Space Exploration

Master in Space Sciences

2020 – 2021

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Chapter I: Introduction

- A brief history of space exploration
- Why go to space?
- ESA’s science programme
- The lifecycle of a scientific space mission

Chapter I: Introduction

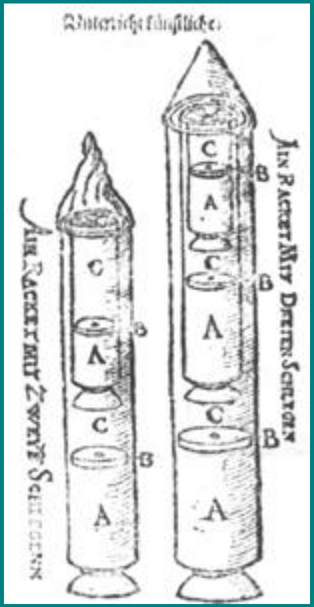
The first documented usage of rockets dates back to the 13th century (Chinese army fighting the Mongols).

Later, rockets were used by the Mongols (conquest of Bagdad in 1258), the Arabs (against French crusaders), the French against the English (1429).

As weapons, rockets were less efficient than cannons, but made their comeback in the 16th century with the Austrian Conrad Haas (1509 – 1576) who built multi-stage rockets and at the end of the 18th century (US independence war).

An application for space travel was not considered at these epochs.


Chinese soldier launches fire-arrow



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Many of the pioneers of space exploration were inspired by Jules Verne's (1828 – 1905) novels *De la Terre à la Lune* and *Autour de la Lune*.

Chapter I: Introduction

Konstantin Tsiolkovsky (1857 – 1935) summarized the basic principles of space flight and rocket propulsion in his publication *The exploration of Cosmic Space by Means of Reaction Devices.*

Tsiolkovsky proposed to build multi-stage rockets using liquid H_2 and O_2.

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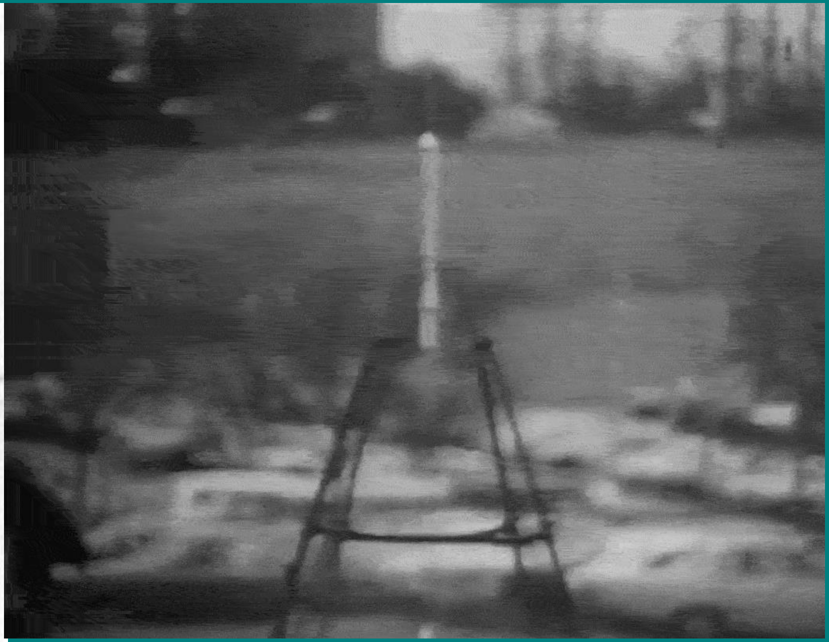
Robert Goddard (1882 – 1945) developed the first liquid-fueled rocket (1926). He worked on the in-flight stabilization of rockets and was the first to use a nozzle to improve the efficiency of his rocket. His book *A method of reaching extreme altitudes* became the basis of von Braun's work during World War II.



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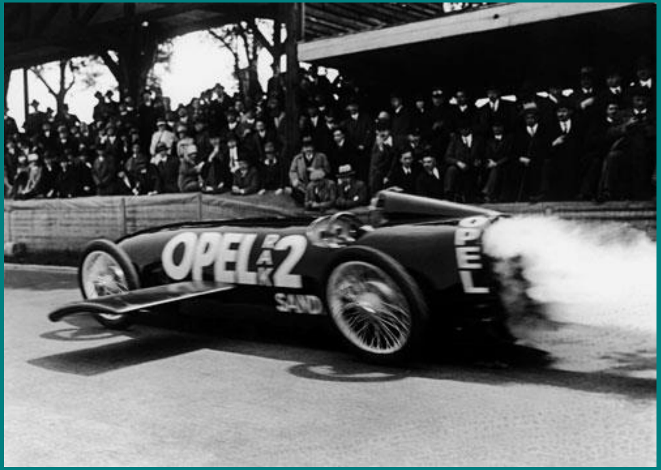
In Germany, Fritz von Opel (1899 – 1971) built racing cars and planes driven by powder rockets (1928). The main goal was public relations.



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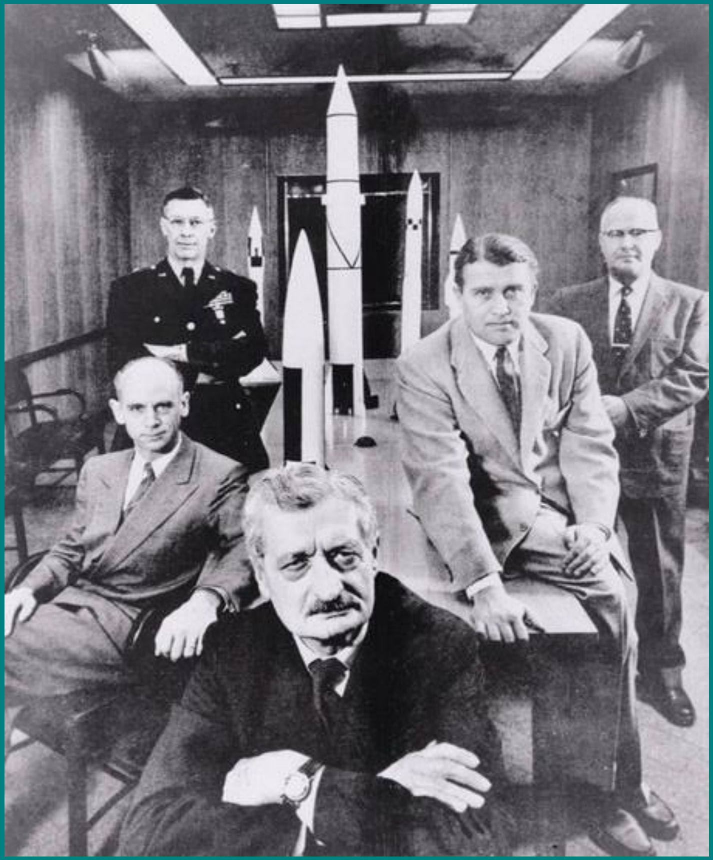
Hermann Oberth (1894 – 1989) published *Die Rakete zu den Planetenräumen* (1922) and developed his own liquid-fueled rockets (1929). His collaborator Wernher von Braun (1912 – 1977) became the chief designer of the V2 rocket during World War II.



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After the war, the USSR and the USA were competing for the conquest of space. The main actors were Sergey Korolyov (1907 – 1966) in the USSR and Wernher von Braun in the USA.

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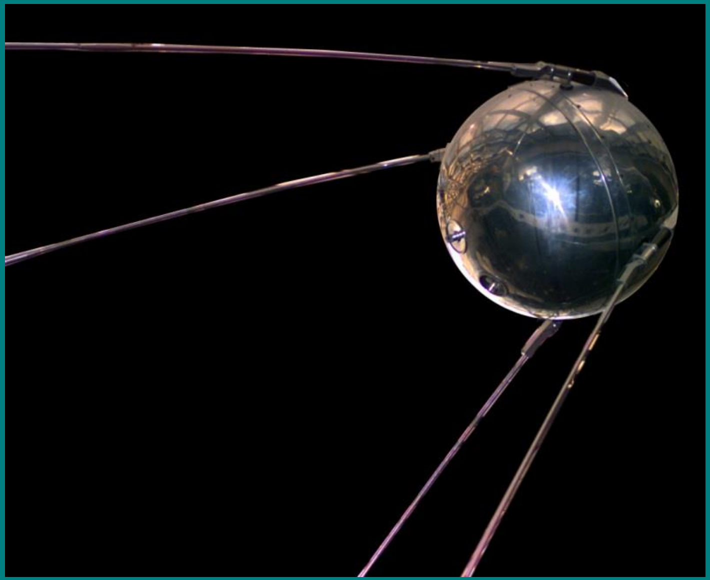
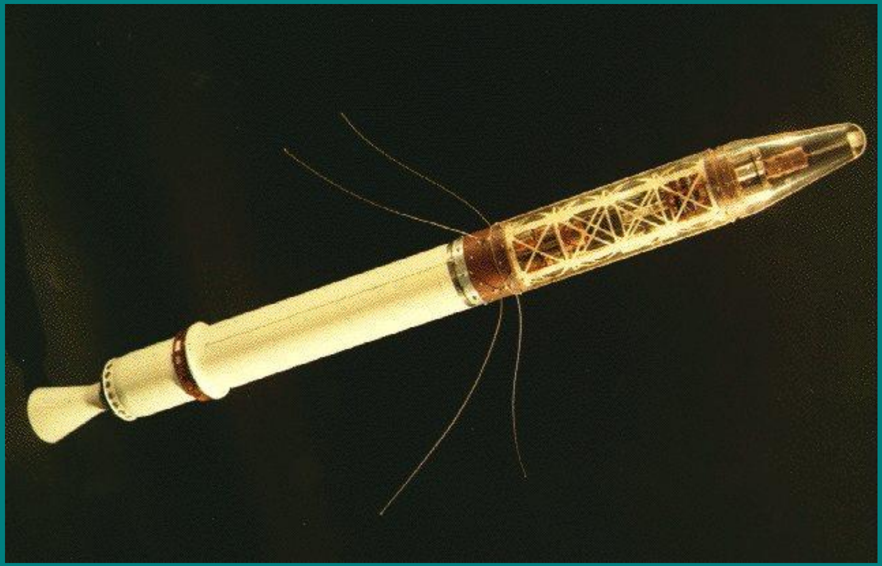
4 October 1957: Sputnik 1 (USSR), first artificial satellite

2 November 1957: Sputnik 2 with the dog Laïka

31 January 1958: Explorer 1 (USA) discovers the van Allen belts





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12 April 1961: Yuri Gagarin (USSR), first man in space

5 May 1961: Alan Shepard, first US suborbital flight

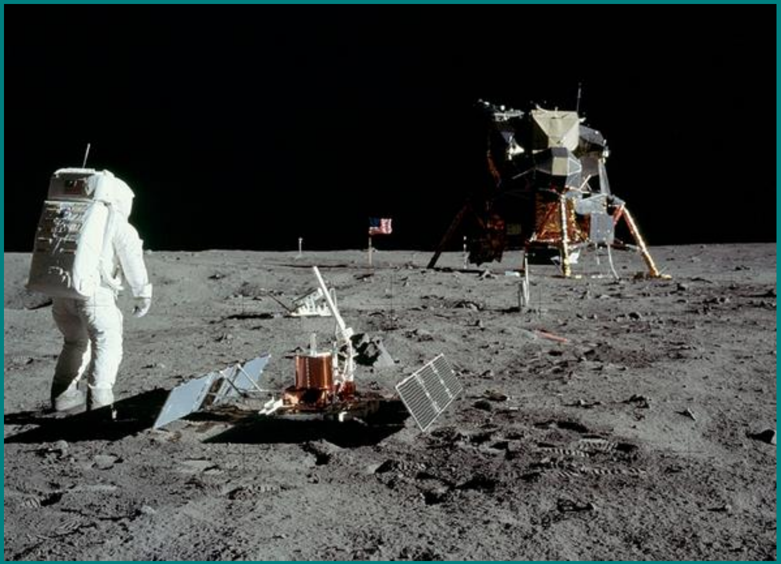
20 February 1962: John Glenn, first US astronaut in space

20 July 1969: Apollo 11 on the Moon

12 April 1981: first flight of the Space Shuttle Columbia

15 October 2003: Yan Li Wei (China), first taikonaut

8 July 2011: last flight of the Space Shuttle Atlantis



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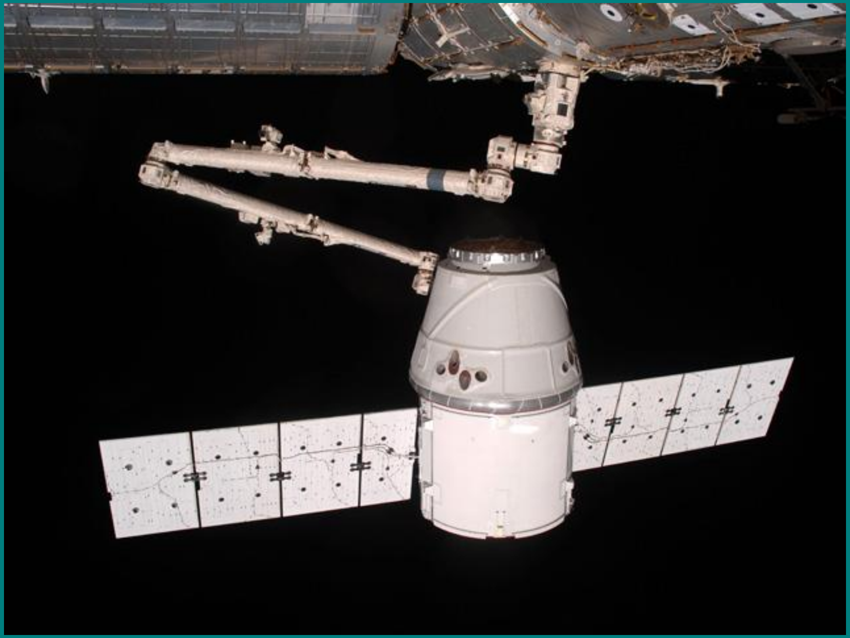
22 May 2012: first launch of the Dragon capsule to the ISS by the Falcon 9 launcher. Dragon and Falcon 9 are designed and operated by the private company Space X.

Space X and Blue Origin have developed a technology for landing and re-using the first stages of their launchers.



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New Space: private companies become leading actors in space activities (not just as subcontractors). Beginning of a new era??

30 May – 2 August 2020: first manned flight operated by private company (Crew Dragon, Space X).

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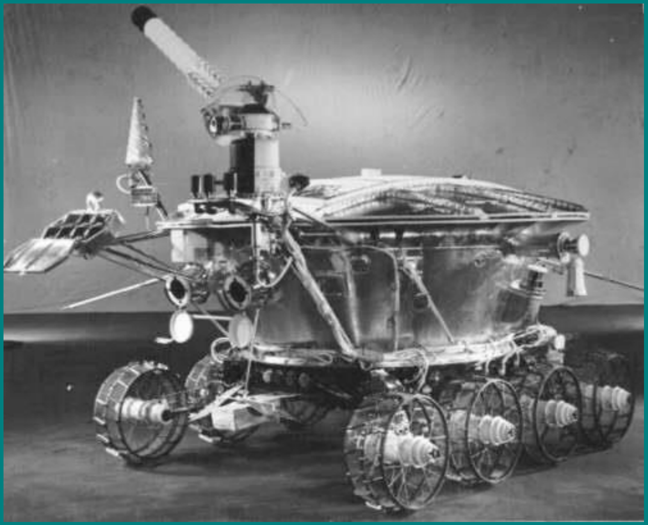
Mariner 2: 1st flyby of Venus (1962)

Mariner 4: 1st flyby of Mars (1965)

Lunokhod 1 & 2: first lunar rovers (1970, 1973)



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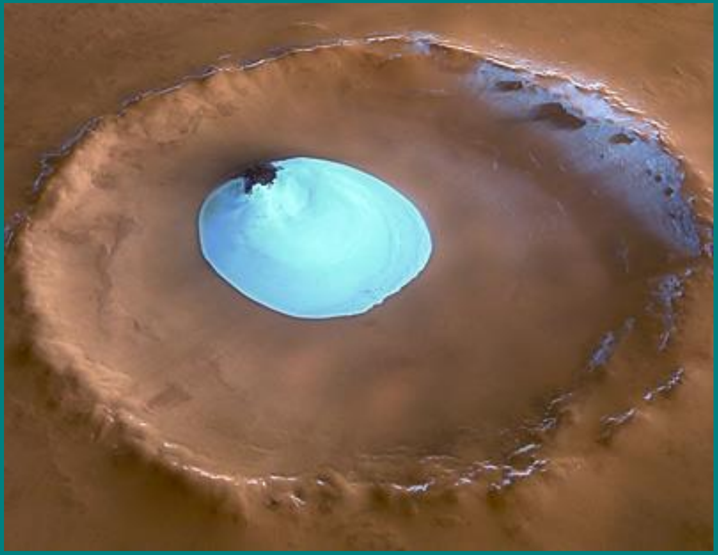
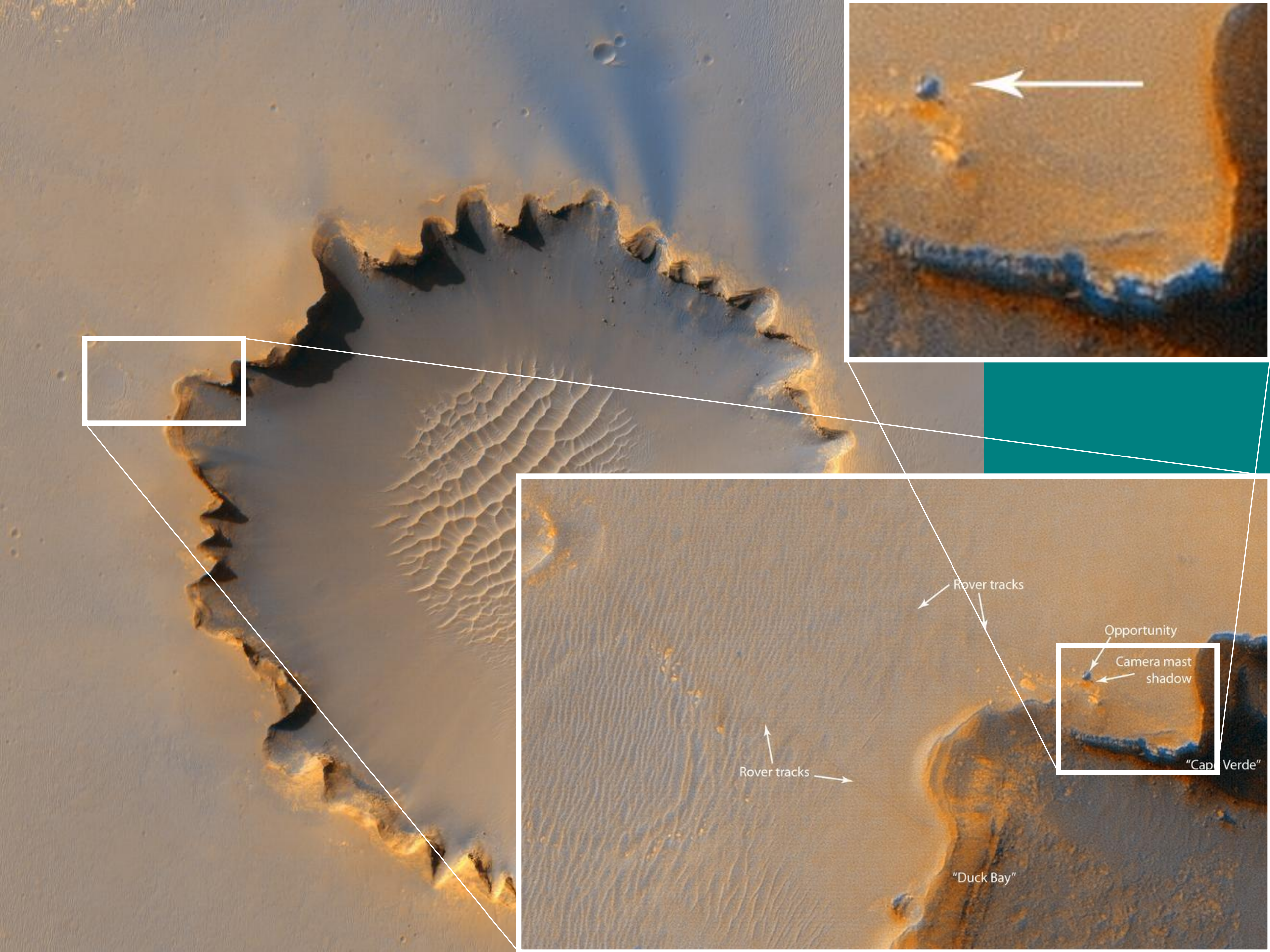
Viking 1 & 2 (1976): in-situ mineralogy

Mars Express (ESA, 12/2003), Spirit & Opportunity (NASA, 01/2004)




Rover tracks
Opportunity
Camera mast
shadow
Rover tracks
"Cape Verde"
"Duck Bay"

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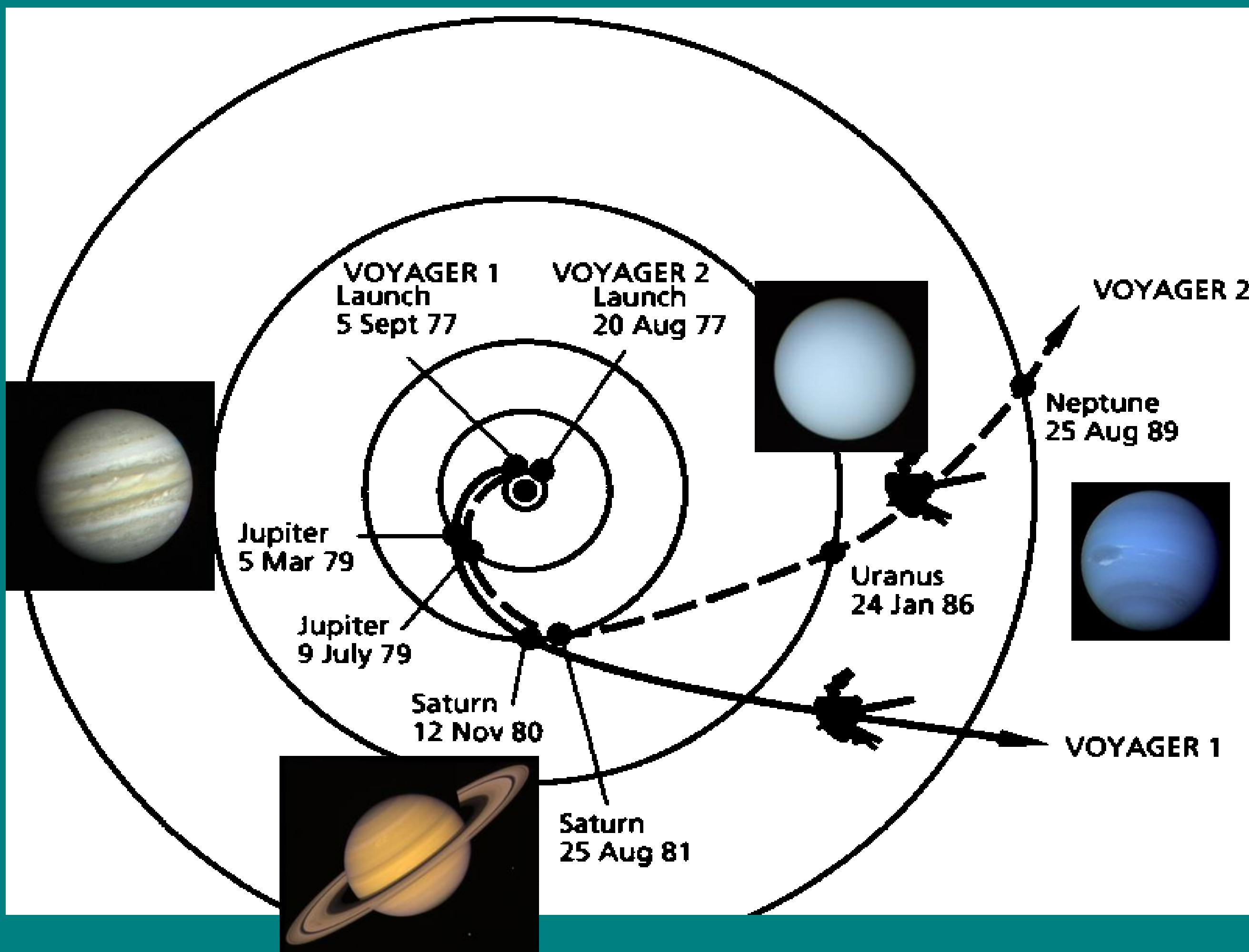
Pioneer 10 & 11: first flybys of Jupiter (12/1973 & 12/1974) and Saturn (9/1979)

Voyager 1 & 2: grand tour of the giant planets



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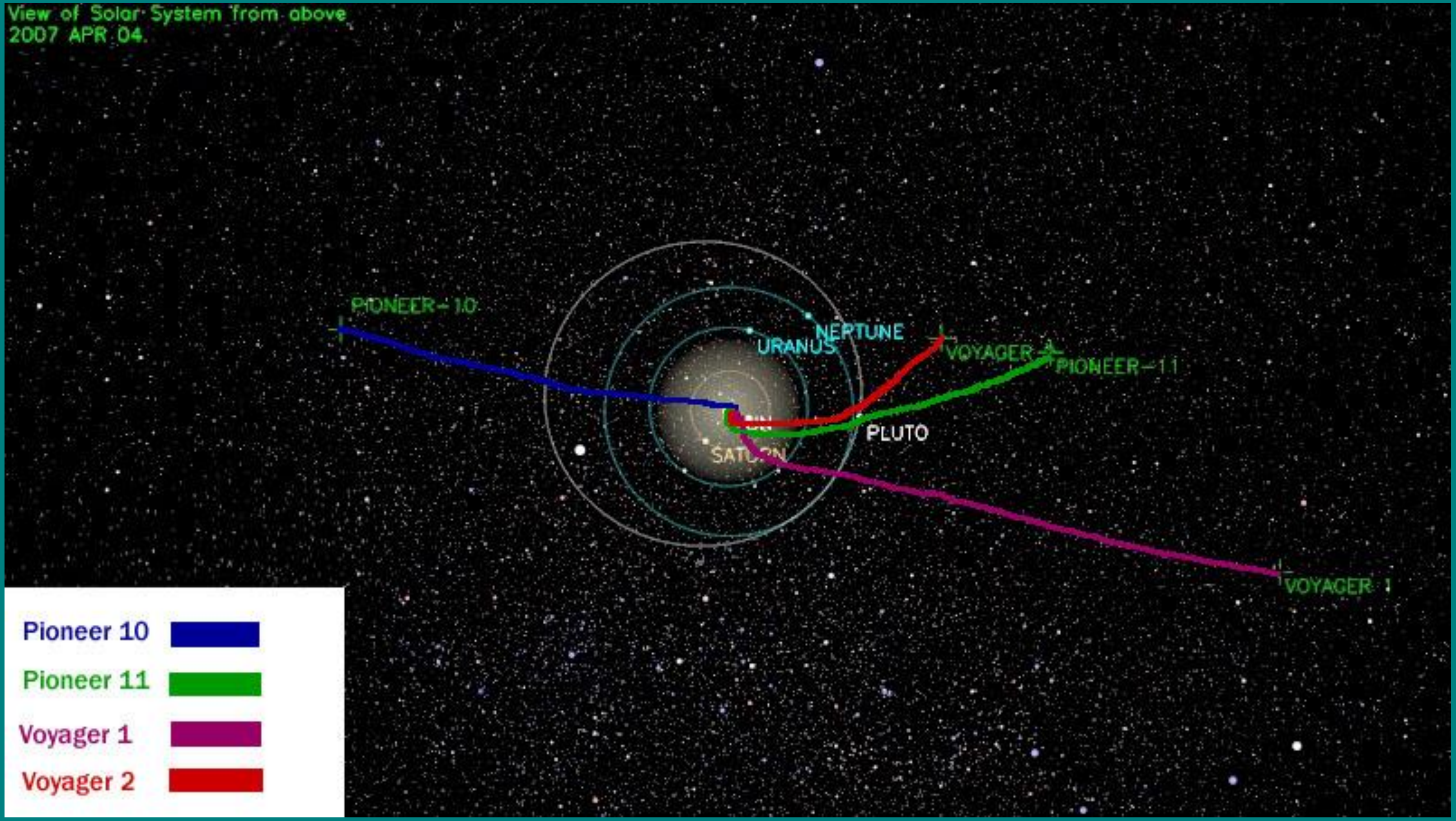
Voyager 1 & Pioneer 10: on their way to the edges of the Solar System



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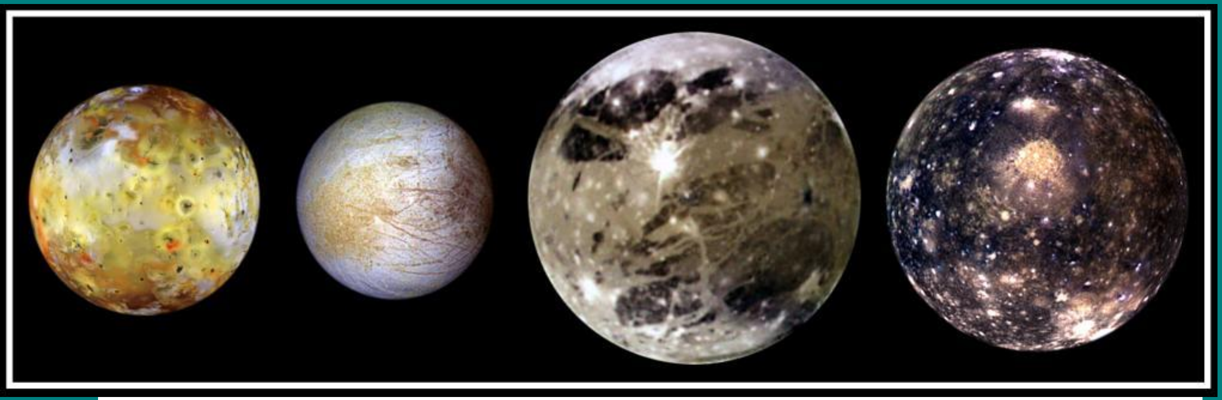
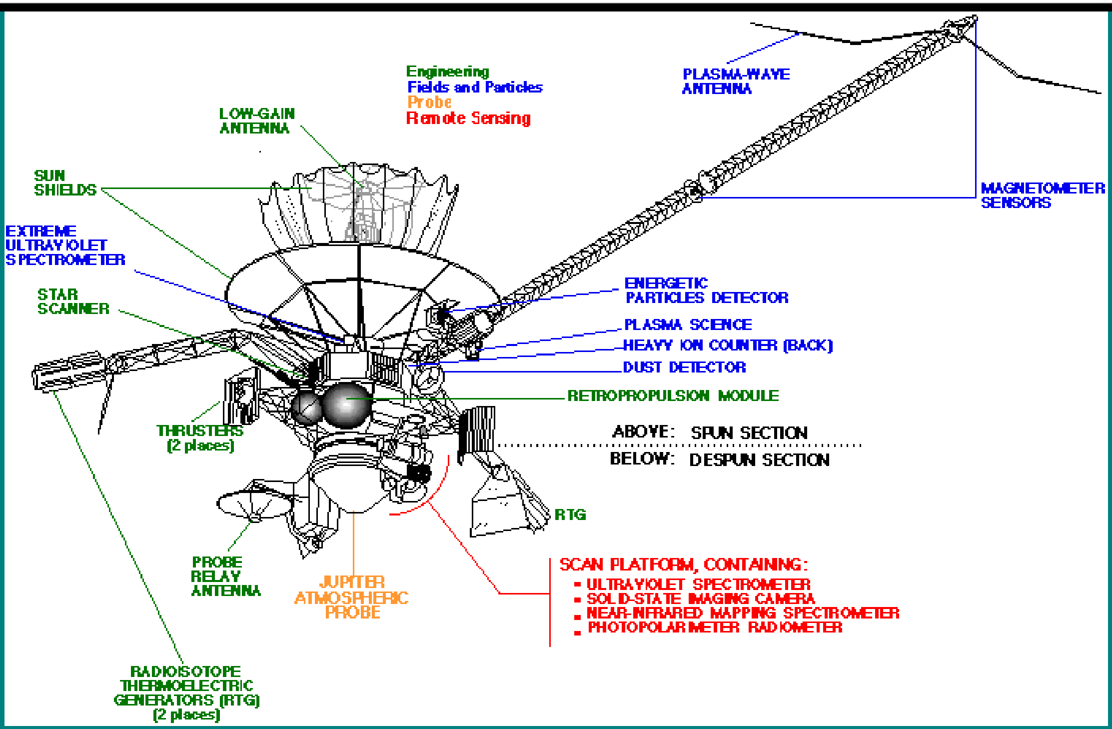
Galileo: 1st orbiter of Jupiter (12/1995 – 9/2003)





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Cassini-Huygens: orbiter around Saturn (7/2004 – 9/2017) + landing on Titan (Huygens 14/1/2005)

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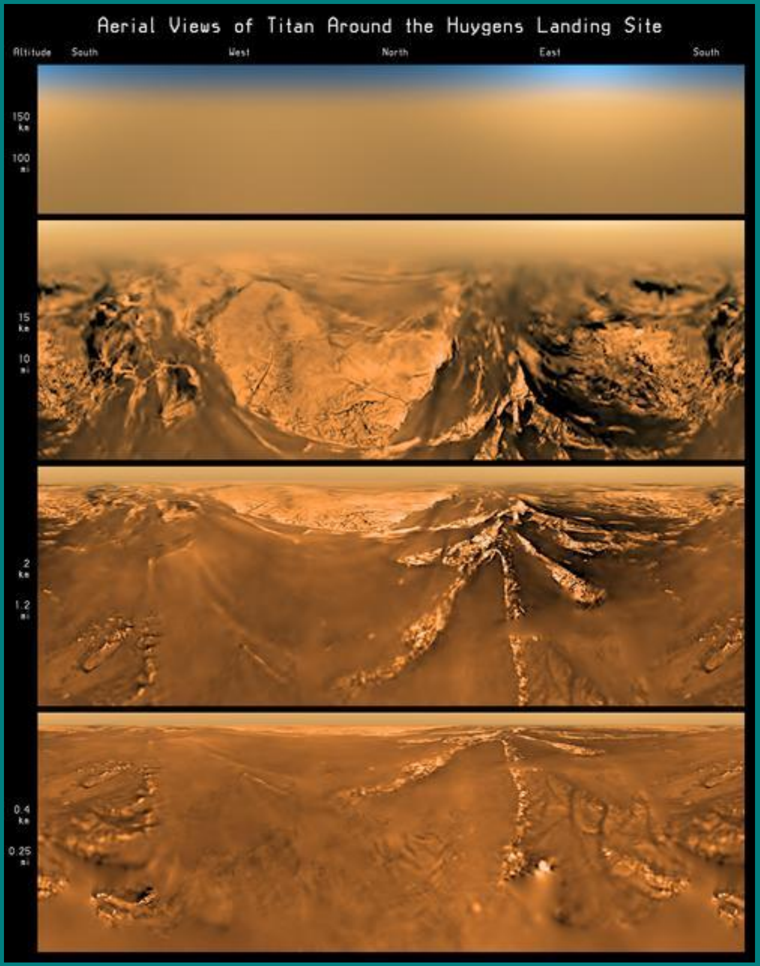

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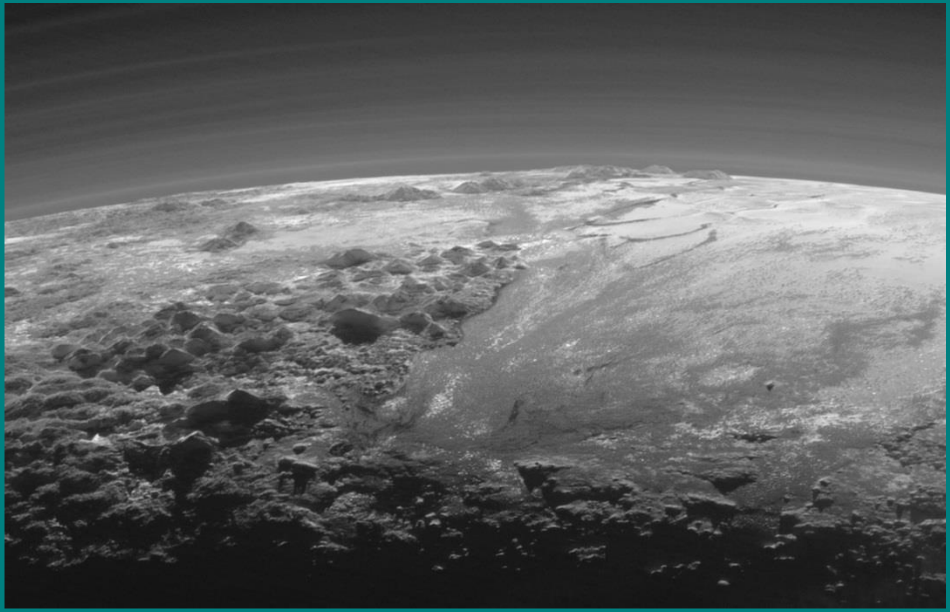
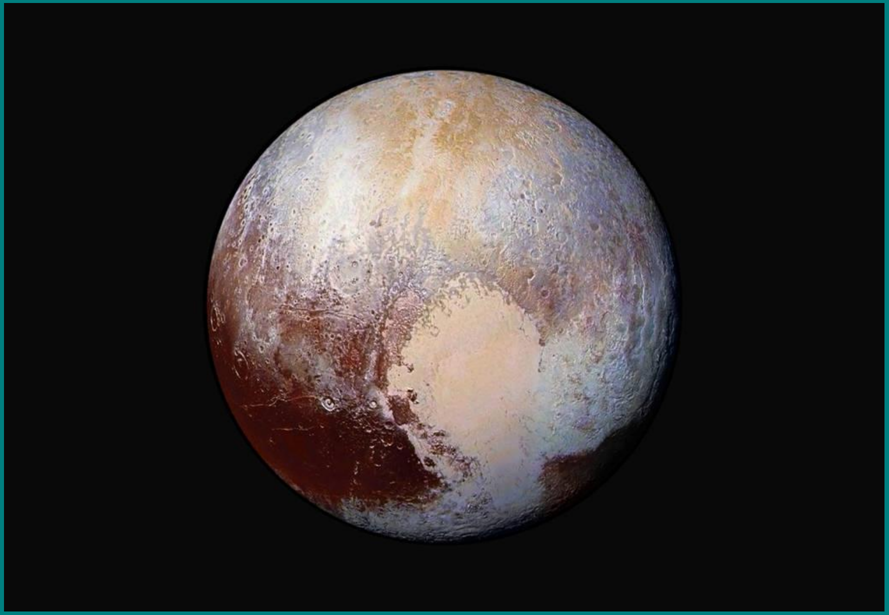
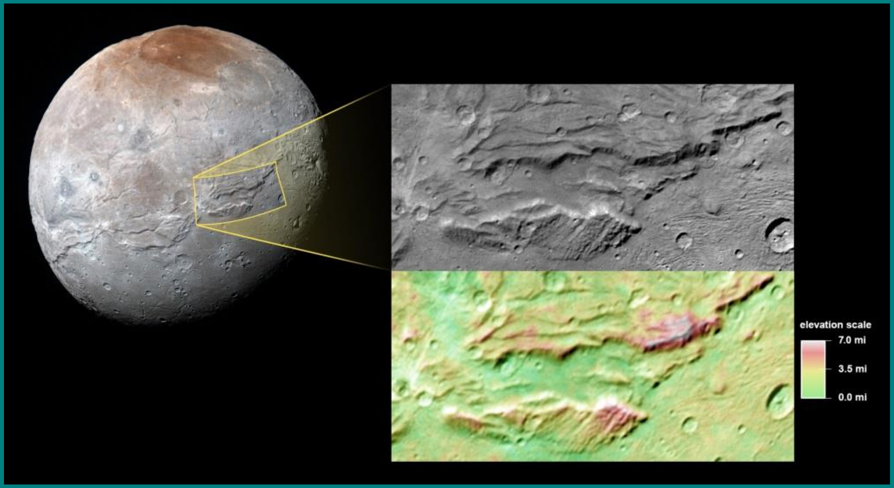
New Horizons: fly-by of Pluto (7/2015)







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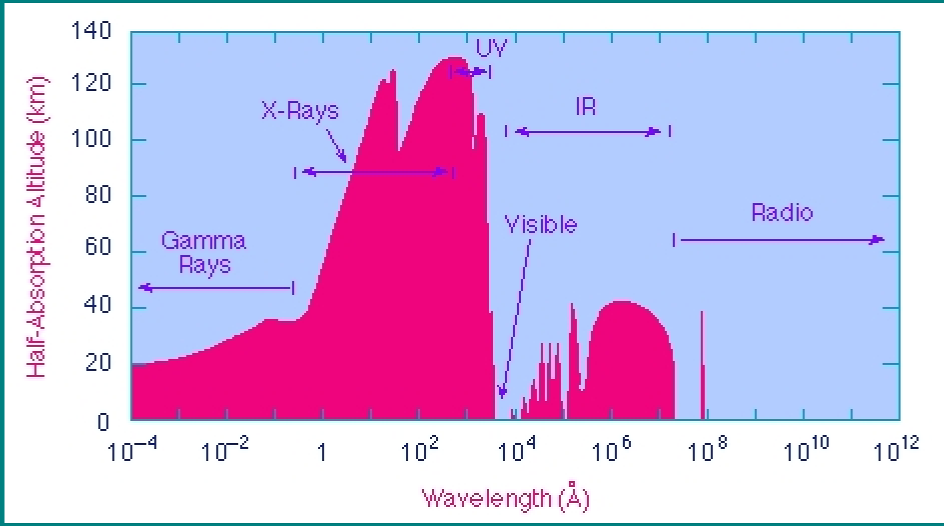
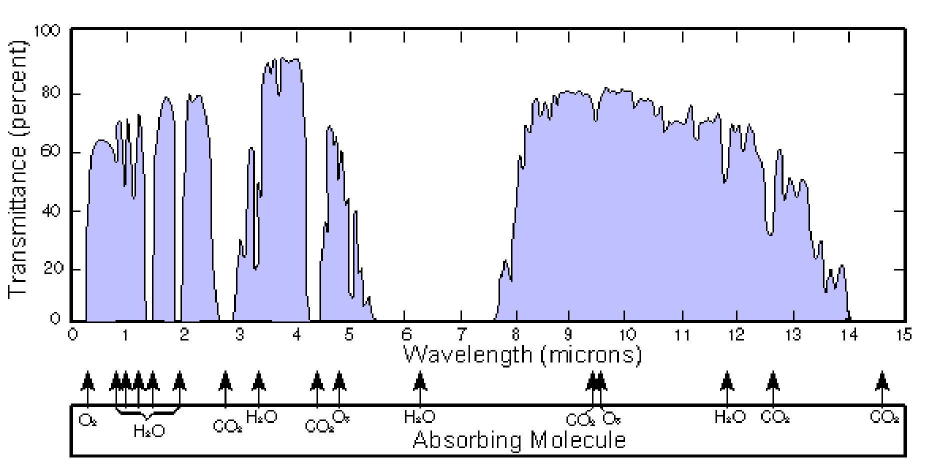
Why do science from space?

- Get out of the Earth's atmosphere: access to wavelengths that cannot be observed from the ground due to absorption by the atmosphere.





