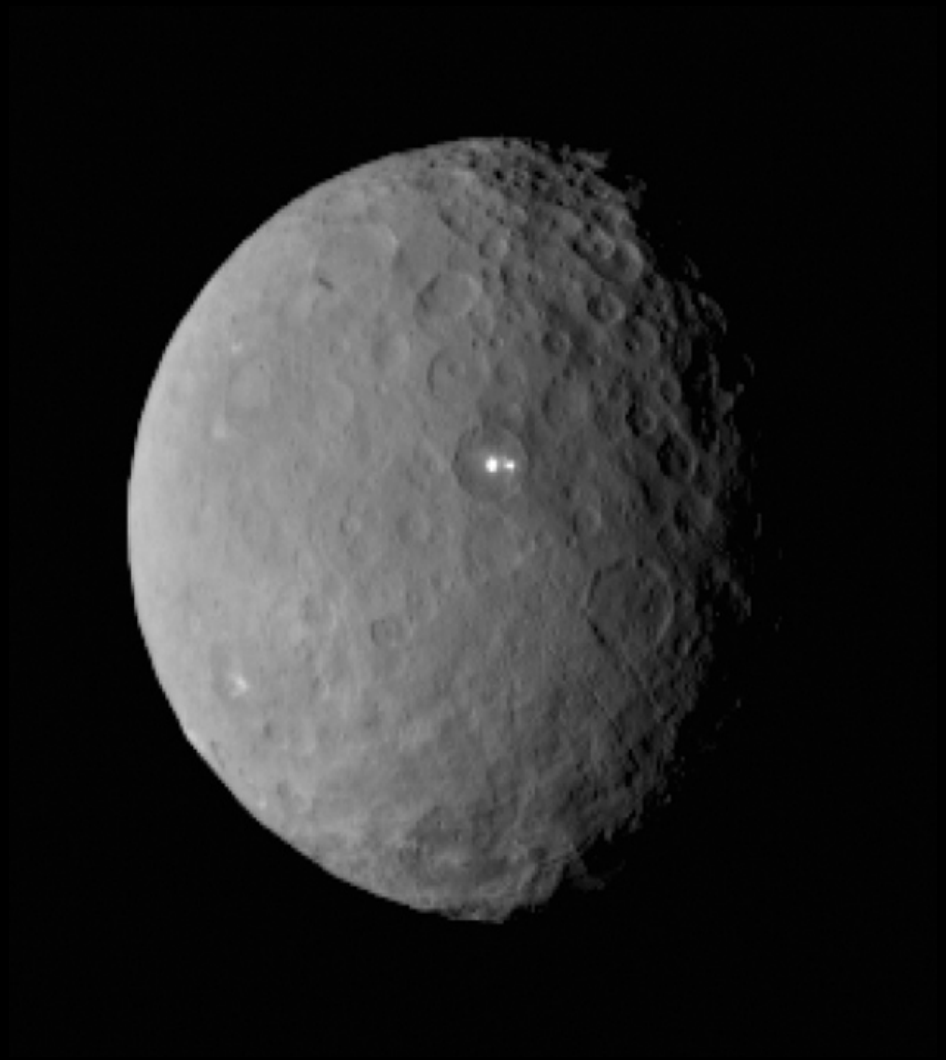
Astéroïdes visités par sondes spatiales hors Vesta et Cérès



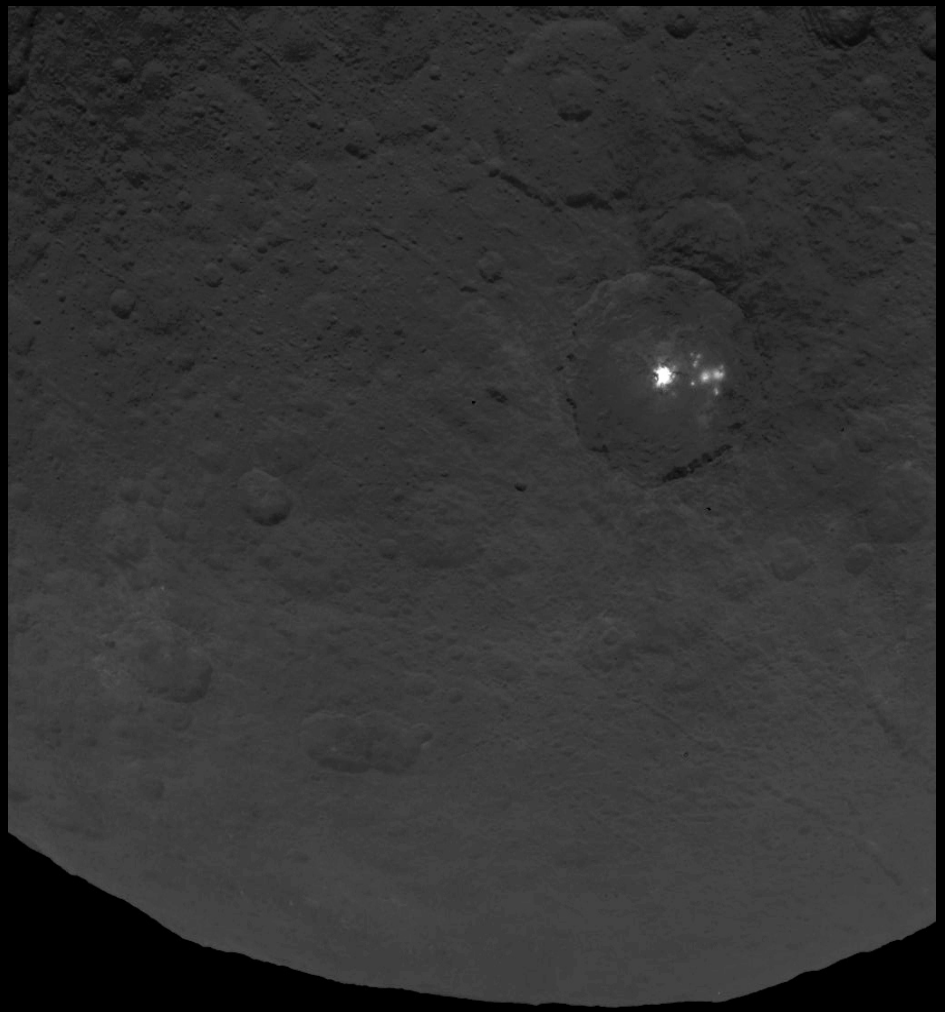
[E. Lakdawalla (2012)]

Ceres' bright spots observed by Dawn

February 19th, 2015



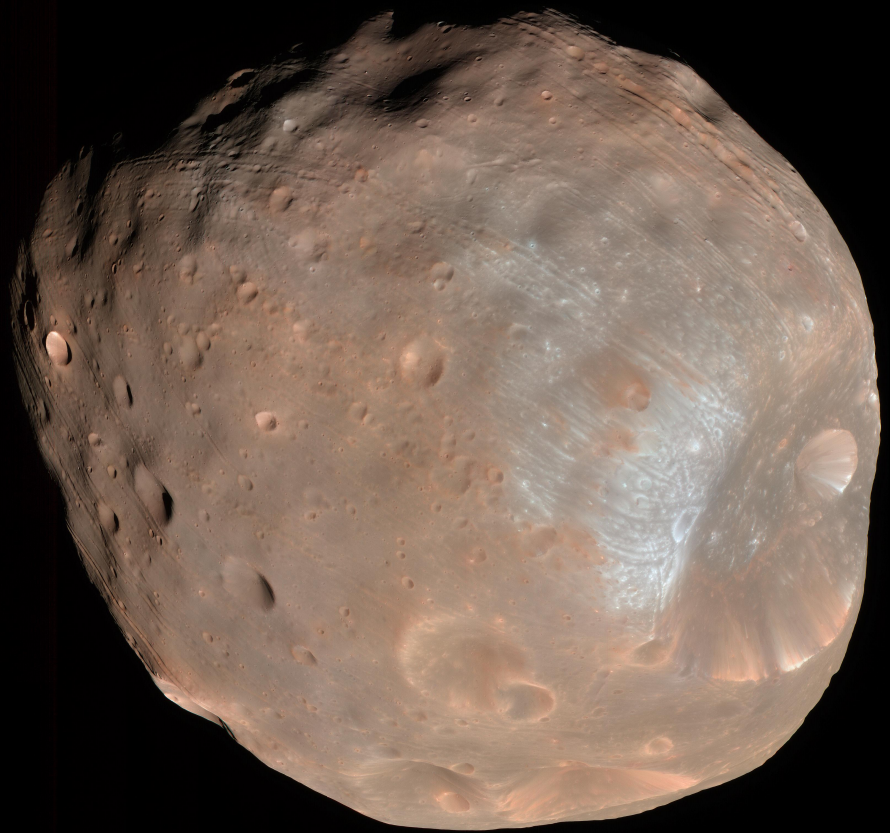
June 9th, 2015



Satellites de Mars

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

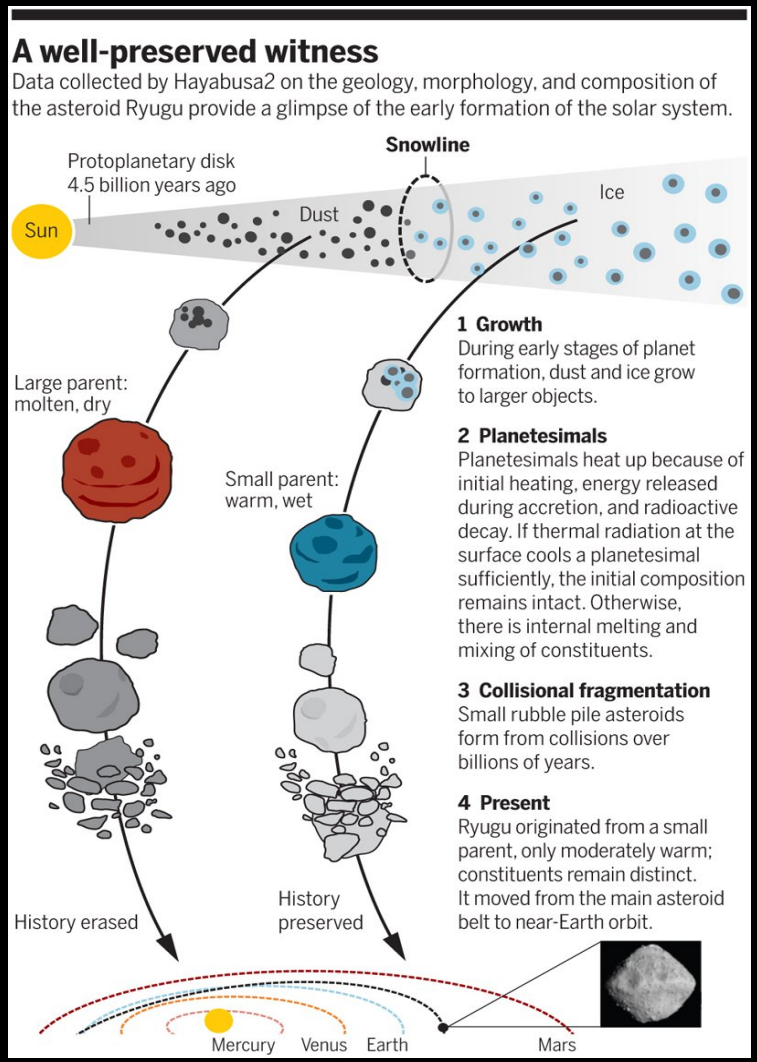
Phobos (d=21 km)



Deimos (d=12 km)

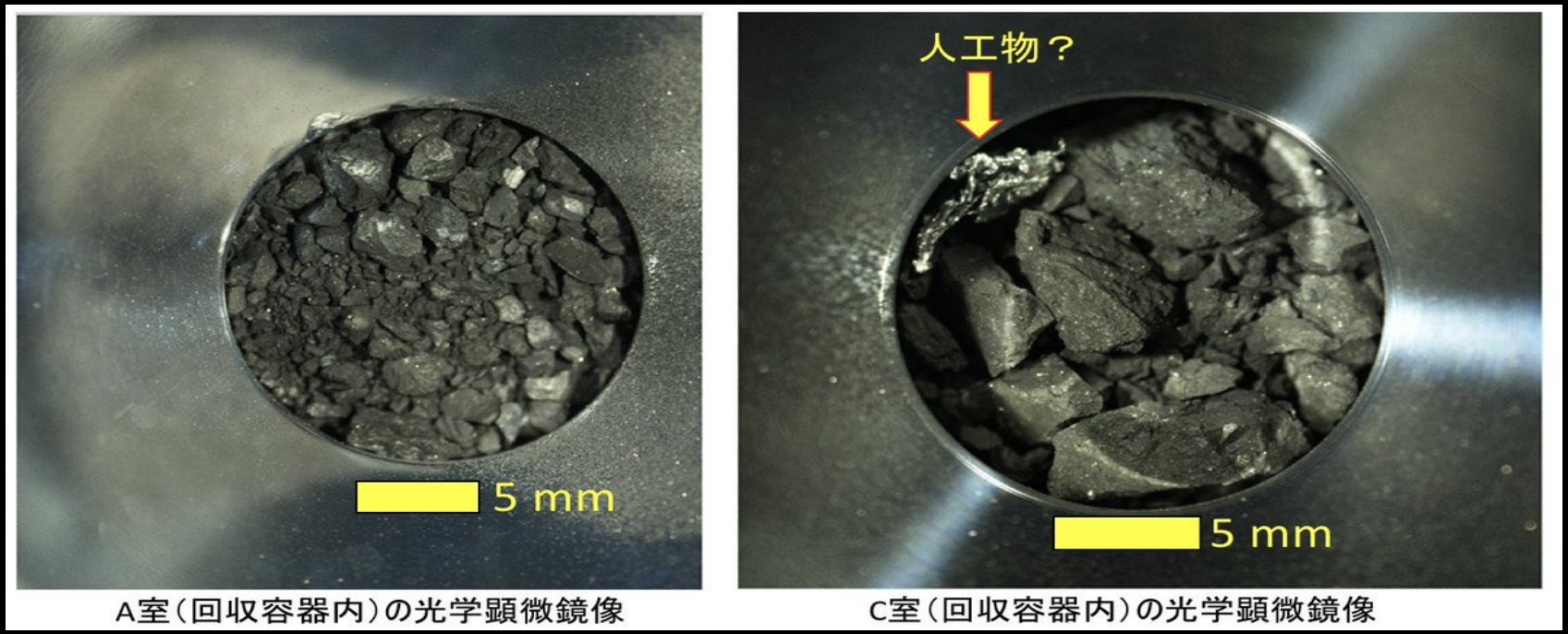
Ryugu astéroïde de classe C visité par Hayabusa 2

[JAXA / University of Tokyo]



[Infography from Science journal]

Ryugu sample captured by Hayabusa 2



[Credits JAXA December 2020]

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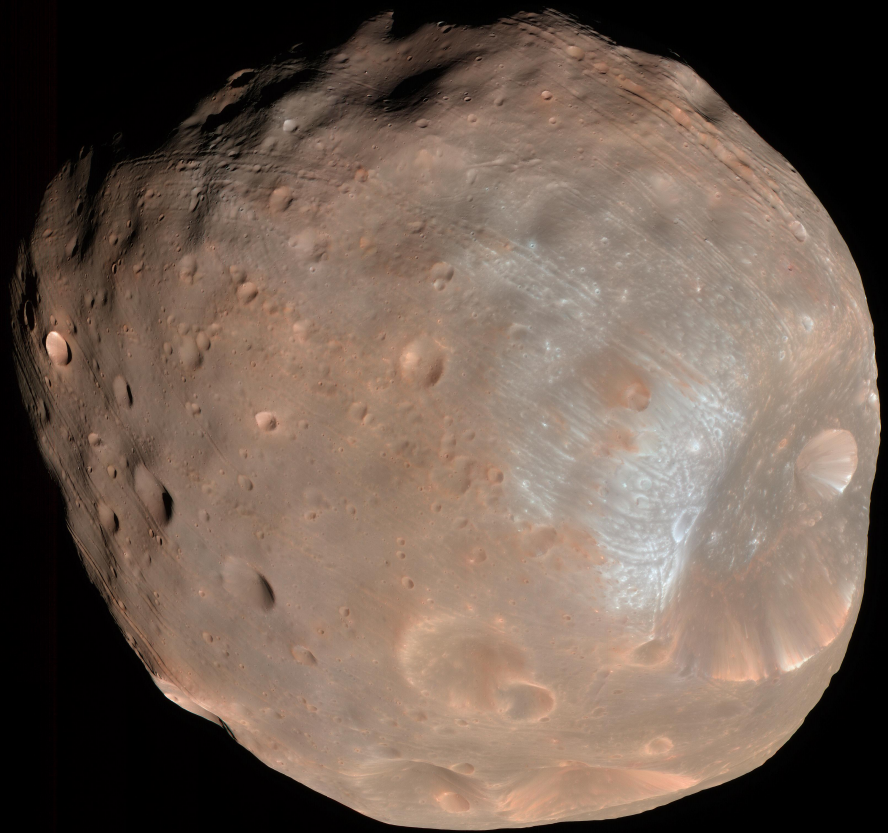


Deimos (d=12 km)

Comète de Halley et tapisserie de Bayeux en 1066

Invasion de l'Angleterre par Guillaume Le Conquérant

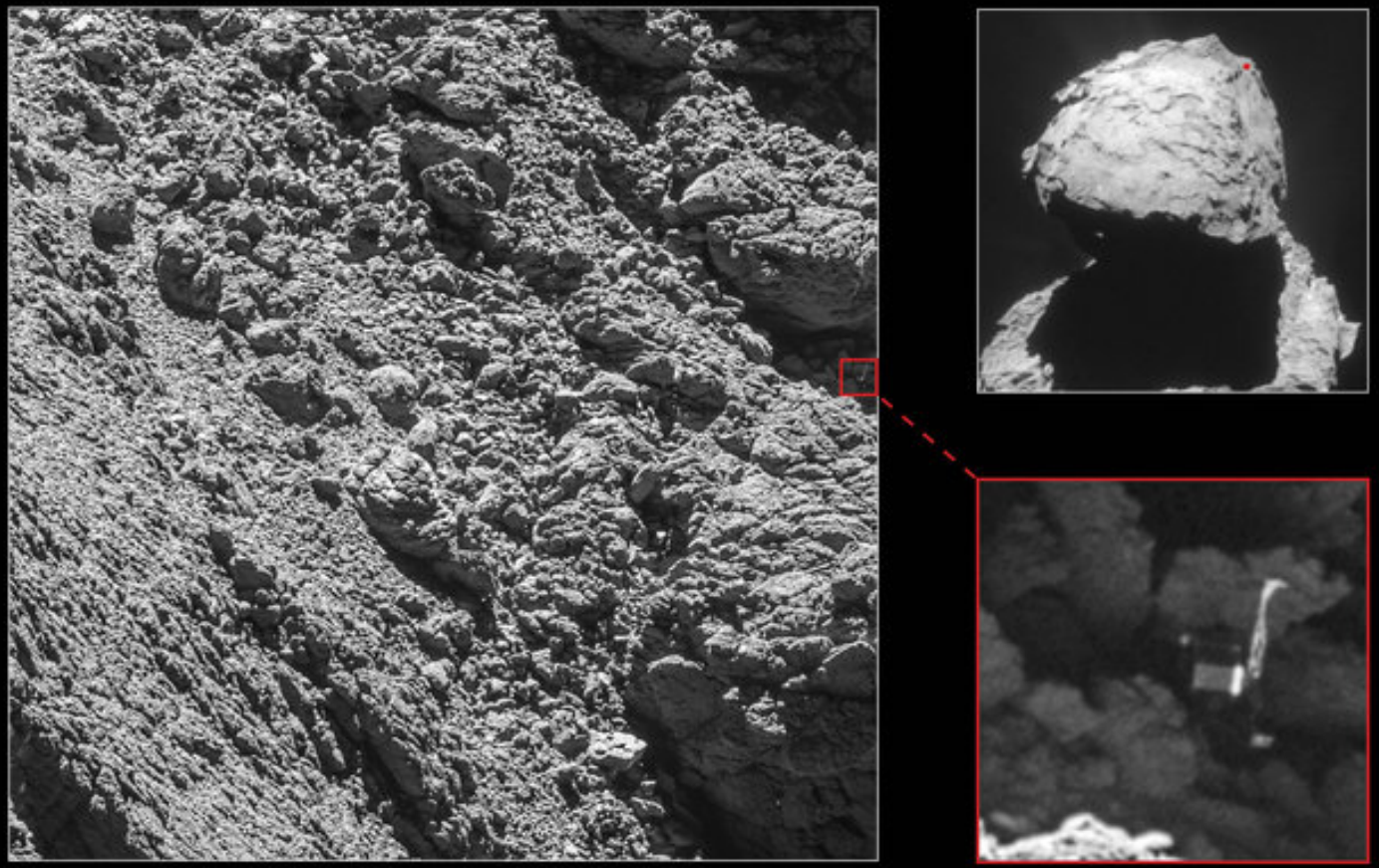
[in Pater et Lissauer, Planetary Sciences, 2010 after Beatty et al. 1999]

Rosetta in front of 67P-Churyumov-Gerassimenko

Image by CIVA on board Philae on board Rosetta !

2 months of 67P-Churyumov-Gerassimenko

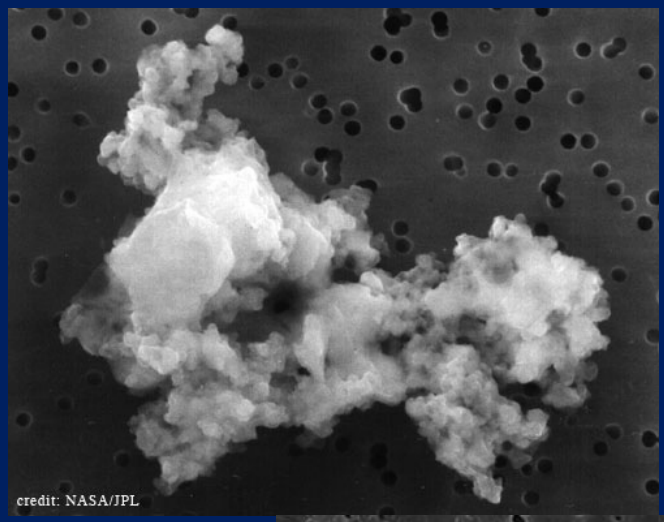
Philae found ! (Sep 2th, 2016)

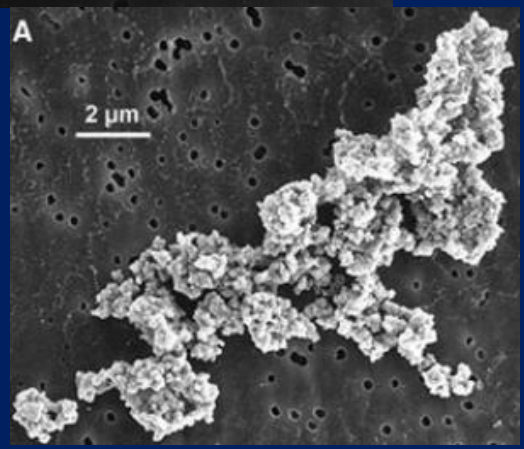


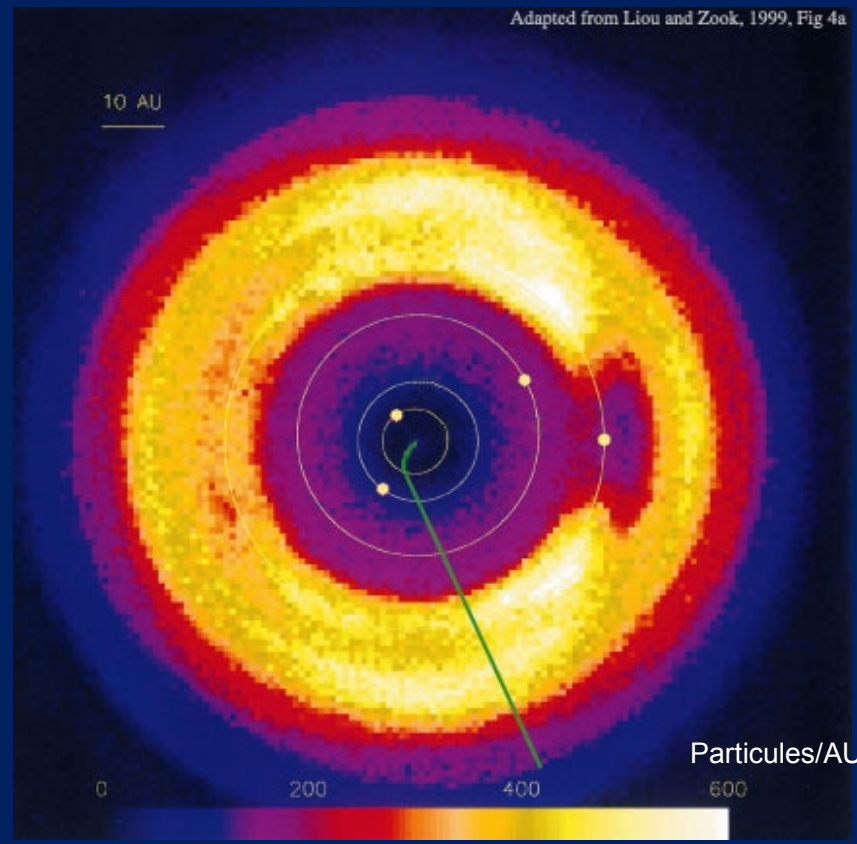
[OSIRIS narrow-angle camera, 5cm/pixel, ESA/Rosetta]

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





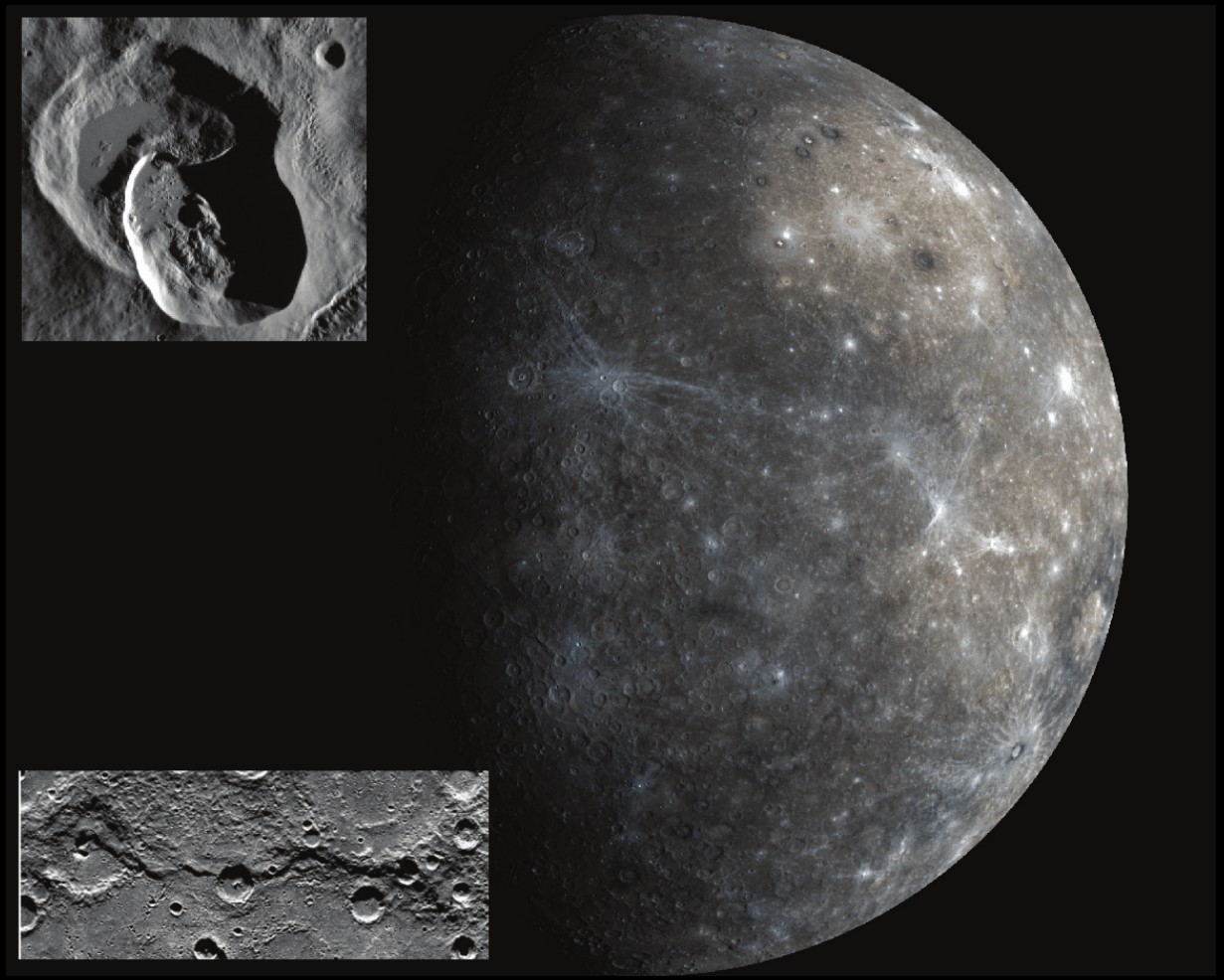


Transparent emprunté à C. Szopa (LATMOS/UVSQ)

