



Exploration of habitable worlds in the solar system

Athena Coustenis

LIRA, Paris-Observatory, PSL, Univ. Sorbonne, FR

Ecole Joliot Curie 2026
13 September, Ile d'Oléron



Why space? A privileged tool for exploration and more...

- ❑ Space exploration for the benefit of scientists and citizens
 - Satisfy the need to know and learn
 - Satisfy the natural curiosity of humans that can only be achieved from space
- ❑ Mobilize resources space offers for energetic transitions
- ❑ Resources and applications of space discoveries (medicine etc)
- ❑ space for cooperation but also in competition

"πάντες ἄνθρωποι τοῦ εἰδέναι ὀρέγονται φύσει"
("Tous les hommes désirent par nature savoir")

- Aristote, *Métaphysique*, 1.980a.22)

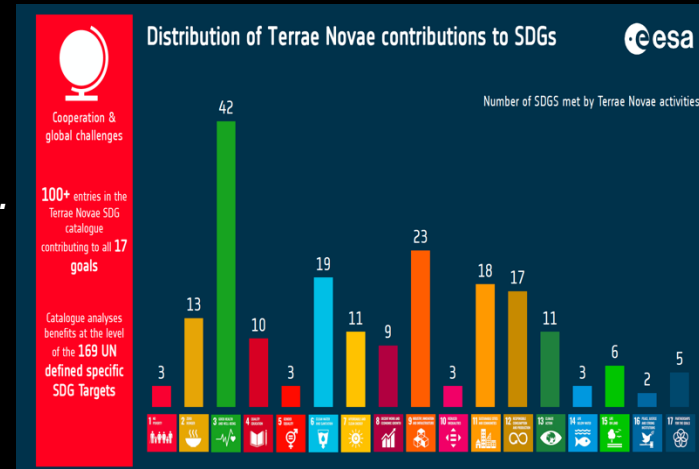


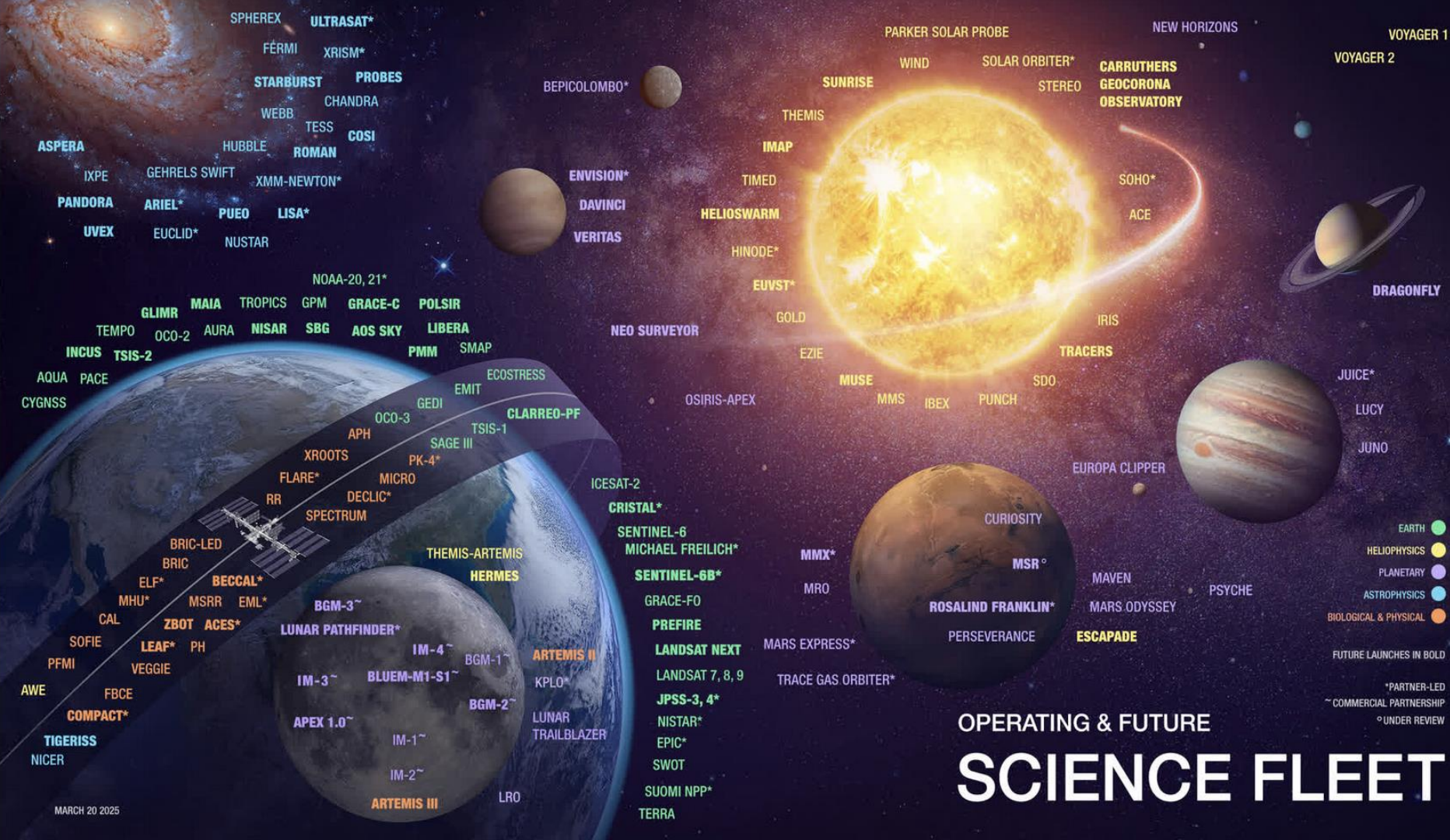
Space science and technology innovations lead to scientific, SDG and socio-economic benefits

- ❑ Scientific themes leading to innovations and applications
 - Astronomy, planetary, physical, and life sciences, Earth observations, Medicine, telecommunications, connectivity
- ❑ Individuals initiating new partnerships and building capacity
 - *Scientists, engineers, of all ethnicities, genders, etc.*
- ❑ From space laboratories to space agencies and the commercial sector
 - Politicians, businessmen, billionaires, all stakeholders...

The Sustainable Development Goals benefit from advances in space science and technology, as demonstrated at UNISPACE50+, and future space programs should build upon and be strengthened by the results of space activities and tools.

Interdisciplinary, international, competitive, Earth-friendly, curious, and progressive, space leaves no one behind and addresses all concerns with new approaches and tools.

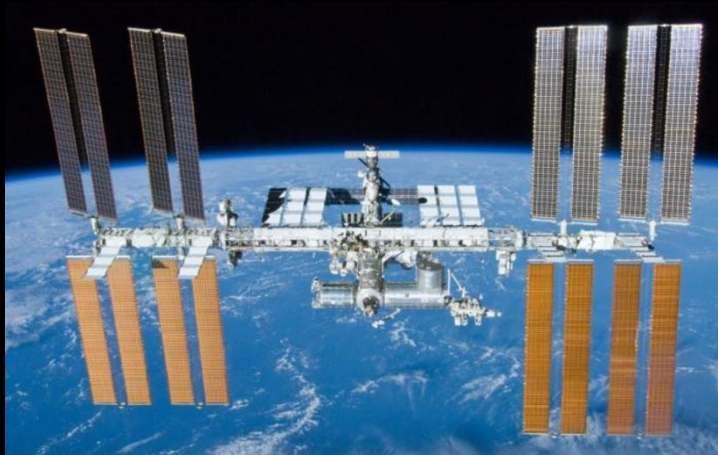




In Low Earth Orbit

In low-Earth (LEO) and cis-lunar orbits

- i. LEO
- ii. Moon
- iii. Mars
- iv. Science exploration
- v. Technological and safety innovations



ISS located at 415 km



China's space station, Tiangong, orbits Earth at an altitude between ~340 to 450 km

Improving health and lifespan in space and on Earth

Direct applications to improve our living conditions

- ❑ Extreme environmental conditions in space:
 - Weightlessness, altered circadian rhythms, confinement, altered atmosphere, radiation, scarce resources
- ❑ Physiological changes related to premature aging:
 - Muscle/bone loss, cardiovascular deconditioning, radiation damage
- ❑ Technology enables new research methodologies and countermeasures



Launched on Crew Dragon of SpaceX on 13 February and arrived on ISS on 15 February 2026

Will perform more than 200 experiments in 6-8 months



Beyond Earth...
Fly me to the Moon
Take me ... to Mars

Exploration: ESA Terrae Novae 2040

Continuing the European heritage



2020 > 2030

ESA in mutual inter-dependence

2030 > 2040

European-led capabilities



ExoMars
Trace Gas Orbiter &
Rosalind Franklin Rover



Mars Sample Return
Sample Fetch Rover & Earth
Return Orbiter



Preparing to send humans to Mars



Orion - European
Service Module



Gateway – permanent
habitation in deep space



Living and working on the Moon



Core ISS Partner



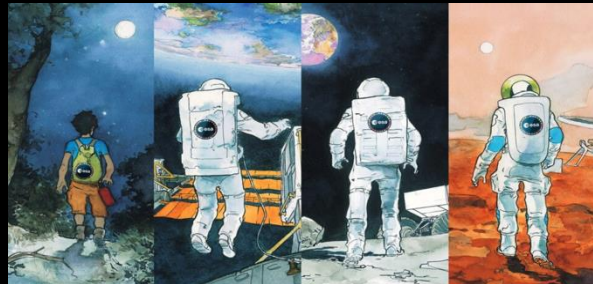
Post-ISS
Commercial platforms



Cargo launch
and return



Independent
human transport

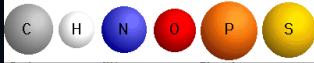


Habitability: four requirements

Water



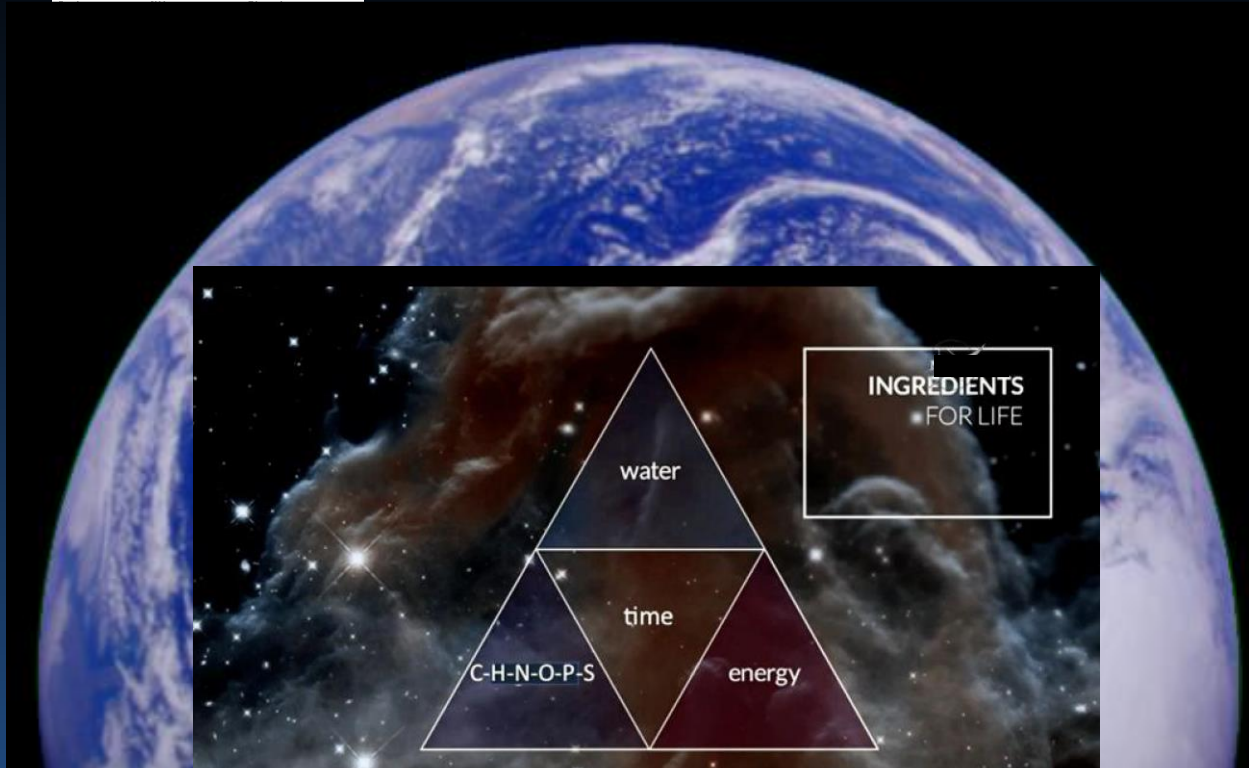
Essential
elements
(CHNOPS...)



Energy

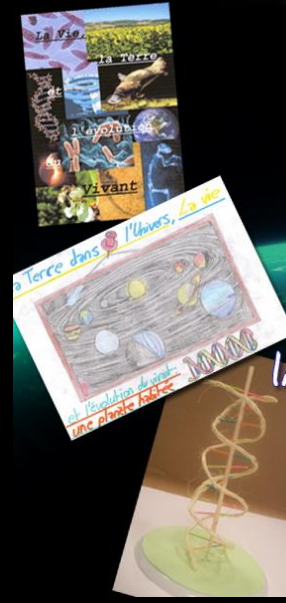
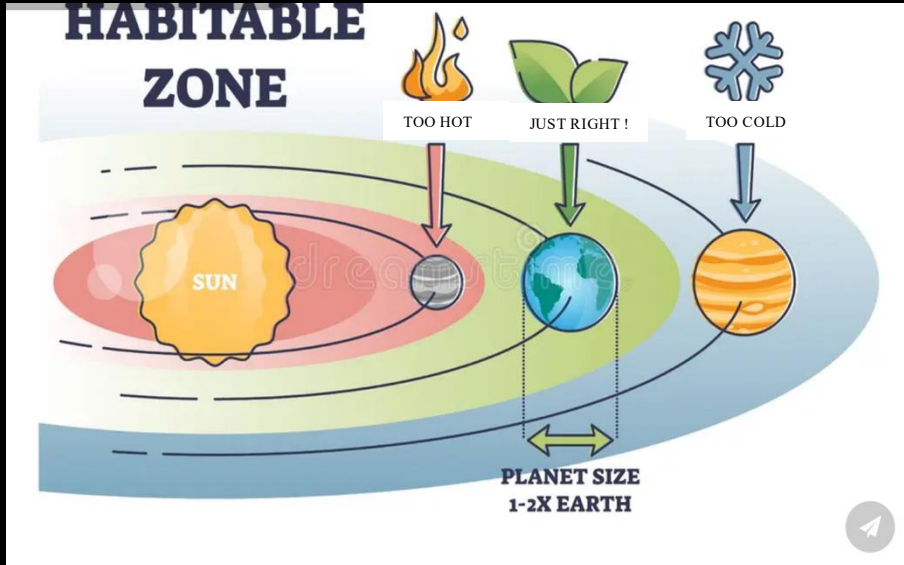


Stable
environment



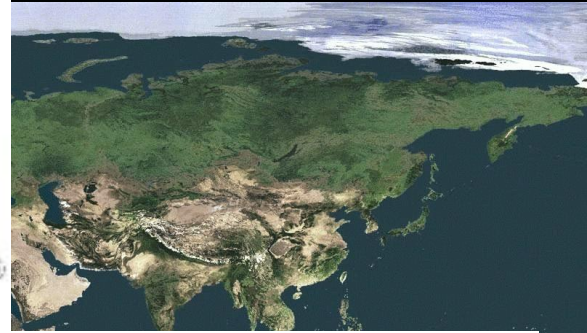
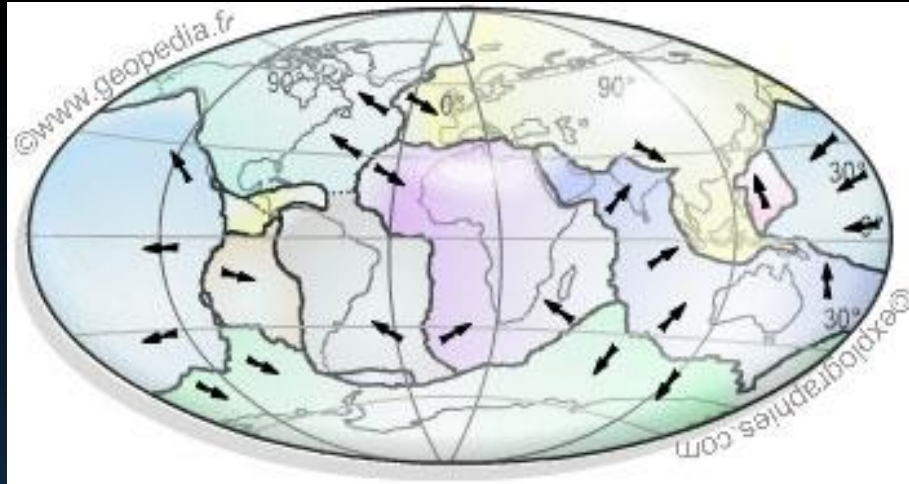
Goldilock and the 3 planets

Only one inhabited planet ?

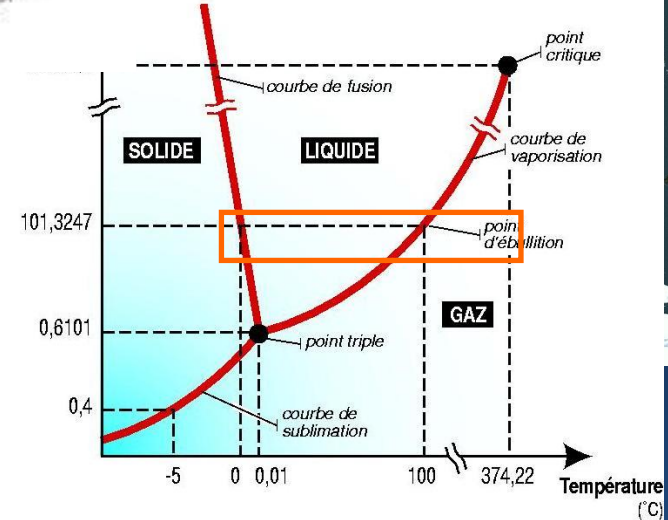


La Terre dans l'Univers,
la vie et l'évolution du vivant:
une planète habitée

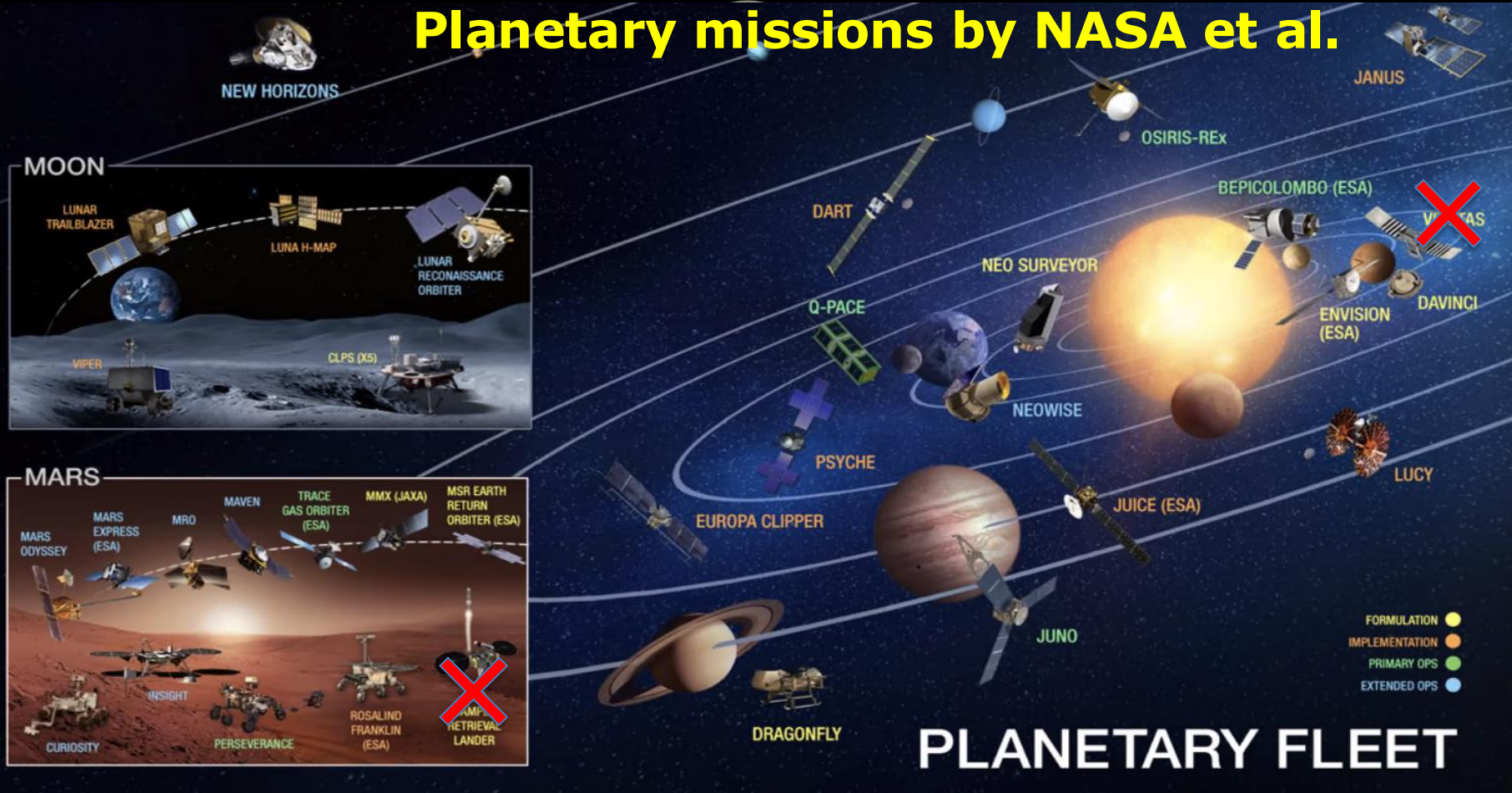
Only one inhabited world: the Earth



- Plate tectonics
- water in three states: L-S-G
- Little water...(0.01 %wt)
- Dense atmosphere
- Protection by the magnetic field
- Stable environment



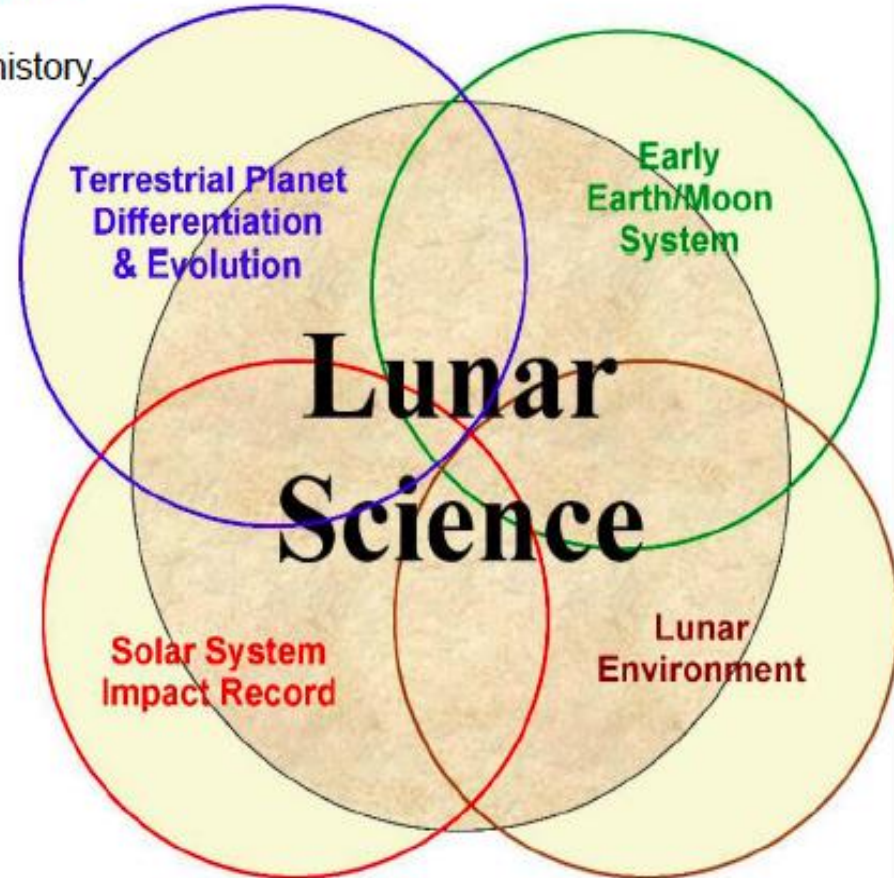
Planetary missions by NASA et al.



Combination of space missions by ESA and NASA (38; Credit L. Glaze) but more from other countries and agencies: Japan, Russia, India, China, UAE, Canada, other nations, etc...

The Moon: Overarching Themes in Lunar Science

- Been there – Done that! **NO, we still have numerous questions!**
- The Moon is a *witness* to 4.5 billion years of solar system history
- The Moon presents a record of planetary *geologic processes in the purest form*
 - Early crustal evolution
 - Differentiation
 - Impact craters
 - Volcanic processes
 - Regolith processes and early Sun
- The Moon provides accessible *unique environments*
 - Polar regions
 - Exosphere (atmosphere)
 - Stable Platform for astronomy



Property	Scientific Importance
Reference planetary body	The benchmark for how planetary bodies are formed and evolve
Common origin with Earth	Key to understanding the origin of Earth and Moon
Ancient surface	A unique witness plate to Earth's early history and the history of the Solar System
No atmosphere	Reference point for space-surface interactions and physics
Cold trapped volatiles including ice	A record of life-enabling chemistry in the Solar System
Radio quiet	Unique platform for astronomy
A source of resources	Materials on the Moon can be a source of water, propellant, metals, oxygen, which are key for sustainable exploration
Lunar surface environment	Natural laboratory for testing the impact of hypogravity and radiation on biological models in preparation for future long duration exploration

Table 1 - Summary of some of the key properties of the Moon and their relevance for the Moon as a destination for scientific research.



Lunar cold traps provide an accessible, natural laboratory for analyzing volatiles found across the Solar System.

The low-temperature lunar poles are analogs for small bodies (comets, asteroids, trojans, centaurs), icy outer satellites (e.g., Europa, Enceladus), Kuiper Belt objects (e.g., Pluto), and the poles of Mercury—all targets that are also interesting due to the presence of various volatiles.

LUNAR EXPLORATION

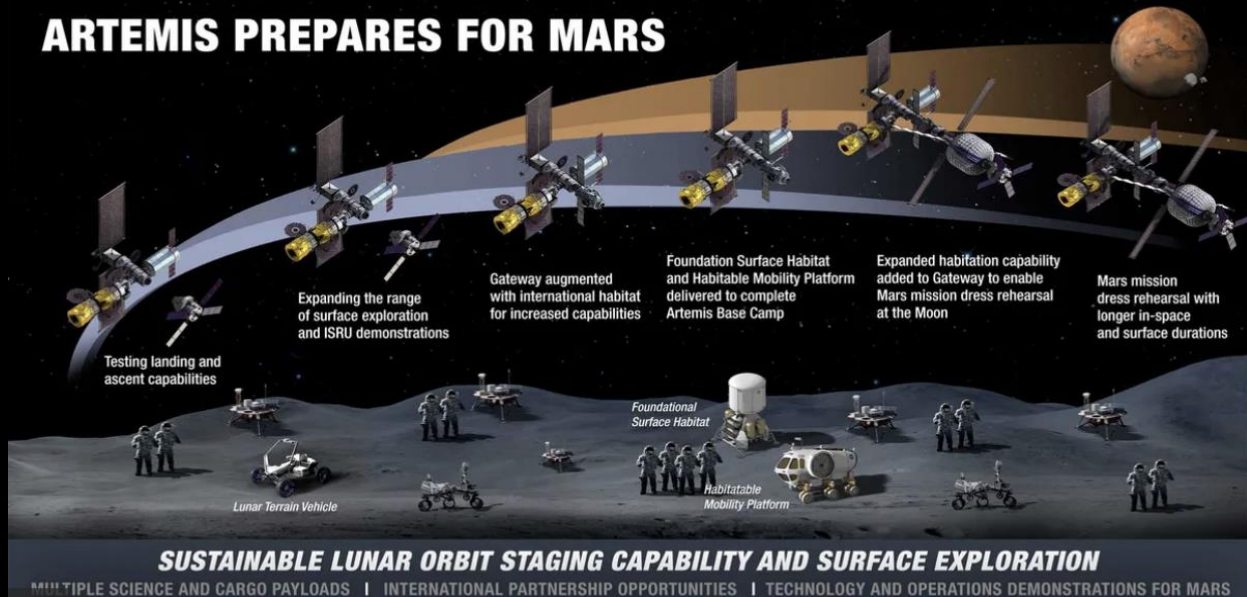
The Artemis program

Mission	Planned Date	Main Purpose
Artemis II	April 2026 (launched)	Crewed lunar flyby (total 10 days)
Artemis III	~2027 (in LEO)	Crewed test / pre-landing mission
Artemis IV	Early 2028	First Artemis Moon landing
Artemis V	Late 2028	Landing + base development
Artemis VI+	~late 2020s–2030s.	Regular missions, Moon base expansion

Understanding Solar System volatiles will enable sustained human exploration through in situ resource utilization (ISRU) at the Moon, Mars, and beyond.