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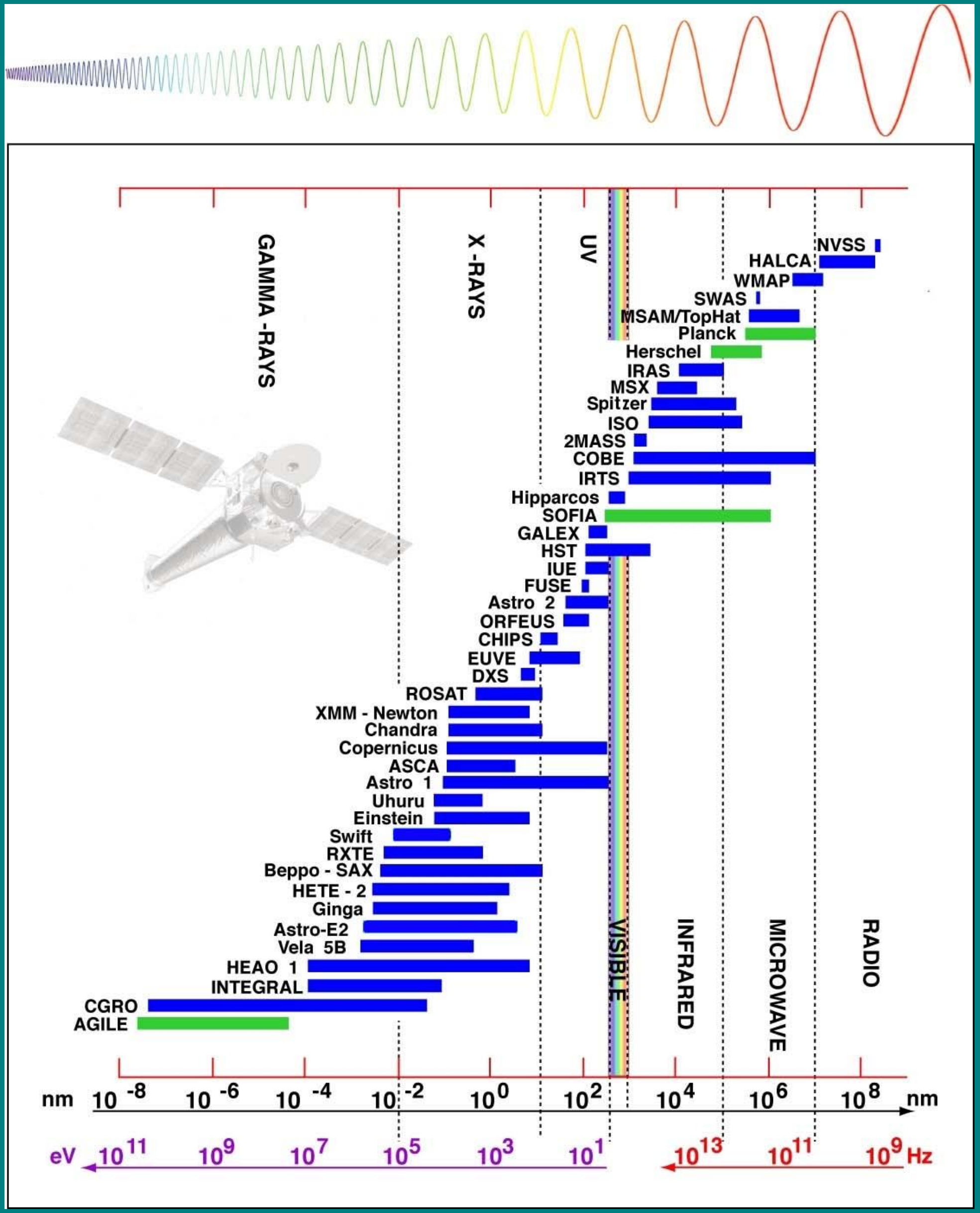
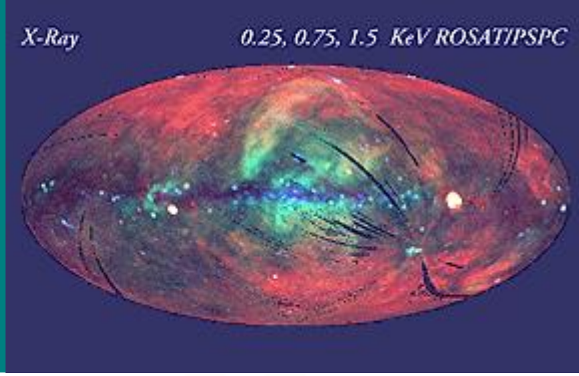
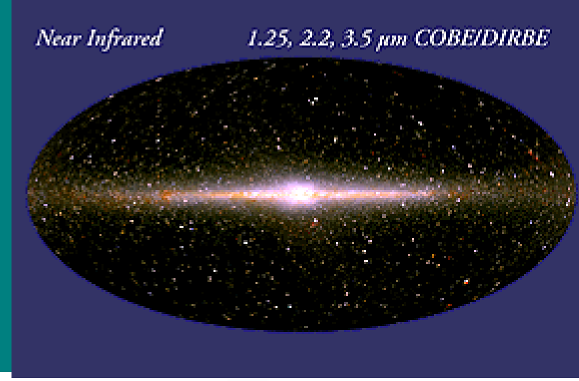
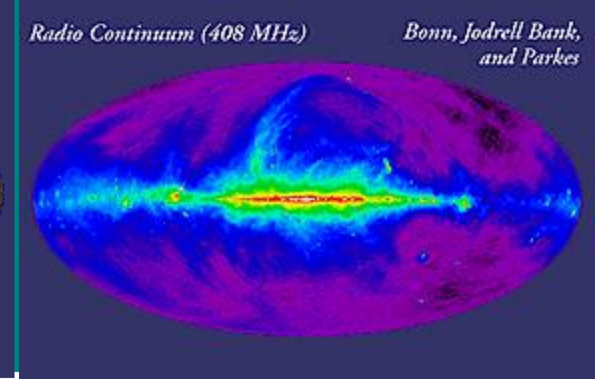
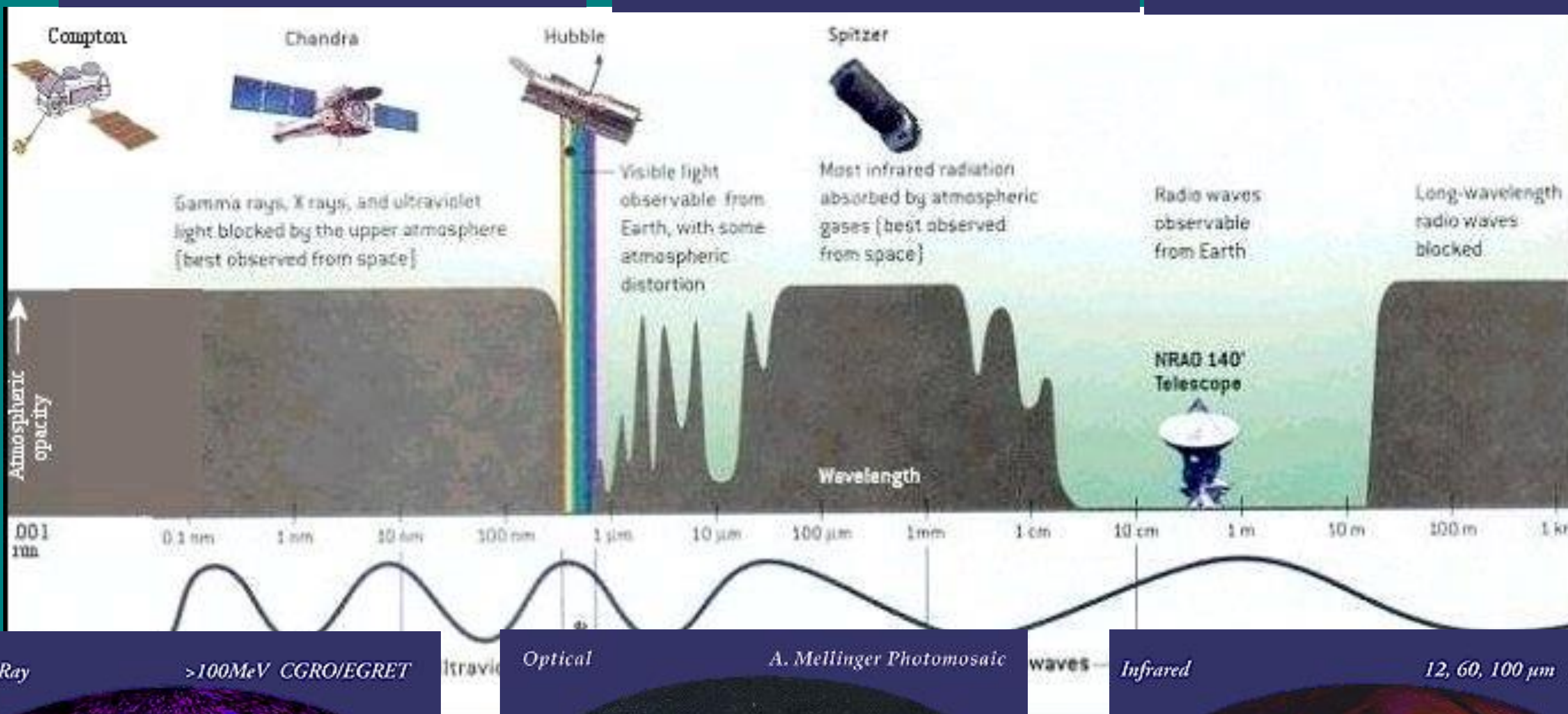
Multi-wavelength observations of the Universe

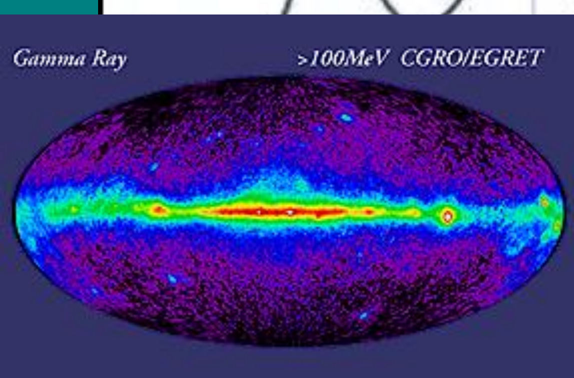



X-Ray
0.25, 0.75, 1.5 KeV ROSAT/PSPC

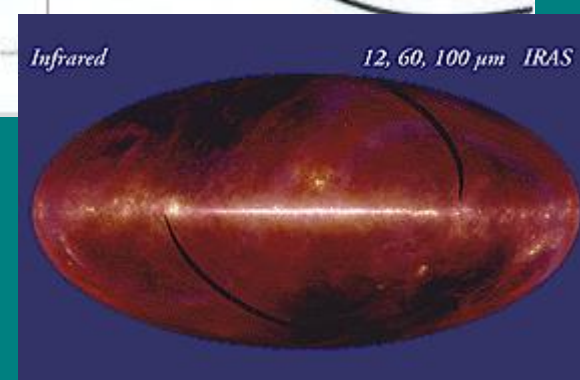

Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE


Radio Continuum (408 MHz)
Bonn, Jodrell Bank, and Parkes


Compton
Chandra
Hubble
Spitzer
Gamma rays, X rays, and ultraviolet light blocked by the upper atmosphere (best observed from space)
Visible light observable from Earth, with some atmospheric distortion
Most infrared radiation absorbed by atmospheric gases (best observed from space)
Radio waves observable from Earth
Long-wavelength radio waves blocked
NRAO 140' Telescope
Atmospheric opacity
Wavelength
.001 nm
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1mm
1 cm
10 cm
1 m
10 m
100 m
1 km
waves


Gamma Ray
>100MeV CGRO/EGRET


Optical
A. Mellinger Photomosaic


Infrared
12, 60, 100 μm IRAS

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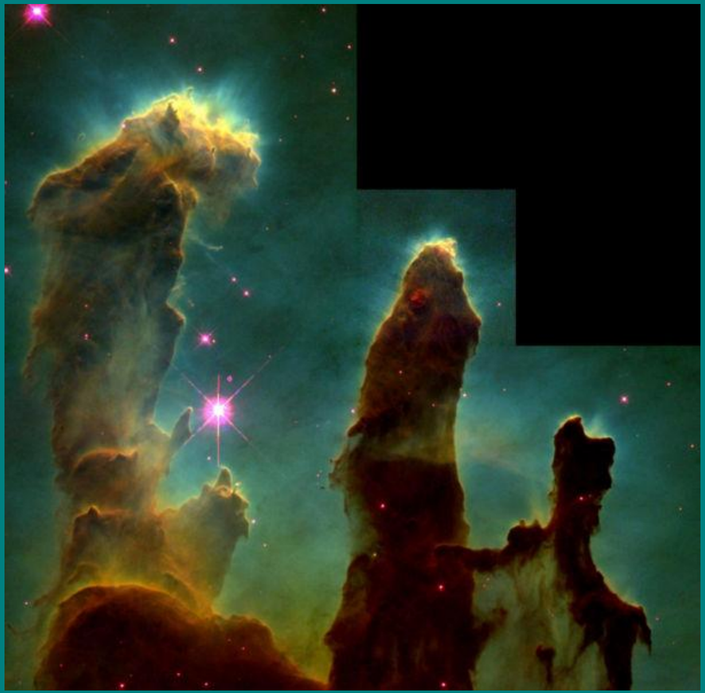
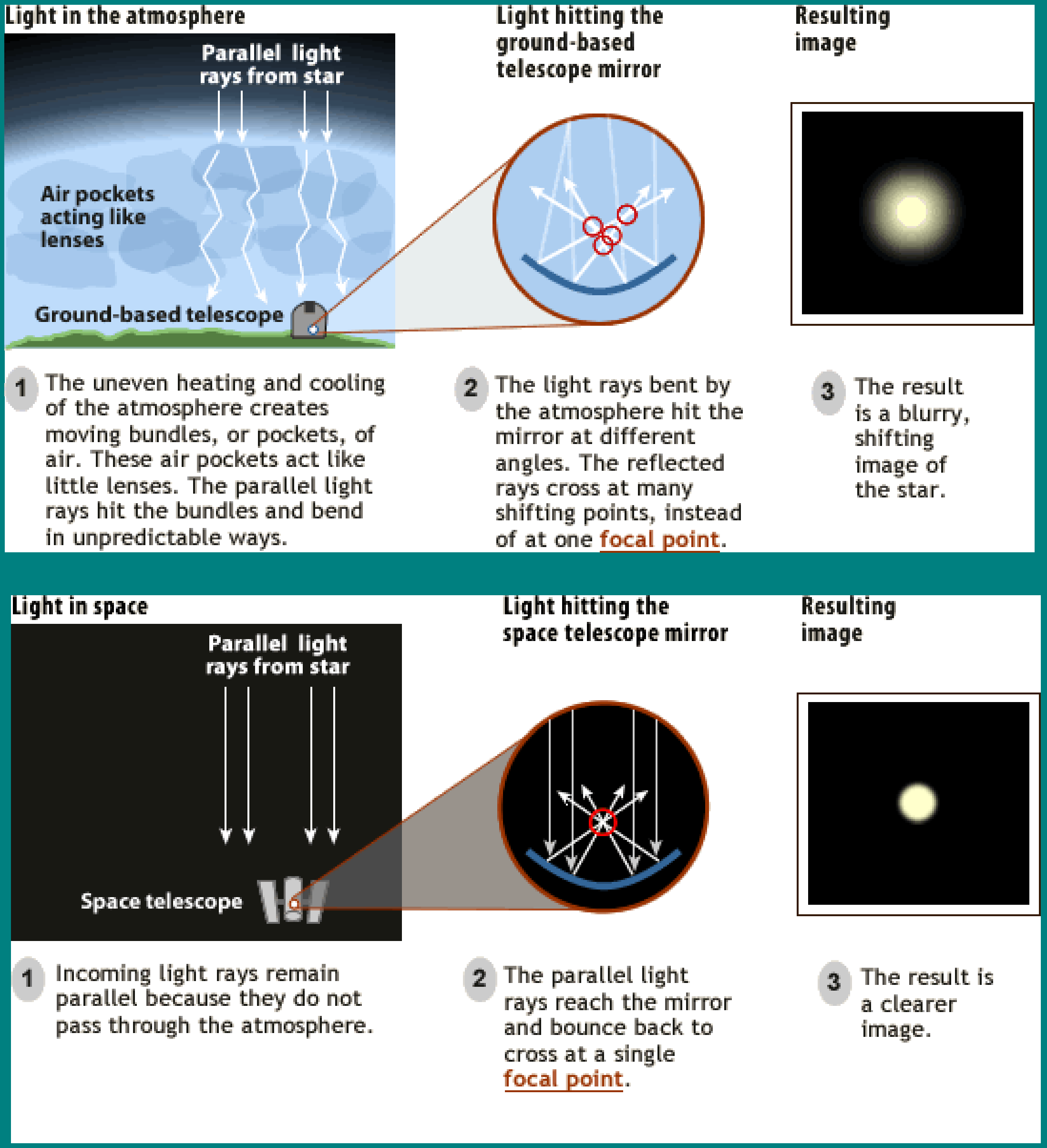
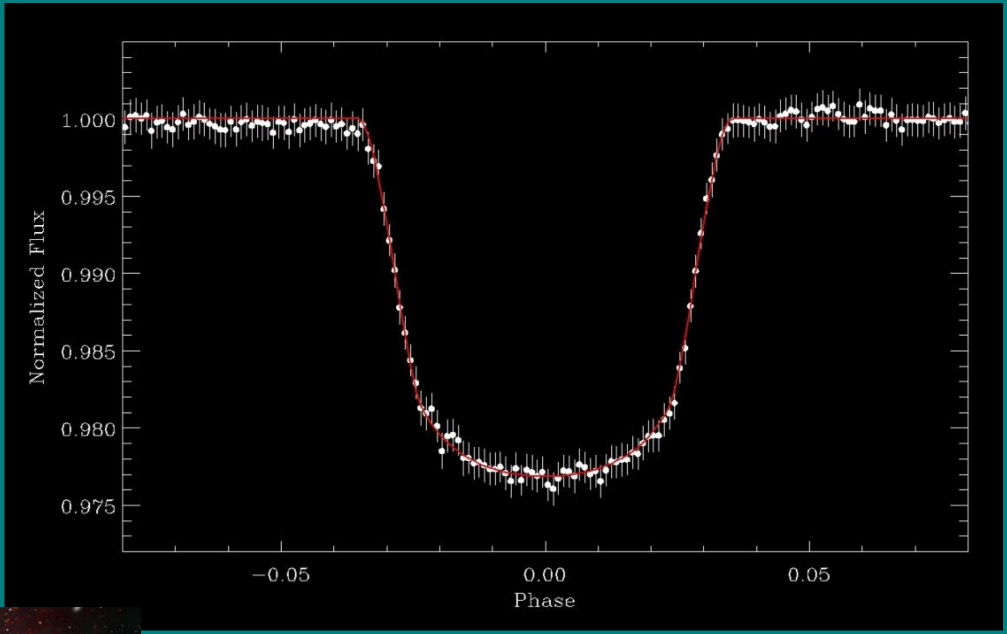
- Get out of the Earth's atmosphere: get rid of the turbulence to improve the angular resolution

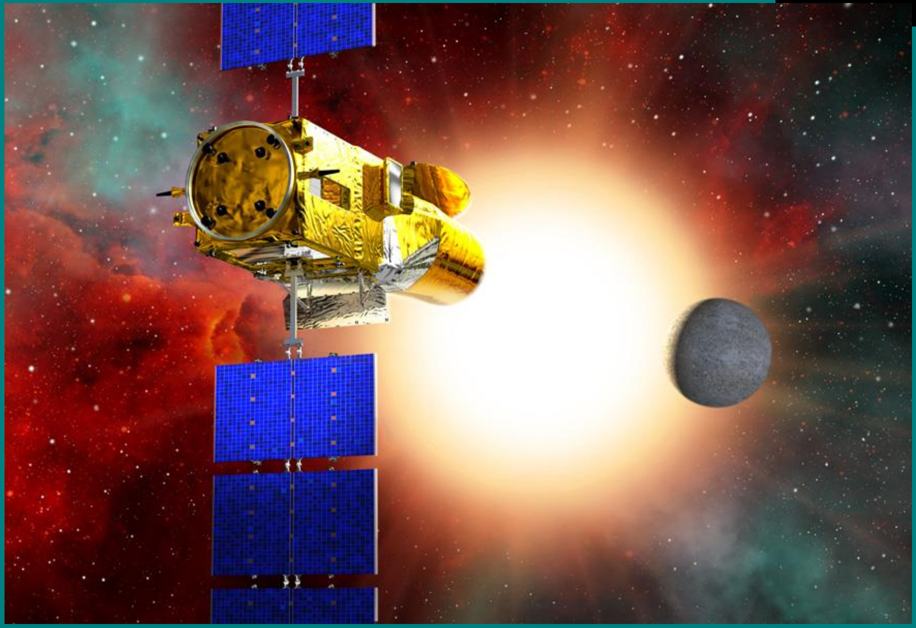




Chapter I: Introduction

- Get out of the Earth's atmosphere: get rid of the variability of the atmospheric transmission (high precision photometry)





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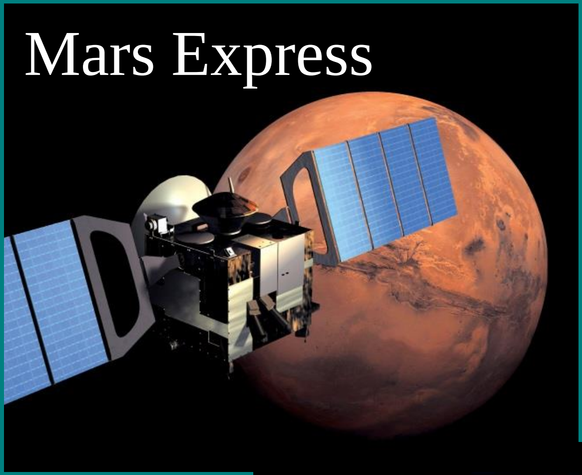
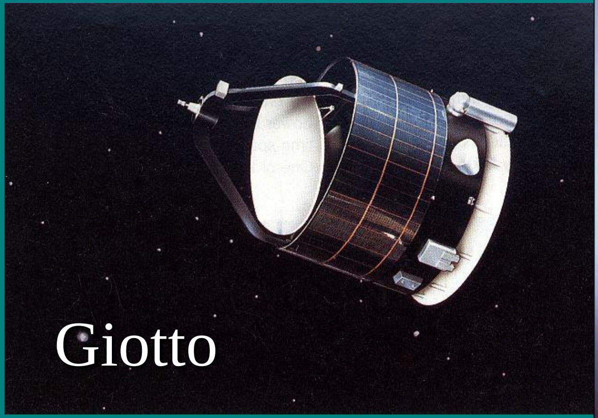
Why do science from space?

- Observations in orbit around a planet: detailed cartography (3D) of the planet, measure the magnetic field.
- Rendez-vous with comets, asteroids and minor planets…





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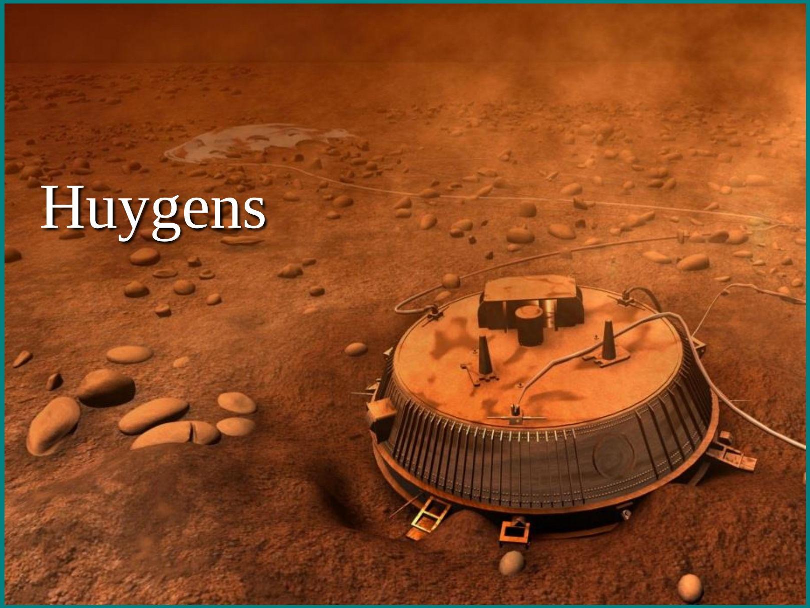
Why do science from space?

- In-situ measurements on the surface of a planet, either with a static lander or a rover



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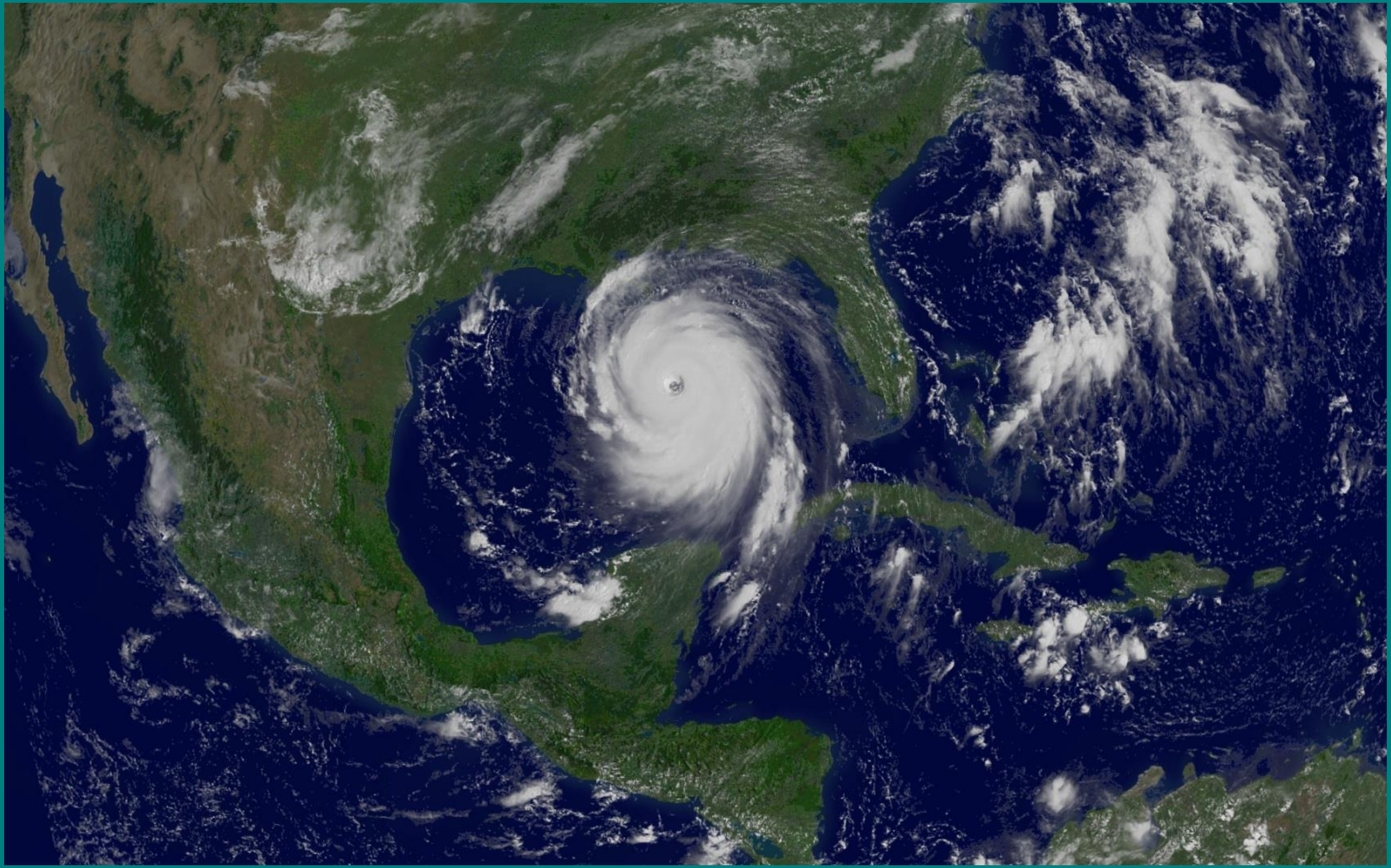
Why do science from space?

- Observations of the Earth (climate change, weather,…)



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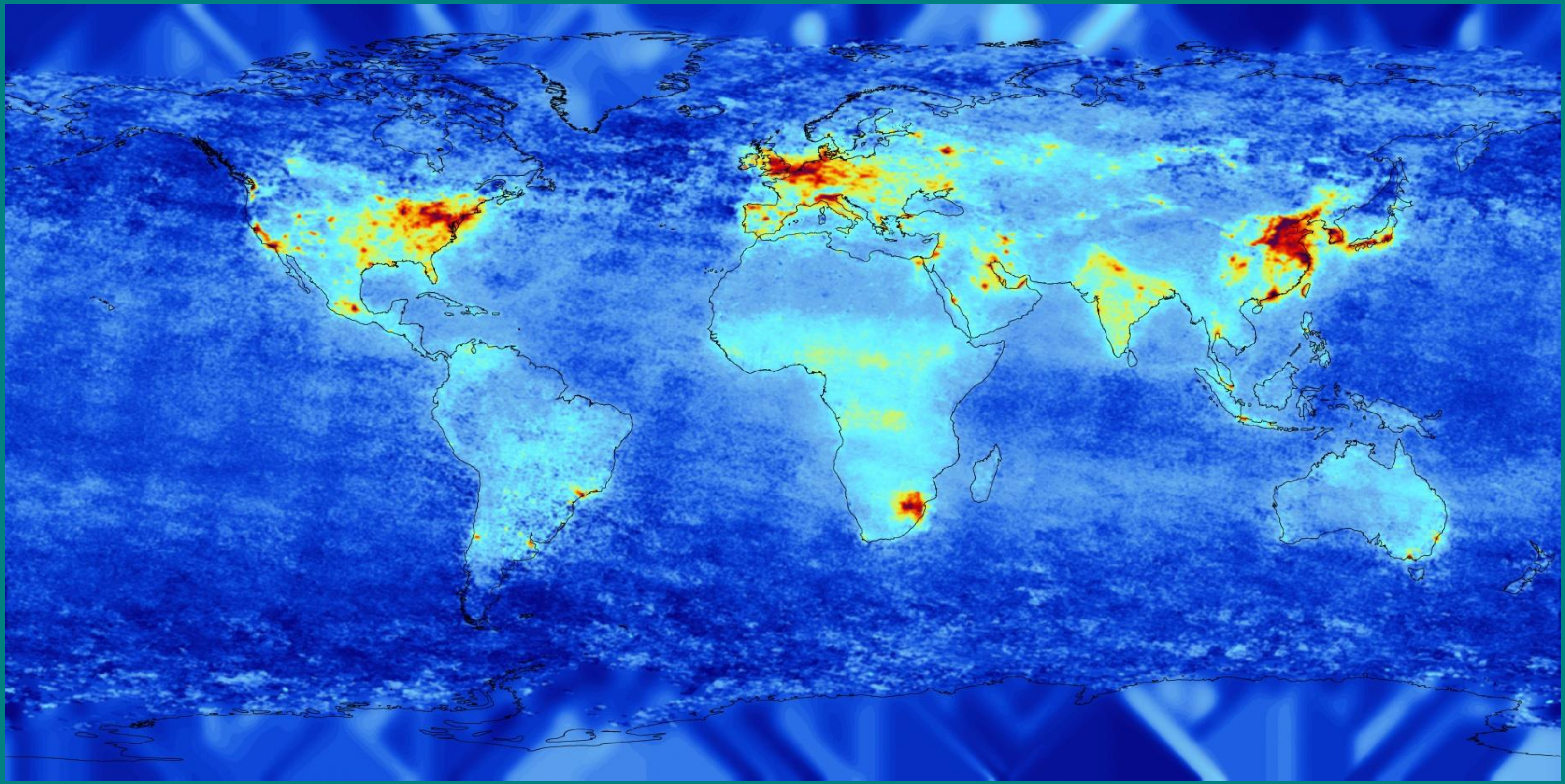
Why do science from space?

- Observations of the Earth (production of pollutants, e.g. NO_2 released by combustion of fossil combustibles).



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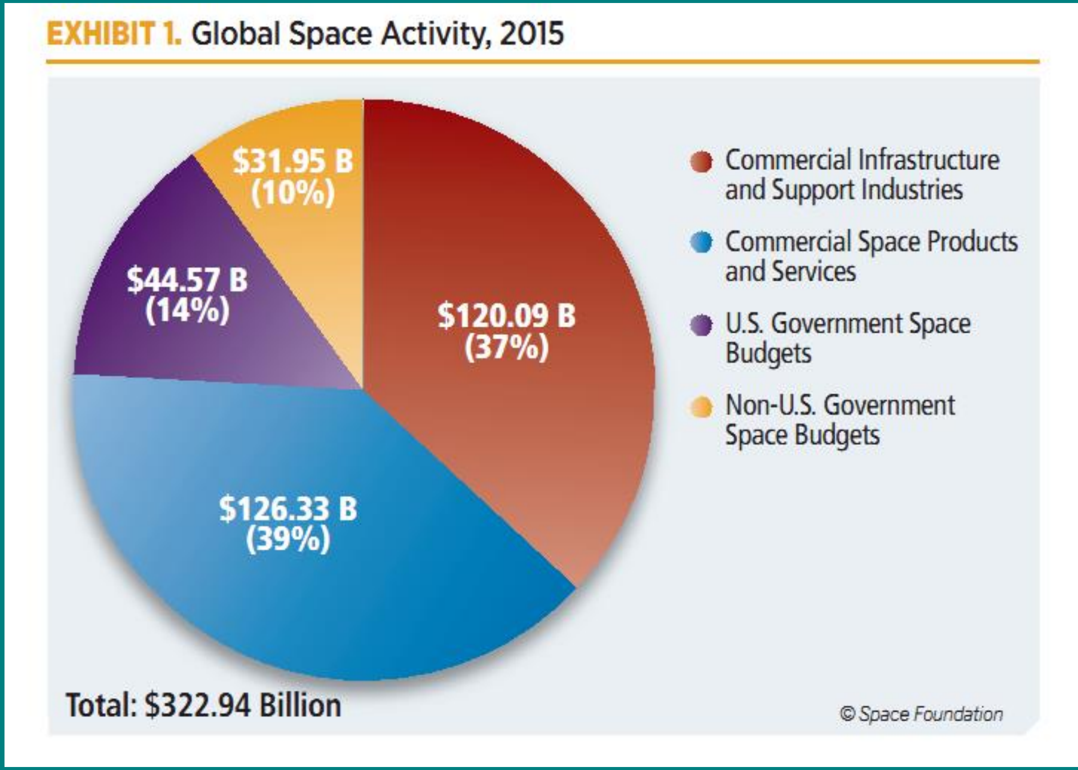
Why go to space?

- The scientific space programmes often trigger technical developments, but the latter should not be used as excuses for fundamental research!
- The bulk of the space activities do not concern scientific research, but rather deal with commercial or political aspects.
- The most obvious examples are telecommunications, microgravity, Earth observation and manned spaceflight.
- Some activities failed to meet the expectations: microgravity, transatlantic telecommunications by satellite, research aboard the ISS...
- Others are success stories: GPS, Earth observation (military and civil)..., that have opened important markets.

Chapter I: Introduction

Economic impact of space activities (nearly impossible to get accurate and exhaustive figures):

- Global budget in 2015 = 323 billion $ US,
- ¾ of the investment related to commercial applications,
- ~ 40,000 jobs in European space industry.



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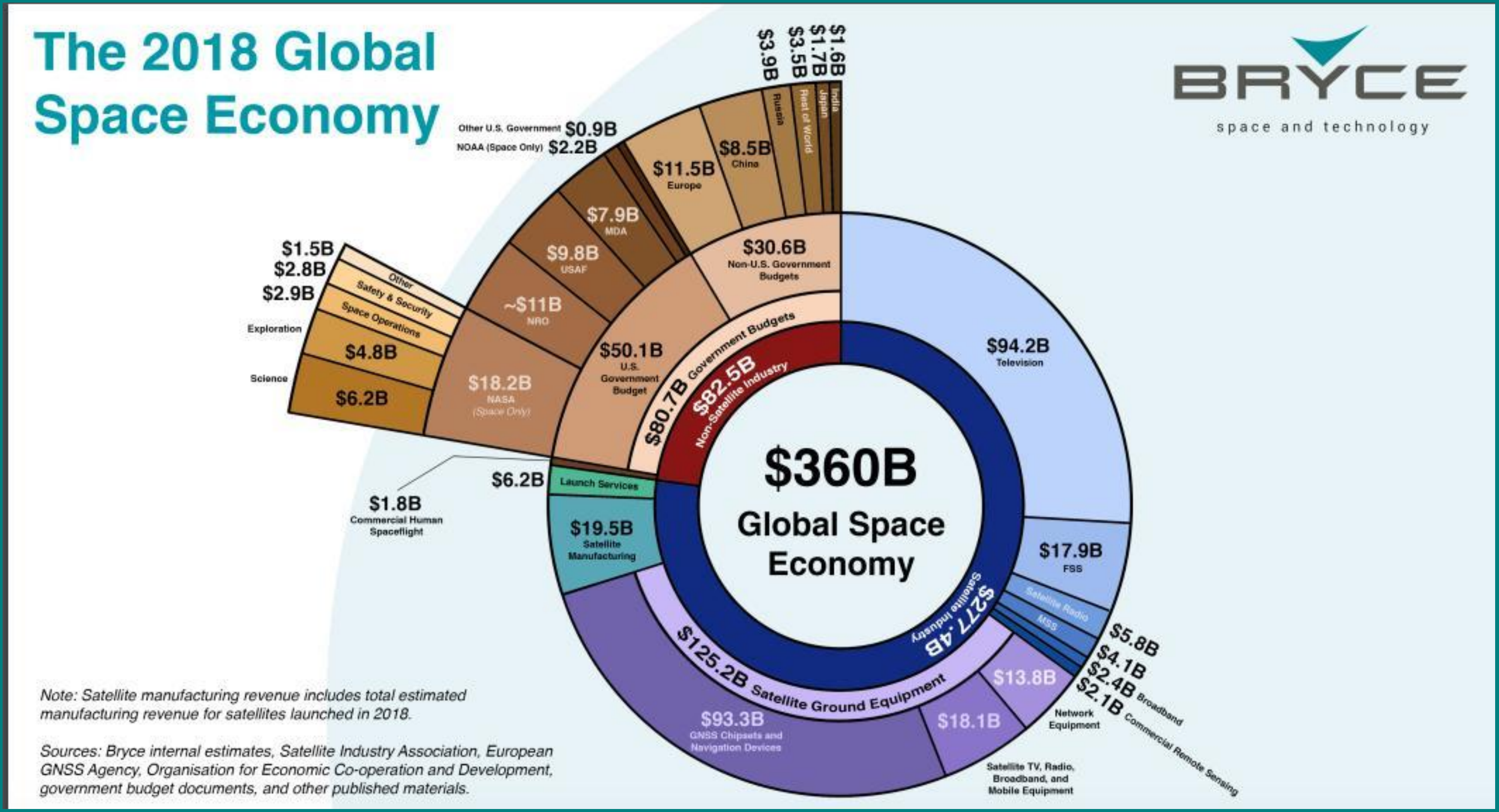
Economic impact of space activities goes well beyond building rockets and satellites:



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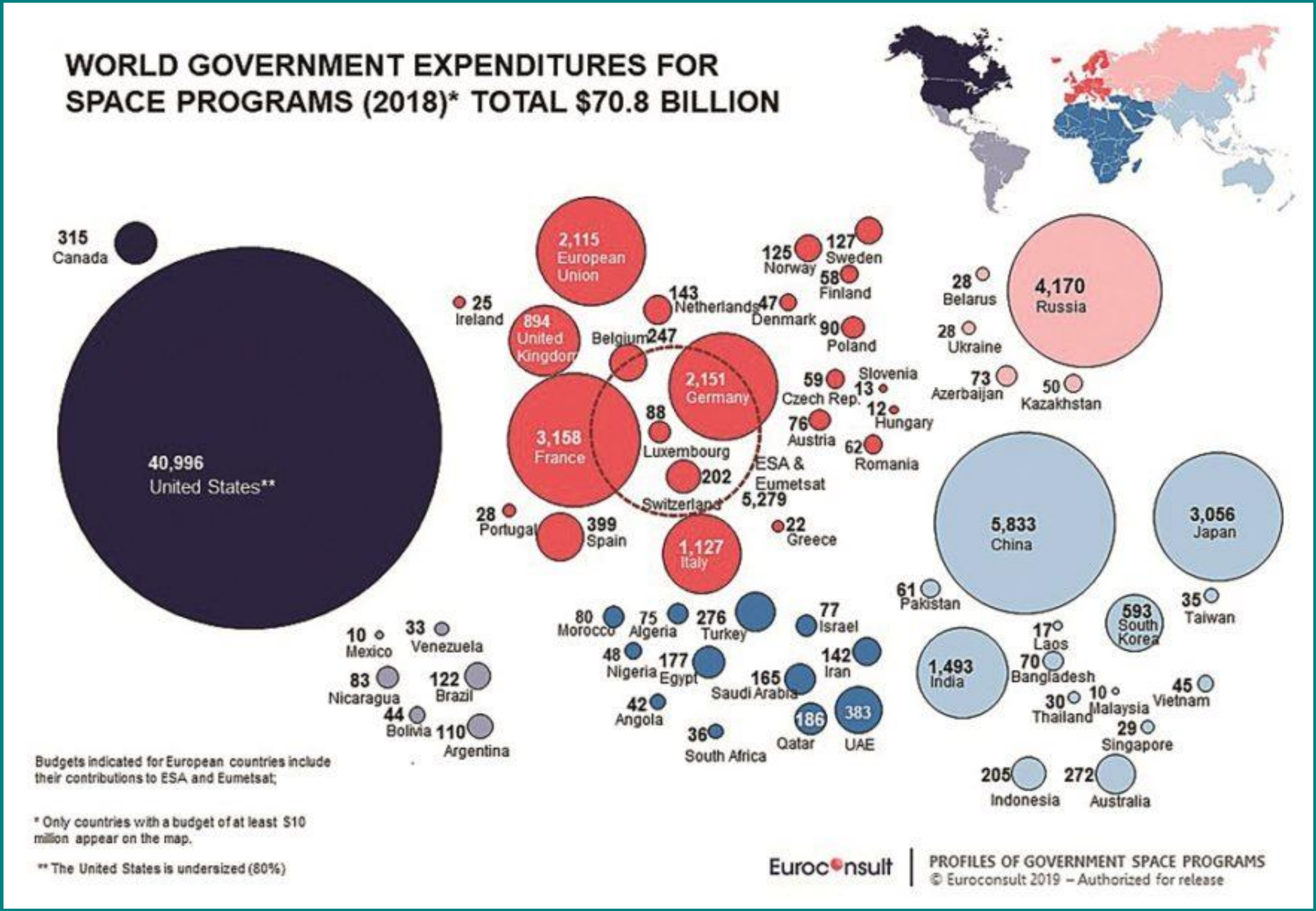

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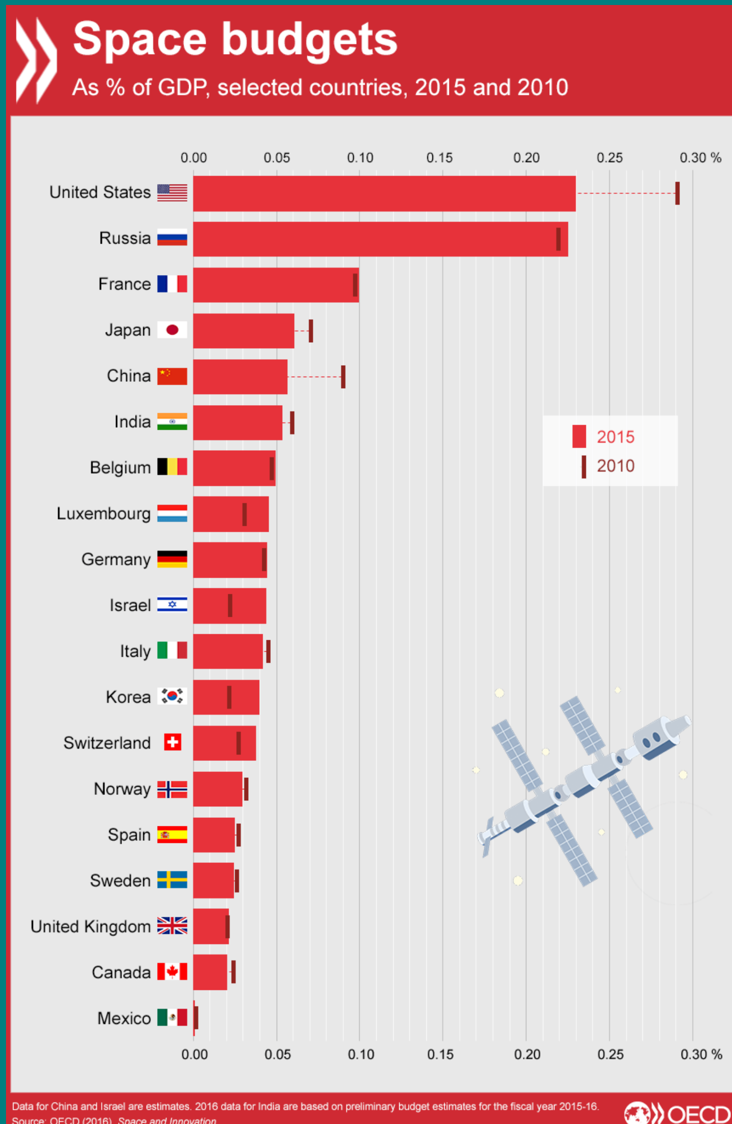
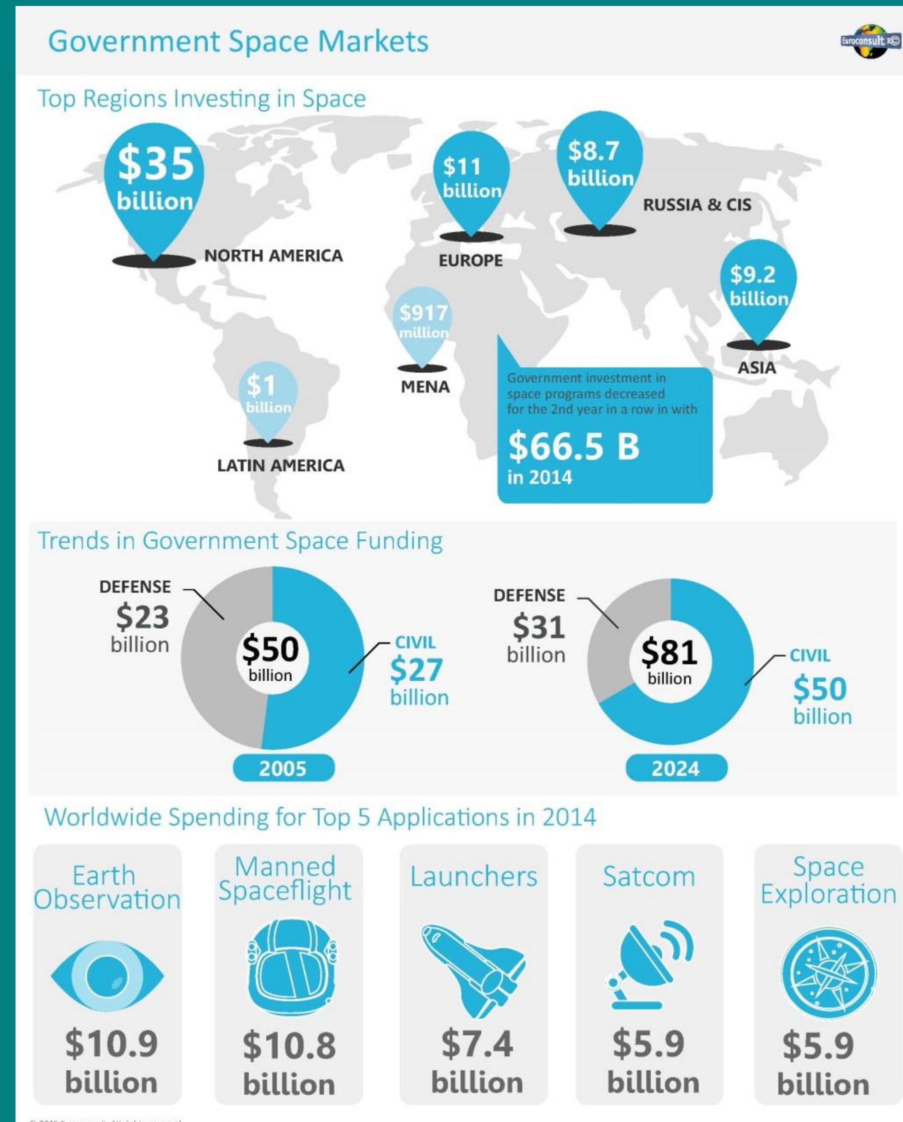
Science is (by far) NOT the biggest chunk in the space expenditures.





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Space, a big business!

- In 2015, the total annual budget of space activities were 35 and 11 billion $ US in the USA and Europe, respectively. In the USA, about half of this budget was used for military applications.
- Belgium spends 0.085% of its GNP for space projects. This is the 2nd highest fraction in Europe, behind France (0.18%). Every € invested into space activities in Belgium, results in a return of 1.4 € for Belgian industry.