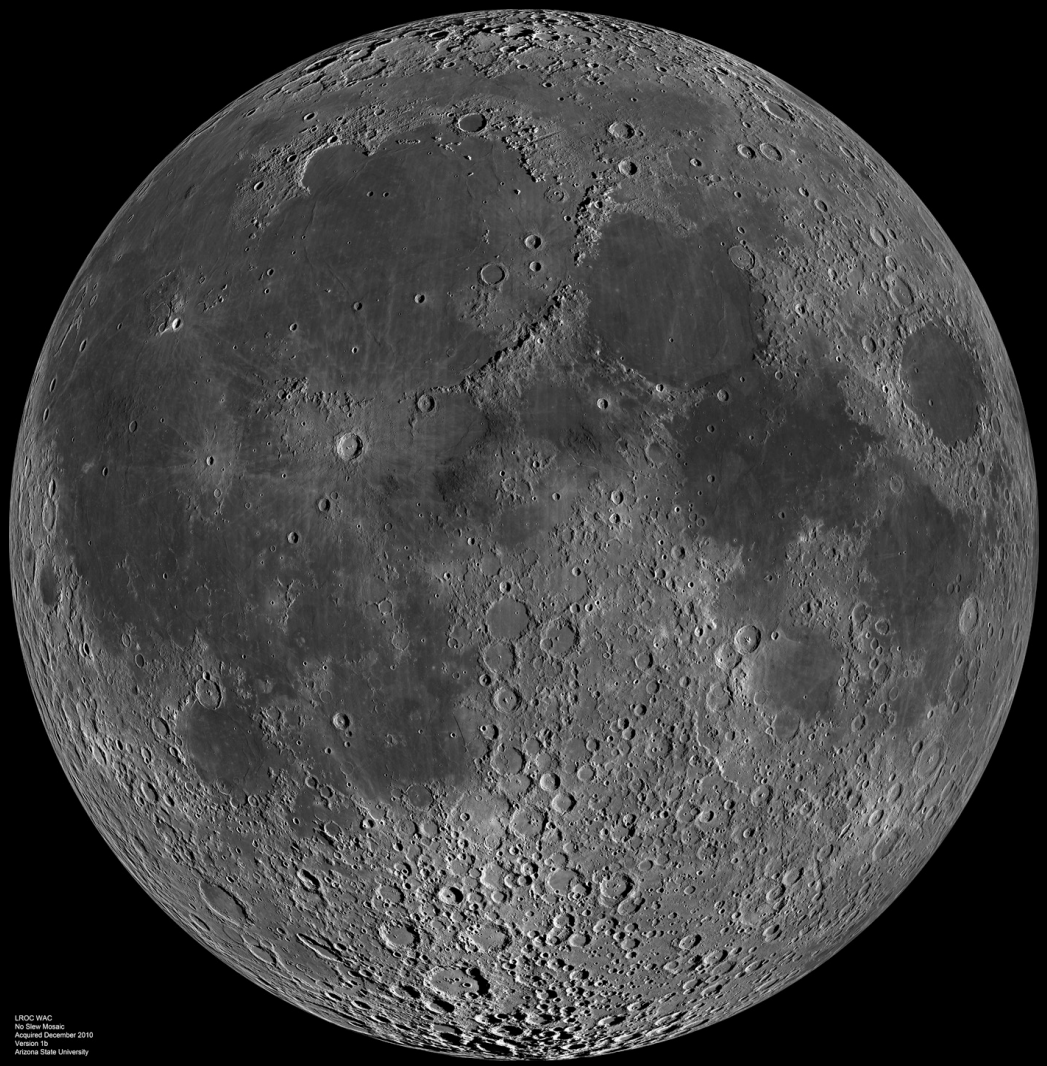
Plan

Mercure

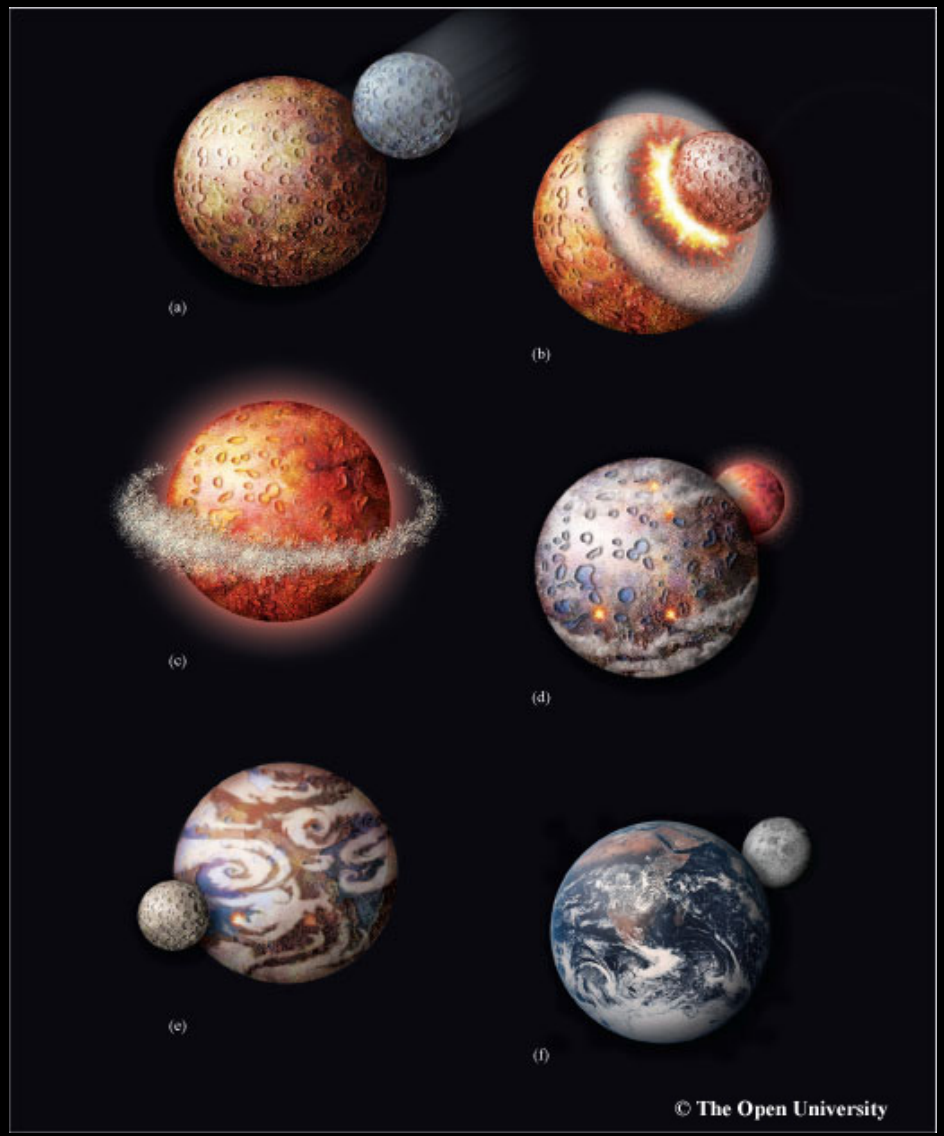
moisson de découvertes de la sonde MESSENGER



Near-side Moon imaged by LRO in 2010



The formation of the Moon

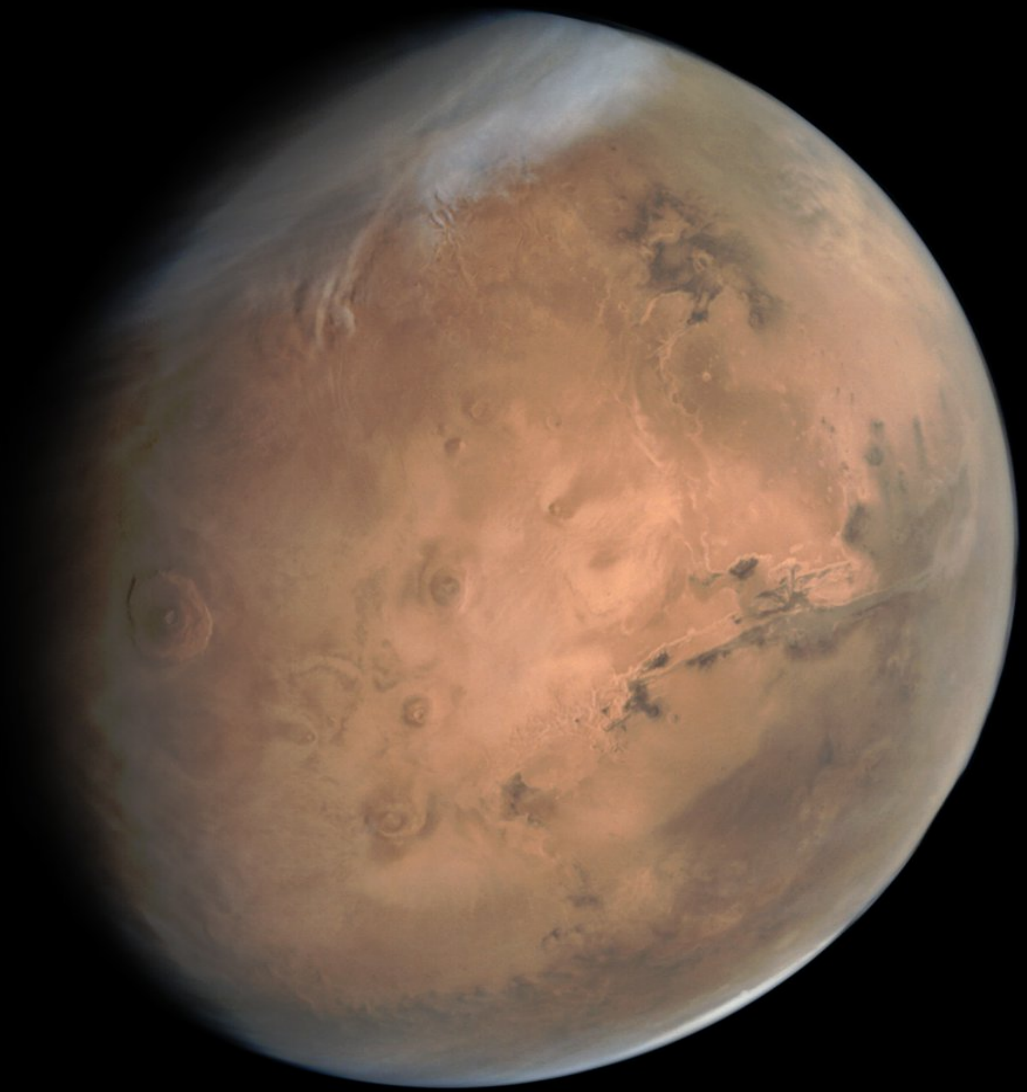


Science Magazine, October 2013

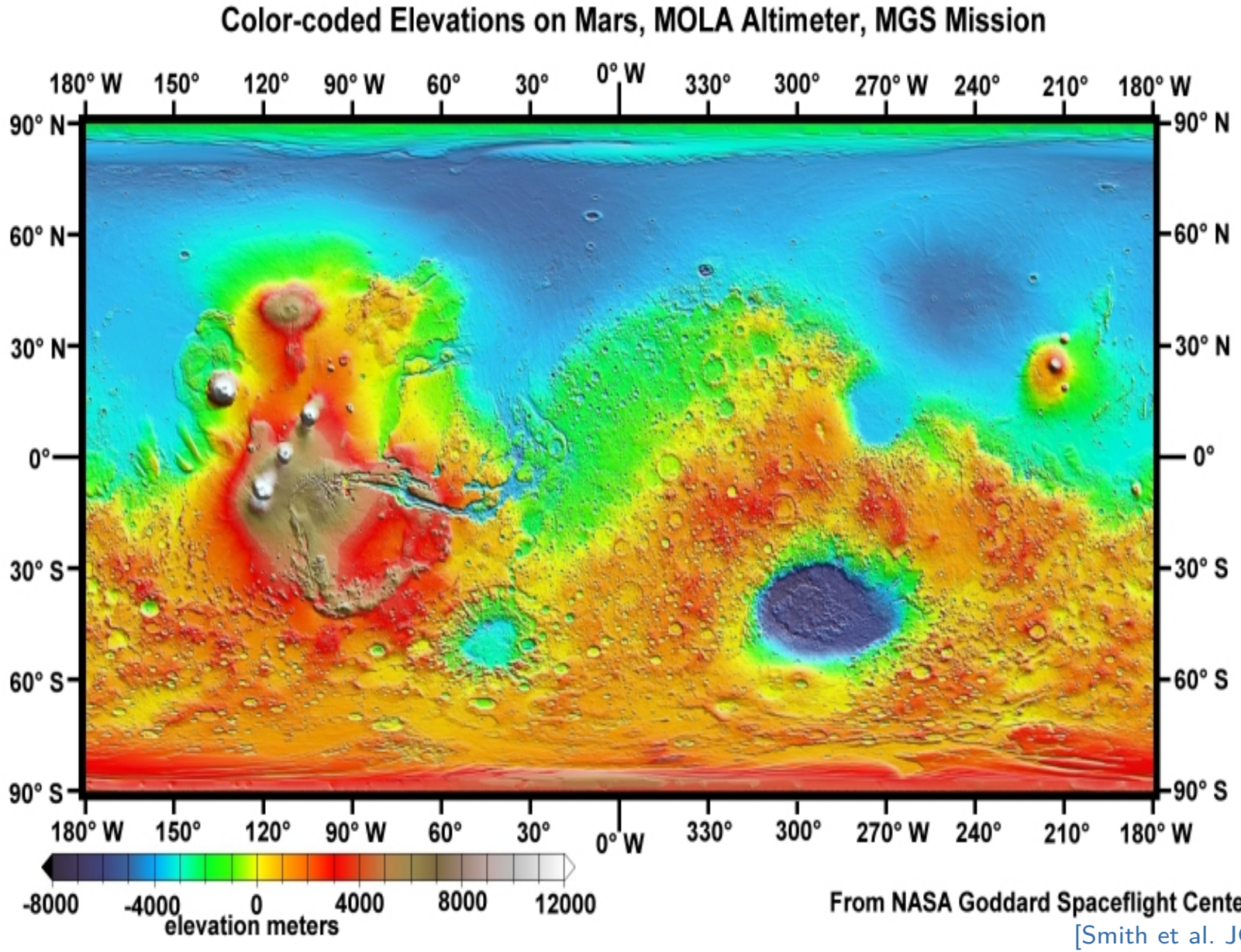
Where did the moon come from ? For 3 decades, planetary scientists have agreed that it happened something like this : While the solar system was still forming, a body the size of Mars struck Earth a glancing blow that reduced both to rubble. The cloud of debris reformed itself into the modern Earth and 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.

[McBride and Gilmour, An Introduction to the Solar System

Mars seen by Mangalayaan in 2016

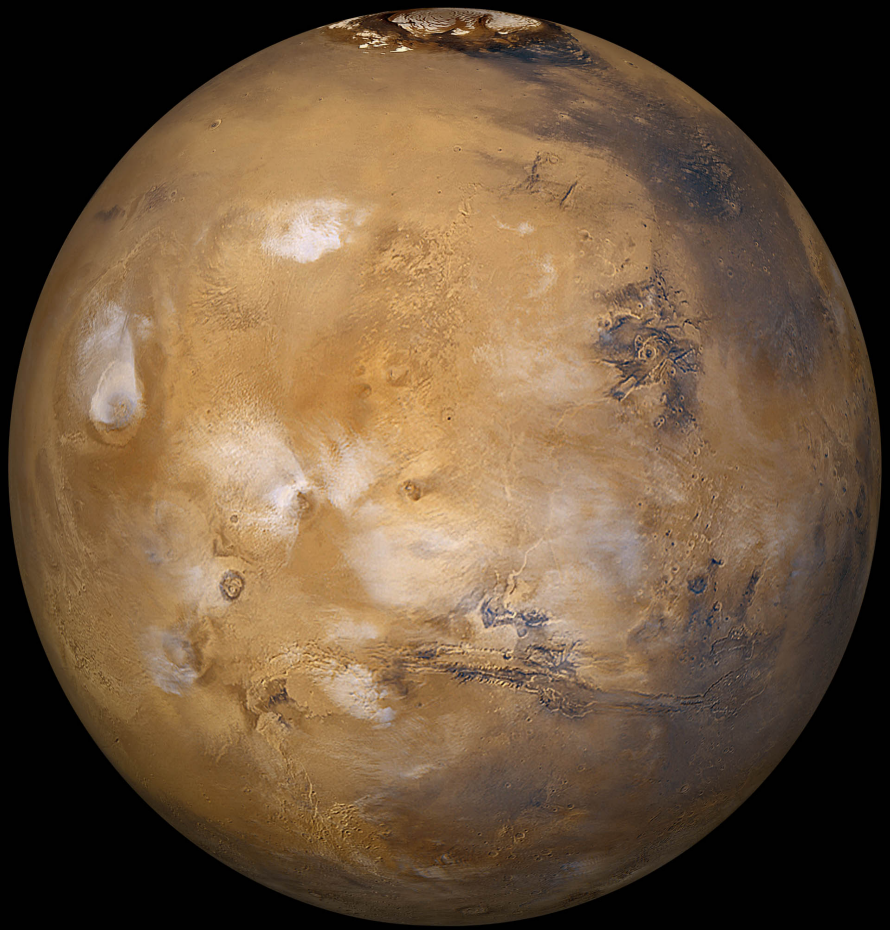


Les reliefs de Mars par altimétrie laser MOLA

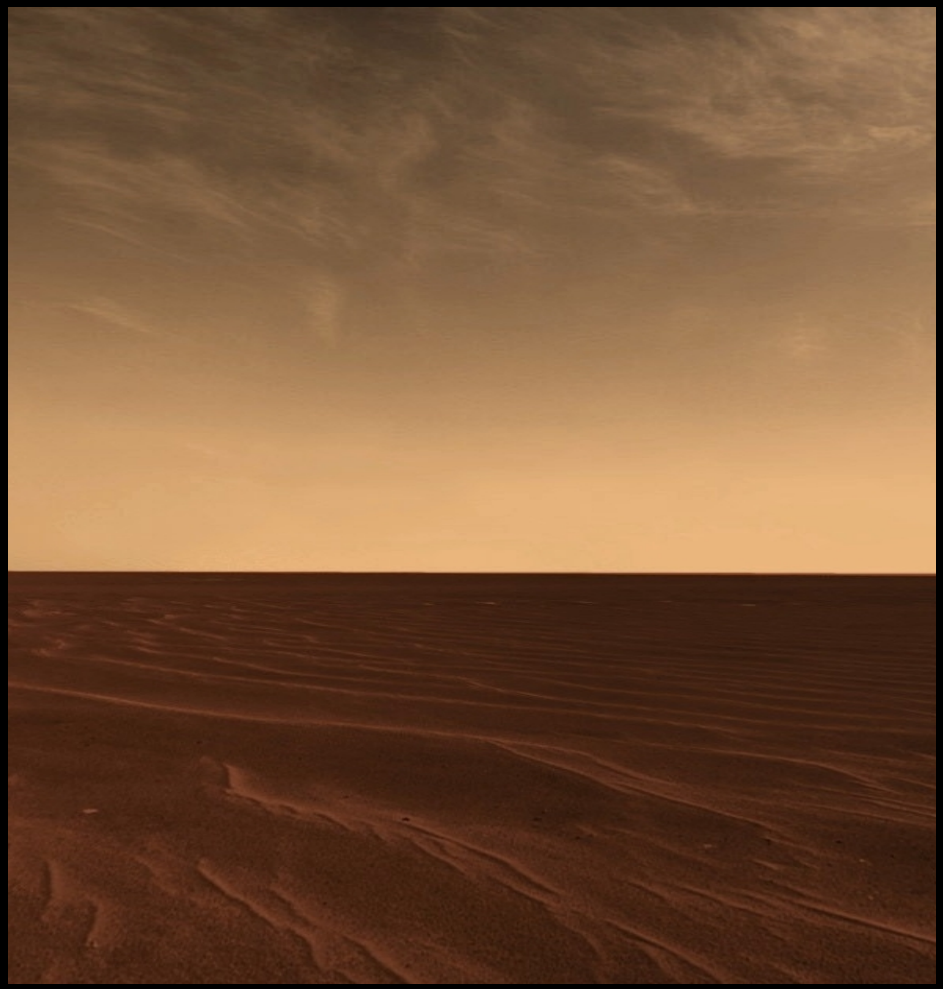


[Smith et al. JGR 2001]

Mars



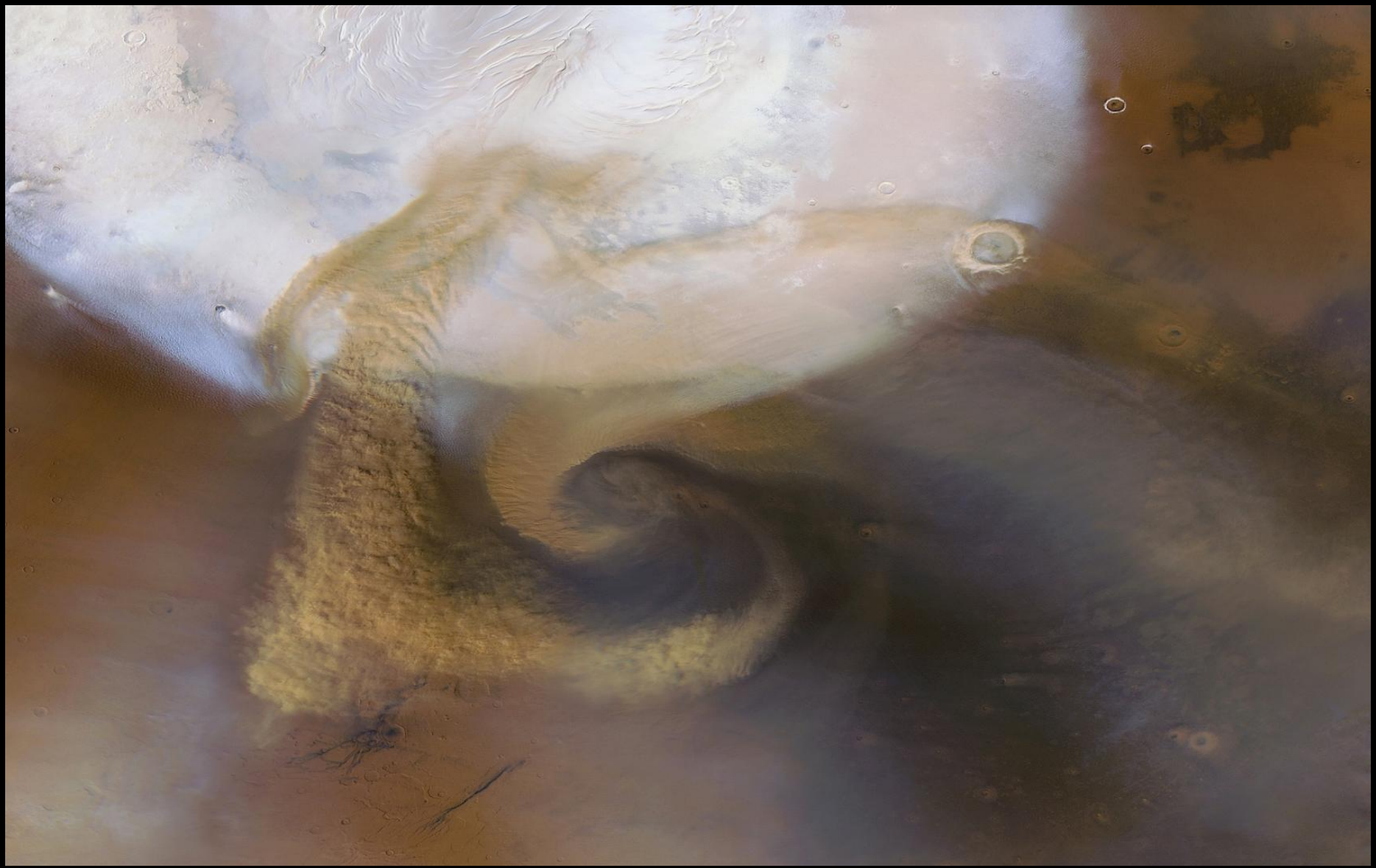
[Mars Global Surveyor, 2002]



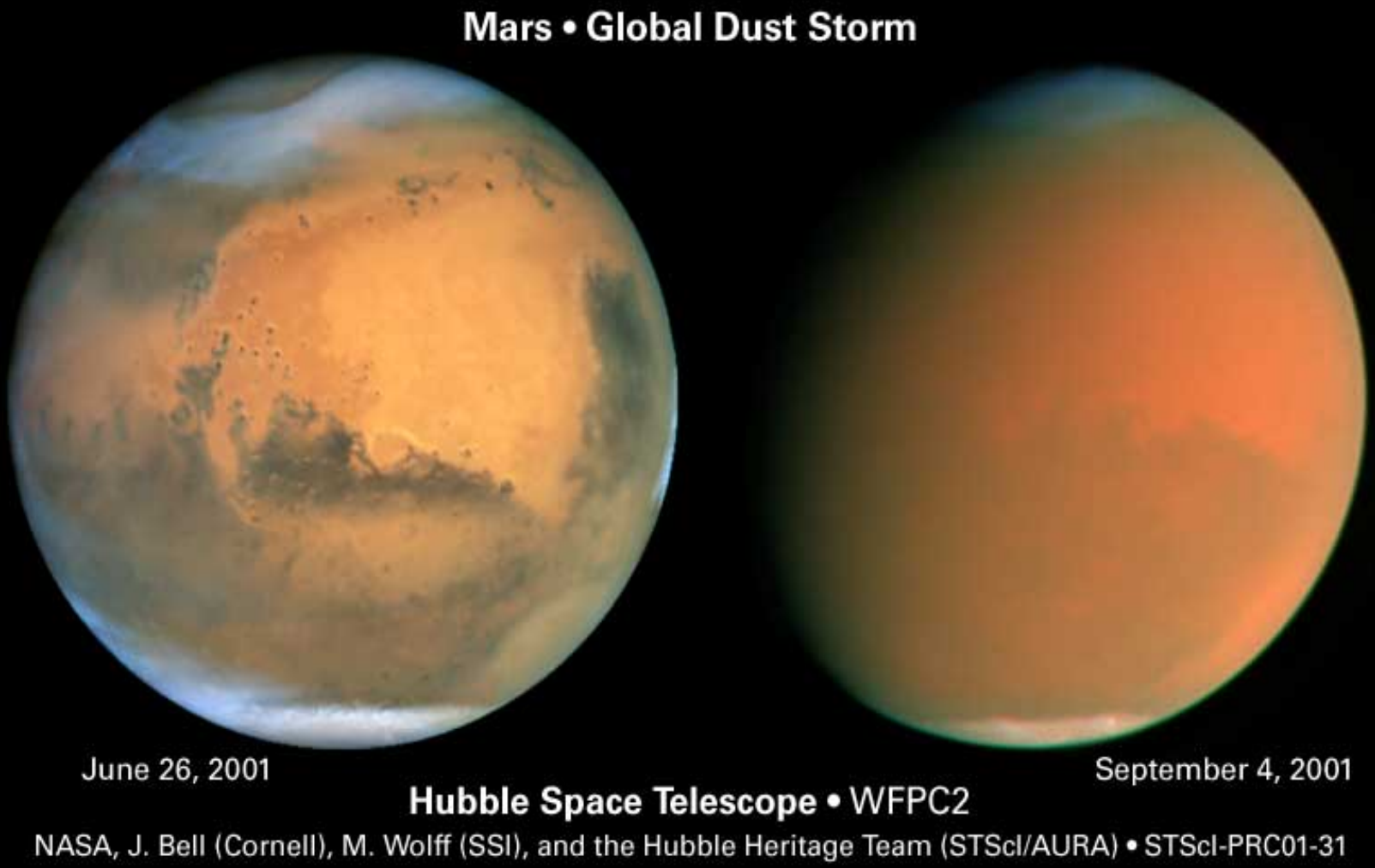
[Mars Opportunity panorama, 2006]

Mars, un monde de CO_2, poussière et eau

Vue du pôle nord, sur environ 2500 km

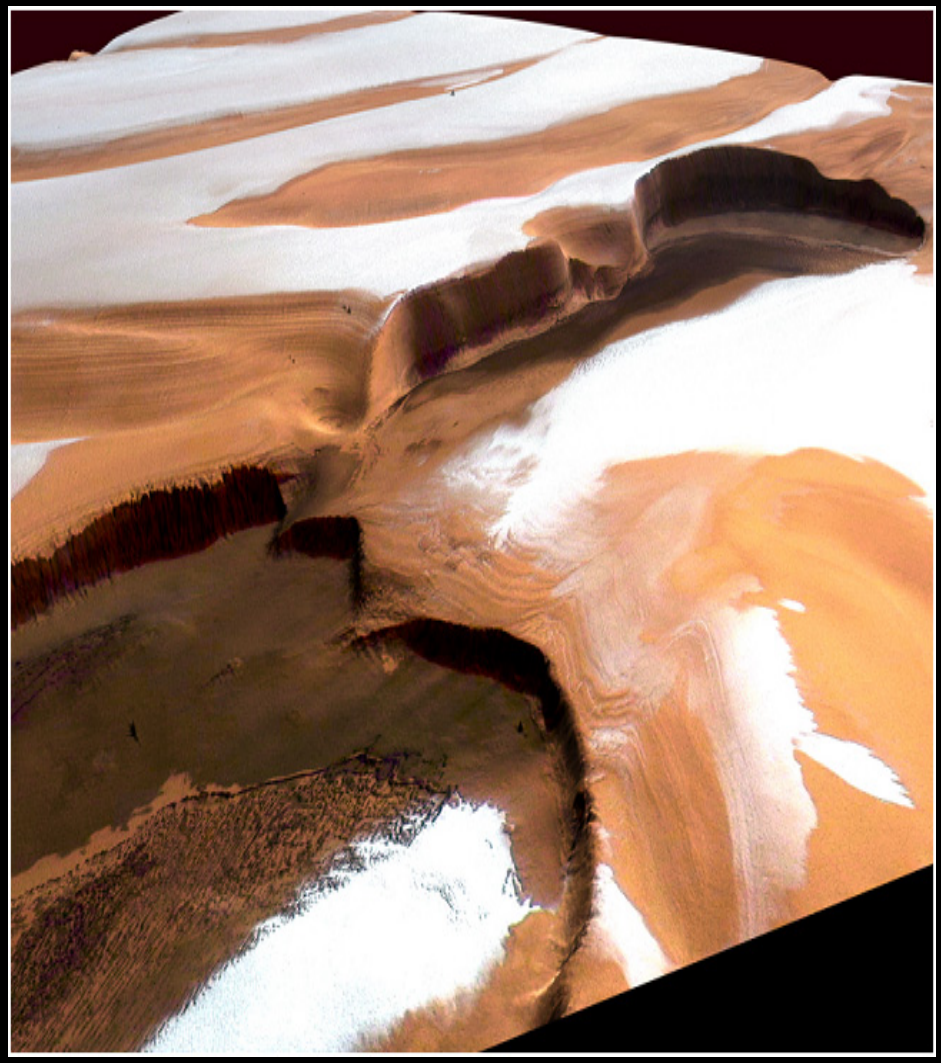


Tempêtes de poussière “globales”