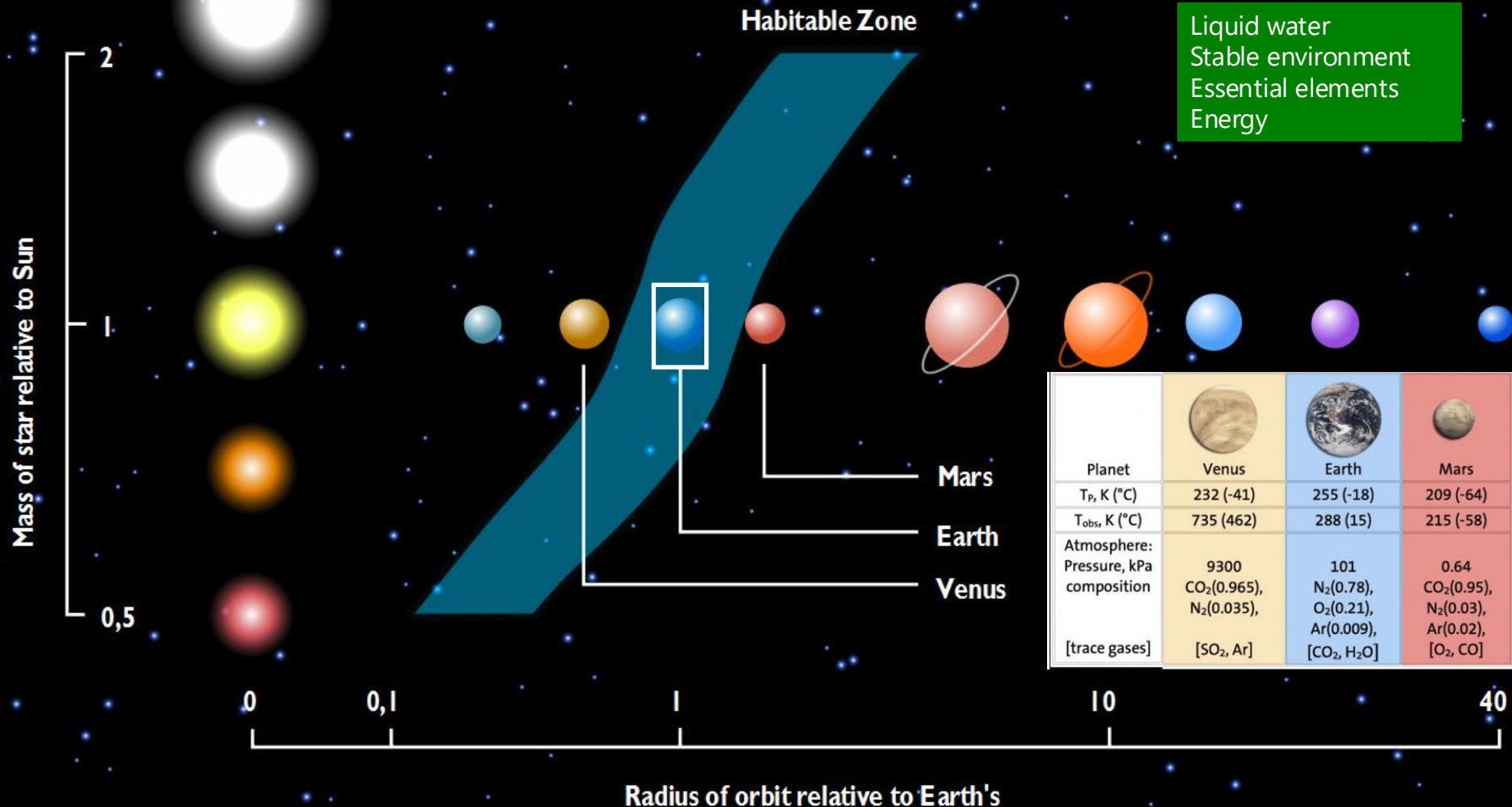


ARTEMIS PREPARES FOR MARS



The terrestrial planets

Habitability in the Solar System



COSPAR planetary protection Panel

The primary objective of the COSPAR Panel on Planetary Protection is to develop, maintain, and promote the COSPAR policy and associated requirements for the reference of spacefaring nations and to guide compliance with the Outer Space Treaty ratified today by 114 nations, to protect against the harmful effects of forward and backward contamination, i. e.



- The conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized.
- In addition, the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from an interplanetary mission.
- *This policy must be based upon the most current, peer-reviewed scientific knowledge, and should enable the exploration of the solar system, not prohibit it. The Panel has several meetings and invites all stakeholders including the private sector.*
- *It is not the purpose of the Panel to specify the means by which adherence to the COSPAR Planetary Protection Policy and associated guidelines is achieved*

				COSPAR Panel on Planetary Protection Members			
				Chair: Athena Coustenis (Paris Observ., FR; planetary sciences, astrobiology)			
				Vice-Chairs: Niklas Hedman (space law and policy) &			
				Peter Doran (LA State Univ., USA; Hydrogeology, Extreme Environments)			
				11 members appointed by space agencies		10 experts + 9 ex-officio	
				Canada/CSA	Tim Haltigin (planetary sciences)	France	Olivier Grasset (geodynamics, planetary)
				China/CNSA	Jing Peng (engineering)	Russia	Vyacheslav K. Ilyin (microbiology, medicine)
				ESA	Silvio Sinibaldi (astrobiology)	Spain	Maria-Paz Zorzano Meier (astrob. bioph.)
				France/CNES	Christian Mustin (astrobiology)	Japan	Yohey Suzuki (microbiology)
				Germany/DLR	Jan Grosser (contamination, Product assurance)	USA	Alex Hayes (planetology)
				India/ISRO	Anand Jain (engineering science)	China	Kanyan Xu (microbiology, biochemistry)
				Italy/ASI	Eleonora Ammannito (planetologist)	Russia	Maxim Zaitsev (astrochem, organic chem.)
				Japan/JAXA-ISAS	Masaki Fujimoto (space plasma physics)	UAE	Jeremy Teo (mechanical and bio engin.)
				UAESA	Omar Al Shehhi (engineering)	UK	Mark Sephton (astrobiol., org. geochem.)
				UK/UKSA	Karen Olsson-Francis (astrob., microb.)	ESA PPO Ex-officio	Luca Stoll
				USA/NASA	Elaine Seasley (contamination, engineer)	NASA PPO Ex-officio	James N. Benardini Erin Lalime
Invited commercial 				NASEM Ex-officio	Aru Mozhi Aeron., Astron. Physics, & Space Sci Director	JAXA PPO Ex-officio	Takashi Yamazaki
				COSPAR CIR Ex-officio	John Reed	UNOOSA Ex-officio	Romana Kofler
				Space Law observers	Kai-Uwe Schrogl Les Tennen		



Planetary protection categories

The different planetary protection categories (I-V) reflect the level of interest and concern that contamination can compromise future investigations or the safety of the Earth; the categories and associated requirements depend on the target body and mission type combinations

Category I: All types of mission to a target body which is not of direct interest for understanding the process of chemical evolution or the origin of life; *Undifferentiated, metamorphosed **asteroids**; others TBD*

Category II: All types of missions (gravity assist, orbiter, lander) to a target body where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote¹ chance that contamination carried by a spacecraft could compromise future investigations; **Venus; Moon (Ila and lib with organic inventory only for landed missions at the poles and in PSRs)** Comets; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; **Ganymede†; Titan†; Triton†; Pluto/Charon†; Ceres; Kuiper-Belt Objects > 1/2 the size of Pluto†; Kuiper-Belt Objects < 1/2 the size of Pluto; others TBD**

Category III: Flyby (i.e. gravity assist) and orbiter missions to a target body of chemical evolution and/or origin of life interest and for which scientific opinion provides a significant² chance of contamination which could compromise future investigations; **Mars; icy worlds; others TBD**

Category IV: Lander (and potentially orbiter) missions to a target body of chemical evolution and/or origin of life interest and for which scientific opinion provides a significant² chance of contamination which could compromise future investigations. 3 subcategories exist (IVa,b,c) depending on instruments, science investigations, special regions etc.; **Mars; Europa; Enceladus; icy worlds, others TBD**

Category V: All Earth return: 2 subcategories - unrestricted return for solar system bodies deemed by scientific opinion to have no indigenous life forms (**e.g. Martian Moons**) and restricted return for all others

¹Implies the absence of environments where terrestrial organisms could survive and replicate, or a very low likelihood of transfer to environments where terrestrial organisms could survive and replicate

²Implies the presence of environments where terrestrial organisms could survive and replicate, and some likelihood of transfer to those places by a plausible mechanism

Why did Venus and Mars did not become Earths ??

Could our planet become like Venus and Mars ?

Venus

Ps = 93 bar (CO_2)
Ts = 730K (457°C)



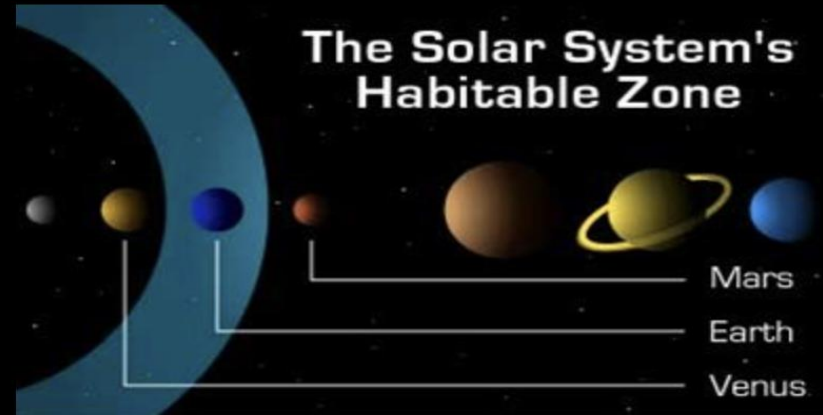
Earth

Ps = 1 bar (N_2, O_2)
Ts = 288K (15°C)



Mars

Ps = 6 mbar (CO_2)
Ts = 230K (-43°C)



Planet Venus

Our closest neighbour



*Venus atmosphere and surface
As revealed by the
Magellan mission (1990-1994)*

- Distance to the Sun : 0,7 UA
- Mass : 0,8 x M (Earth)
- Obliquity : 177° -> retrograde rotation
- Atmosphere : ~96% CO₂, N₂, water vapor : < 0,01 %
- Cloud deck below 50 km composed of sulphuric acid and other divers corrosive components, with little water
- High-speed winds in the upper atmosphere, decreasing towards the surface
- Surface temperature= 740 K (467° C)
- Surface pressure = 93 bars.

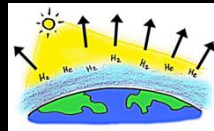
• As solar heating



T ↗ and H₂O ↗



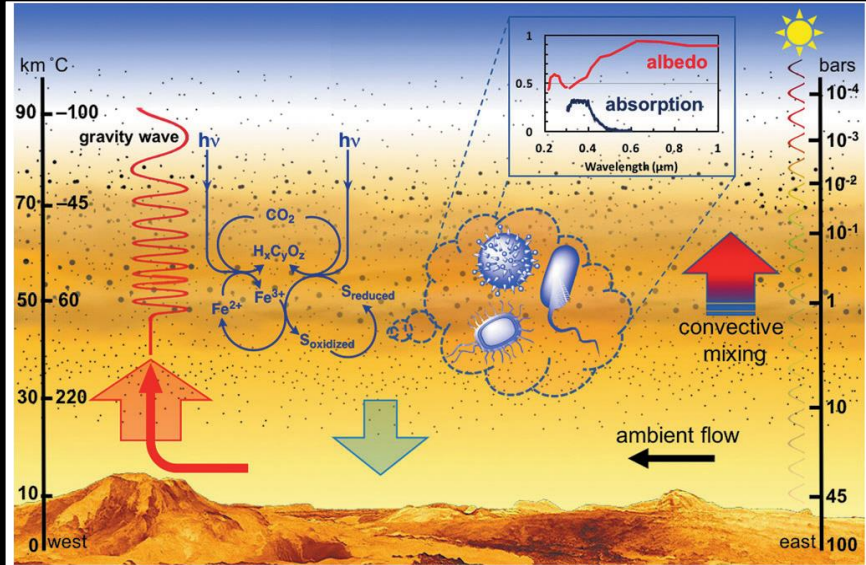
• Atmospheric H₂O escaped into space as H₂ and O₂.



• No rain or plants: CO₂ not bound in the rocks as on Earth

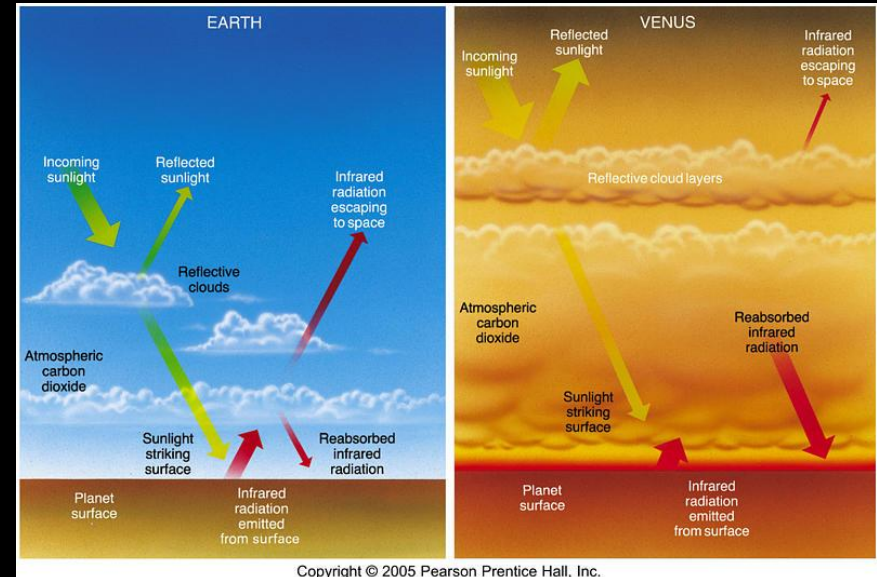
Very hostile conditions: high pressure, high temperature, little water, corrosive clouds... which prevents it from being a possible habitat... because of a runaway greenhouse effect.

Venus in the past



- At the beginning, the Sun was less bright and on Venus there was abundant water !
- -> Maybe even oceans ...
- ... and lifeforms could have appeared, ... long gone today!
- ... or hiding in the clouds ???

For the temperatures to be so high today there must be a mechanism in the Venusian atmosphere that traps solar radiation very effectively : a ***runaway greenhouse effect ?***



Venus : habitable in its clouds?

- Based on existing measurements, **THE CLOUDS OF VENUS ARE NOT SPECIAL REGIONS.**
- Because of the very low water activity in the clouds, even in regions where temperatures are sufficiently moderate, **life as we know it could not reproduce there**, even if nutrients were available and assuming protection from radiation, sulfuric acid, etc.
- Unless new measurements demonstrate a water activity greater than 0.5 ($R_h > 50\%$), **the clouds of Venus do not represent a planetary protection concern**, because “life as we know it” on Earth could not proliferate under these conditions.

*They are, of course, of major interest to planetary science, particularly with regard to **atmospheric chemistry, the phosphorus cycle**, and related processes.*

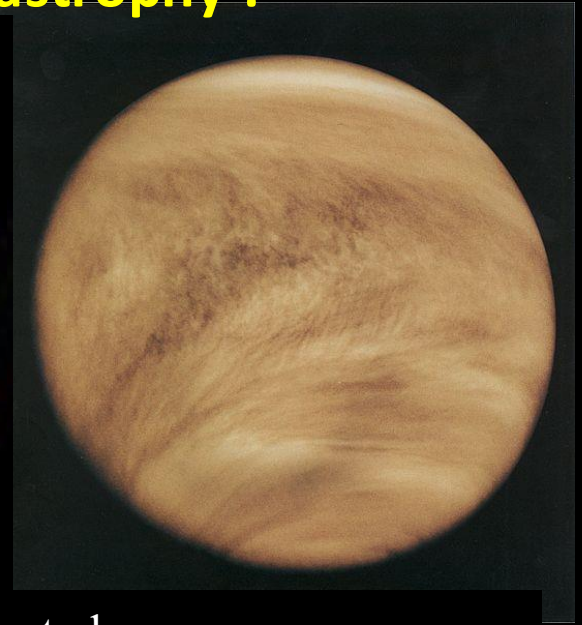


Studies published in 2020 reported a possible detection of phosphine in the clouds of Venus, which, if confirmed, could potentially be considered a biosignature of life as we know it. However, subsequent analyses have questioned the robustness of the detection and suggested that the reported signal could result from data-processing or analysis artifacts (Zorzano et al., 2023).

Venus : an environmental catastrophe !



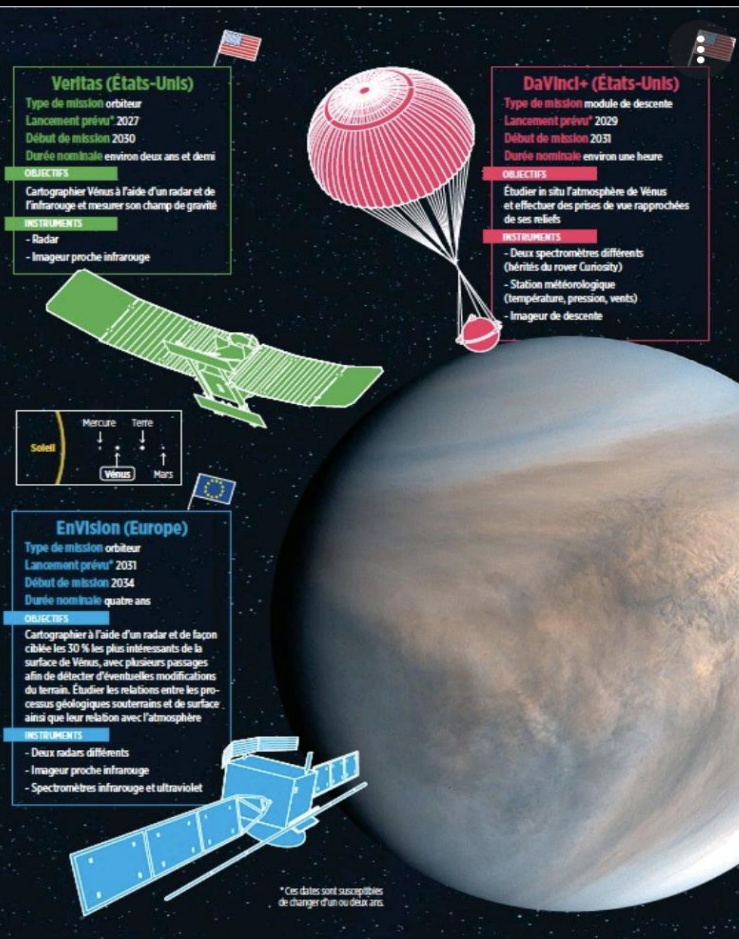
Venus as it could have been in
the past



Venus today
(96% CO₂, 90 bars, 470° C)

Venus became uninhabitable because of a runaway greenhouse effect that trapped solar heat. Enormous amounts of carbon dioxide and sulfuric acid... which turned out to increase the surface temperature, completely evaporated the oceans, and drastically increased the surface pressure. Can this happen to us on Earth? By burning fossil fuels, we are adding to the atmosphere/greenhouse gases... which acts like a pane of glass.

VENUS : The Envision mission selected as the ESA M5 in Cosmic Vision – launch in 2031-2032



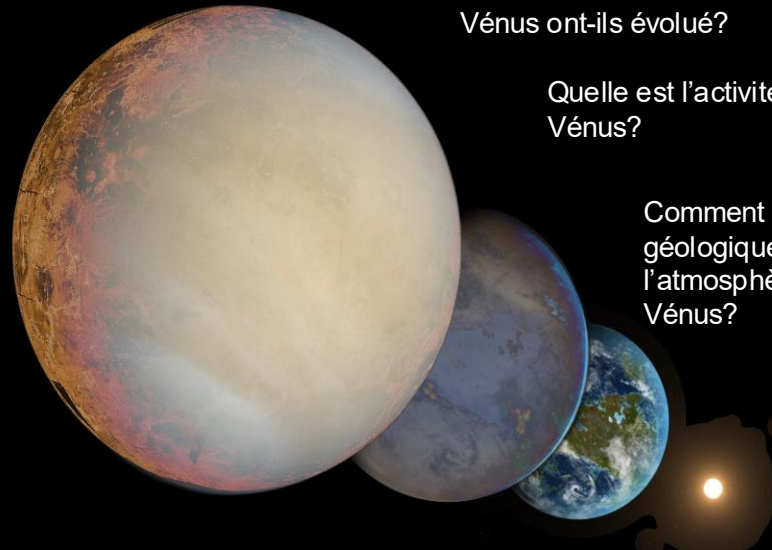
With complementary missions *Veritas and Da Vinci* (NASA), a full international « Venus program » is coming together

Pourquoi la voisine & jumelle de la Terre est-elle si différente de celle-ci?

Comment la surface et l'intérieur de Vénus ont-ils évolué?

Quelle est l'activité géologique de Vénus?

Comment les processus géologiques façonnent-ils l'atmosphère et le climat de Vénus?



Planet Mars



- A planet close to Earth: $R_h = 1.5 \text{ UA}$, $R = 0.6 \text{ RT}$
- Less dense and massive than Earth: $d = 3,9 \text{ g/cm}^3$, $M = 0,1 M_E$
- High obliquity (25°) $\rightarrow$ Seasonal effects as on Earth
- Cold and tenuous CO_2 atmosphere : $95\% \text{ CO}_2 + 3\% \text{ N}_2$
+ traces of H_2O & CO

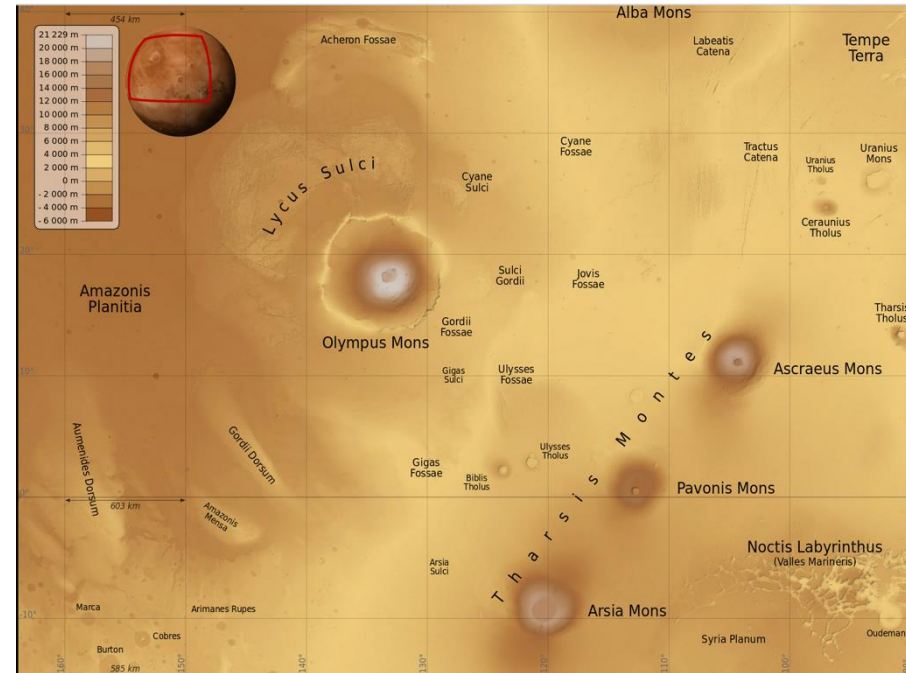
- $P_s = 0,006 \text{ bars}$, T_s (average) : -40° C
- Strong seasonal variations
- Seasonal and permanent polar caps : CO_2 , H_2O
- Extinct volcanoes, highest in the solar system



Planet Mars

A planet that has similarities with the Earth but with a CO₂ tenuous and dry atmosphere. Could have been in the habitable zone in the past...