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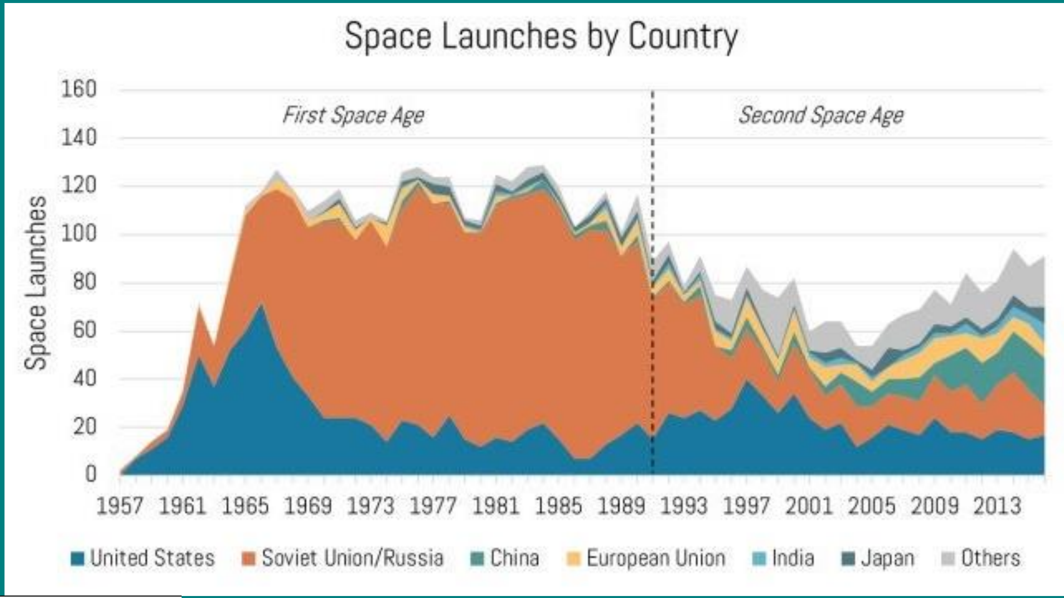
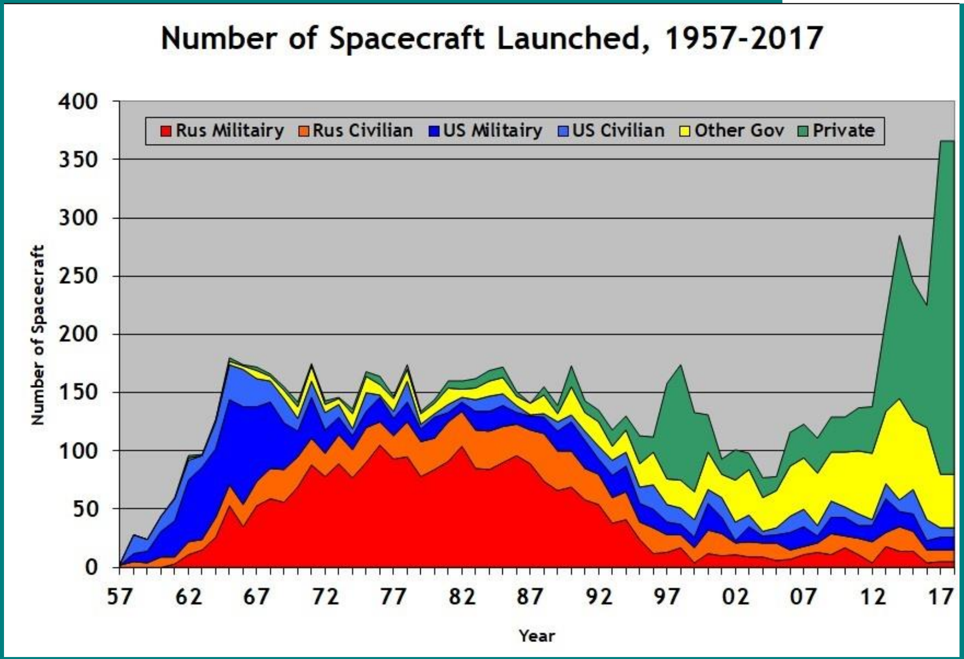
The landscape of space exploration is changing…





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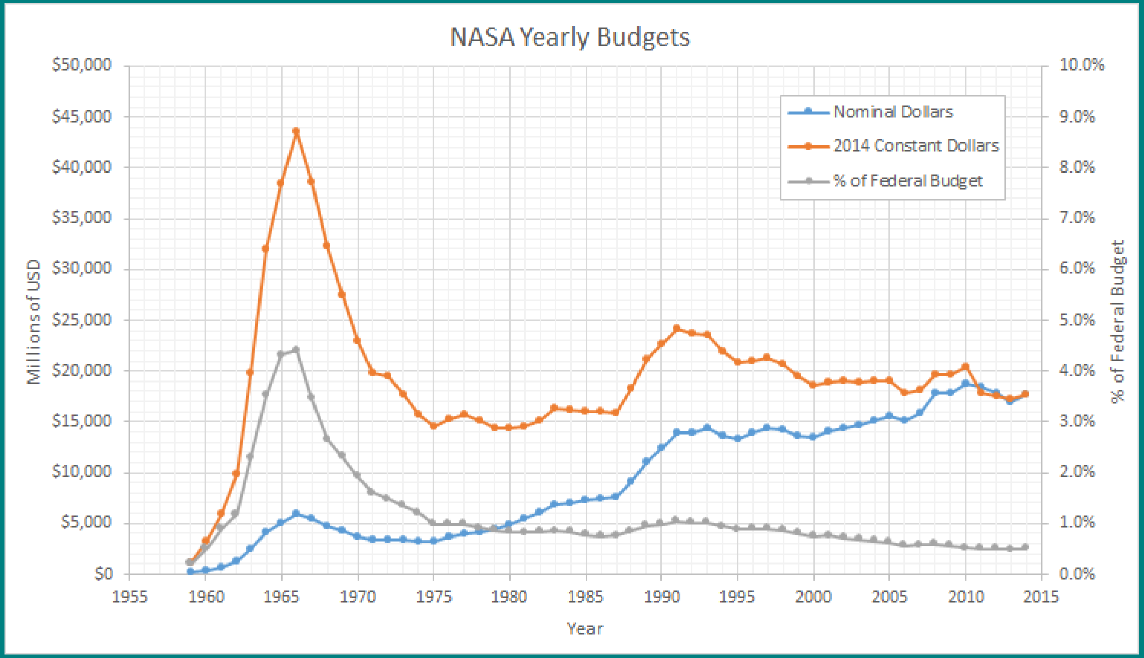

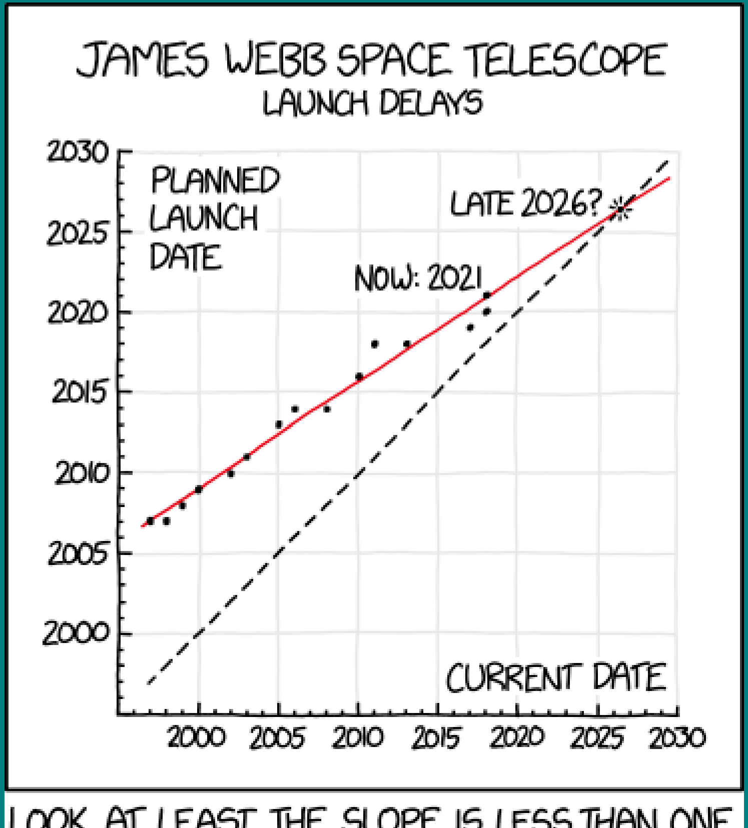

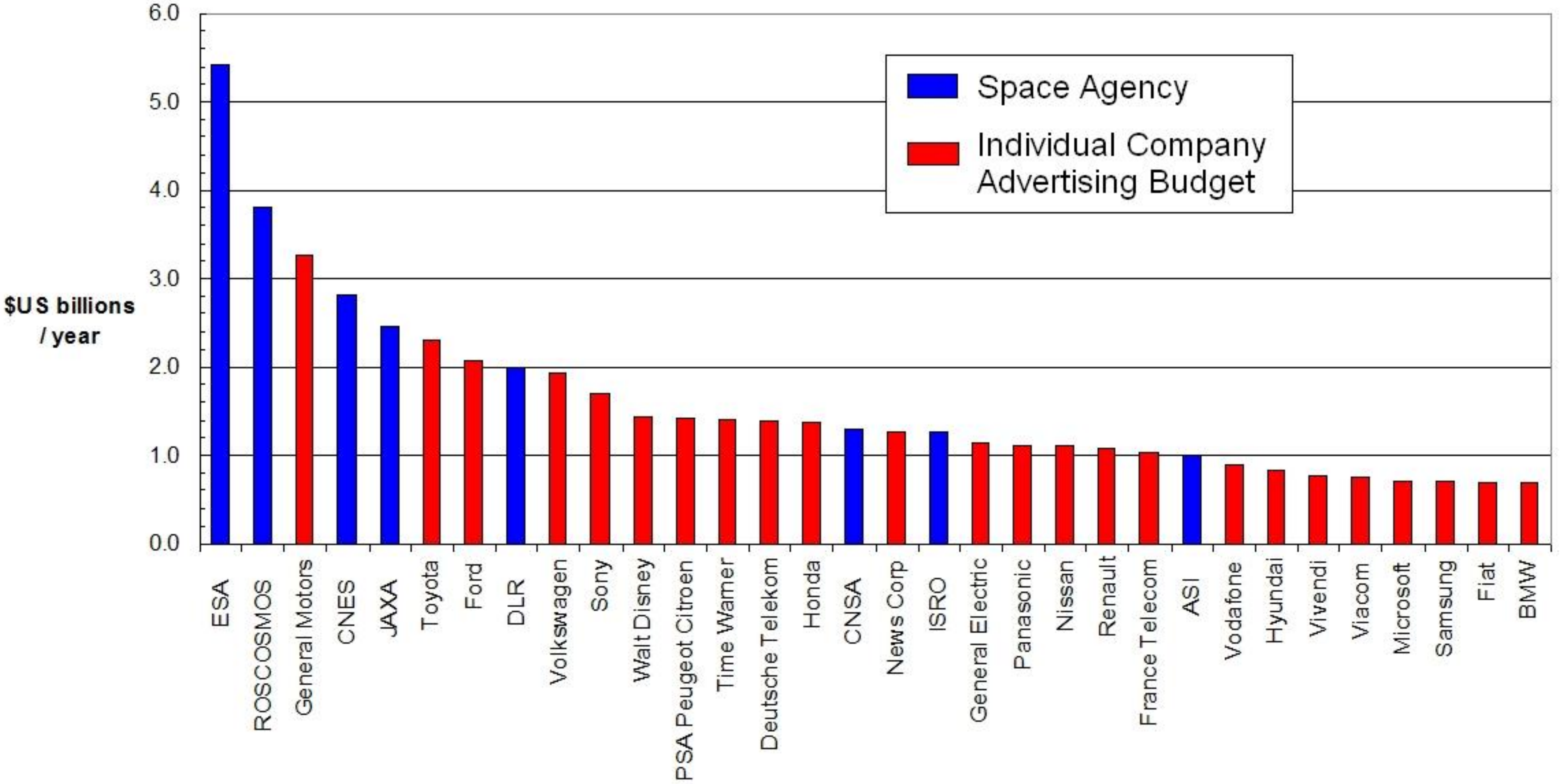
6.0
5.0
4.0
3.0
2.0
1.0
0.0
$US billions / year
Space Agency
Individual Company Advertising Budget
ESA
ROSCOSMOS
General Motors
CNES
JAXA
Toyota
Ford
DLR
Volkswagen
Sony
Walt Disney
PSA Peugeot Citroen
Time Warner
Deutsche Telekom
Honda
CNSA
News Corp
ISRO
General Electric
Panasonic
Nissan
Renault
France Telecom
ASI
Vodafone
Hyundai
Vivendi
Viacom
Microsoft
Samsung
Fiat
BMW

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The European Space Agency (ESA) has currently 22 member states.

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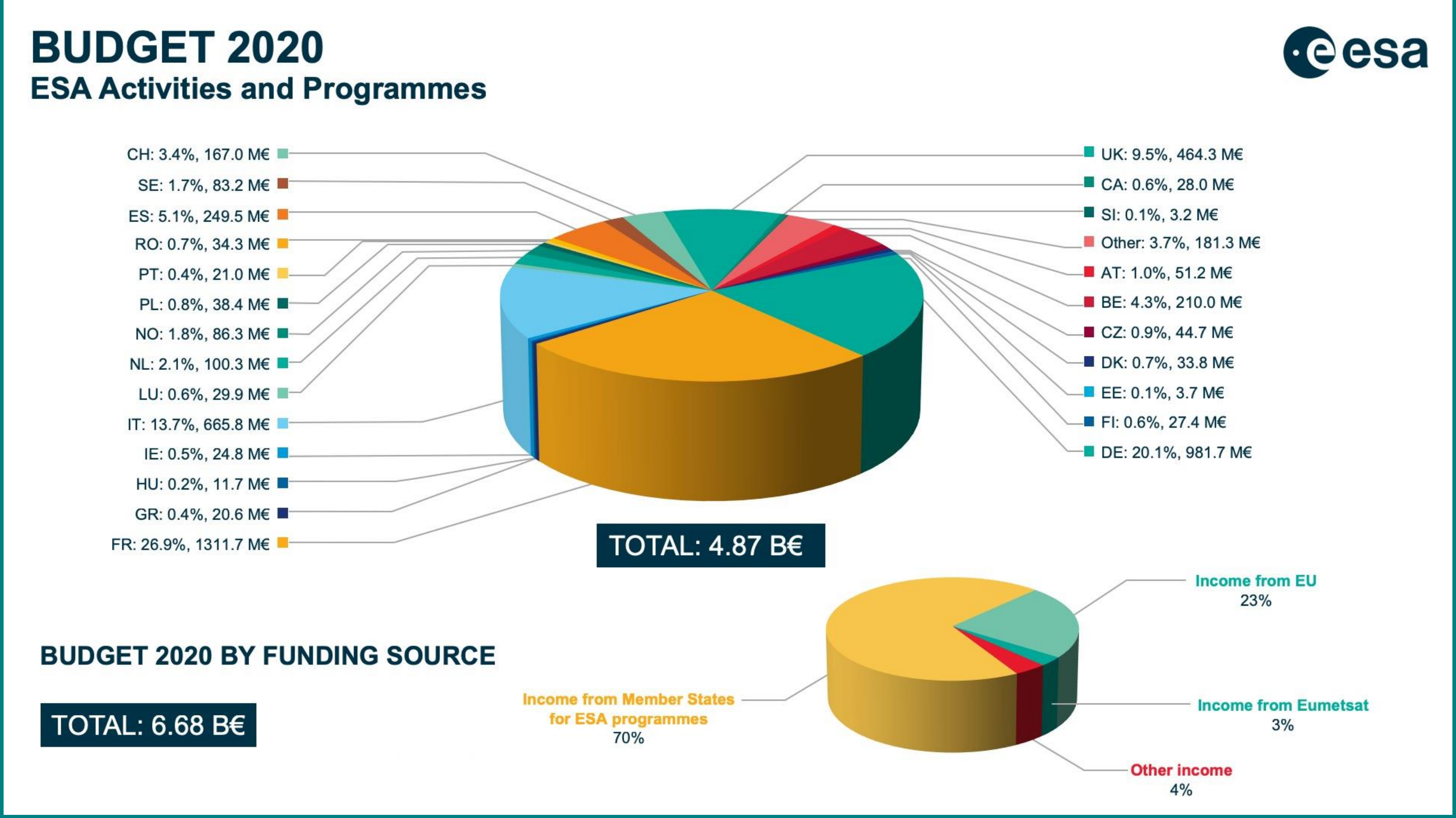
The highest level of decision of ESA is the ministerial council (one country = one voice). ESA applies the policy of « fair return ».



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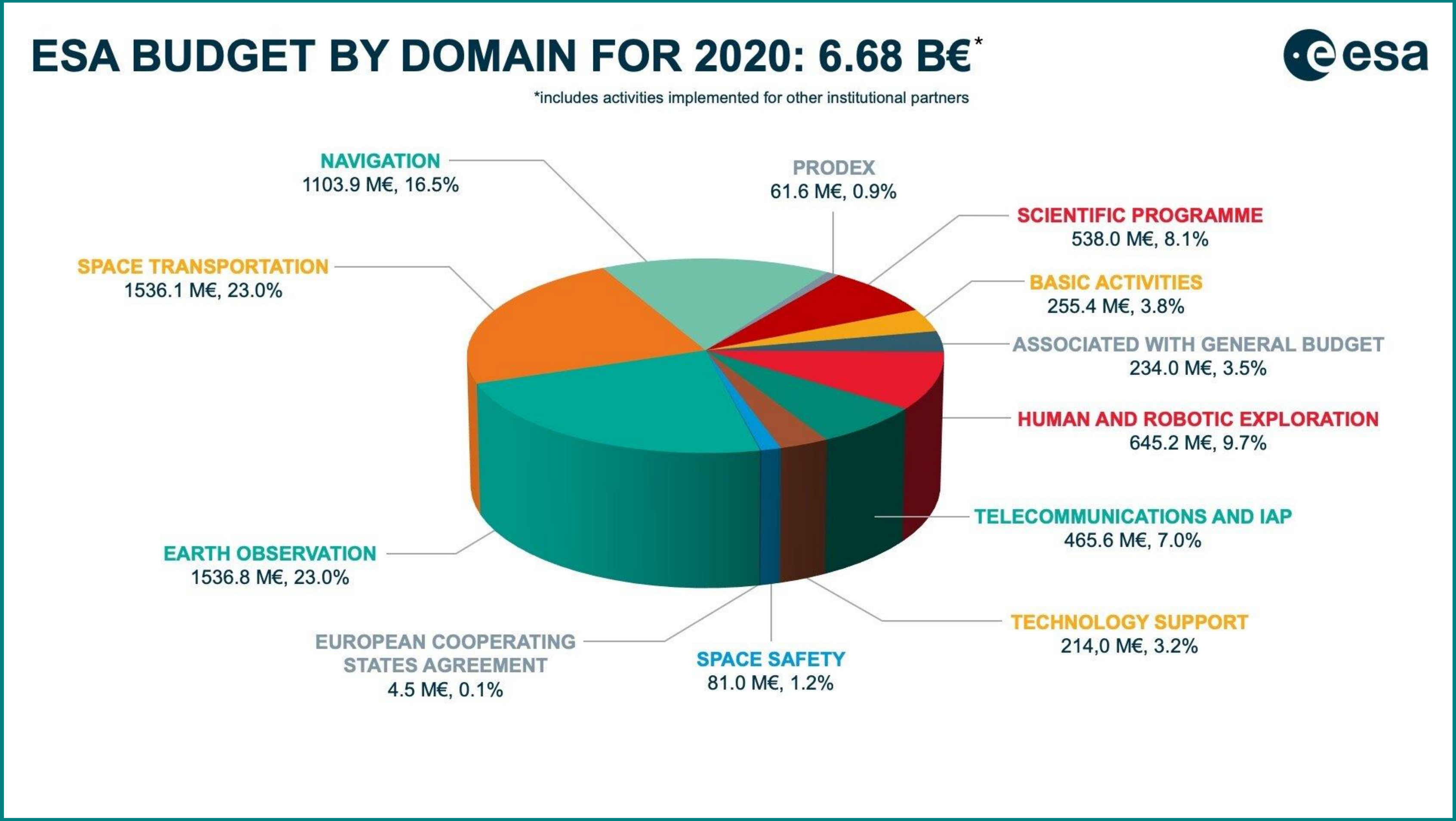
The ESA science programme (only mandatory domain). ESA science budget = 8,1% of total budget.



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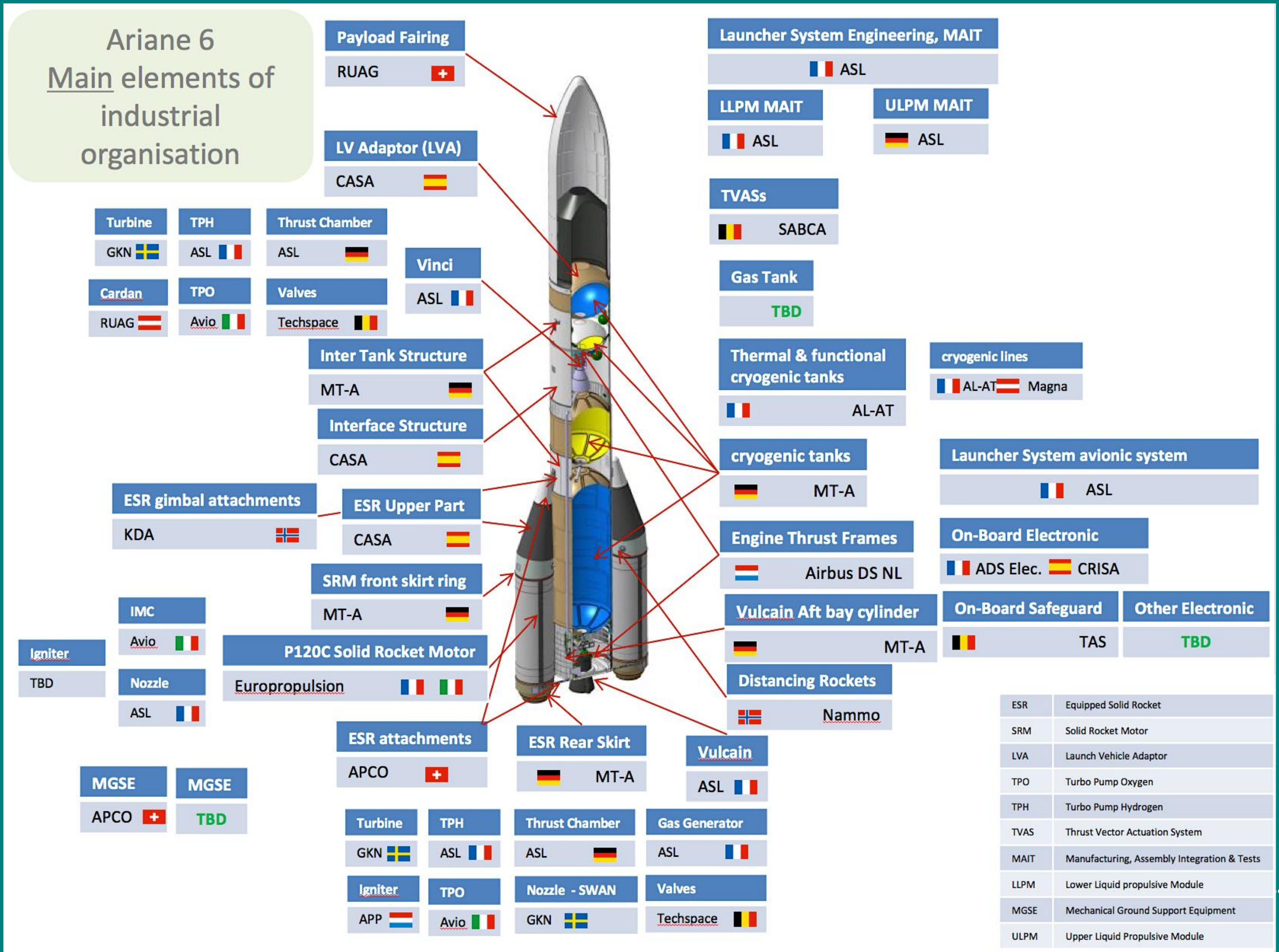
ESA concept of fair industrial return (ex. Ariane 6)



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ESA missions:

Sun	Solar System	Astrophysics	Fundamental Physics
IMPLEMENTATION			
	[2022] JUICE	[2026] PLATO [2022] Euclid [2021] JWST	
OPERATIONS / POST-OPERATIONS			
[2020] Solar Orbiter [2009] PROBA2 [1995] SOHO	[2018] BepiColombo [2016] ExoMars TGO & Schiaparelli [2004] Rosetta [2003] Mars Express [2003] Double Star [2000] Cluster	[2019] CHEOPS [2013] Gaia [2002] INTEGRAL [1999] XMM-Newton [1990] Hubble	
LEGACY			
[1990] Ulysses	[2005] Venus Express [2003] SMART-1 [1997] Cassini-Huygens [1985] Giotto	[2009] Planck [2009] Herschel [1995] ISO [1989] Hipparcos [1983] EXOSAT [1978] IUE [1975] Cos-B	[2015] LISA Pathfinder

Missions in the Cosmic Vision 2015-2025 Programme	
L1 mission	JUICE
L2 mission	Athena
L3 mission	LISA
M1 mission	Solar Orbiter
M2 mission	Euclid
M3 mission	PLATO
M4 mission	ARIEL
S1 mission	CHEOPS
Collaborative mission with China	SMILE

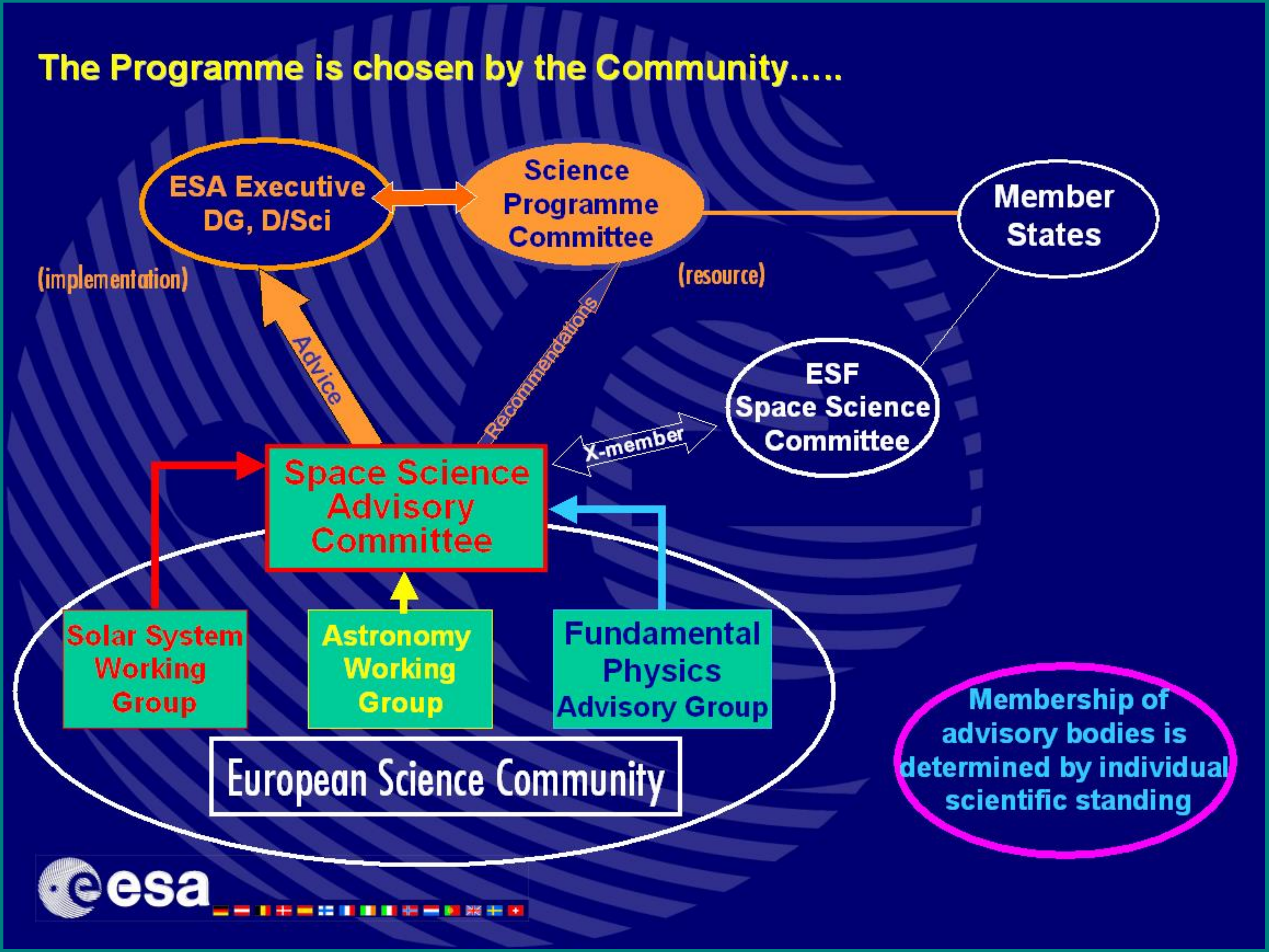
Chapter I: Introduction

Call for ideas: identify the most important science themes and prepare the necessary technological developments.

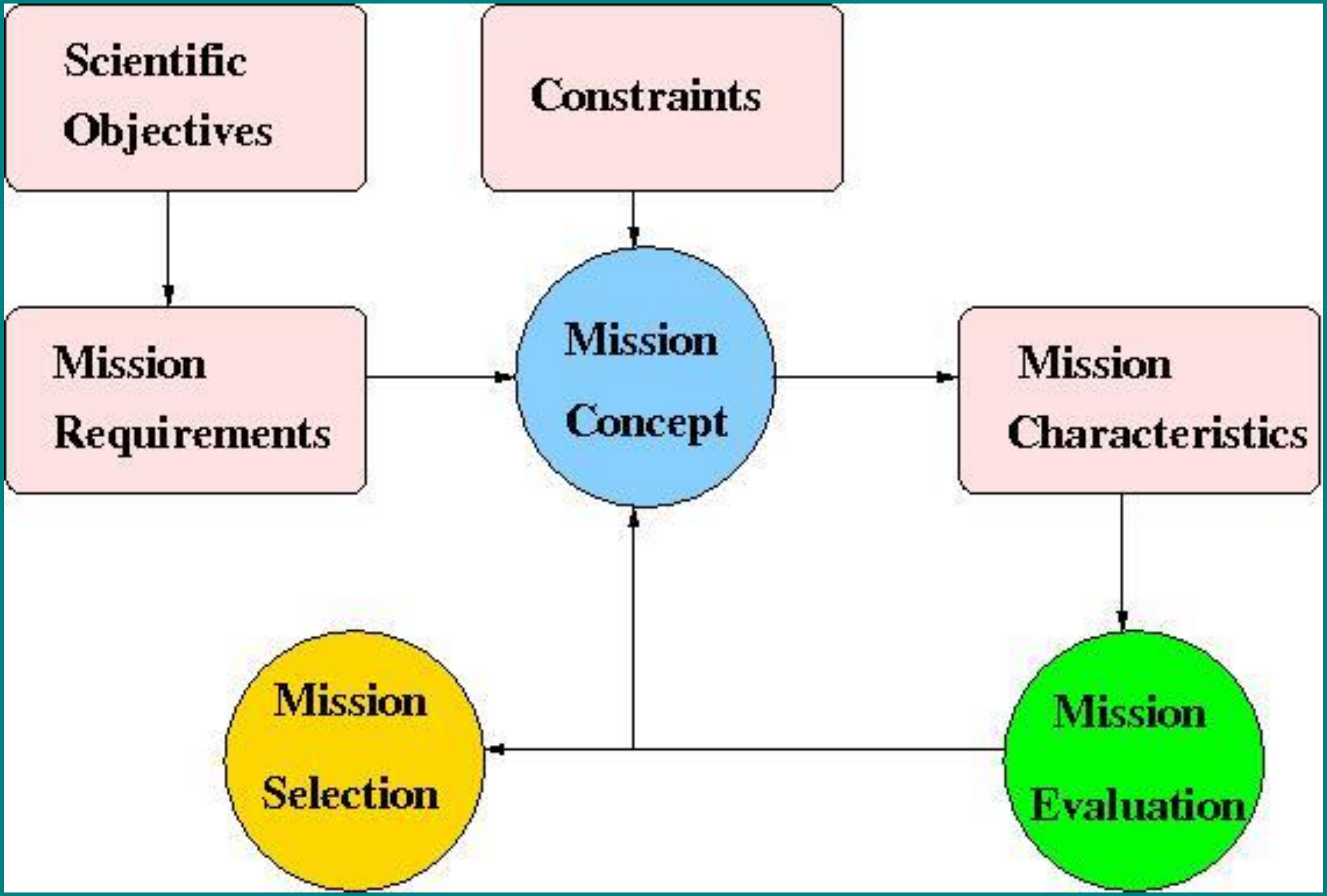
The 4 major themes of the « Cosmic Vision 2015-2025 » plan:

1. *What are the conditions for planet formation and the emergence of life?*
2. *How does the Solar System work?*
3. *What are the fundamental physical laws of the Universe?*
4. *How did the Universe originate and what is it made of?*

The selection process of scientific ESA missions.



Chapter I: Introduction



Chapter I: Introduction

After the selection of a mission:

1. Definition phase: 2 parallel industrial studies + announcement of opportunity for instruments of the payload (2 to 3 years)
2. Implementation phase: selection of a lead industrial partner, finalisation of the design of the mission, critical technical developments, tests of the various components, integration of the instruments into the spacecraft, ground calibration, launch and commissioning (4 to 5 years)
3. Scientific exploitation: observations/measurements (limited in time by on-board consumables, aging of the instruments, available budget,…)

Chapter II: Our Solar System and its ingredients

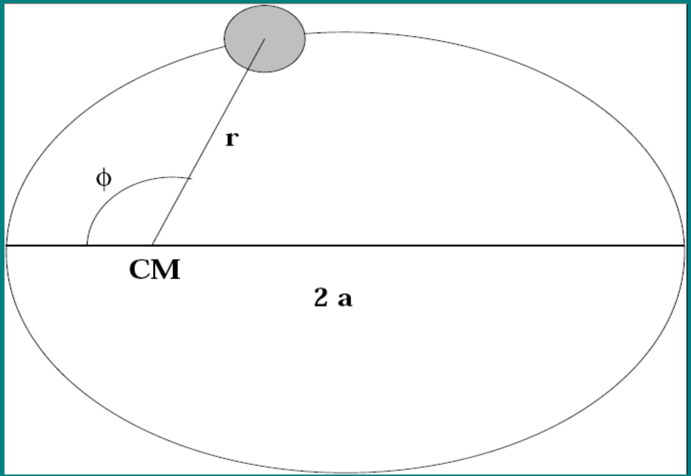
- Reminder: the Solar System
- The Roche potential and the Lagrangian points

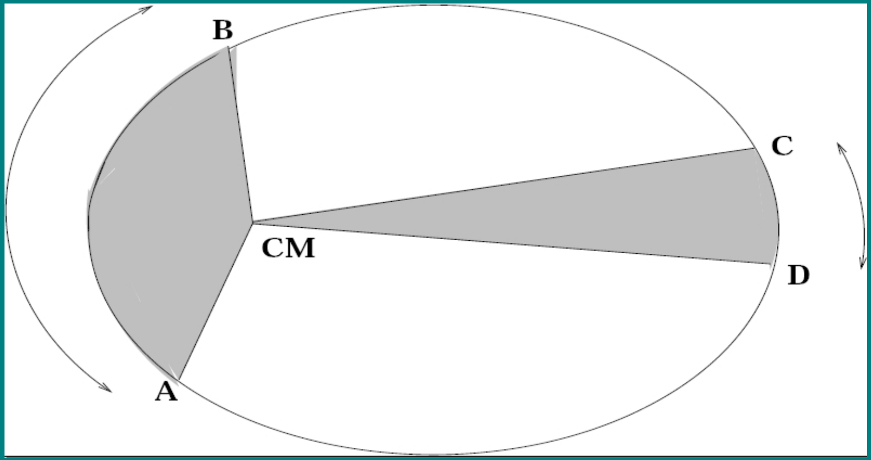
Chapter II: Our Solar System and its ingredients

The Sun: star of spectral type G2 V, 99.86% of the mass of the Solar System.

Planets: orbit the Sun according to Kepler's laws.

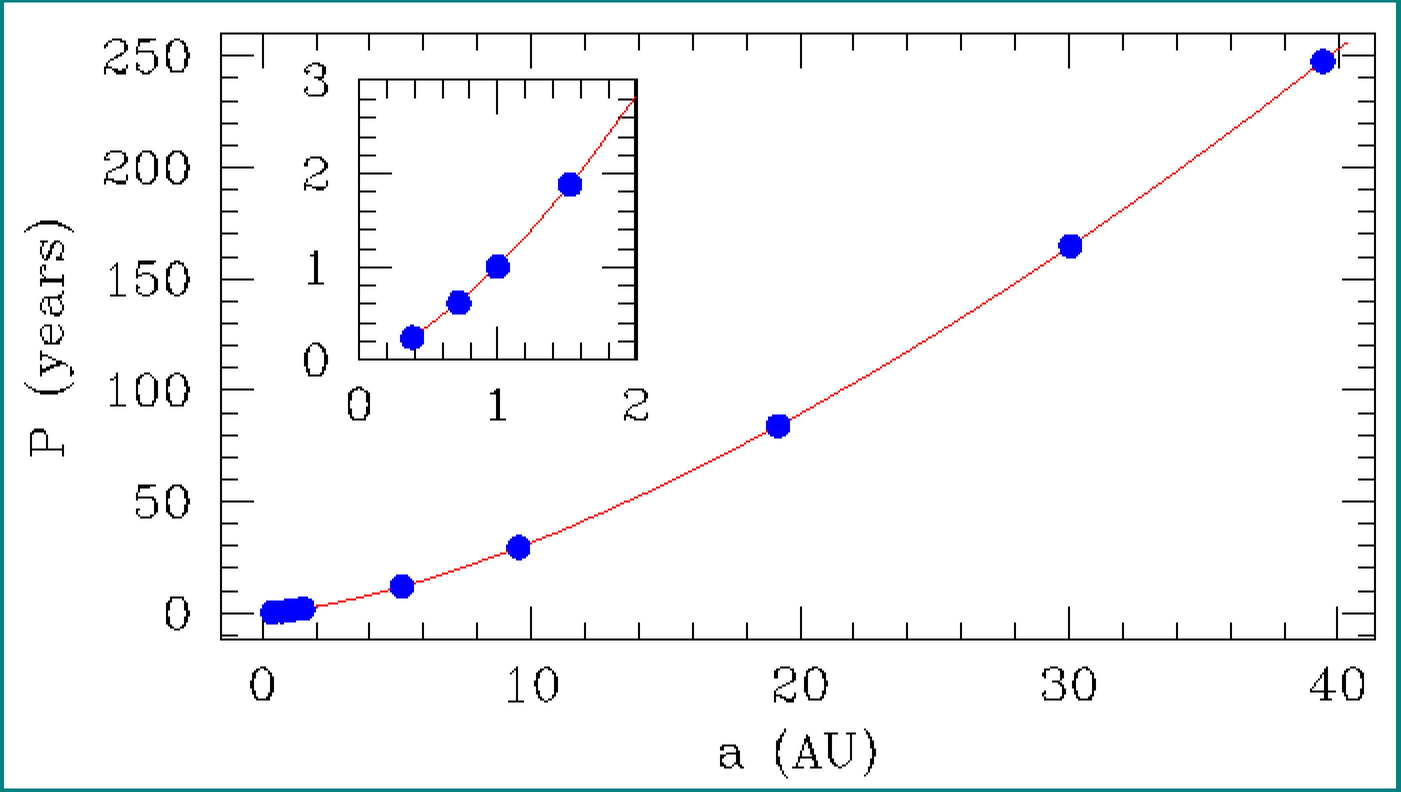
1. The orbit of a planet around the Sun is an ellipse with the Sun occupying one of the foci.
2. The areas swept out by the line joining the planet and the Sun is proportional to the time needed to sweep it out.
3. $a = [G(M_{\odot} + m)]^{1/3}\, P^{2/3}\, (2\pi)^{-2/3}$



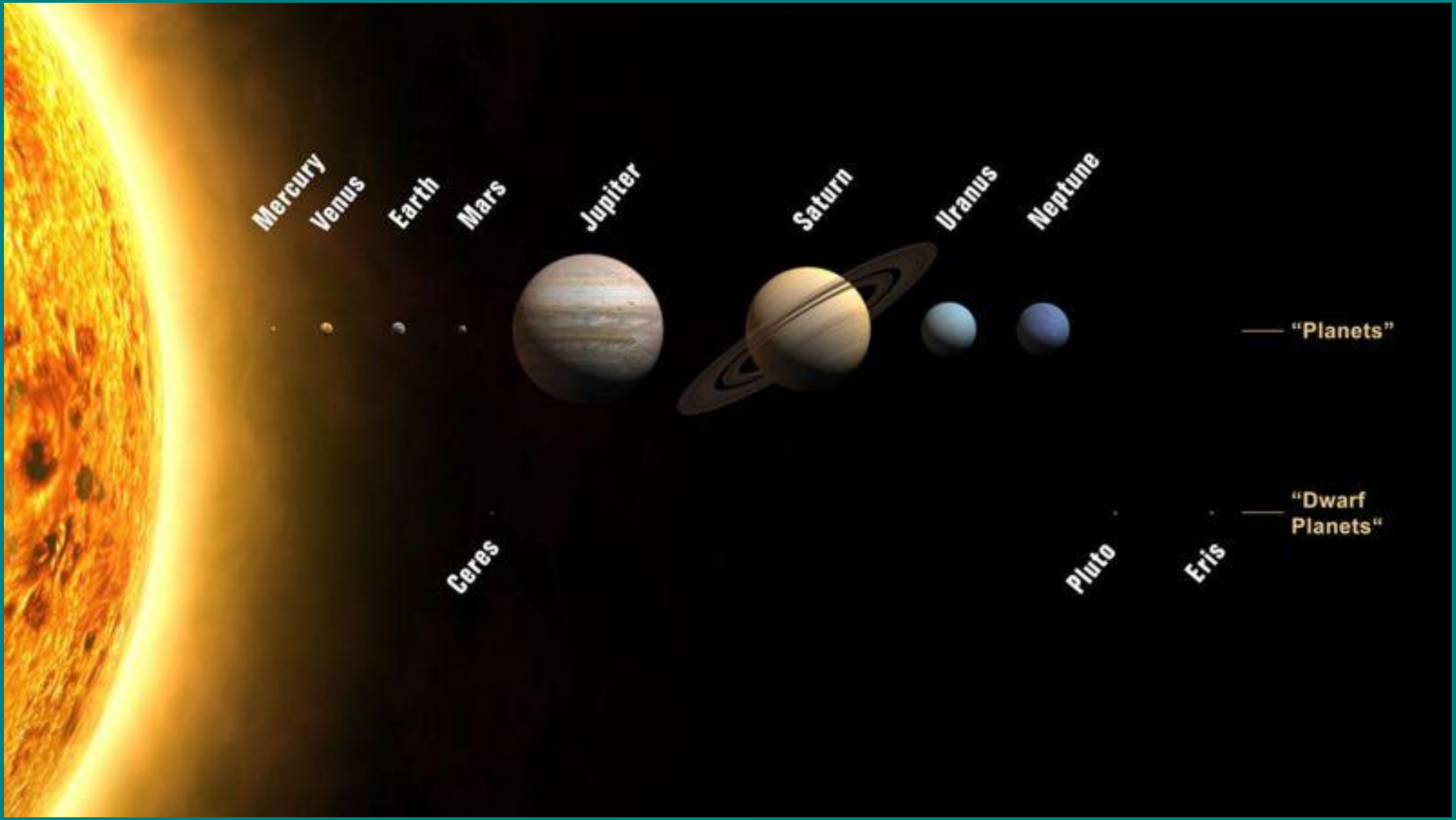


Chapter II: Our Solar System and its ingredients

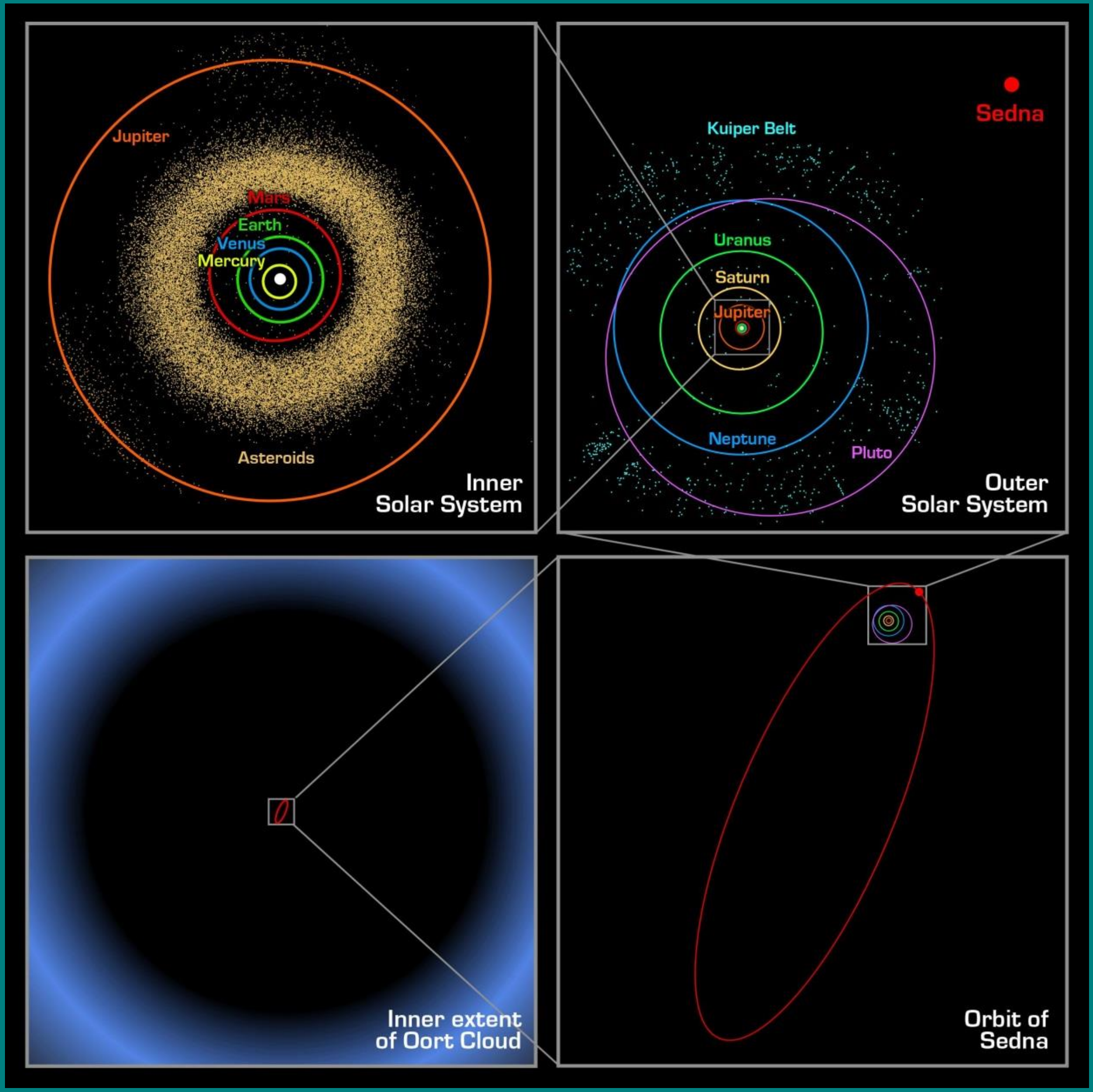
$$a = [G(M_\odot + m)]^{1/3} P^{2/3} (2\pi)^{-2/3}$$



Chapter II: Our Solar System and its ingredients



Chapter II: Our Solar System and its ingredients



Asteroid belt: between 2.3 and 3.3 AU.

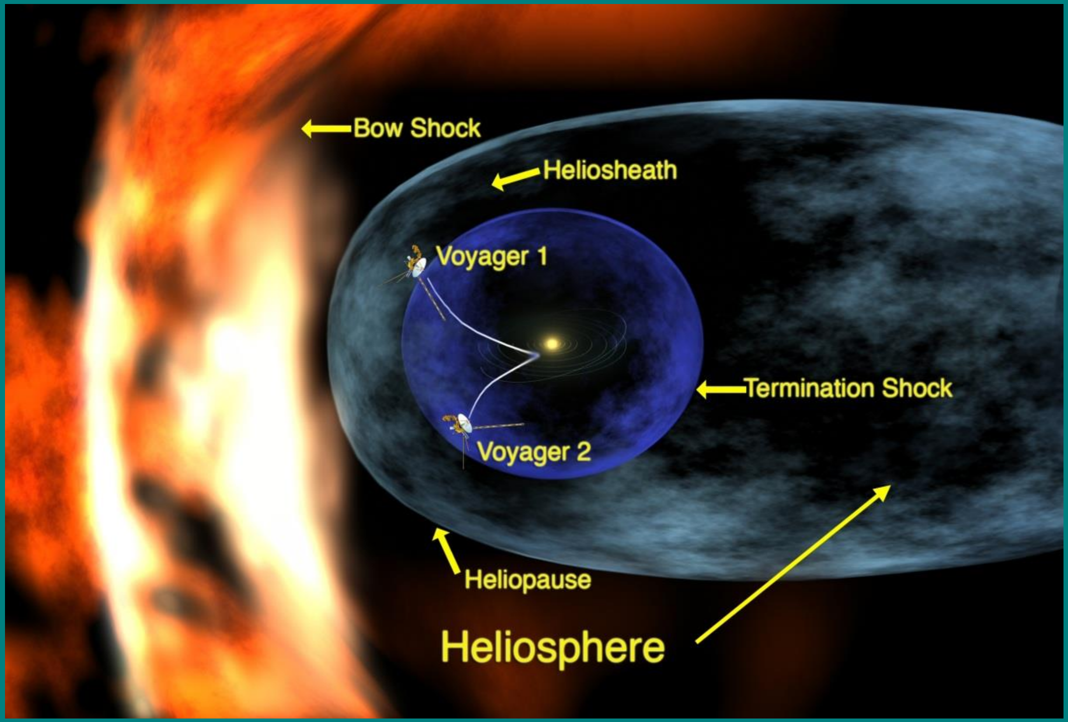
Kuiper belt: between 30 and 50 AU.

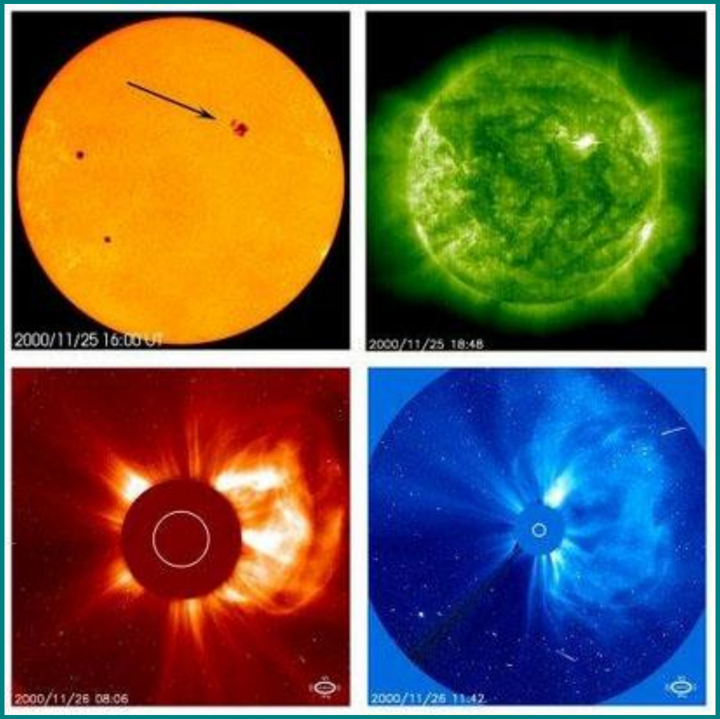
Oort Cloud: between 50000 and 100000 AU.

Nearest star: α Cen at about 4.4 light years (= 278000 AU)

Chapter II: Our Solar System and its ingredients

Heliosphere: region dominated by the solar wind (extends at least to about 100 AU).