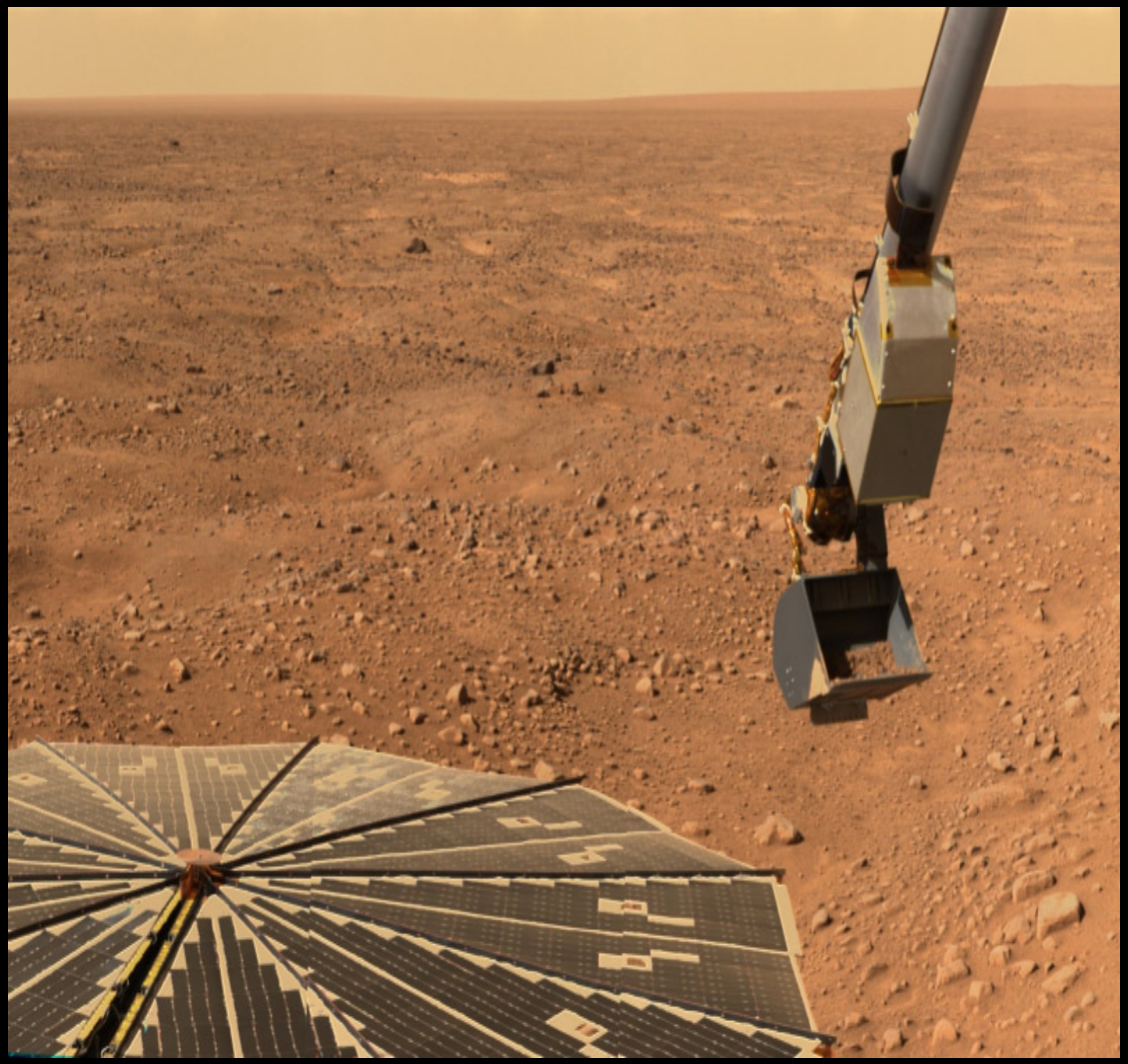
Martian northern polar cap

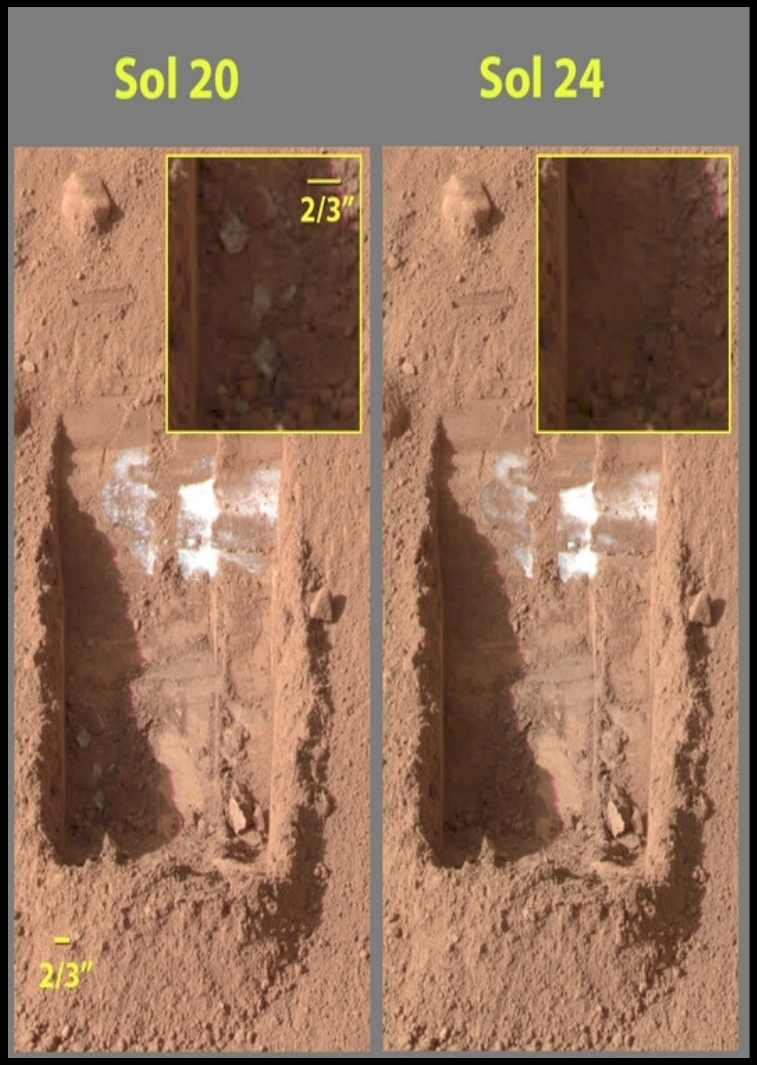
[MGS/MOC visible image]



[HRSC visible image (3D-projected)]

Phoenix mission on Mars 2009





Histoire de Mars à travers les âges

[Wordsworth et al. Annual Review of Earth and Planetary Sciences 2016]

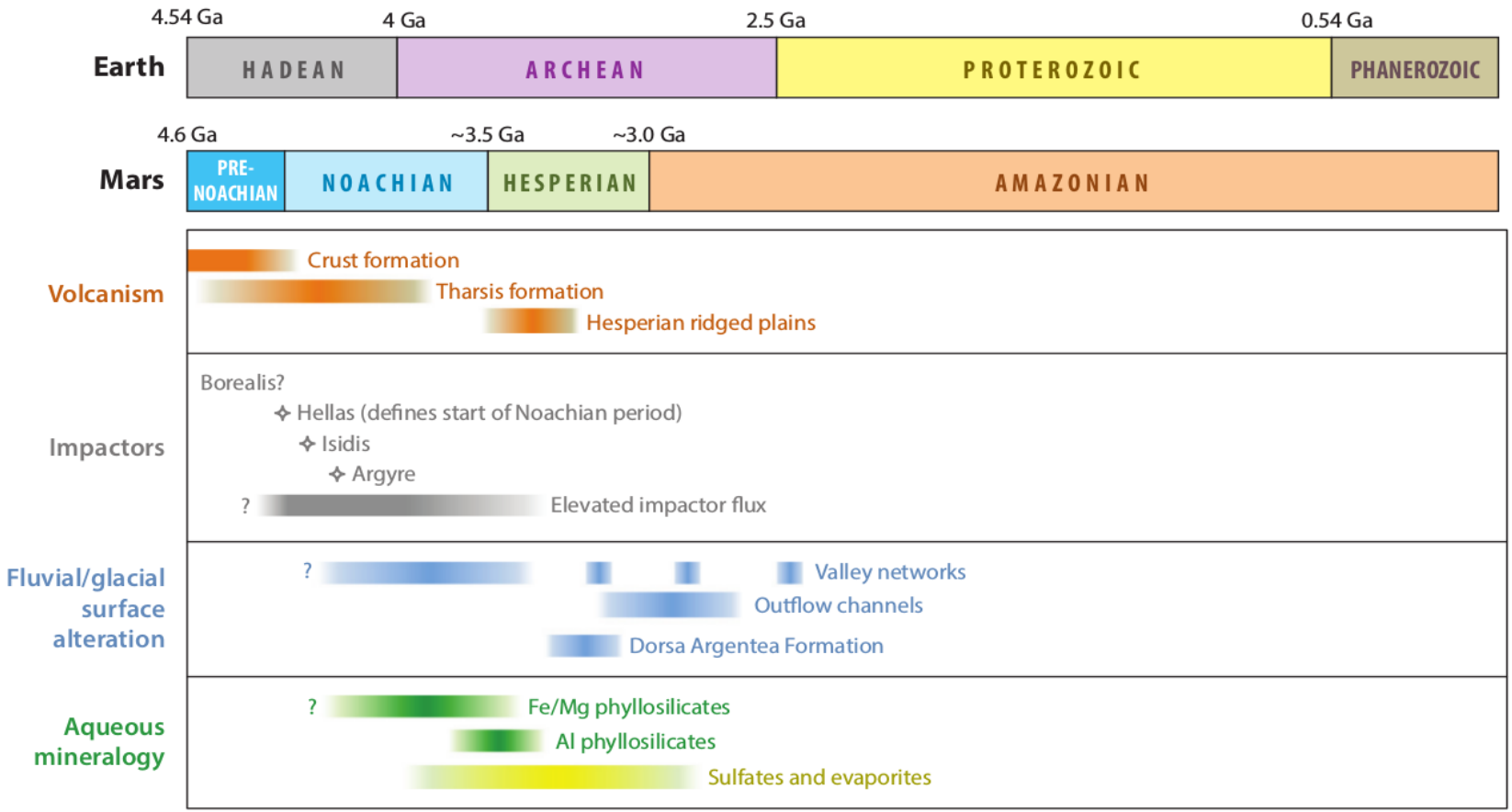


Figure 2

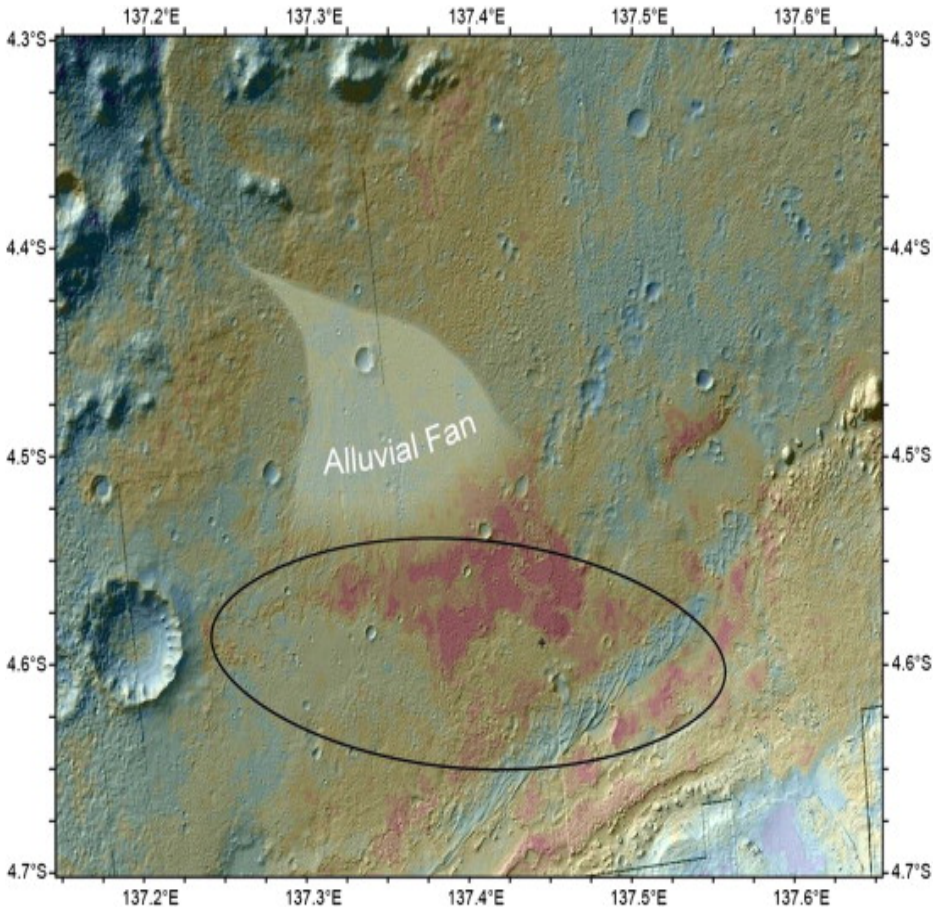
Timeline of major events in Mars history, with the geologic eons of Earth displayed above. In general, the absolute timing of events on Mars is subject to considerable uncertainty, but the sequencing is much more robust. Question marks indicate cases where processes could also have occurred earlier but the geologic record is obscured by subsequent events. Based on data from Werner & Tanaka (2011), Fassett & Head (2011), Ehlmann et al. (2011), and Head & Pratt (2001).

Auto-portrait Curiosity hiver 2013 (“selfie”)

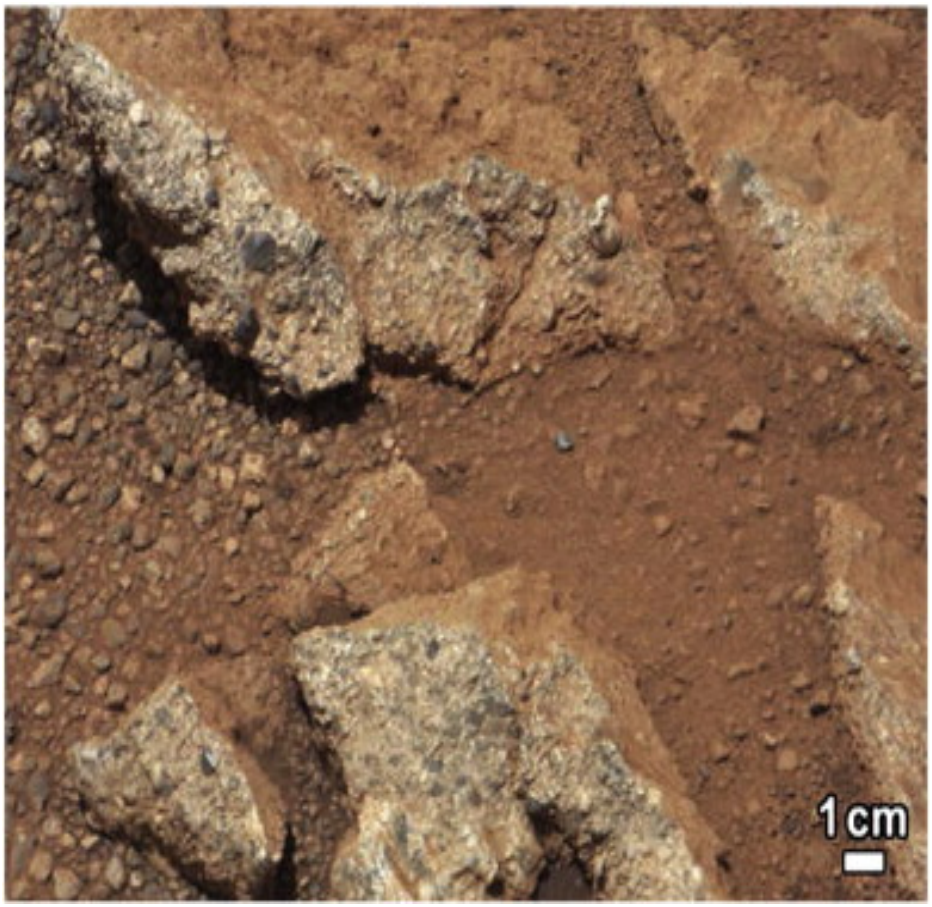
[référence PIA16764]

Curiosity in fluvio-lacustrine Gale crater (3.6 Gyr)

Context



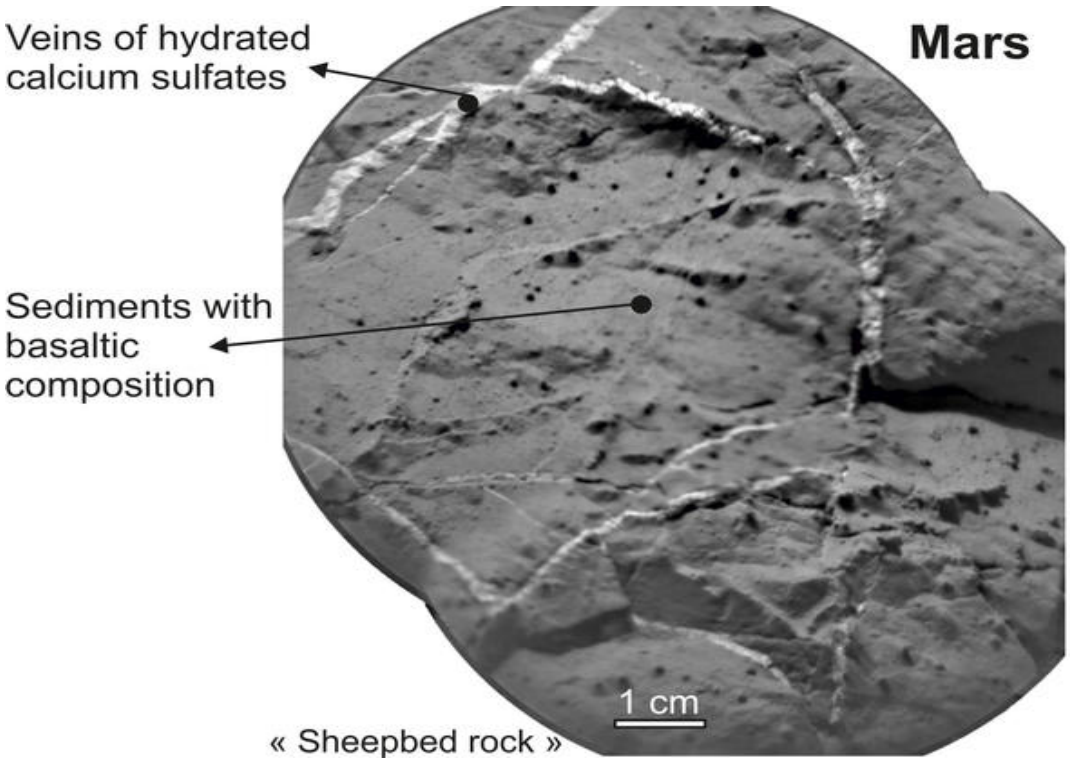
Terrain Fluvial conglomerates



[Williams et al. Science 2013 ; Baker et al. Geomorphology 2015]

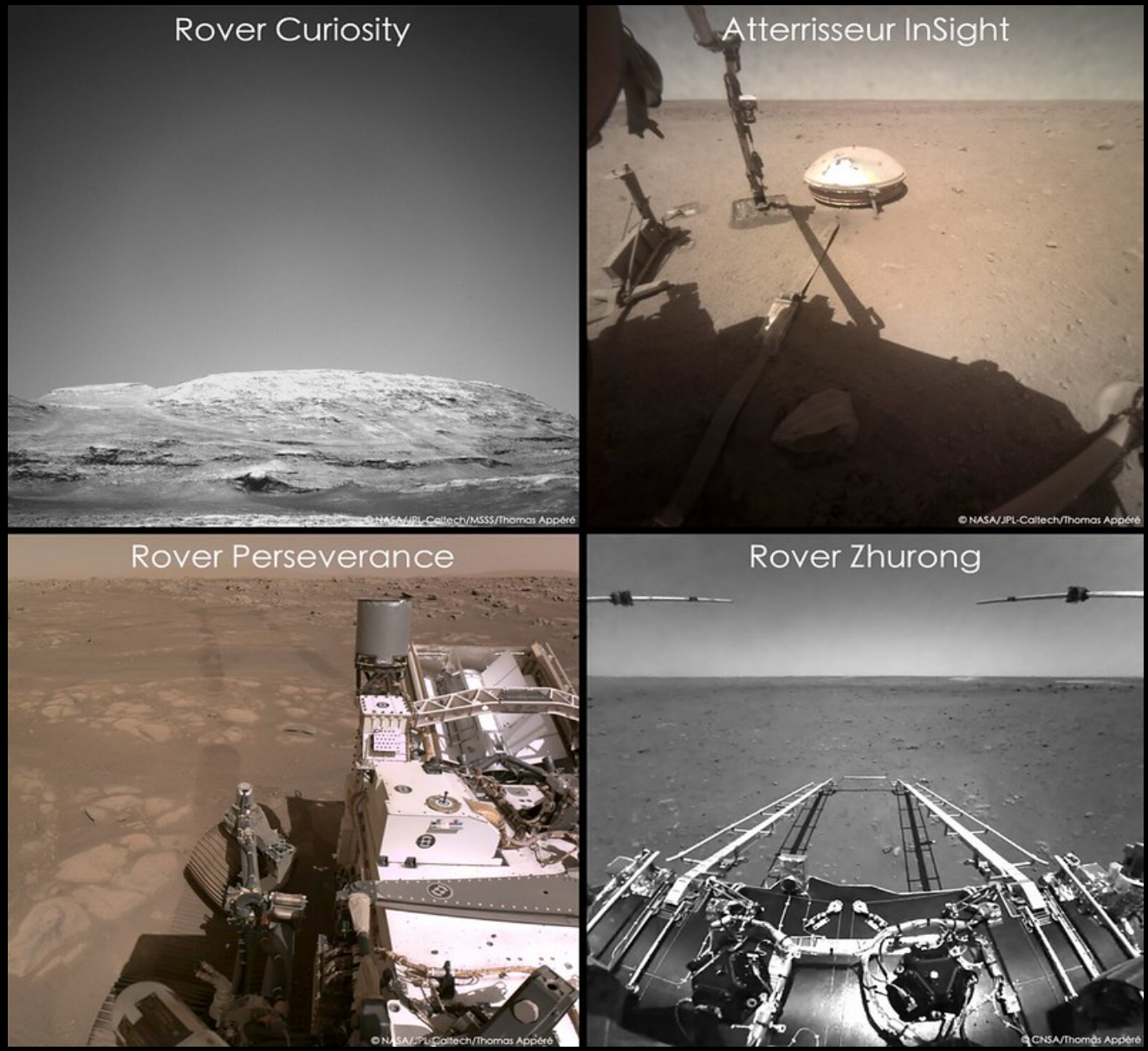
Veines de gypse découvertes par Curiosity en 2014

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



[PIA16617 NASA / Université Nantes]

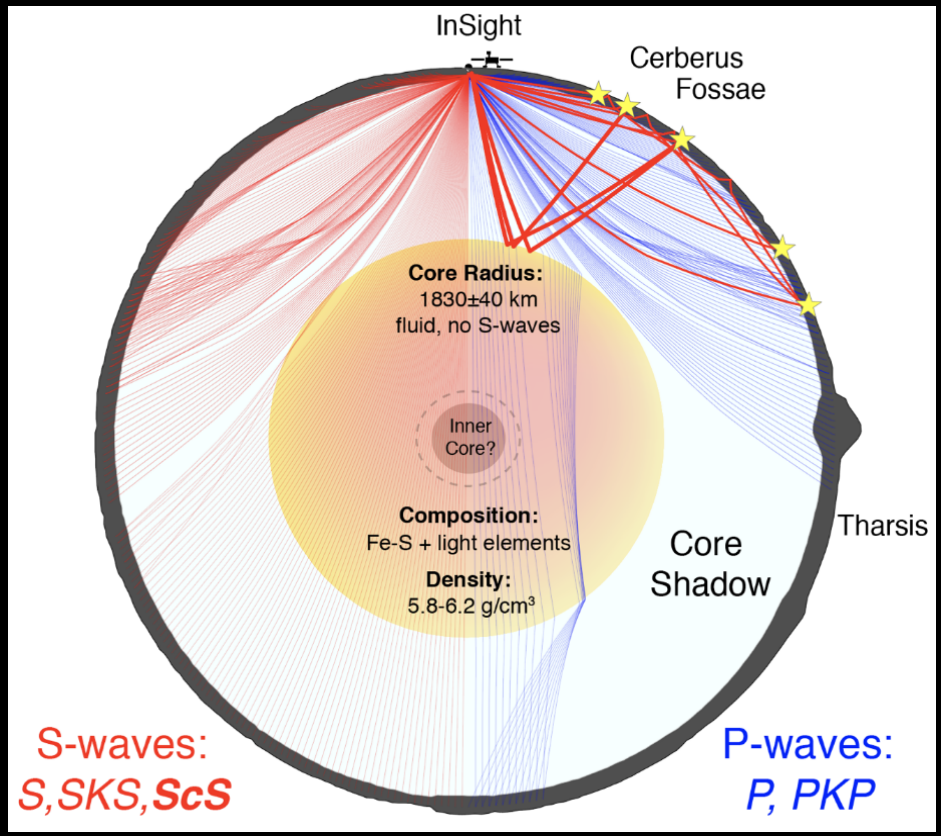
Quatre robots en simultané à la surface de Mars



[Montage T. Appéré. Images du 15 mai 2021. Curiosity & Perseverance NavCam / InSight ICC]

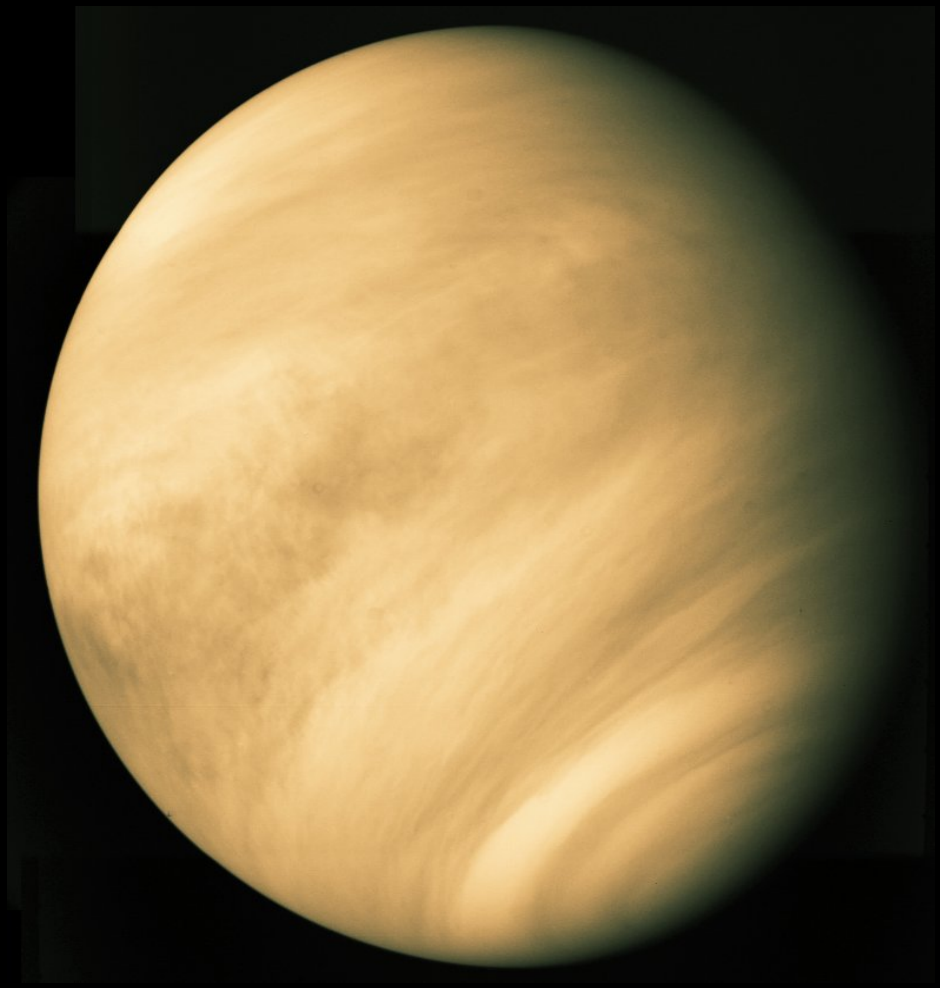
InSight's seismometer detects Mars' core

Large liquid metal core

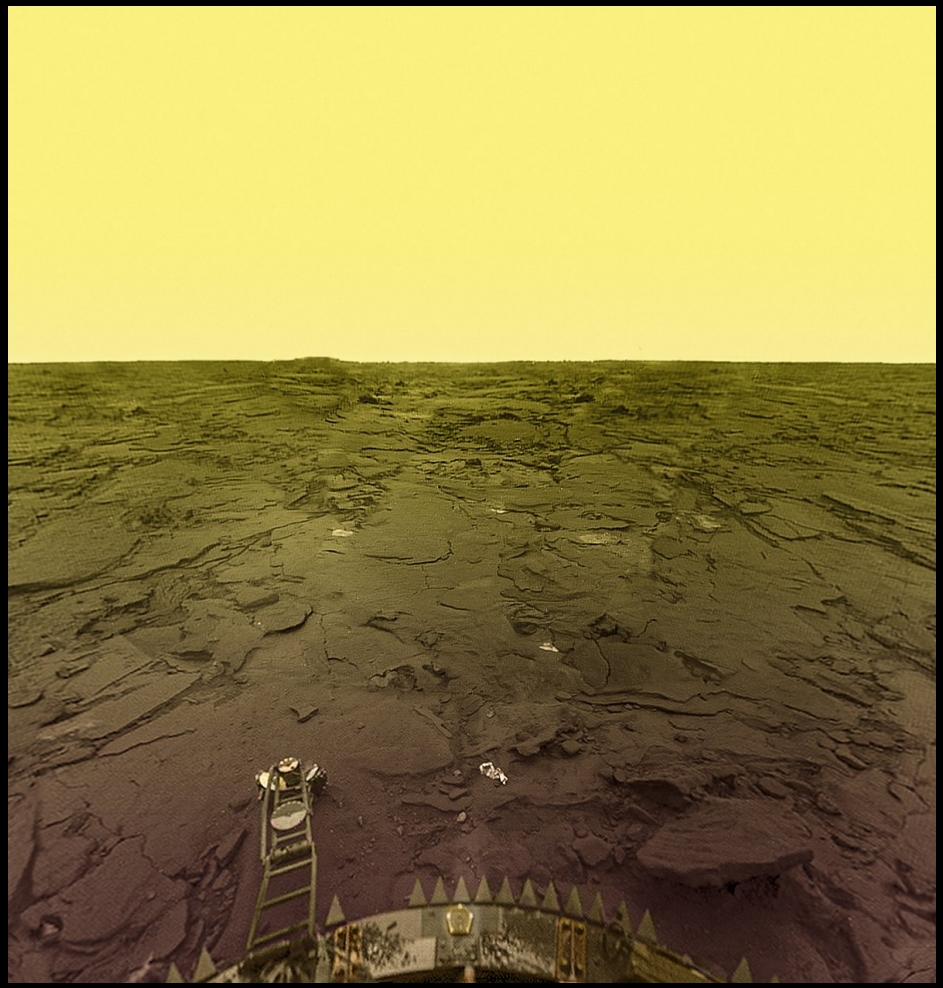


[Staehler et al. Science 2021 https://doi.org/10.1126/science.abi7730]