Short distance to the Earth



Mars Exploration Family Portrait until 2018



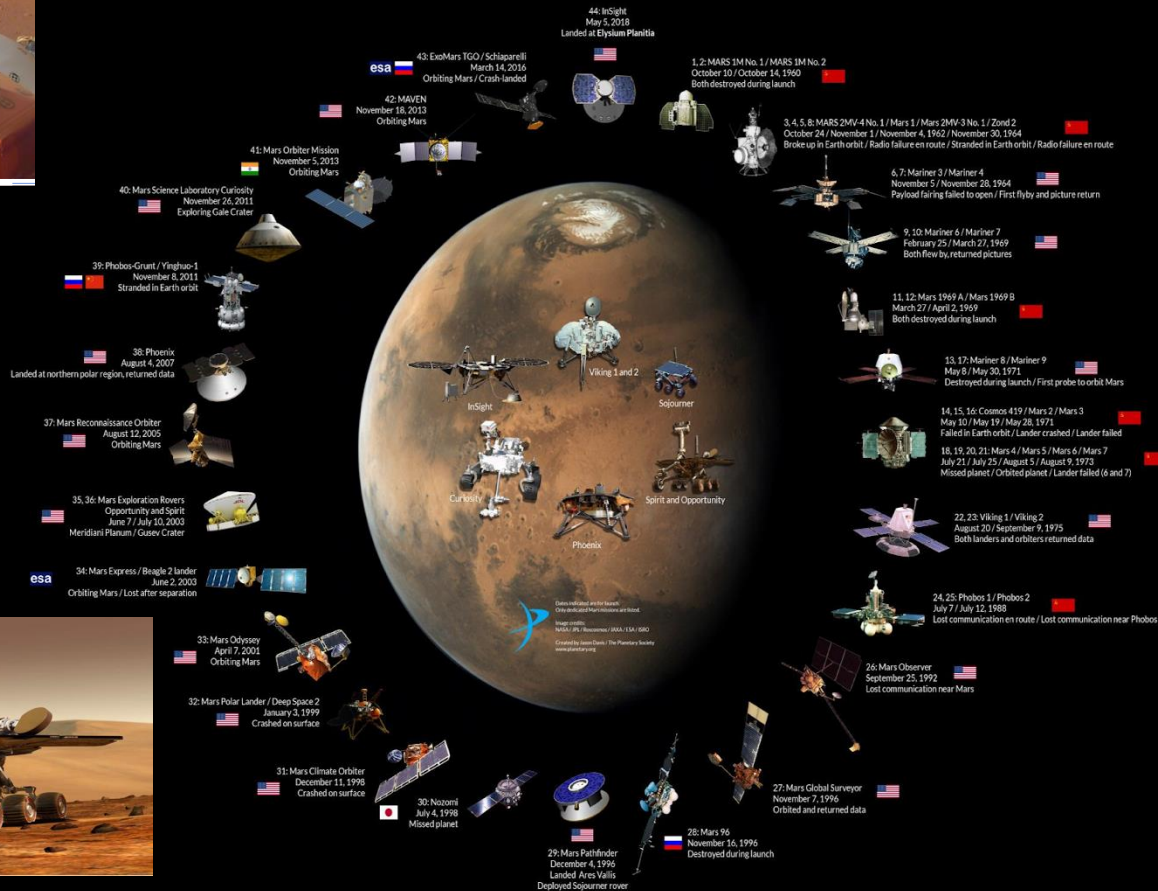
InSight



MRO



MSL Curiosity



Viking



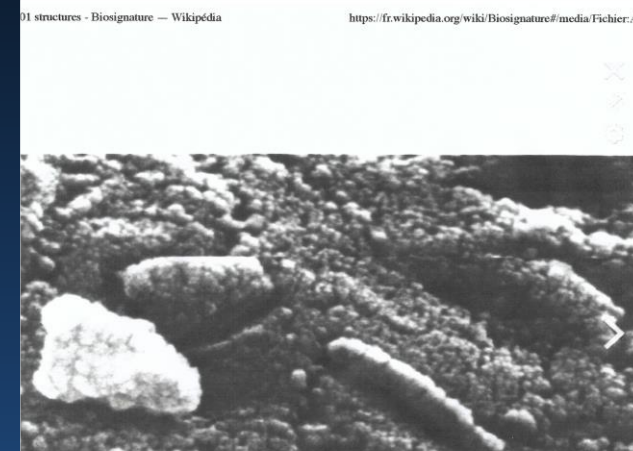
MAVEN



Mars Express

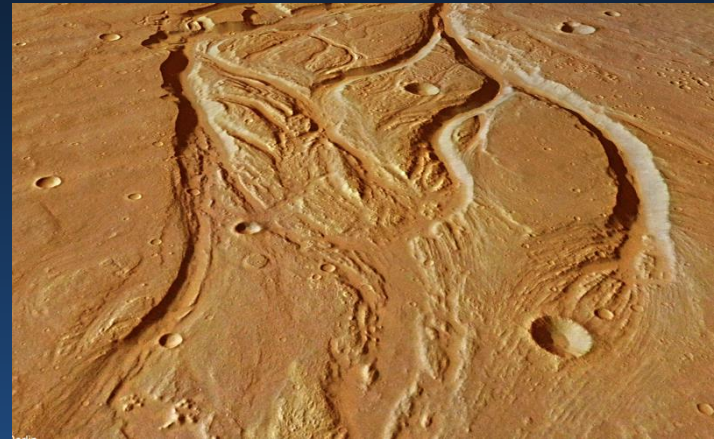
1996 : the martian meteorite ALH84001

- Discovered in **Allan Hills** (Antarctica) in December 1984 (mass: 2 kg)
 - Age: 4,1 Ga, ejected 16 million years ago, fell on Earth 13000 years ago
 - **1996: Lifeforms are announced! (nodules of carbonates, nanobacteria fossils, magnetite crystals, PAHs...)**
 - BUT.... The meteorite was largely contaminated after falling on Earth (as was the d'Orgueil and Murchison ones)
- > There is no definitive proof of the presence of fossil life traces in the ALH84001 meteorite (nor in any other)**

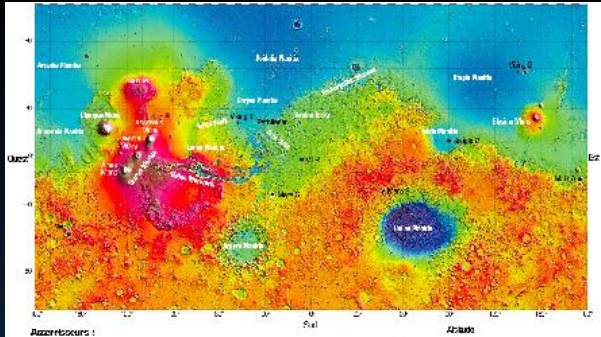


1996 : Searching for water on Mars

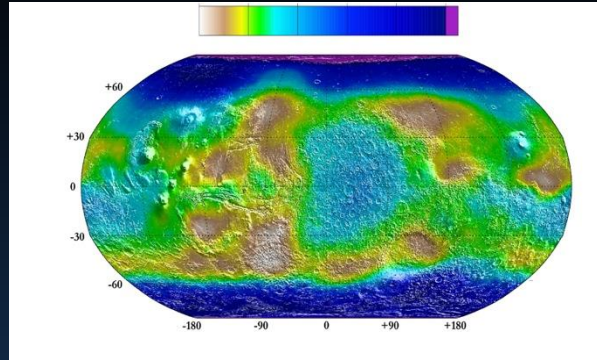
- The images of Mariner and Viking showed possible traces of **fluvatile flow**
- Networks of ramified valleys -> **presence of past liquid water flowing**
- -> New search based on sites where this water could have existed in the past : « Follow the water! »



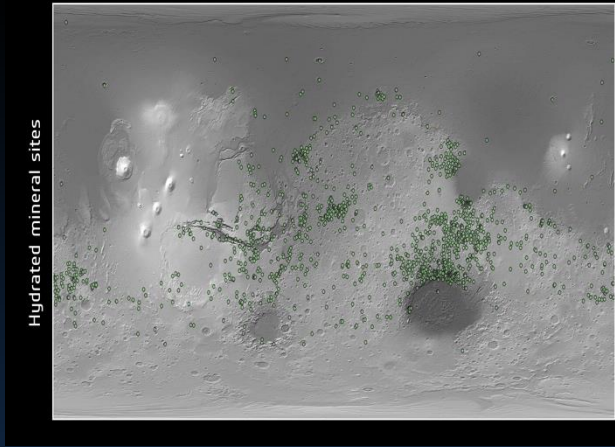
New clues in favor of the presence of past liquid water on Mars



Mars Global
Surveyor: (1996)
Flat surface in the
North -> **possible
boreal ocean**



Mars Odyssey
(2001)/GRS
Presence of water
under the poles



Mars Express
(2003)/OMEGA
Argiles in ancient
terrains

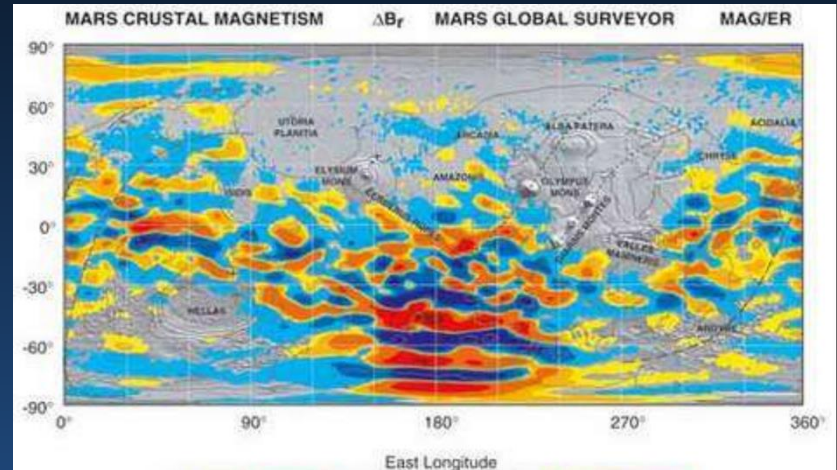
Mars, at the beginning was more hospitable

TODAY

- Weak gravity field
- Reduced internal energy
- > Tenuous atmosphere

BUT

- At first an internal dynamo
- Volcanic and tectonic activity
- Thicker atmosphere and more liquid water



Mars exploration

Missions to Mars

There have been
**49 missions by
9 nations**
to Mars since 1960.



* INCLUDES JOINT MISSIONS

■ FUTURE MISSIONS
■ FAILED
■ SUCCESSFUL
■ ON GOING

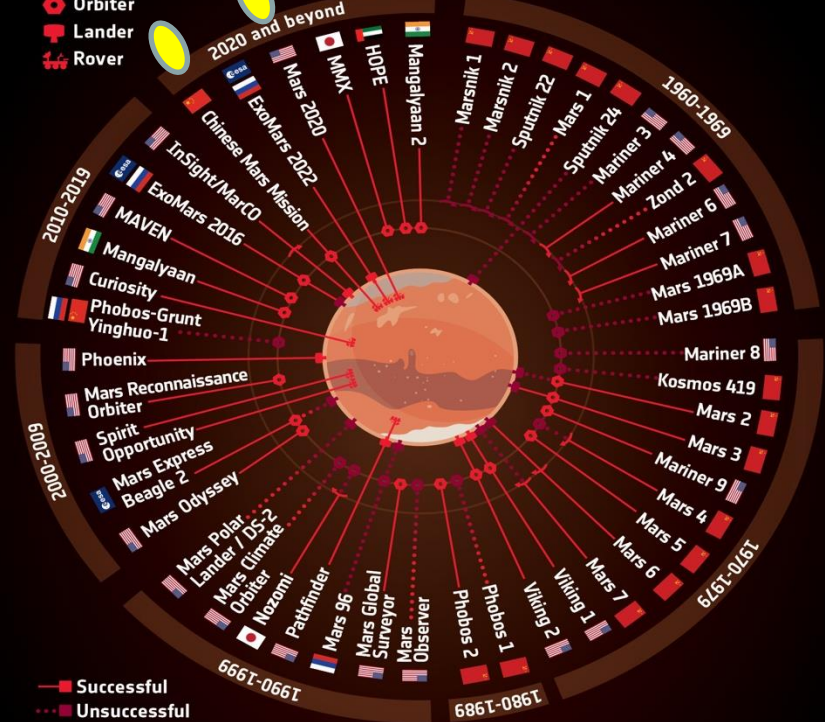


Source: NASA | February 18, 2021

→ MARS MISSIONS



- Flyby
- Orbiter
- Lander
- Rover



- European Space Agency
- China
- India
- Japan

- Russia
- United States of America
- Soviet Union
- United Arab Emirates

#ExploreFurther

Current missions at Mars

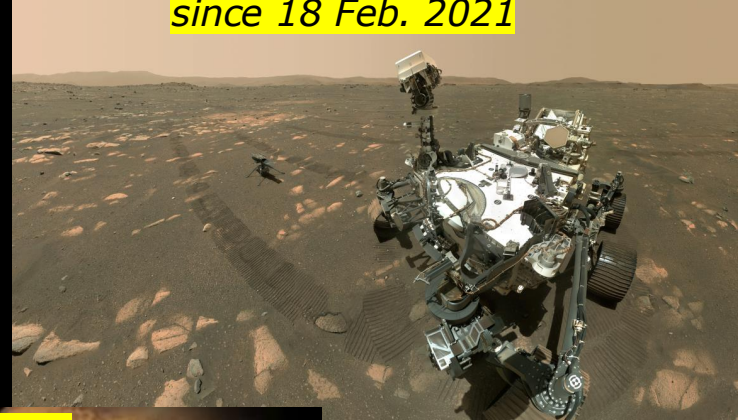
MRO-NASA Since 2006



Al-Amal (Hope) – UAE
since 9 Feb. 2021



Mars 2020/Perseverance – NASA
since 18 Feb. 2021



Curiosity-NASA Since 2012



ExoMars/TGO-ESA
since 2016



Tianwen-1 – China
since 10 Feb. 2021

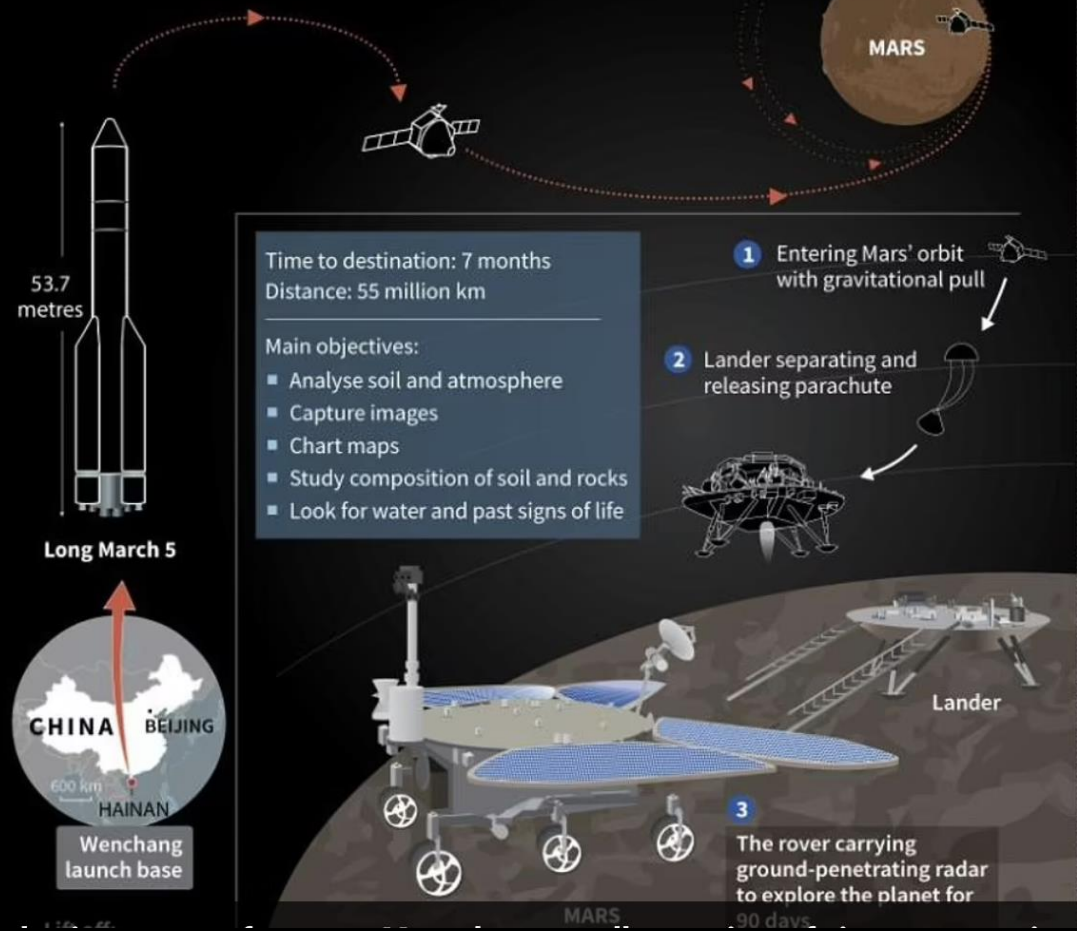


MAVEN-NASA Since 2014



Tianwen-1: China's Mars debut

First mission to study the Red Planet with orbiter, lander and rover

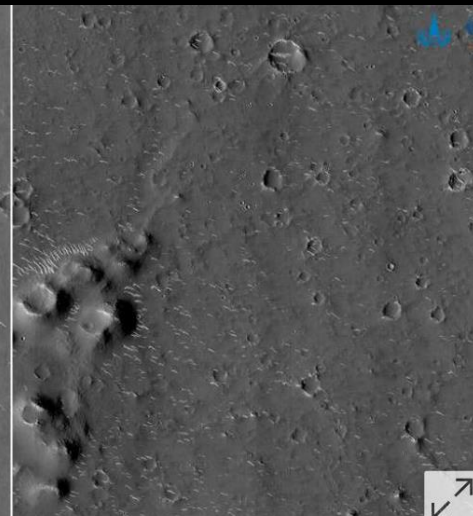
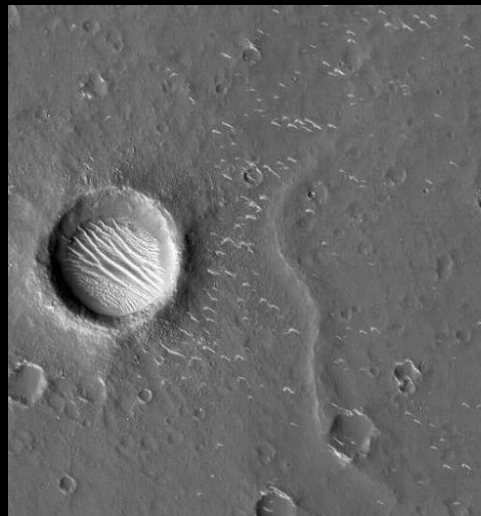
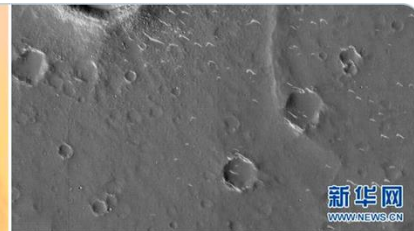
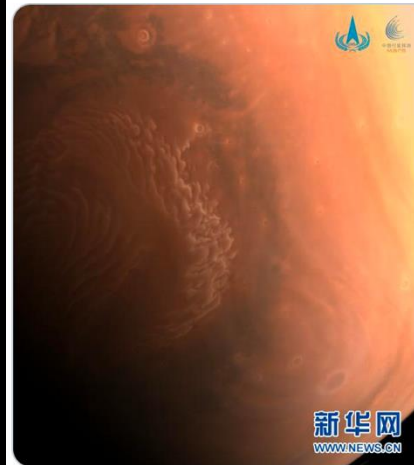
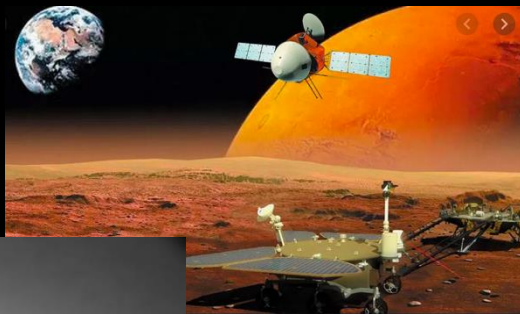


Images of Mars by Tianwen-1/Zhurong

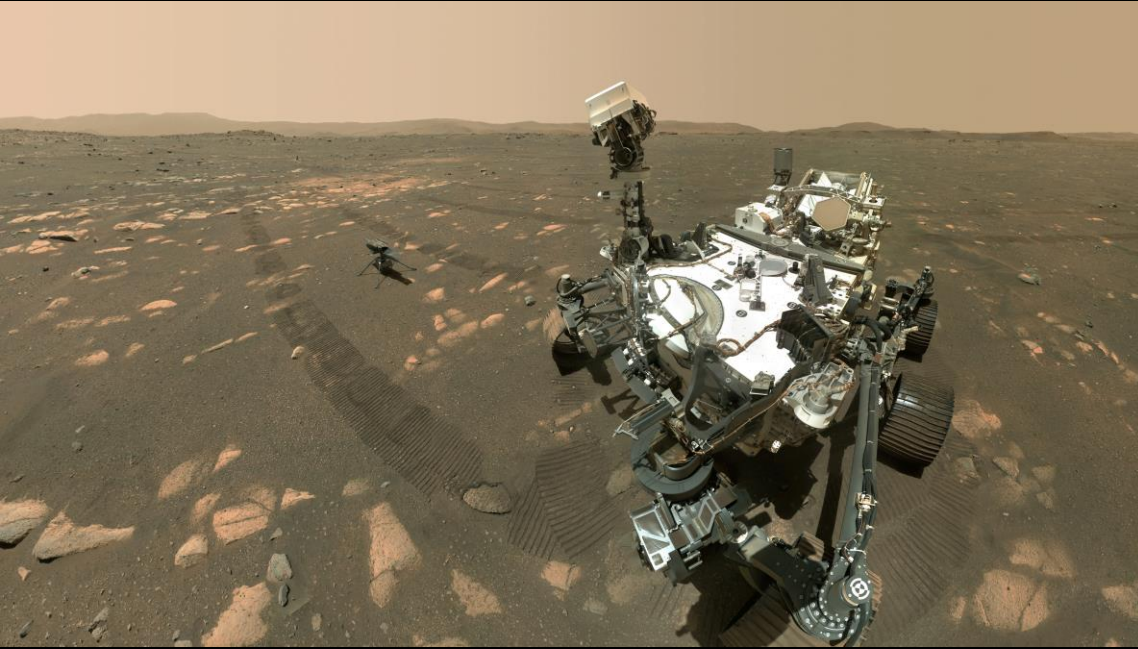


CNSA : Tianwen-1 & Zhurong

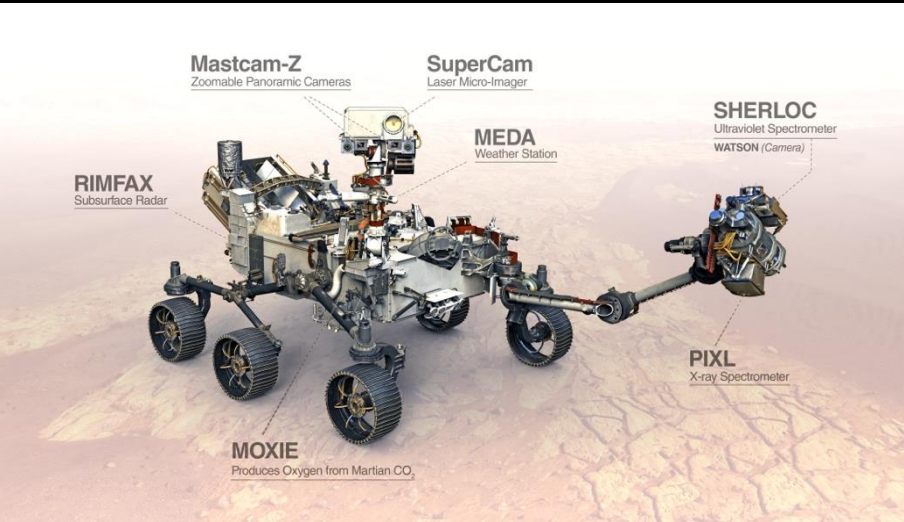
on.china.cn/3uWmRQD



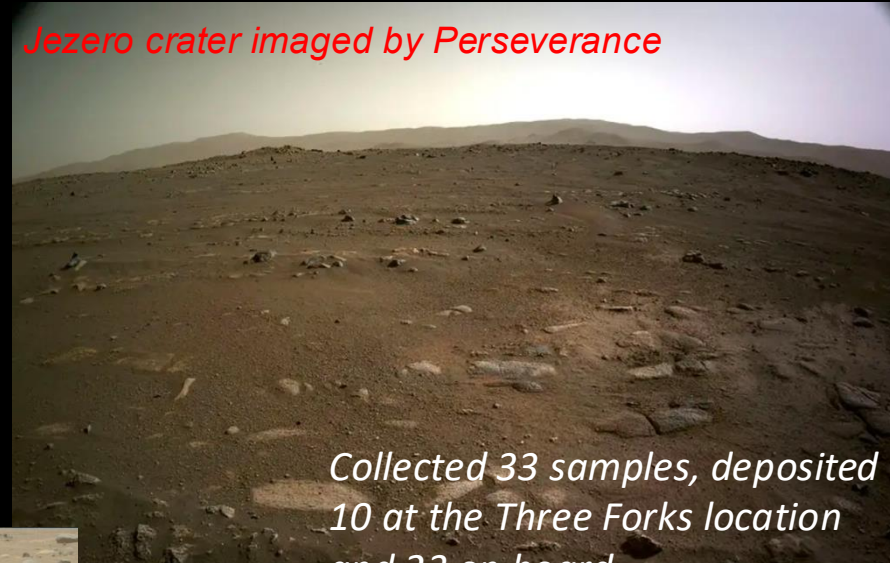
MARS 2020/PERSEVERANCE



Perseverance/Ingenuity at Jezero



Jezero crater imaged by Perseverance



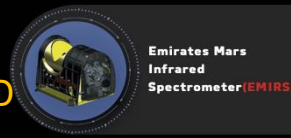
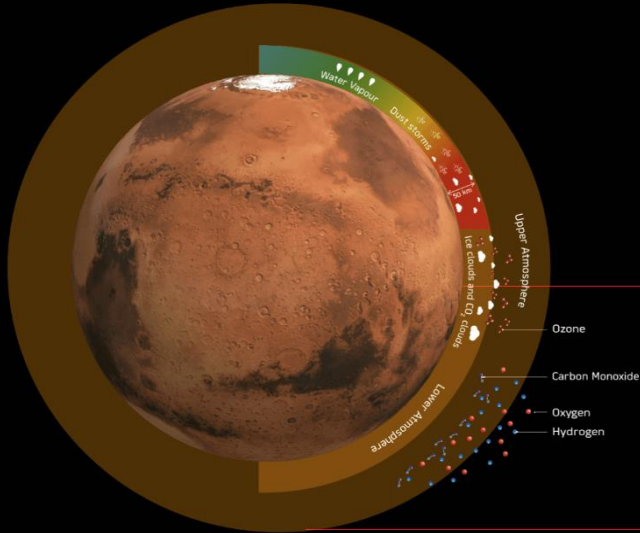
*Collected 33 samples, deposited
10 at the Three Forks location
and 23 on board*



Source :
[NASA/JPL-Caltech](https://www.nasa.gov/jpl-caltech)

UAE AL-HAMAL (HOPE) PROBE

- Understand climate dynamics and the global weather map through characterizing the lower atmosphere of Mars
- Explain how the weather changes the escape of hydrogen and oxygen through correlating the lower atmosphere conditions with the upper atmosphere
- Understand the structure and variability of hydrogen and oxygen in the upper atmosphere as well as identifying why Mars is losing them into space





Search for water and methane on Mars

(OMEGA/Mars Express) :
argiles and hydrated salts

MSL: Discovery of stratified area
close to Mont Sharp

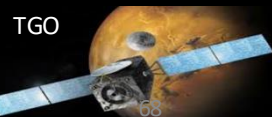
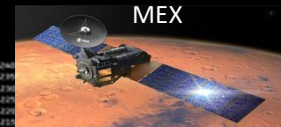
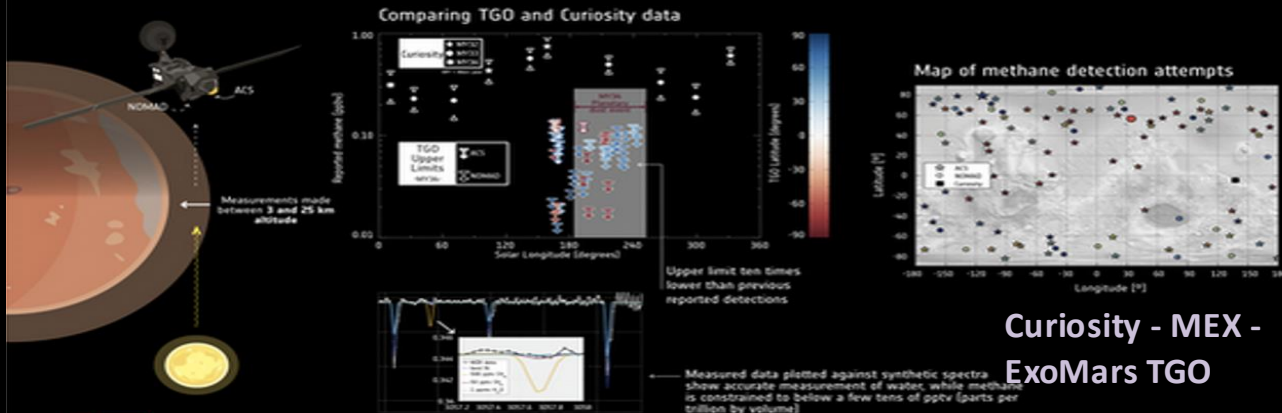
Hydrated mineral sites