Chapter II: Our Solar System and its ingredients

Gravitational sphere of influence: let's consider a small test mass under the influence of two masses m_1 and m_2 on circular orbit around each other (e.g. the Sun and a planet) ⇒ Roche potential accounts for centrifugal force:

$$\Phi = -\frac{G\,m_1}{|\underline{r} - \underline{r}_1|} - \frac{G\,m_2}{|\underline{r} - \underline{r}_2|} - \frac{1}{2}\,|\underline{\omega} \wedge \underline{r}|^2$$

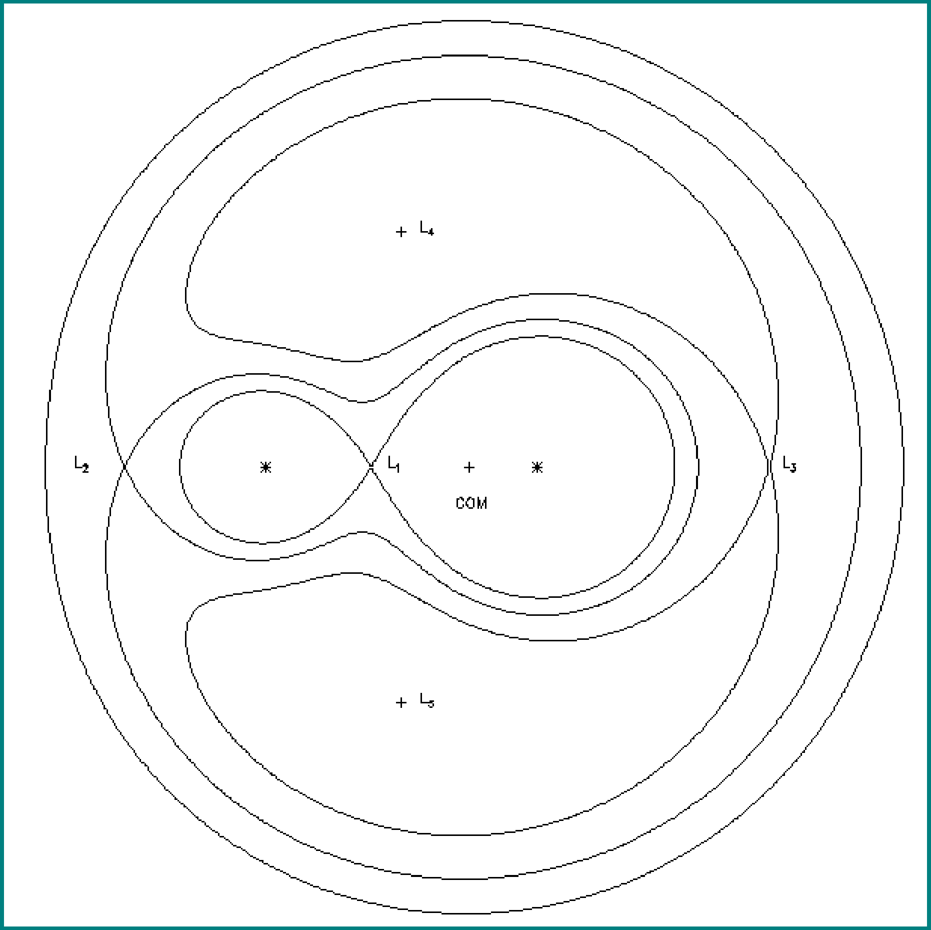
Dimensionless potential: $\Omega = -\frac{\Phi\,a}{G\,m_1}$.

$$\Omega = \frac{1}{r_1} + \frac{q}{r_2} + \frac{q+1}{2}\,(x^2 + y^2) - q\,x$$

$$q = \frac{m_2}{m_1} \qquad r_1 = \sqrt{x^2 + y^2 + z^2} \qquad r_2 = \sqrt{(x-1)^2 + y^2 + z^2}$$

Chapter II: Our Solar System and its ingredients

$$\Omega = \frac{1}{r_1} + \frac{q}{r_2} + \frac{q+1}{2}\left(x^2 + y^2\right) - q\,x$$

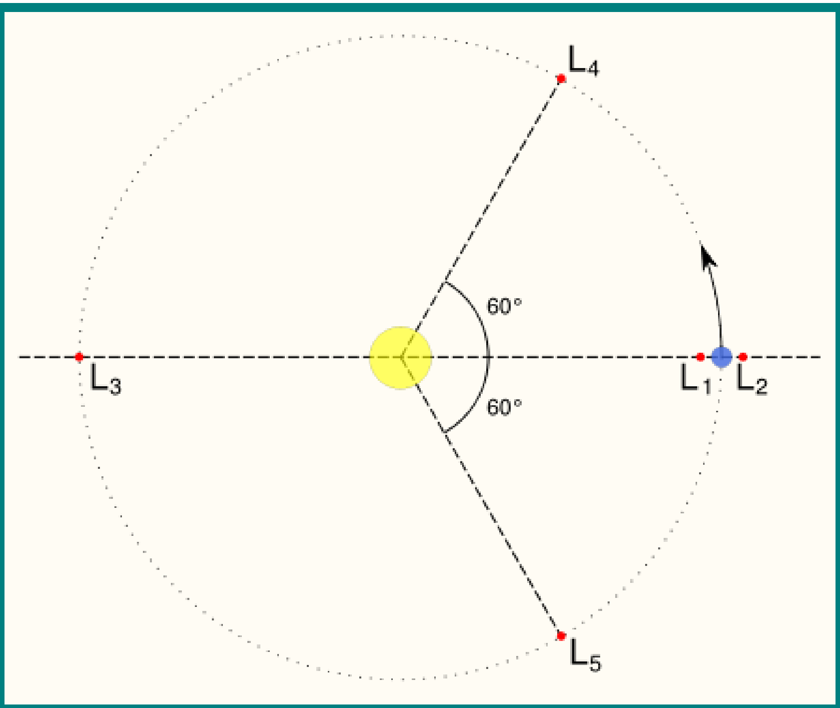


Chapter II: Our Solar System and its ingredients

The Roche potential features 5 points of relative equilibrium, the Lagrangian points solution of the equation $\underline{\nabla}\,\Omega = 0$

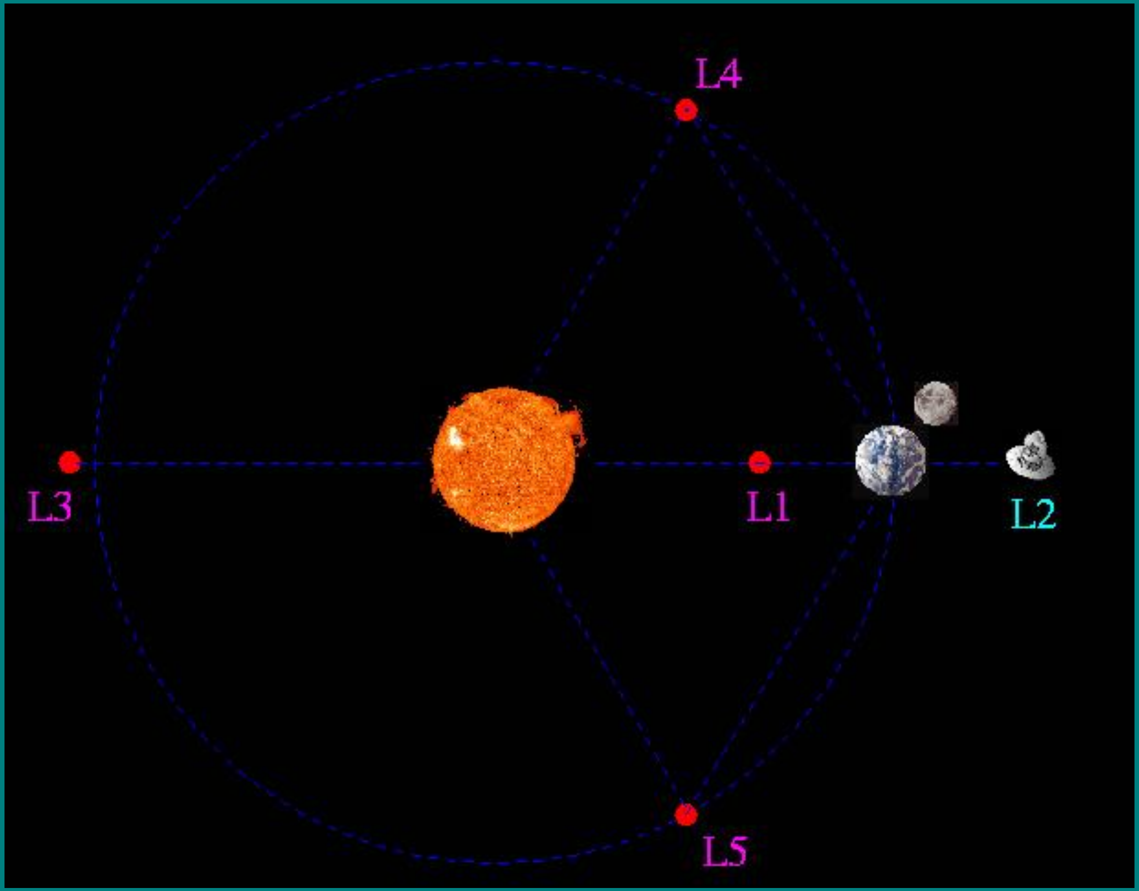
The L1, L2 and L3 points are solution of

$$\frac{-x}{|x|^3} - \frac{q(x-1)}{|x-1|^3} + (q+1)\,x - q = 0$$



Chapter II: Our Solar System and its ingredients

Lagrangian points of the Sun – Earth system: L1 and L2 are located at 1.5 million km from the Earth. They are ideal sites for solar observations (L1) and certain astrophysical observations (L2)



Chapter II: Our Solar System and its ingredients

Lagrangian points of the Sun – Earth system:

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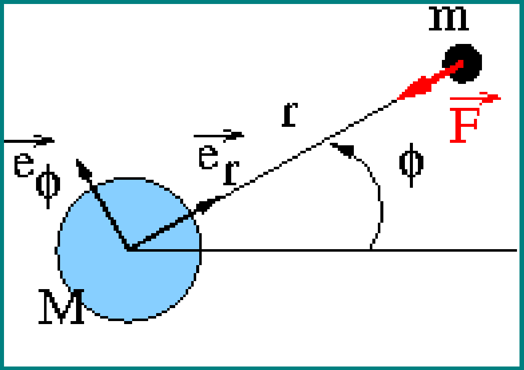
file:///D:/Cours%20Master/OnOrbitL3.swf

Chapter III: How to travel in space?

- Reminder: Newton's law of universal gravity
- The different types of orbits
  1. Orbits around the Earth or a planet
  2. Orbits around the Lagrangian points
- The rocket equation
- Interplanetary trajectories
  1. The Hohmann transfer orbit
  2. Gravity assisted manoeuvres

Chapter III: How to travel in space?



- Consider a mass m << M under the action of gravity.
- Newton's equation: $$m\,\ddot{\vec{r}} = -\frac{G\,M\,m}{r^2}\,\vec{e_r}$$
- Using polar coordinates within the plane of the motion:
$$\vec{r} = r\,\vec{e_r} \quad \& \quad \dot{\vec{r}} = \dot{r}\,\vec{e_r} + r\,\dot{\phi}\,\vec{e_\phi}$$
- Conservation of angular momentum: $$r^2\,\dot{\phi} = h = Cte$$
$$\Rightarrow \quad r\,\dot{\phi} = \frac{h}{r}$$

Chapter III: How to travel in space?

- Conservation of the total energy: $$\frac{1}{2}\,v^2 - \frac{G\,M}{r} = E$$

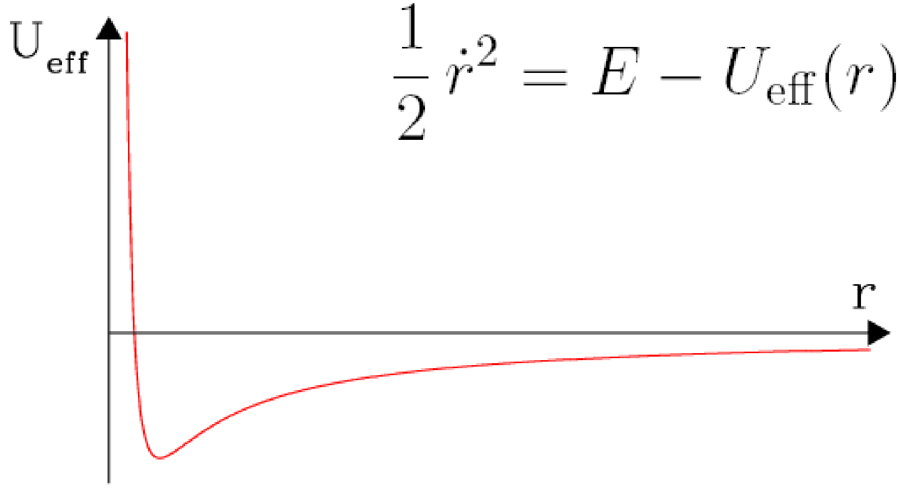
& $$\vec{v} = \dot{r}\,\vec{e_r} + r\,\dot{\phi}\,\vec{e_\phi}$$

$$\Rightarrow \quad \frac{1}{2}\,(\dot{r}^2 + r^2\,\dot{\phi}^2) - \frac{G\,M}{r} = E$$

and $$r\,\dot{\phi} = \frac{h}{r}$$

$$\Rightarrow \quad \frac{1}{2}\,\dot{r}^2 + \frac{h^2}{2\,r^2} - \frac{G\,M}{r} = E$$

$$U_{\text{eff}}(r) = \frac{h^2}{2\,r^2} - \frac{G\,M}{r}$$

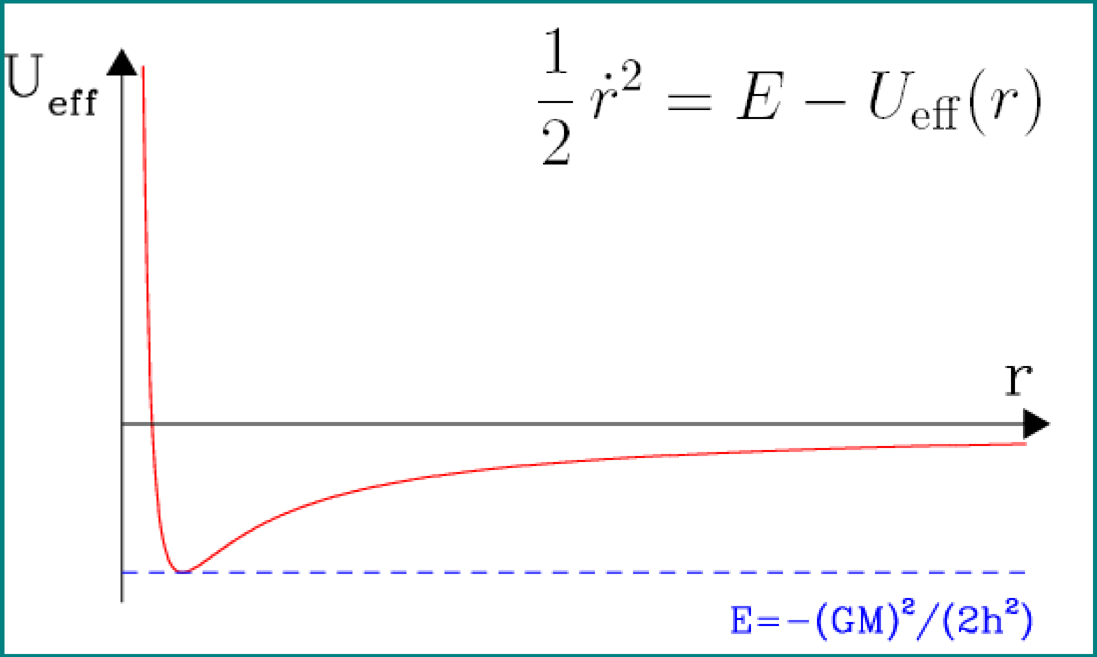


$$\frac{1}{2}\,\dot{r}^2 = E - U_{\text{eff}}(r)$$

Different types of trajectories depending on the total energy:

1. Circular orbit

If E = minimum of U_{eff}: $\dot{r} = 0$ & $\frac{dU_{\text{eff}}}{dr} = 0$



Chapter III: How to travel in space?

$$\frac{dU_{\text{eff}}}{dr} = 0 \quad \Rightarrow \quad \begin{aligned} \frac{d}{dr} U_{\text{eff}}(r) &= \frac{d}{dr}\left(\frac{h^2}{2\,r^2} - \frac{G\,M}{r}\right) \\ &= -\frac{h^2}{r^3} + \frac{G\,M}{r^2} = 0 \end{aligned} \quad \Rightarrow \quad r = \frac{h^2}{G\,M}$$

and $h = r\,v_c \quad \Rightarrow \quad v_c = \sqrt{\frac{G\,M}{r}}$

$$V_c = \sqrt{\frac{G\,M_\oplus}{R_\oplus}}$$

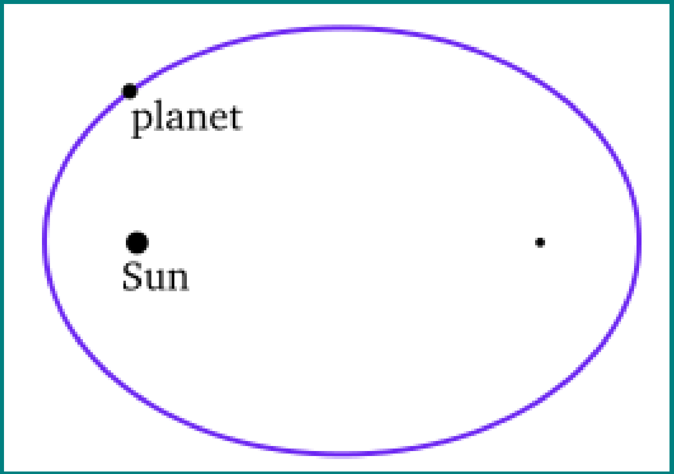
Velocity on a circular orbit of radius equal to the radius of the Earth: V_c = 7.90 km/s

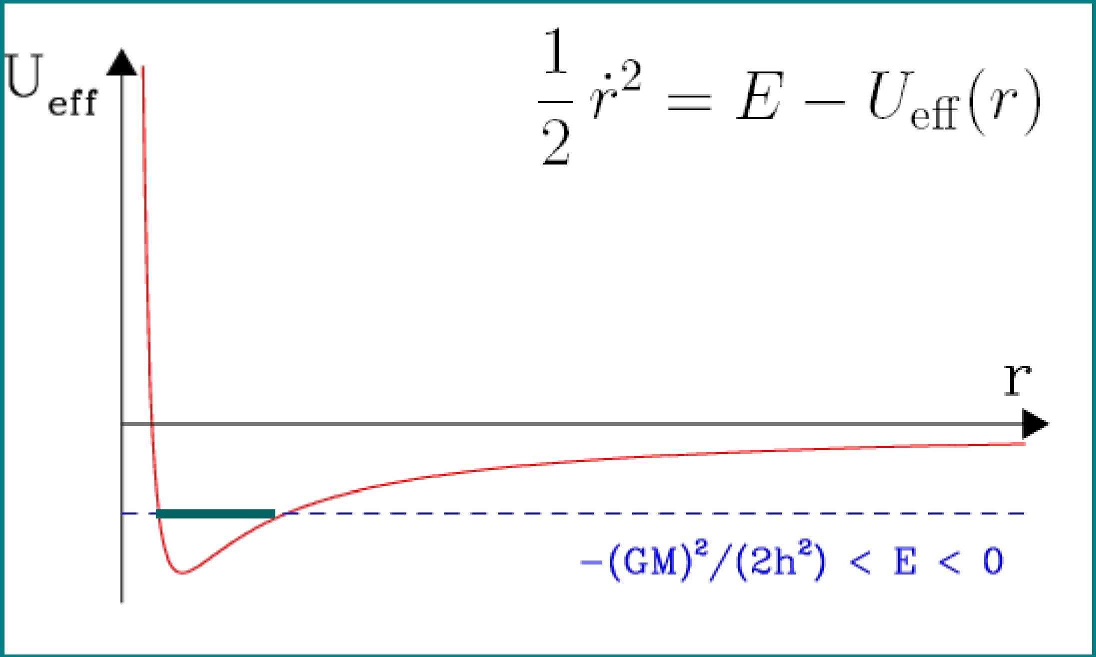
To place a satellite into orbit around the Earth, one has to provide it with a velocity of at least V_c = 7.90 km/s.

Different kinds of trajectories depending on the total energy:

2. Elliptical orbit

Example: the planets of the Solar System



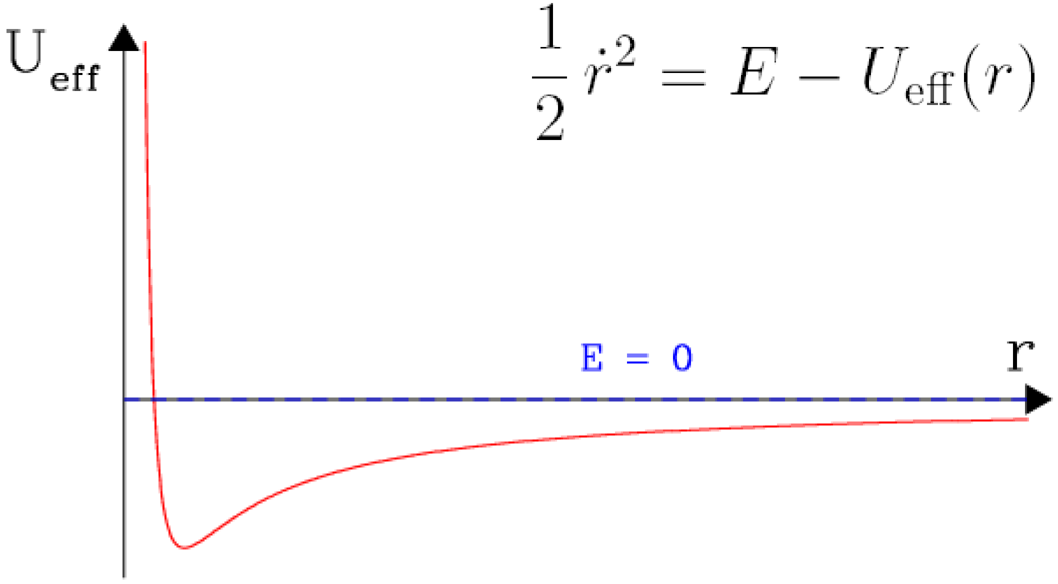


Chapter III: How to travel in space?

Different kinds of trajectories depending on the total energy:

3. First open trajectory

$$\frac{1}{2}v^2 - \frac{GM}{r} = E \quad \& \; E = 0 \Rightarrow \quad \frac{1}{2}v^2 = \frac{GM}{r}$$



$$\frac{1}{2}\dot{r}^2 = E - U_{\rm eff}(r)$$

Velocity required to overcome the Earth's attraction:

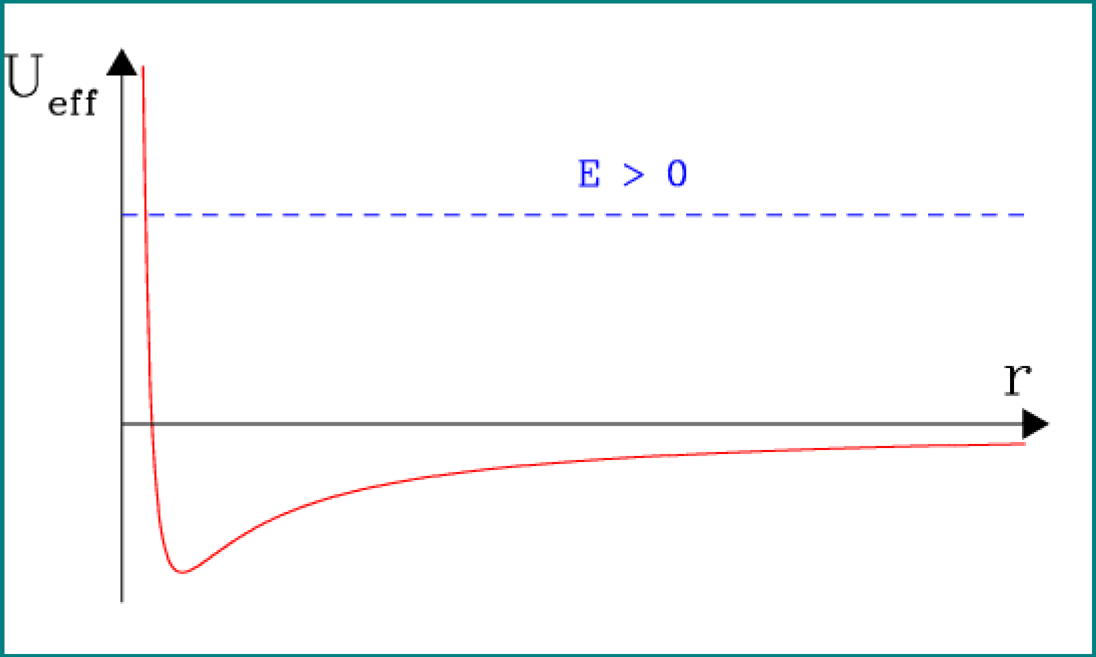
$$V_{lib} = \sqrt{\frac{2GM_\oplus}{R_\oplus}}$$

To leave the Earth's attraction, the spacecraft must reach a velocity V_{esc} = 11.18 km/s

Chapter III: How to travel in space?

Different kinds of trajectories depending on the total energy:

4. Hyperbolic trajectories



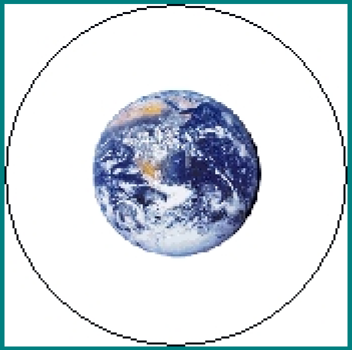
$$V_\infty^2 = V_{\text{peri}}^2 - V_{\text{lib}}^2$$

Chapter III: How to travel in space?

Different types of orbits around the Earth or another planet depending on the inclination, eccentricity, orbital period…

The choice of an orbit depends on the mission of the satellite.

« Mission analysis » = study of the trajectory to ensure that the spacecraft fulfils its mission under optimal conditions.



Chapter III: How to travel in space?

Geostationary orbit:

Satellite orbits the Earth in 24h in the equatorial plane ($i=0°$). Seen from the Earth, it remains fixed in the sky $\Rightarrow$ antennas do not have to track the satellite.

Altitude of 35 860 km.

Used for weather satellites, telecommunications.

Chapter III: How to travel in space?

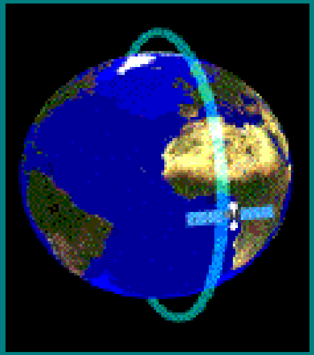
Low Earth orbits (LEOs):

Altitudes between 300 and 1000 km.

Little power required for communications with the ground, satellite below the radiation belts.

Applications:

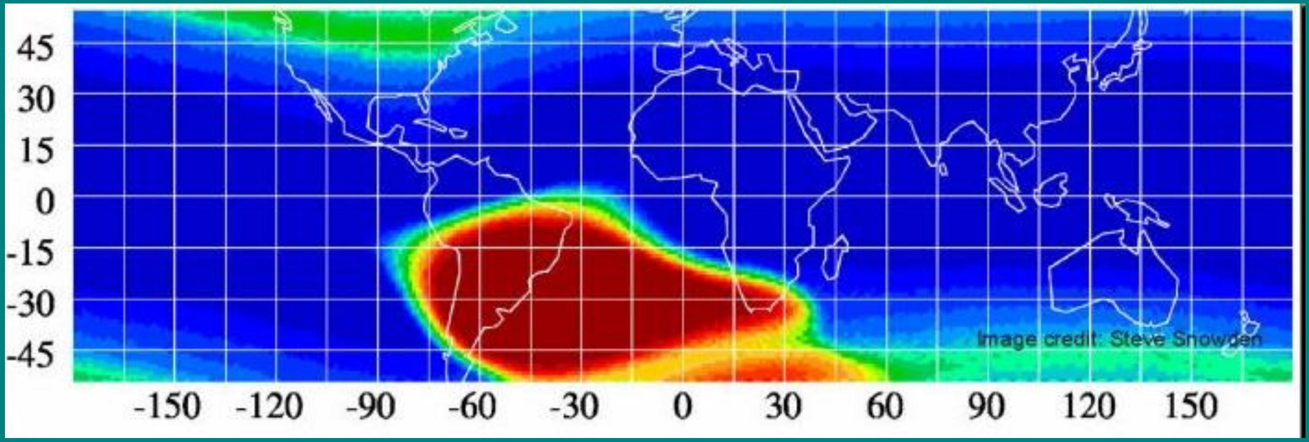
1. mapping the planet, follow changes of the climate requires access to as large a part as possible of the planet $\Rightarrow$ polar orbit provides access to the entire surface.



Chapter III: How to travel in space?

Low Earth orbits (LEOs):

2. Astronomical observations in the high-energy domain (detectors protected against charged particles). But orbital periods are short and spacecraft crosses South Atlantic Anomaly.



Chapter III: How to travel in space?

Low Earth orbits (LEOs):

Limitations of LEOs: residual atmosphere, several satellites needed for a continuous coverage, heavy batteries needed, polar orbit difficult to reach.

Special application: *heliosynchronous orbit.*

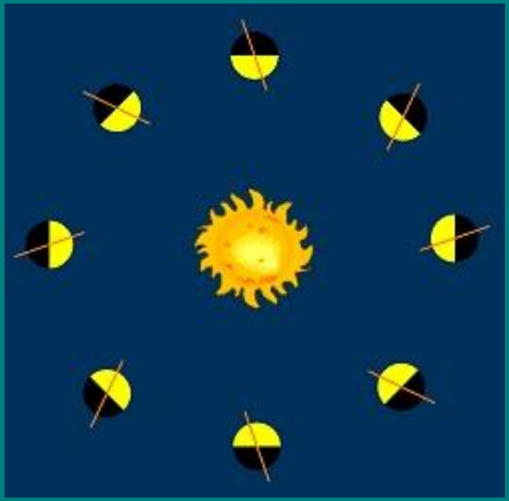
The satellite passes always at the same local time over a specific location. The plane of the orbit rotates once per year.

Precession of the orbit due to J2 term.

$$V = -\frac{G\,M}{r}\left[1 - \sum_{n=2}^{\infty} J_n \left(\frac{R}{r}\right)^n P_n(\cos\theta) + \sum_{n=2}^{\infty}\sum_{m=1}^{n} J_{nm}\left(\frac{R}{r}\right)^n P_n^m(\cos m\,(\lambda - \lambda_{nm}))\right]$$

$$J_2 = 1.082 \times 10^{-3}$$

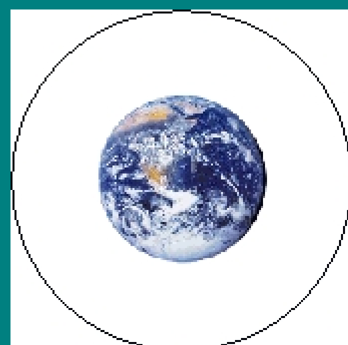
$$\frac{d\Omega}{dt} = -\frac{3\,\pi\,R_{\oplus}^2}{a^2\,P_{\rm orb}}\,J_2\,\cos i$$



Chapter III: How to travel in space?

Mean Earth orbits (MEOs):

Altitudes around 10 000 km. Often used for navigation and communication satellites.



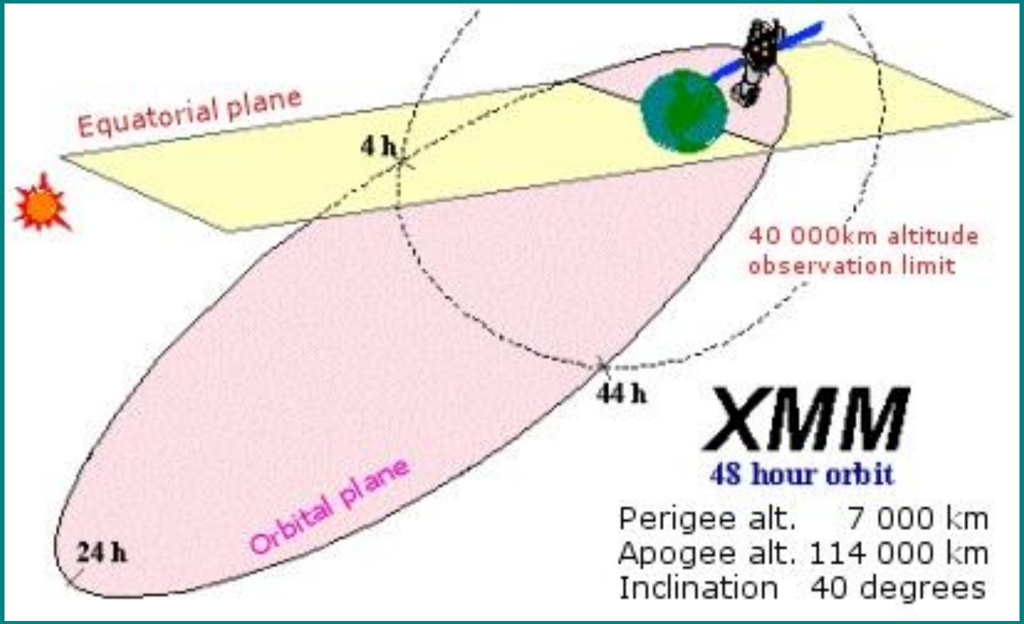
High Earth orbits (HEOs):

Scientific (astrophysical) satellites outside the radiation belt: long duration observations and formation flight (little differential acceleration).

Chapter III: How to travel in space?

High Earth orbits (HEOs):

Scientific (astrophysical) satellites outside the radiation belt: long duration observations and formation flight (little differential acceleration).

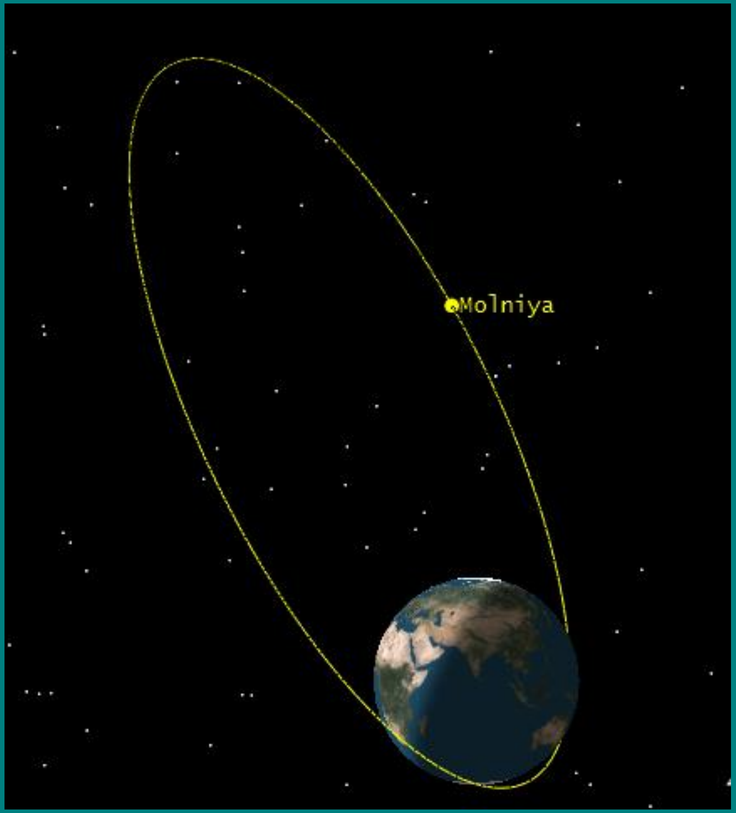


Chapter III: How to travel in space?

Molniya:

Solution for telecommunications at high geographic latitudes: highly eccentric orbits, inclined by 63.43° with an orbital period of 12h.

The satellite moves slower at apogee ⇒ it remains longer above a region of the Earth.



Chapter III: How to travel in space?

Molniya:

3 satellites are needed to ensure a 24h/24 coverage.

Problem: the satellite crosses the van Allen belts twice per orbit.

Why this inclination of 63.43°?

$$V = -\frac{G\,M}{r}\left[1 - \sum_{n=2}^{\infty} J_n \left(\frac{R}{r}\right)^n P_n(\cos\theta) + \sum_{n=2}^{\infty}\sum_{m=1}^{n} J_{nm}\left(\frac{R}{r}\right)^n P_n^m(\cos m\,(\lambda - \lambda_{nm}))\right]$$

$$J_2 = 1.082 \times 10^{-3}$$

$$\frac{d\omega}{dt} = -\frac{3\,\pi\,R_\oplus^2}{2\,a^2\,P_{\rm orb}}\,J_2\,\frac{5\,\cos^2 i - 1}{\sqrt{1 - e^2}}$$

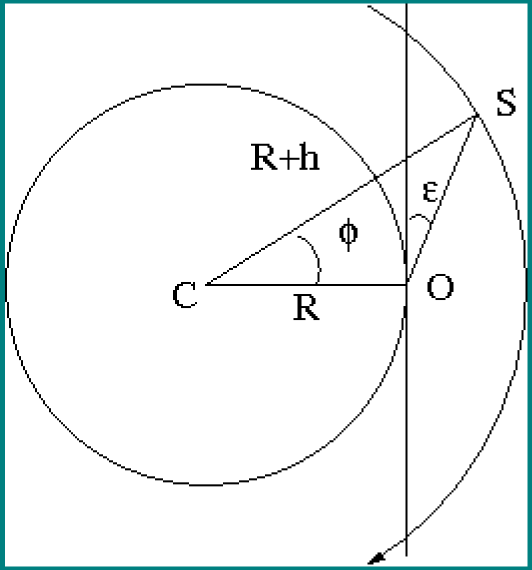
The longitude of apogee remains constant!

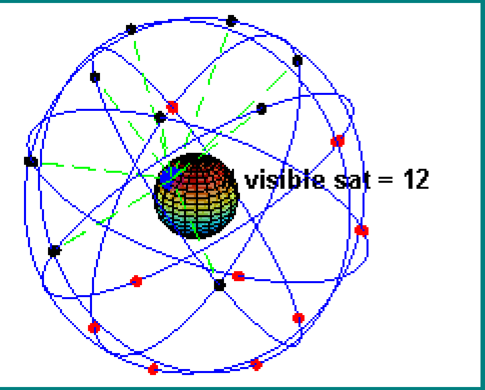
Chapter III: How to travel in space?

Constellations of satellites (LEOs and MEOs):

The visibility of a ground station is limited to an elevation ε above the horizon.

Continuous visibility of one or several satellites requires a constellation of satellites (e.g. GPS).

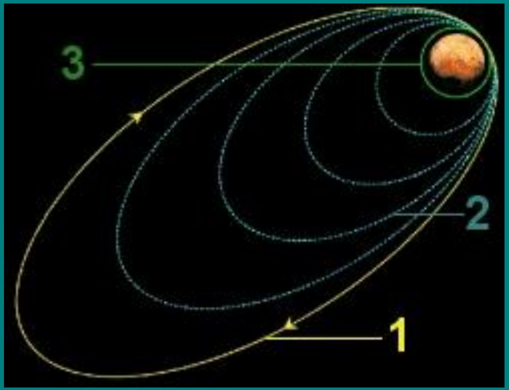


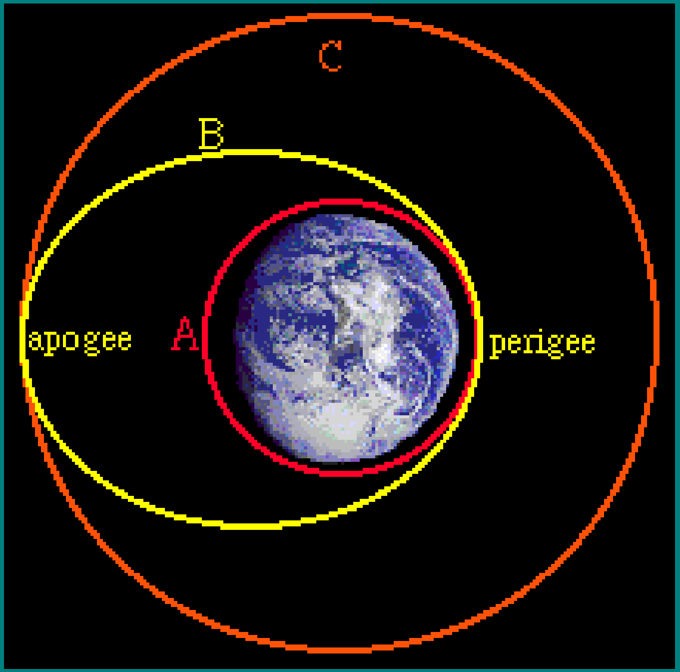


GPS: 24 satellites in 6 orbital planes, 4 satellites per plane, altitude 20 200 km, i = 55°

Chapter III: How to travel in space?

Orbital transfer: accelerate or brake at perigee. Aerobraking to circularise orbits or Hohmann transfer orbit to go from LEO to MEO or geostationary orbit.



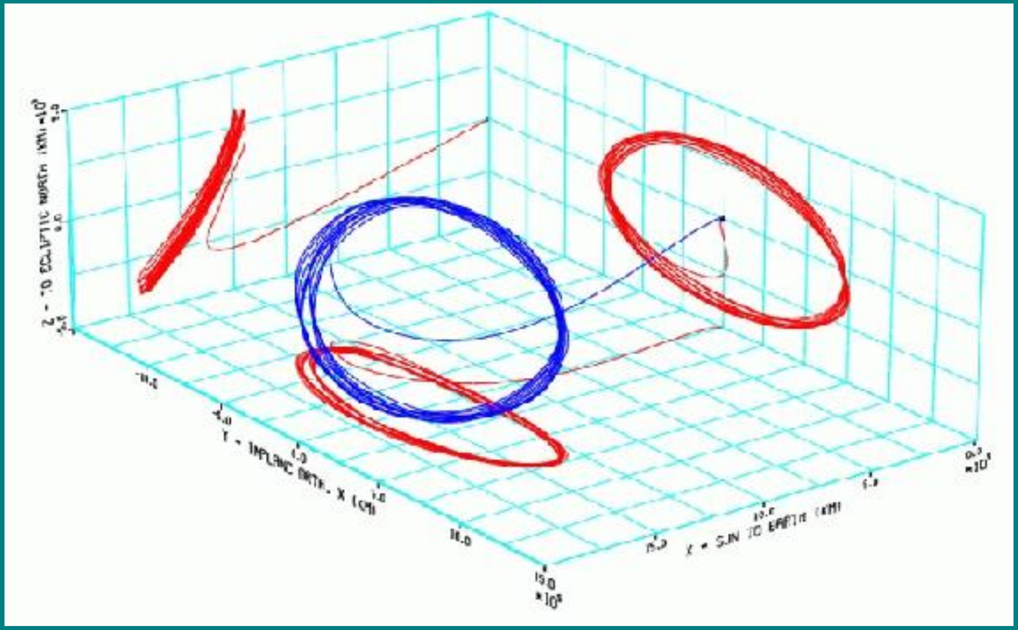


Chapter III: How to travel in space?

Orbits about the Lagrangian points

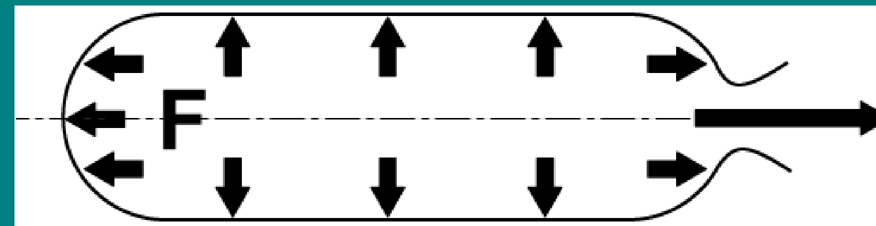
L1 and L2 are unstable equilibrium points, but there exist halo or Lissajous orbits (typical amplitude 100 000 km) about these points that are semi-stable.

Objectives: observe the Sun continuously from L1, observe outer space from L2 with a stable thermal and gravitational environment.

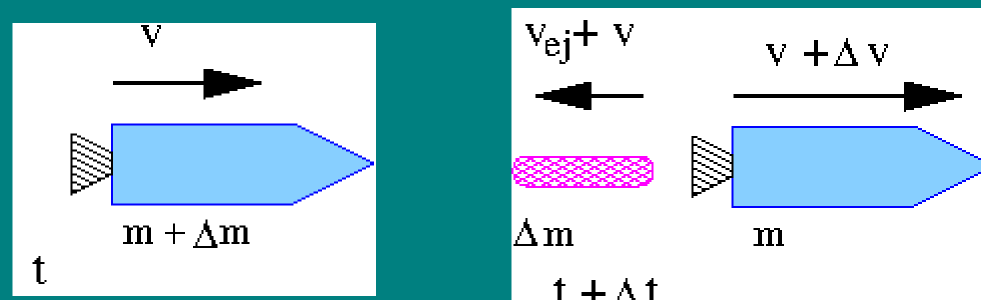


Chapter III: How to travel in space?

- Rocket in empty space.



- Rocket equation :



$$\Delta(m\,\vec{v}) = \vec{0} \quad \Rightarrow \quad (\cancel{m} + \cancel{\Delta} m)\,\vec{v} = m\,(\cancel{\vec{v}} + \Delta\vec{v}) + \Delta m\,(\cancel{\vec{v}} + \vec{v}_{\rm ej})$$

$$\Rightarrow \quad m\,\Delta\vec{v} + \Delta m\,\vec{v}_{\rm ej} = \vec{0} \quad \Rightarrow \quad \Delta\vec{v} = -\frac{\Delta m\,\vec{v}_{\rm ej}}{m}$$

$$\Rightarrow \quad \int_{t_1}^{t_2} \frac{dv}{dt}\,dt = -\int_{t_1}^{t_2} \frac{1}{m}\,\frac{dm}{dt}\cdot v_{\rm ej}\,dt \qquad \Delta v_{\rm total} = -\ln\left(\frac{m_{final}}{m_{init}}\right) v_{\rm ej}$$

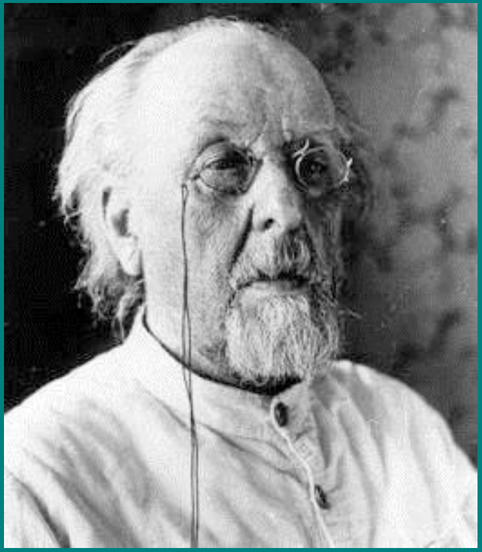
Tsiolkovski's equation : $$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\rm total}}{v_{\rm ej}}\right)$$

Chapter III: How to travel in space?

For a given rocket, the mass of the payload decreases exponentially with the velocity to be reached:

This fundamental relation, called Tsiolkovski's (1857 – 1935) equation was already established in 1873 by the Belgian officer Casimir Erasme Coquilhat (1811 – 1890) in his article «*Trajectoires des fusées volantes dans le vide*» published in the *Mémoires de la Société Royale des Sciences de Liège*.

$$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\mathrm{total}}}{v_{\mathrm{ej}}}\right)$$



Chapter III: How to travel in space?

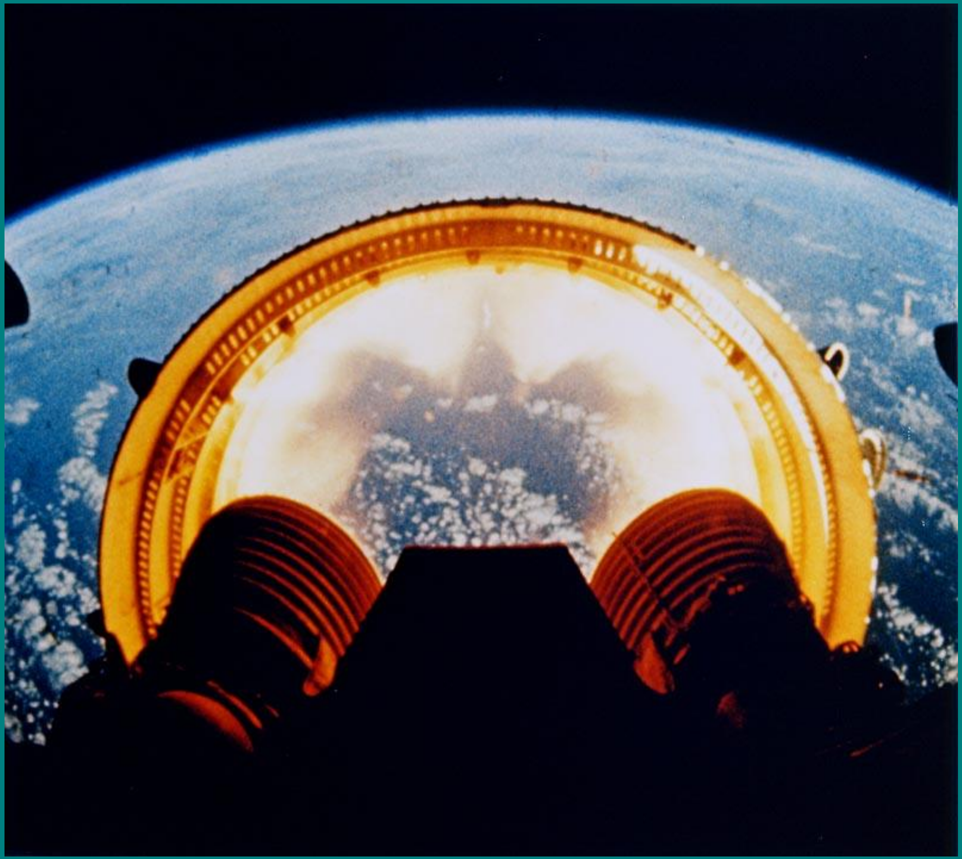
$$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\mathrm{total}}}{v_{\mathrm{ej}}}\right)$$

- Single-stage rocket.
- For chemical propulsion engines the ejection velocities of the exhaust gases are typically of order 3 to 4 km/s
- Upper limit on ΔV of about 6 – 8 km/s due to the mass of the structure of the stage, the engine and the tanks.