Vénus

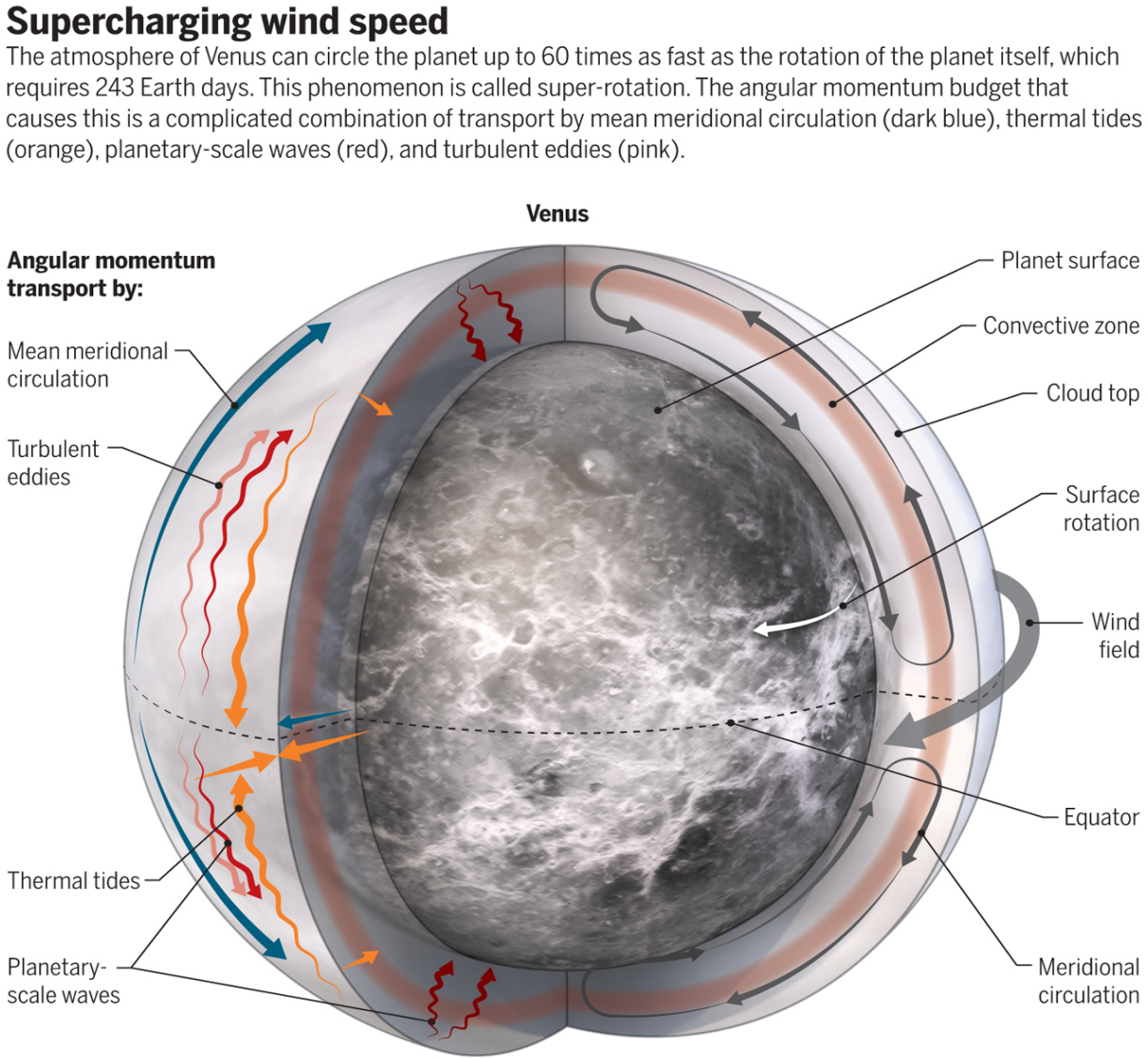


[Pioneer Venus, 1979]



[Venera 13, 1982 (reprocessed)]

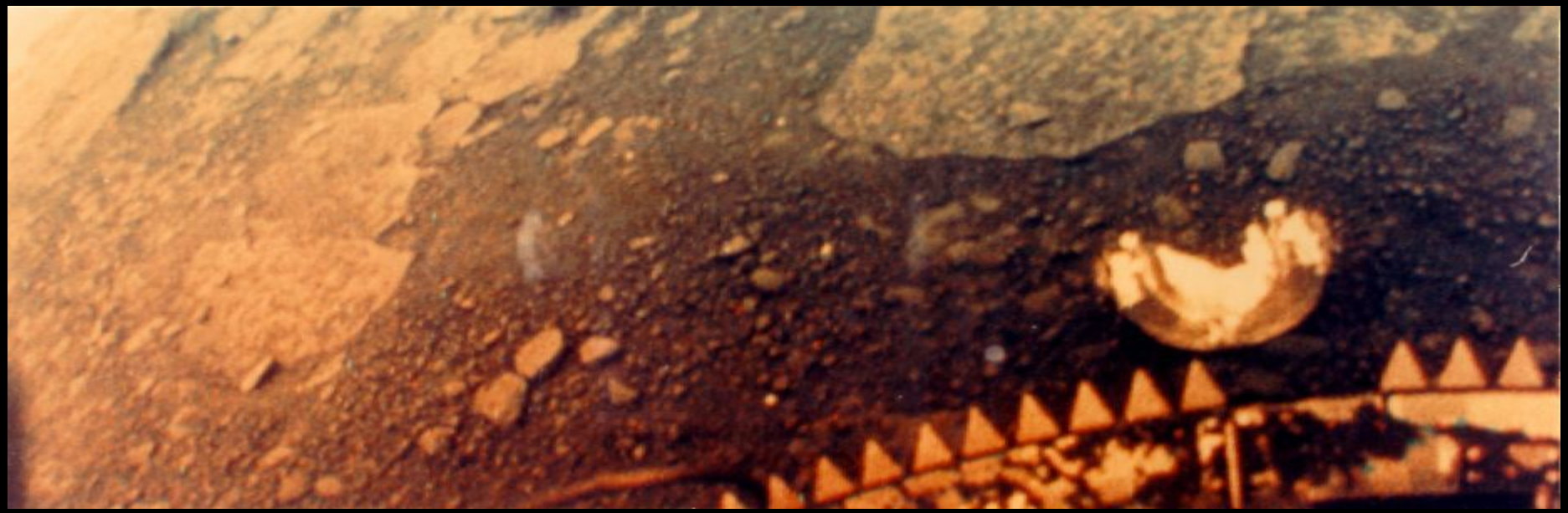
Mechanisms for super-rotation on Venus



[Figure by S. Lebonnois in Science, referencing Horinouchi et al. Science 2020]

A la surface de Vénus

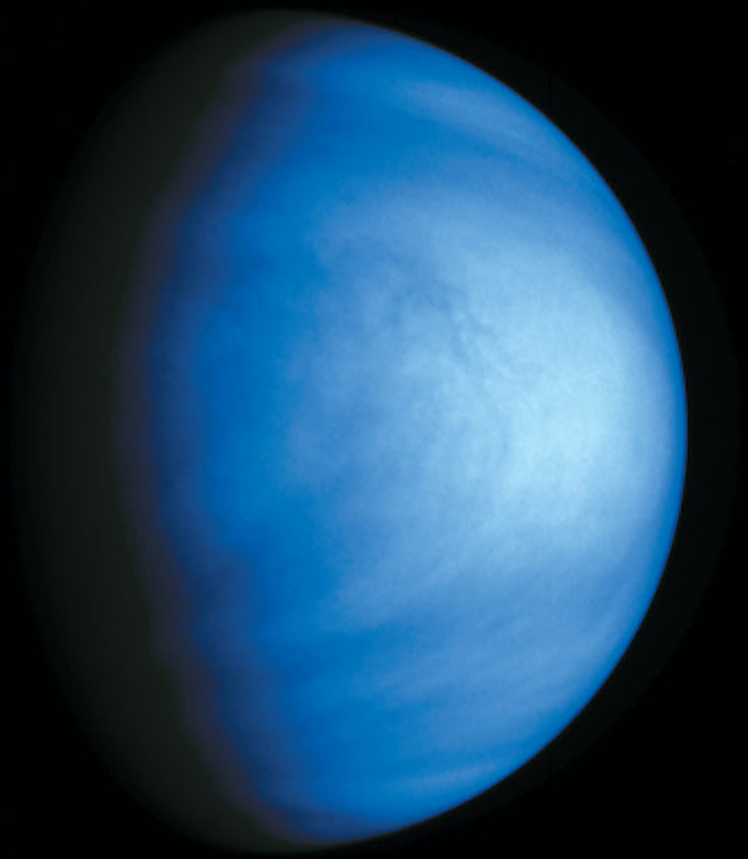
$p = 90$ bars et $T = 450°C$



[Image captured by Venera 13 in 1982]

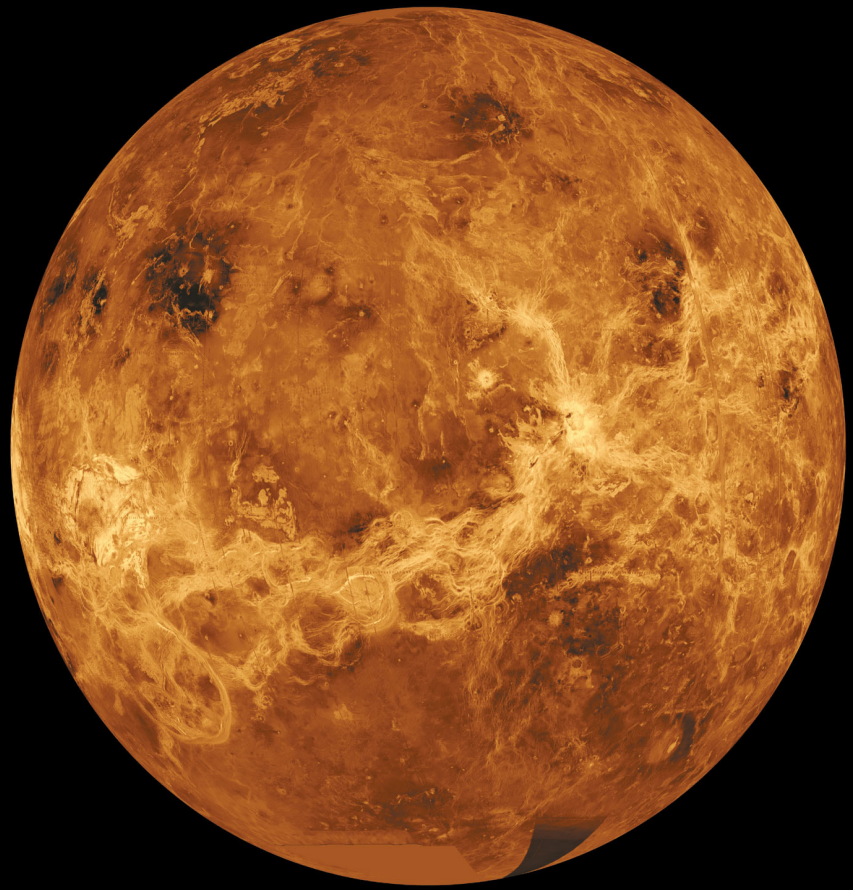
Vénus

vue par Galileo (image visible fausses couleurs)



Courtesy of NASA

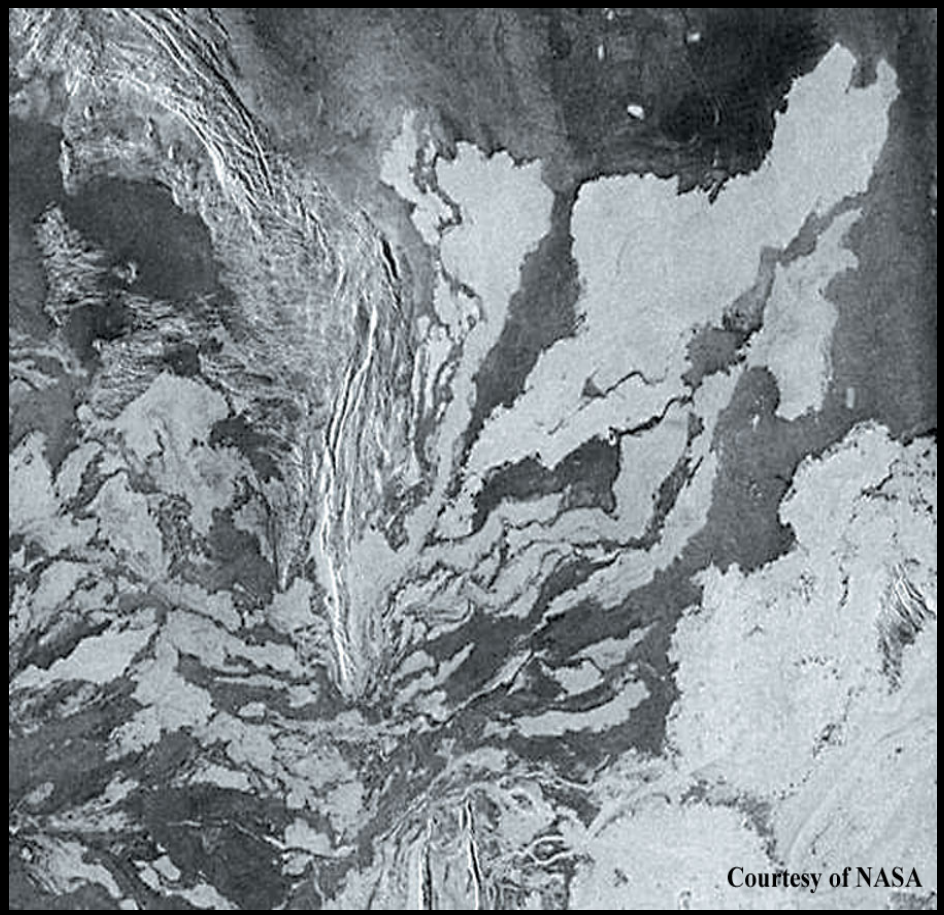
vue par Magellan (cloud-penetrating radar)



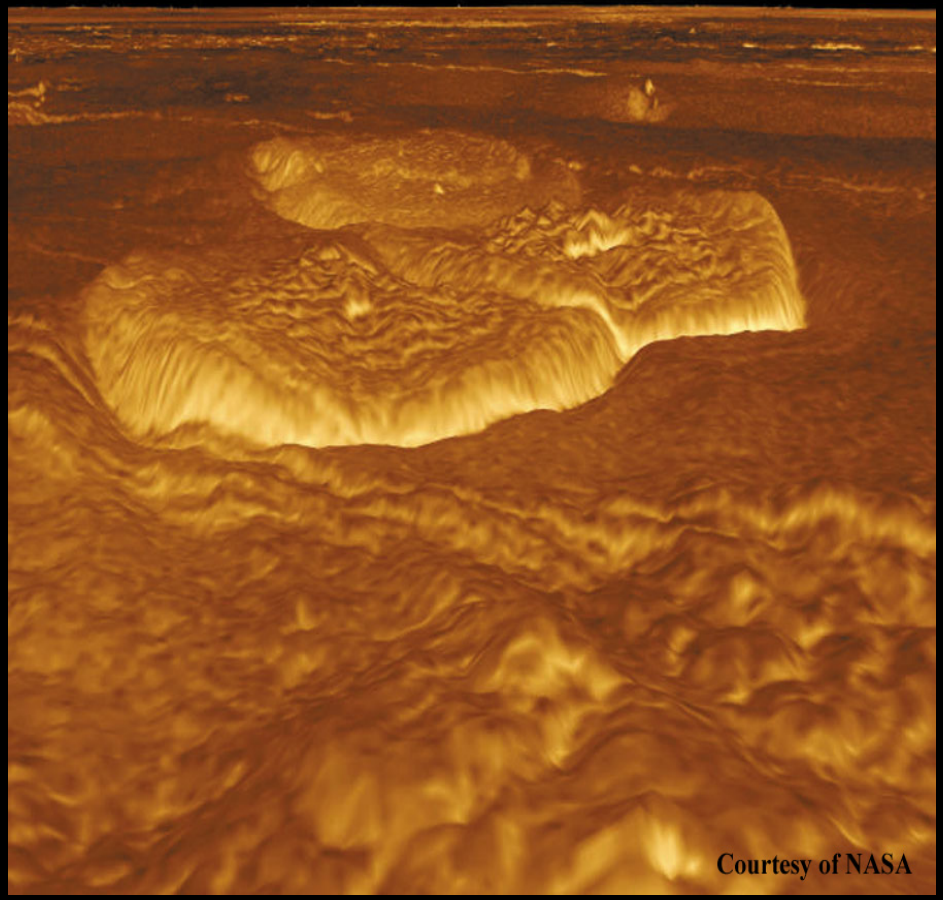
Courtesy of NASA

Traces de volcanisme sur Vénus

Lava flows (400 km)



Pancake domes (25 km, 750m)



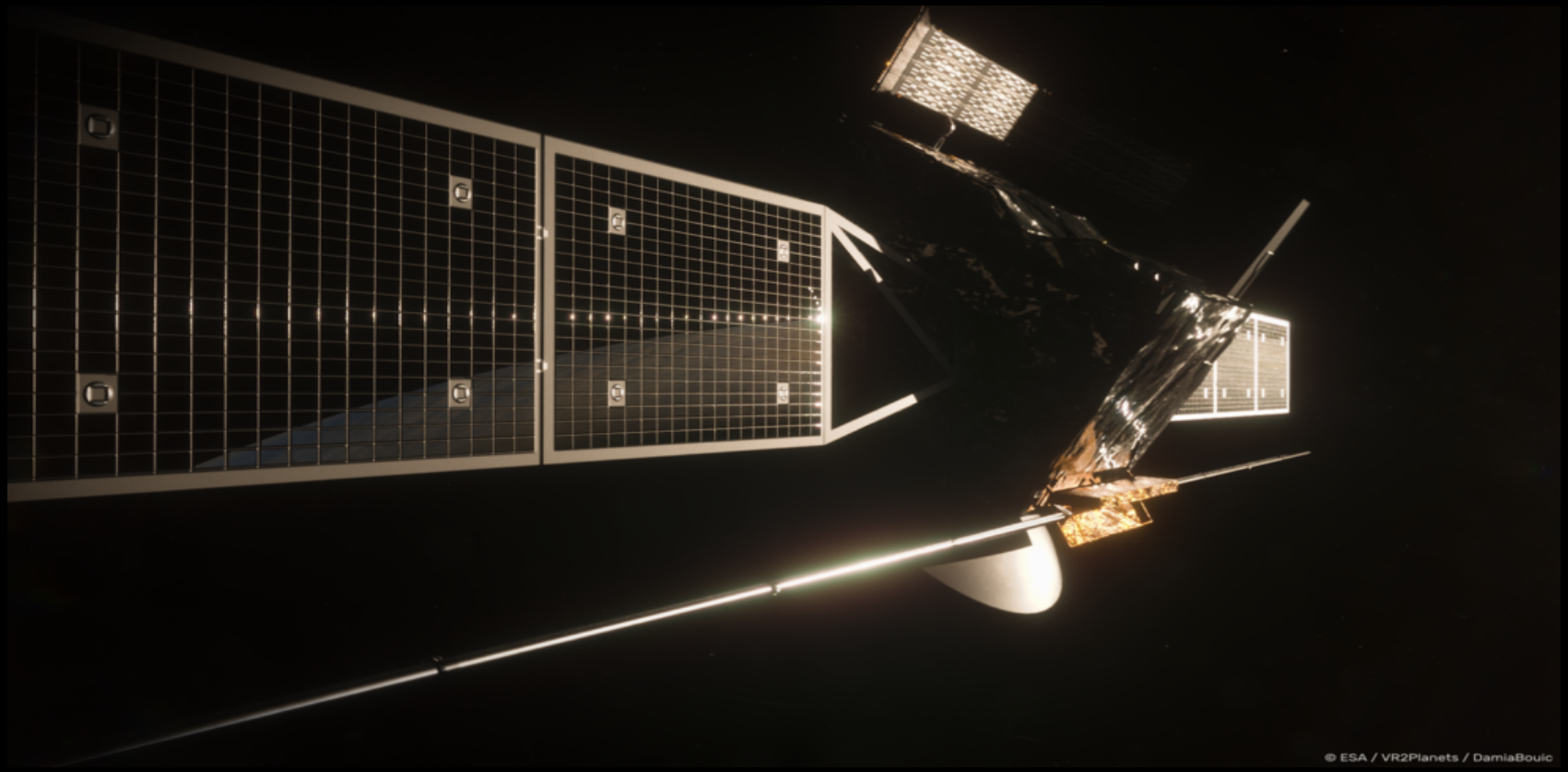
Two new NASA missions for the 2030s

DAVINCI+ Deep Atmosphere Venus Investigation of Noble gases, Chemistry, & Imaging

VERITAS Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy

EnVision mission ESA Launch early 2030s

- Spectrometers : atmospheric + surface composition & changes
- Radar imager : volcanic, tectonic, geomorphic surface changes
- Radar sounder : underground layering
- Radio science : probe internal structure and layering



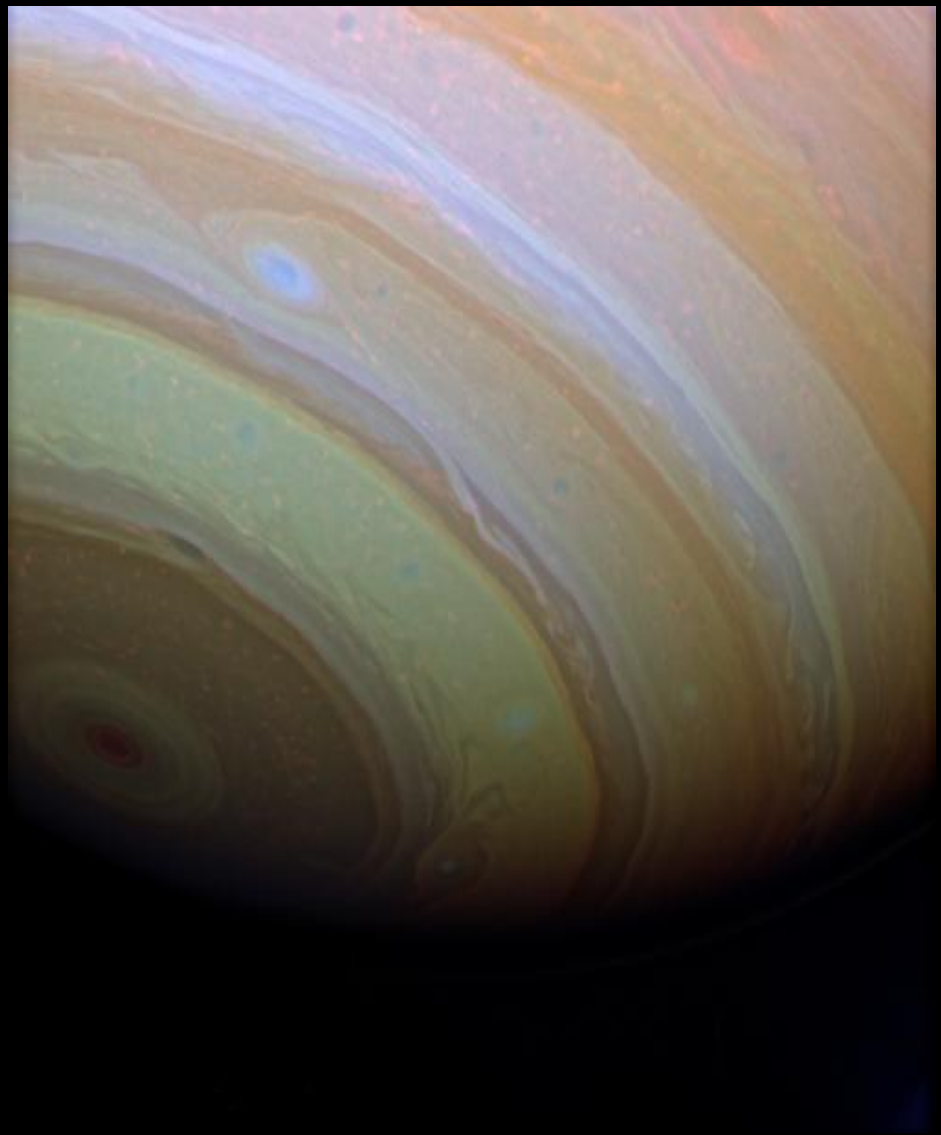
[Credits : European Space Agency/Paris Observatory/VR2Planets]

Plan

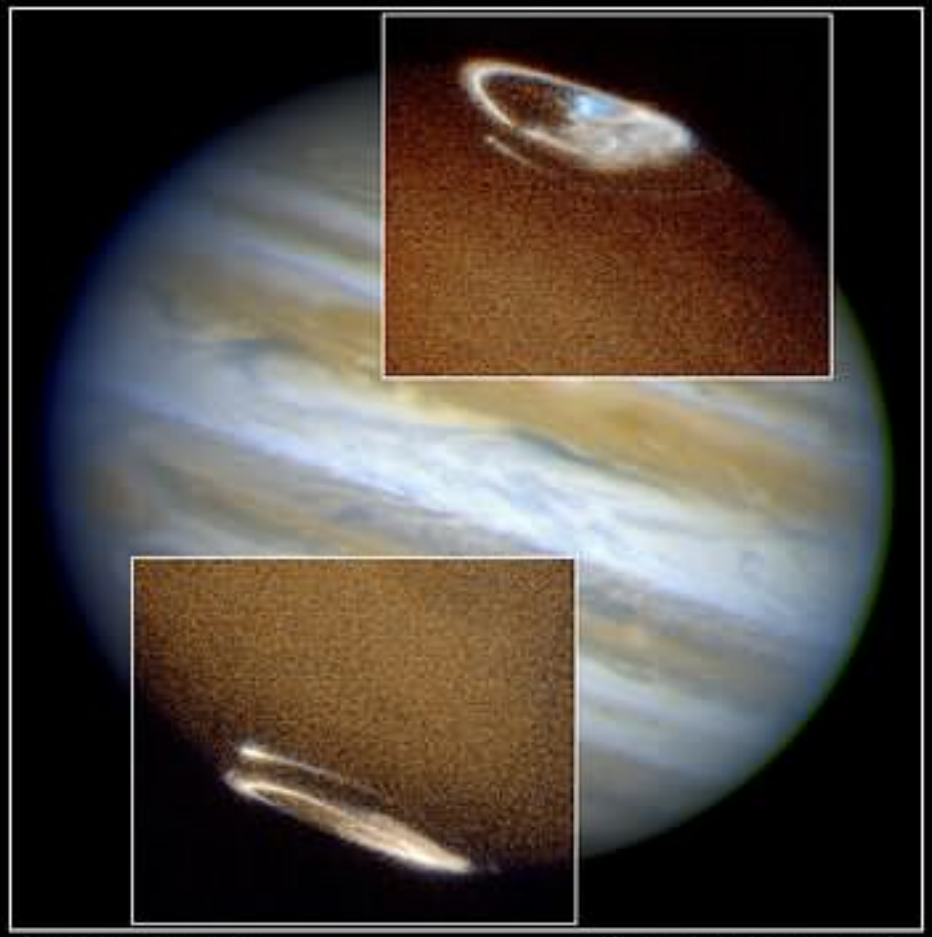
Les géantes gazeuses : courants-jets et tourbillons