Indication of the presence of abundant liquid water in the past



Traces of methane detected by some instruments and not others

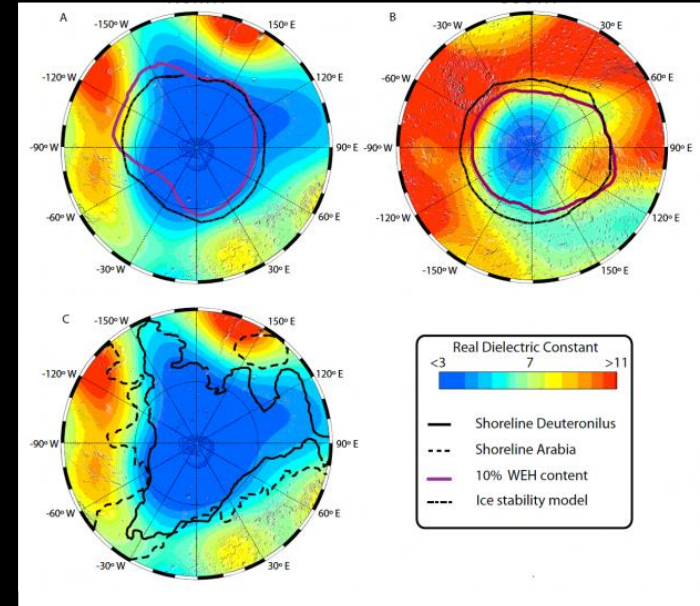
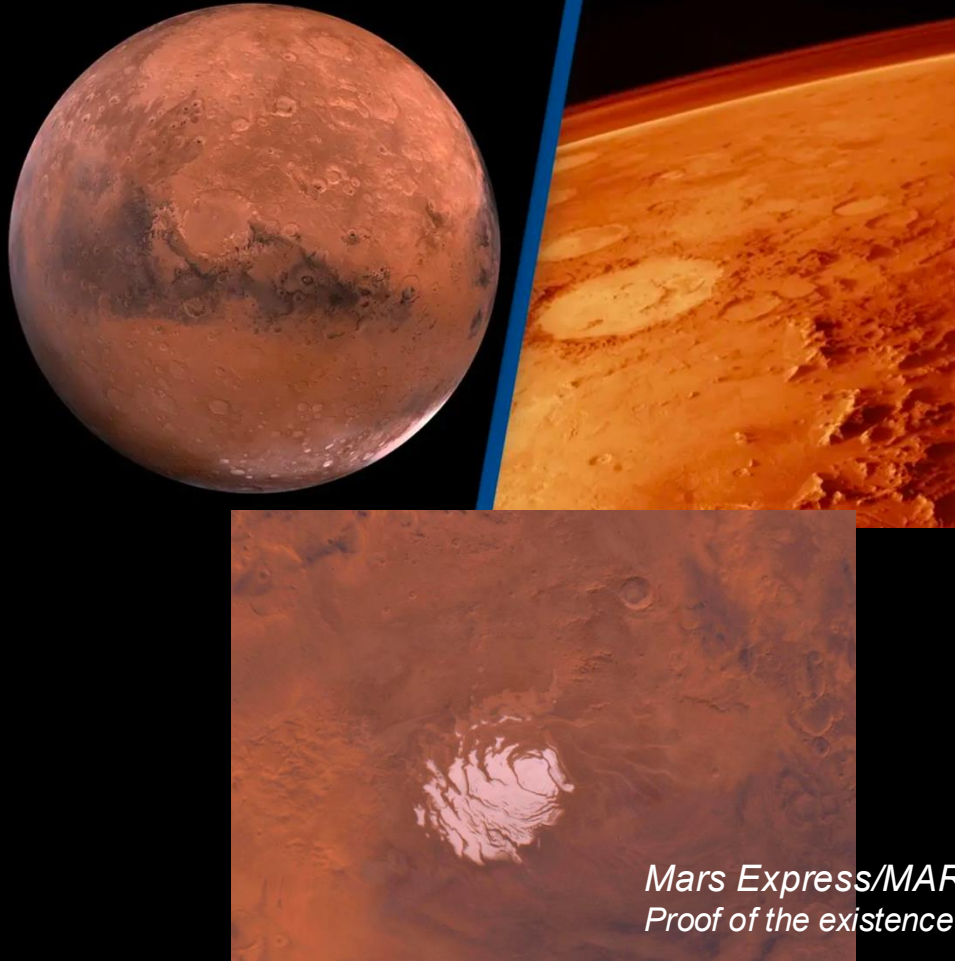


Curiosity - MEX -
ExoMars TGO

Space missions
allowed to
enhance our
knowledge on
CH₄ and water
on Mars, as
well as
atmospheric
escape

But mysteries
remain and
further in situ
exploration is
needed

Mars explored by Mars Express and ExoMars/TGO

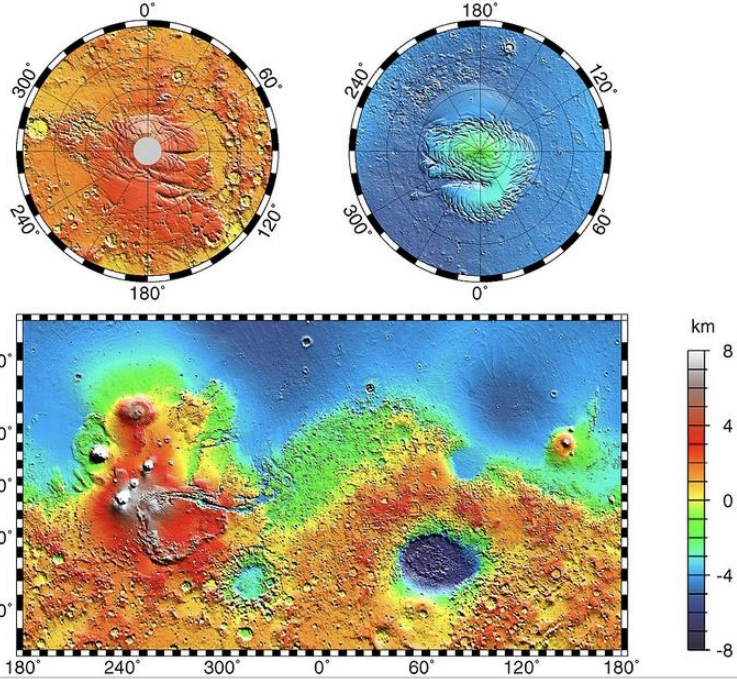


Confirmation of an ancient martian ocean by the radar of Mars Express (Mouginot et al. 2012)

Mars Express/MARSIS (2020)

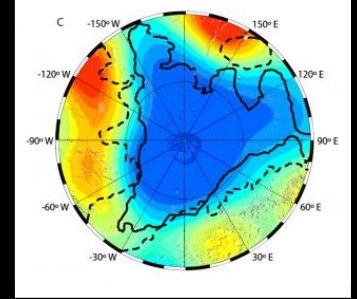
Proof of the existence of extends of salty liquid water under the surface

Oceanus Borealis sur Mars



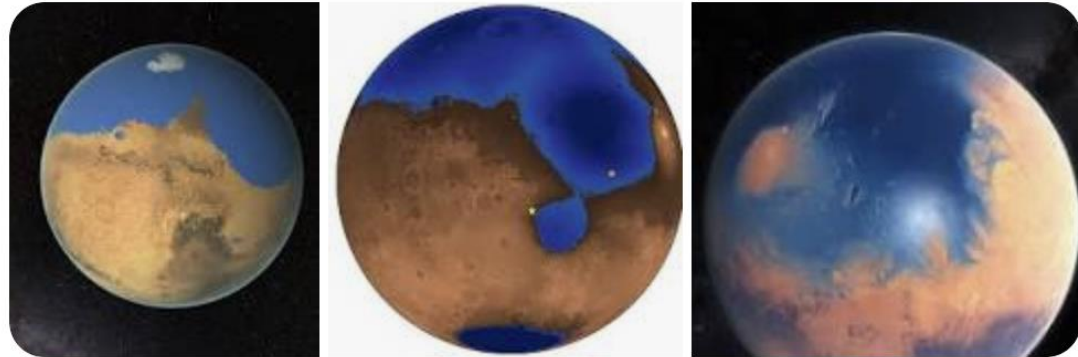
The blue region in the Northern pole has weak topography and was perhaps the site of a primordial ocean of liquid water in the past.

Schmidt et al., 2022;
Cardenas et al., 2022;
Argadestya et al., 2026



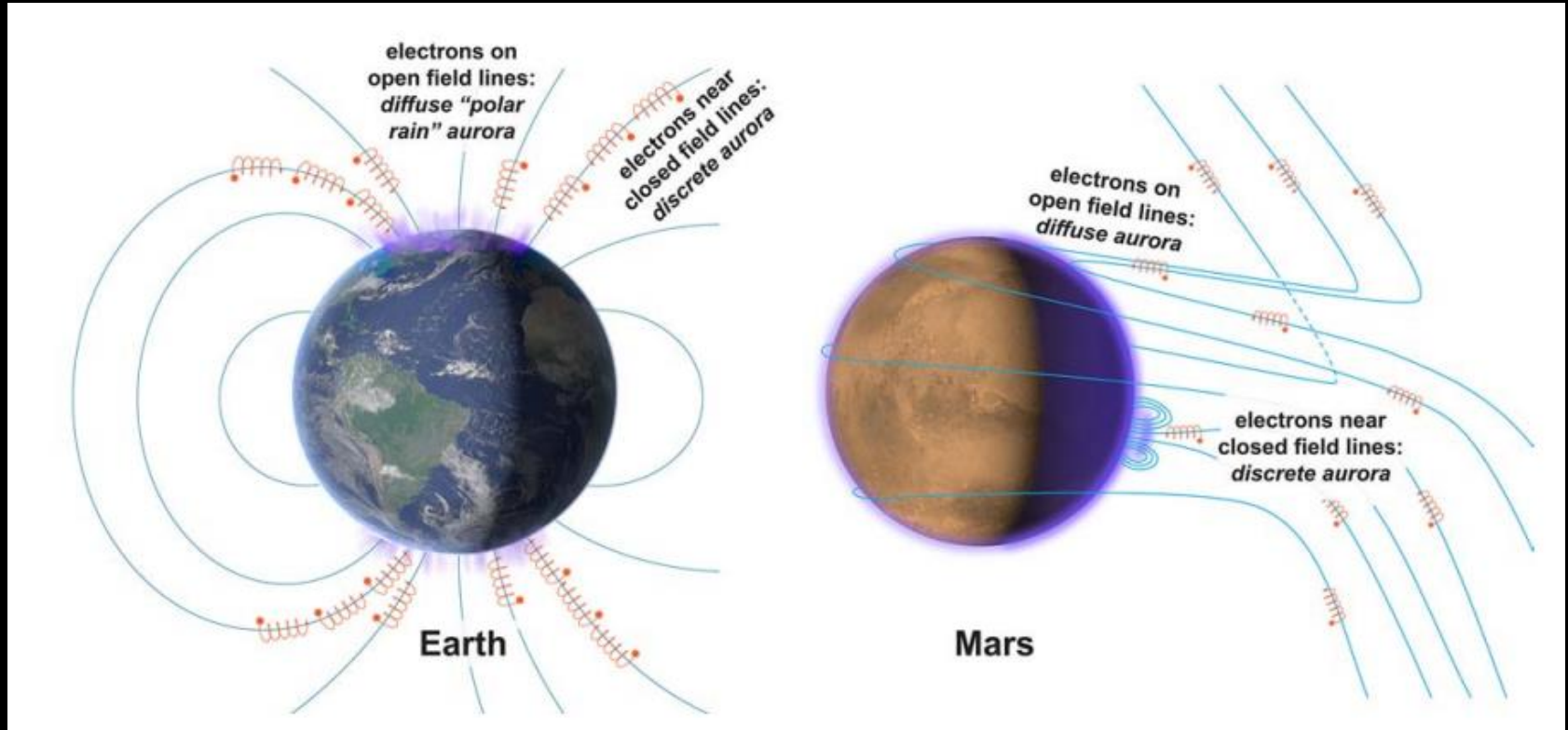
Mars Express (2003)/Radar

A frozen ocean under the north pole of Mars ?
Current or past ?



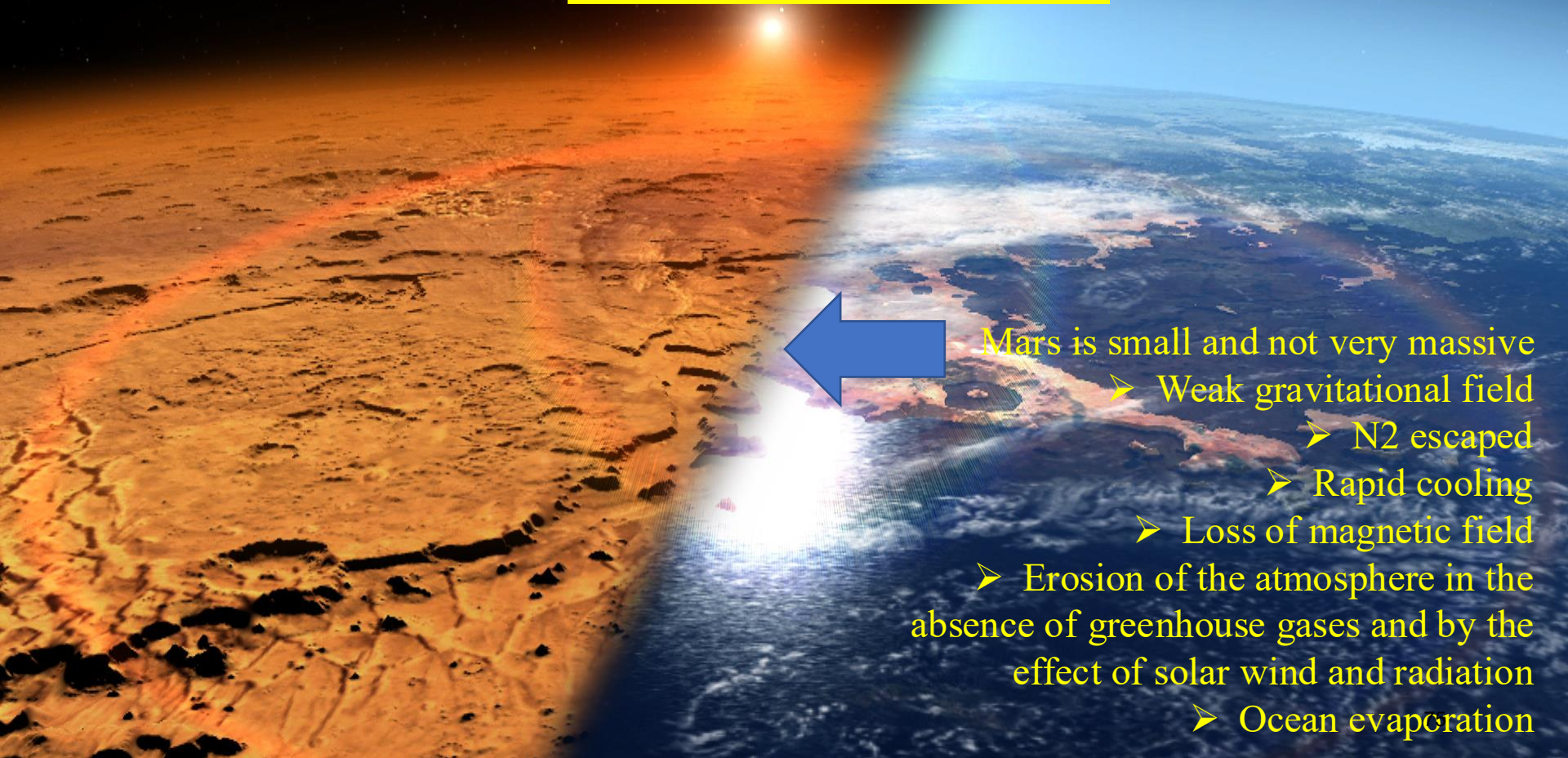
“Strong water isotopic anomalies in the Martian atmosphere : probing current and ancient reservoirs”, Villanueva et al., Science 2015.

Magnetic fields around the Earth and Mars



The terrestrial shield acts at higher altitudes. Under the effect of the solar wind, on the other hand, the magnetic lines "flow" around Mars at very low altitude, tearing off part of its atmosphere. (*Nature*, Nov. 2015)

Mars currently and in the past
was Mars ever habitable?



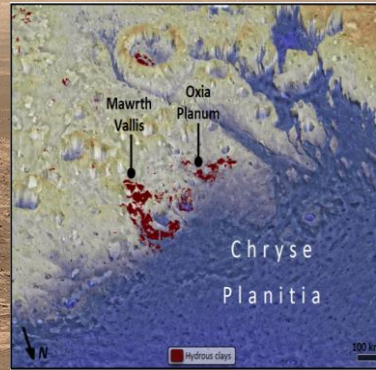
Mars is small and not very massive

- Weak gravitational field
- N₂ escaped
- Rapid cooling
- Loss of magnetic field
- Erosion of the atmosphere in the absence of greenhouse gases and by the effect of solar wind and radiation
- Ocean evaporation

ESA ExoMars missions

Trace Gas Orbiter and the Rosalind Franklin

2028 Rover : searching
for traces of past life



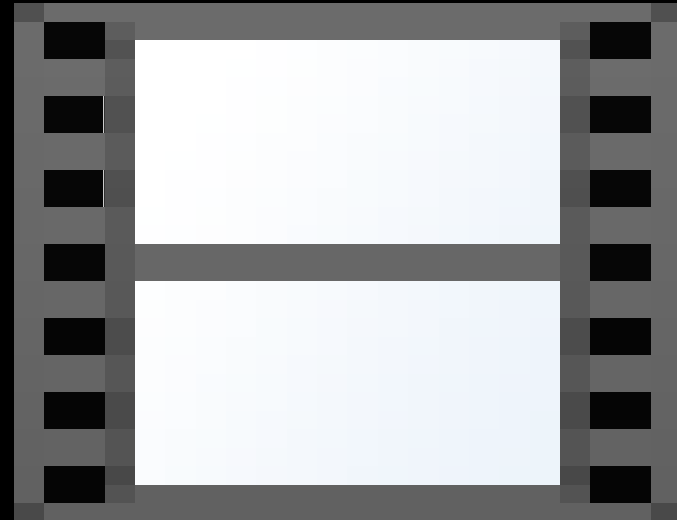
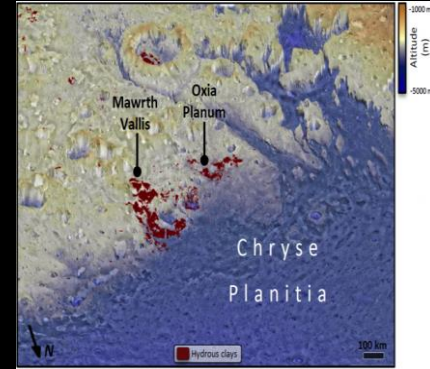
esa



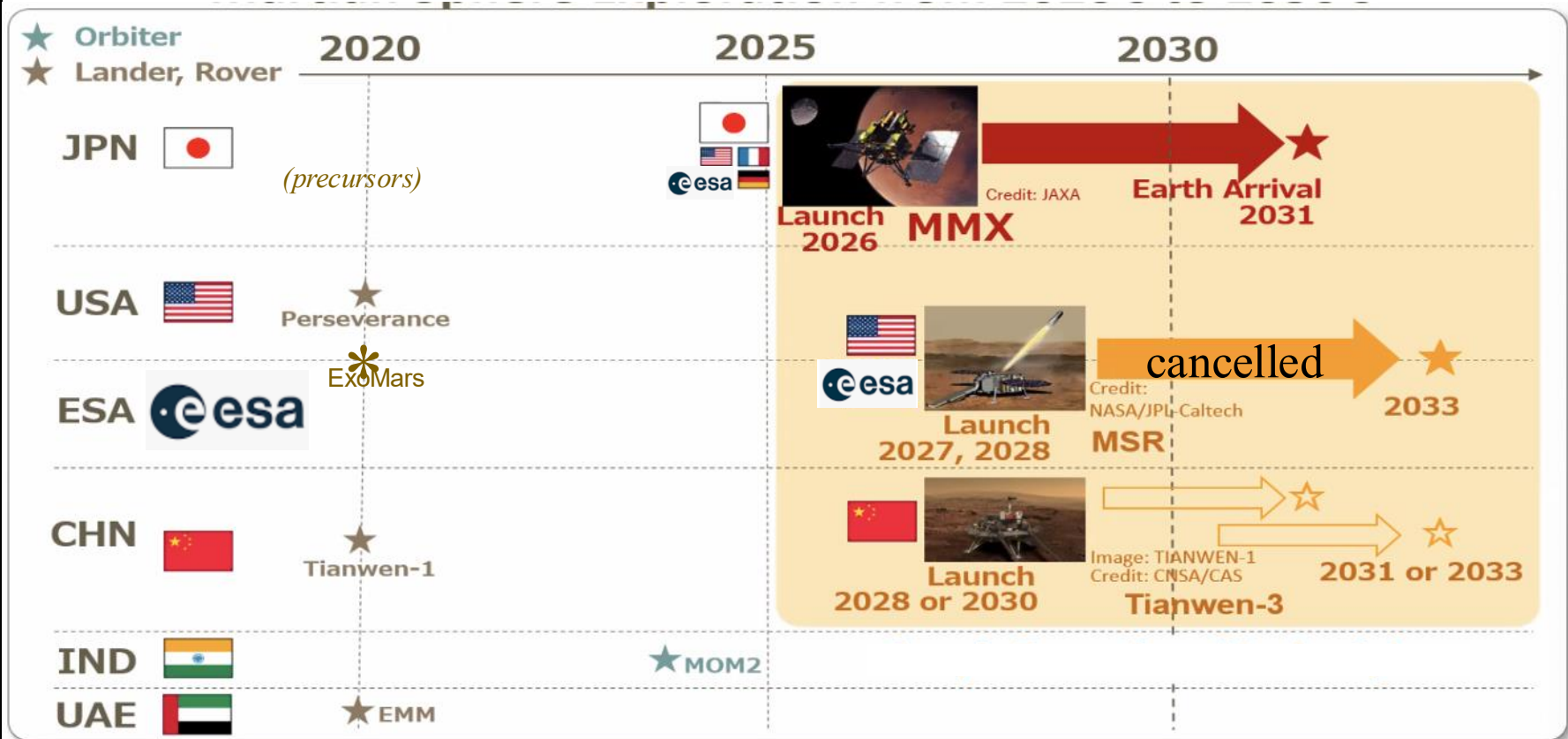
Next steps: EXOMARS 2028 : Rosalind Franklin Rover



*2028 Rover :
measurements
on past life*

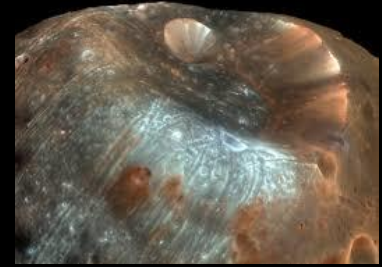


Martian & martian Moons exploration: sample return era





Launch in Oct. 2026



Science objectives

1) Clarify the origins of the Martian moons and constrain processes for planetary formation and material transport in the region connecting the inner and outer solar system

MO1.1.1) Spectroscopically reveal the surface-layer distribution of the materials that make up Phobos with the spatial resolution required for scientific evaluation of sampling points and geological structures.

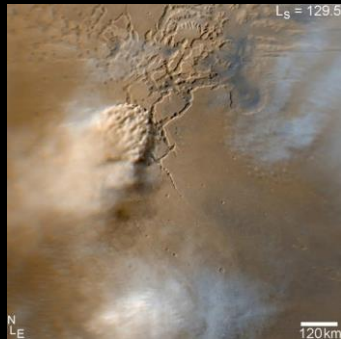
MO1.3.1) Clarify the surface distribution of materials composing Deimos through spectroscopy with the spatial resolution necessary for grasping its geological structures and compare this with Phobos.

2) Clarify the driving mechanism of the transition of the Mars-moons system and add new knowledge to the evolution history of Mars.

MO2.3.1) Impose constraints on dust and water transport processes in the Martian atmosphere and the processes of their exchange between the atmosphere and the surface through observations of the temporal changes in dust storms and the global distributions of water vapor and clouds.



by HiRISE MRO
NASA/JPL/Arizona Univ.



by HiRISE MRO
NASA/JPL/Arizona Univ.

Origin of the moons : (A) the pair are asteroids captured after the formation of Mars or
(B) the moons are fragments scattered during a giant collision (Giant Impact) with Mars that then coalesced.

Martian Moons eXploration

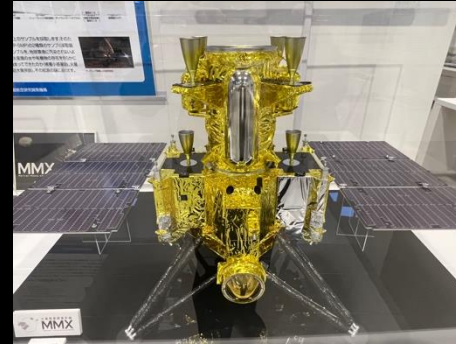
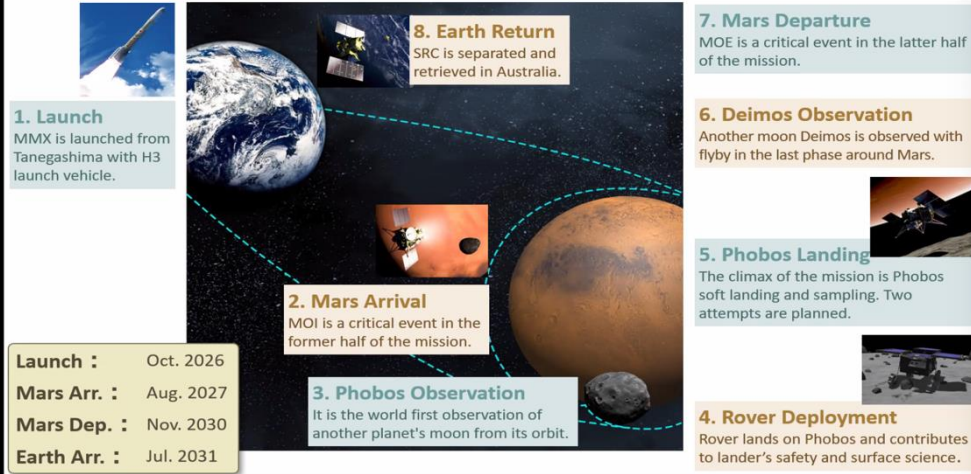
Three Major Items of MMX Mission Value

MMX is a **unique Martian sphere exploration** mission lead by Japan. It sets in its view of Martian moons, Martian life, and future crewed exploration in one mission.

Mission Profile

The mission is targeting the launch in 2026. A five-year trip is planned to retrieve samples back to Earth within three years of staying around Mars. The mission is full of critical and attractive events.

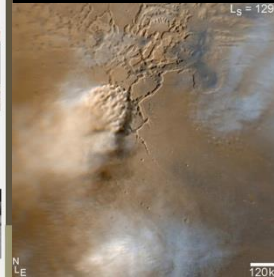
by HiRISE MRO NASA/JPL/Arizona Univ.



MMX Mission maquette au Japon, Tokyo, JAXA/ISAS



The MMX Rover au DLR, Munich, tenant une des roues...

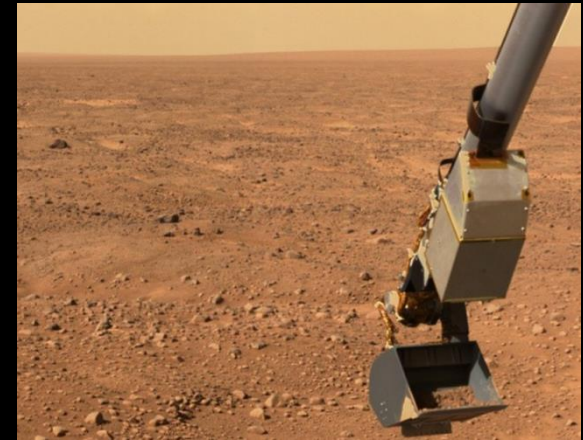
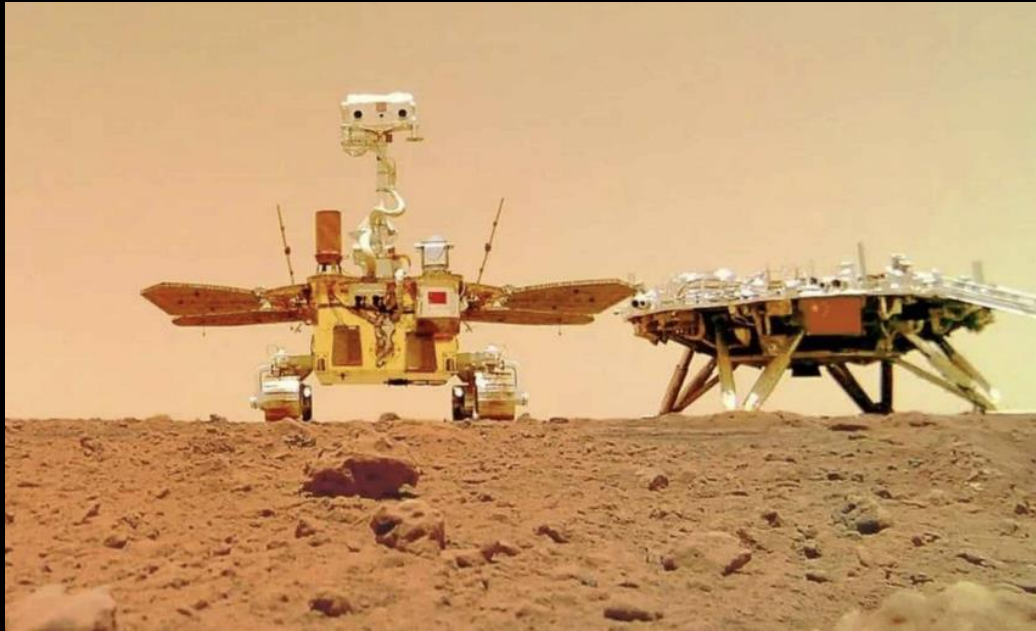


*HiRISE MRO
NASA/JPL/Arizona Univ.*



CAST : Tianwen-3 mission for Mars sample return

<https://spacenews.com/china-unveils-planetary-exploration-roadmap-targeting-habitability-and-extraterrestrial-life/>



中国行星探测
Zhōngguó Xíngxīng Tàncè



中国行星探测
PEC

Emblem of Planetary Exploration of China
Reaching for the Planets

Possible scenario: two spacecraft to launch around 2030. Together, the two spacecraft will seek to obtain samples of Martian rocks and soil and then return the cached samples to Earth.