Chapter III: How to travel in space?

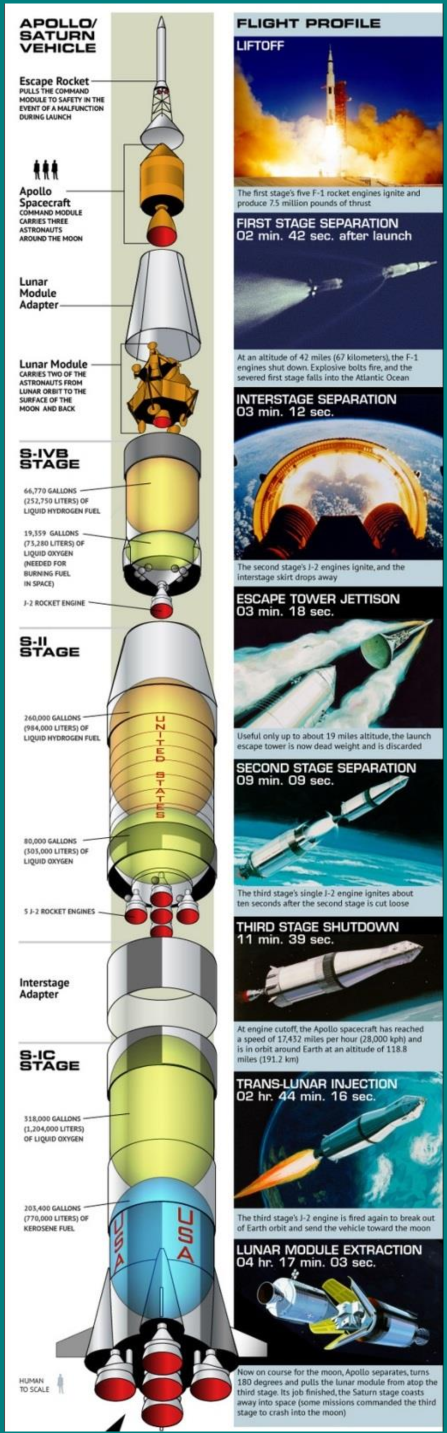
- For a multi-stage rocket, each stage follows the rocket equation.
- The ΔV produced by an individual stage depends on the payload and the mass of the upper stages.
- The total ΔV is the sum of the ΔV of the individual stages.

$$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\text{total}}}{v_{\text{ej}}}\right)$$



Chapter III: How to travel in space?

- Example: Saturn V launcher with 3 stages
- 1st stage: liquid oxygen + kerosene
- 2nd and 3rd stage: liquid oxygen and hydrogen

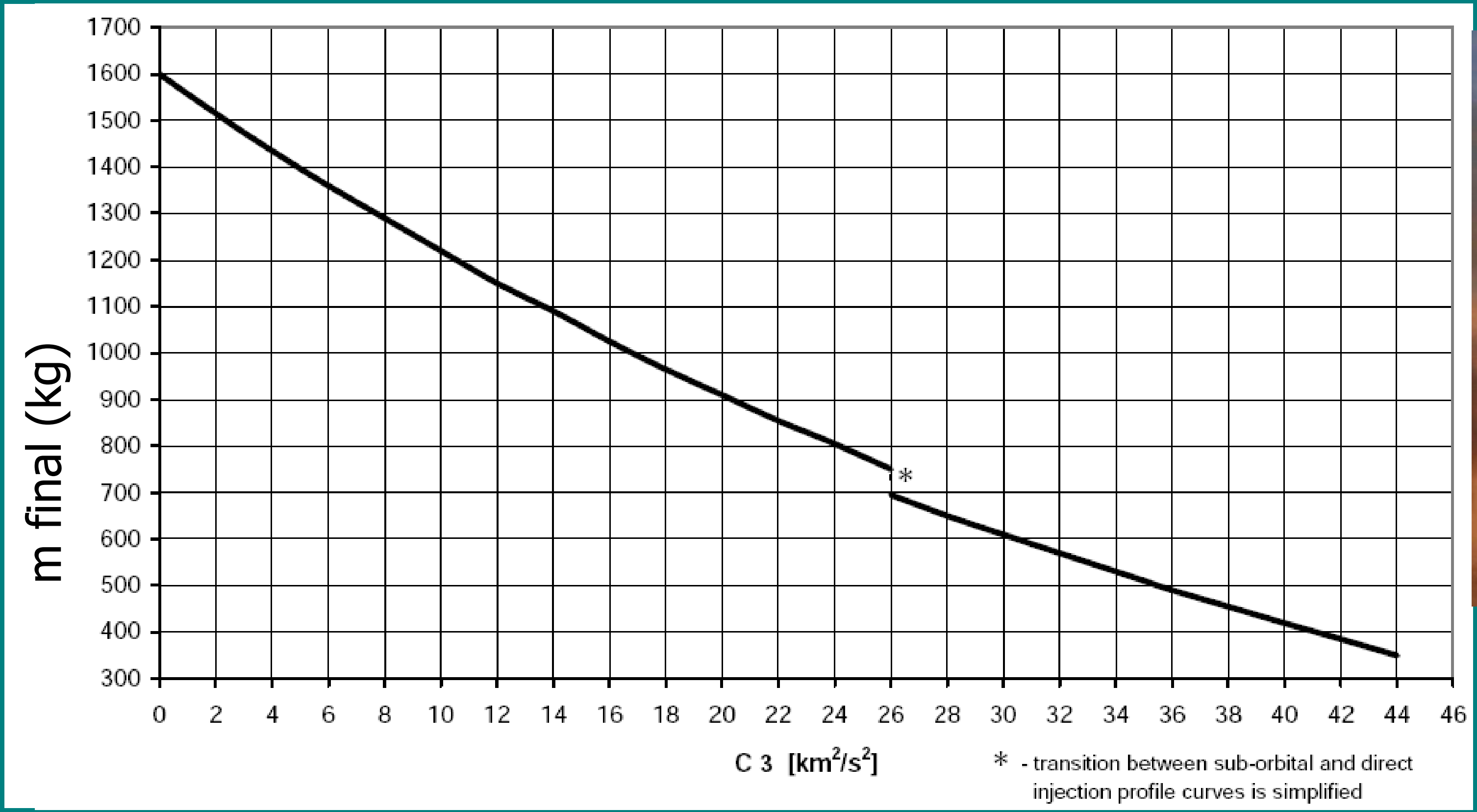


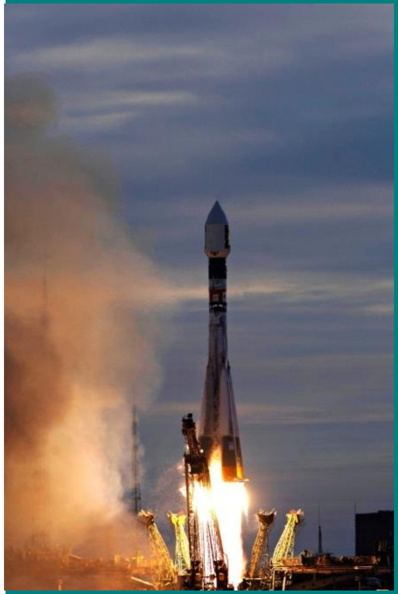
Chapter III: How to travel in space?

- The ΔV to be reached limits the mass that can be launched with a given launcher.

$$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\text{total}}}{v_{\text{ej}}}\right)$$

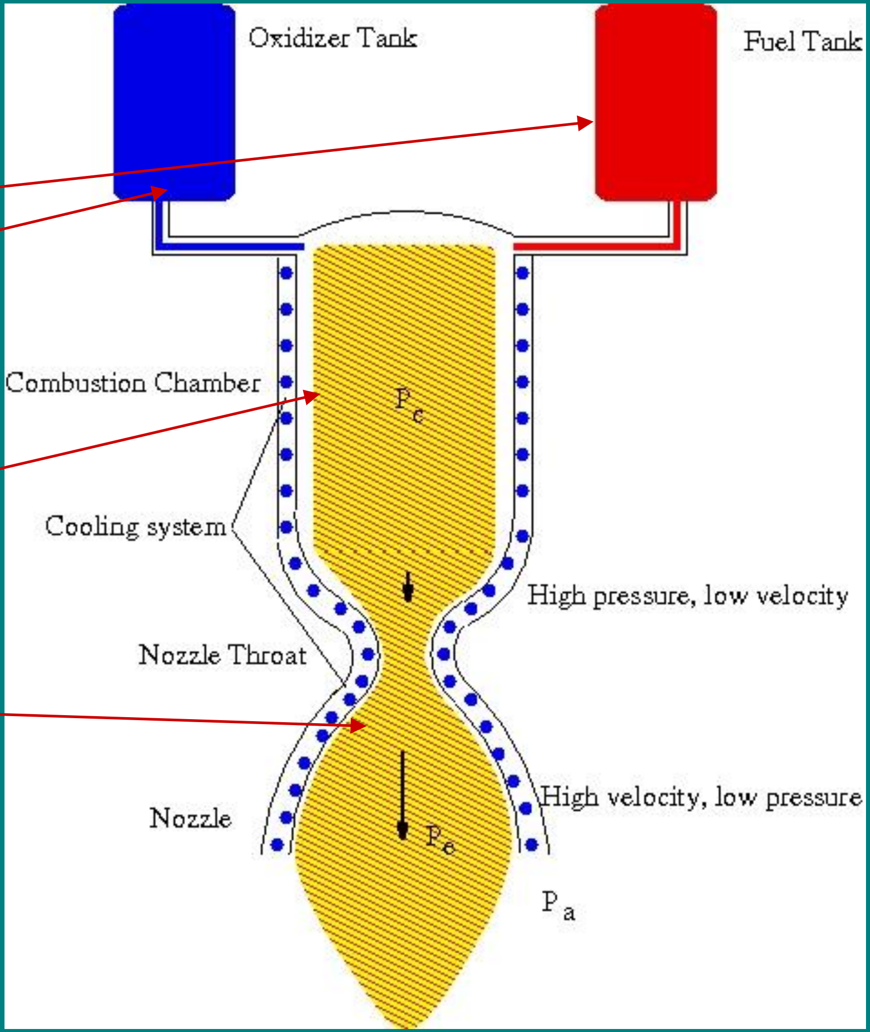
$$C3 = V_{\infty}^2 = V_{\text{per}}^2 - V_{\text{esc}}^2$$





Chapter III: How to travel in space?

- Liquid fuel rockets produce very hot exhaust gases via reactions between a liquid fuel (H_2, CH_4, $C_{12}H_{26}$) and a liquid oxidizer (O_2).
- The combustion occurs in a chamber at temperatures of order 3000 K (cooling).
- Nozzle with a large ratio between the exit and throat areas. This converts the heat into kinetic energy.



Chapter III: How to travel in space?

- The nozzle reduces the gas pressure and thrust becomes:

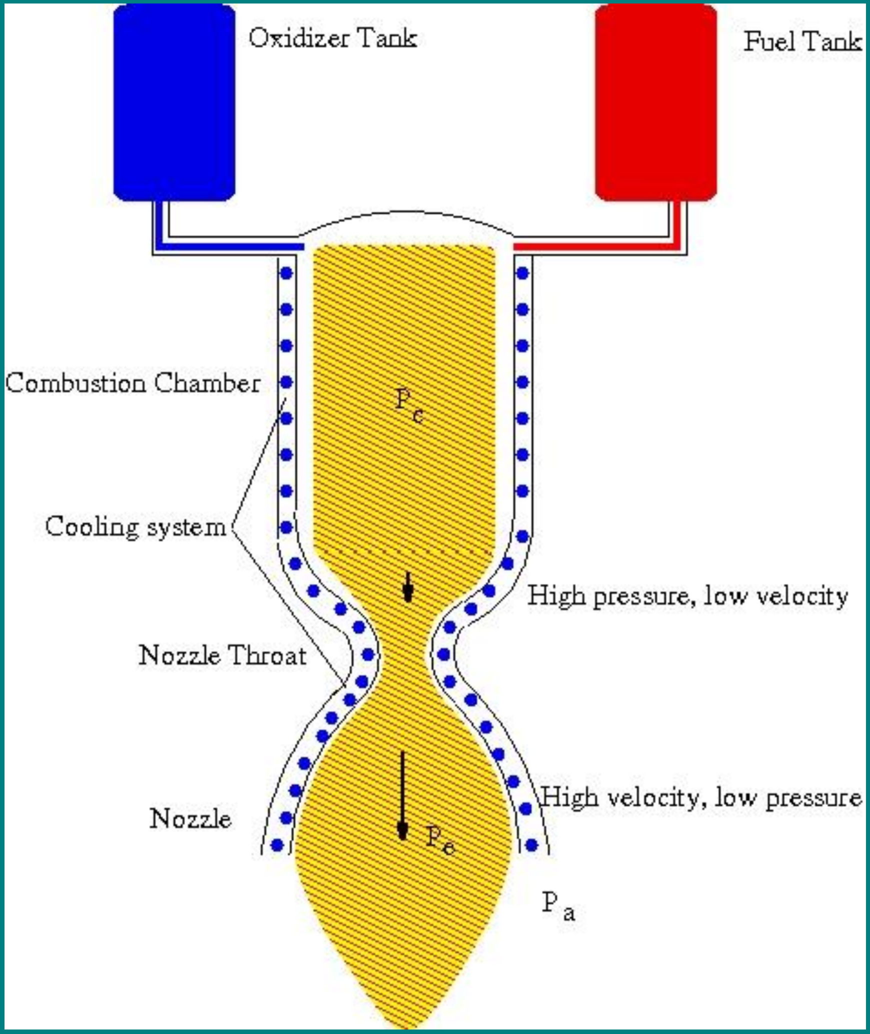
$$F = -\frac{dm}{dt} v_{\rm ej} + (P_e - P_a)\, A_e$$

- Thrust is maximum when $P_e = P_a$ and a nozzle has thus its maximum efficiency at a given altitude.

$$v_{\rm ej} = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right)\left(\frac{\mathcal{R}\, T_c}{\mathcal{M}}\right)\left(1 - \left(\frac{P_e}{P_c}\right)^{(\gamma-1)/\gamma}\right)}$$

- Specific impulsion:

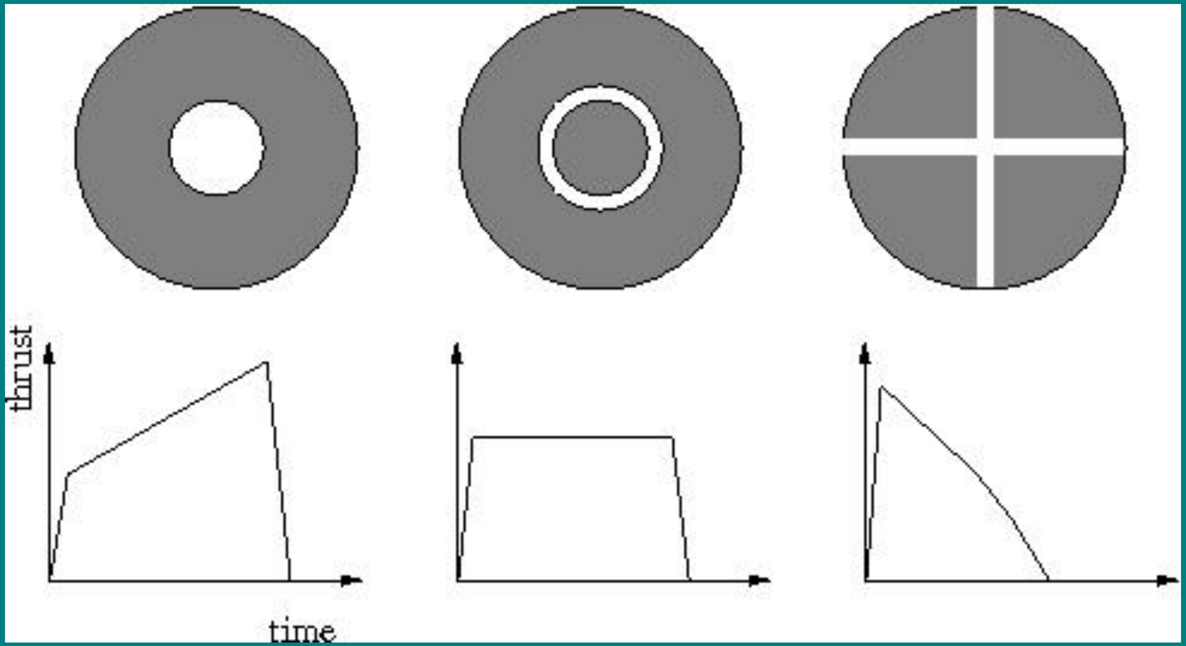
$$I_{\rm sp} = \frac{F}{-\frac{dm}{dt}\, g}$$



Chapter III: How to travel in space?

- Solid fuel rockets use a mix (powder) of solid fuel and oxidizer. Once ignited, the combustion cannot be stopped. Different geometries are used for the cross-sections:

1. Cylindrical bloc, full cross-section: constant thrust.
2. Cylindrical channel: variable thrust regimes.



Chapter III: How to travel in space?

- ESA and Arianespace have increased the capabilities of the Ariane launchers, up to Ariane V:

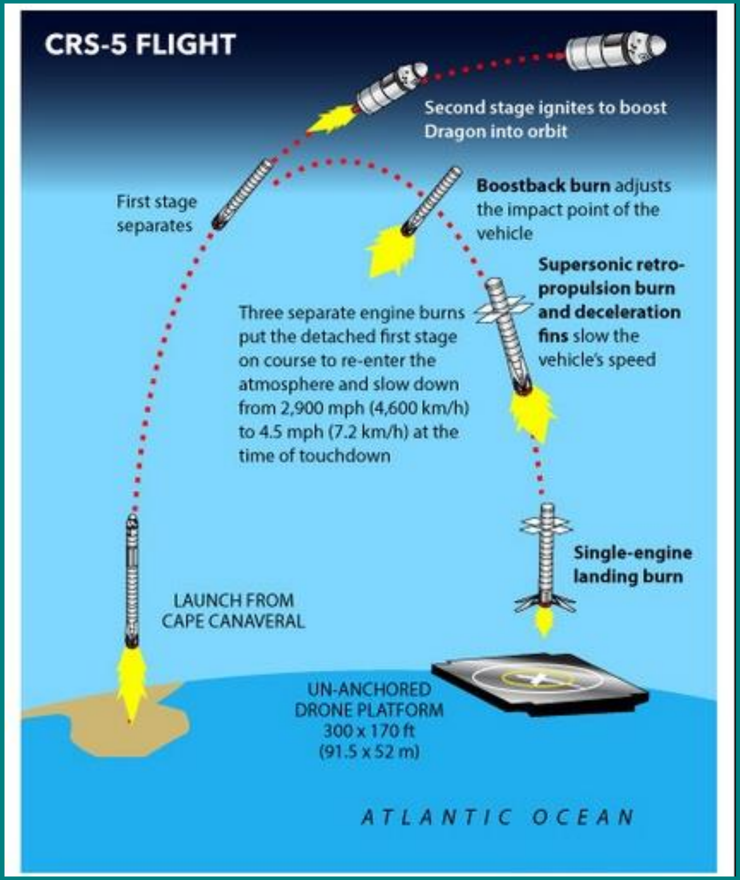
1. Ariane V ECA can launch 10 tons into GTO.
2. Ariane V ES can send more than 20 tons to the ISS.

Chapter III: How to travel in space?

- By August 2020, Ariane V had been launched 108 times.
- First launch of Soyuz-ST from Kourou in October 2011 (23 launches in total). Soyuz is an intermediate launcher.
- The first launch of the Vega launcher took place in February 2012 (15 launches so far). Small launcher able to put 1.5 tons into a polar circular orbit at an altitude of 700 km.

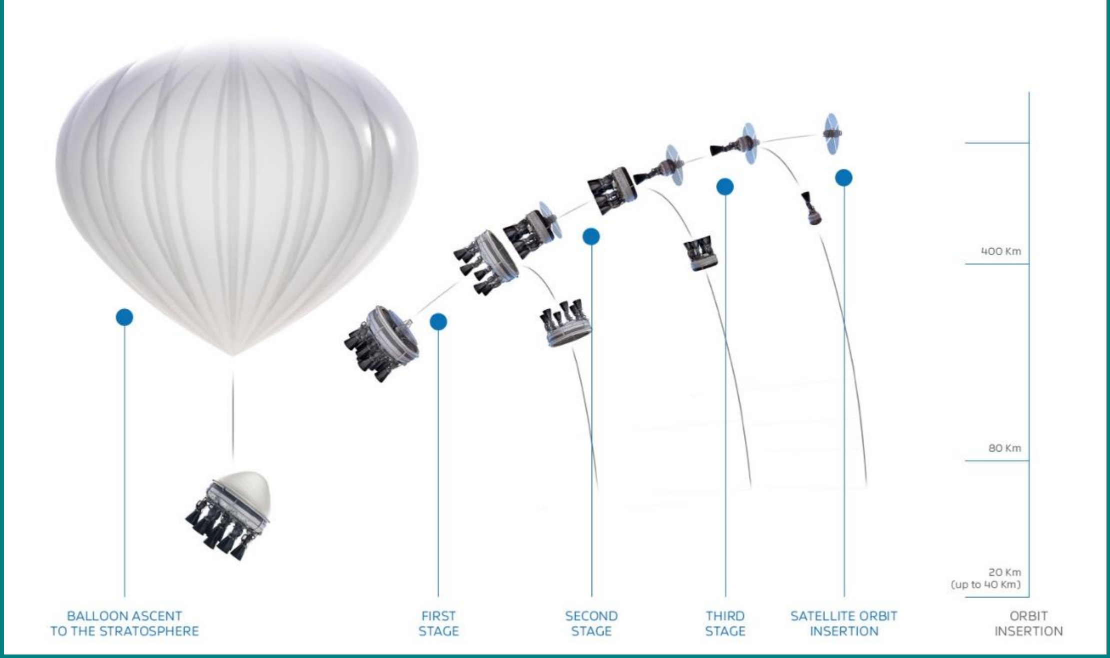
Chapter III: How to travel in space?

- The future? Re-usability by recovering the first stages (Falcon 9, Falcon Heavy, etc.)?
- Requires about 1/3 of the propellant → impact on launch capability!



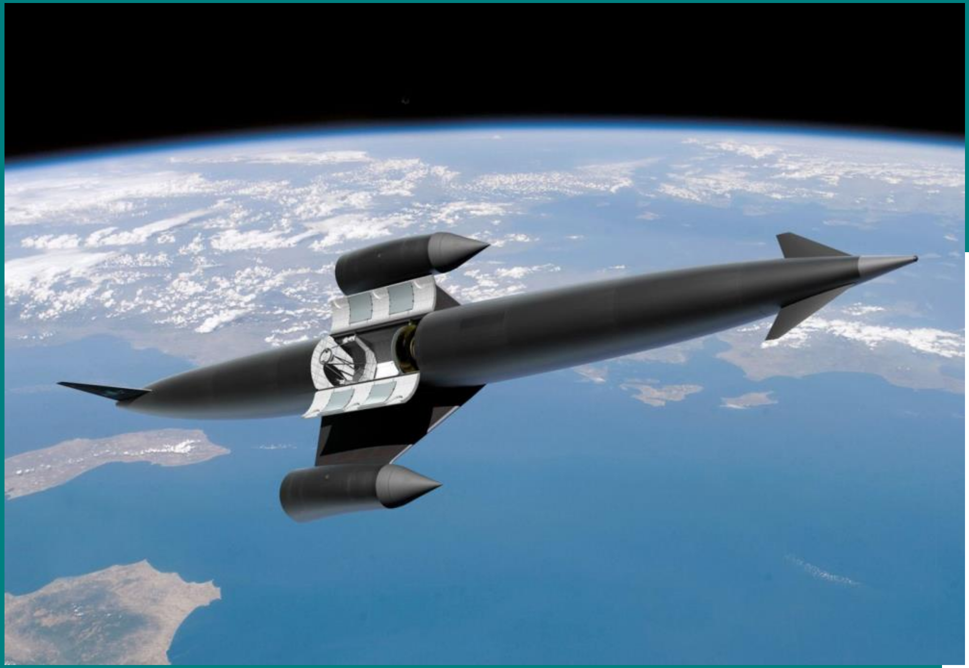
Chapter III: How to travel in space?

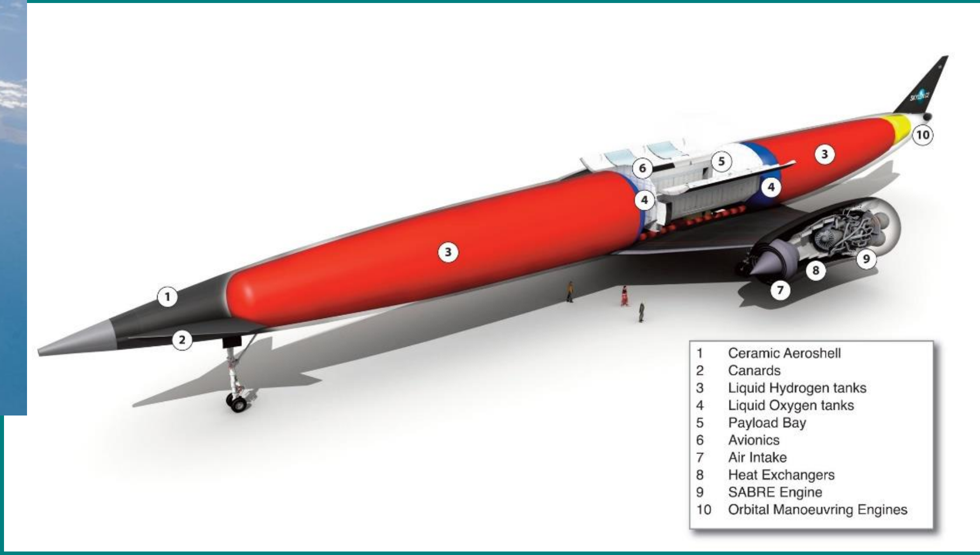
- Alternative launch techniques?
- Launch from the stratosphere via a plane or a balloon (Stratolaunch and Zero2Infinity)



Chapter III: How to travel in space?

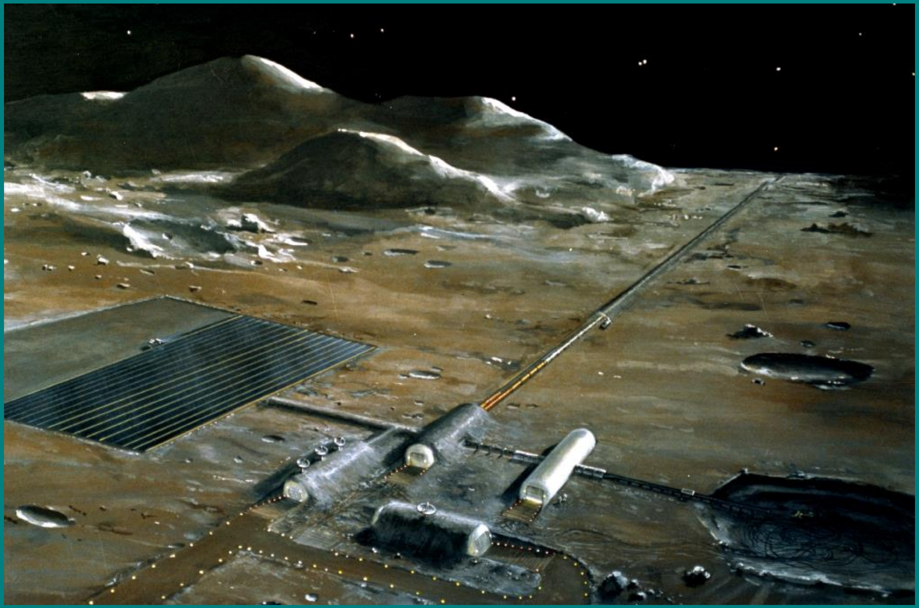
- Alternative launch techniques?
- Hybrid hydrogen-fuelled engines: breathing the air up to 28 km altitude, conventional rocket engine beyond (SABRE on Skylon)





Chapter III: How to travel in space?

- Alternative launch techniques?
- Mass drivers = electromagnetic catapults.
- Long rails in vacuum needed.
- Best done from the surface of an airless body (Moon)?



Chapter III: How to travel in space?

- Alternative launch techniques?
- Nuclear propulsion? Either pulsed plasma propulsion or nuclear thermal propulsion (NERVA like).
- Not suited for take-off from Earth.

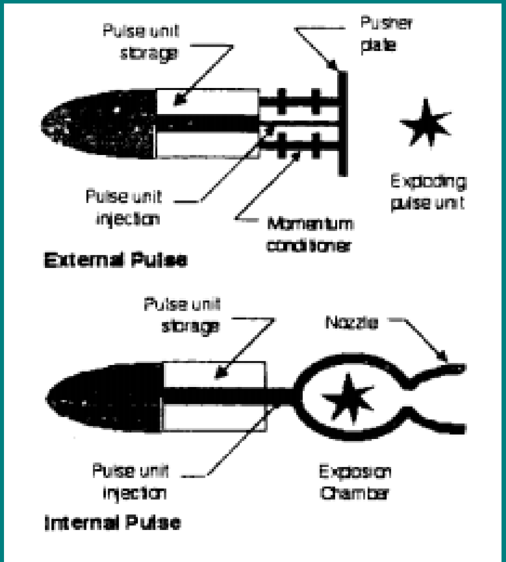
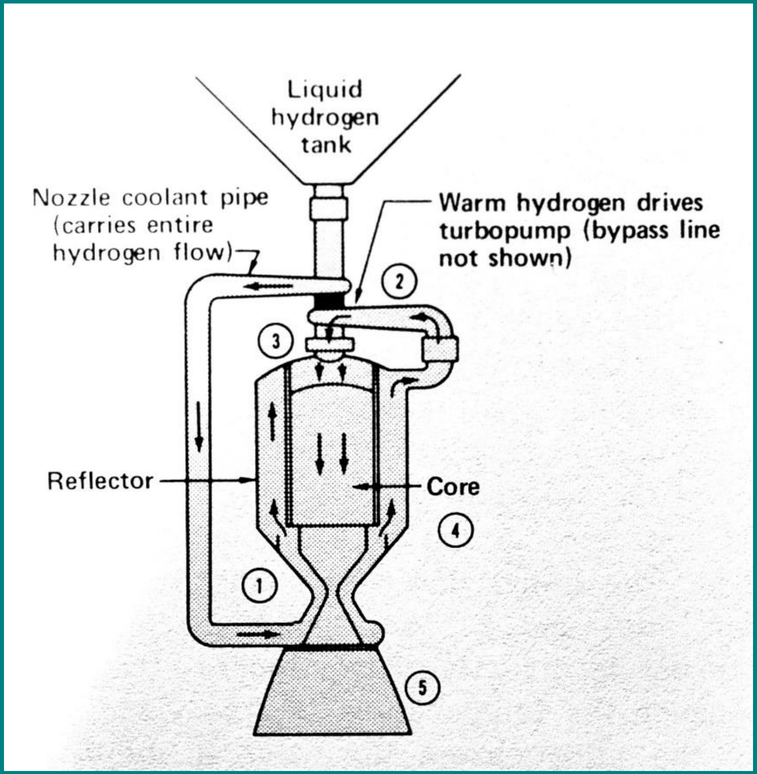
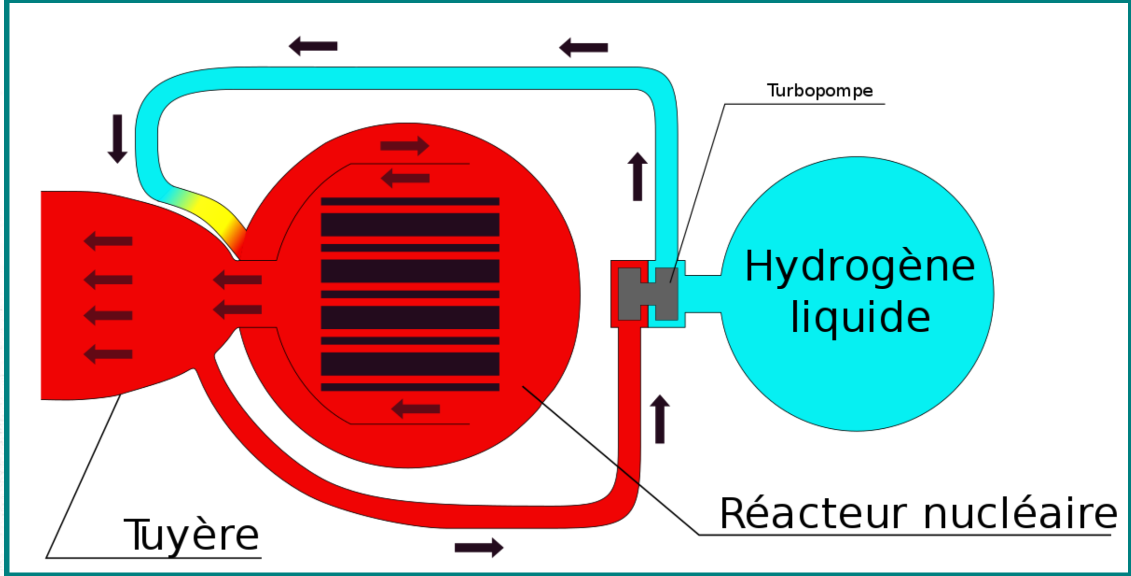


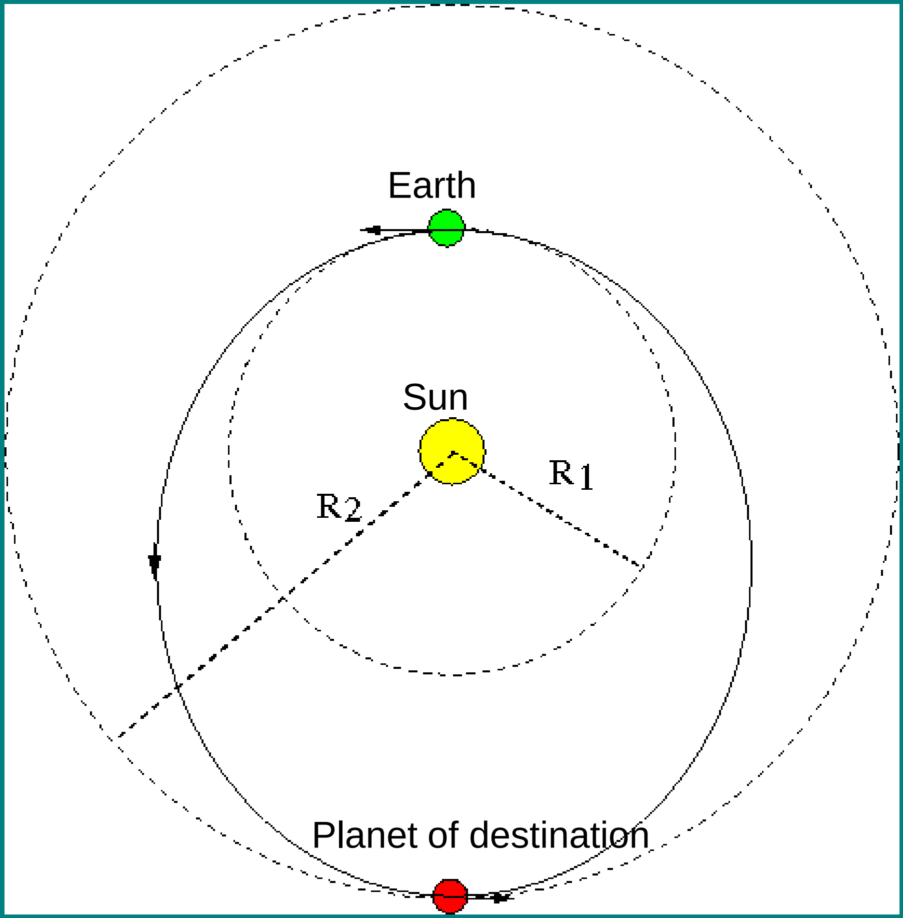
Figure 1: NPP Concepts





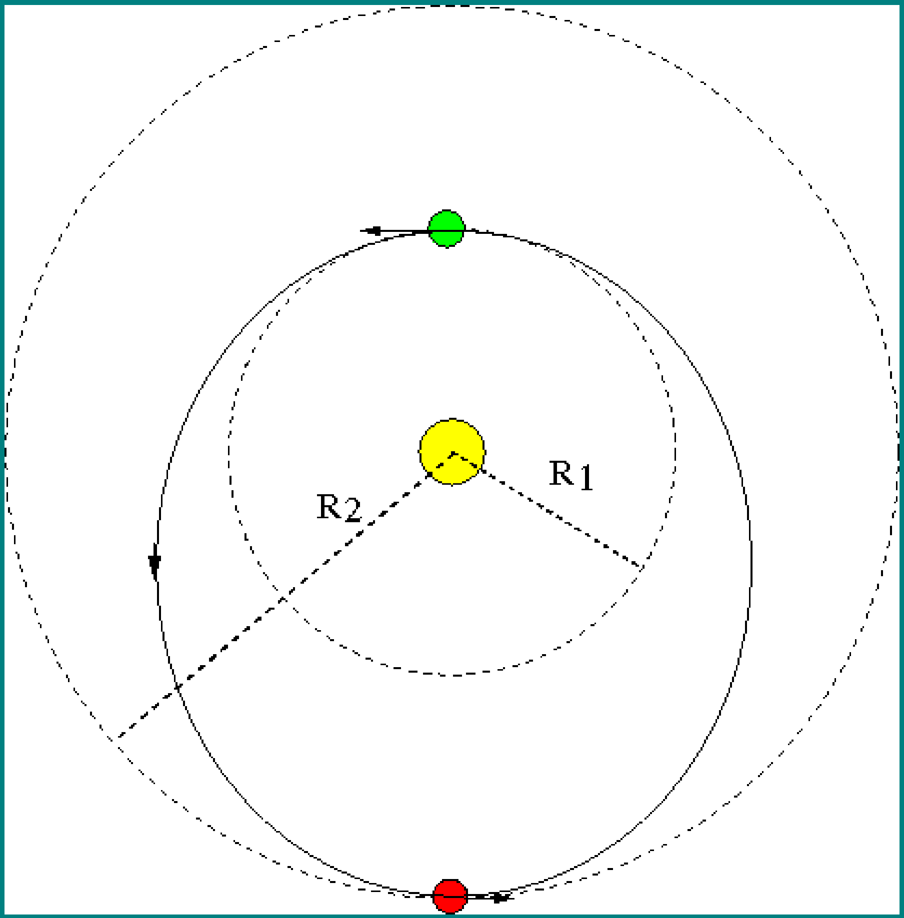
Chapter III: How to travel in space?

- Hohmann transfer orbit for interplanetary journeys
- Coplanar approximation: the orbits of the planet of destination and of the Earth are assumed to be in the same plane.
- Let us assume that the spacecraft has reached the 2nd cosmic velocity of the Earth.
- One has to provide an acceleration to put the probe on an elliptical orbit around the Sun with $a = (R_1+R_2)/2$.



Chapter III: How to travel in space?

- The spacecraft is launched in the direction of the Earth's motion around the Sun to take advantage of the Earth's orbital velocity (29.8 km/s).
- Velocity increment at departure.
- Velocity increment upon arrival + capture by the planet of destination.
- $\Delta V_{total} = \Delta V_{dep} + \Delta V_{arr}$

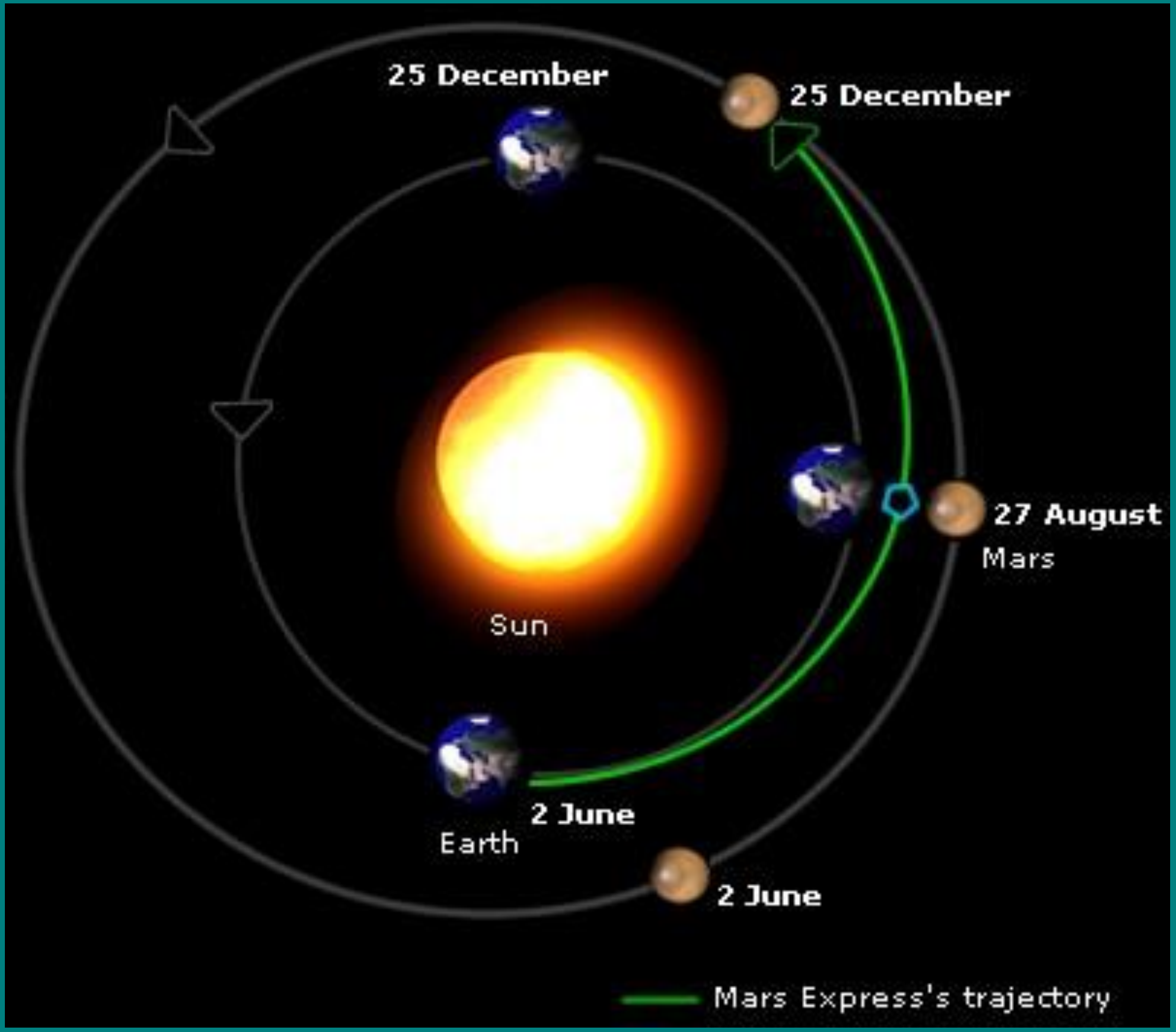


$$V_{rel}^{dep} = \sqrt{\frac{G\,M_\odot}{R_1}}\left(\sqrt{\frac{2\,R_2}{R_1+R_2}}-1\right)$$

$$V_{rel}^{arr} = \sqrt{\frac{G\,M_\odot}{R_2}}\left(1-\sqrt{\frac{2\,R_1}{R_1+R_2}}\right)$$

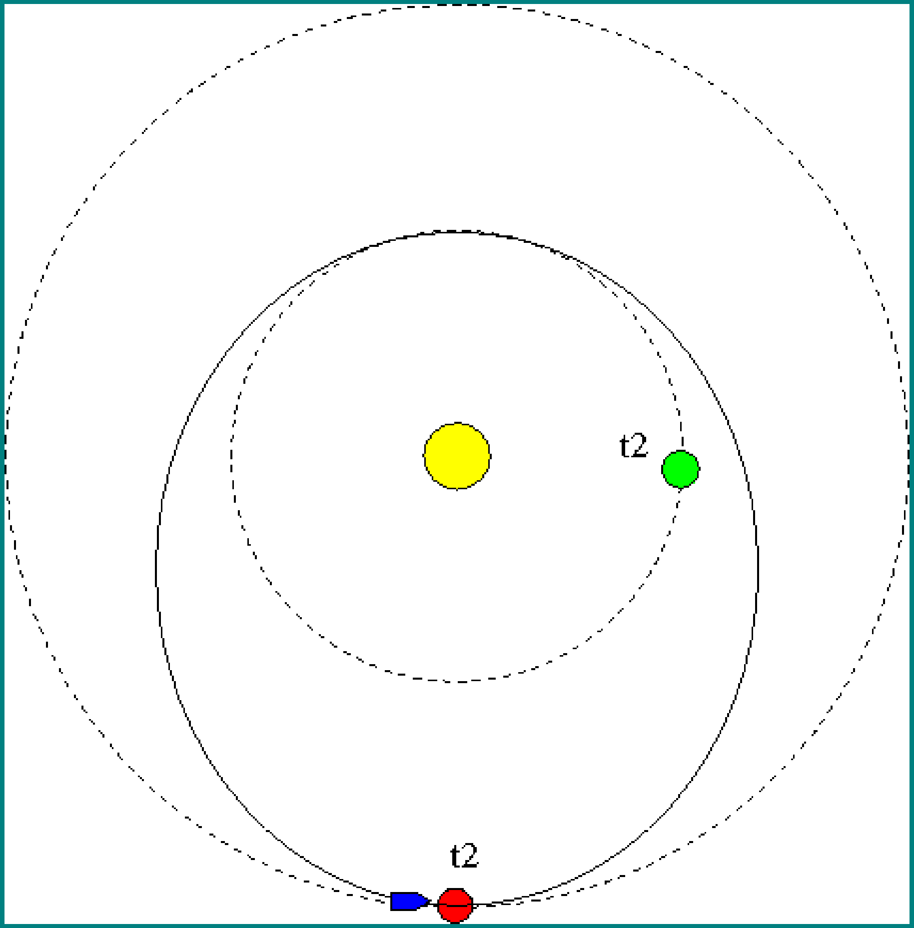
Chapter III: How to travel in space?

- Example: ESA's Mars Express probe



Chapter III: How to travel in space?

- The Earth, the Sun and the planet of destination need to be in a specific configuration at launch.
  $\Rightarrow$ concept of *launch windows*.



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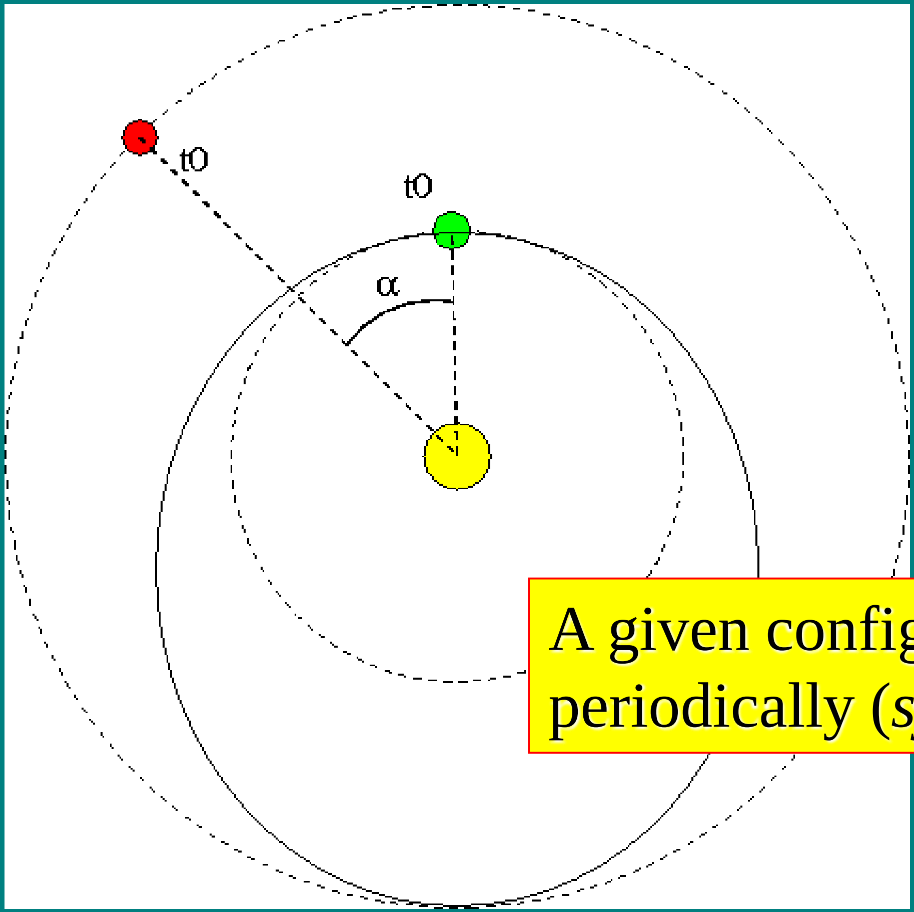


A given configuration repeats periodically (*synodic period*).