Jupiter

Saturne

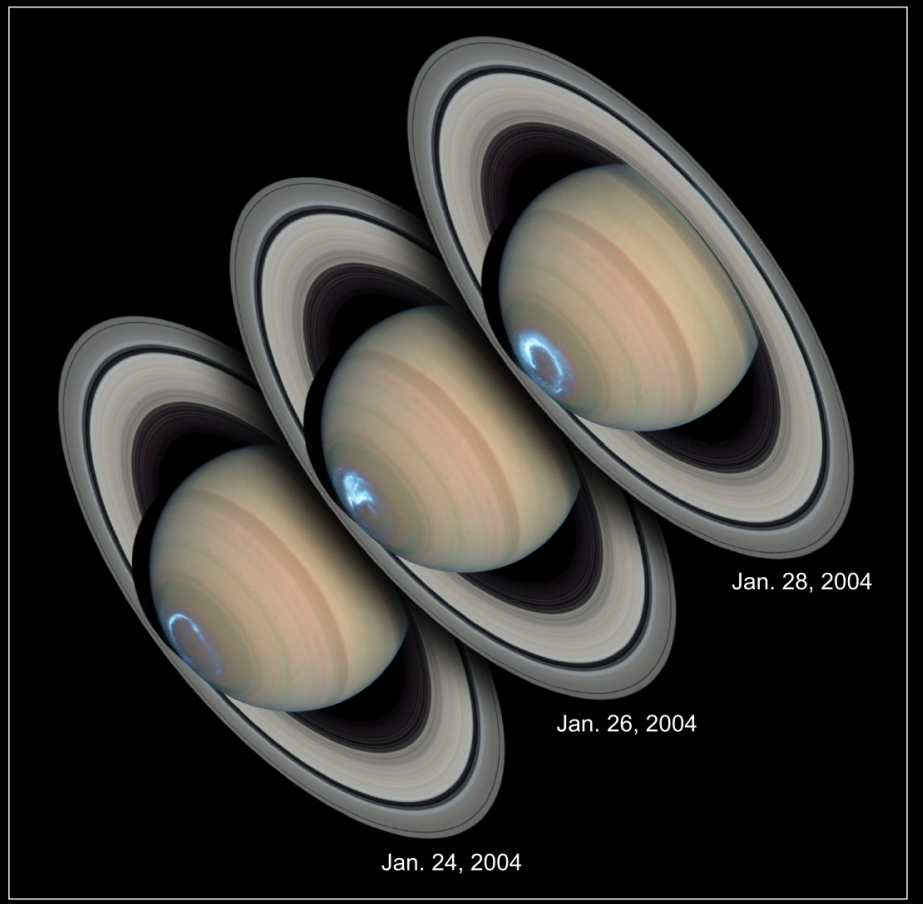


Aurores boréales sur les planètes géantes



Jupiter Aurora HST • STIS • WFPC2

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

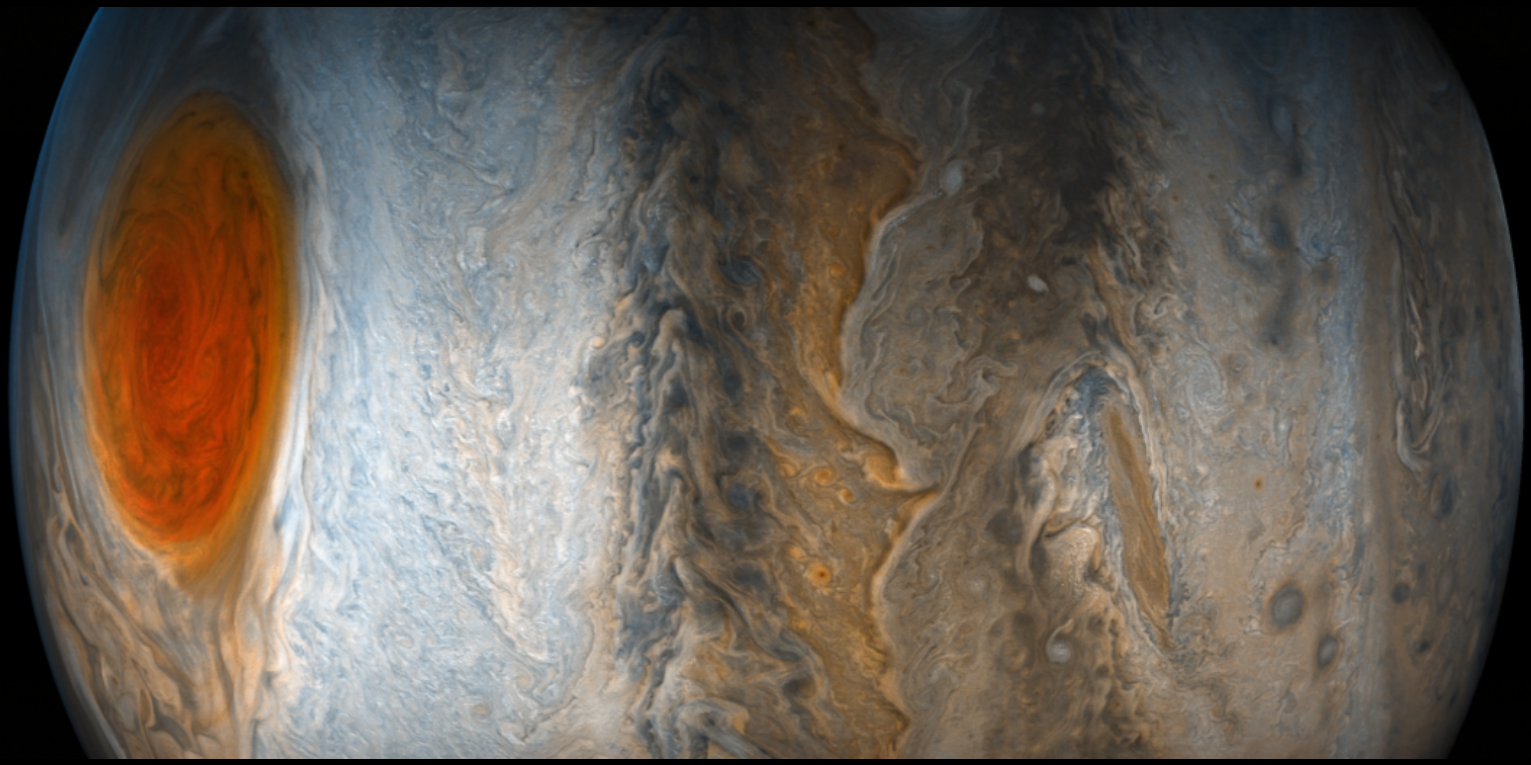


Saturn Aurora
Hubble Space Telescope • ACS • STIS

NASA, ESA and J. Clarke (Boston University) STScI-PRC05-06a

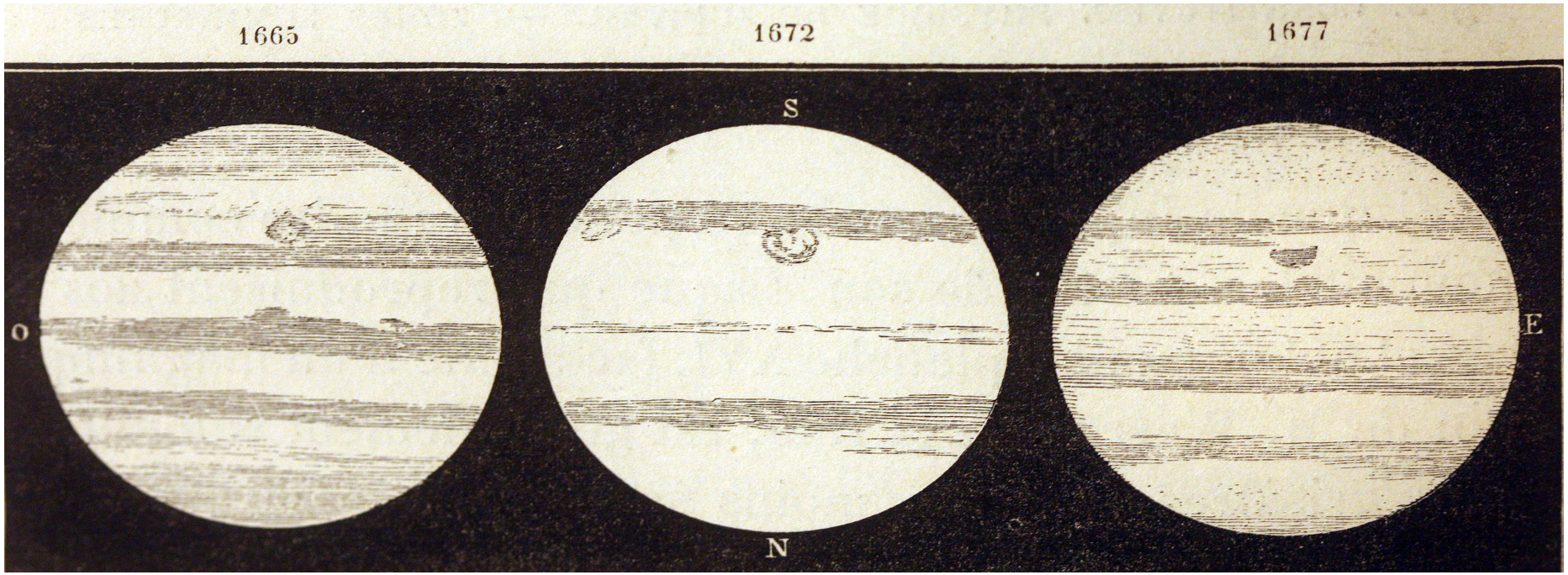
[Composite image HST visible/UV]

Juno, nouvelles vues sur la Grande Tache Rouge



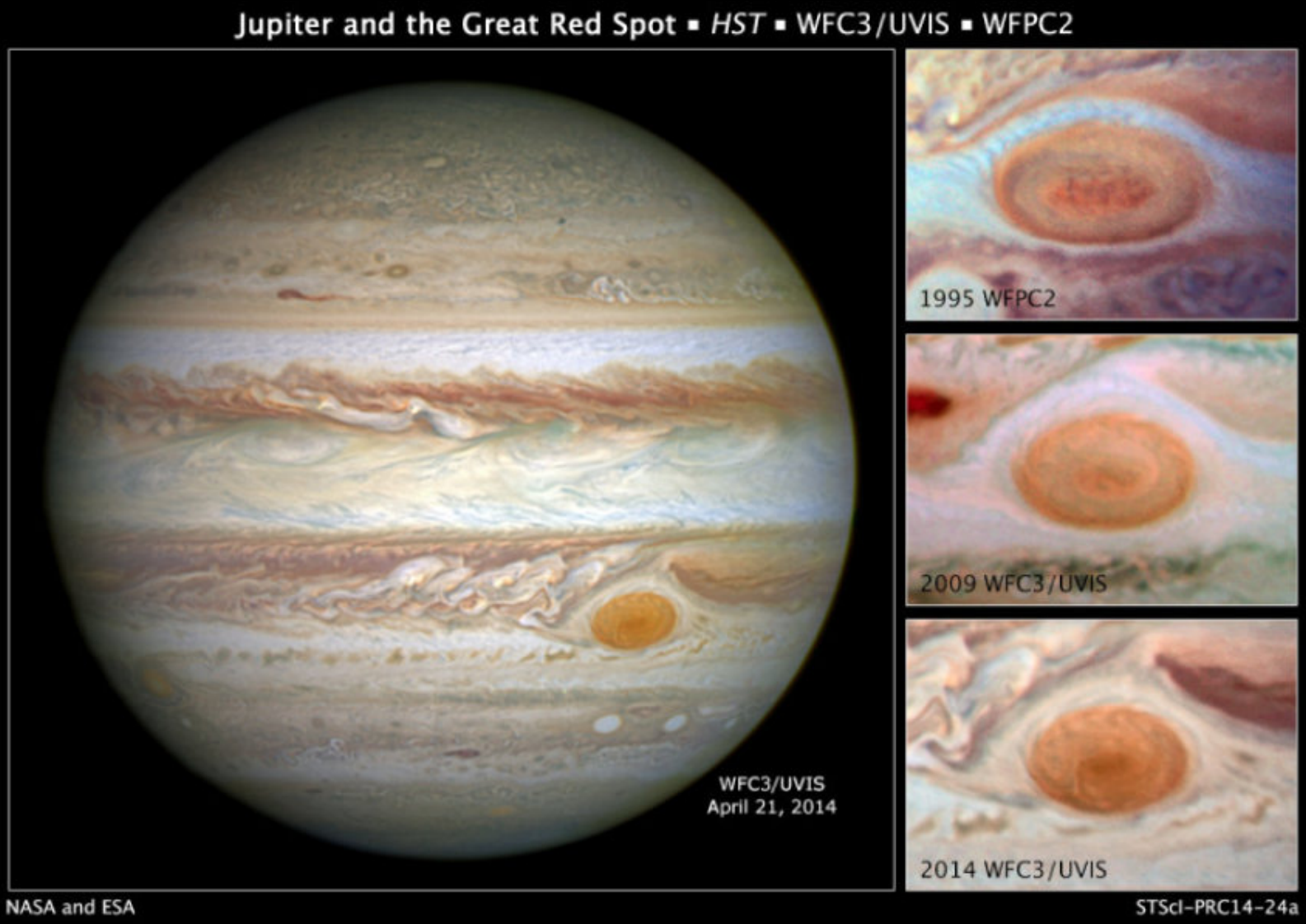
[Sanchez-Lavega et al. AJ 2018, Junocam image P07 (07-2017) NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstad]

Dessins de Cassini de la Tache Rouge



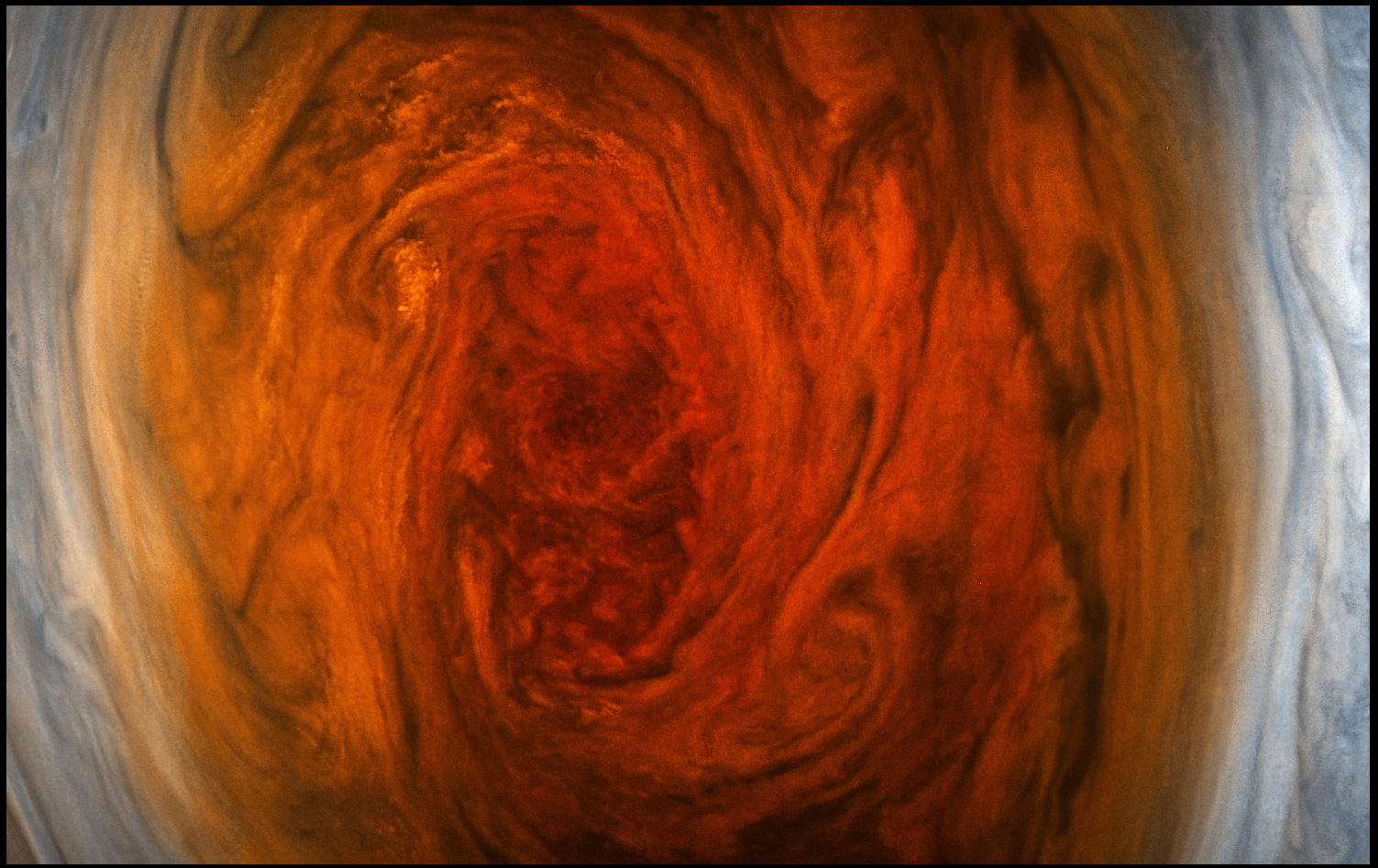
[Extraits de Amedee Guillemin "Le Ciel" 1877]

Shrinking of the Great Red Spot



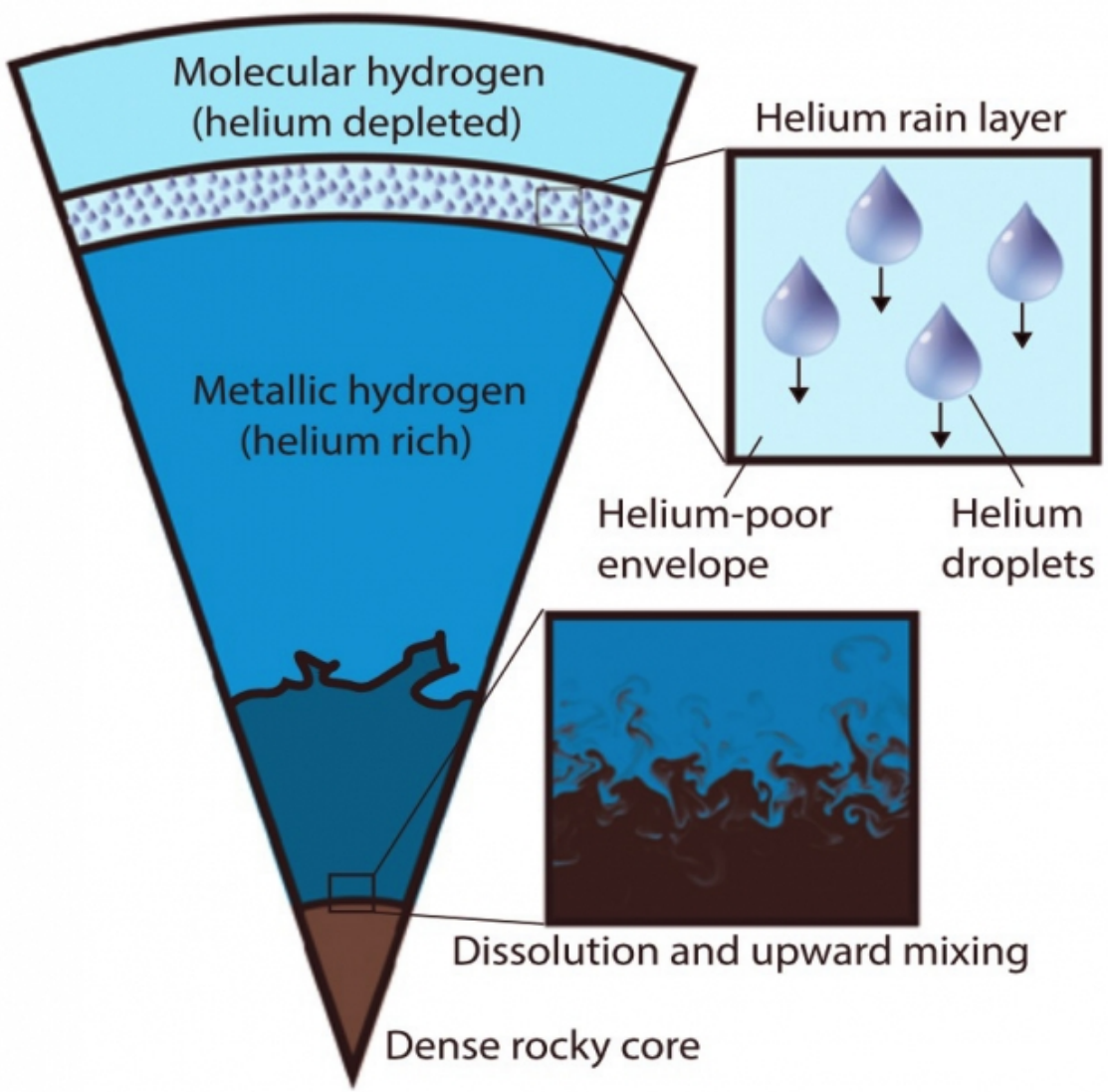
[Simon-Miller et al.]

Juno, nouvelles vues sur la Grande Tache Rouge



[Junocam image P07 (07-2017) NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstädt and Seán Doran]

Jupiter's interior structure



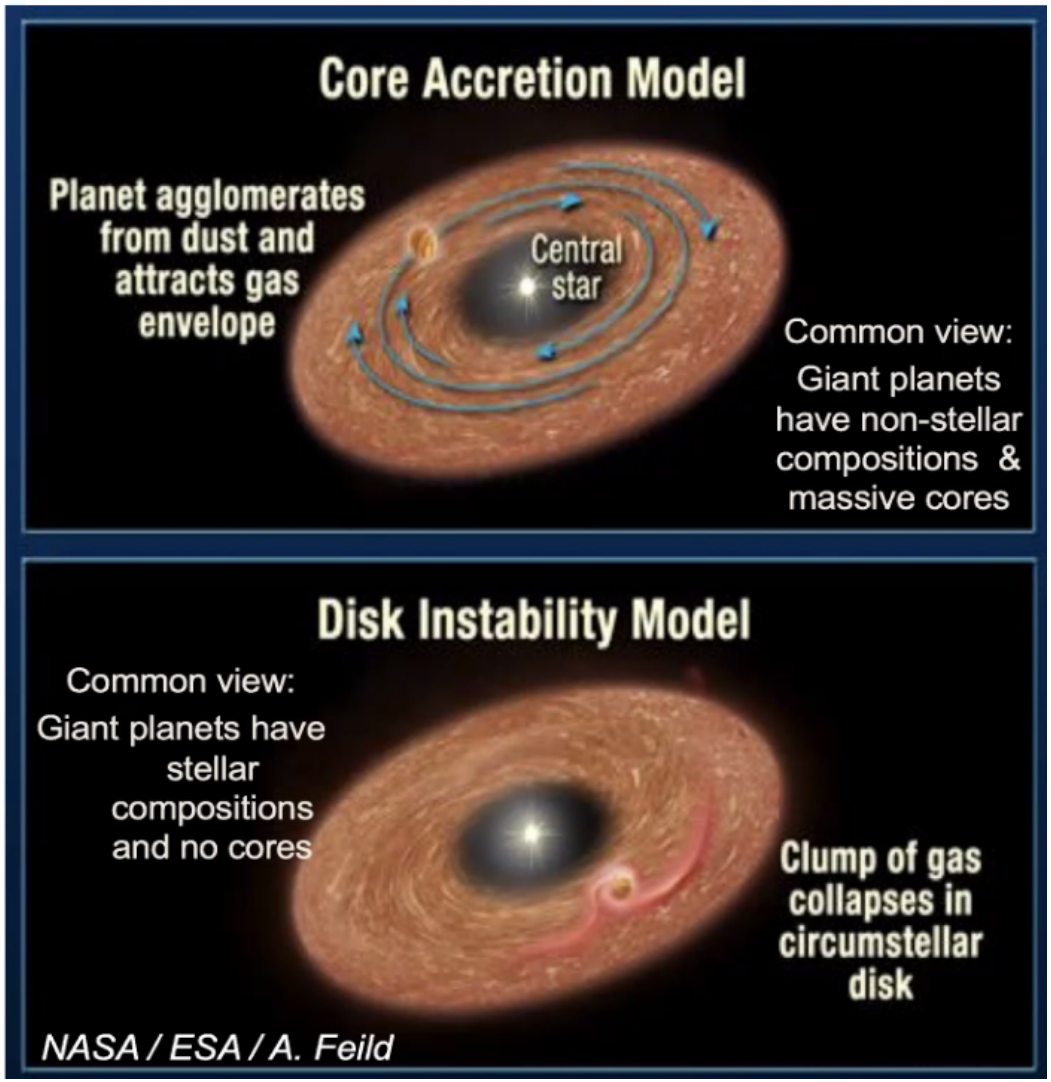
[Wahl et al. GRL 2017]

Giant Planet Formation

1. **Core accretion (standard):**
Planetesimal coagulation and core formation followed by accretion of a gaseous envelope.

2. **Disk instability:**
Formation as a result of gravitational instability and fragmentation in the proto-planetary disk.

*see review by Helled et al. 2014, Protostars & Planets VI



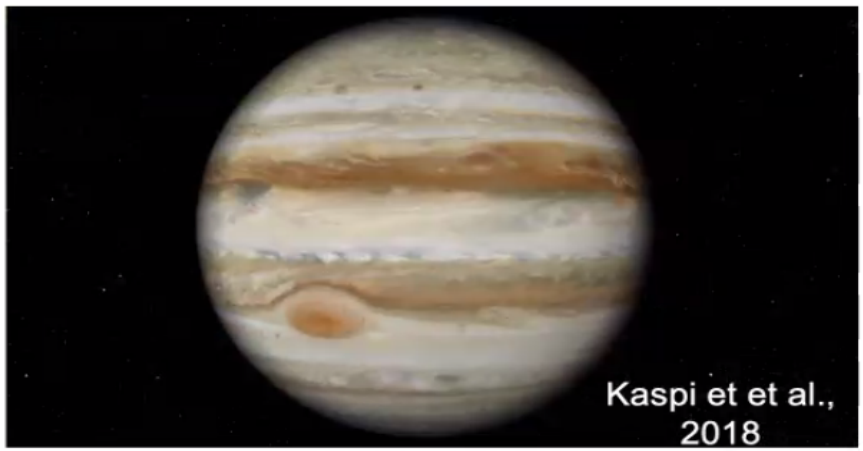
Results from the Juno mission

in orbit around Jupiter since 2016

Some other key recent Juno results..

JUNO

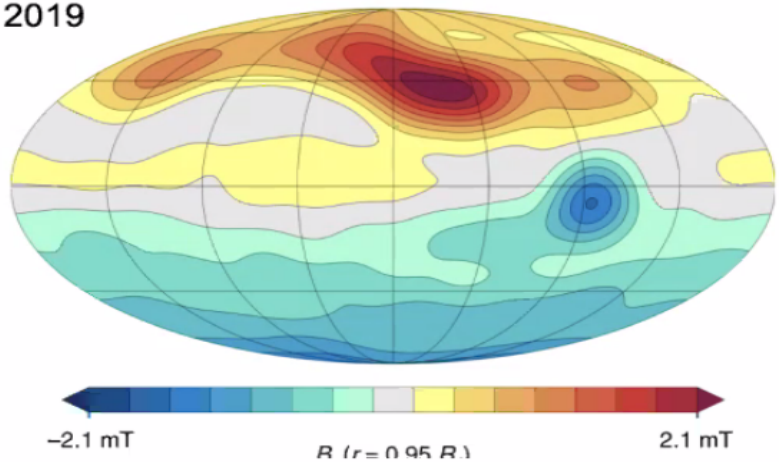
Constraining the depth of Jupiter's winds



Credit: NASA

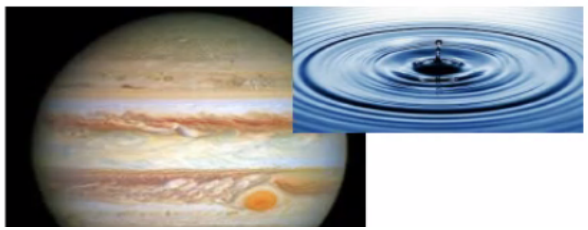
Jupiter's magnetic field
(a complex dynamo)

Moore et al.
2019



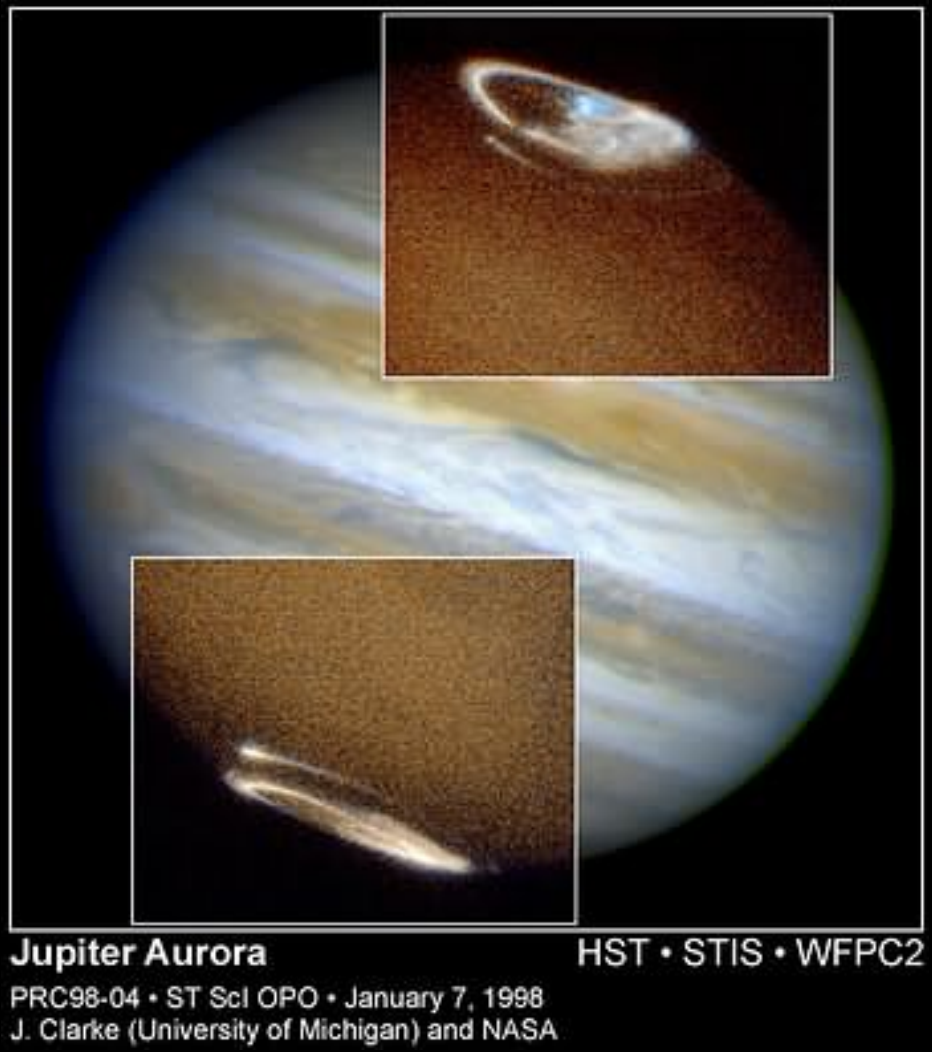
Atmospheric water abundance:
$2.7^{+2.4}_{-1.72}$ x solar

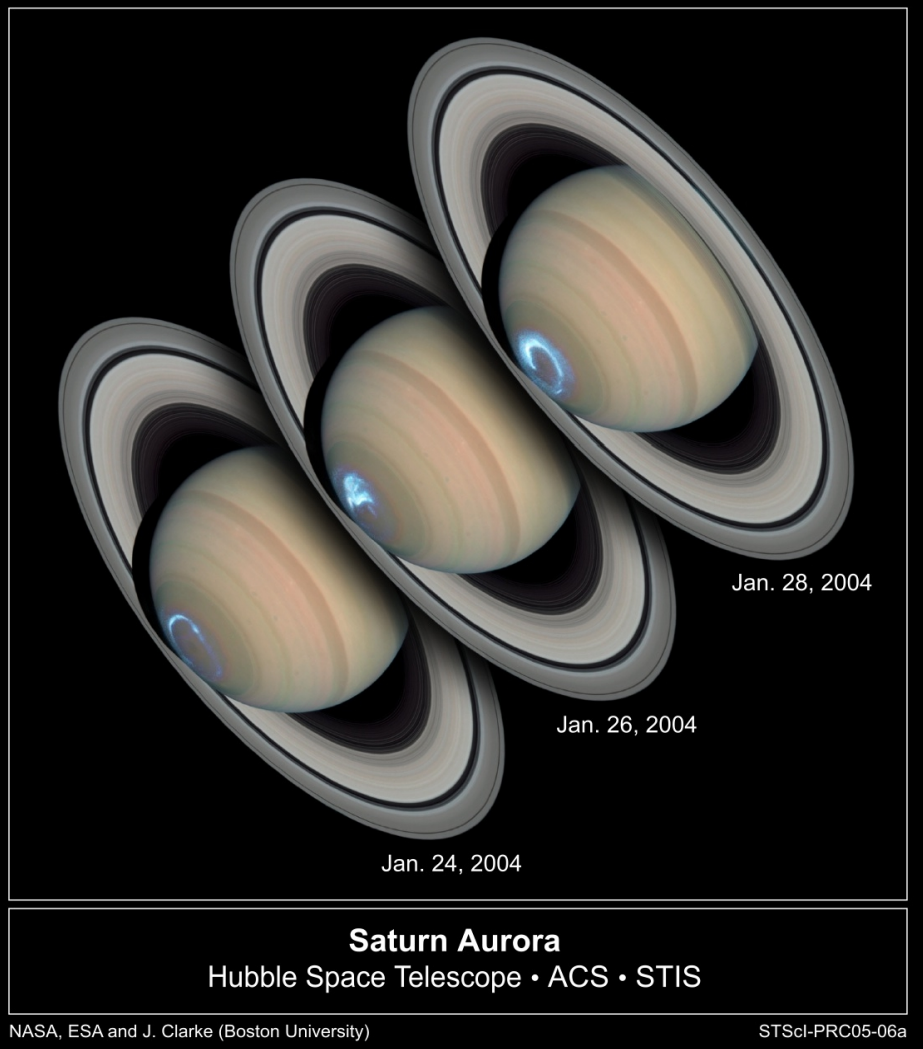
Li et al.
2020



and many more to come...