This is assigned Category V : restricted Earth return



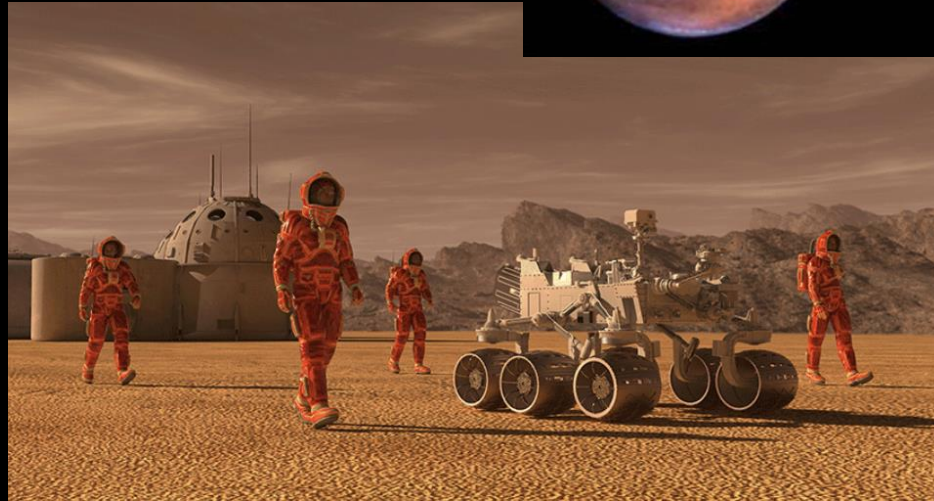
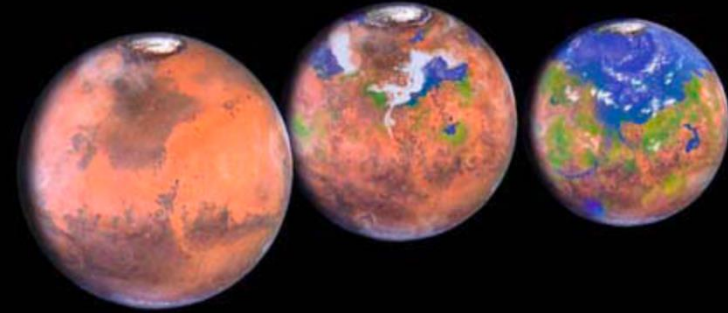
Planetary protection requirements for sample return from Mars : Cat V “Restricted Earth return”

- Unless specifically exempted, the outbound leg of the mission shall meet Category IVb requirements
- Unless the samples to be returned from Mars are subjected to an accepted and approved sterilization process, the canister(s) holding the samples returned from Mars shall be closed, with an appropriate verification process, and the samples shall remain contained during all mission phases through transport to a receiving facility where it (they) can be opened under containment
- The mission and the spacecraft design must provide a method to “break the chain of contact” with Mars, i.e. no uncontained hardware that contacted Mars, directly or indirectly, shall be returned to Earth
- Reviews and approval of the continuation of the flight mission shall be required at three stages: 1) prior to launch from Earth; 2) prior to leaving Mars for return to Earth; and 3) prior to commitment to Earth re-entry.
- For unsterilized samples returned to Earth, a program of life detection and biohazard testing, or a proven sterilization process, shall be undertaken as an absolute precondition for the controlled distribution of any portion of the sample

And in a very very long time...

Humans on Mars ?

Mars terraformed?



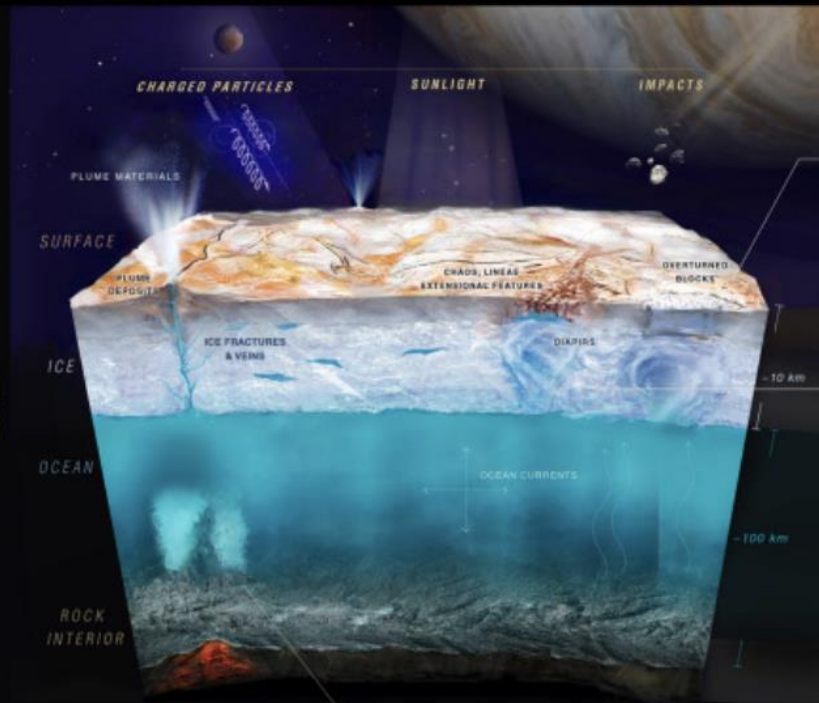
And in the future.... Humans on Mars?



- No scientific justification
 - Robotic missions are useful with no risk
- Risk of contamination of local traces of life if they exist
- Technological challenges
- Outrageous cost at this time
 - 10 to 100 times that of a robotic mission
- Danger to the human body (lack of water, atmosphere, gravity, strong radiations, long travel time (7-10 months),etc)

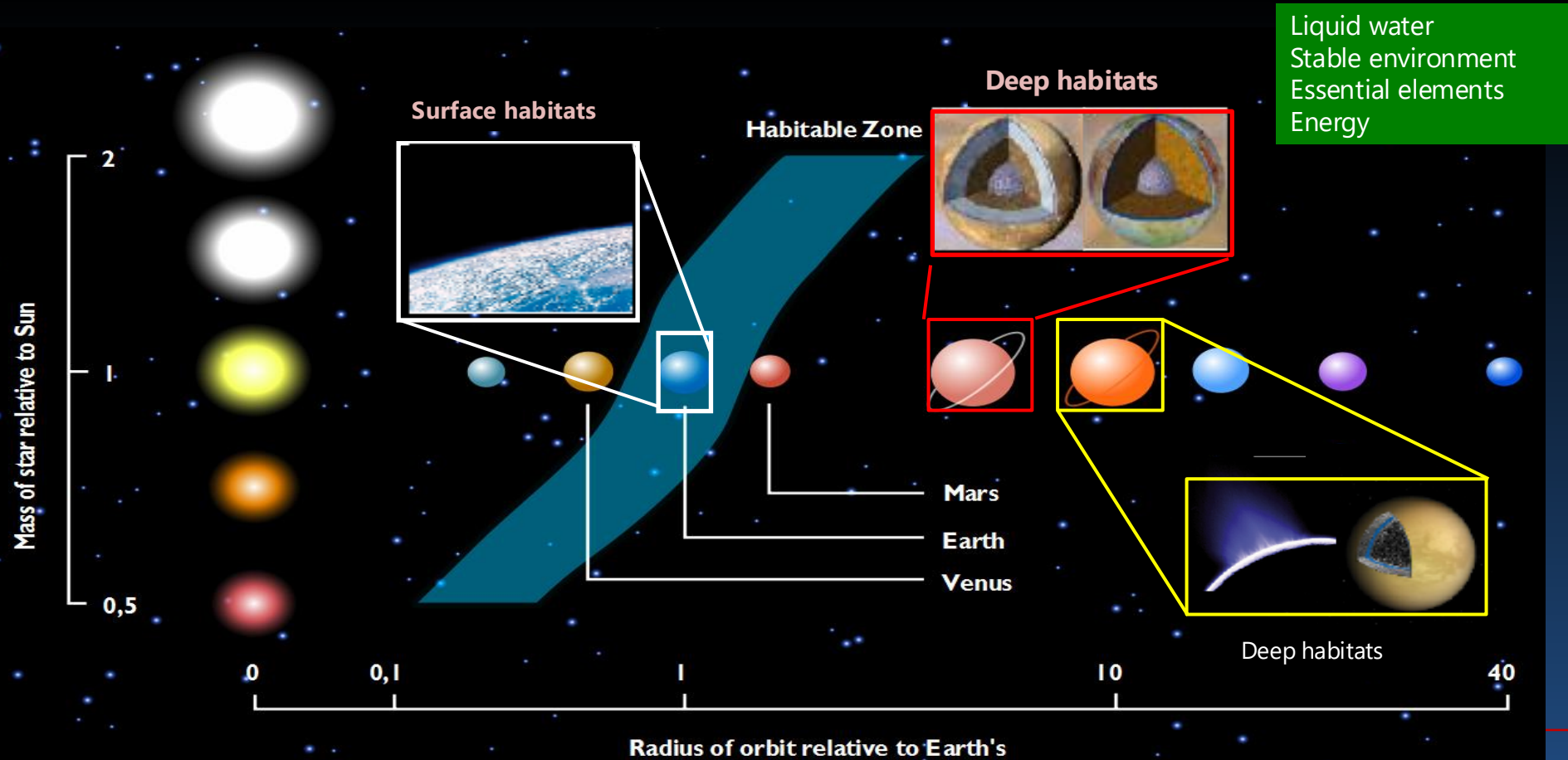
Outer solar system

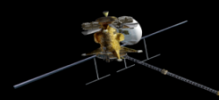
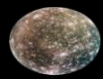
Icy Worlds (not a cold case...)



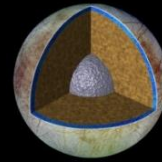
Habitability in the outer Solar System: extended HZ

Are icy satellites like Ganymede, Europa, Titan or Enceladus habitable worlds ?





Giant planets and their satellites



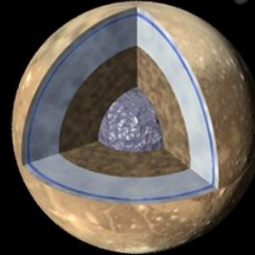
Europa



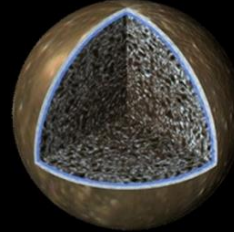
Earth



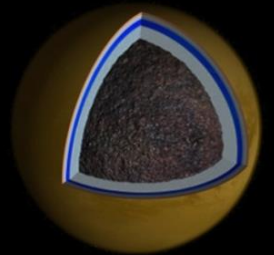
Enceladus



Ganymede

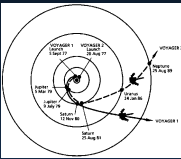


Callisto



Titan

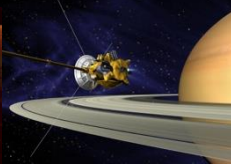
- ice
- water
- rock
- metal



Voyager
1980s



Galileo
1995-2000



Cassini-Huygens
2004-2017



Juno
2016-



Europa Clipper
2030-



JUICE
2031-



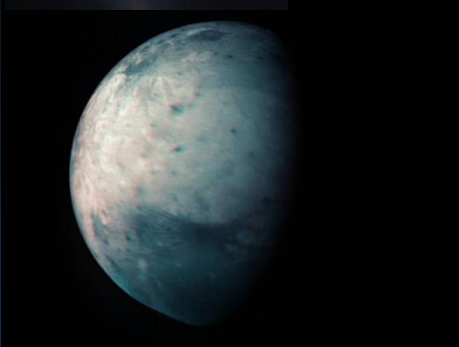
Dragonfly
2034-

Satellites : updates

Jupiter : 97

Saturn: 230 !!!

Potential habitats around Jupiter

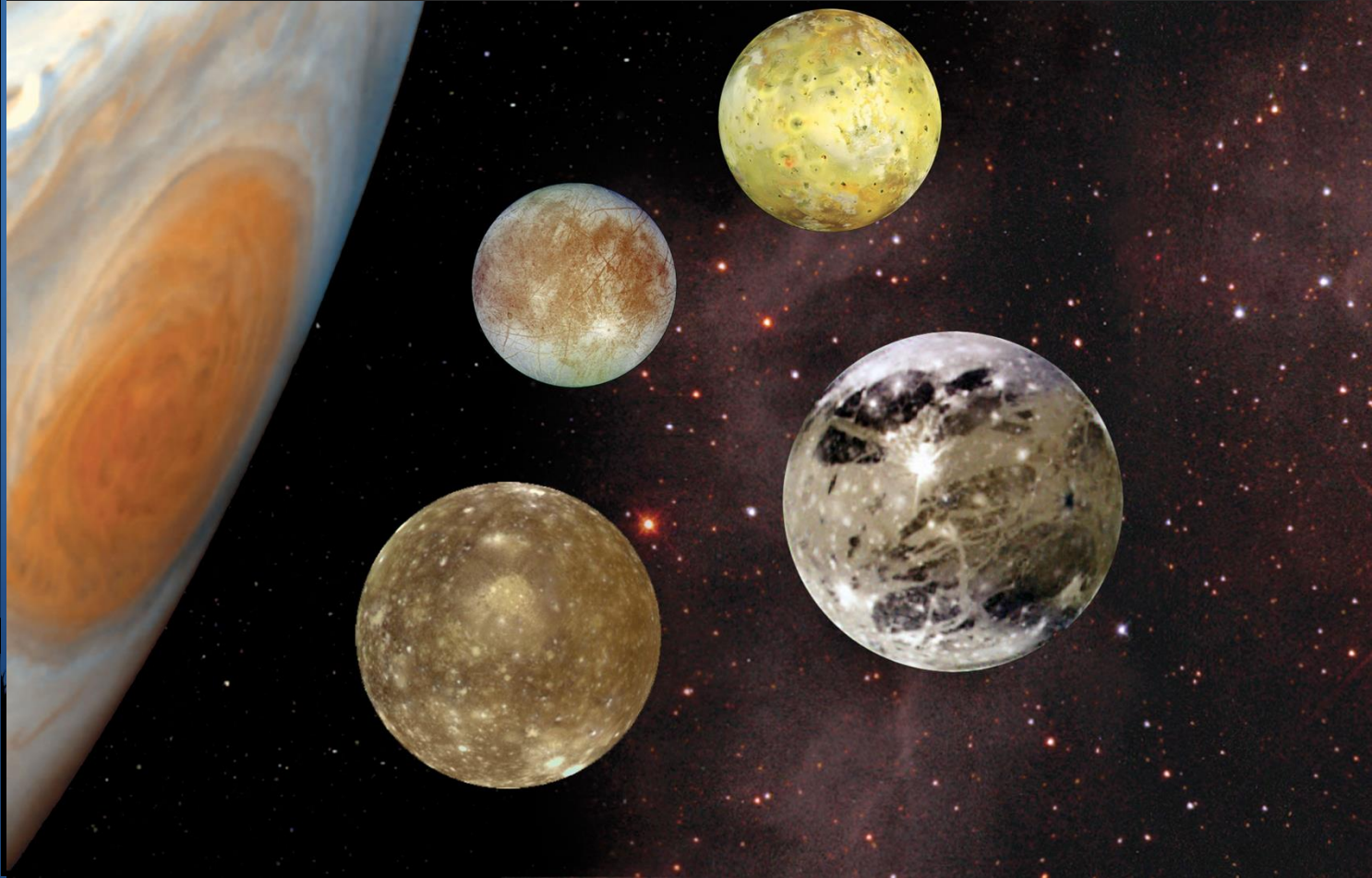


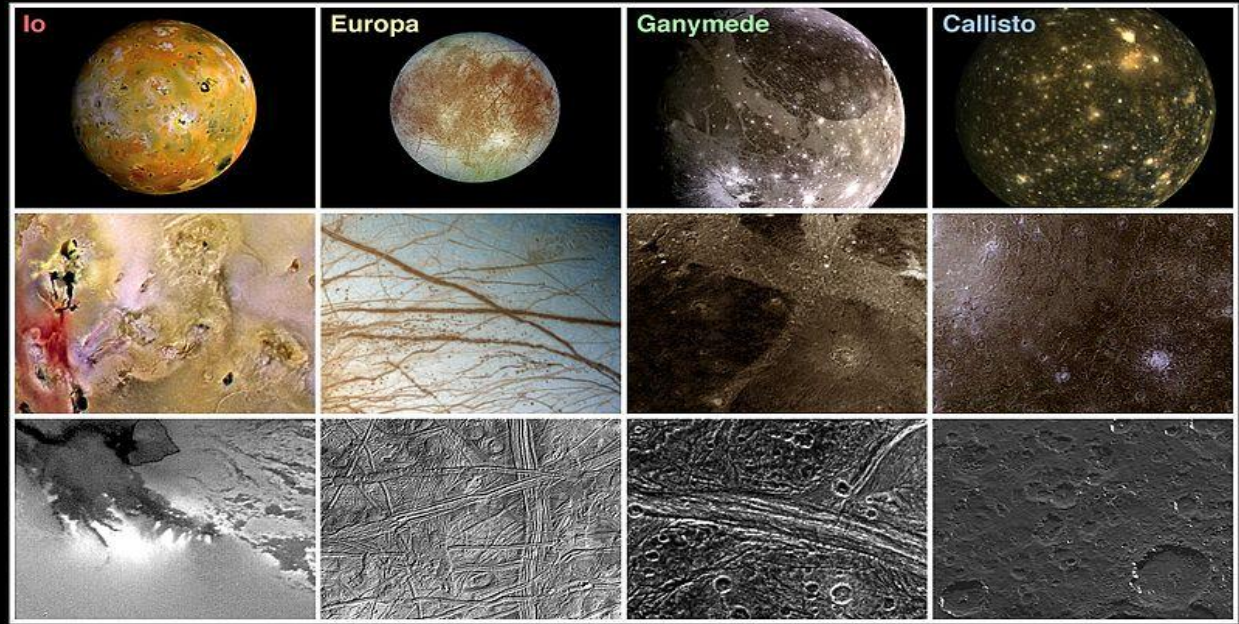
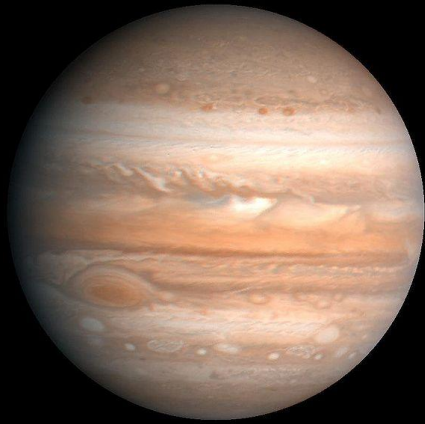
*Ganymede
in the IR by Juno*



Galileo: mission and man

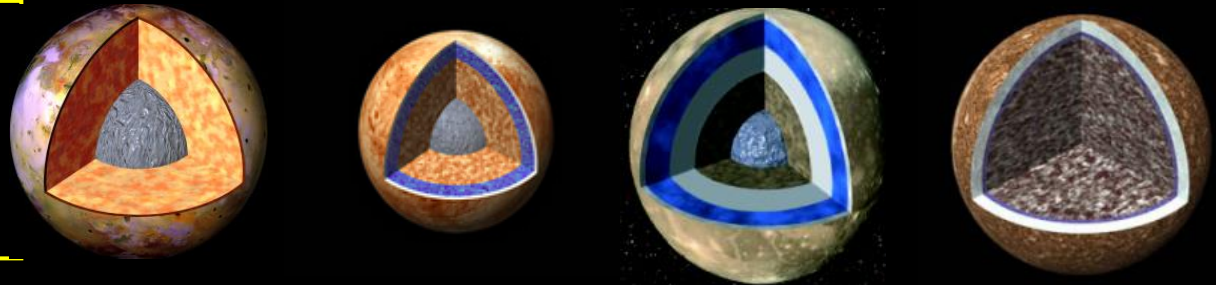
A giant planet, an enormous magnetosphere, 97 natural satellites with 4 large Galilean ones





Io

- Closest one, 400 volcanoes, active
- Magnetic field?
- Silicate rocks on a molten iron layer... !!!



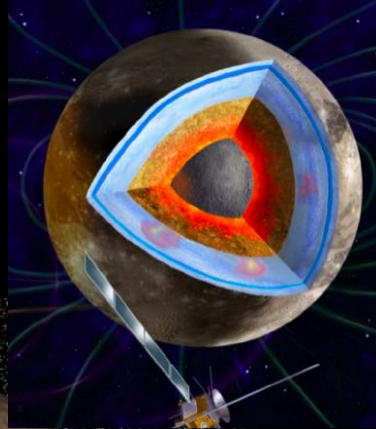
The closer a moon is to Jupiter, the hotter its interior and better chance of differentiation, while the surface is subject to dynamic movements

Possible habitable worlds around Jupiter

Three large icy moons to explore

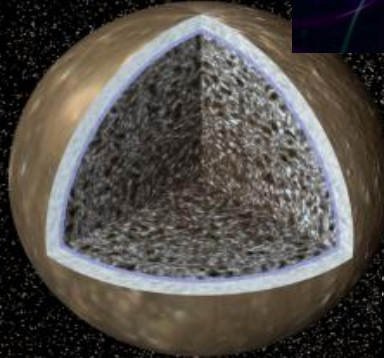
Ganymede

- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies
- **Best example of liquid environment trapped between icy layers**



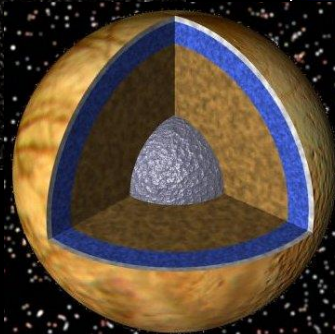
Callisto

- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- **The witness of early ages**



Europa

- Smaller than the Moon
- Silicate rocks, ice crust; iron core
- An active world? A deep ocean?
- **Best example of liquid environment in contact with silicates**

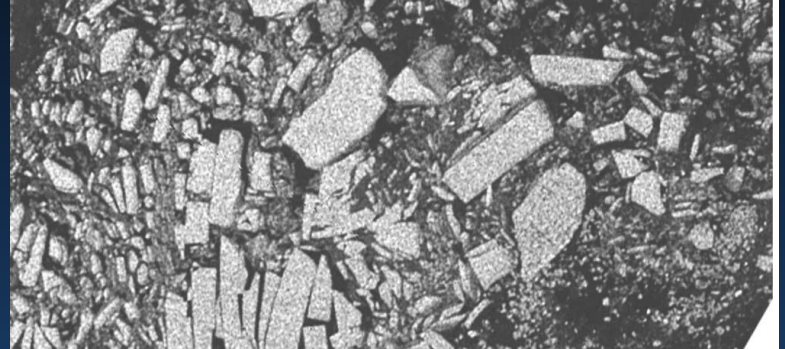


Europa: clues on the surface



The Galileo mission : this image covers a surface of 30 x 70 km, and shows what looks like pieces of ice floating on a frozen sea which could have been liquid in the past

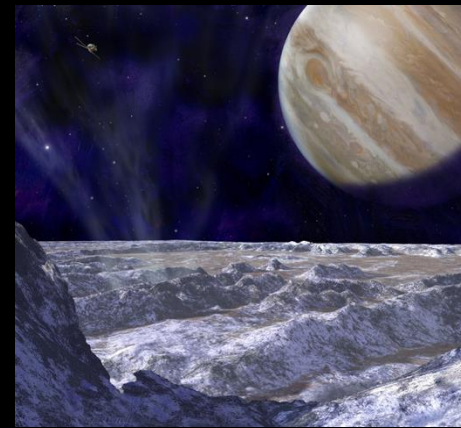
Same on the Antarctic ocean on Earth...



The resemblance between the two images leads the scientists to believe that there is a liquid water ocean underneath Europa's surface

Europa: surface and ocean

- Surface covered with **water ice** (width $\sim 10\text{-}100\text{ km}$) several stries and cracks (lineae), bands and chaotic terrains. $T_{\text{moy}} : \sim 90\text{K}$ (-183 C)
- **Surface** most smooth known in the solar system and very few impact craters, **young** ; age : about 100 Myr.
- Surface indices and presence of an induced magnetic field suggest the existence of an **internal visquous layer : salty liquid water ocean under the ice**, at a depth of $\sim 100\text{ km}$.
- A unique **geological activity** : movements of the ice comparables to plate tectonics and subduction. A first outside Earth where **the interactions between the salty water and the rock** at the bottom of the ocean lead to **hydrothermal vents** -> life



Images by Galileo

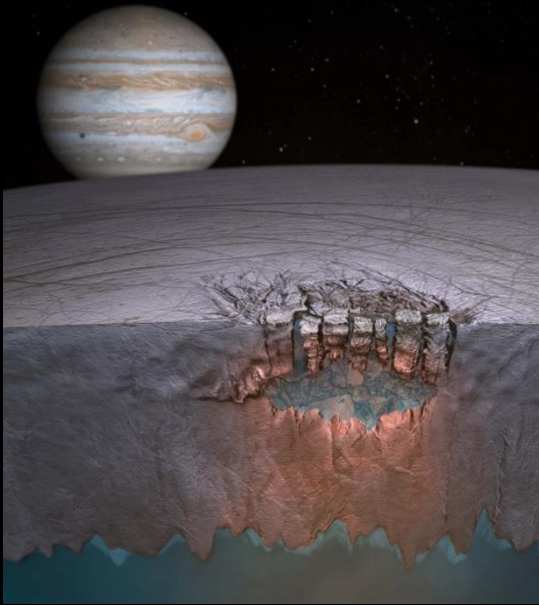
Hints **for habitability** : Salt deposits observed on the surface -> exchanges between the subglacial ocean and the ice crust -> chemical elements favorable to the apparition of life. **Subduction** to carry them in the ocean (Kattenhorn et Prockter, 2014)



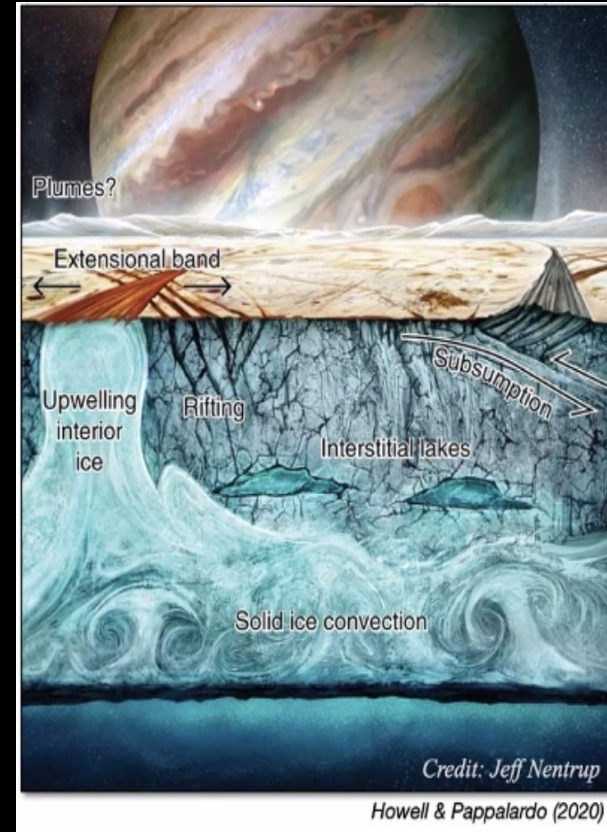
Europa: subterranean ocean

But ! new constraints for life on Europa...

- Byrne et al (2026) contest plate tectonics on Europa ! They predict a **tectonically inert oceanfloor** not favorable to sustainable habitability : improbable case for habitability based on the fractures at the level or inside the European oceanfloor
- Future habitability studies should focus on the **production of energy for chemioautotrophic life** through mechanisms not needing active tectonics in the oceanfloor



Liquid water due to the gravitational interactions with Io, Ganymede and Jupiter -> internal heating by **tidal effects**.