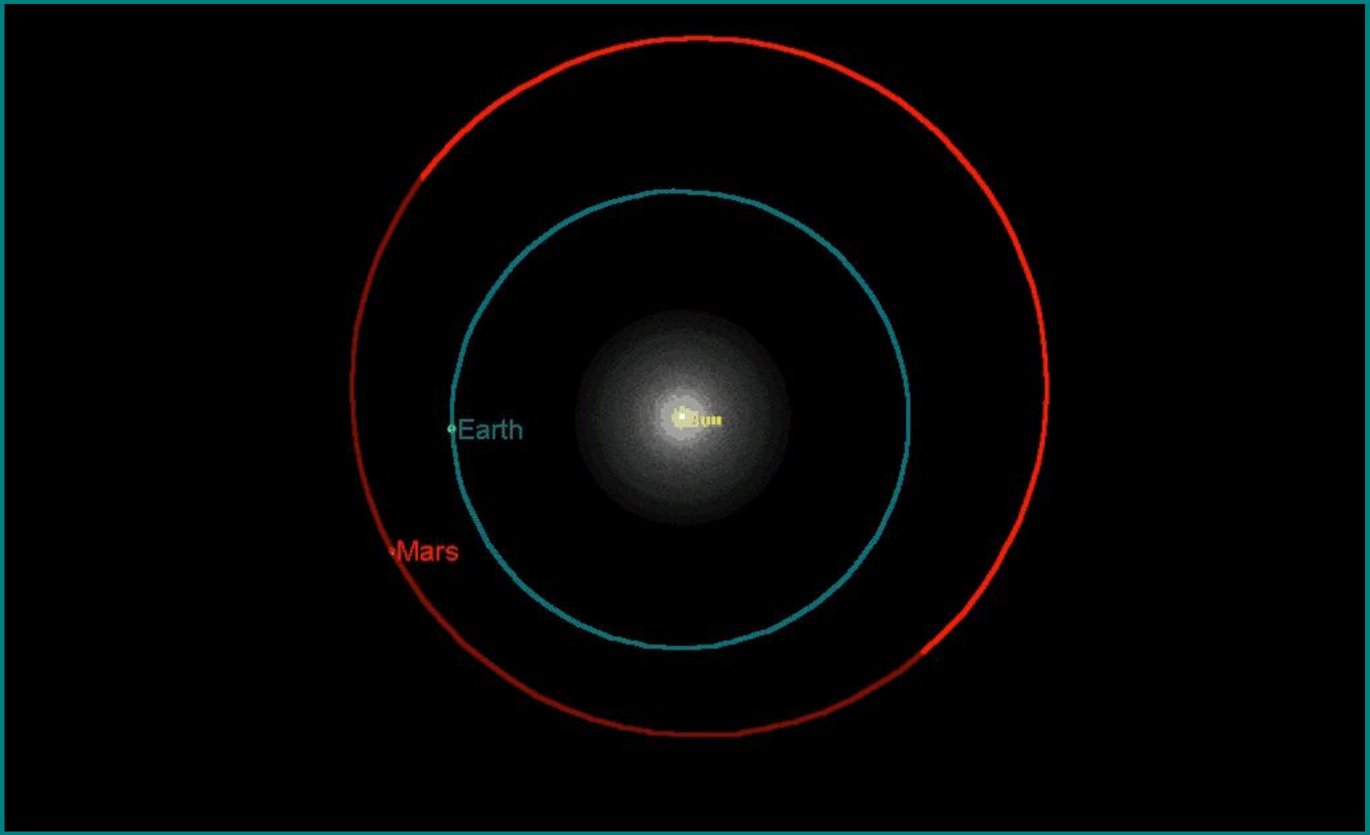
Chapter III: How to travel in space?

Synodic period (in years):

Inner planet: $P_{syn} = P_{planet}/(1 - P_{planet})$

Outer planet: $P_{syn} = P_{planet}/(P_{planet}-1)$

E.g. Mars: $P_{planet} = 1.88$ years, $P_{syn} = 2.14$ years



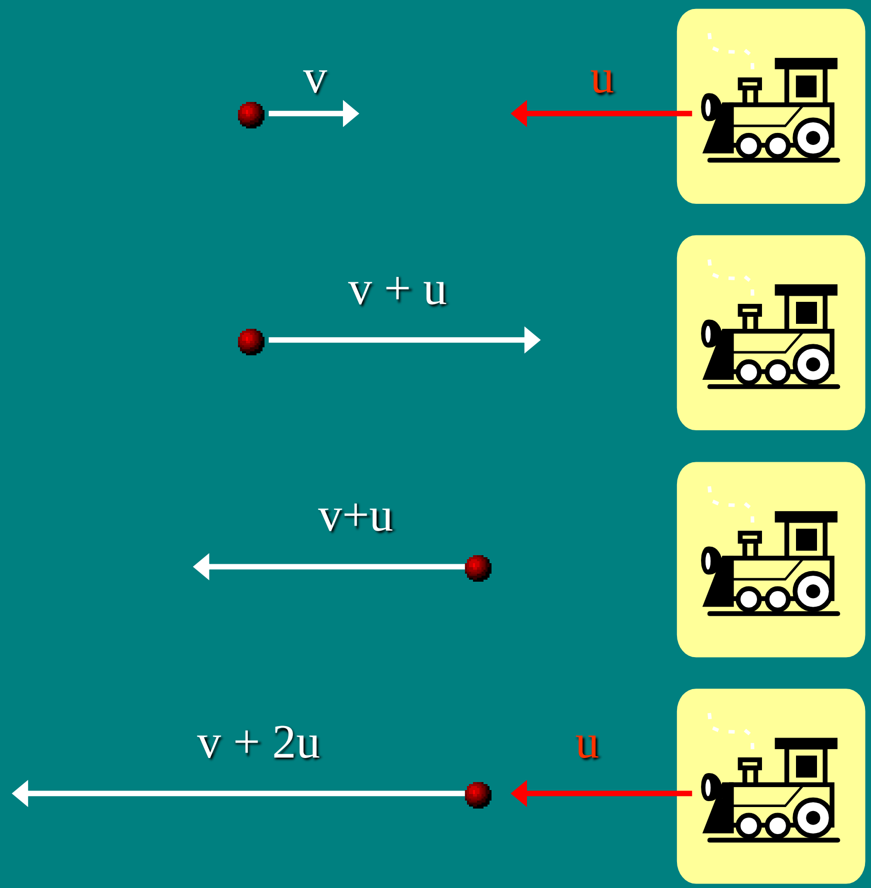
Chapter III: How to travel in space?

Planet	a(AU)	Orbital period (years)	Synodic period (years)	i(°)	e	ΔV total (km/s)
Mercury	0.387	0.241	0.32	7.0	0.205	8.70
Venus	0.723	0.615	1.60	3.4	0.007	0.62
Earth	1.000	1.000	–	0.0	0.017	–
Mars	1.52	1.88	2.14	1.9	0.094	1.07
Jupiter	5.20	11.9	1.09	1.3	0.049	3.55
Saturn	9.58	29.4	1.04	2.5	0.057	4.24

- The ΔVs (over escape) are given in the coplanar approximation.
- They increase tremendously if there is a large change in inclination.
- Chemical propulsion is not sufficient to reach certain destinations.

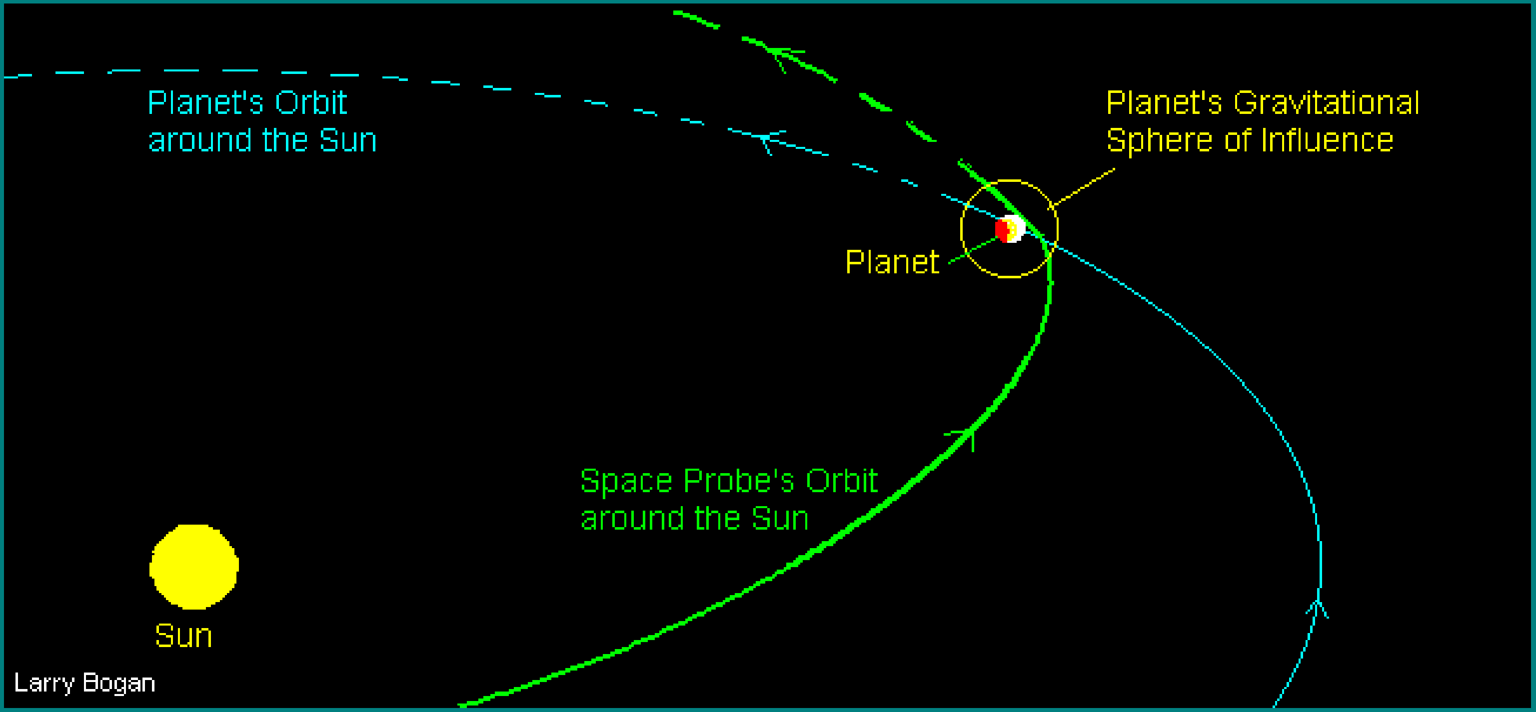
Chapter III: How to travel in space?

- The encounter of a spacecraft with a planet can increase the probe's velocity in the heliocentric frame of reference.
- Analogy: elastic collision between two bodies of masses m and M>>m:



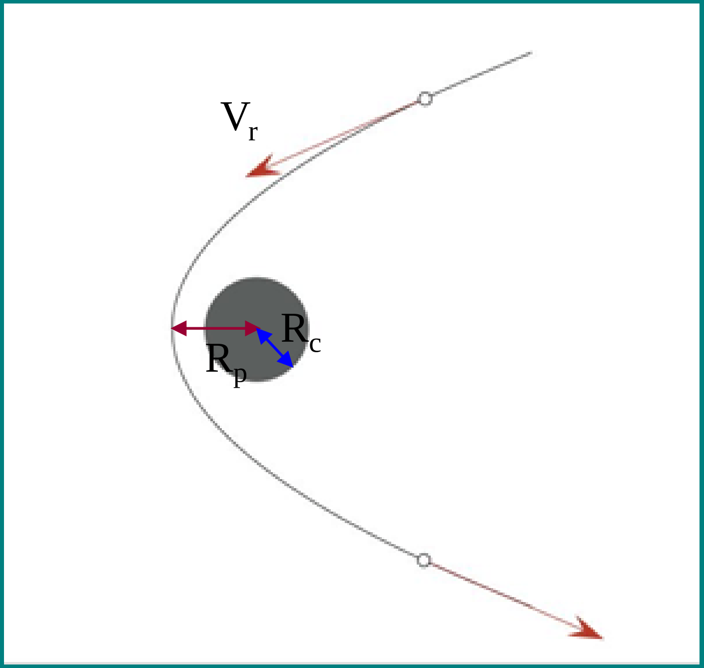
Chapter III: How to travel in space?

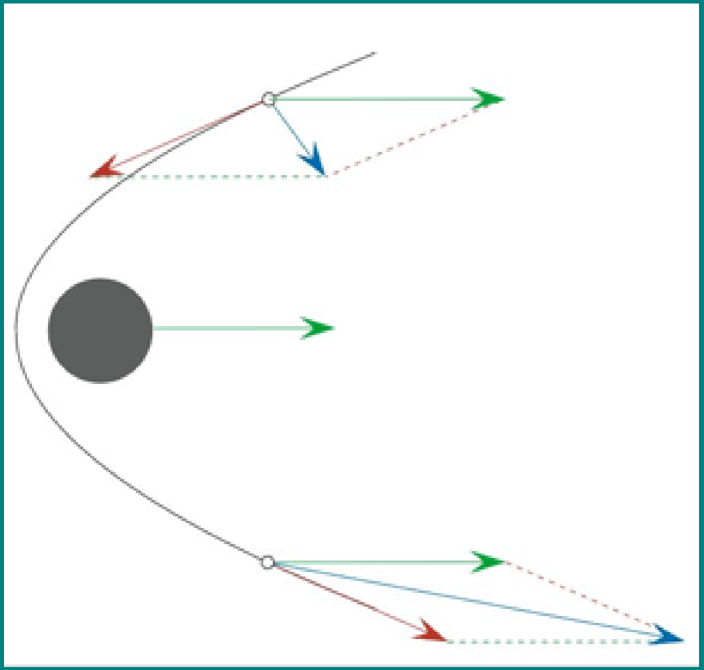
- Let's imagine a probe on a heliocentric orbit. When it encounters a planet, it enters the planet's *gravitational sphere of influence*.



Chapter III: How to travel in space?

- With respect to the planet, the probe arrives at a relative velocity V_r on a hyperbolic trajectory.
- R_c = radius of the planet, R_p = distance of nearest approach.



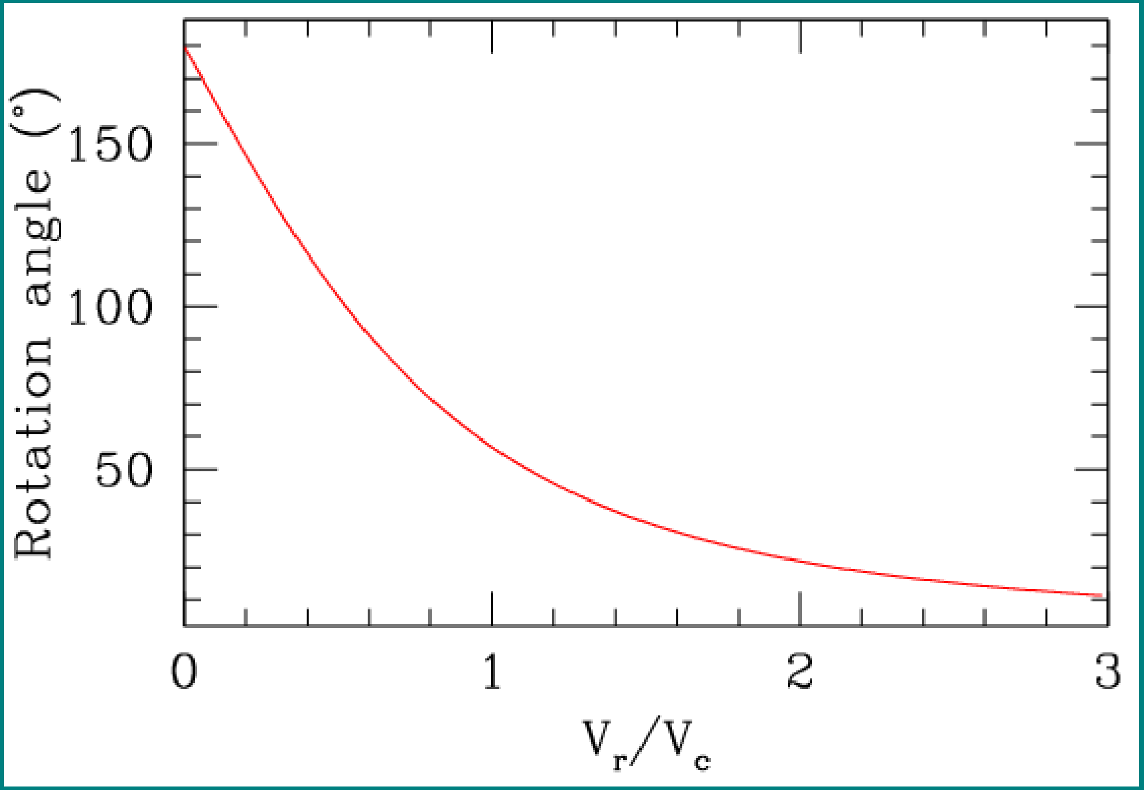


Chapter III: How to travel in space?

- The velocity vector rotates during the manoeuver.

$$2 \arcsin \left[\frac{1}{1 + \frac{R_p V_r^2}{R_c V_c^2}} \right]$$

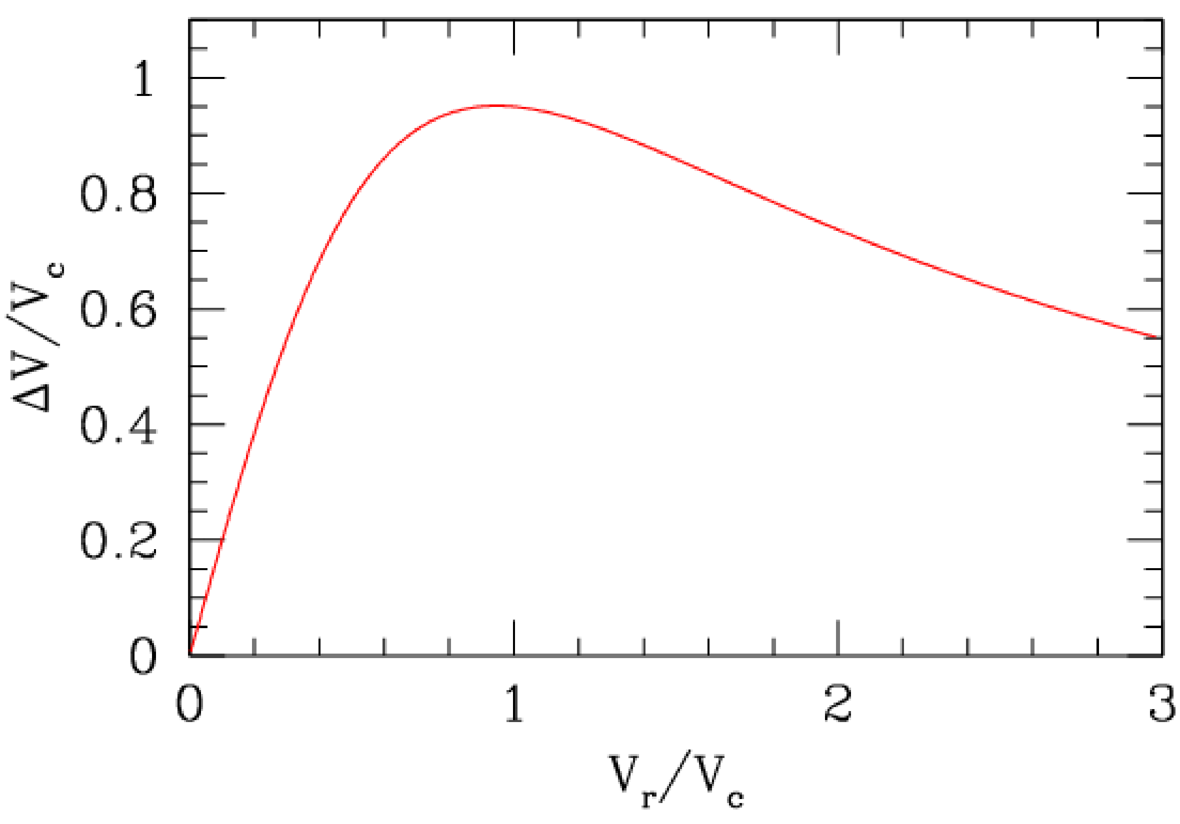
$$V_c = \sqrt{\frac{G M_c}{R_c}}$$



Chapter III: How to travel in space?

- For most planets, one can reach $R_p = 1.1\ R_c$ (exceptions : Saturn and Jupiter).
- Maximum gain up to 95% of V_c

$$V_c = \sqrt{\frac{G M_c}{R_c}}$$



$$\frac{2\,V_r}{1+\frac{R_p V_r^2}{R_c V_c^2}}$$

Chapter III: How to travel in space?

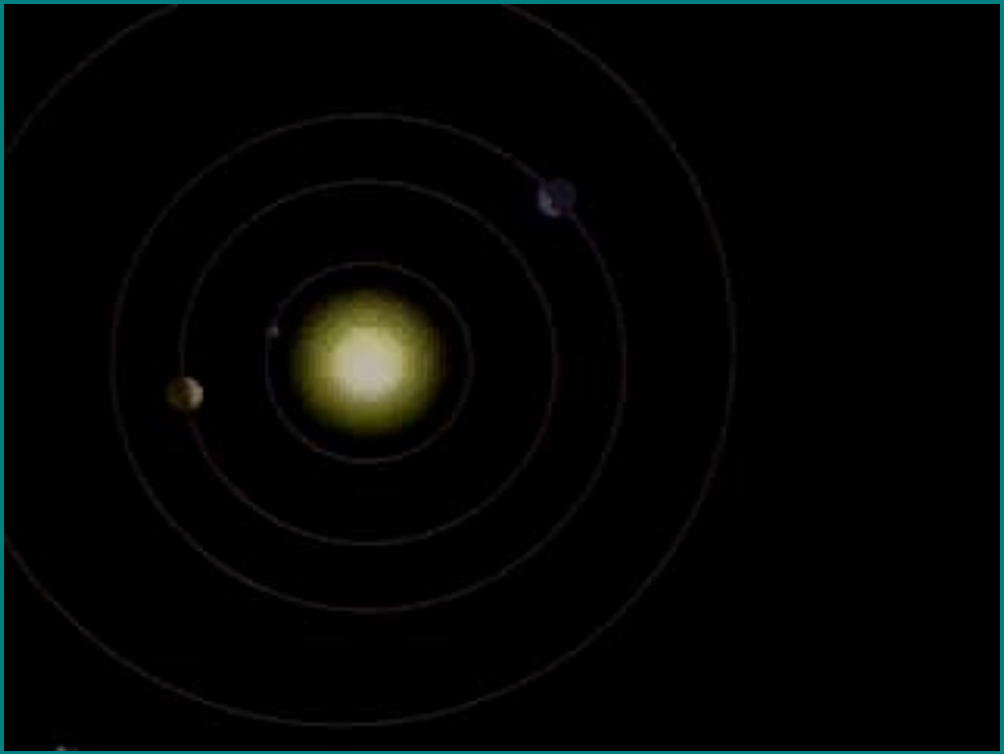
Object	V_c (km/s)	Minimum flyby altitude (km)	Mass (Earth)	Radius (Earth)	ΔV maximum (km/s)
Mercury	3.1	200	0.055	0.383	2.9
Venus	7.6	300	0.815	0.949	7.4
Jupiter	45	30 000	318	11.2	37
Saturn	27	80 000	95.2	9.45	17
Moon	1.7	200	0.012	0.273	1.6

Gravitational assistance allows to gain substantial velocity increments, that are impossible to achieve with conventional engines.

Chapter III: How to travel in space?

- This technique allows reaching almost any destination of the Solar System.
- Price to pay: duration of the journey and complexity of the launch window increase!

- Example: the Cassini-Huygens mission to Saturn: encounters with Venus (twice), the Earth and Jupiter. Duration of the journey: 7.5 years.



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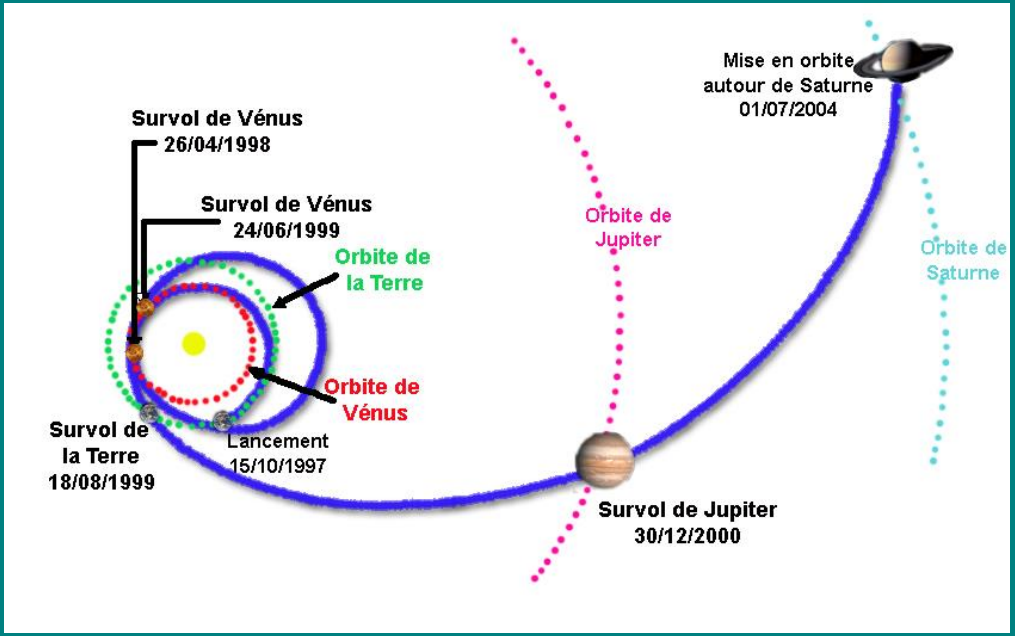
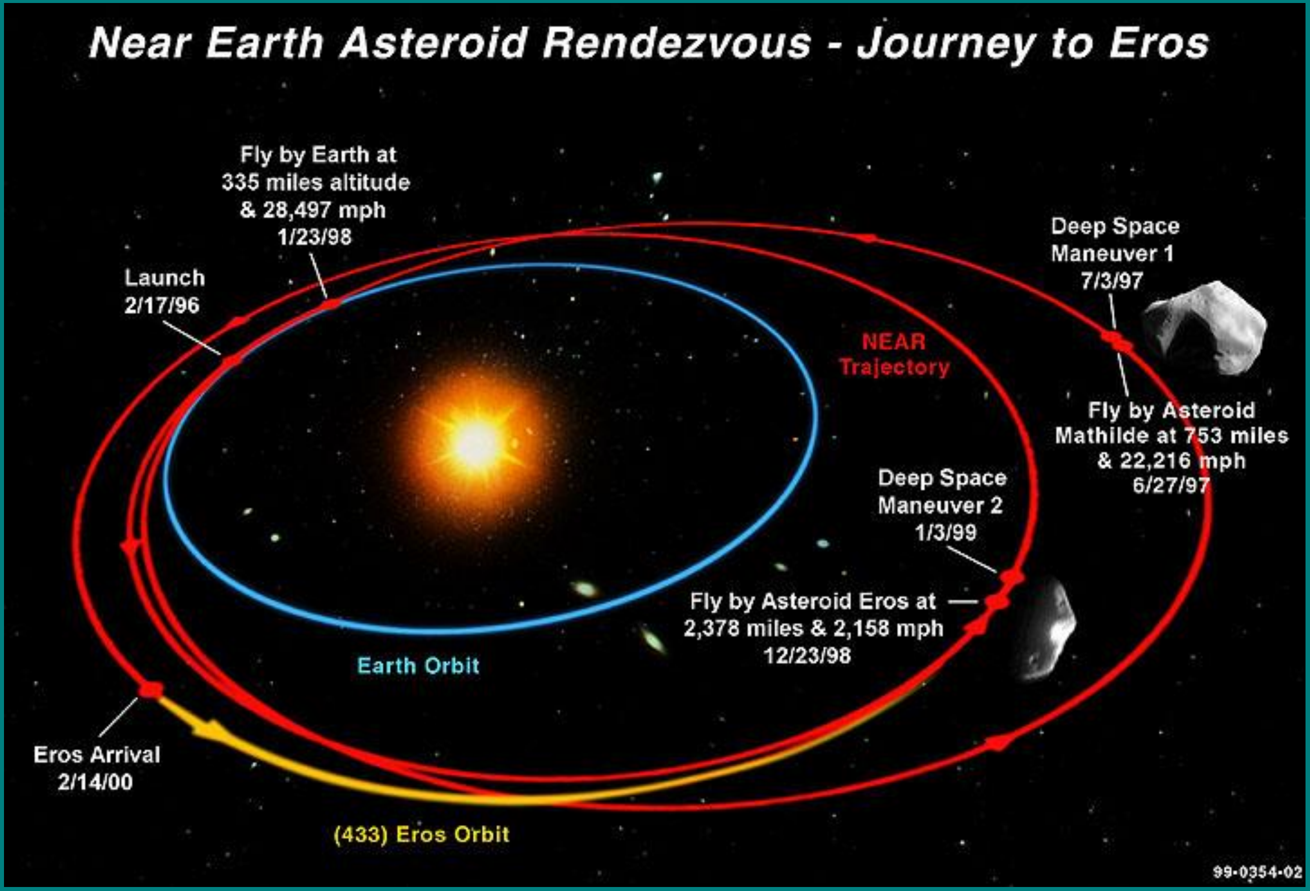


Chapter III: How to travel in space?

- Gravity assist can be combined with active propulsion to correct the trajectory (delta V – gravity assist) to ensure the required effect of the flyby (example NEAR).



Chapter III: How to travel in space?

- Gravity assist manoeuvres can be combined with active propulsion via ionic engines. This is the case of the Bepi Colombo probe on its way to Mercury.

19/07/2014 launch (actually 2018)

25/07/2015 flyby of the Earth

17/01/2016 1st Venus flyby

28/08/2016 2nd Venus flyby

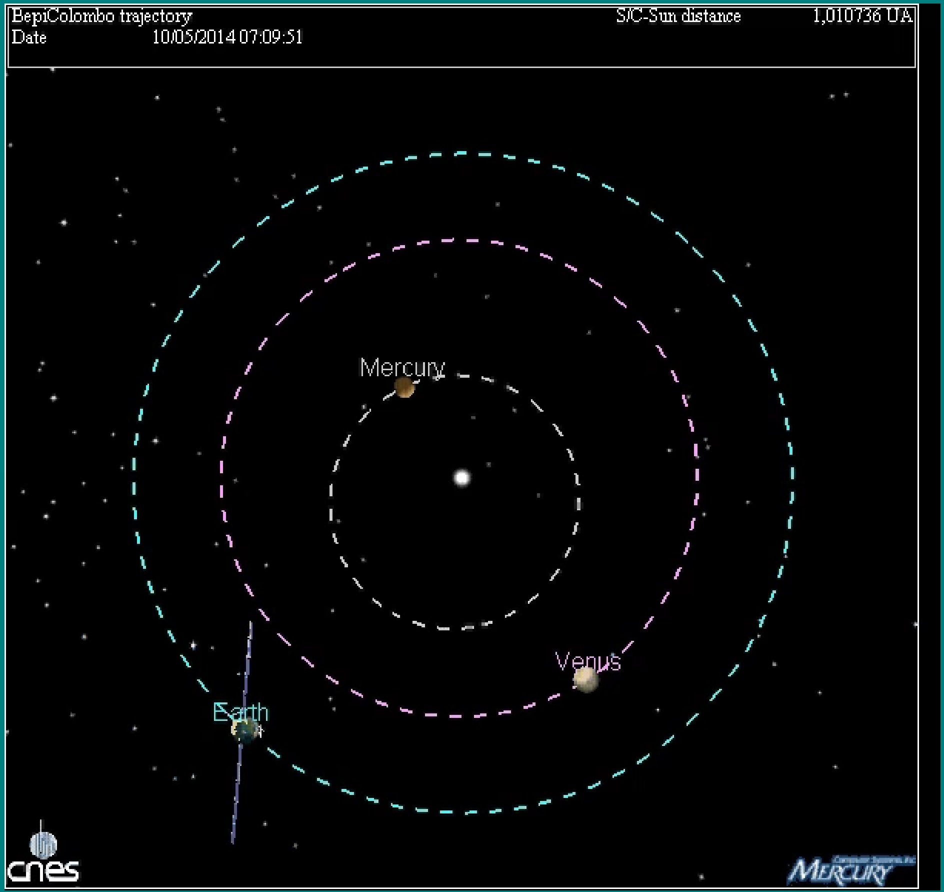
04/09/2017 1st Mercury flyby

27/05/2018 2nd Mercury flyby

17/08/2019 3rd Mercury flyby

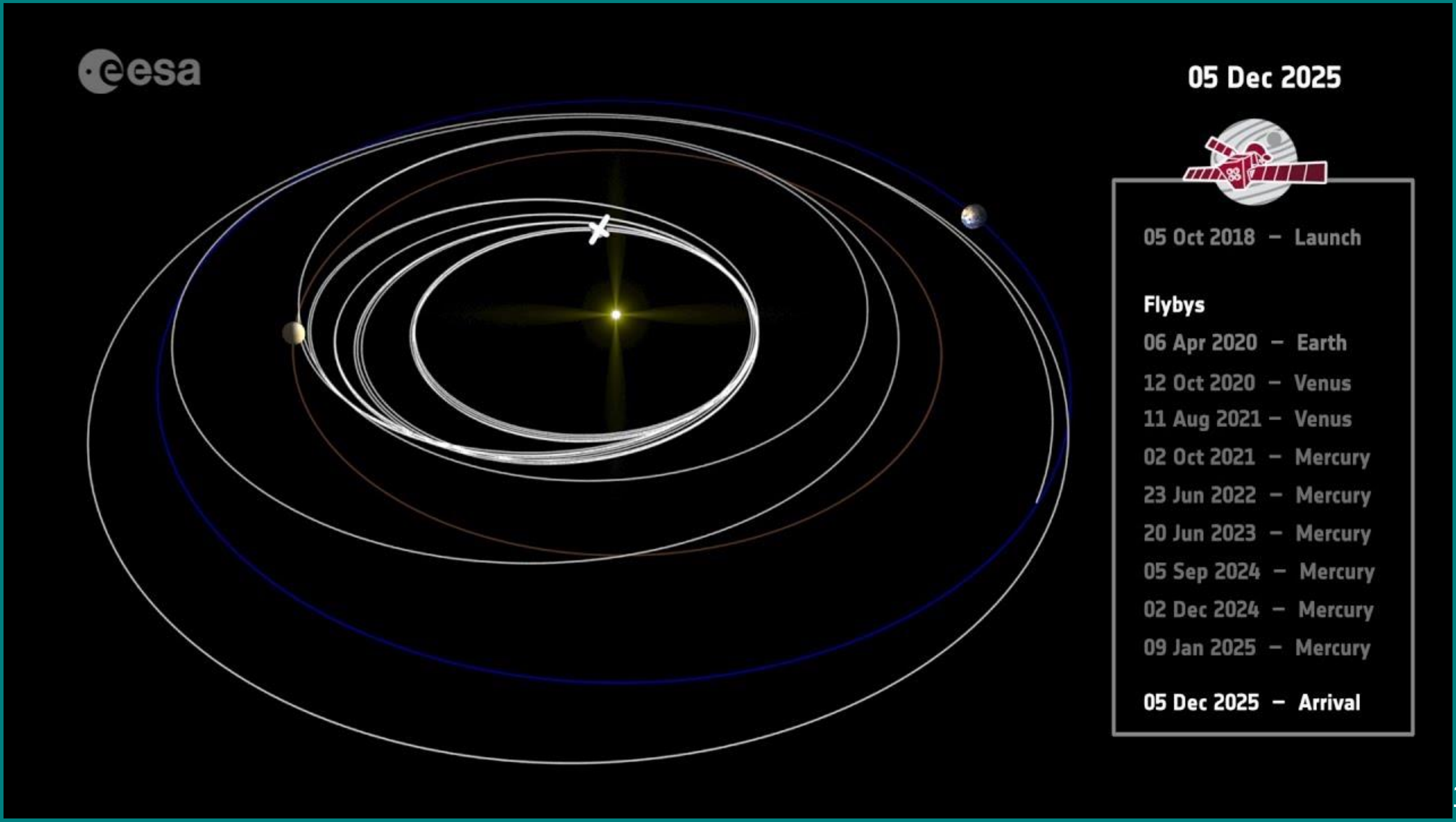
25/09/2019 4th Mercury flyby

21/05/2020 Mercury orbit insertion



Chapter III: How to travel in space?

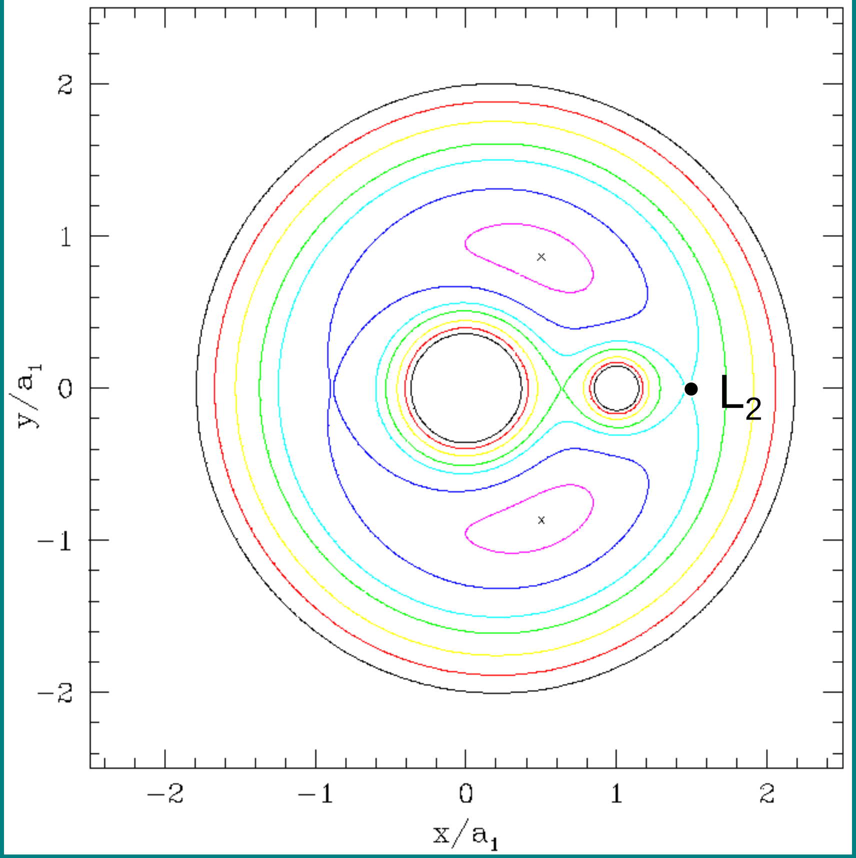
- Actual cruise of Bepi Colombo to Mercury



Chapter III: How to travel in space?

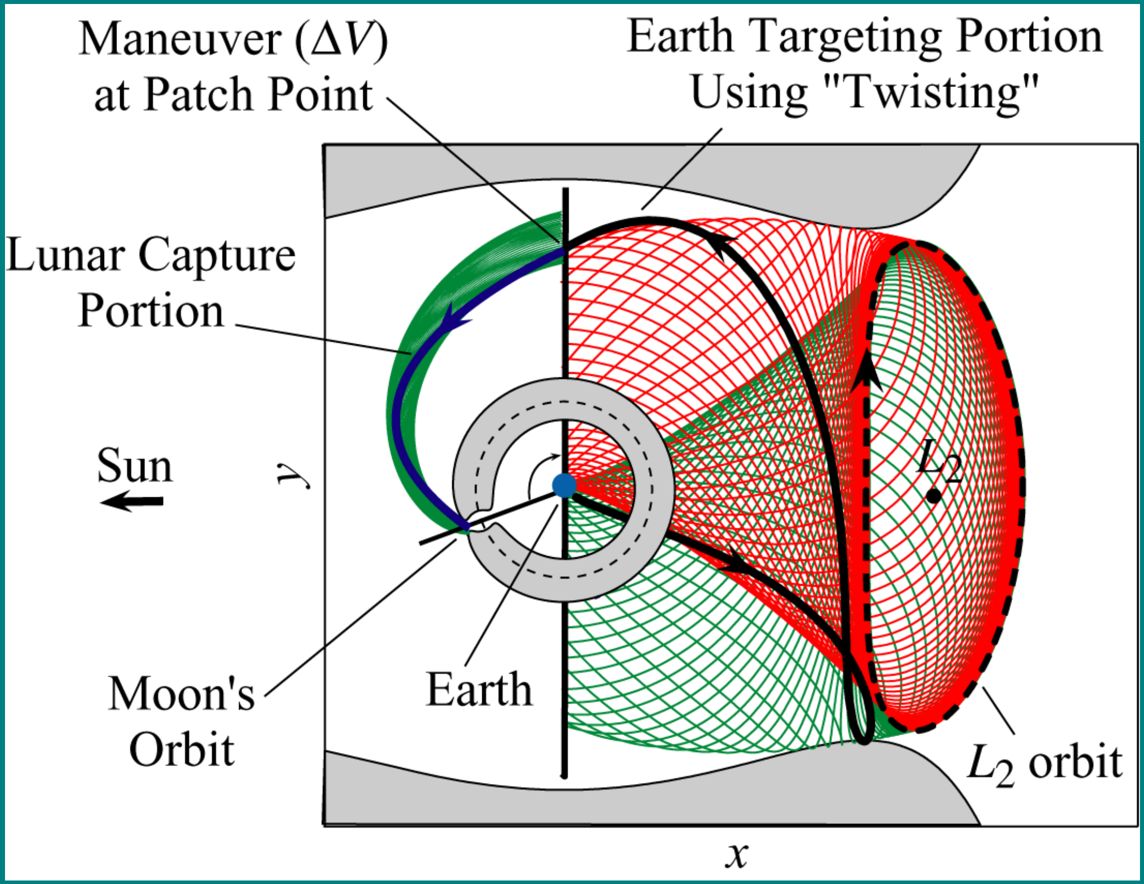
- There exist some particular solutions allowing to travel to certain destinations at reduced cost.
- These solutions are usually based on the properties of the Roche potential.

- E.g. journey to the Moon: the 4-body problem (Sun, Earth, Moon, spacecraft) is approximated as the combination of two restricted 3-body problems.



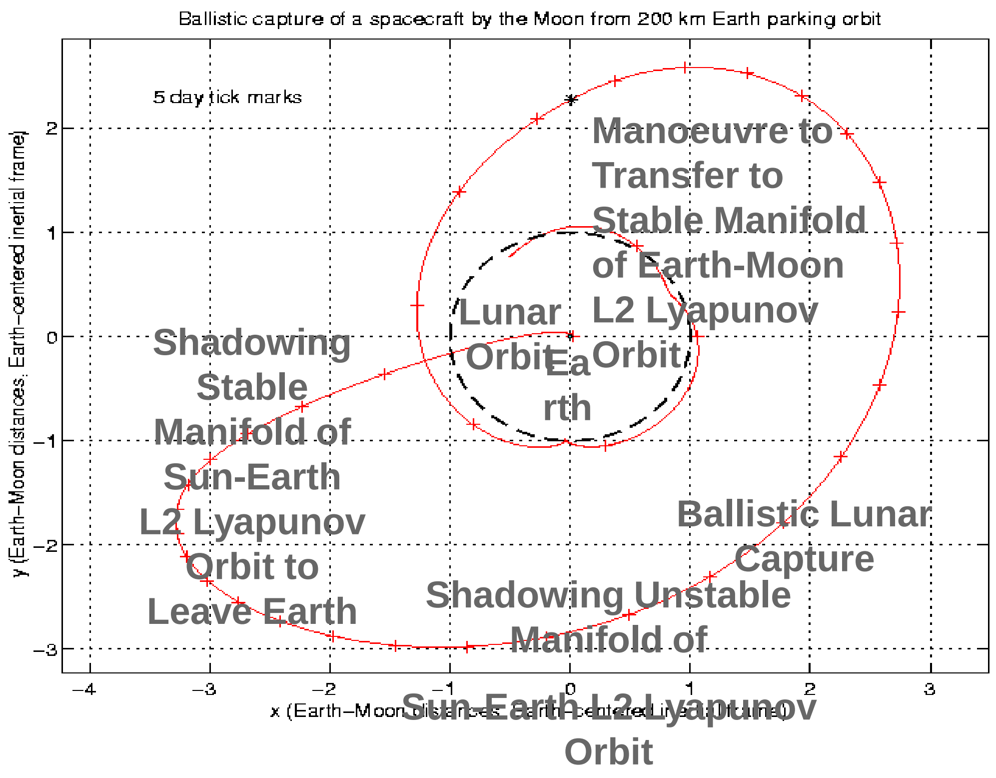
Chapter III: How to travel in space?

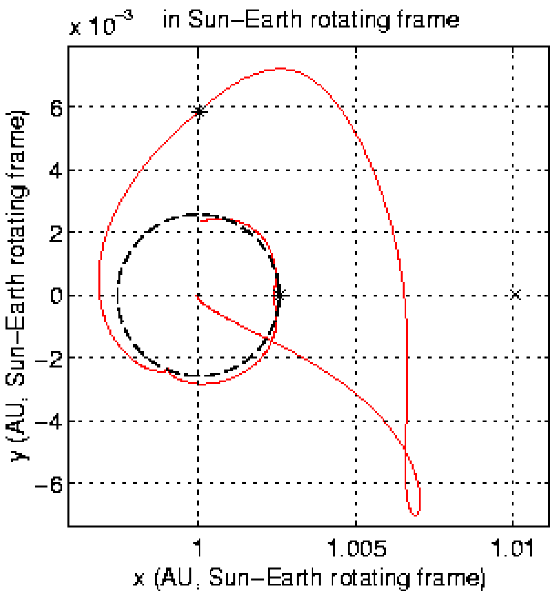
- The probe is sent towards the L2 point of the Sun – Earth system on an orbit such that it will return to the Earth.
- The orbit is adjusted in such a way that the probe enters the Earth – Moon system through the corridor that leads to its L2 point.



Chapter III: How to travel in space?

- Cost of this operation: duration of the journey: 3 months to go to the Moon instead of 3 days…





Chapter IV: The environment of a space mission

- The energetic particles environment
  1. Interactions between the Solar wind and the Earth
  2. The Van Allen radiation belts
  3. Cosmic rays
- The thermal environment
- Micrometeorites and space junk
- Microgravity and outgassing

Chapter IV: The environment of a space mission

- On the ground: building, integration, assembly and tests of spacecraft are done in clean rooms with controlled temperature (near 20°C) and humidity (about 50%).

Chapter IV: The environment of a space mission

- Clean rooms are classified according to the level of requirement on the number of particles in the air.
- US FED STD 209E standards: e.g. « class 100 » = less than 100 particles of size ≥ 0.5μm per cubic foot of air.

class	≥0.1μm	≥0.2μm	≥0.3μm	≥0.5μm	≥5μm
1	35	7	3	1	
10	350	75	30	10	
100		750	300	100	
1000				1000	7
100 000				100 000	700

Chapter IV: The environment of a space mission

- New standards ISO 14644-1
- « Class 100 » equivalent to « ISO 5 » = less than 100 000 particles of ≥ 0.1µm per cubic meter of air.

class	≥0.1µm	≥0.2µm	≥0.3µm	≥0.5µm	≥1µm	≥5µm	FED STD 209E
ISO 1	10	2					
ISO 2	100	24	10	4			
ISO 3	1000	237	102	35	8		1
ISO 5	100 000	23 700	10 200	3250	832		100
ISO 7				352 000	83 200	2930	10 000

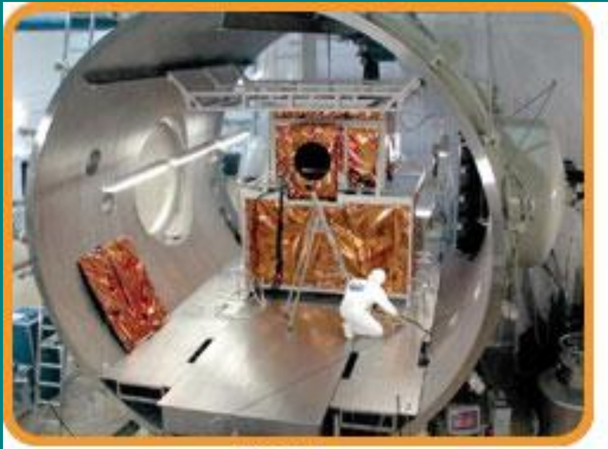
Chapter IV: The environment of a space mission

- During transportation to the launch site and during integration into the launcher's fairing, the satellite undergoes important changes in temperature, pressure and humidity.
- During the launch the satellite undergoes important vibrations $\Rightarrow$ need to test the structural stability of the spacecraft on the ground, prior to launch.
- In this chapter, we focus on the space environment: some of these aspects can be simulated on the ground (thermal environment, vacuum,…) by means of specific facilities such as those of CSL.