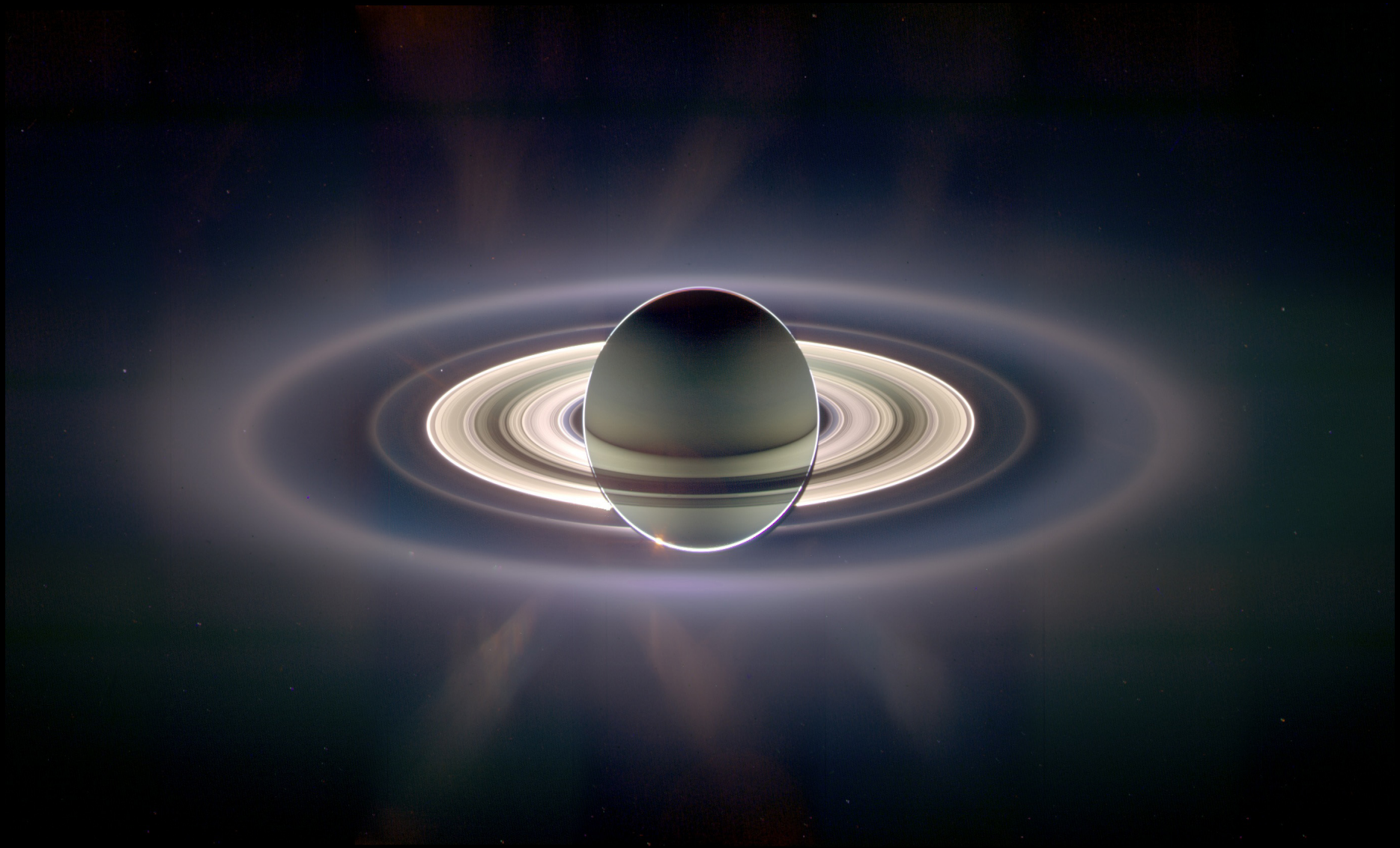
Aurores boréales sur les planètes géantes



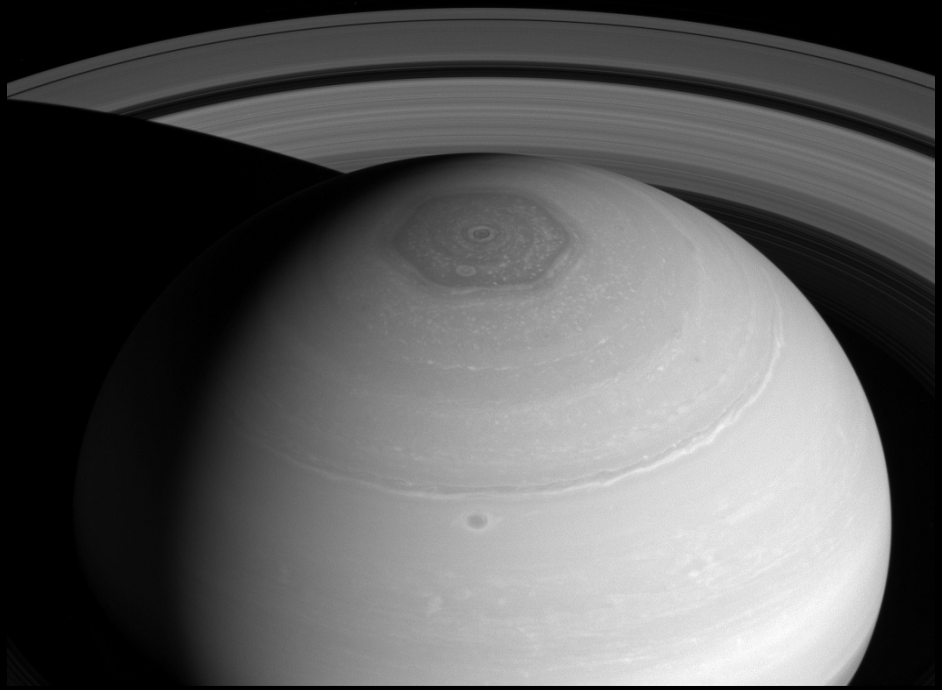


[Composite image HST visible/UV]

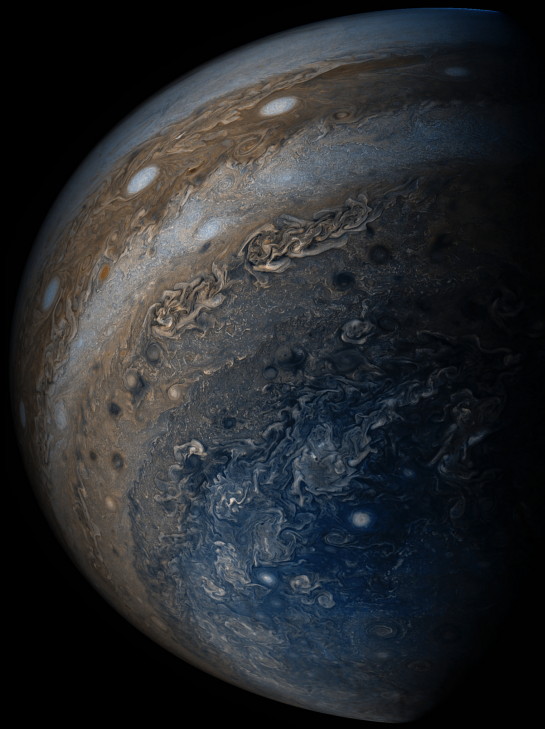
Saturne et ses anneaux (vue en éclipse par Cassini)



Les pôles contrastés de Jupiter et Saturne

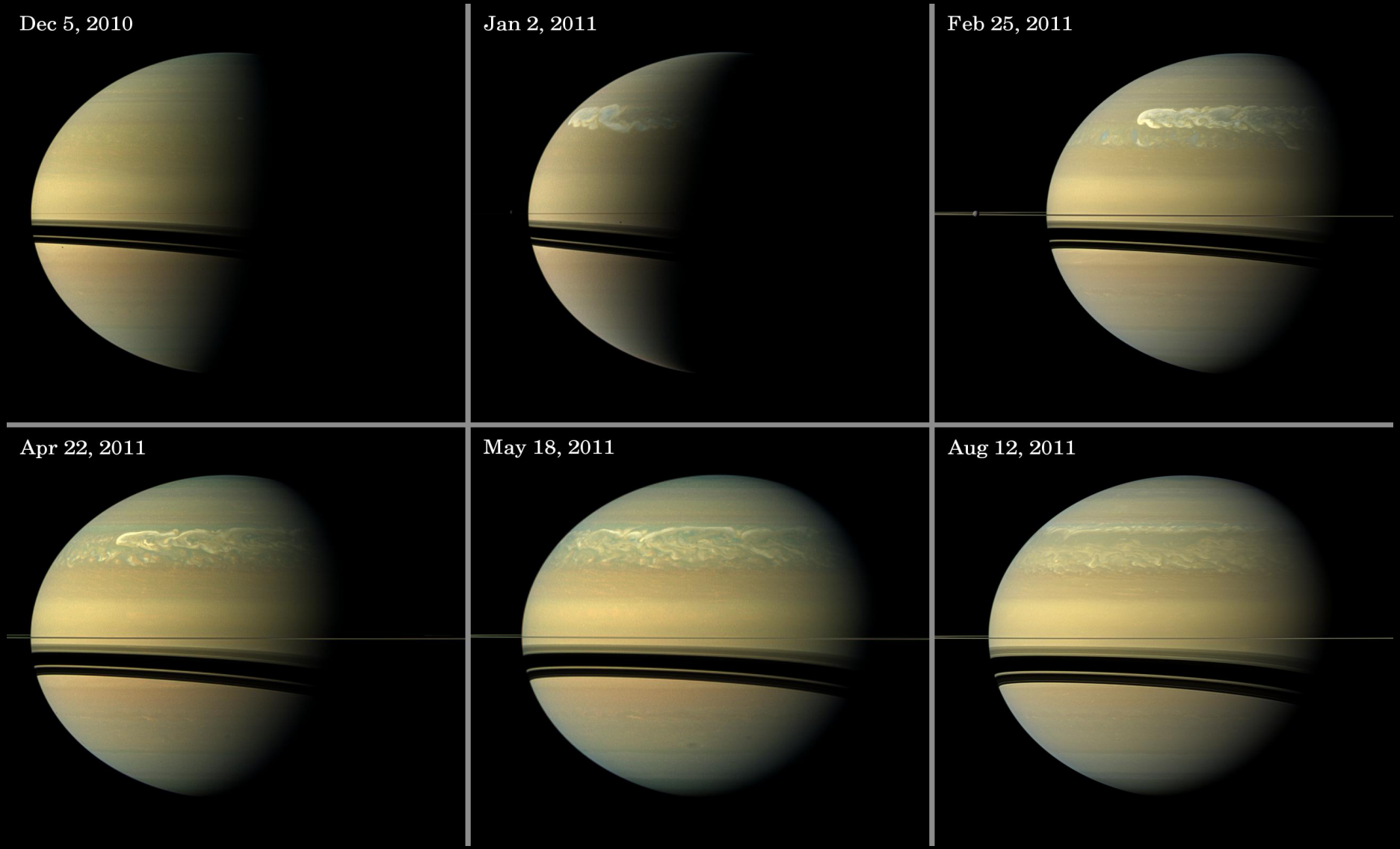


[Cassini ISS image of Saturn's northern pole]



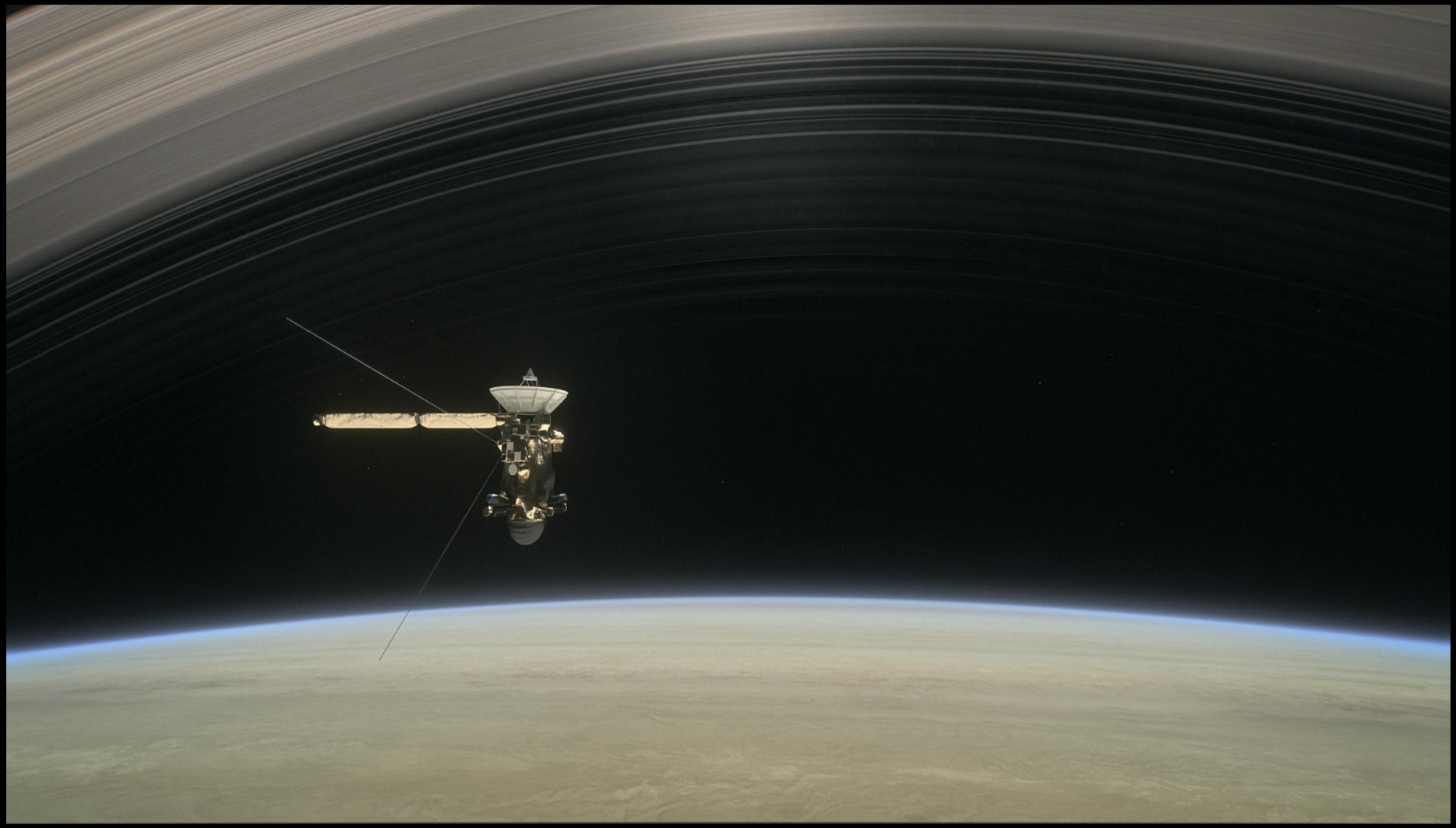
[Juno Junocam processed image]

Les orages géants sur Saturne *Great White Spots*

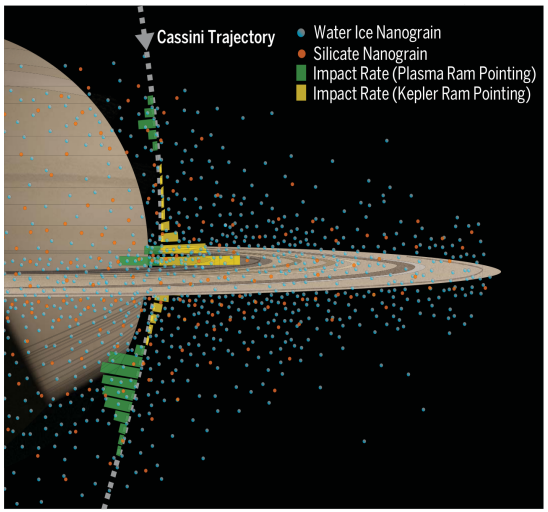


[Images Cassini-Huygens PIA14905]

Cassini “Grand Finale” solstice mission

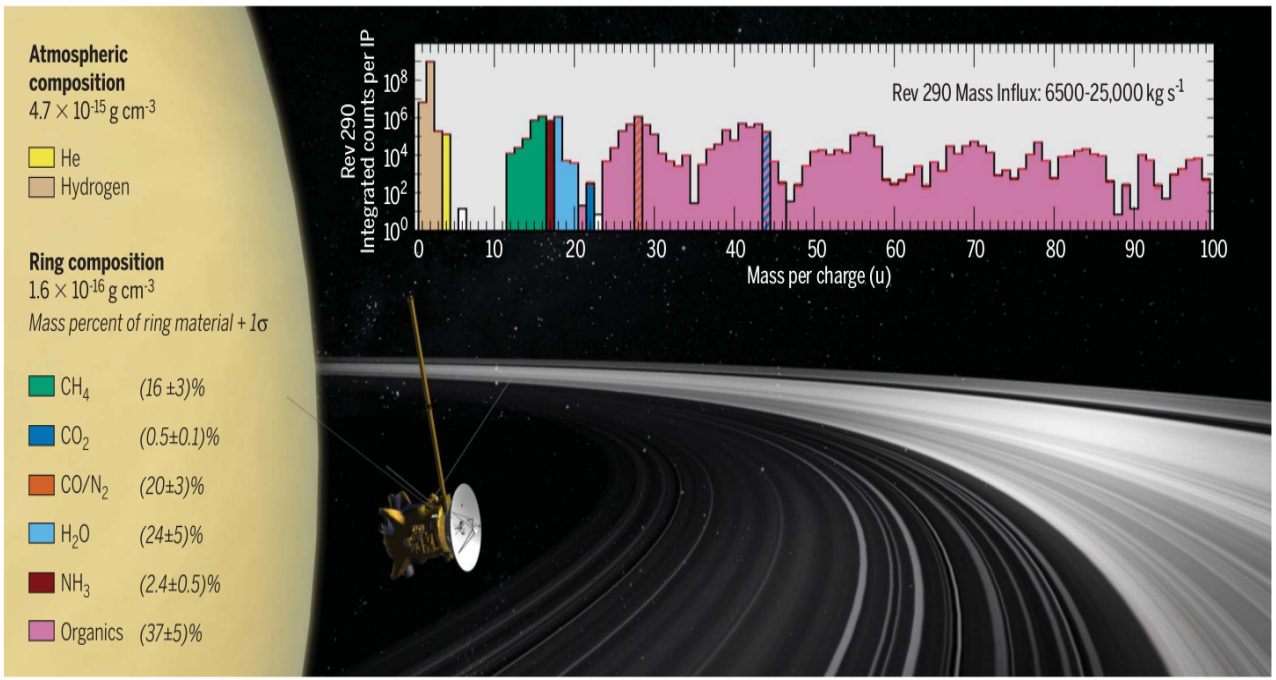


Cassini Grand Finale : travelling within "ring rain"



Schematic view of the nanometer-sized ring ejecta environment in the vicinity of Saturn. CDA measurements were taken during Cassini's Grand Finale mission. The measured dust flux profiles, presented by the histograms along the spacecraft trajectory, show different patterns depending on the instrument pointing configuration. The highest dust flux occurred at the ring plane under Kepler ram pointing (yellow). The profiles registered with plasma ram pointing (green) show two additional, mid-latitude peaks at both sides of the rings with substantial north-south asymmetry. This signature in the vertical profiles indicates that the measured nanograins in fact originate from the rings and are whirling into Saturn under the dynamical influence of the planet's offset magnetic field. Blue and orange dots represent the two grain composition types identified in the mass spectra, water ice and silicate, respectively.

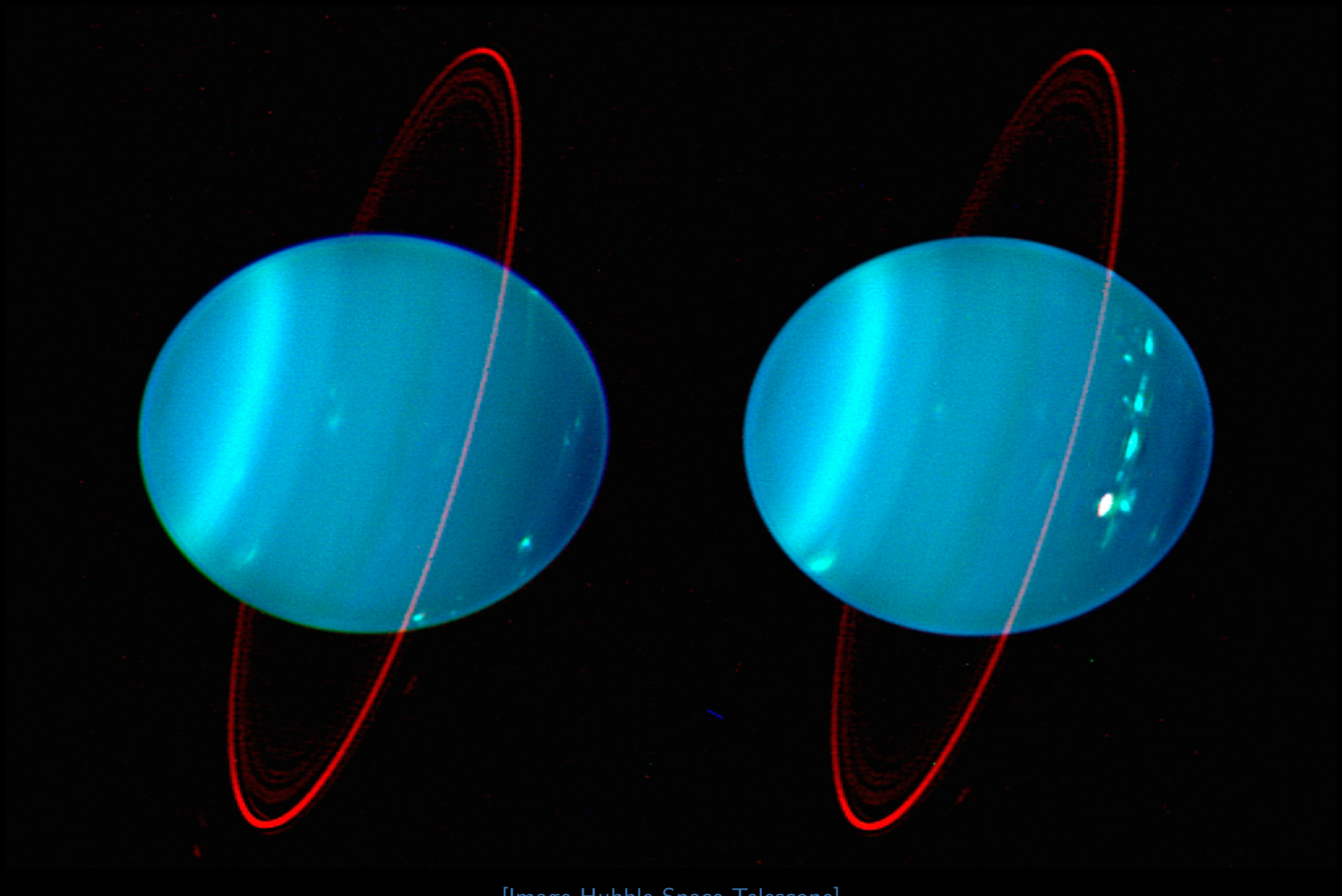
[Hsu et al. Science 2018]



INMS mass spectra from the Grand Finale. The graphic depicts the Cassini spacecraft as it passes from north to south between Saturn and its rings. The inset spectrum shows the mass deconvolution of compounds measured by INMS on rev 290. The *x* axis is in units of mass per charge (u) and extends over the full mass range of INMS (1 to 99 u). The *y* axis is in counts per measurement cycle integrated over the closest-approach data. The mass influx rate for rev 290, derived from mass deconvolution of the rev-integrated spectrum, is shown as embedded text in the spectrum. The side panel gives the average of the mass deconvolution of revs 290, 291, and 292 in mass density units (g cm^{-3}). The composition of the ring-derived compounds in terms of percentage mass density is also shown.

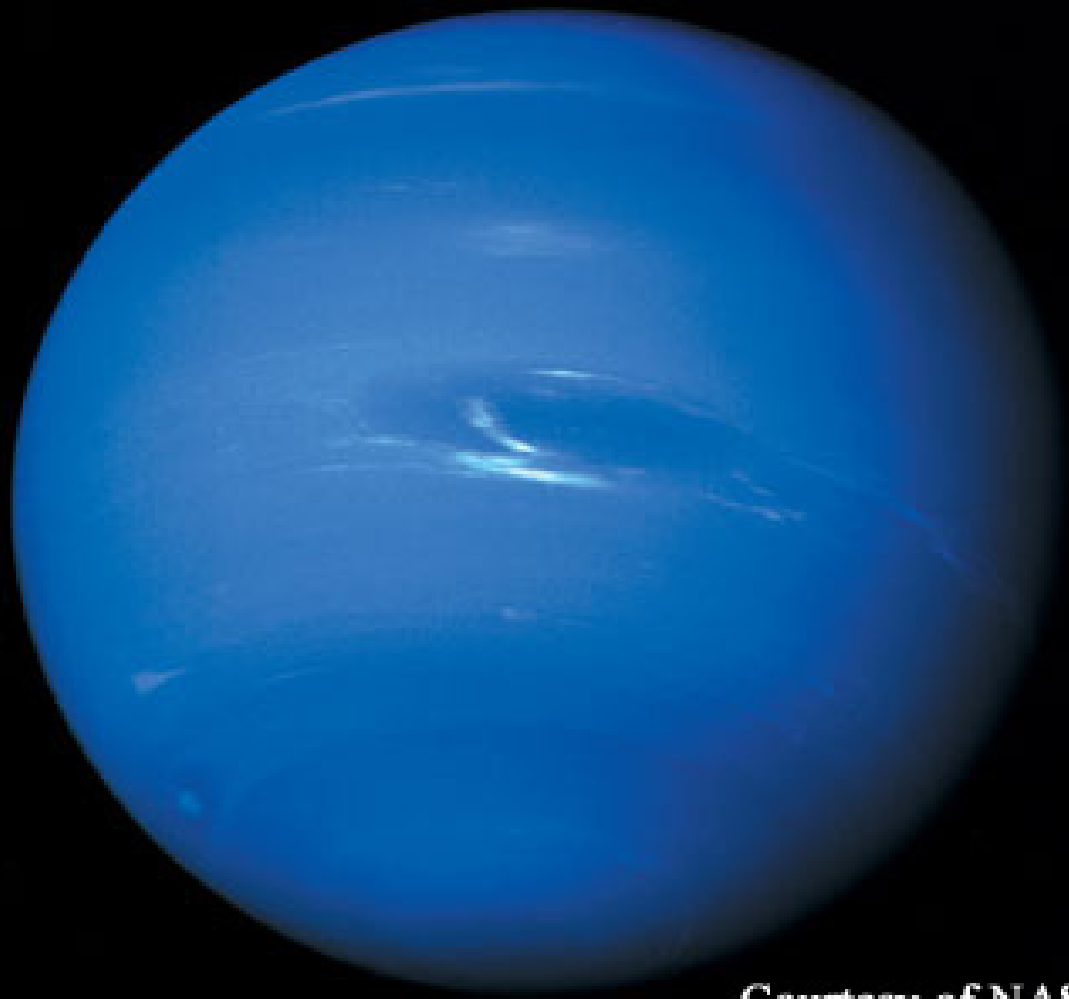
[Waite et al. Science 2018]

Uranus et ses nuages orageux



[Image Hubble Space Telescope]

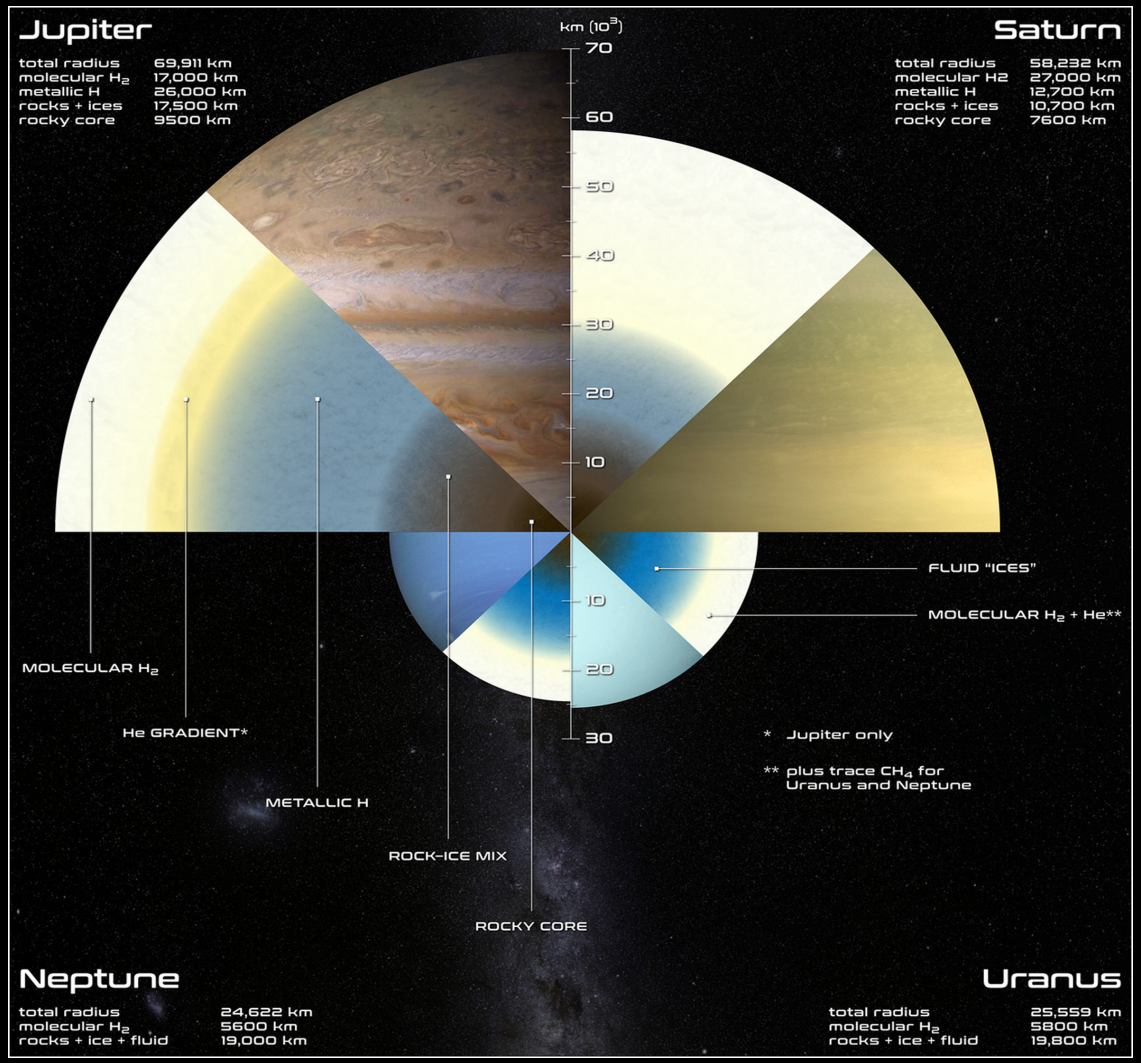
Neptune et son *Great Dark Spot* (image Voyager 2)



Neptune from ESO's VLT

[Narrow-Field adaptive optics mode of the MUSE/GALACSI instrument. ESO/P. Weilbacher (AIP).]