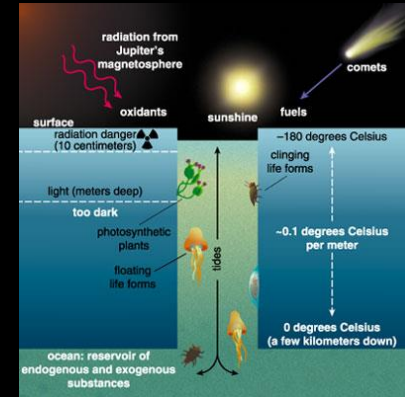
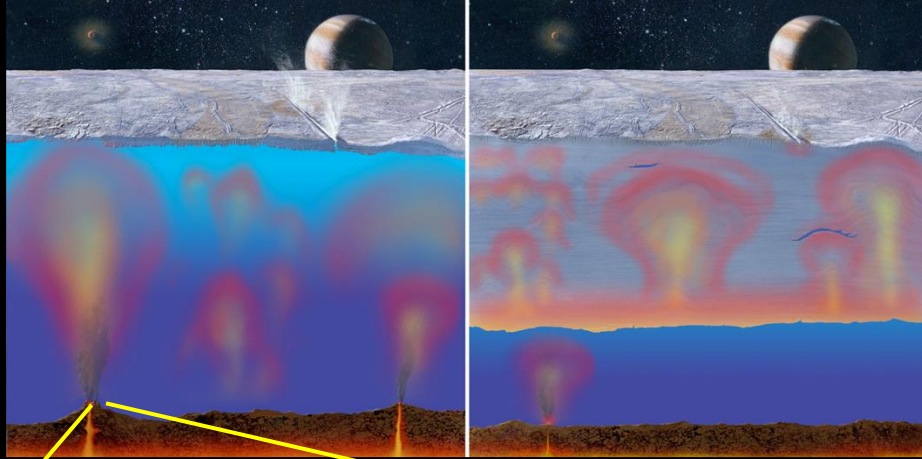
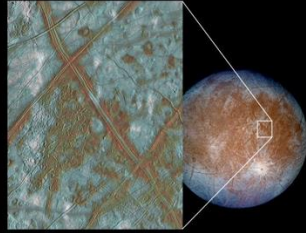


What are the possible habitable worlds around Jupiter?

Subsurface oceans in contact with silicates - Europa

Europa-like

- Water:
 - Warm salty H₂O ocean.
- Essential elements:
 - Accretion of CO₂?
 - Impactors.
 - But radiation destroys organics in upper ~10s cm of ice.
- Chemical energy:
 - Radiation of H₂O ⇒ oxidants.
 - Mantle contact: serpentinization and possible hydrothermal activity.
- Relatively stable environment:
 - Large satellite retains heat.
 - But activity might not be steady-state.

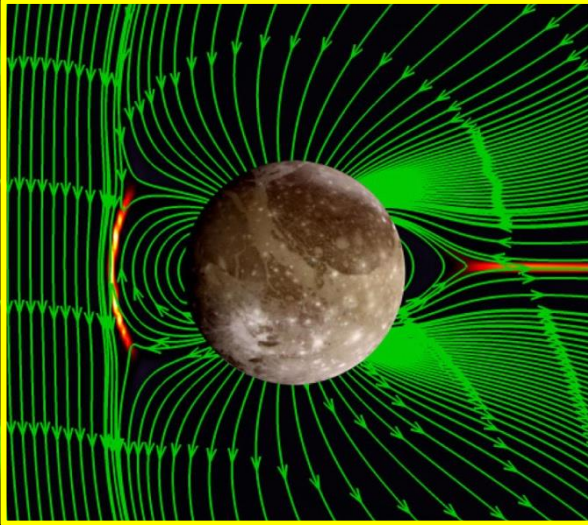


About the existence of deep oceans : GANYMEDE

Galileo evidences

Induced magnetic field from interaction of jovian magneto with conducting layer (ocean?)

Observed but not characterised



- Own internally-driven dipole magnetic field
- Interaction of Ganymede's mini-magnetosphere with Jupiter's

Ganymede possesses a unique characteristic for a moon: it generates its own intrinsic magnetic field (thanks to a convectively flowing liquid iron core).

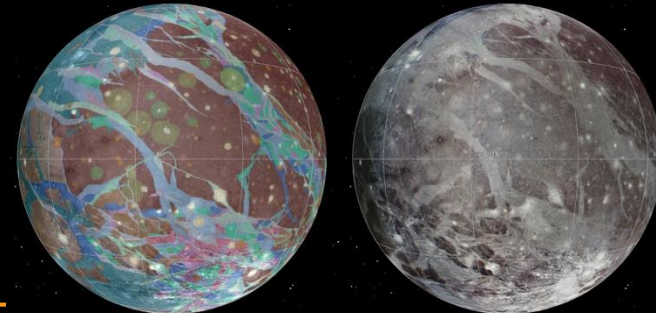
This field interacts with Jupiter's giant magnetosphere, creating observable auroras.

It was precisely by observing the oscillations of these auroras with the Hubble Space Telescope that scientists measured the electrical conductivity of the subsurface, thus confirming the presence of liquid salt water inside!

- Liquid water
- Chemistry: silicate needed...?
- Energy: heat transfer ?
- Stable environment



Indications for a young surface from water flooding



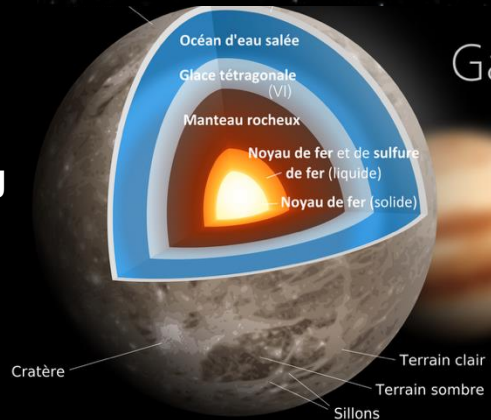
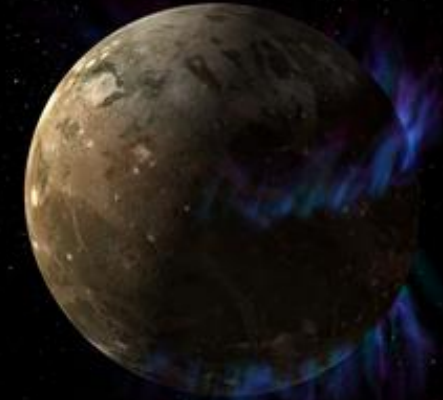
Ganymede: magnetic field, ocean and habitability

Magnetic Field & Surface Environment

- Surface shows ancient, heavily cratered **dark terrain** and younger, tectonically fractured **bright terrain** covered in grooves and ridges.
- Unique among moons: Ganymede generates its own **intrinsic magnetic field**, driven by convection in its liquid iron core.
- The field interacts with Jupiter's magnetosphere, producing **auroras** whose oscillations revealed electrical conductivity in Ganymede's interior -> evidence for salty subsurface ocean (*Moirano et al., 2026*)

Subsurface Ocean & Habitability

- Ocean trapped between **ice layers** of high-pressure : Its enormous mass creates extreme pressures, producing dense ice phases (V, VI, VII) between the ocean and rocky core (*Saur et al., 2015*)
- Major habitability constraint: the high-pressure ice separates water from rock, preventing direct water-rock interactions and likely **limiting hydrothermal activity and mineral supply**.
- Ganymede's salty ocean is a confirmed water reservoir, but its isolation from the rocky interior and the surface limits nutrient and chemical-energy supply, making sustained chemoautotrophic life challenging. Can life be sustained in such an ocean?



Ganymède
couches à l'éche

Habitable worlds in the outer solar system ?

Future exploration

So, what next?

Need for further in-depth and in situ
exploration of the deep habitats and the
extended habitable zone around gas giants

A TRIO OF MISSIONS: JUNO, JUICE AND EUROPA CLIPPER

Their destination may be the same, but Juno, Juice and Europa Clipper are all unique missions with different goals and instruments. Juno's discoveries are being used to optimise plans for Juice and Europa Clipper.



JUNO

Target: Jupiter

Arrival: 2016

Special skill: a polar orbit that goes very close to Jupiter, allowing deep mapping of its gravity and magnetic fields

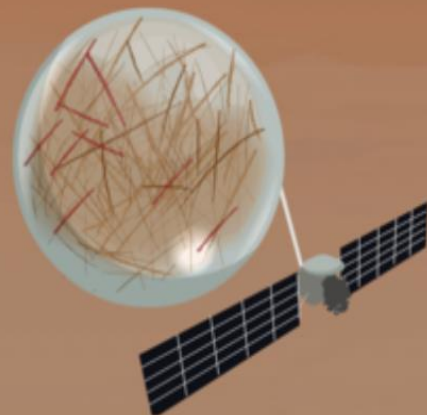


JUICE

Targets: Jupiter, Ganymede, Europa, Callisto

Arrival: 2031

Special skill: observing Jupiter and its icy moons to provide a complete view of habitable conditions in the Jovian system



EUROPA CLIPPER

Target: Europa

Arrival: 2030

Special skill: investigating the potential for life on Europa; helping select a landing site for a future Europa lander

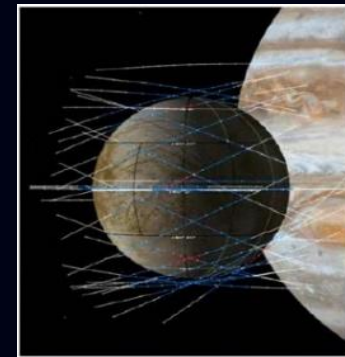
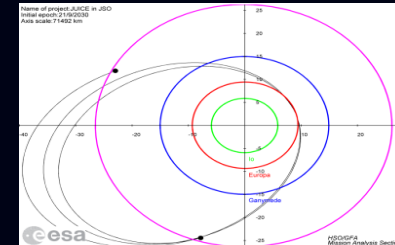
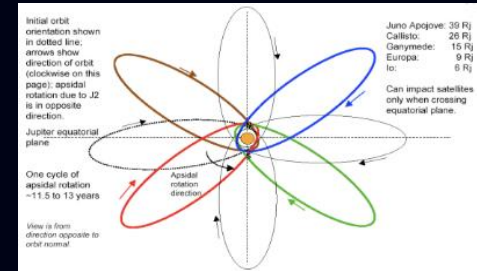
Planetary protection requirements

Missions in the Jovian system

On site since 2016: JUNO: orbiter; main mission target is Jupiter; probabilistic risk assessment for final Jupiter de-orbit manoeuvre, assessment of sterilisation in natural Jovian environment, assessment of sterilisation during high velocity impact: **Cat. II**

En route (launched April 2023): JUICE: orbiter; main mission target is Ganymede, with 2 Europa fly-bys using Callisto transfers; reliability assessment for spacecraft failure, assessment of problematic species on flight hardware, assessment of sterilisation in natural Jovian environment : **Cat. II* -> Cat. II** (see Grasset et al., 2013 and Tobie et al., 2025, PTA)

En route (launched Oct. 2024): EUROPA CLIPPER: orbiter; main mission target is Europa, with 45 Europa fly-bys; bioburden control of spacecraft before launch, assessment of sterilisation during flight : **Cat. III**

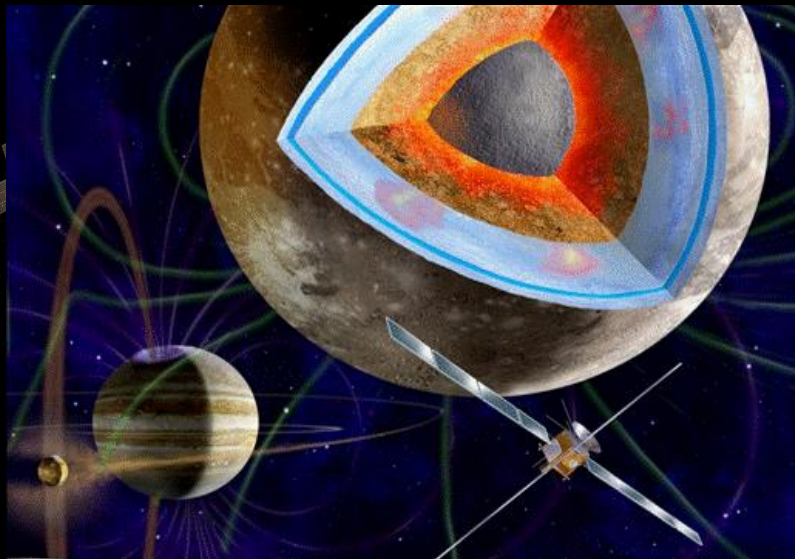


FIRST LARGE ESA MISSION JUICE : SPACECRAFT, PAYLOAD & SCENARIO



“JUICE & children of the world” calendar

JUICE: JUPiter Icy moons Explorer

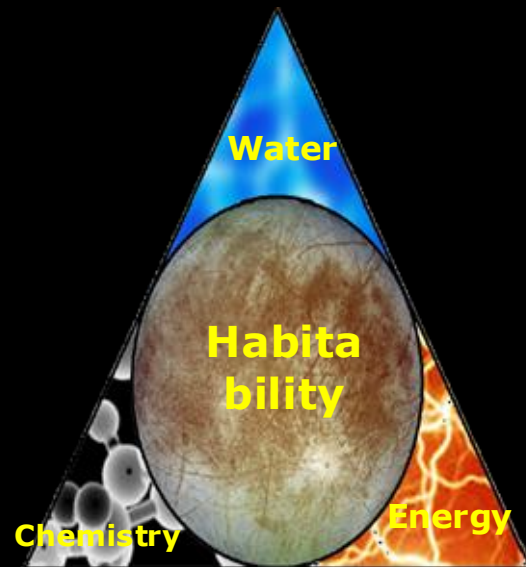


JUICE Science Goals

- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

JUICE : the 1st Large CV mission concept

- *Single spacecraft mission to the Jovian system*
- *Investigations from orbit and flyby trajectories*
- *Synergistic and multi-disciplinary payload*
- *European mission with international participation*



Timeline



The instrument PIs

ESA JUICE



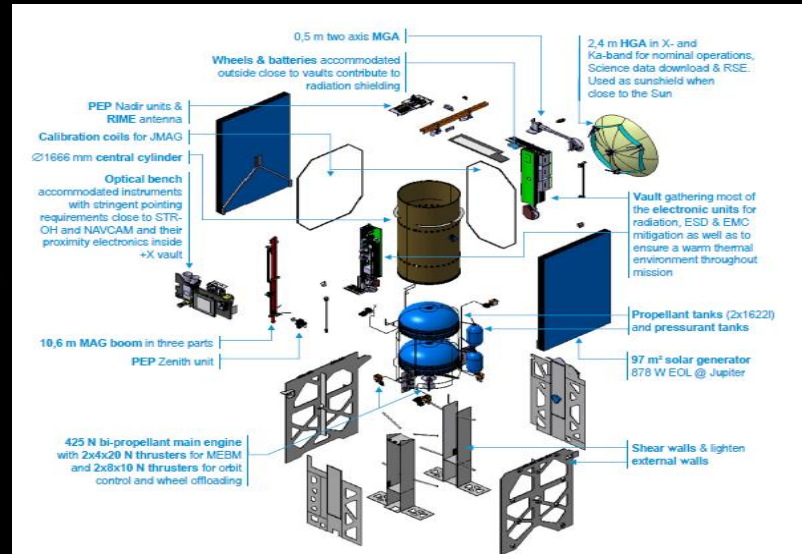
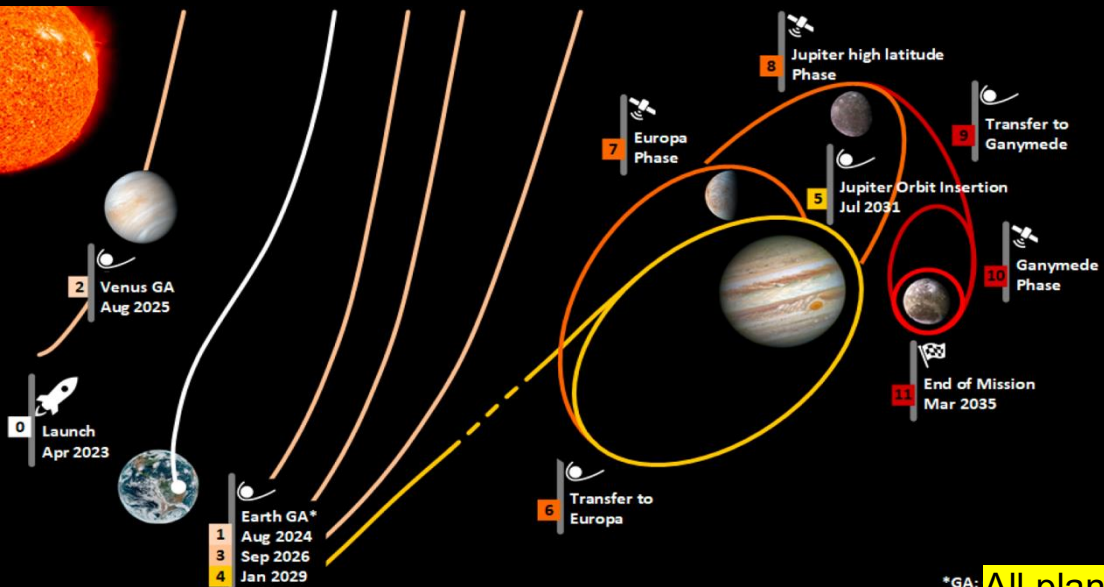
- **14 April 2023 14:14 CEST:**
Launch from Kourou
- 4 gravity assists: Moon-Earth, Venus, Earth, Earth
- July 2031: Jupiter Orbit insertion
- Jupiter tour and moon flybys
(2 Europa, 21 Callisto, 12 Ganymede)
- December 2034: Ganymede orbit insertion
- September 2035: end of the nominal mission
- Impact on Ganymede

*14 April 2023, 14:14
CEST: JUICE
launched from the
SCG in French
Guiana*

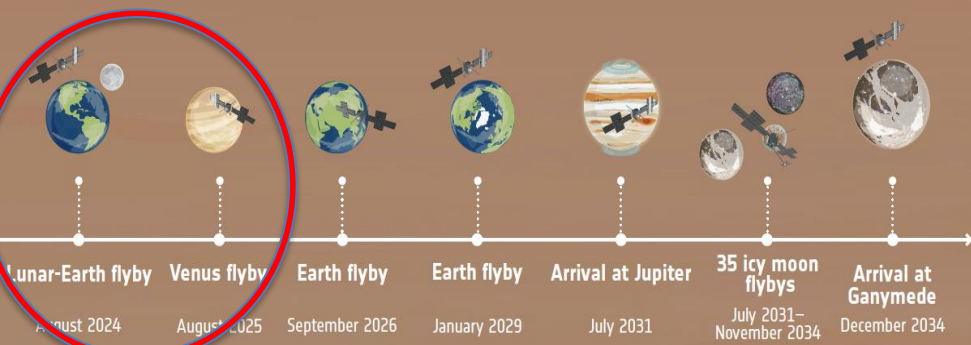


*Launch and selfies taken
shortly after launch by the Juice
monitoring camera 2 (JMC2),
with Earth in the background*

Categorisation of JUICE : Cat. II* -> Cat. II



*GA: All planetary protection requirements are met for Cat. II



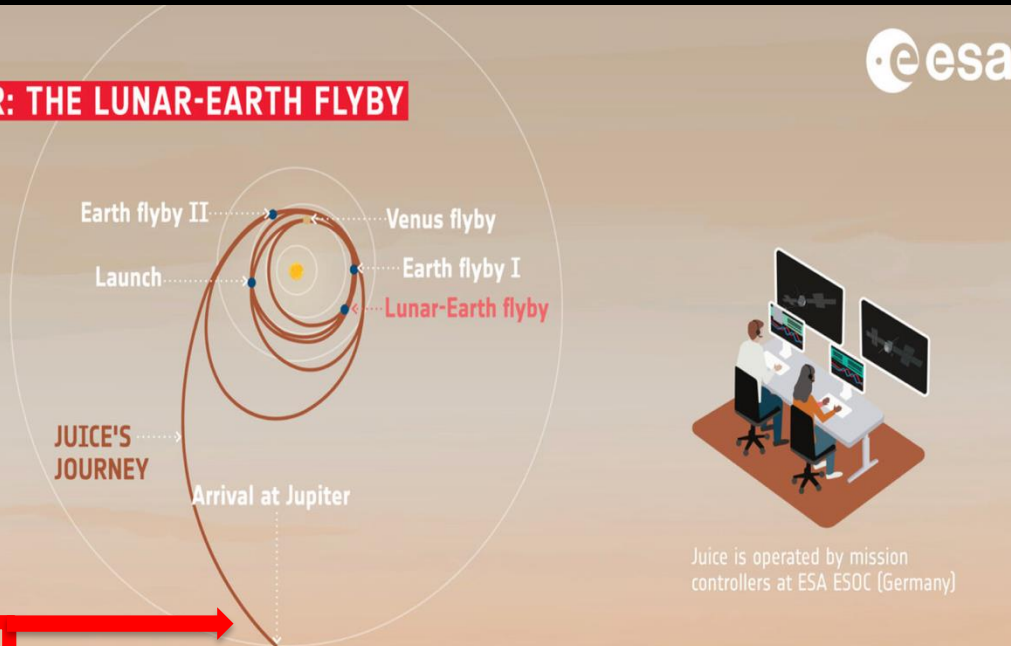
- Planetary Implementation and reports were reviewed and approved by ESA Planetary Protection Officer and Quality Control during all steps
- All spacecraft subsystems are fully operational after launch, no update of PP pre-launch documentation needed
- In addition, bioburden was sampled during all main assembly stages *Grasset et al. (2013) and Tobie et al. (2025)*

Juice achieved the first-ever flyby of the Moon towards Earth, and, using Earth's gravity, launched itself towards Venus, on a shortcut to Jupiter, and returns to Earth in Sept. 2026

JUICE'S JOURNEY TO JUPITER: THE LUNAR-EARTH FLYBY

A world first

- First-ever lunar-Earth flyby
- First-ever double gravity assist
- Brings Juice one step closer to Jupiter
- Saves a huge amount of propellant
- Ensures extra science at Ganymede
- Requires ultra-precise, real-time navigation
- Lines Juice up for a Venus flyby
- Inherently risky

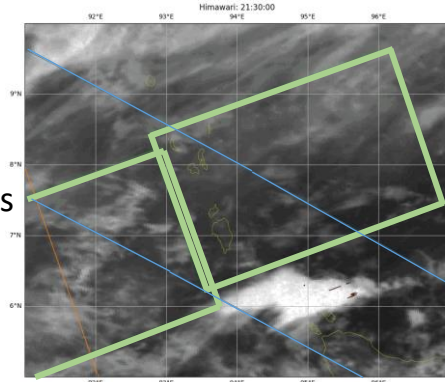


Another Earth flyby for gravity assist late Sept.-early Oct. 2026

Aug.-Sept. 2024: Observations by JUICE/JANUS during the Earth-Moon flyby and predictions for the Jupiter system

Jupiter observations will be performed at distances of 670 000 km to 4,5 million km. Such distances are 70 to 450 times greater than those of the Earth observations by JANUS.

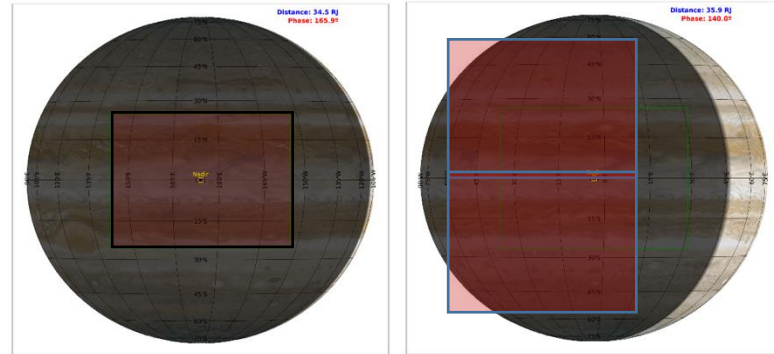
JANUS
observations
of Earth
lightnings



JUICE Multi-instrument Earth observations near the lightning. Image by Benoit Seignovert (Université de Nantes) with data from MAJIS, JANUS and NAVCAM

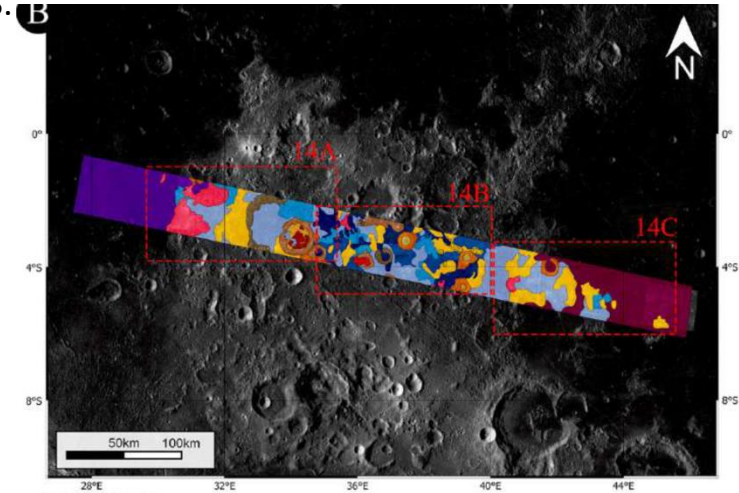
Jupiter as viewed from JUICE on: 2033-12-08T04:00:00

Jupiter as viewed from JUICE on: 2033-12-19T03:00:00



*Hueso,...,
Coustenis,
et al. 2026;
ANGEOS*

Example of lightning observations foreseen on Jupiter from orbits scheduled in December 2033

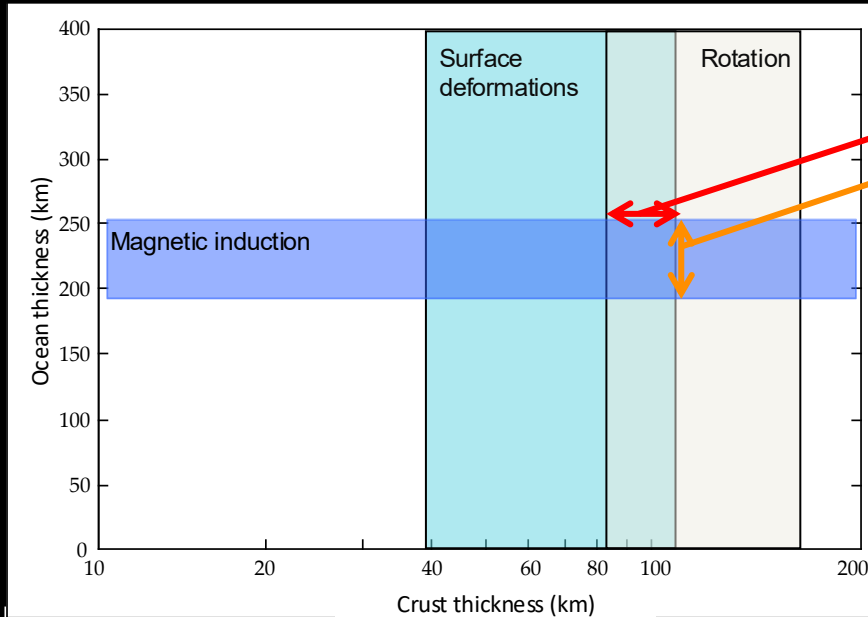


Geologic map of the isthmus next to the Langrenus crater on the lunar surface with JANUS
Lucchetti,...,Coustenis, et al. 2026; ANGEOS

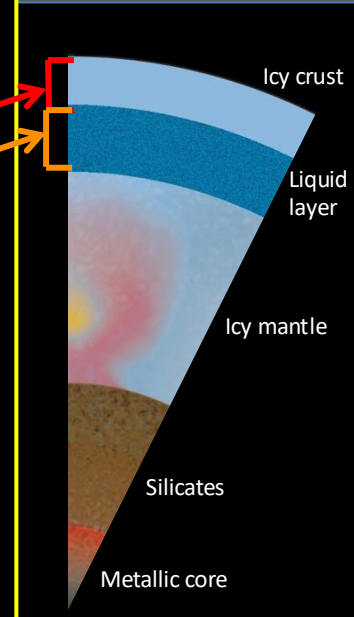
JANUS should amass the largest sample of data ever obtained on the extraterrestrial flashes and will contribute significantly to the study of atmospheric electricity beyond Earth