Chapter IV: The environment of a space mission

- Ground-based test facilities at the Centre Spatial de Liège: vacuum chambers, cryogenic tests, shakers…

Seviri Instrument (MSG) in Focal 5



Focal 5

Shaker 4522 LX

Chapter IV: The environment of a space mission

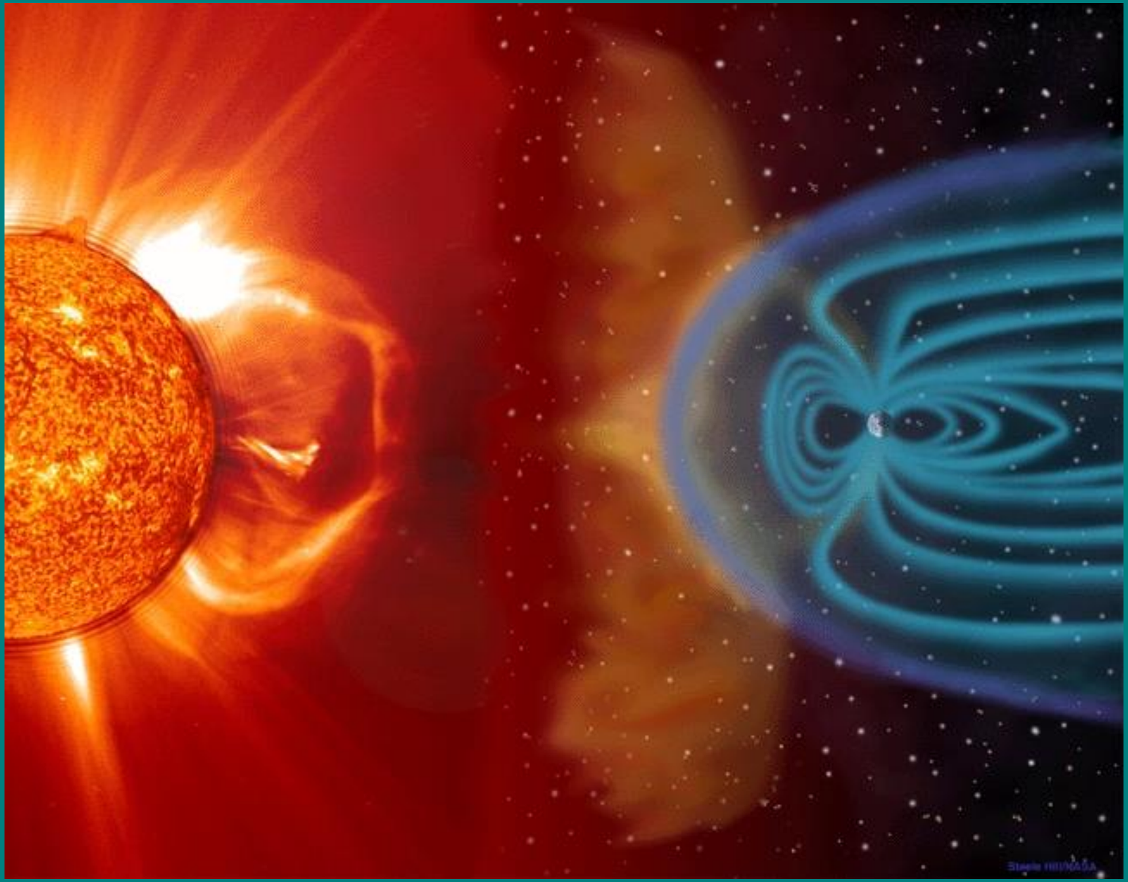
- Interactions between highly energetic charged particles and the satellite leads to
  1. degradation of the performances of the solar panels,
  2. damage of the electronics (uncontrolled on/off switches, SEUs, short circuits,…)
  3. degradation of the coating of the satellite…
- Shielding of the electronics is often not sufficient ⇒ need to foresee redundant electronics and treat the components to make them less sensitive to radiation damages.

Chapter IV: The environment of a space mission

- The charged particle environment essentially consists of three components: the Solar wind, the Van Allen radiation belts and cosmic rays.
- “Space weather” is the combination of the phenomena that rule the number energetic charged particles in a given place and at a given time. Space weather depends strongly on the Solar activity.

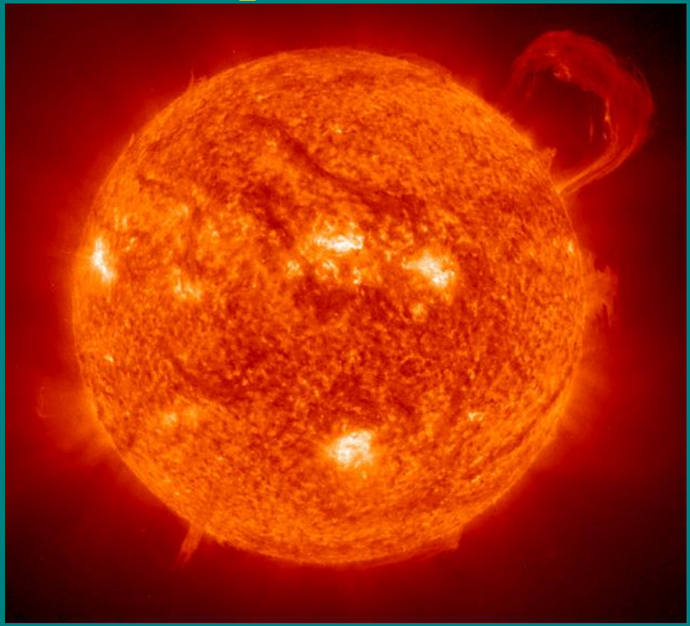
Chapter IV: The environment of a space mission

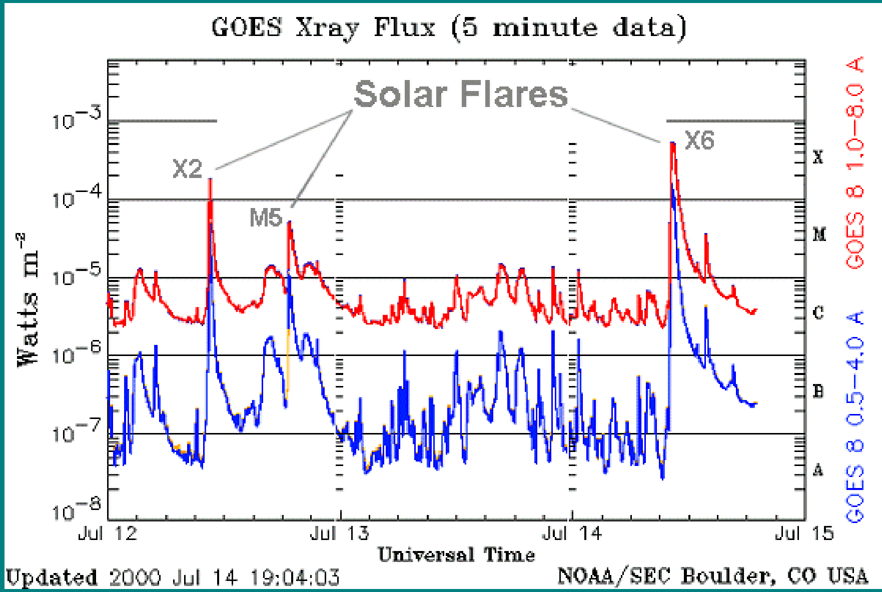
- Solar wind: mainly p^+ and e^-, typical velocities in the plane of the ecliptic 200 to 600 km/s.
- Interactions with magnetic field of the Earth:



Chapter IV: The environment of a space mission

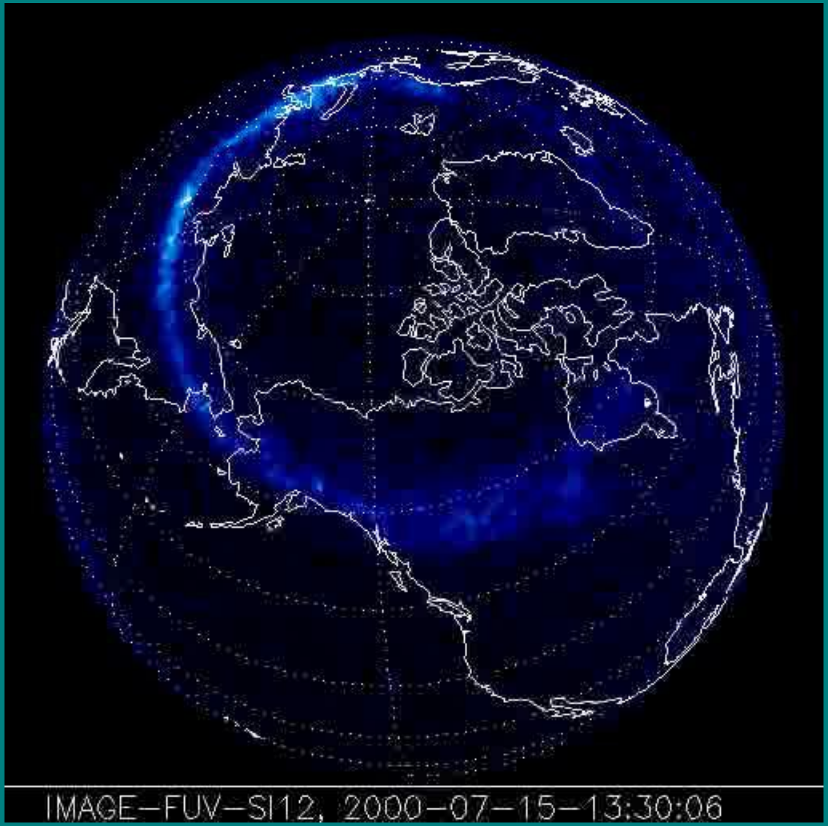
- Coronal mass ejection: associated with Sunspots. Increase of the X-ray emission and of the flux of particles.
- Time delay between X-rays and particles allows to take protective measures.
- Intensity of X-ray flux yields the class of the eruption and provides an indication of the danger associated with the flux of particles.





Chapter IV: The environment of a space mission

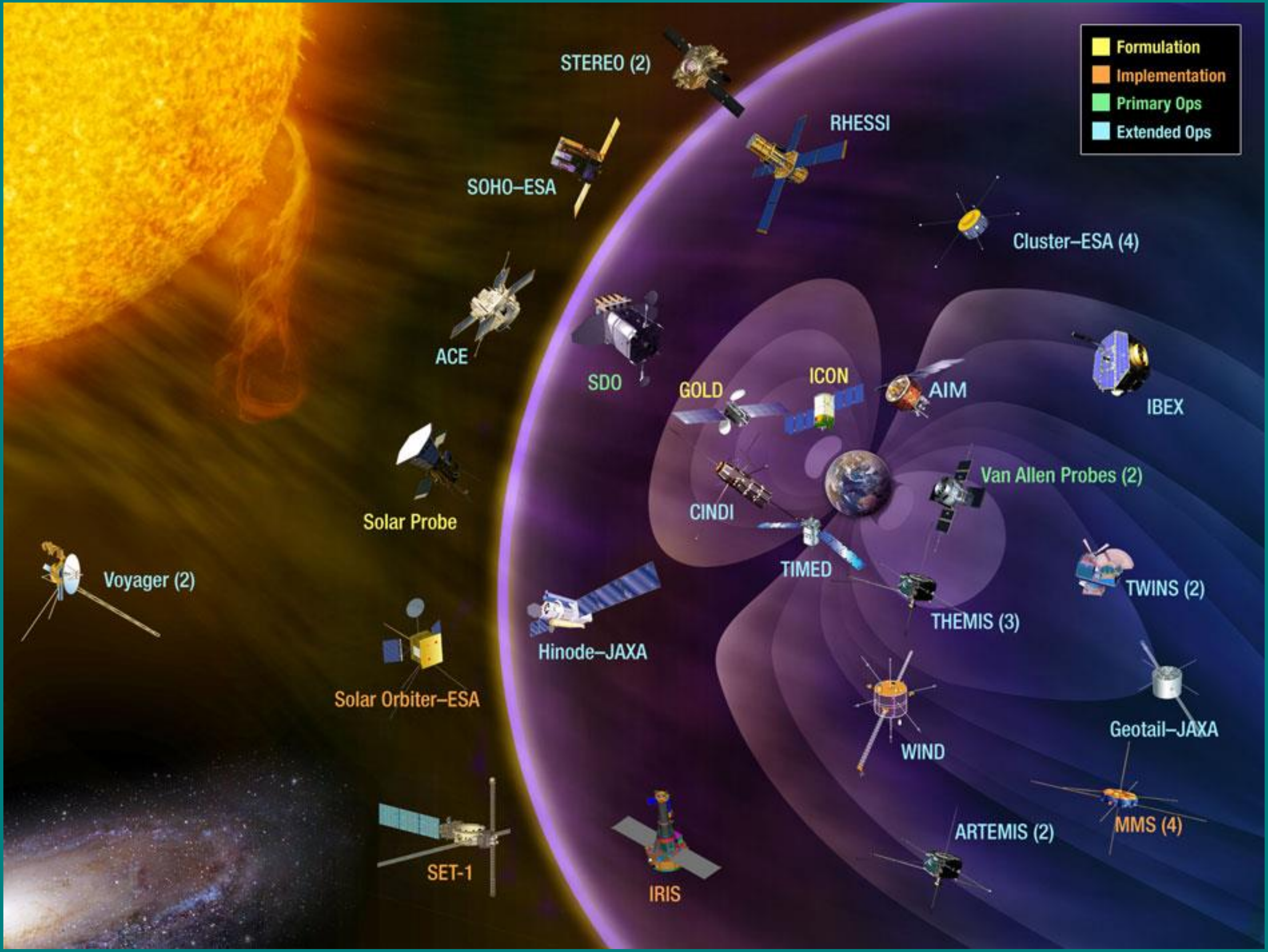
- Aurora = charged particles of the Solar wind and/or CME events are deviated by the geomagnetic field and channelled into the upper atmosphere:



http://www.spaceweather.com/

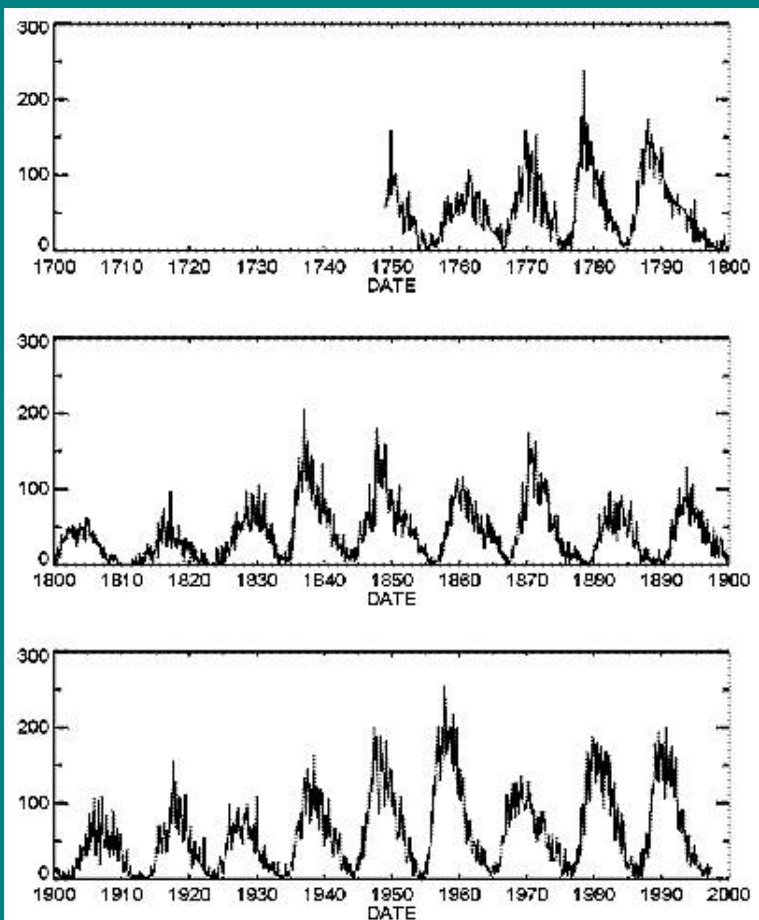
Chapter IV: The environment of a space mission

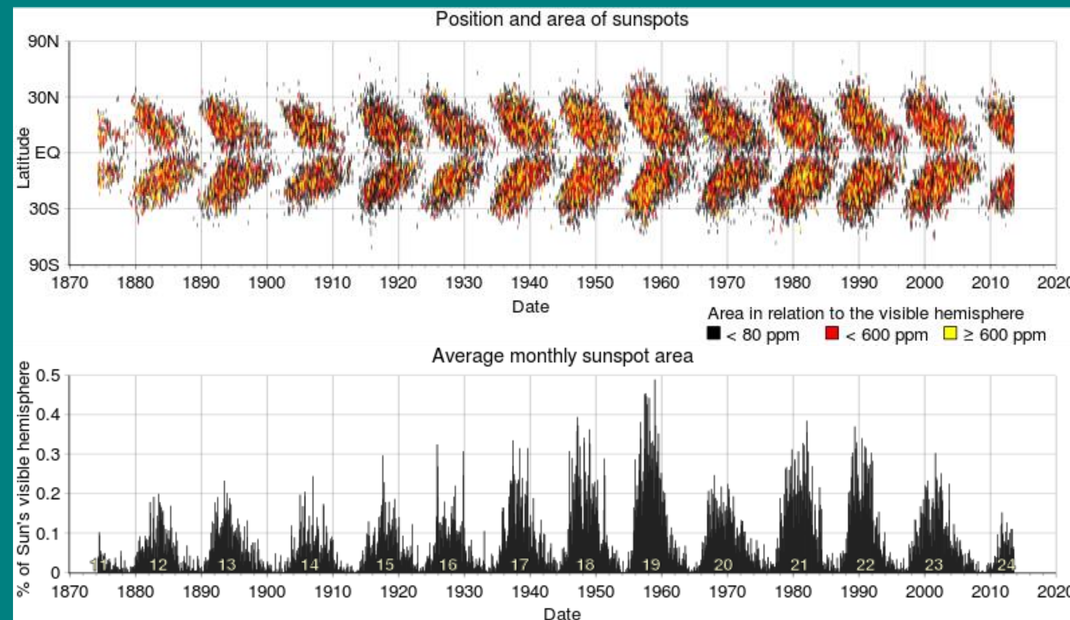
- Space weather monitored by a constellation of spacecraft:

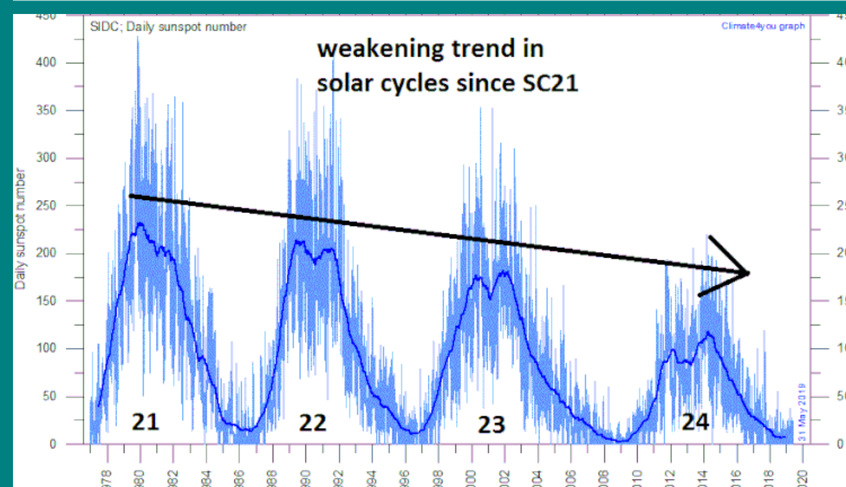


Chapter IV: The environment of a space mission

- Frequency of CME events modulated by the “11 years Solar cycle” (Sunspot cycle).

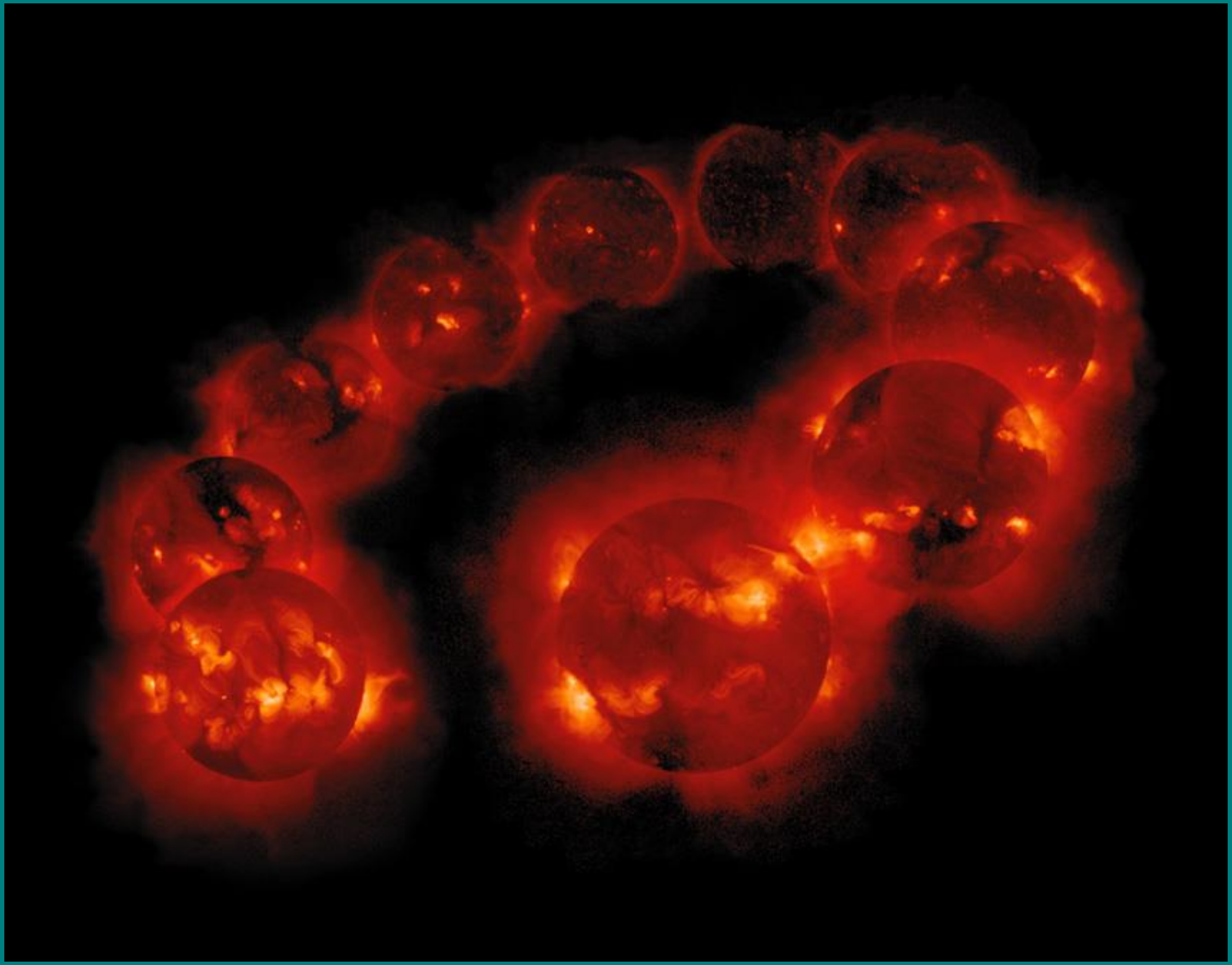






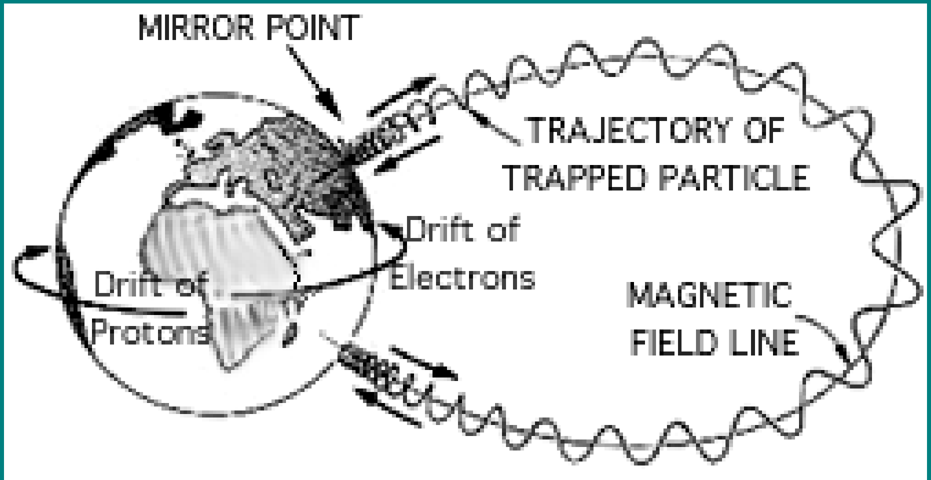
Chapter IV: The environment of a space mission

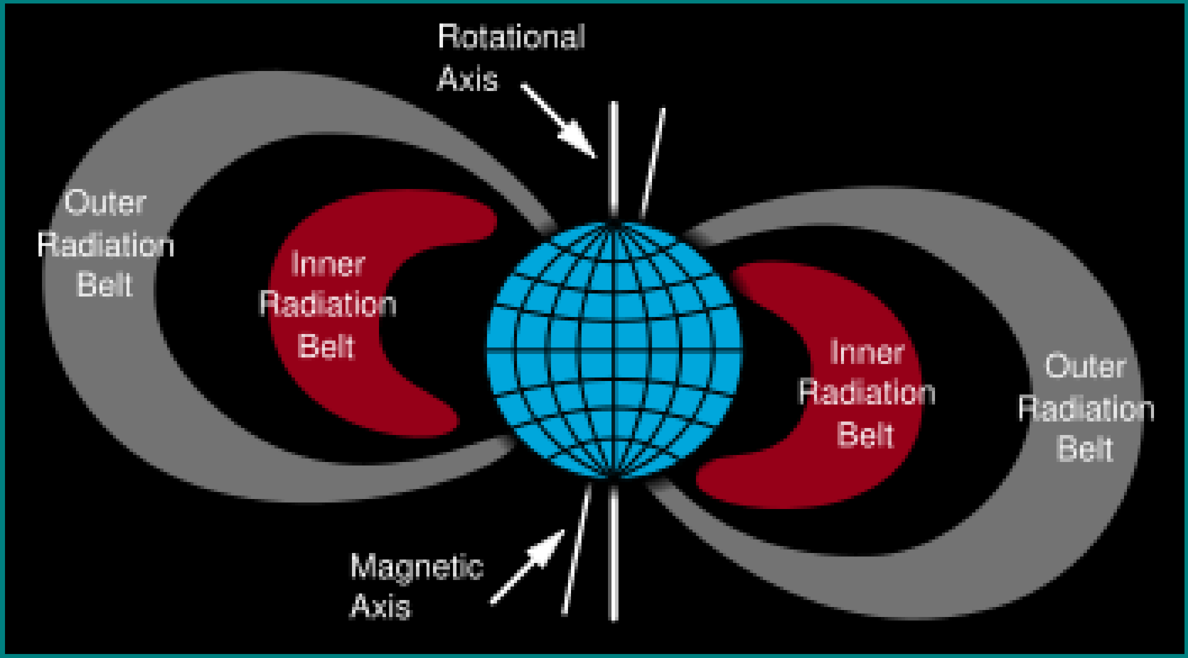
- Frequency of CME events modulated by the “11 years Solar cycle” (Sunspot cycle).



Chapter IV: The environment of a space mission

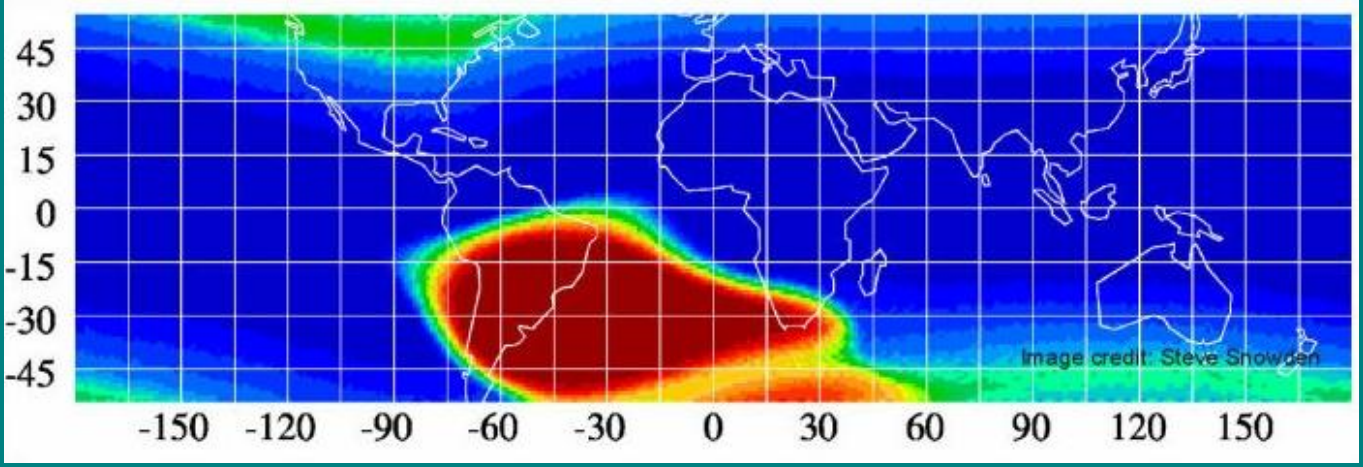
- The « Van Allen » radiation belts host energetic particles (p^+ and e^-) trapped by the (essentially dipolar) geomagnetic field.





Chapter IV: The environment of a space mission

- The dipolar geomagnetic field is shifted with respect to the centre of the Earth (430 km towards the South-East of Asia). This leads to a depression in the strength of the geomagnetic field on the opposite side of the Earth: the so-called « South Atlantic Anomaly » (SAA).
- This region is a potential threat for the electronics of satellites in LEO (especially regarding the frequency of SEU).



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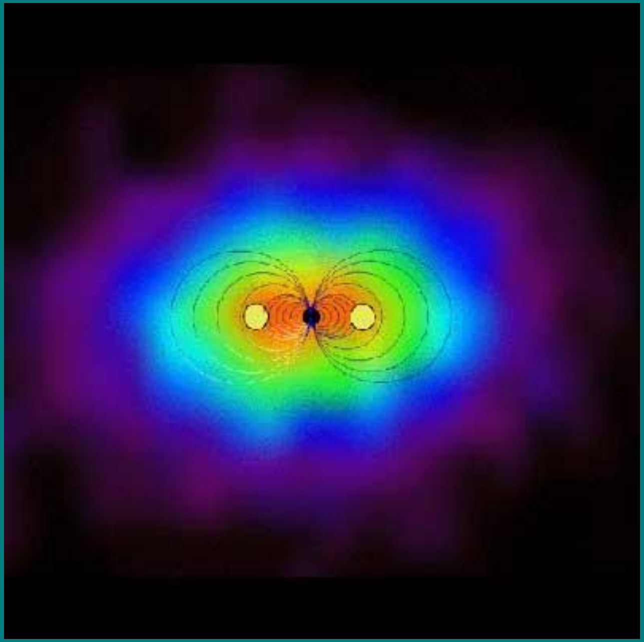
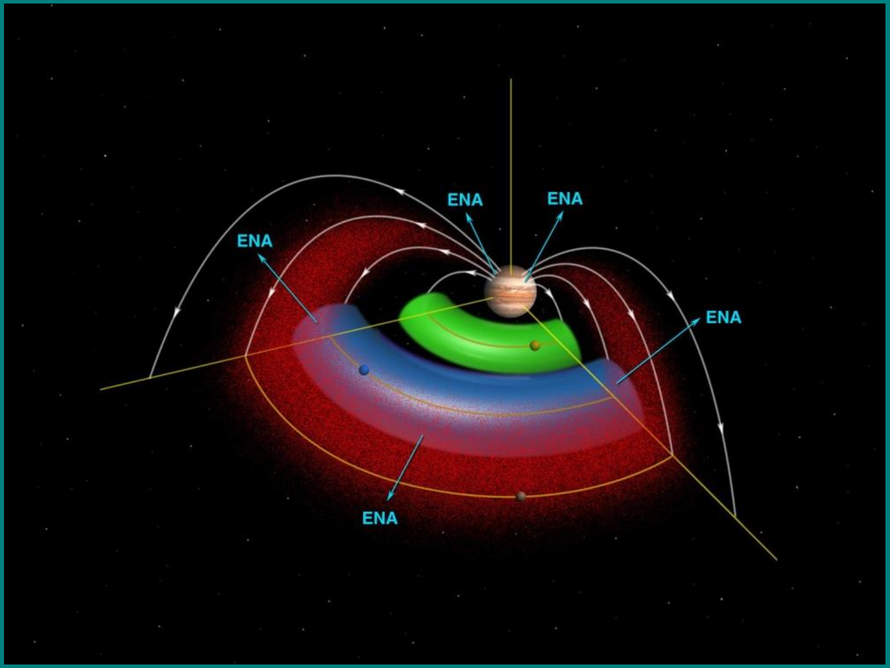
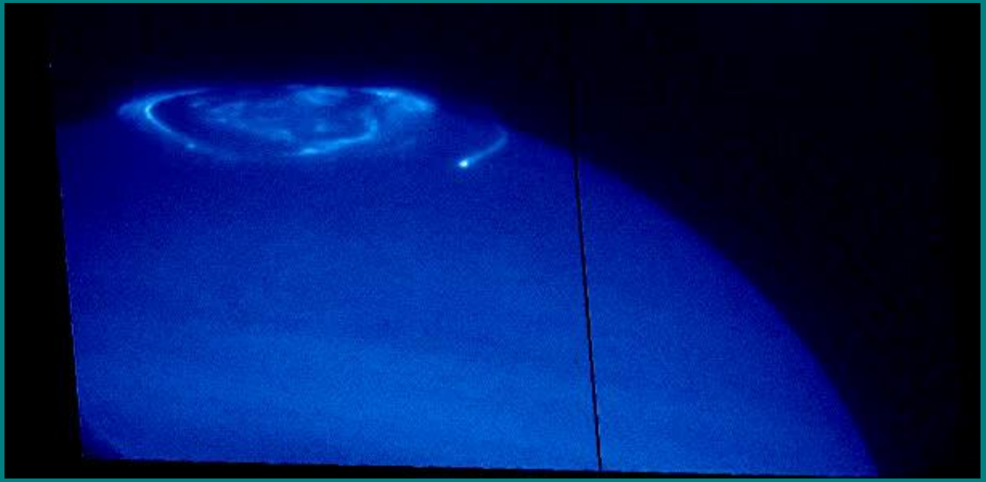
- Jupiter features a very strong magnetic field and is surrounded by several radiation belts partially fed by the volcanic activity of Io:

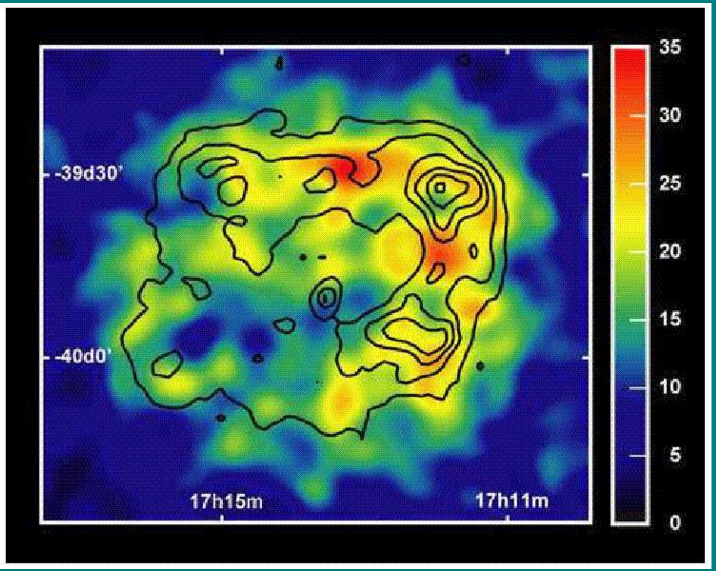






Chapter IV: The environment of a space mission

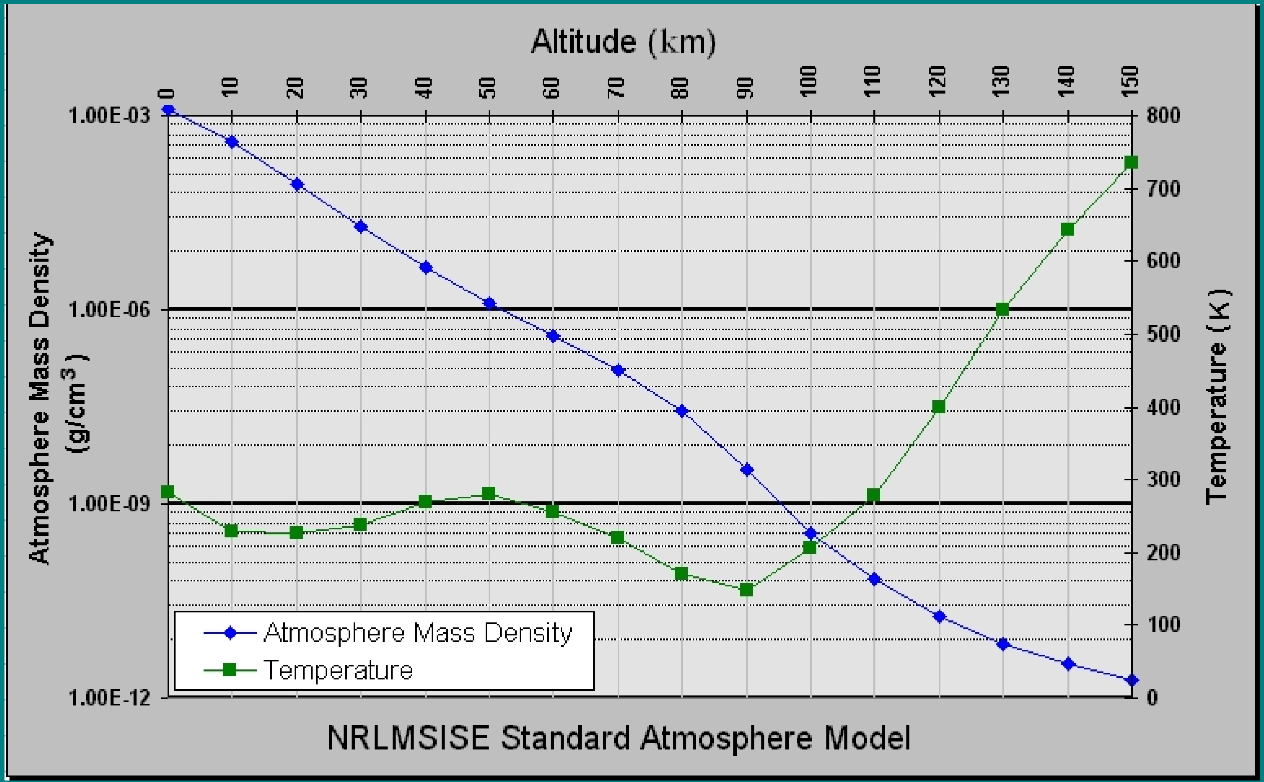
- Cosmic rays (energies up to 10^{20} eV) come from the deep space. For energies up to 10^{14} eV, the particles are accelerated in supernova remnants.



- The flux of cosmic rays is anti-correlated with Solar activity.
- Cosmic rays pose a threat to manned space flight outside the zone protected by the Earth's magnetosphere.

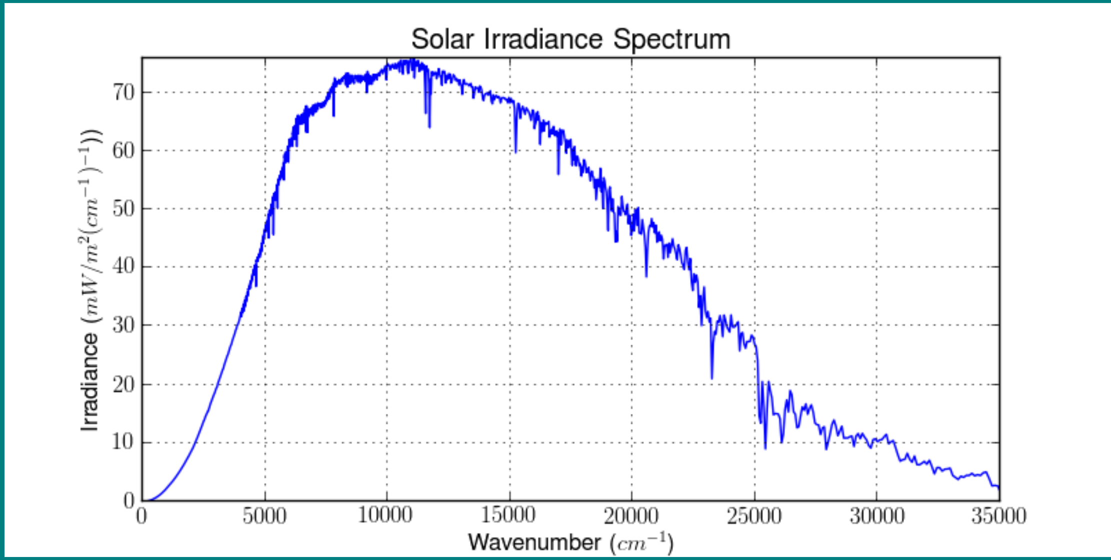
Chapter IV: The environment of a space mission

- In the thermosphere (altitude between 90 and 700 km), temperature strongly increases, whilst density drops off rapidly. The mean free path of the ions exceeds the size of the spacecraft. ⇒ Convection and conduction are negligible in the thermal balance of the satellite which is rather set by radiation.



Chapter IV: The environment of a space mission

- The Solar spectrum can be approximated by a black body at 5800 K. Maximum of the spectral energy distribution near 5000Å.
- About 2% of the flux are emitted at wavelengths below 1300Å. This fraction varies with Solar activity.



Chapter IV: The environment of a space mission

- Thermal balance: the Solar flux decreases as $1/r^2$. At 1AU, it amounts to 1370 Wm^{-2}, at the position of Mercury, it amounts to 9145 Wm^{-2}, whereas at the orbit of Jupiter, 50 Wm^{-2} remain.
- Temperature of equilibrium of a spherical black body:

Flux received: $$(1 - c_A)\, \pi\, R^2\, \frac{L_\odot}{4\, \pi\, r^2}$$

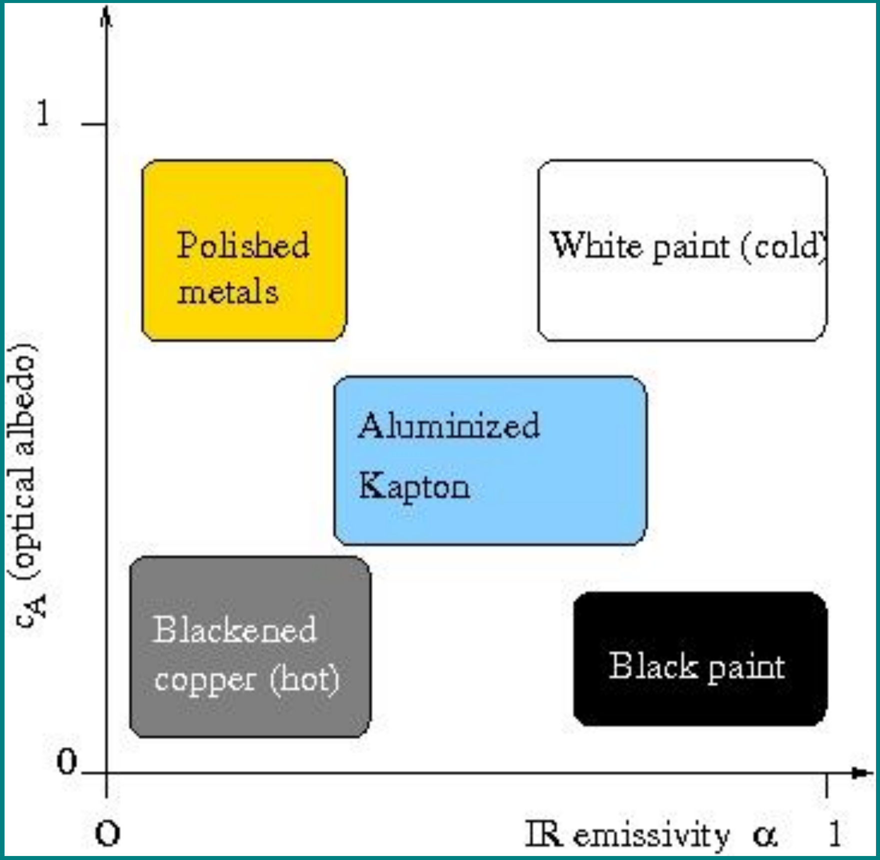
Flux radiated: $$4\, \pi\, R^2\, \alpha\, \sigma\, T^4$$

$\Rightarrow$ 288 K @ 1AU, 465 K and 123 K near Mercury and Jupiter

- For landers and atmospheric probes, convection becomes important and the equilibrium temperature is the ambient atmospheric temperature.

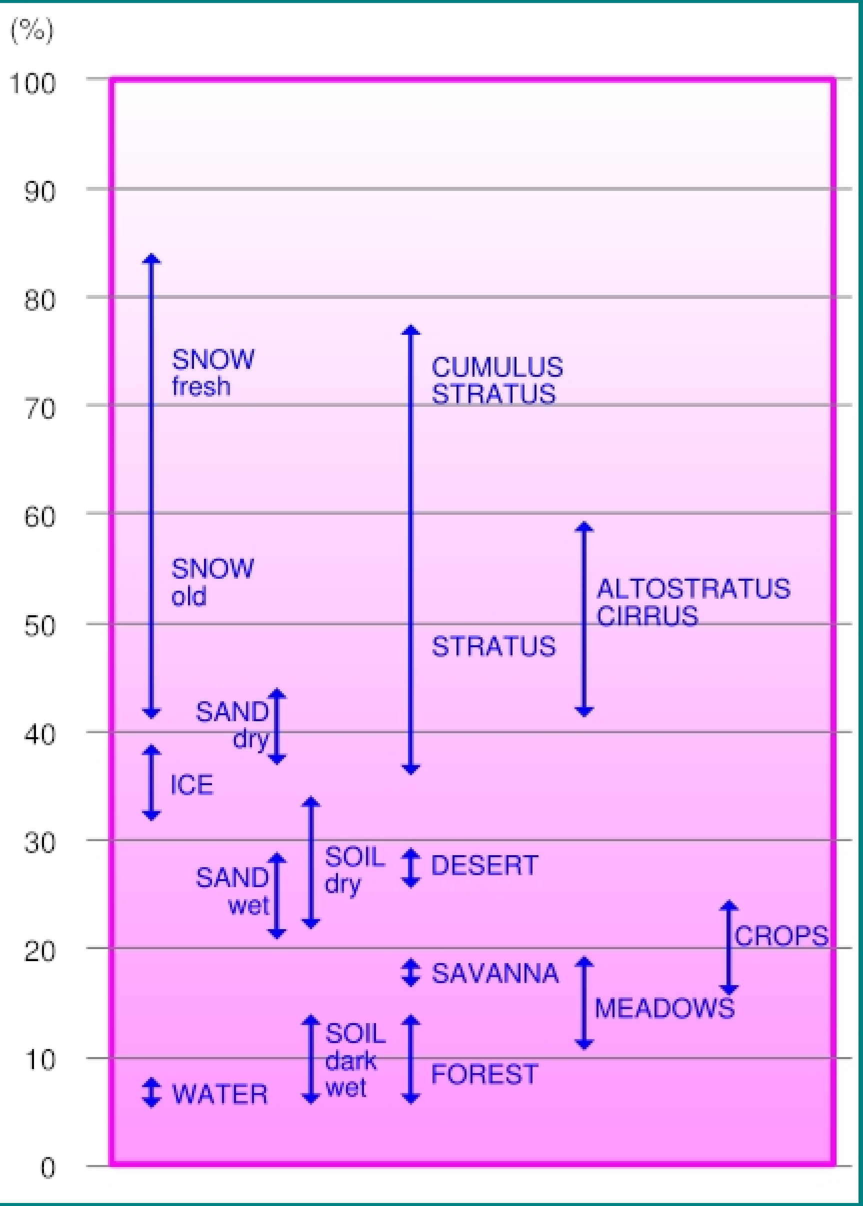
Chapter IV: The environment of a space mission

- A passive thermal control (for radiative exchanges) can be achieved using an appropriate coating.
- The Sun-lid side of the satellite accumulates positive charges compared to the shaded side (ionizing radiation). The coating ought to be as conductive as possible.
- The ionizing radiation can degrade the performances of the coating of the satellite.