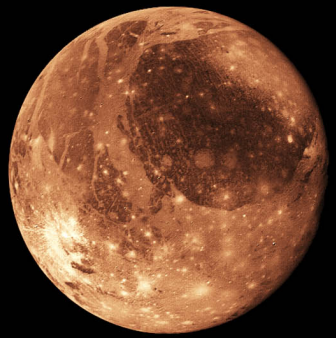
Internal structure of satellites of giant planets



[Kane et al. JGR planets 2021]

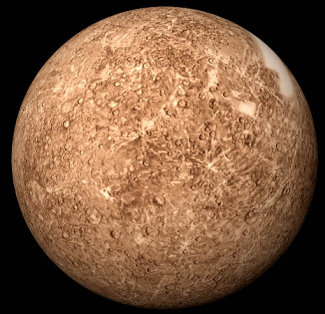
Plan

Les plus grandes lunes et les plus petites planètes



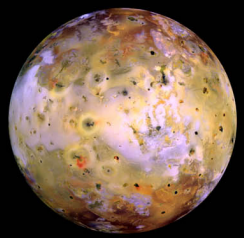
Ganymede
5262 km

Titan
5150 km



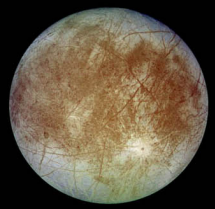
Mercury
4880 km

Callisto
4806 km

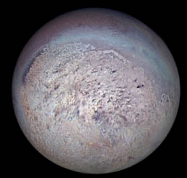


Io
3642 km

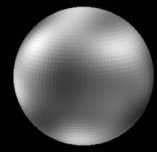
Moon
3476 km



Europa
3138 km



Triton
2706 km

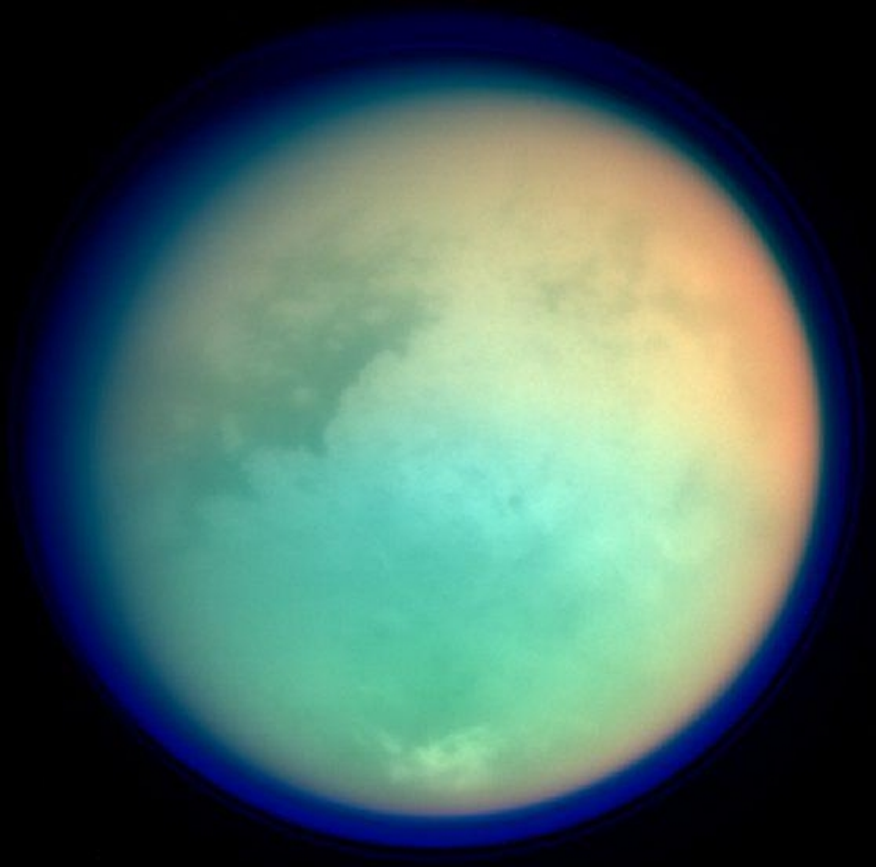


Pluto
2300 km

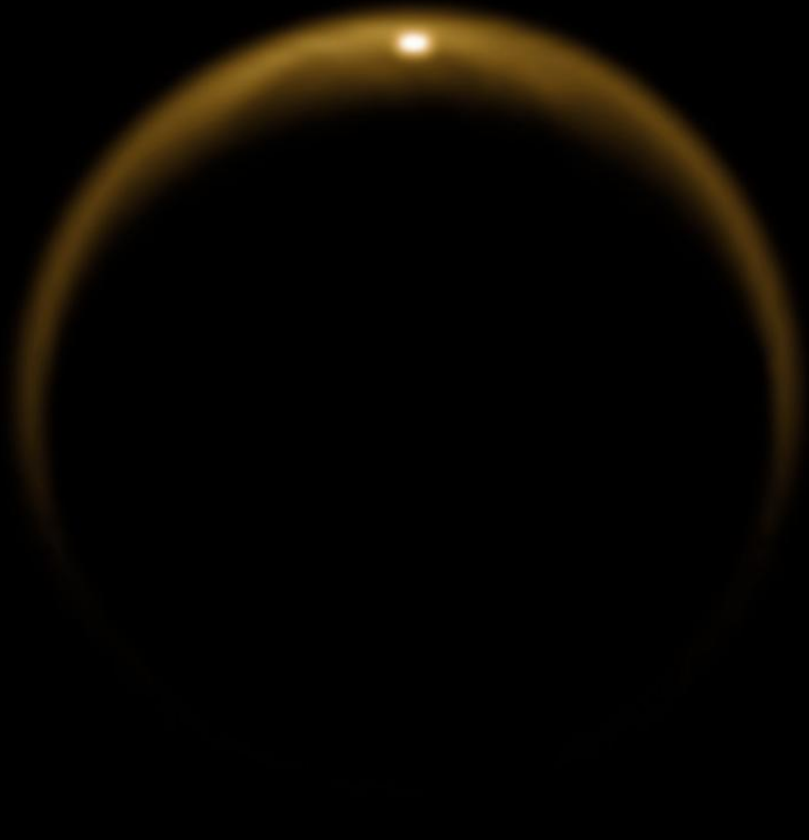
Titania
1580 km

The Largest Moons and Smallest Planets

Titan

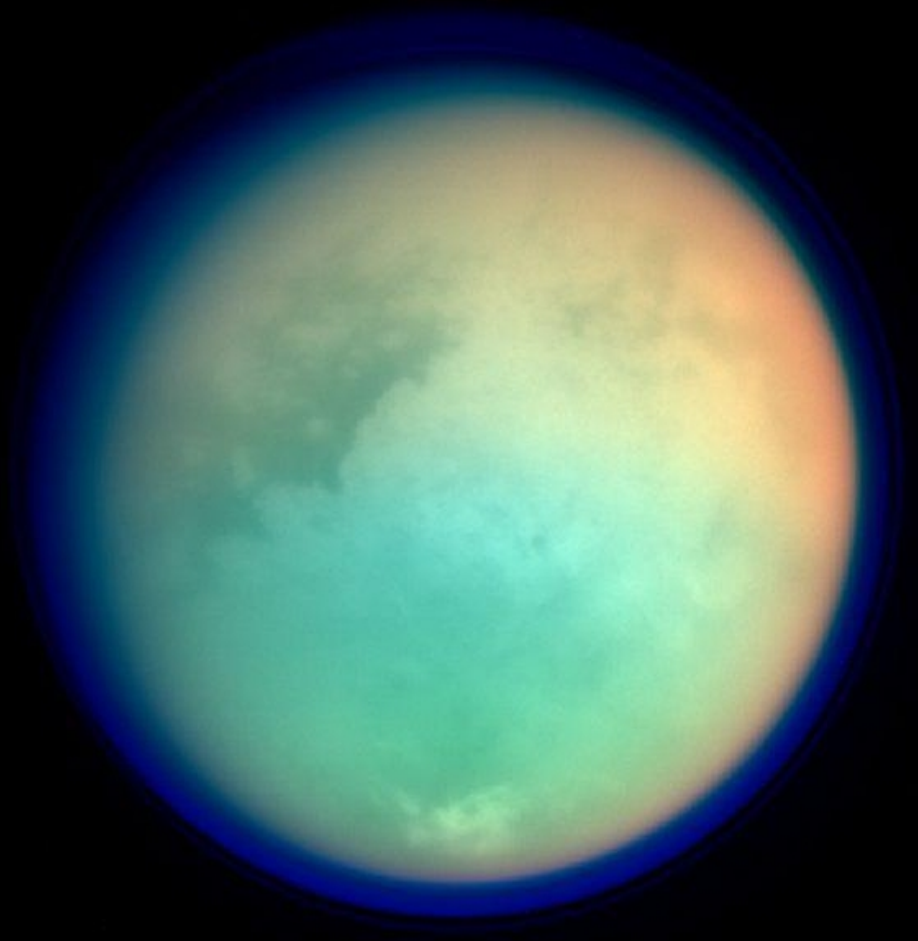


[Cassini-Huygens, 2004]

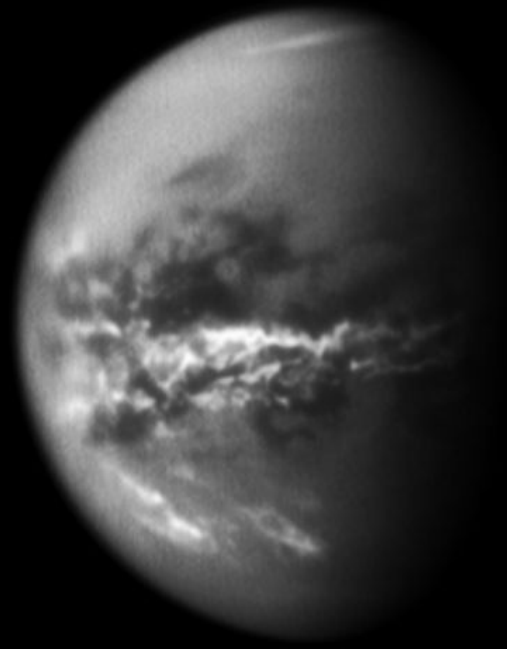


[Cassini-Huygens, 2009 ; Stephan et al., 2010]

Sur Titan, un cycle du méthane



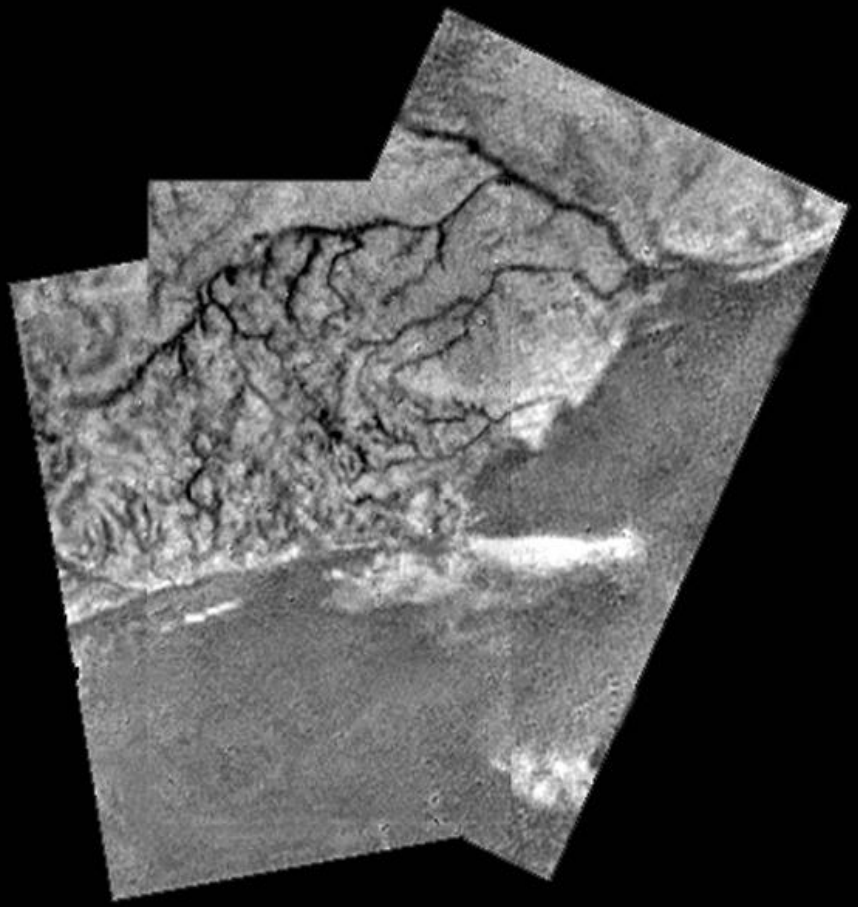
[Cassini-Huygens, 2004]



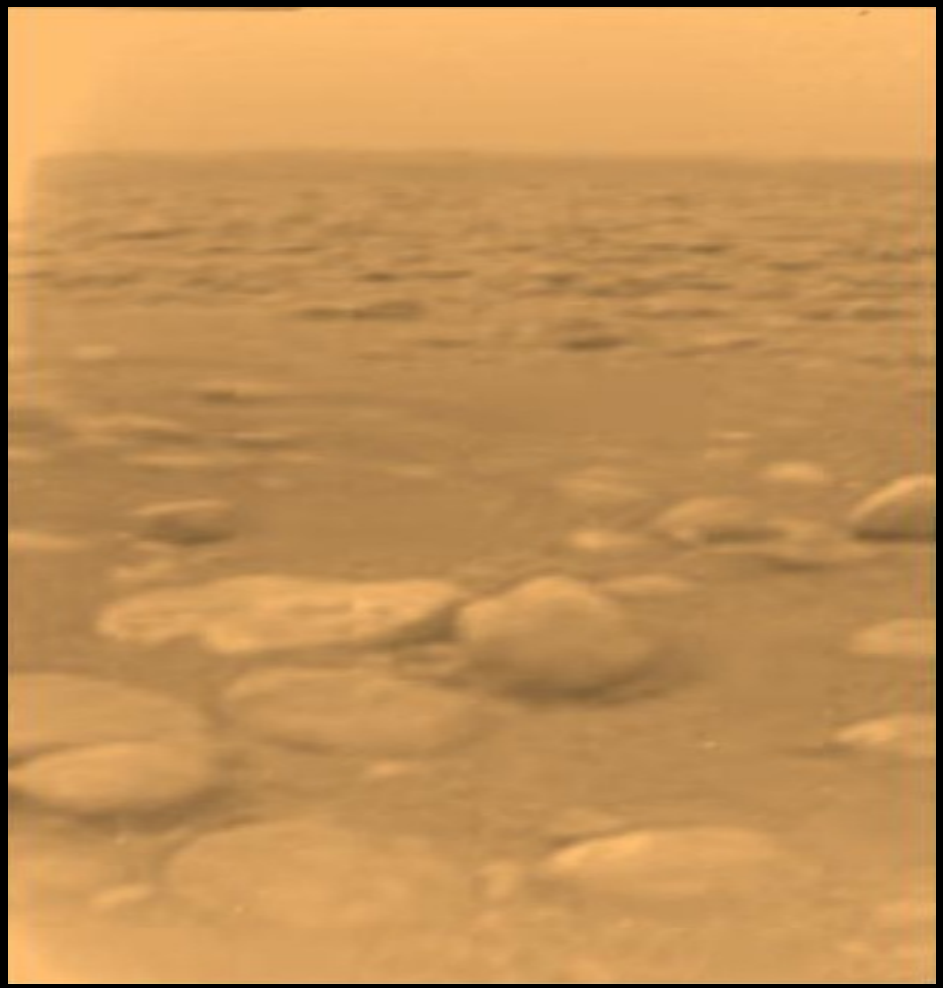
[Cassini-Huygens, 2010]

Titan : DISR imagery from the Huygens probe

Fluvial valleys (scene 15 km)

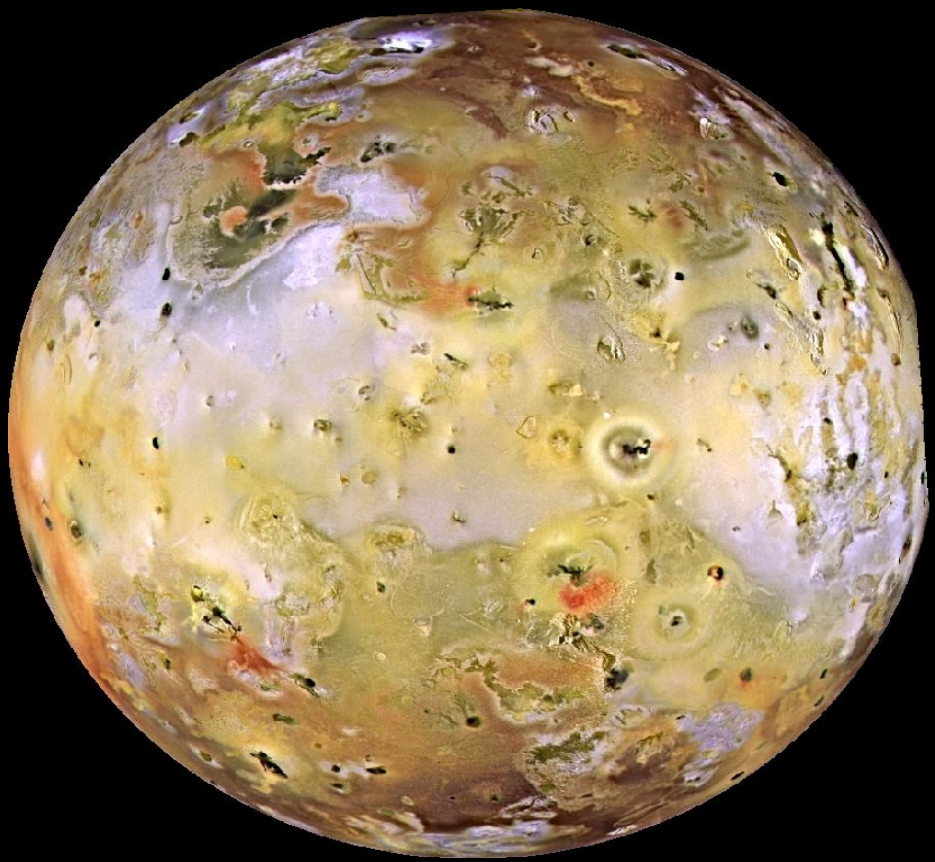


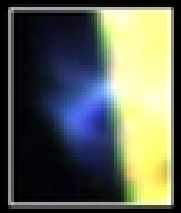
Surface (pebbles 5-10 cm)

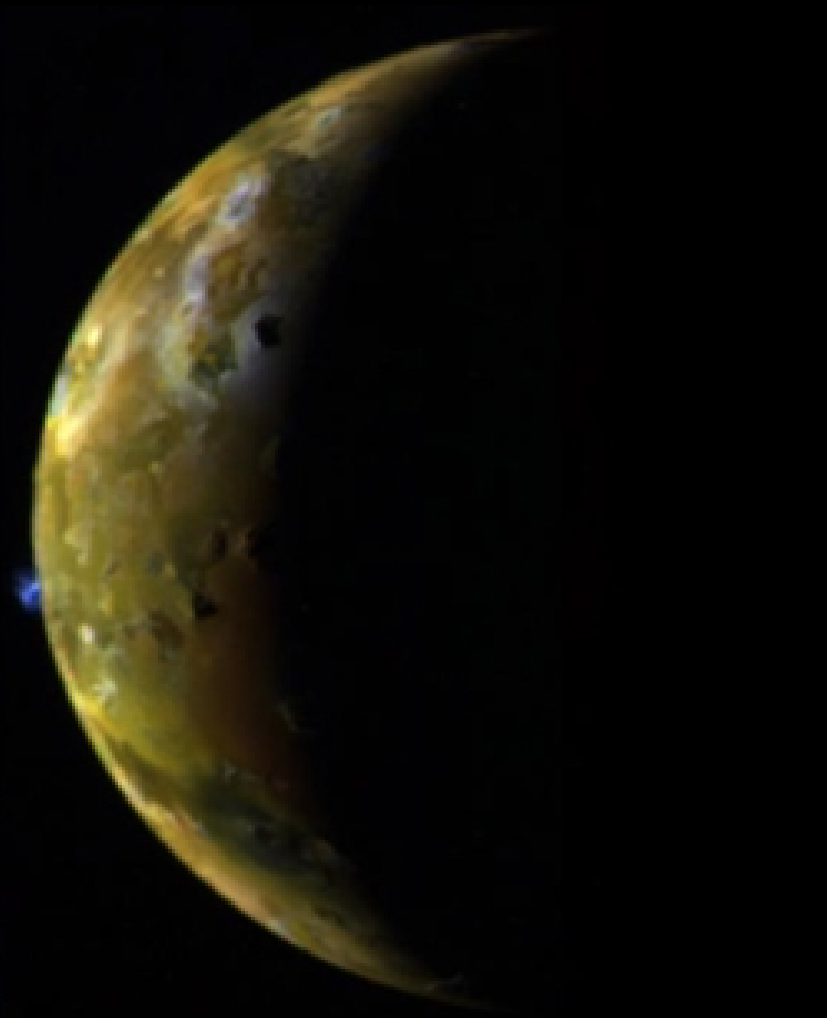


[left : PIA07236, right : PIA07232]

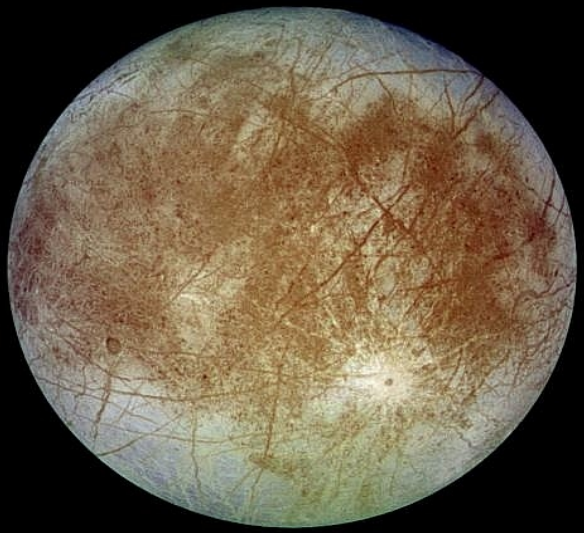
Io et son volcanisme intense (images de Galileo)