Characterise Ganymede and Europa as planetary object and possible habitats

1. Extent of the ocean and its relation to the deeper interior



Internal structure



JUICE measurements

- Eccentric orbit -> Surface deformations
- Periodic variations in the rotation (librations)
- Magnetic induction from the field vector

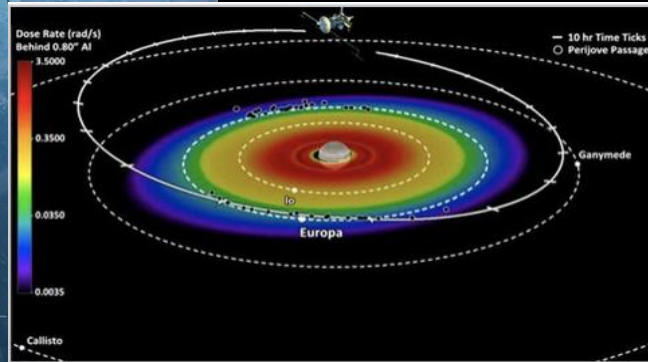
Instrument Packages

- In situ Fields and Particles
- Imaging
- Sounders and Radio Science

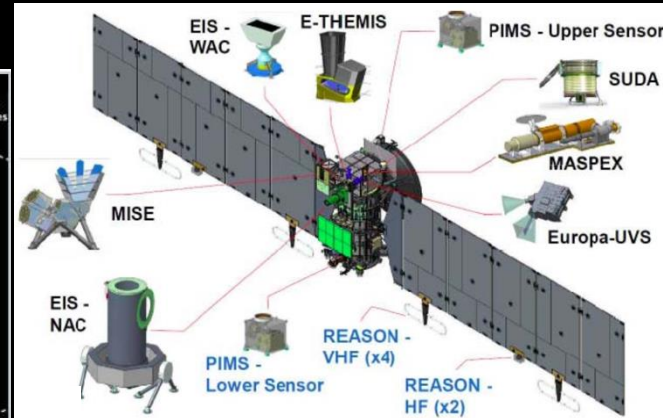
NASA Europa Clipper mission (*Cat. III*)

- Spacecraft in orbit around Jupiter with massive solar arrays and radar antennas
- Science goal: Europa's habitability
- Multiple (~ 50) close flybys of Europa
- 9 instruments selected: cameras, magnetometers, radar, dust analyser, spectrometers, plasma + mass spectrometer
- Launch on Falcon Heavy Oct. 2024; arrival : mid 2030
- Synergistic activities with JUICE

Europa Multi-flybys



NASA EUROPA CLIPPER
JOURNEY TO AN OCEAN WORLD



The biggest planet, the biggest magnetosphere, and a mini solar system

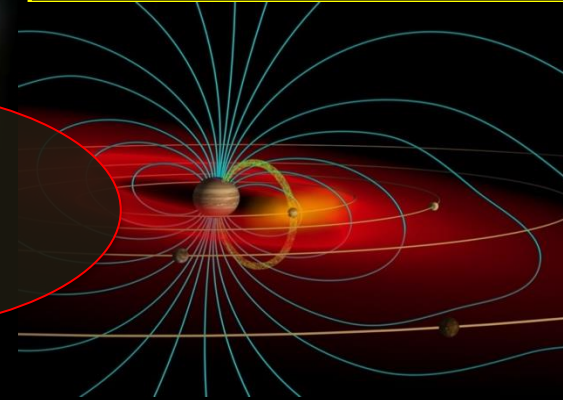
Jupiter

- Archetype for giant planets
- Natural planetary-scale laboratory for fundamental fluid dynamics, chemistry, meteorology,...
- Window into the formational history of our planetary system



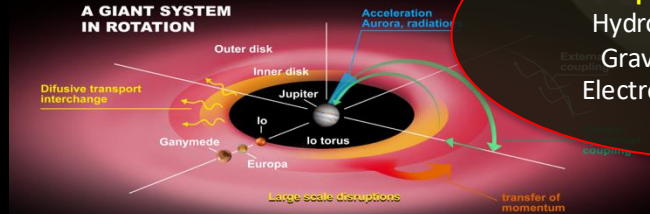
Magnetosphere

- Largest object in our Solar System
- Biggest particle accelerator in the Solar System
- Unveil global dynamics of an astrophysical object

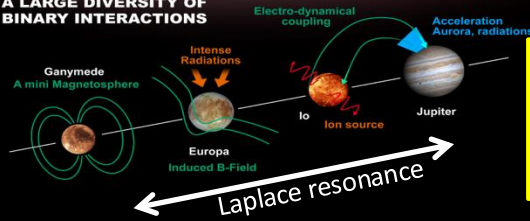


Coupling processes

Hydrodynamic coupling
Gravitational coupling
Electromagnetic coupling



A LARGE DIVERSITY OF BINARY INTERACTIONS



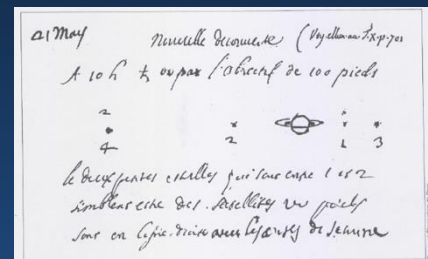
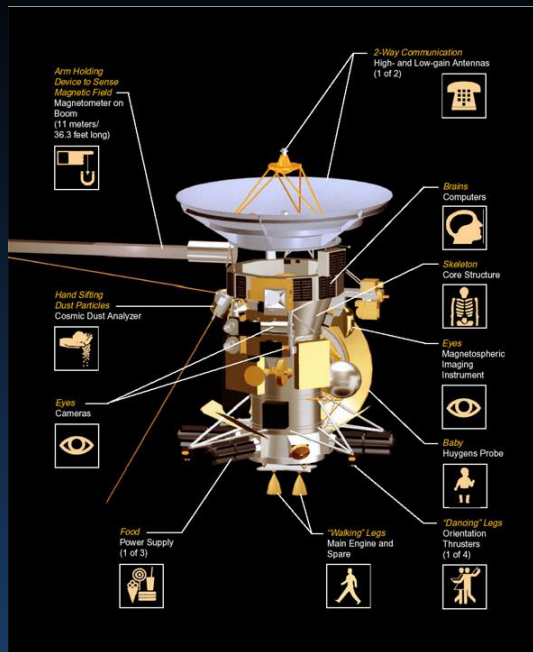
Satellite system

- Tidal forces: Laplace resonance
- Electromagnetic interactions to magnetosphere and upper atmosphere of Jupiter

What are the habitable worlds in the outer solar system ?
Around SATURN

Habitats in the Saturnian system :
The Cassini mission

Potential habitats around Saturn



The Cassini-Huygens mission

Huygens : Systema Saturnium (1659)

Cassini observing Saturn from Paris
Observatory (17th century)

La mission Cassini-Huygens en chiffres

1997-2017

Cassini-Huygens: Mission to Saturn BY THE NUMBERS

2.5 MILLION
COMMANDS
executed

635 
SCIENCE DATA
collected

6 NAMED MOONS
discovered

162 TARGETED
FLYBYS
of Saturn's moons

27 NATIONS
participated

4.9 BILLION
MILES TRAVELED
since launch
(7.9 BILLION KILOMETERS)

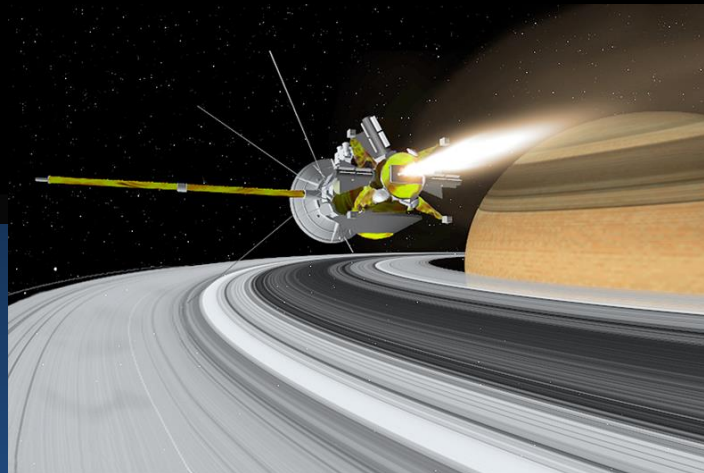
3,948
SCIENCE PAPERS
published

294 ORBITS
completed

453,048
images taken

360 ENGINE
burns

30 Juin/ 1 Juillet 2004



Enceladus : plumes, ocean and habitability

Active Plumes

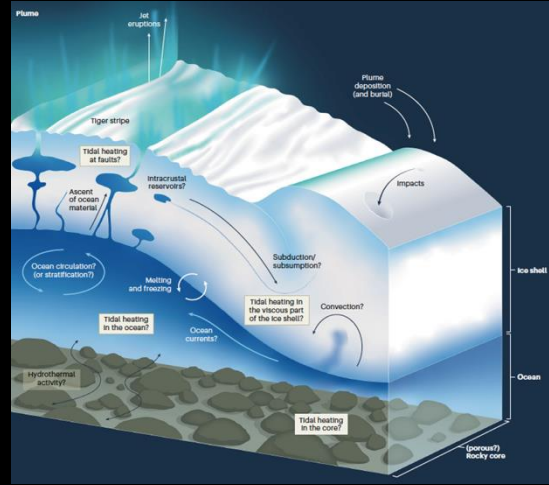
- Active icy **plumes** erupt from fractures in the southern polar region, supplying material to Saturn's E-ring.
- Plumes contain water vapor and ice grains, salts, organics, nanograin dust, H_2 & NH_3 .
- Ice grains carry complex macromolecular organic matter providing direct access to material from the global subsurface ocean.

Subsurface Ocean

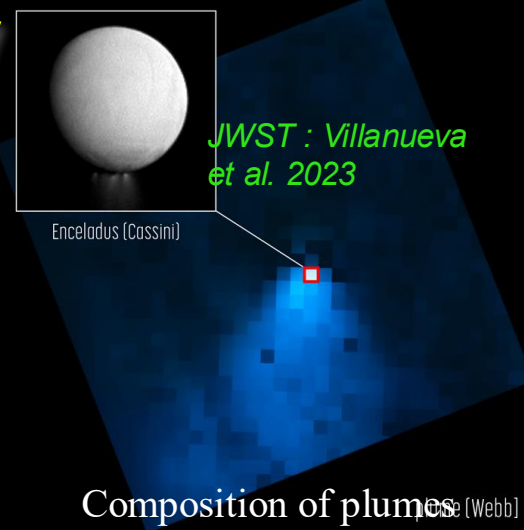
- Heat concentrated along the south-polar fractures, -> active internal heat source.
- H_2 and evidence for hydrothermal chemistry suggest water-rock interactions at the ocean floor.

Habitability

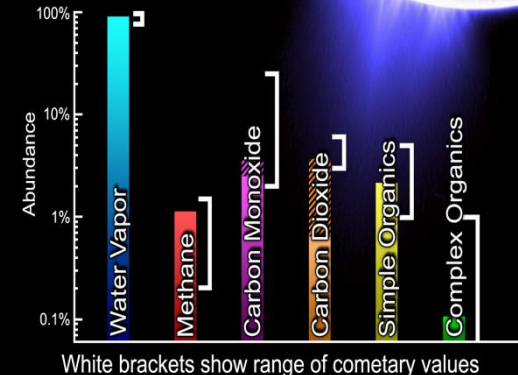
- Detection of **HCN** and diverse redox species (*Peter et al., 2023*) and **phosphorus** (*Postberg et al., 2023*) adds key chemical ingredients for life.
 - Laboratory ocean simulations show that Enceladus-like conditions can support **abiotic synthesis of complex organic molecules**
- **Water + chemical diversity + energy + organic molecules** → **strong evidence for a potentially habitable ocean.**



Cockell et al. 2024

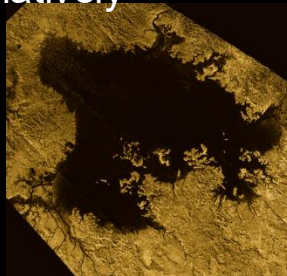
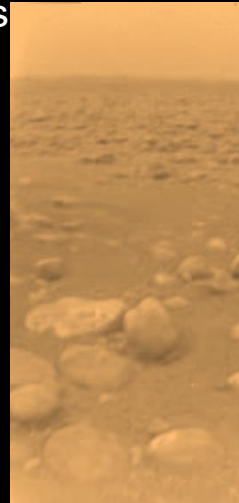
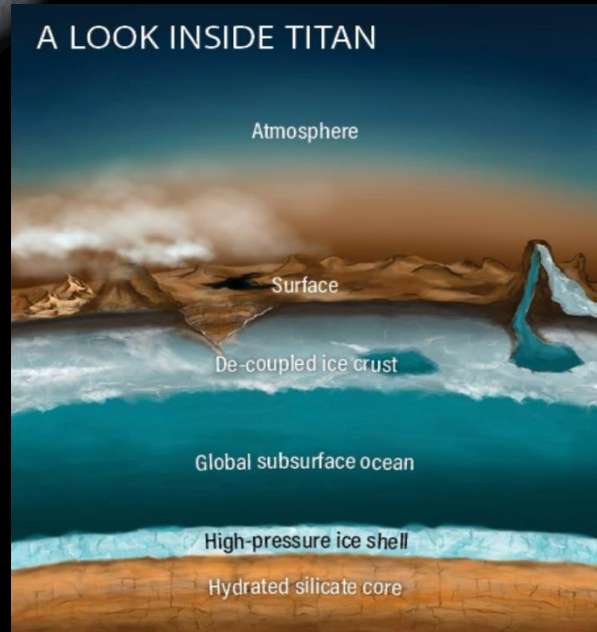
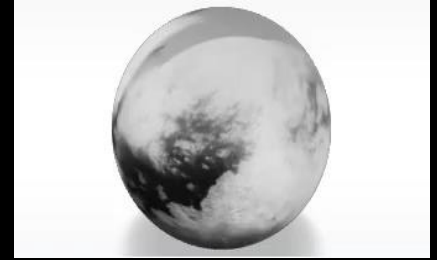
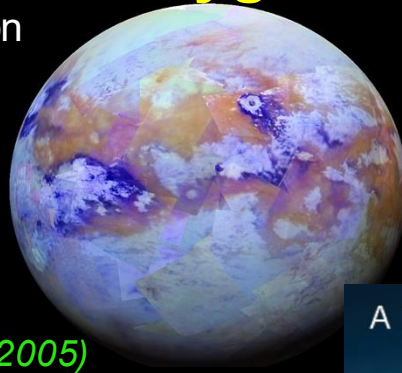


Waite et al. 2007



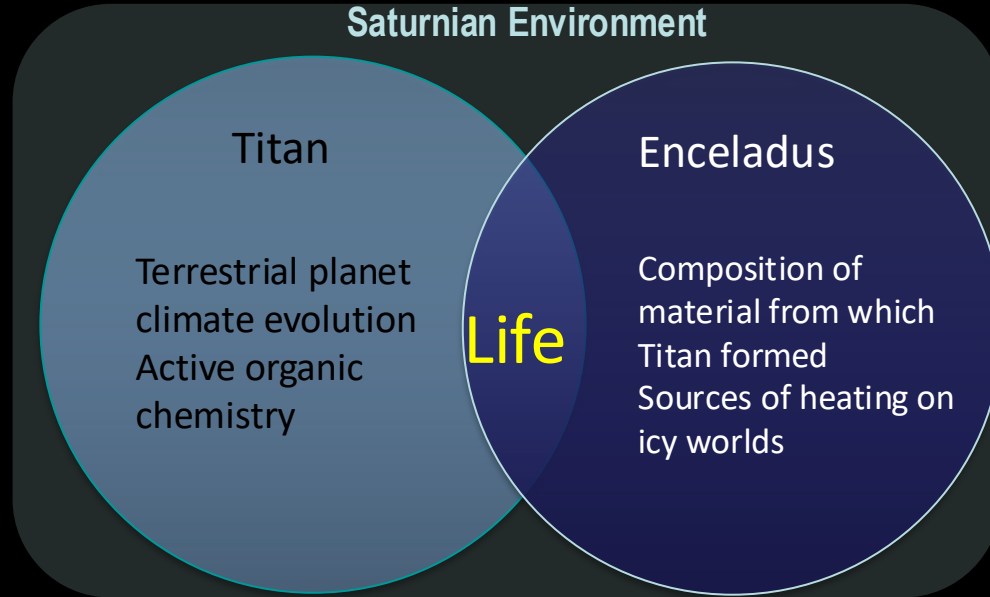
Titan Highlights from Cassini-Huygens (2004-2017)

- 2005: ESA's **Huygens probe** makes first landing on moon in outer solar system (farthest away today)
- Titan revealed as an Earth-like world with intense prebiotic **organic chemistry** initiated in the upper atmosphere mainly composed of N_2 (97%), CH_4 (1.5%), H_2 (0.1%) (*Coustenis, 2021, Nixon, 2024*)
- Surf T= 93.4K, surf P= 1.5 bar (*Fulchignoni et al. 2005*)
- Discovery of variety of weather patterns, diurnal effects including rainstorms, rain, rivers, lakes and seas (*Stofan et al. 2007*)
- Seasonal changes affecting the surface and atmospheric content especially at the poles
- Discovery of dense, salty global ocean below a thick crust (*less et al. 2012*) and a relatively low density core

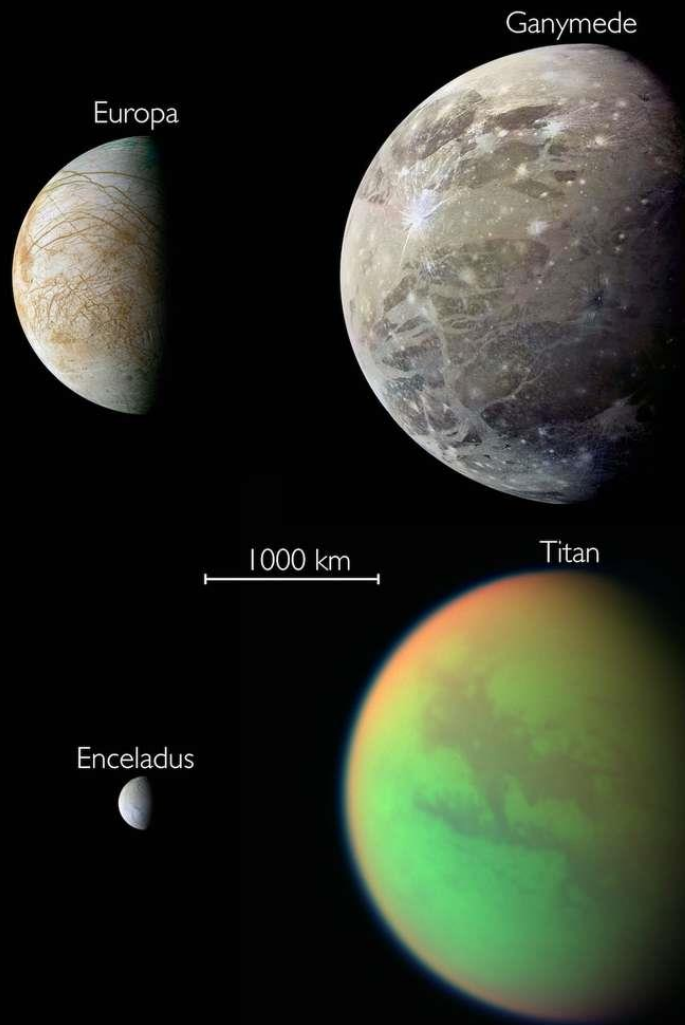


Titan's internal structure (Astronomy: R. Kelly, after A. Karagiotas and T. Shalamberidze and Tobie et al. 2006)

The exploration of the Saturnian system : habitats



- The Saturnian system is rich in worlds that could bring insights on important aspects of Earth's
 - *climate,*
 - *organic chemistry and*
 - *emergence of life.*

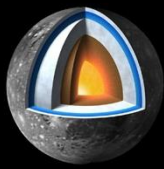


Two categories of icy moons as possible habitats : oceans in contact with the silicate core or not.

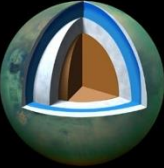
How do we explore them in the future?

With caution !

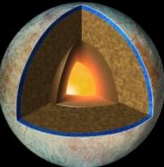
The icy moons sit at the intersection of terrestrial worlds with an atmosphere and ocean worlds of the outer solar system



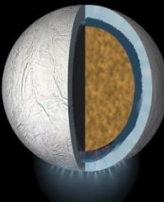
GANYMEDE



TITAN



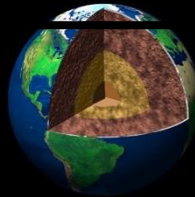
EUROPA



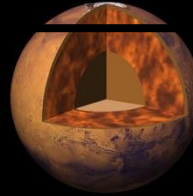
ENCELADUS



VENUS



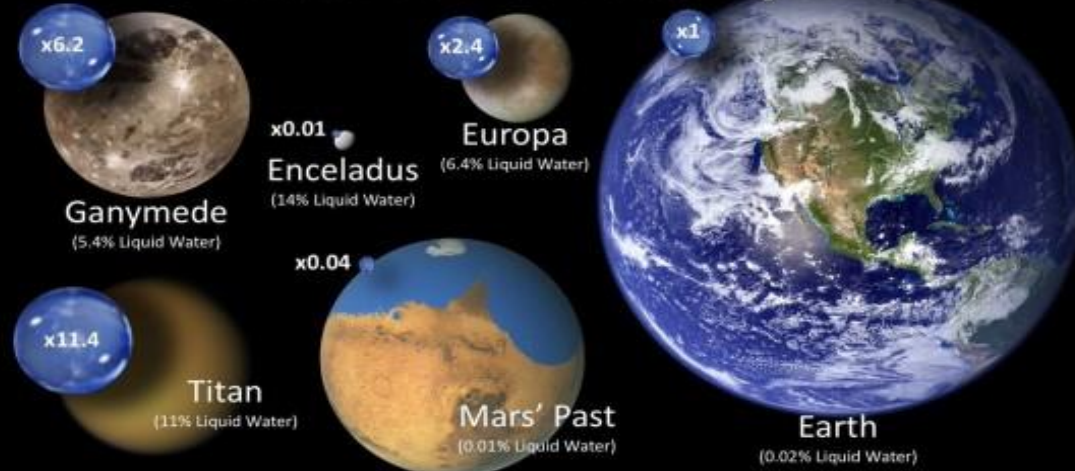
EARTH



MARS

Lots of water in the solar system !

Oceans in the Solar System



**The Saturnian system:
a Post-Cassini mission...**

Titan exploration : Dragonfly

The logo for the Dragonfly mission, featuring a stylized insect-like figure above the word "DRAGONFLY" in a bold, sans-serif font.

E-10 min
EI=1270 km

E+6 min
h=134 km

E+88 min
h=4 km

E+105 min
h=1.2 km



Dragonfly Mission to Titan

(Turtle et al., 2018

Barnes et al., 2021

Lorenz et al., 2022)

Multidisciplinary science measurements at dozens of potential landing sites

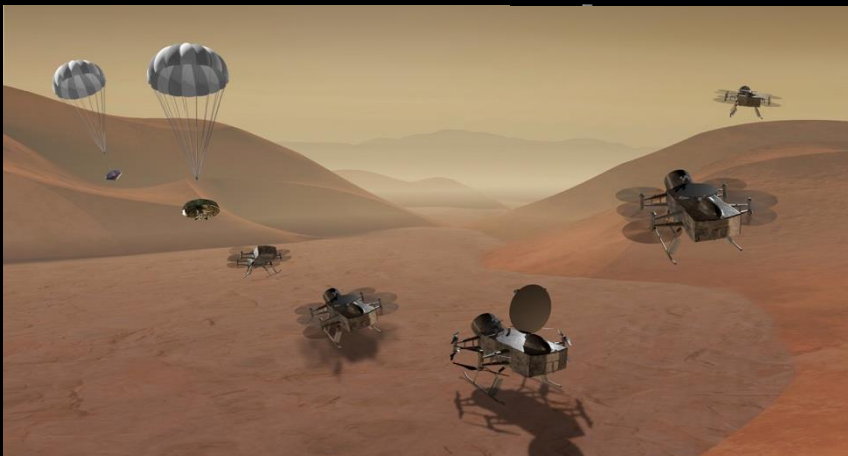


PP Cat. II*->II

Launch: 2028

Arrival: 2034

- Prebiotic chemistry
 - Analyze chemical components and processes at work that produce biologically relevant compounds
- Habitable environments
 - Measure atmospheric conditions, identify methane reservoirs, and determine transport rates
 - Constrain processes that mix organics with past surface liquid water reservoirs or subsurface ocean
- Search for biosignatures
 - Search for chemical evidence of water- or hydrocarbon-based life



- DraMS: Mass Spectrometer
- DrACO: Drill for Acquisition of Complex Organics
 - GSFC, Honeybee – MSL SAM, ExoMars MOMA
- DraGNS: Gamma-ray Neutron Spectrometer
 - APL, LLNL – MESSENGER GRNS, Psyche GRNS
 - GSFC, Schlumberger – Pulsed Neutron Generator
- DraGMet: Geophysics & Meteorology Package
 - APL sensor suite + JAXA Lunar-A seismometer
- DragonCam: Camera Suite
 - MSSS – OSIRIS-REx ECAM, MSL Mastcam, Mars 2020 descent camera



Rotorcraft Lander
Surface configuration
with HGA deployed

And in the longer-term future?

With my crystal ball....



In the making
But certainly exciting

ESA Voyage 2050

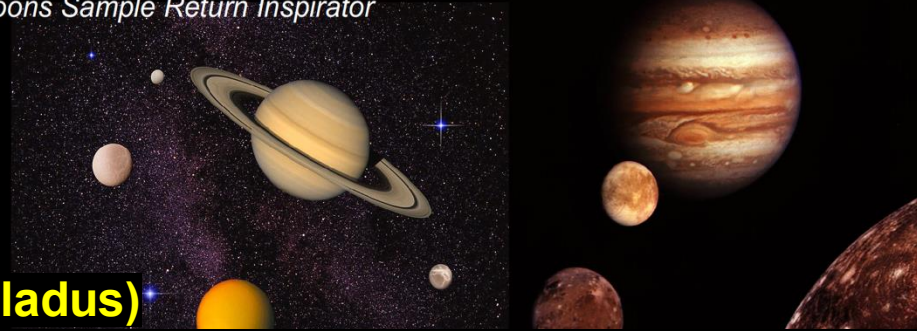
- Moons of Giant Planets
- Temperate Exoplanets/Milky Way
- New Physical Probes of the Early Universe

A mission to the moons of Jupiter or Saturn

The ambitious next destination for the Science Programme

A competitively selected team of European scientists has started to define the first "Large" mission of Voyage 2050...

... also look into much more ambitious mission profiles, paving the way for the *Icy Moons Sample Return Inspirator*



ESA L4: Moons of the Giant Planets (Enceladus)

Exploring the issues of habitability of ocean worlds, searching for biosignatures, and studying the connection of moon interiors, near-surface environments, and the implications for the exchange of mass and energy into the overall moon-planet system. This theme follows the science from Cassini-Huygens and expected scientific return from JUICE.