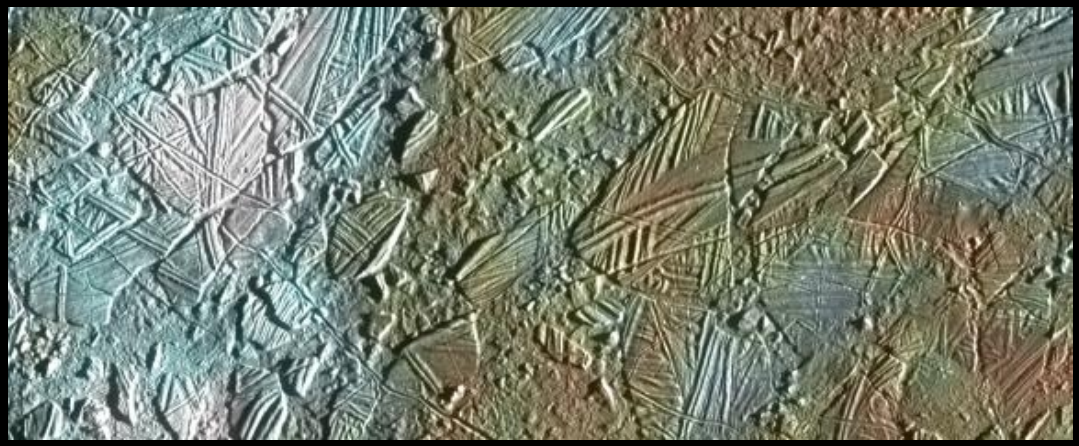


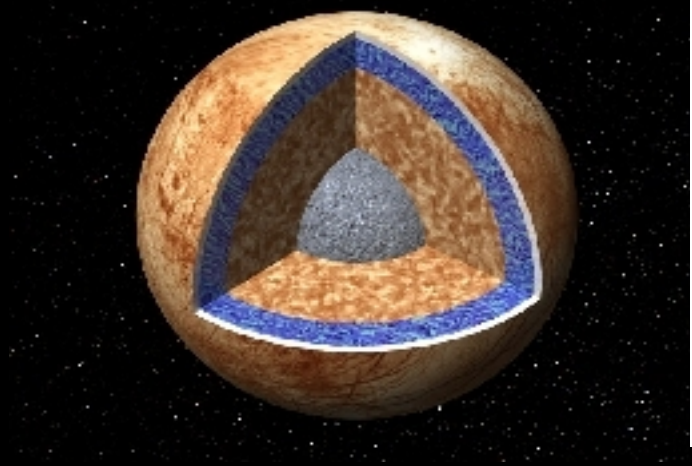


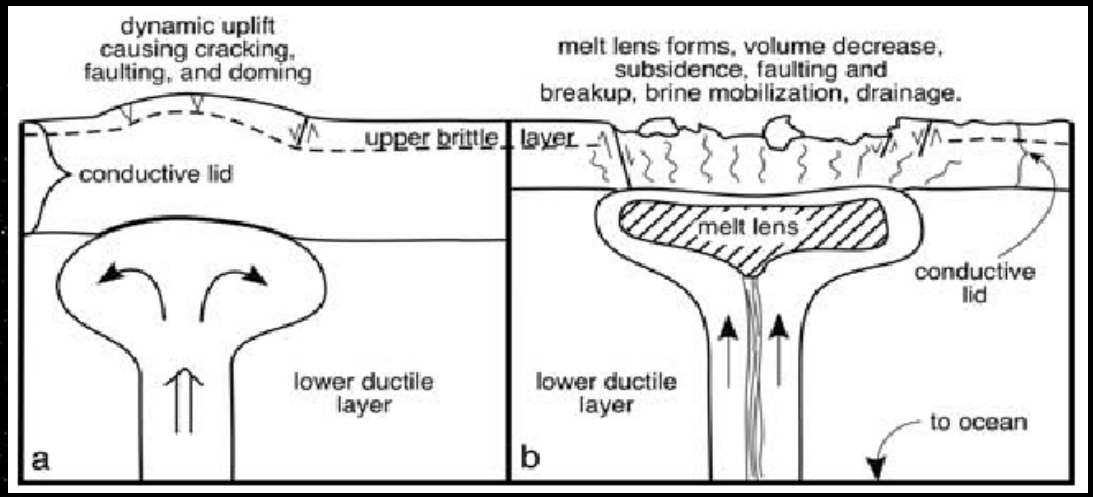


Europe









Sotin et al. 2002

Autres satellites de Jupiter

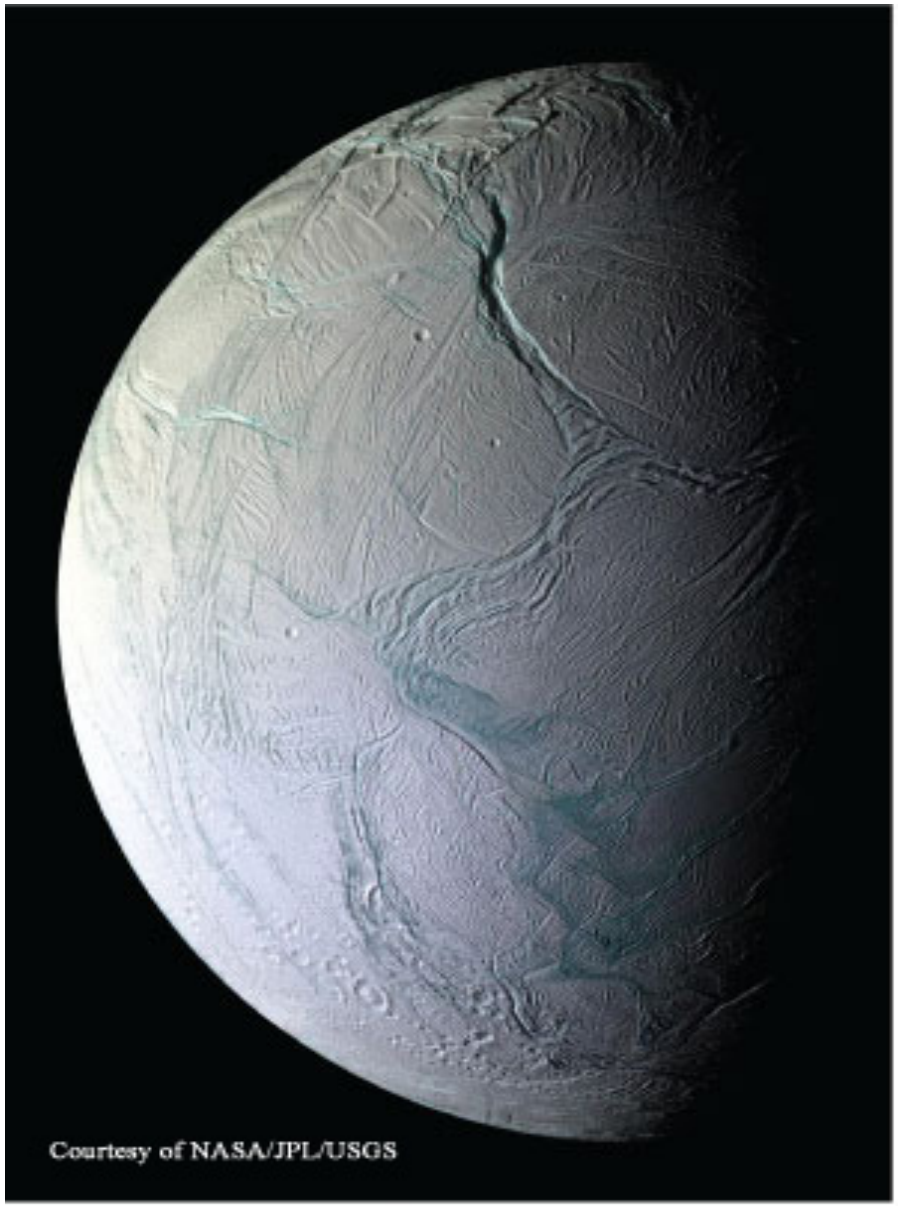
Ganymède

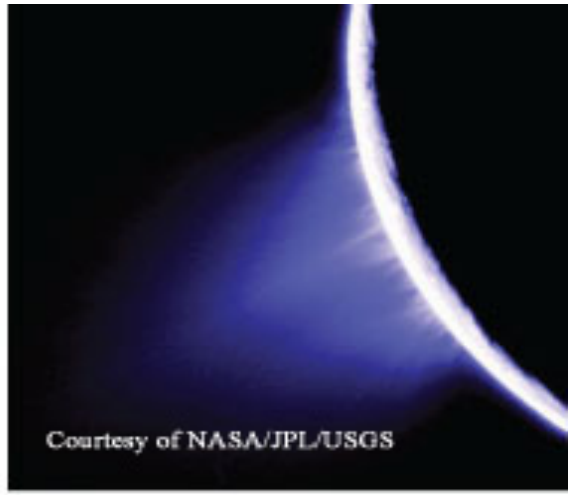
Courtesy of NASA

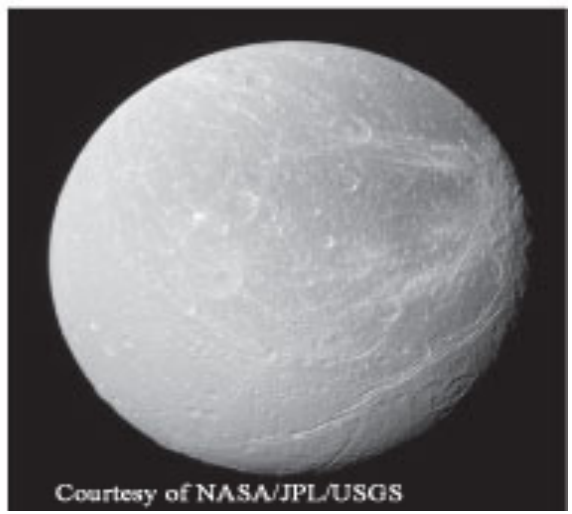
Callisto

Courtesy of NASA

Cryo-volcanisme sur Encelade et Dione

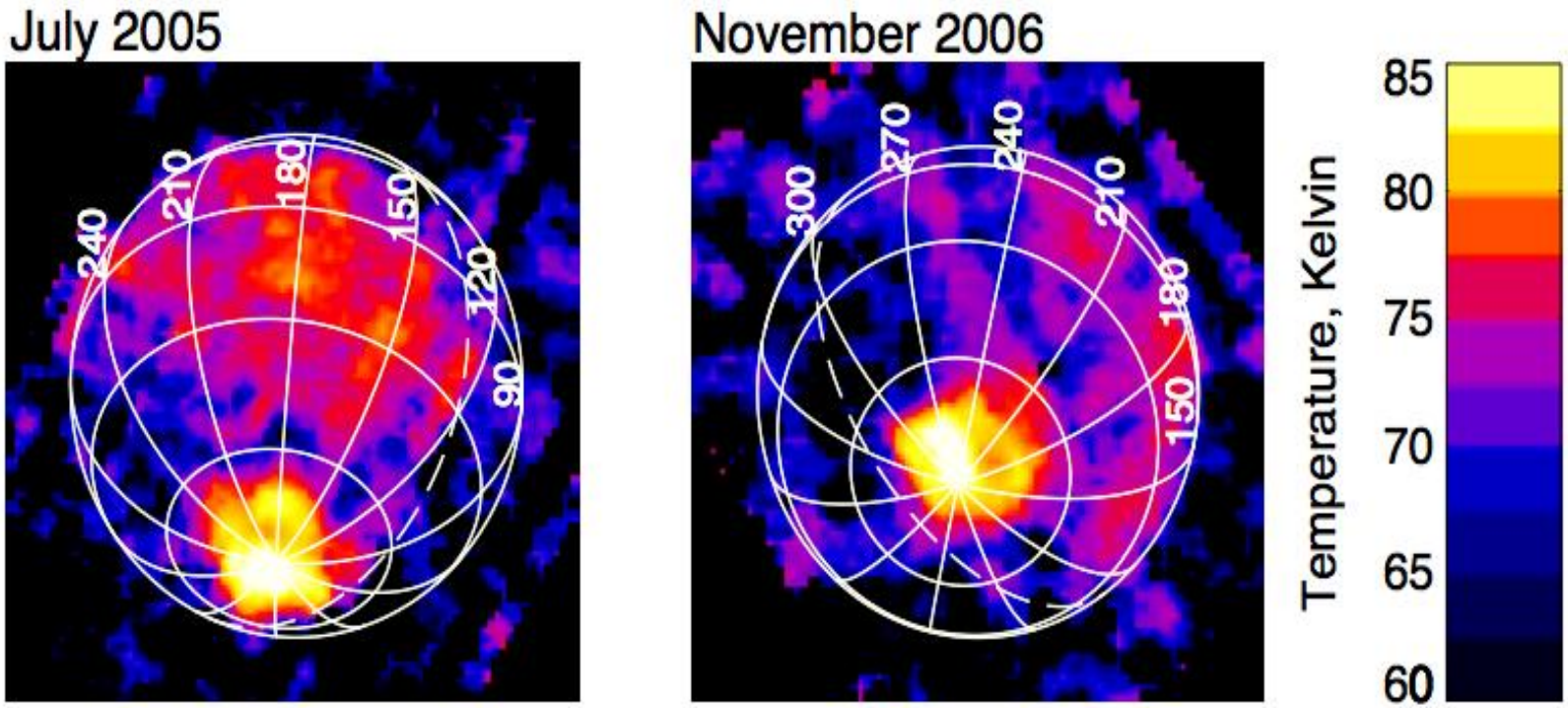






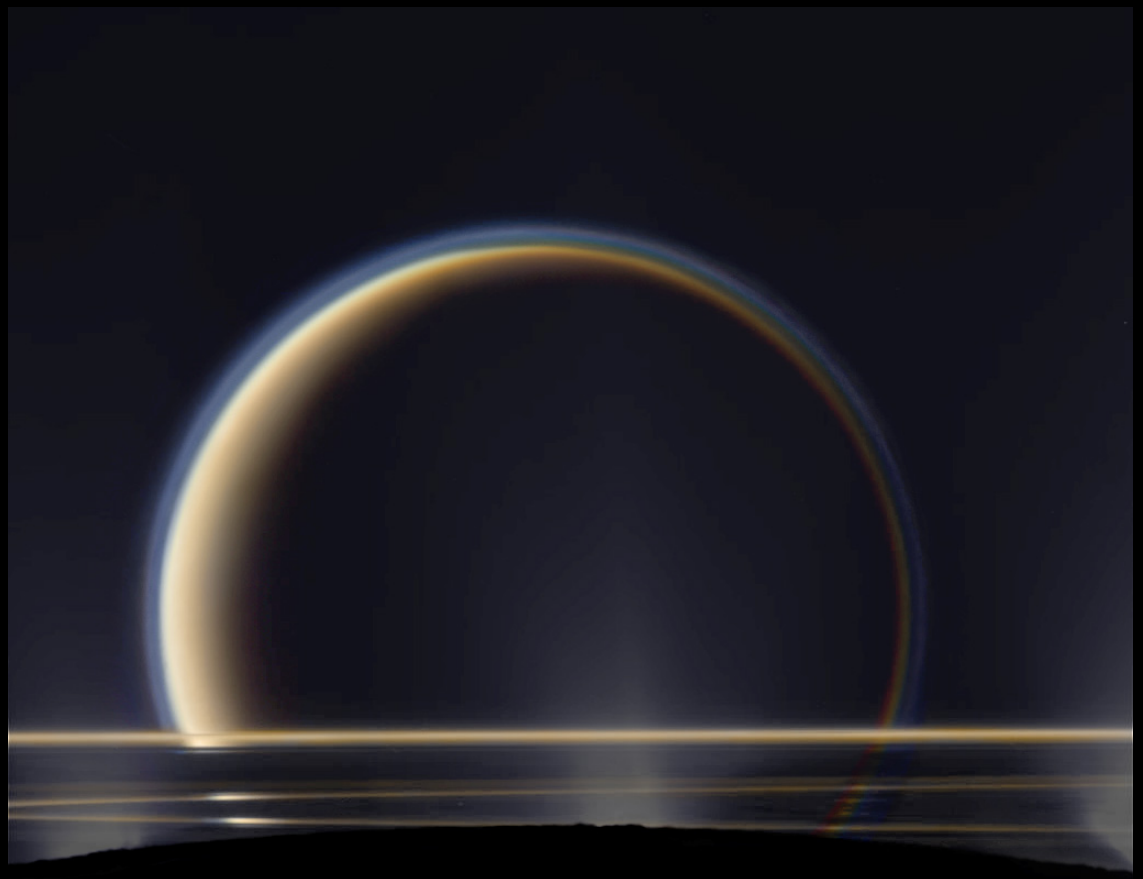
Tidal forcing on Enceladus' south pole

Surface temperature 15 K than expected



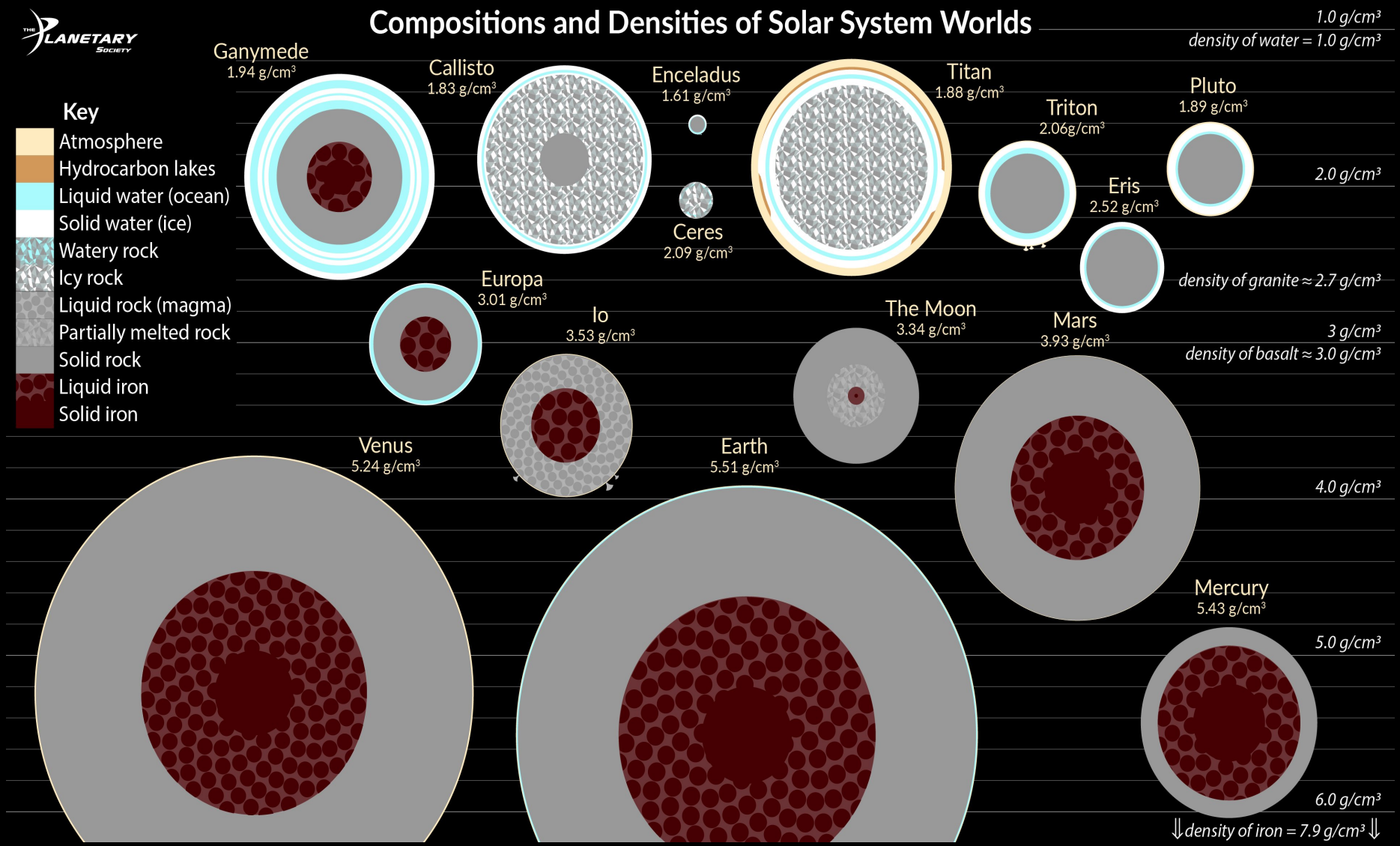
[Cassini Composite InfraRed Spectrometer map PIA09037]

Image Cassini : 2 lunes et les anneaux de Saturne



NASA/JPL-Caltech/Space Science Institute/Don Davis

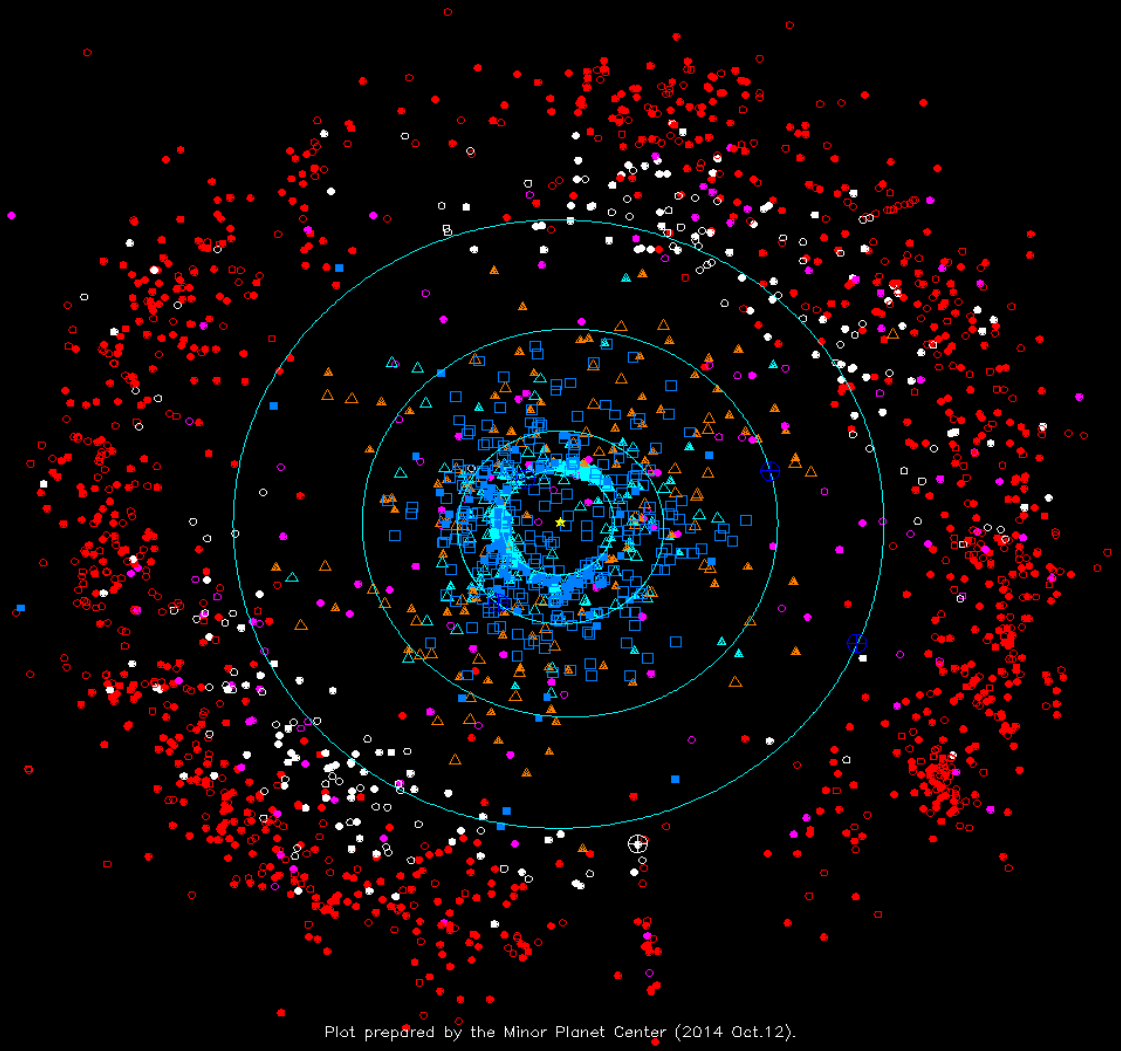
[Colorisé d'après une image originale Cassini noir & blanc]


Compositions and Densities of Solar System Worlds
Key
Atmosphere
Hydrocarbon lakes
Liquid water (ocean)
Solid water (ice)
Watery rock
Icy rock
Liquid rock (magma)
Partially melted rock
Solid rock
Liquid iron
Solid iron
Ganymede 1.94 g/cm³
Callisto 1.83 g/cm³
Enceladus 1.61 g/cm³
Ceres 2.09 g/cm³
Titan 1.88 g/cm³
Triton 2.06g/cm³
Pluto 1.89 g/cm³
Eris 2.52 g/cm³
Europa 3.01 g/cm³
Io 3.53 g/cm³
The Moon 3.34 g/cm³
Mars 3.93 g/cm³
Venus 5.24 g/cm³
Earth 5.51 g/cm³
Mercury 5.43 g/cm³
1.0 g/cm³
density of water = 1.0 g/cm³
2.0 g/cm³
density of granite ≈ 2.7 g/cm³
3 g/cm³
density of basalt ≈ 3.0 g/cm³
4.0 g/cm³
5.0 g/cm³
6.0 g/cm³
⇓density of iron = 7.9 g/cm³⇓

Plan

Ceinture de Kuiper

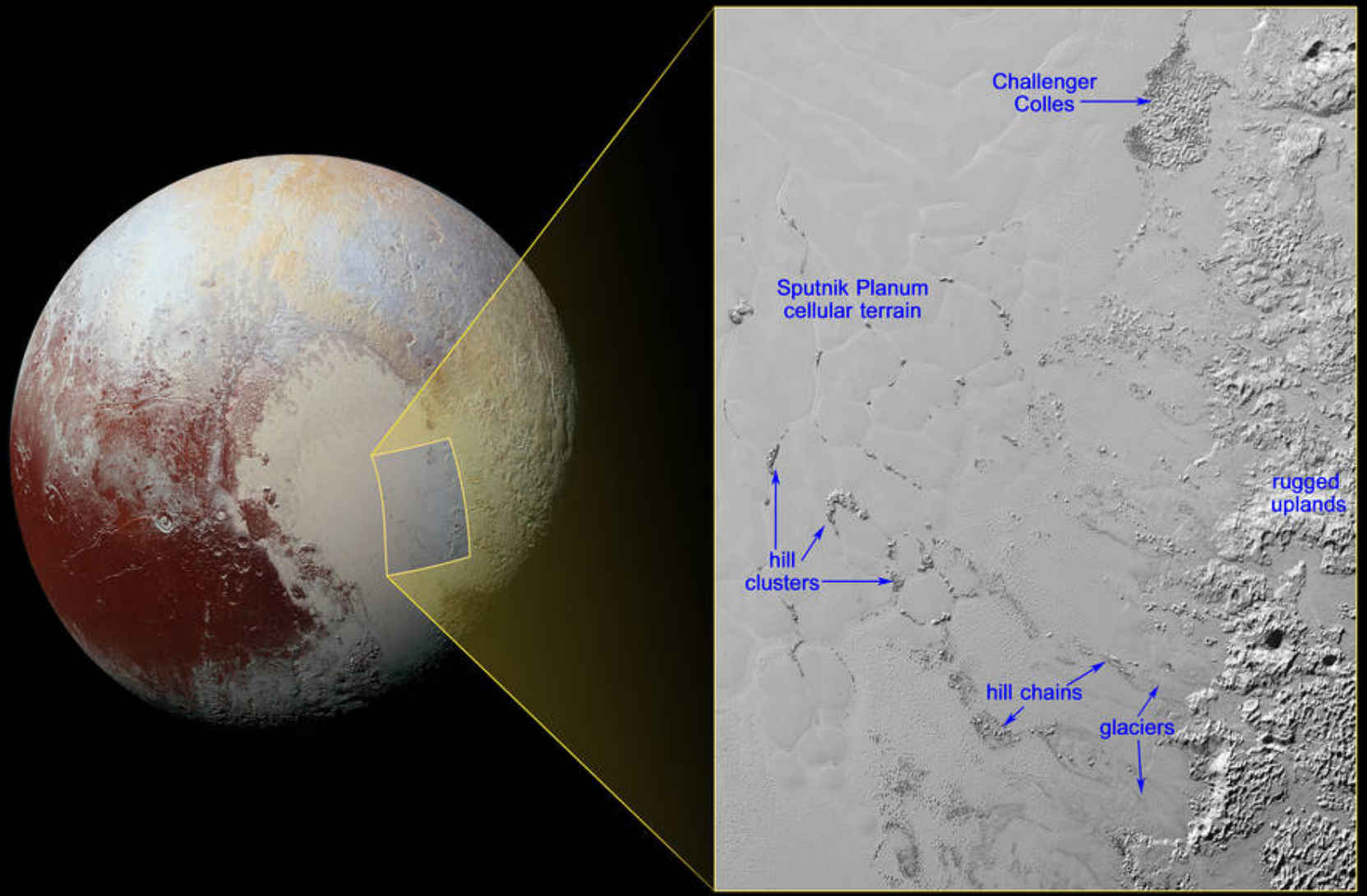
Objets trans-neptuniens



Survol de Pluton+Charon par New Horizons

14 juillet 2015

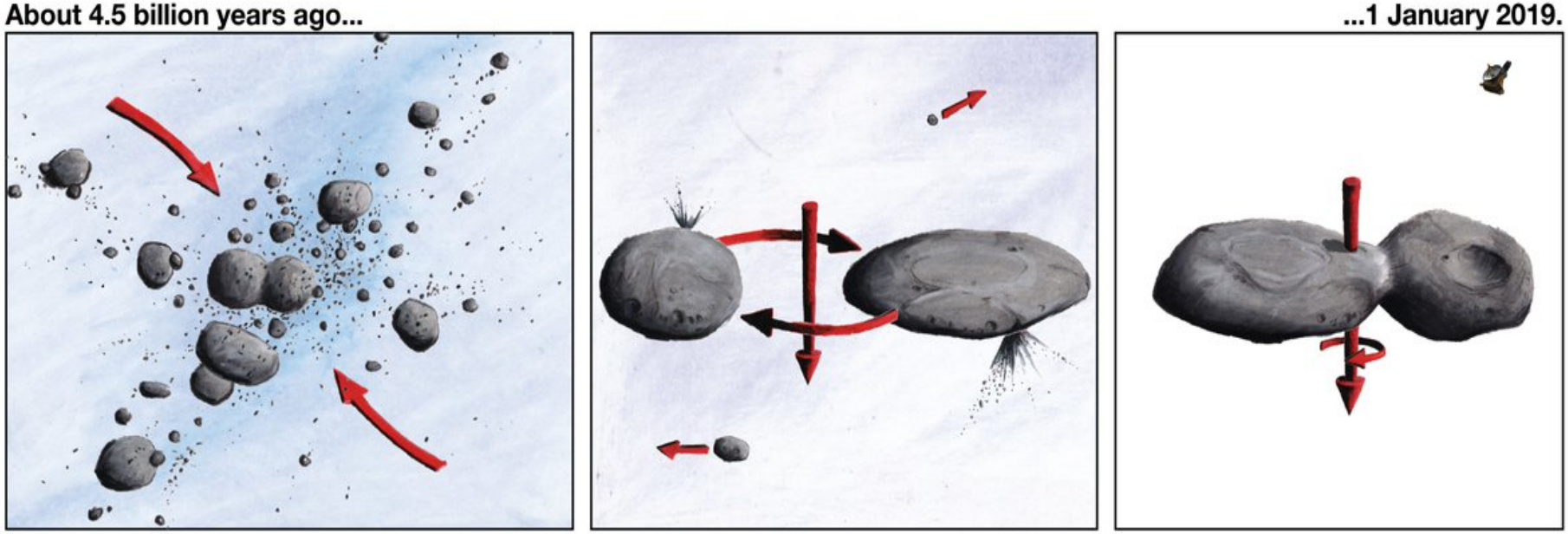
Sputnik Planitia seen by New Horizons



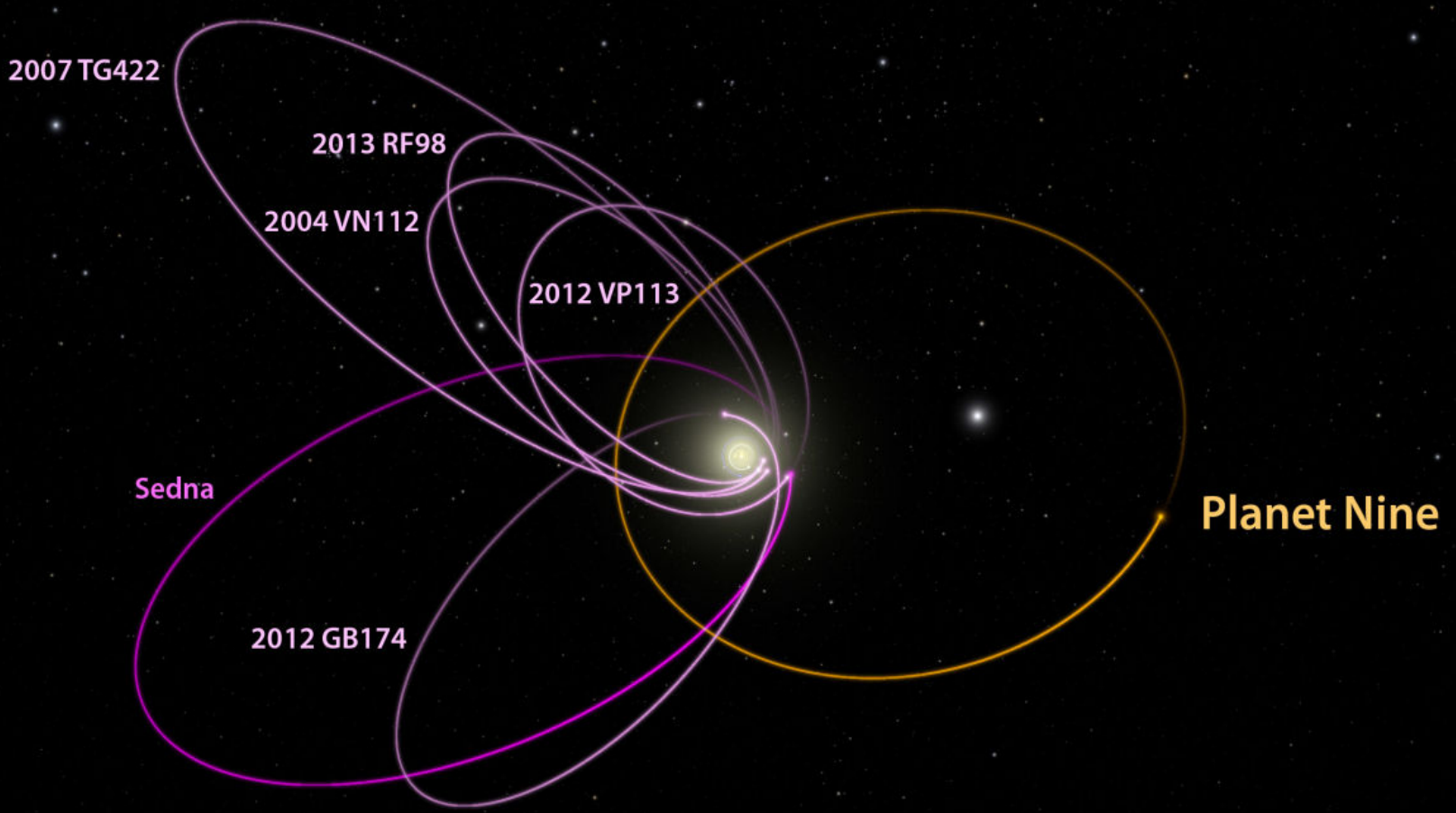
Arrokoth, Kuiper Belt Object

Visited by New Horizons on January 1st 2019, farthest object explored

The Formation of 2014 MU69



Planet Nine ?



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