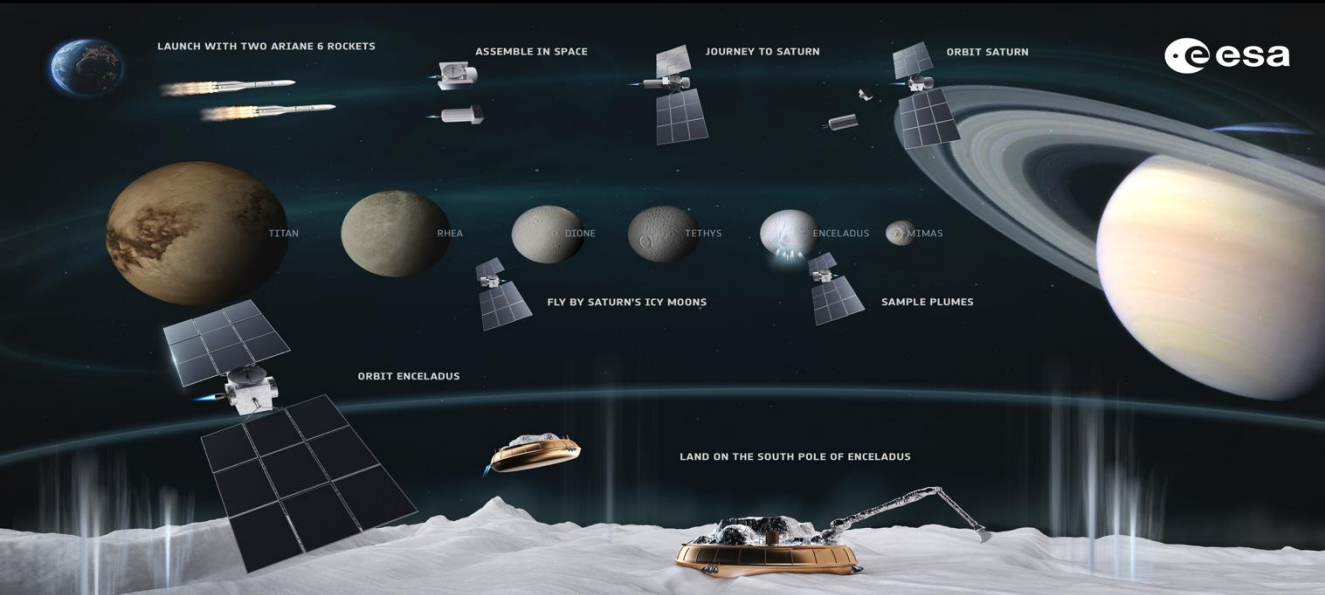
NAS Planetary 2023

NAS Decadal: 2nd Flagship, after Uranus, to be an orbilander to Enceladus

L4 (Enceladus) launch foreseen around 2041, while the PSDS advocated for Enceladus Orbilander launch ~2038 and Enceladus science operations ~2050-2054. This is in similar timeframes.

ESA's Future L4 mission to Enceladus

Exploring the issues of habitability of ocean worlds, searching for biosignatures, and studying the connection of moon interiors, near-surface environments, and the implications for the exchange of mass and energy into the overall moon-planet system. Theme follows the science from Cassini-Huygens and scientific return from JUICE.



- 2026-2034: Mission definition phase
- ~2034: Mission adoption
- 2035-2042: Implementation phase
- ~2042: Launch
- ~2050: arrival at Saturn



Preliminary timeline

Courtesy of J. Helbert



Future exploration of Icy Worlds and planetary protection

After a thorough review of the current knowledge for Icy Moons+Ocean Worlds (**Icy Worlds**: *a new definition was issued* : “Icy Worlds in our Solar System are defined as all bodies with an outermost layer that is believed to be greater than 50% water ice by volume and have enough mass to assume a nearly round shape.”) and this was published in 2 articles (Doran et al.) and implemented in the new Policy...

Doran et al., 2024, LSSR, 41 pp. 86–99.

DOI: <https://doi.org/10.1016/j.lssr.2024.02.002>

And Doran et al., 2026 – PTA, 384



The COSPAR planetary protection policy for missions to Icy Worlds: A review of history, current scientific knowledge, and future directions

P.T. Doran^{a,*}, A. Hayes^a, O. Grasset^a, A. Coustenis^b, O. Prieto-Ballesteros^a, N. Hedman^{c,d}, O. Al Shehhi^e, E. Ammannito^f, M. Fujimoto^g, F. Groen^h, J.E. Mooresⁱ, C. Mustia^j, K. Olsson-Francis^k, J. Peng^l, K. Praveenkumar^m, P. Rettbergⁿ, S. Sinibaldi^o, V. Ilyin^p, F. Raulin^q, Y. Suzuki^r, K. Xu^s, L.G. Whyte^t, M. Zaitsev^u, J. Buffo^v, G. Kminek^w, B. Schmidt^x



		OCEAN WORLDS							
		Europa	Ganymede	Callisto	Enceladus	Titan	Mid-Size Saturnian Moons	Uranian Moons	Triton
WATER	Surface Liquid	X	X	X	X	X	X	X	X
	Subsurface Liquid	✓	✓	?	✓	✓	?	?	?
	Ground Ice	✓	✓	✓	✓	✓	✓	✓	✓
	Water Vapor				✓			?	?
CHEMISTRY	CHNOPS ¹	?			✓	✓	?	✓?	✓
	Complex Organics	✓			✓	✓			
	Solar Heating	X	X	X	X	X	X	X	X
ENERGY	Interior Heating ²	✓	✓	✓	✓	✓	✓?	✓?	
	Redox ³	?			✓	✓			
	Atmosphere ⁴	X	X	X	X	✓	X	X	X
BODY	Magnetic Field ⁵	X	✓	X	X	?	X	?	X
Present Habitability		?	?	?	✓	?	?	?	?
Past Habitability		?	?	?	?	?	?	?	?

Yes/ Present
 Unknown/ Uncertain
 No/ Absent
 Insufficient Information

¹The life-supporting elements carbon, hydrogen, nitrogen, oxygen, phosphorus, or sulfur (not all need be present)
²Interior heating is that energy derived from accretion, differentiation, radiogenic decay, and/or tidal dissipation
³The prospect for any element or molecule to be reduced or oxidized as a source of chemical energy for life
⁴Substantial atmospheres only; exospheres (formed by, e.g., impact sputtering) are not included
⁵Intrinsically generated magnetic fields only

Modified from NASEM Decadal. OWL, Courtesy of P. Byrne

The new 2026 COSPAR PP Policy

- The new 2026 Policy comprises a number of editorial changes relative to the 2024 version to improve consistency, readability, understanding and application of the Policy, and substantive new guidelines for missions to Icy Worlds. The latter is a ground-breaking new introduction into the Policy instrument.
- We have introduced a formal definition of Icy Worlds which are by default assumed a category III unless a mission team can justify reclassification to Category II, addresses these concerns and removes the need for the previous cumbersome II* process in the Policy.
- A specific Icy World categorization in the new Policy provides sufficient clarity for mission planners designing landers, orbiters, or sample return missions.

The Policy



New policy came from the work of the COSPAR PPP Subcommittee: P. Doran (Chair), A. Hayes, O. Grasset, O. Prieto-Ballesteros, A. Coustenis, K. Xu, T. Haltigin

New COSPAR PP Policy

Published In SRT 224 Tuesday 20 January 2026 !

COSPAR Business

COSPAR Policy on Planetary Protection

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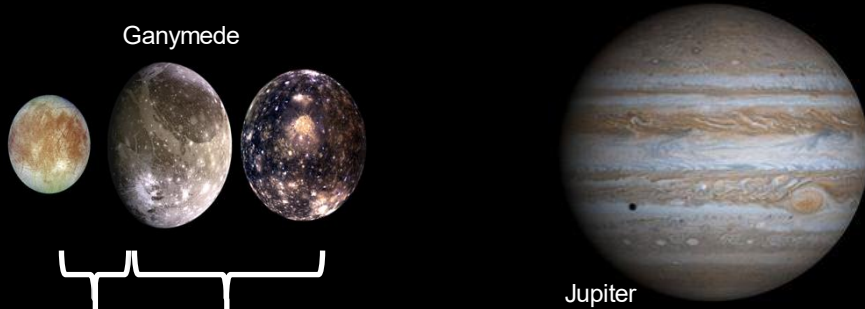


From the Jovian system to extrasolar planetary systems

By studying icy moons, we can characterise an entire family of exoplanets: the waterworlds.

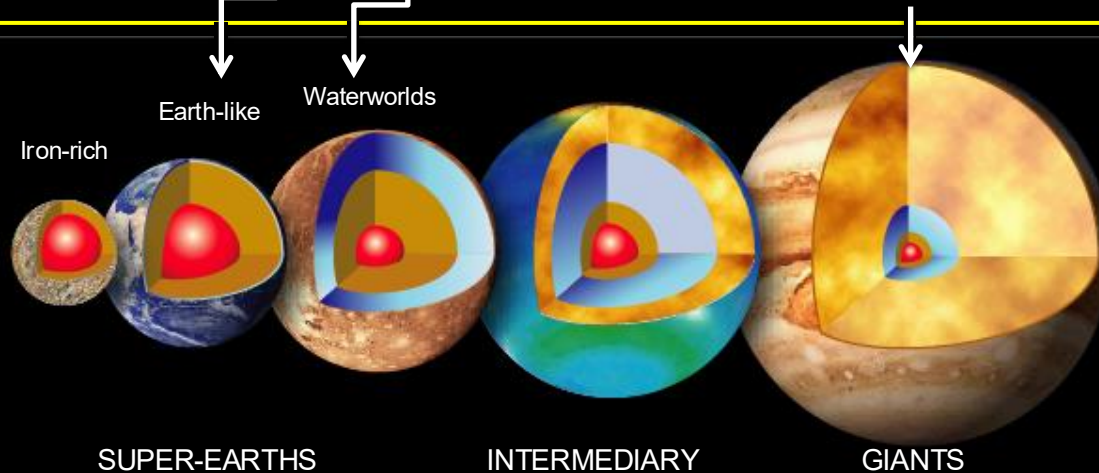
Jupiter system

Three waterworlds
One giant planet

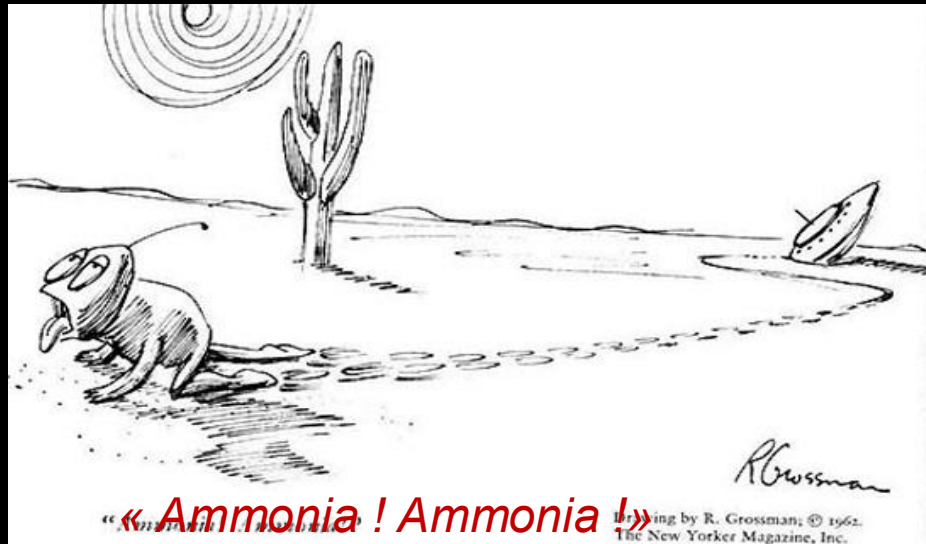
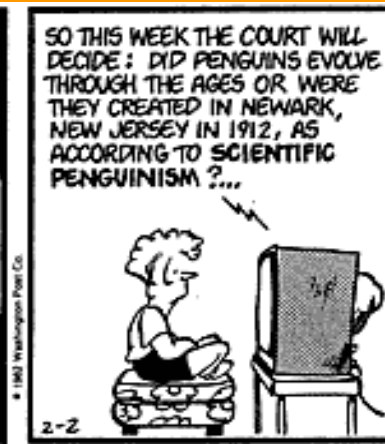


Exoplanets

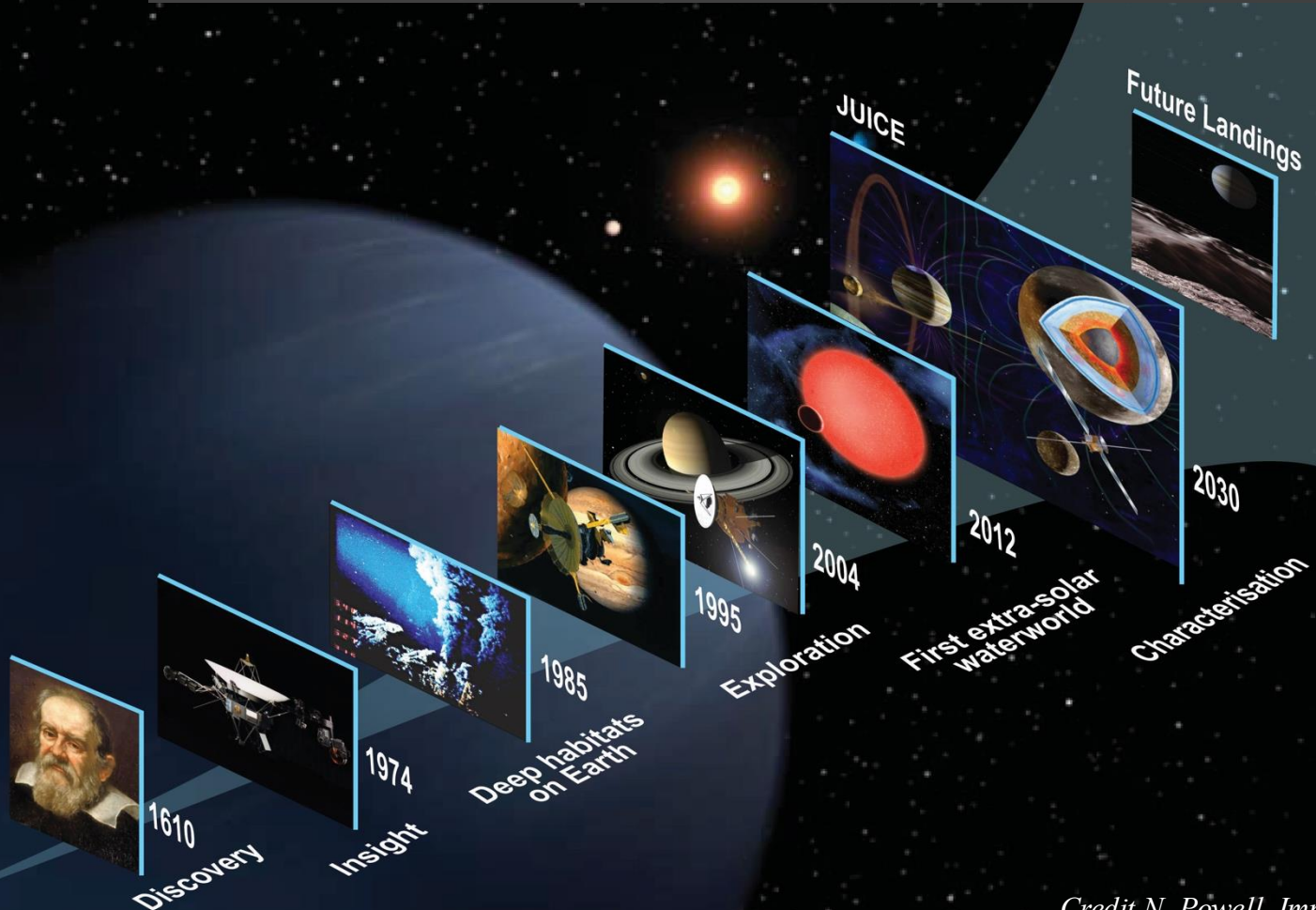
Five families
> 1800 planets



What are habitable worlds?



Future exploration in the outer solar system



- Land on Enceladus, Europa, Callisto, Mimas...
- Dig and explore
- Float or dive in the seas of Titan
- Bring back samples...

Food for thought...

- Terrestrial planet climate studies provide insights on the climate changes currently affecting the Earth, which have generated wide concern about a decline in habitability as the population grows with increasingly harmful effects on the environment.
- Dramatic changes in climate and potential habitability, have also taken place on Mars, and probably on Venus and Titan as well (although the timescales there remain uncertain).
- Modelling of Venus and Mars climate not only allows us to develop detailed scenarios and possible histories for those extreme variants of the terrestrial situation, it shows up deficiencies in our understanding that could make important differences to climate forecast for the near future of life on Earth.
- Model inter-comparisons that work quite well for present-day Earth, Venus, Mars and Titan raise the prospect of extrapolating the model descriptions of climate into the past, and into the future. The study of planetary environments can help us to better understand our own planet, and vice versa

The big questions...

- **How can we better understand and protect our planet?**
 - Follow the water
 - Greenhouse effect : Venus, Mars...
 - Magnetic field
 - Habitable conditions in the Solar System : energy, organics?
- **How can we expand comparative planetology and make it more efficient as related to the Earth?**
 - **Mars** : Liquid water was present at the surface in the past (When? For how long?) **NASA/Mars 2020/Perseverance, China/Tianwen-3, ESA/ExoMars Rover,**
 - **Jovian satellites**: Liquid water is present under the surface (Europa, Ganymede, Mimas) -> **ESA/JUICE and NASA/Europa Clipper**
 - **Titan and Enceladus: habitable?:** hidden oceans, energy and complex molecules -> **Dragonfly & ESA's L4**
- **How can we better explore habitability?**
 - **Combine space measurements from different sources**
 - **Combine also with ground-based and space-borne (JWST)**



Shaping the European Space Agency's space science plan for 2035-2050
cosmos.esa.int/voyage-2050

www.esa.int

European Space Agency

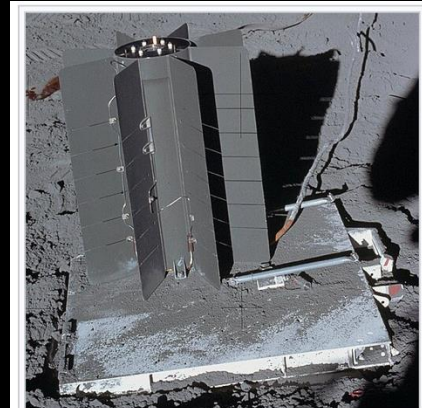
Nuclear power in space

Nuclear power systems and radioisotopes

- Nuclear power in space is **used for electricity, heat, or propulsion**. The most common type is a radioisotope thermoelectric generator (RTG), which has been used on **satellites, space probes and on the crewed Apollo missions to the Moon**.
- **RTG (Radioisotope Thermoelectric Generator)**: A device that converts heat from the natural radioactive decay of an isotope directly into electricity using thermoelectric materials. It has no moving parts and is highly reliable for long-duration missions.
- **MMRTG (Multi-Mission Radioisotope Thermoelectric Generator)**: An advanced type of RTG designed to operate in a variety of environments (space, planetary surfaces, and different climates). It uses plutonium-238 as its heat source, preferred radioisotope fuel for most RTGs, as it generates high levels of heat, has a long half-life (about 87.7 years), and emits primarily alpha radiation, making it well suited for reliable, long-term spacecraft power.
- **Stirling Generator (Radioisotope Stirling Generator)**: A power system that uses heat from a radioisotope to drive a Stirling engine, which converts heat into mechanical motion and then electricity. It is much more efficient than a traditional RTG but includes moving components, increasing system complexity. ASRGs not launched yet (foreseen in the discovery program)
- **Nuclear Thermal Rocket (NTR)**: A rocket propulsion system that uses a nuclear reactor to heat a propellant (usually hydrogen) to extremely high temperatures. The hot gas expands through a nozzle to produce thrust, offering much higher fuel efficiency than conventional chemical rockets while providing significant thrust for deep-space missions.

Nuclear power in space

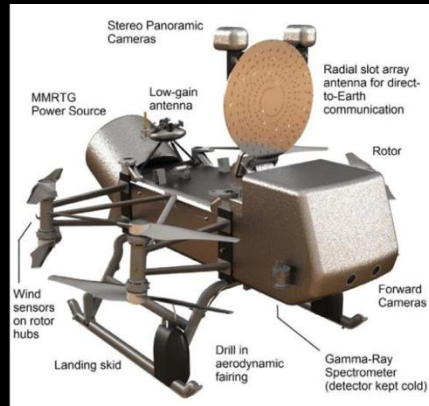
- Among nuclear power systems launched into space, **plutonium-238** is the most common radioisotope fuel. Its half-life of 87.7 years allows RTGs to power spacecraft consistently for decades at electric outputs of hundreds of watts.
- **Americium (Am-241)**: A radioactive isotope that can be used as an alternative fuel for radioisotope power systems. It is more abundant than plutonium-238 but produces less heat per unit mass, resulting in heavier power systems for the same electrical output.
- **Solar power** is commonly used for its low cost and efficiency, primarily in Earth and lunar orbit and for interplanetary missions within the inner Solar System, i.e., **missions to Mercury, Venus, Mars and the asteroid belt**. But recently also for the outer solar system up to Jupiter.
- Nuclear-based systems can have less mass than solar cells of equivalent power, allowing more compact spacecraft that are easier to orient and direct in space. This makes them useful for **radar satellites** such as the **RORSAT** program deployed by the Soviet Union.
- **Nuclear power** has also been used for some of missions such as the **Apollo 12** program's SNAP-27 RTG for lunar surface use (first use of a nuclear power system on a crewed flight) and the MMRTGs on the Mars rovers. In the case of crewed spaceflight, nuclear power concepts that can power both life support and propulsion systems reduce cost and flight time.



A **SNAP-27** RTG deployed by the astronauts of **Apollo 14** identical to the one lost in the reentry of **Apollo 13**

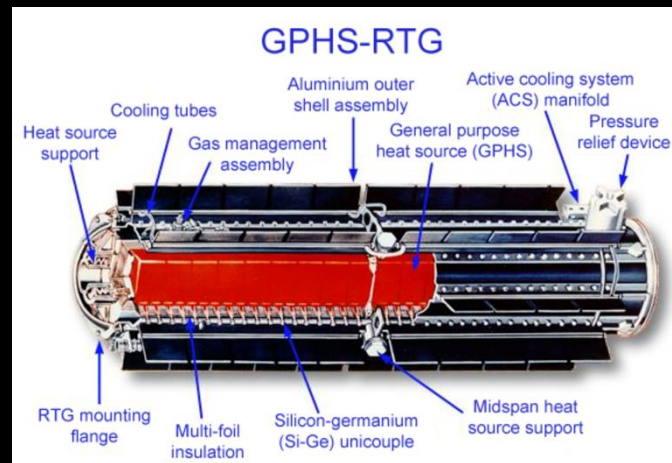
Nuclear power in space missions

- Nuclear power systems function independently of sunlight, which is highly advantageous for long duration in the inner solar system and for the outer Solar System exploration, i.e., Jupiter and beyond.
- RTGs used on Mars missions include the *Curiosity and Perseverance rovers and Viking landers*. All spacecraft leaving the Solar System, i.e., *Pioneer 10 and 11, Voyager 1 and 2, and New Horizons* and the outer planet missions of *Galileo, Cassini, and Ulysses*. Foreseen on *Dragonfly* to Titan
- However, in part due to the global shortage of plutonium-238 and advances in solar efficiency, the more recent Jupiter missions of *Juno, Jupiter Icy Moons Explorer (JUICE) and Europa Clipper*, and the Jupiter trojan asteroid mission of *Lucy*, all opted for large **solar arrays** despite a relative 4% solar flux at Jupiter's orbit of 5.2 AU.



Perseverance MMRTG

Dragonfly : 70 watts (desired) from an MMRTG



Cassini RTG

Planetary Protection & Nuclear Systems

❑ Primary focus of planetary protection

- Prevent **biological /microbial** contamination between Earth and other celestial bodies
- Nuclear contamination is **not traditionally within its scope**

❑ Nuclear safety

- RTGs and nuclear fission systems are subject to:
 - Independent launch authorization procedures
 - Rigorous nuclear safety assessments
- These processes are separate from planetary protection requirements

❑ Emerging questions

- Could **heat** generated by nuclear power systems have detectable effects on planetary environments?
- Could **ionizing radiation** affect sensitive organic compounds?

❑ Current limitations

- We have examined **transport models**, but significant knowledge gaps remain
- More research is needed before firm conclusions can be reached

❑ Future relevance

- The issue potentially applies to **all celestial bodies**
- The first realistic opportunities to investigate such effects may be **10–20 years from now**
- **Enceladus**, for example, could provide an important future case study

Benefits of the space programme for participating countries

- **Research and development** : new industries based on space-related knowledge to support the understanding of space science and the development of experiments in various economic sectors.
- **Economy** : growth in high-tech areas.
- **Education** : formation of academic centers of excellence to study various aspects of space: space sciences, environmental sciences, atmospheric physics, planetary protection and space law, etc..
- **Infrastructure** : creation of supporting infrastructure for experiment development, robotics to manipulate experiments and provide ground operations for space missions.
- **STEAM** : inspire participation in the space program, encouraging education and work in science, technology, engineering, the arts and mathematics.
- **Pride and security** : support international cooperation and global promotion of peaceful uses of outer space.

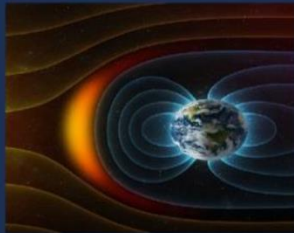
Research & Development



Economics



Education



Infrastructure



National Pride





Inspiration

education

ESA Academy

and

Spaceship EAC

Next generation Terrae Novae explorers

« if you think education is expensive, try ignorance »

A. Lincoln (1809-1865)



drop your
thesis!



fly your
thesis!



spin your
thesis!



orbit your
thesis!



Beth Lomax • 2nd

Researcher - Lunar in-situ resource utilisation (ISRU)

5h • Edited •

New paper out in **Nature Communications** examining the efficiency of gas-evolving electrolysis on the Moon and Mars. Looking at this relationship between 0 and 1 g is important for oxygen producing ISRU systems destined for the Moon, as most previous research focuses on microgravity environments. This paper also validates the use of hypergravity platforms for predicting electrolysis efficiency on the Moon and Mars. The video below shows oxygen bubble behaviour under different gravity levels.

This marks the end of a great project with **Gunter Just, Paul Broadley, Patrick McHugh, Gregory H. Mark Symes, Paul A. Burke, PhD, Katharine Smith, and Matt Roy**. Huge thanks to FlyYourThesis, European Space Agency - ESA, Novespace, UK Space Agency, and Metalysis for making the parabolic flights possible.

Check out the paper here:

<https://lnkd.in/gqhG6mV4>



Spaceship EAC

unites students and young professionals from across Europe to develop and support Educational and Academic activities that facilitate European readiness for any human spaceflight. Total number of team members and alumni since its inception: **150+**.

European Astronaut Center (EAC)

Future meetings

33rd

INTERNATIONAL
ASTRONOMICAL
UNION GENERAL ASSEMBLY

Rome • Italy | 10-19 August 2027



IAU

33rd GENERAL
ASSEMBLY

10-19 AUGUST 2027 | ROME • ITALY



2028

COSPAR

Dubai 47TH July 8-16
SCIENTIFIC ASSEMBLY



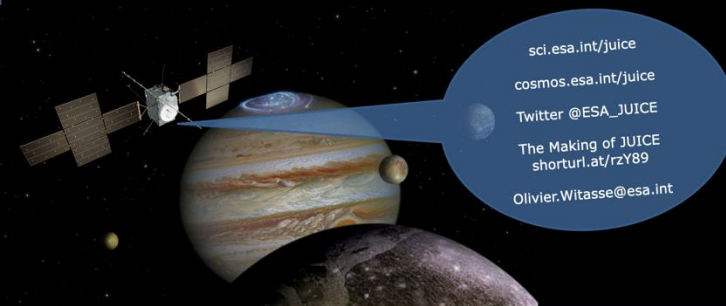
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COMMITTEE ON
SPACE RESEARCH

ADVANCE SPACE
RESEARCH

FOSTER INTERNATIONAL
COLLABORATION

SHAPE THE FUTURE
OF SPACE SCIENCE

VENUE | DUBAI WORLD TRADE CENTRE

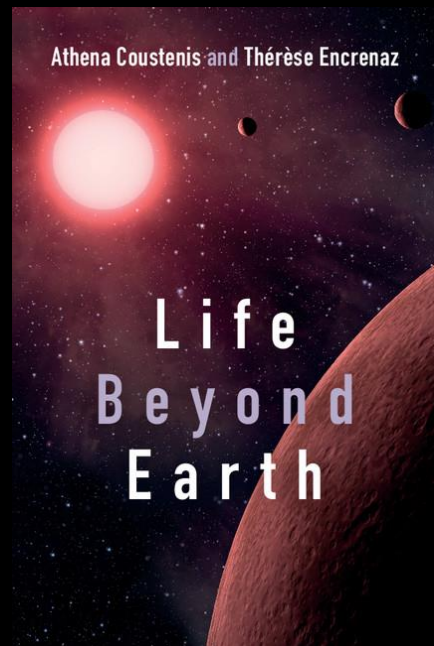


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**Thank you for your
attention !**



*Encrenaz, Th., Coustenis, A.,
2025. L'énigme de la vie dans le
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2013. Life beyond Earth.
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Crédits : Observatoire de Paris, CNRS, ESA, NASA, JPL...