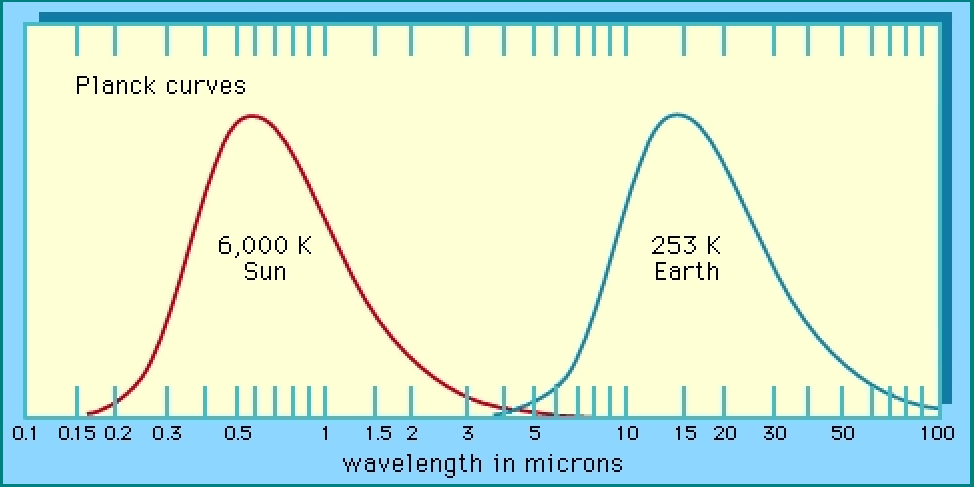
Chapter IV: The environment of a space mission

- A fraction of the solar flux is reflected by the planets: concept of albedo.
- On average, for the Earth, c_A = 0.30; for Venus, c_A = 0.75; for the Moon, c_A = 0.12.

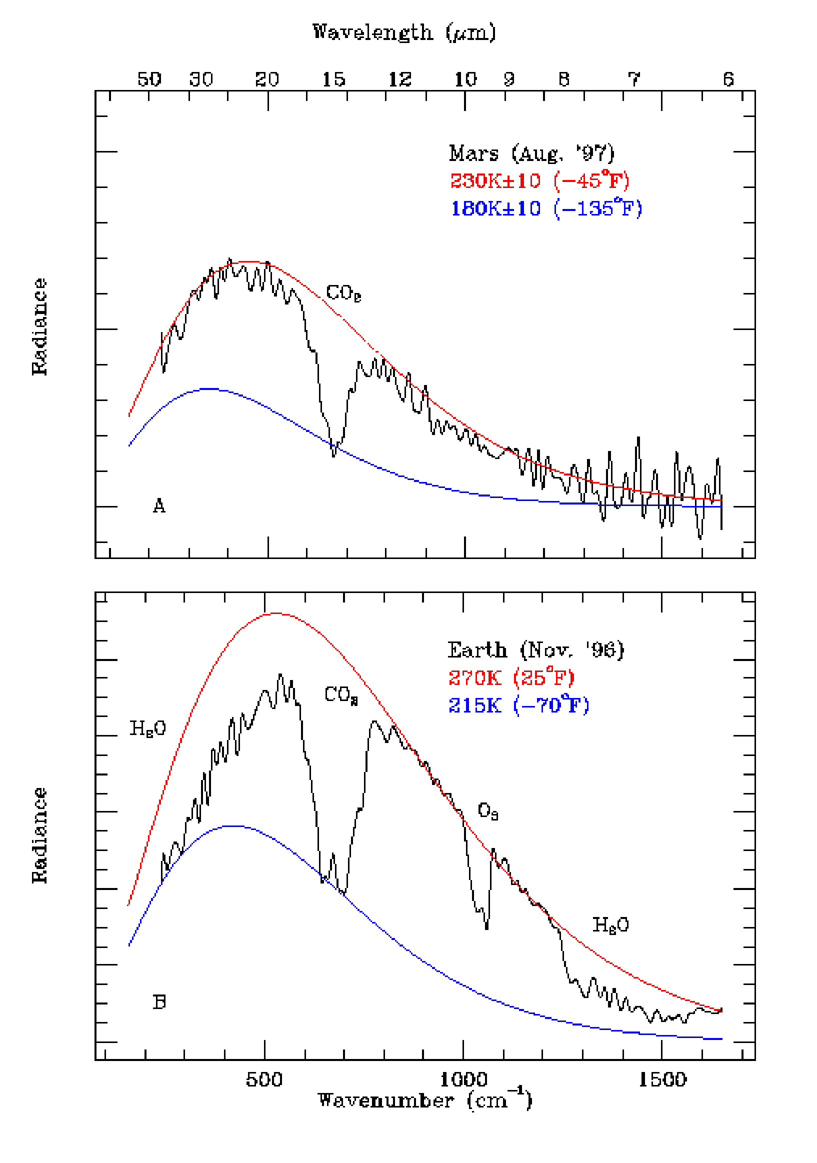


Chapter IV: The environment of a space mission

- Thermal emission of the Earth or of the planet in the IR domain:

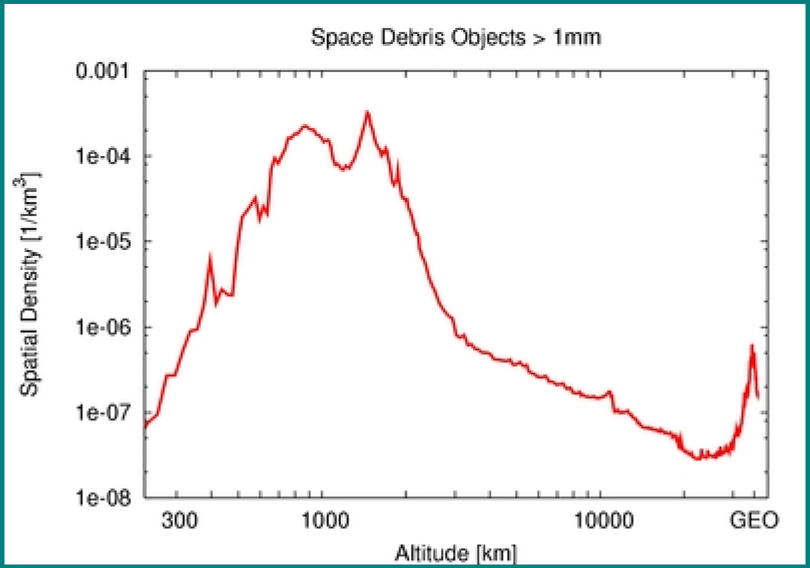


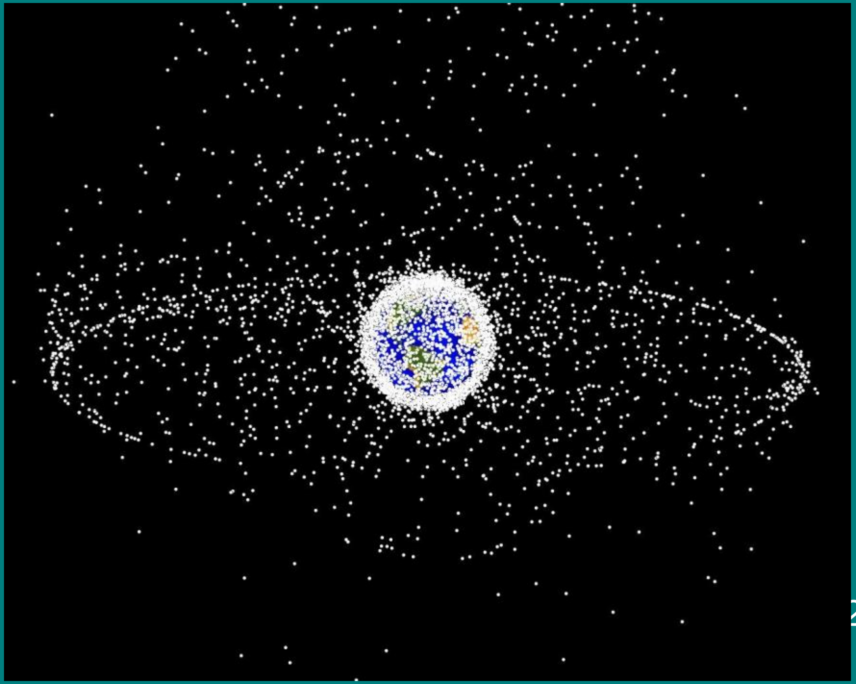
- Passive or active thermal control of a spacecraft is mandatory.



Chapter IV: The environment of a space mission

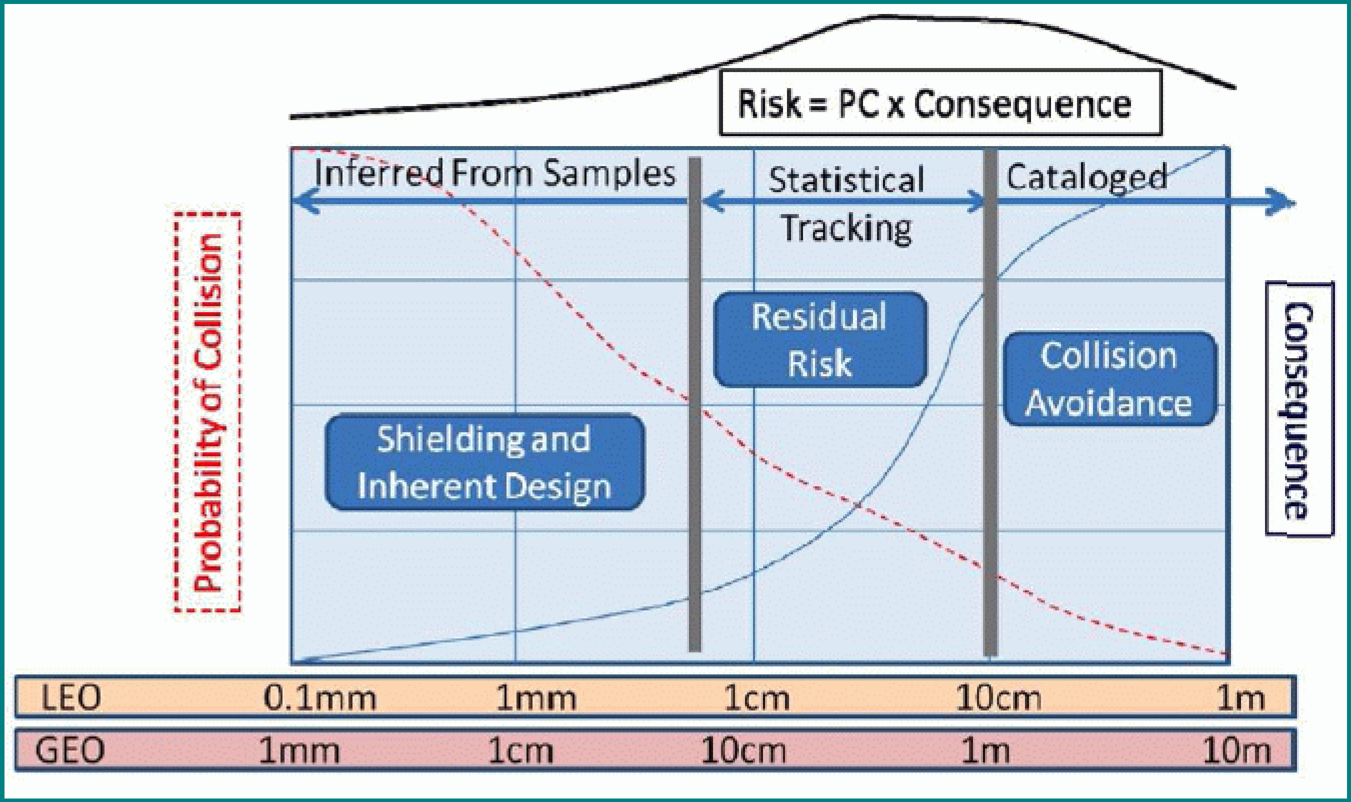
- Micrometeorites of natural origin are usually less dangerous than artificial space debris (more compact and more massive ⇒ less affected by aero-braking in LEO).
- Only the largest debris (> 10cm) are well known (monitored by radar).



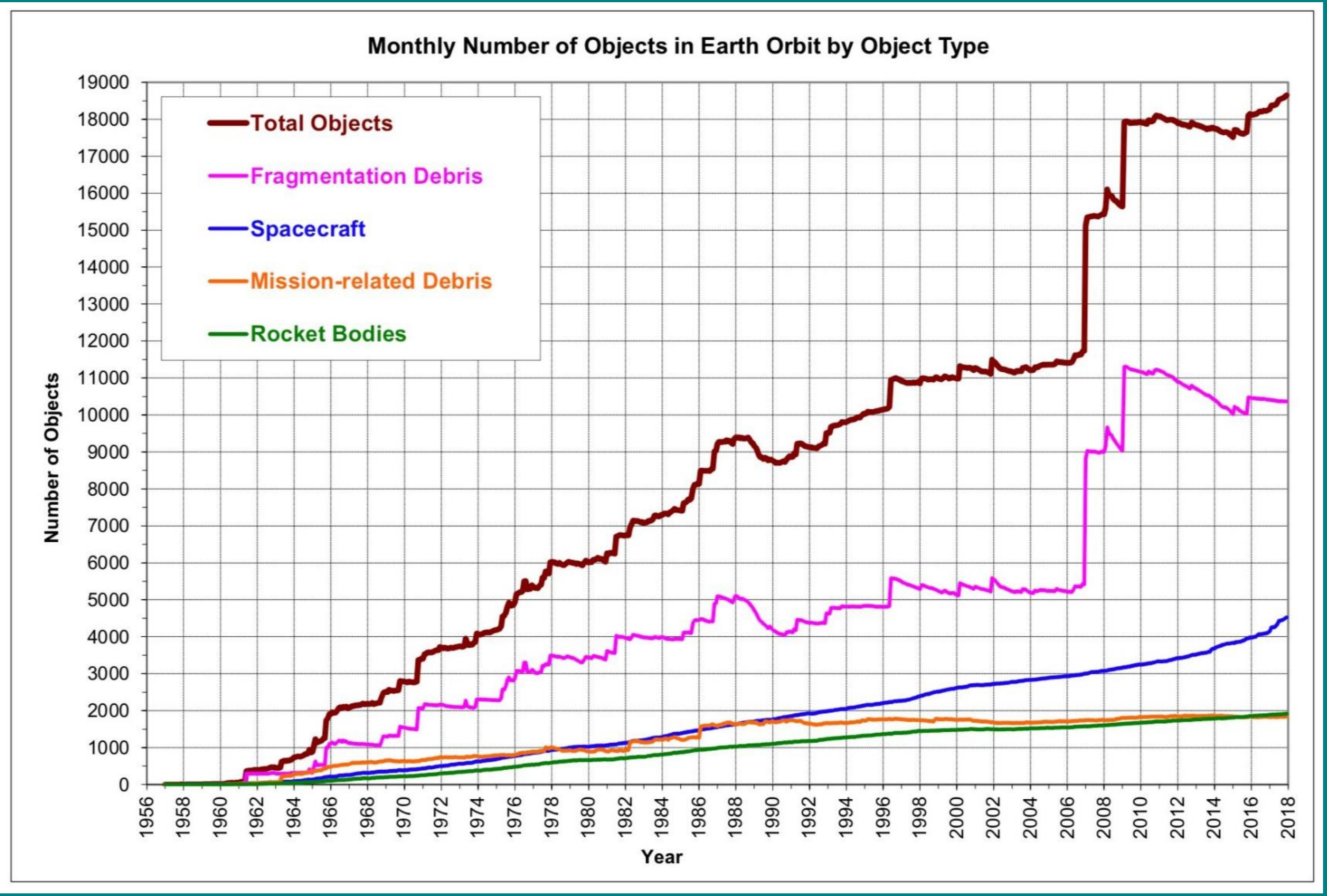


Chapter IV: The environment of a space mission

- Risk associated with a collision with a space debris depends on the probability of such an event and its consequences:



- Collisions lead to new debris → runaway process if no measures are taken (Kessler syndrome)!



Chapter IV: The environment of a space mission

- Collisions with space junk: 1996 Cerise + debris of Ariane launcher, 2009 Iridium 33 + Kosmos 2251
- Solution: prevent collisions and mitigate the risks. Avoid explosions by emptying the tanks of spent rocket stages; favour atmospheric re-entry for satellites in LEO; graveyard orbit beyond the GEO,…
- Lagrangian points: heliocentric graveyard orbit beyond the terrestrial orbit (e.g. Herschel)
- Certain military operations (China) deliberately create debris to test anti-satellite weapons!

Chapter IV: The environment of a space mission

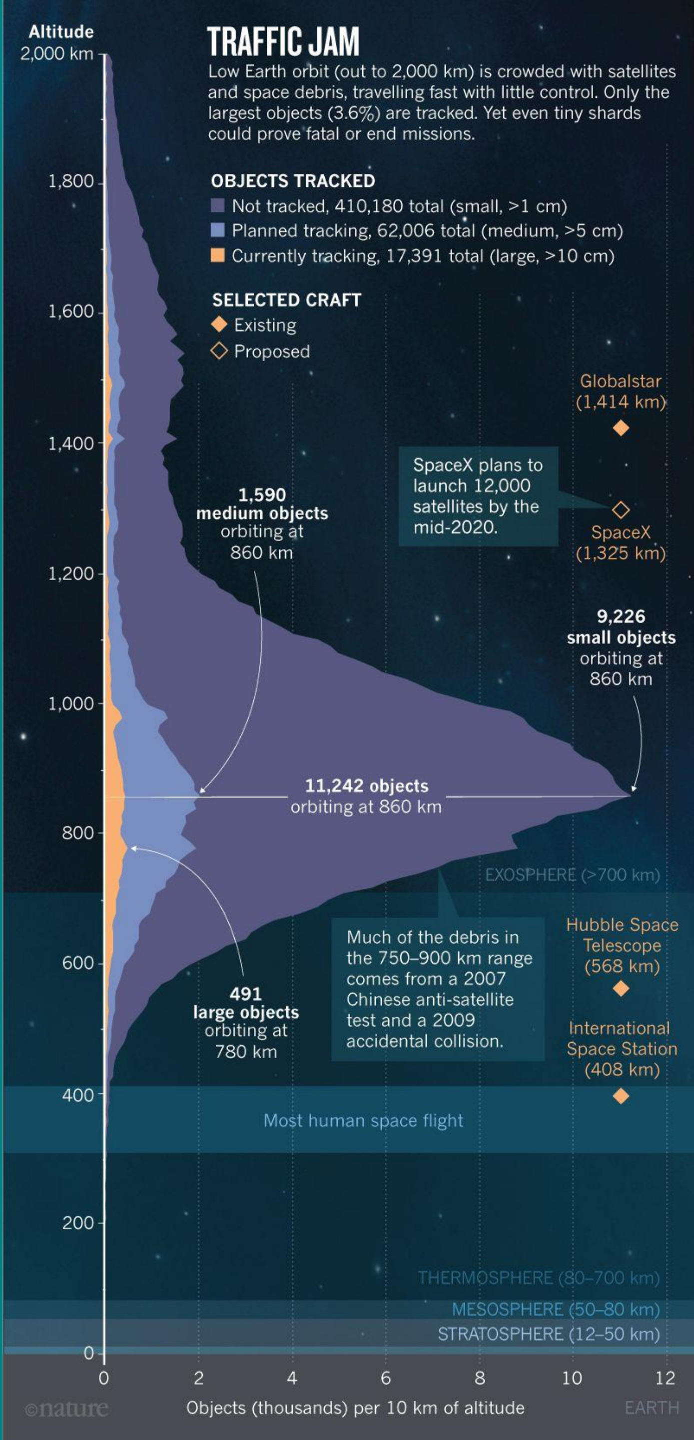
- Animation space debris between 1958 and the year 2000.

Chapter IV: The environment of a space mission

- Some CEOs with a huge ego also create space debris…

Chapter IV: The environment of a space mission

- Multiplication of satellite constellations increases risk of collisions.

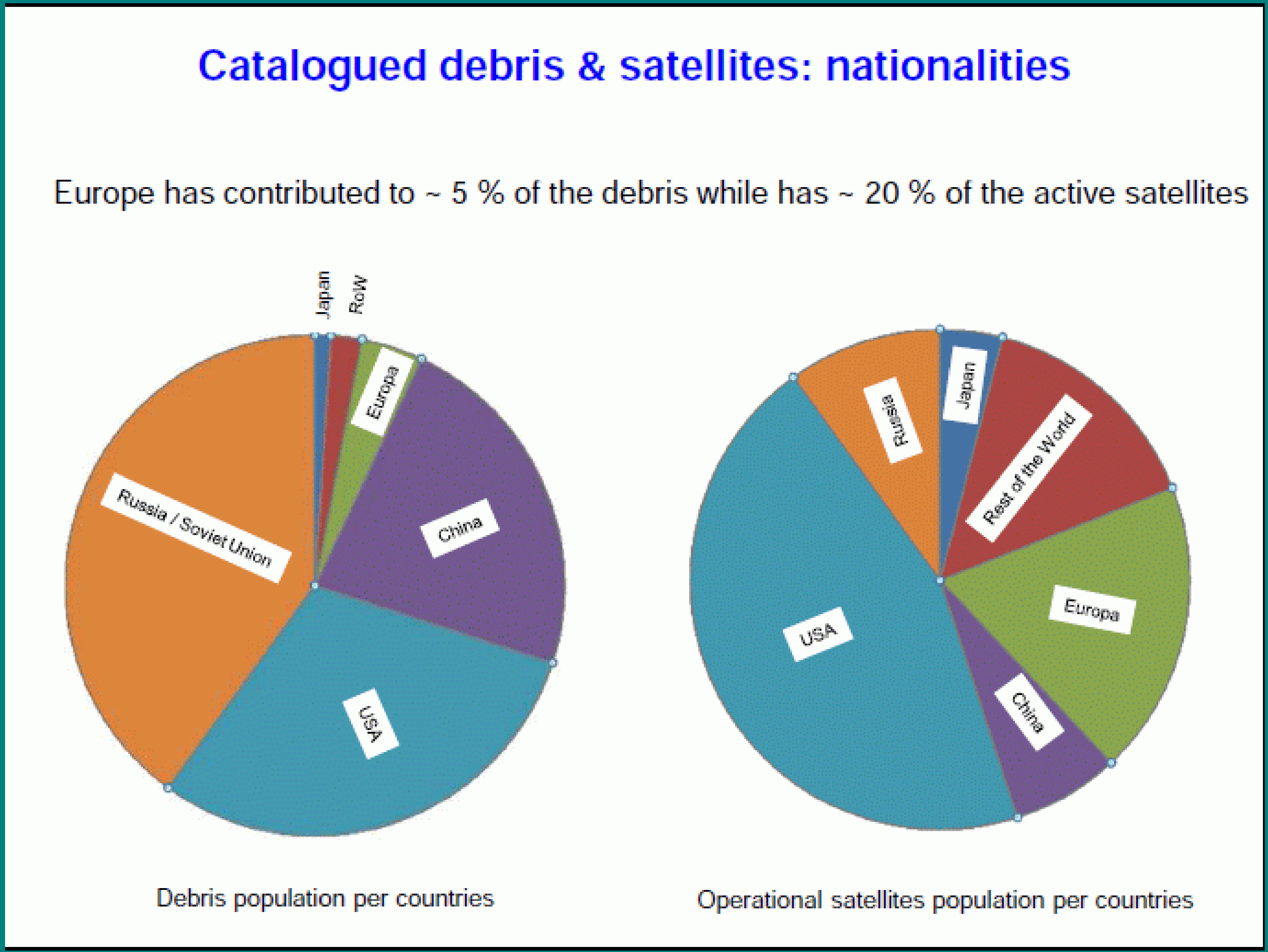


Chapter IV: The environment of a space mission

Active debris removal concepts:

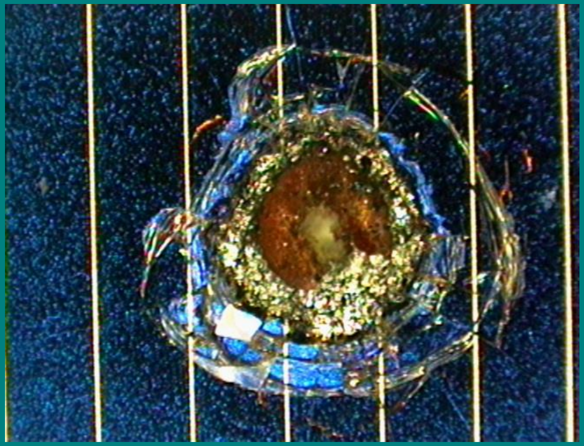
- Collector spacecraft (robotic arm, net,…).
- Lasers to sublimate small debris.
- Ion beams directed on debris to produce thrust.
- Conductive tethers (several km) to lower debris altitude.
- Solar sails.
- Micro-satellites to dock on debris
- Exploitation of “natural” perturbations (Moon, J2, etc.) to increase orbital eccentricity.
- Foam to increase drag.
- Etc.

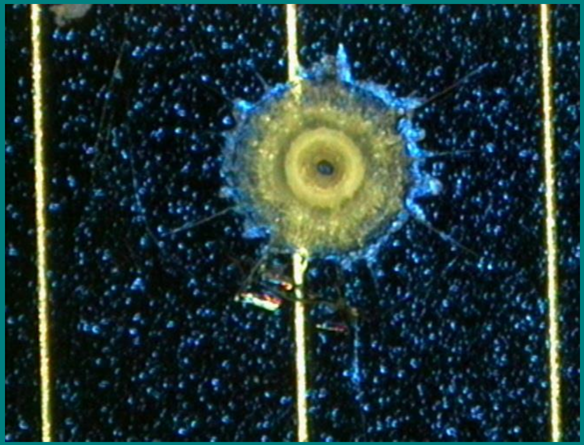
- It's each nation's responsibility to prevent the multiplication of space debris!

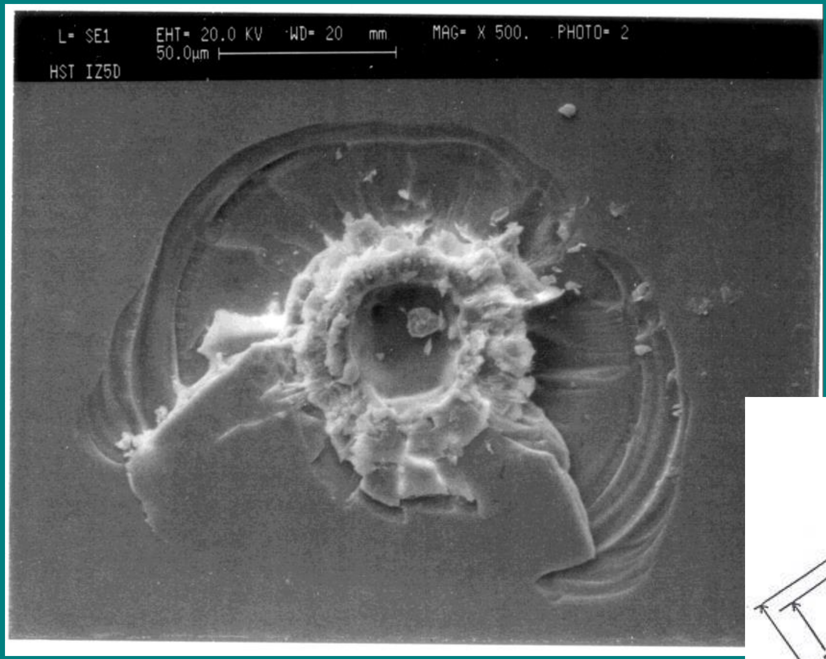


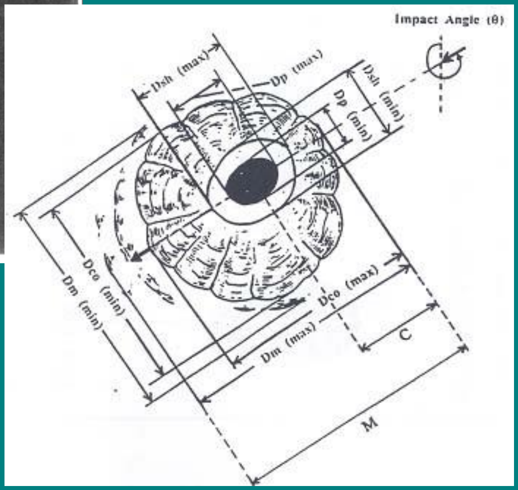
Chapter IV: The environment of a space mission

- ESA and NASA use models to evaluate the risks of collisions with micrometeorites and/or debris. These models are calibrated with old solar panels of the HST.









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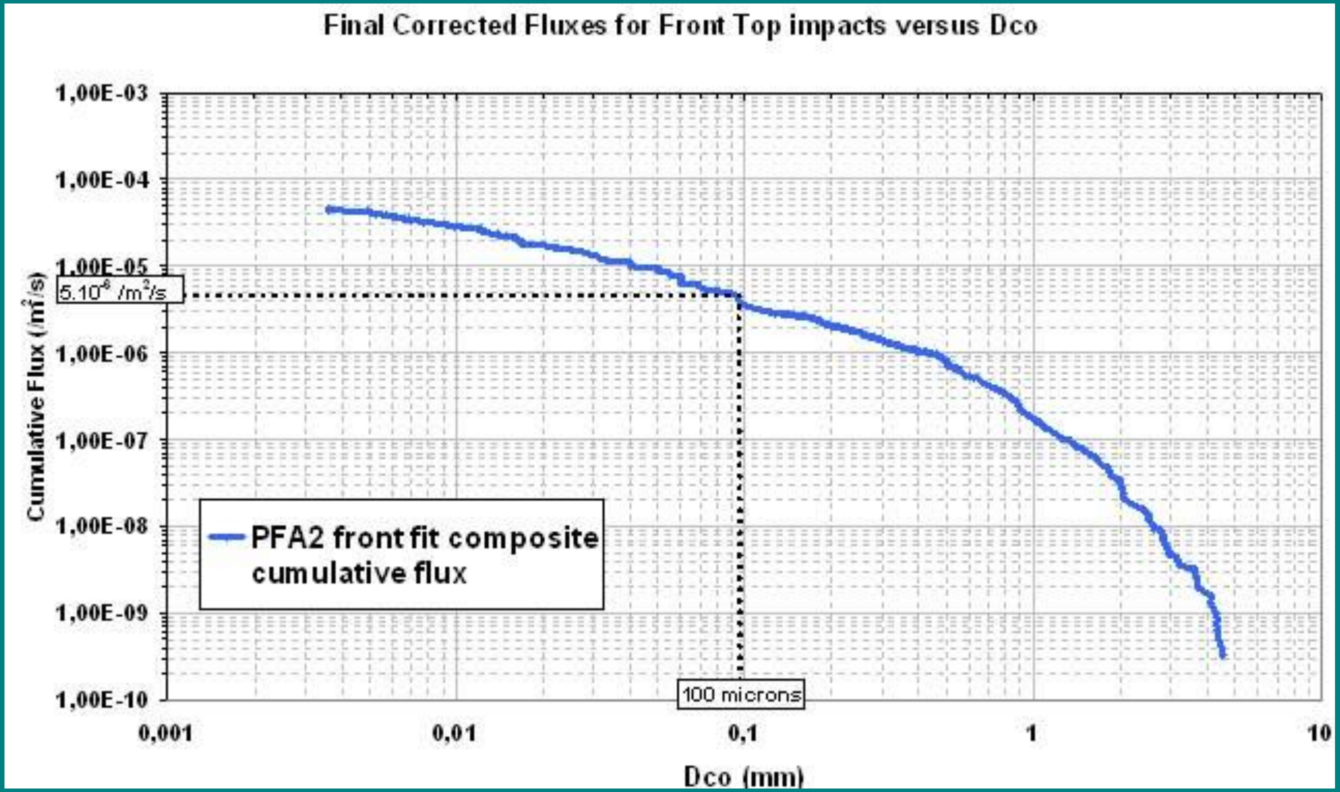


Chapter IV: The environment of a space mission

- Outgassing: when the external pressure drops below the vapour pressure of the material.
- Risk of molecular contamination of cold surfaces (mirrors looking permanently towards the deep space, cooled detectors,…).
- Solutions: avoid materials that are prone to outgassing, heat contaminated parts,…
- Microgravity: capillarity becomes important $\Rightarrow$ difficulties to empty reservoirs (e.g. for the propulsion).

Chapter V: The basic components of a spacecraft

- Restrictions related to space activities
- Electrical power supply
  1. Solar arrays
  2. RTGs
- Attitude and orbit control
  1. Gyroscopes
  2. Ionic propulsion
  3. Solar sails
- Telecommunication and the ground segment

Chapter V: The basic components of a spacecraft

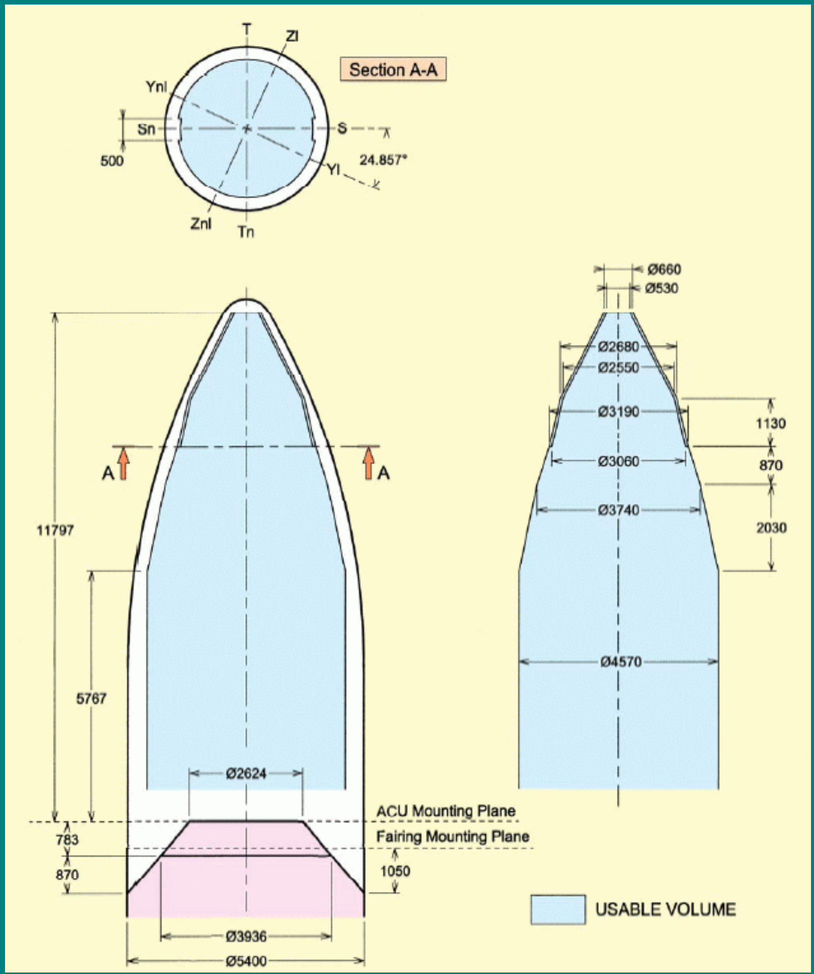
- Constraints on the design of a space mission:

1. Mass budget (rocket equation).
2. Size of the satellite: available space in the shroud.
3. Power budget limited by the size of the solar arrays and/or the output of the generator (mass).
4. Telemetry limited by on-board processing capabilities, size of the antenna and coverage of the ground stations.
5. Budget… limitations on manpower and number of spacecraft.

Launcher	Diameter[1]	Mass HEO	Mass GTO[2]	Mass LEO[3]	SSO	Mass L1/L2[4]	Mass Escape[5]
A5 ECA	4570	7000 to 9000 kg depending on orbit	9600 kg	> 10 000 kg in 800 km	>10 000 kg, 800 km	6600 kg	4300 kg (V_{inf}=3.5 km/s)
Soyuz Fregat 2B	3800 (ST)	1400 kg to 2600 kg depending on orbit	3060 kg	5300 kg	4 900 kg, 660 km	2000 kg	1600 kg (V_{inf}=0)
Vega	2380	No information yet available		2300 kg (5.2°)	1 500 kg, 700 km	*(500 Kg)*	N/A
Rockot-KM	2100 / 2380	N/A	N/A	1850 kg (63°)	1 000 kg 800 km	*(500 Kg)*	N/A

Chapter V: The basic components of a spacecraft

Example: available volume in the shroud of Ariane V ECA
3 different heights: 12.7, 13.8 and 17m.



Chapter V: The basic components of a spacecraft

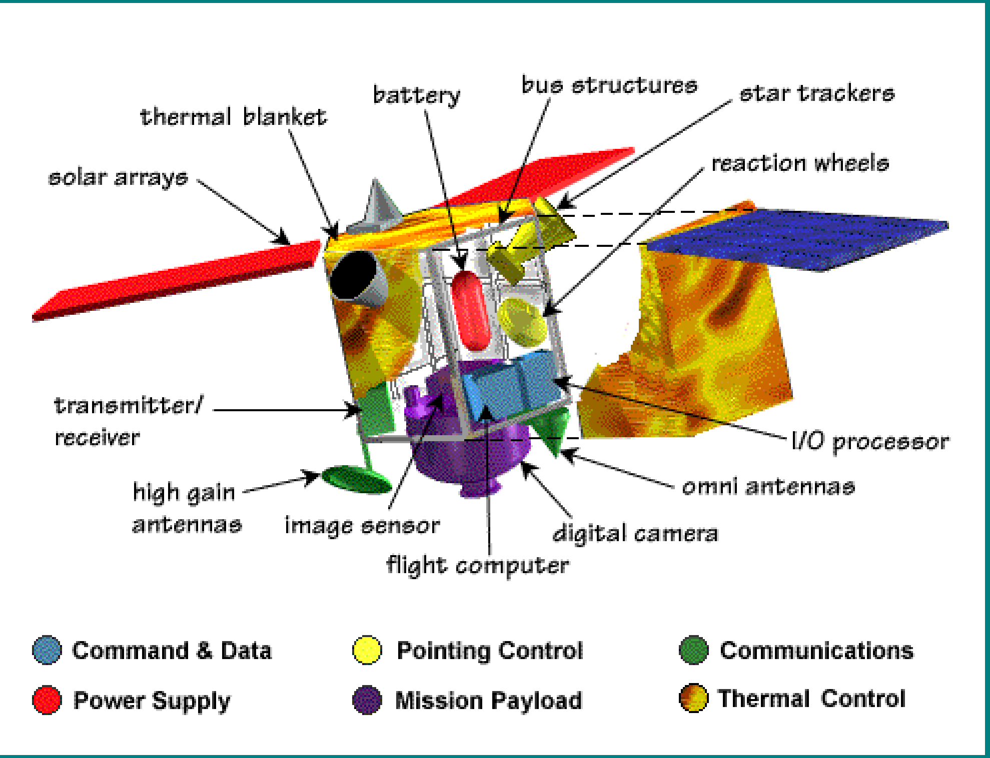
- A technology considered for a space mission must be “space-qualified” through a number of tests. The degree of maturity is quantified through the Technology Readiness Level (TRL):

Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
9	Actual system "flight proven" through successful mission operations

Chapter V: The basic components of a spacecraft

- Every scientific spacecraft features a service module and a payload (the instruments).
- The service module

1. provides the *mechanical stability* of the spacecraft,
2. contains the *electrical power generators*,
3. ensures *communications with the ground*,
4. hosts the *attitude control system.*



Chapter V: The basic components of a spacecraft

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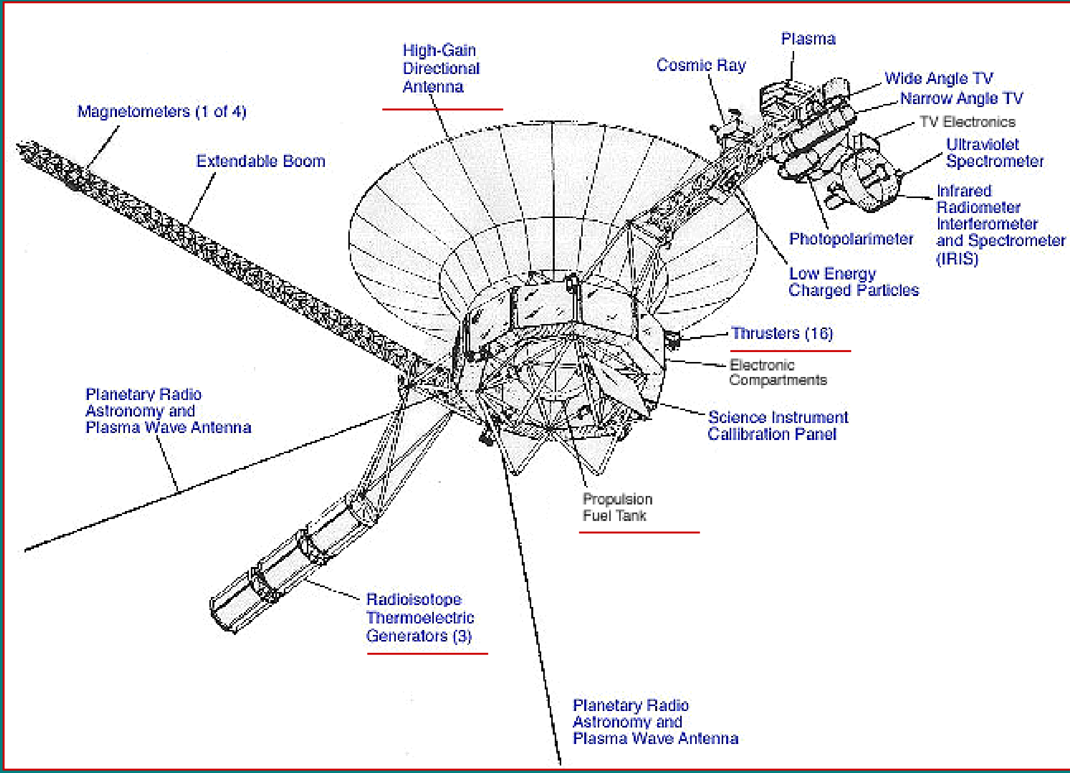
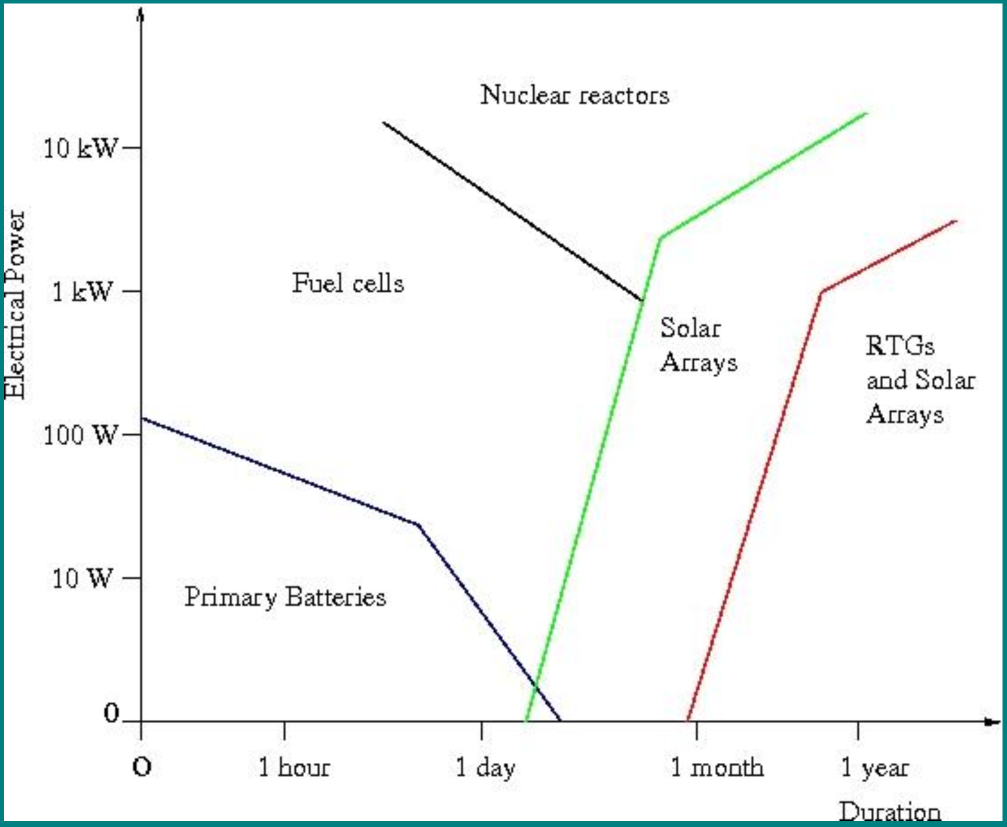


Chapter V: The basic components of a spacecraft

- The optimal solution for the production of electricity depends on the required power and the time over which it must be available.
- For atmospheric probes, one frequently uses primary batteries (non-rechargeable). Fuel cells are only used for manned spacecraft.



Chapter V: The basic components of a spacecraft

- For satellites orbiting the Earth, the production of electrical power mostly relies on solar arrays (photovoltaic). Their efficiency is currently < 29%.
- Total power radiated by the Sun = $3.9\ 10^{26}$ W. At 1AU, flux received = 1370 W m^{-2} $\Rightarrow$ maximum production of 350 W per m^2 of solar arrays (at best!!).
- Solar flux decreases as r^{-2} $\Rightarrow$ difficulty to use solar arrays in the outer Solar System (beyond the asteroid belt).

Chapter V: The basic components of a spacecraft

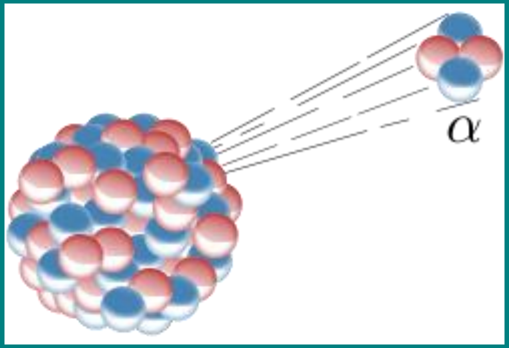
- Rosetta: 64m^2 of solar panels $\Rightarrow$ allow to operate out to 5.25 AU.
- ISS: 4500m^2 of solar arrays provide 110 kW

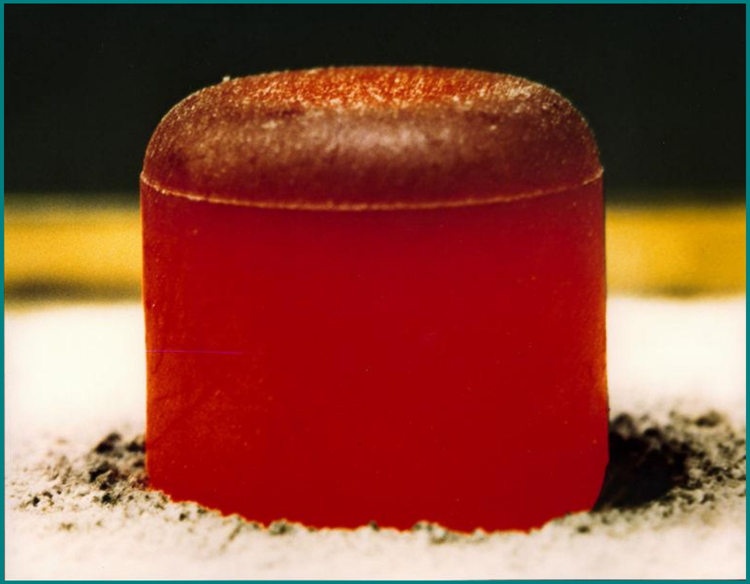
Chapter V: The basic components of a spacecraft

- HST: $2 \times 2.6m \times 7.1m$ ($36.9m^2$) provide 2.8 kW of electrical power.
- LEO of 97 min. $\Rightarrow$ eclipses of 36 min. per orbit.
- Batteries able to store the energy needed for 7.5 hours of nominal operations.
- Solar arrays replaced during service mission SM3B (Columbia, March 2002).

Chapter V: The basic components of a spacecraft

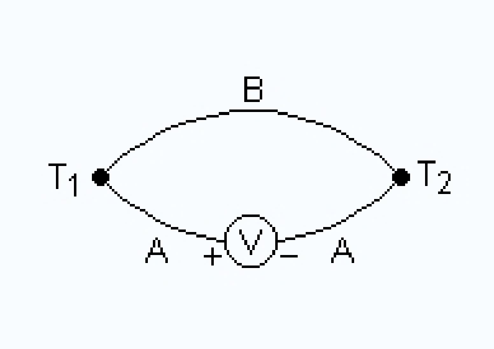
- In the outer Solar System, one has to use radio-isotope thermoelectric generators (RTG). Working principle: radioactive decay of radio-isotope releases heat.
- Plutonium 238 decays into uranium 234 + an alpha particle releasing energy (half-life time of 87.7 years).





Chapter V: The basic components of a spacecraft

- The heat is converted into electricity using thermocouples (Seebeck effect)



$$V = \int_{T_1}^{T_2} \left(S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T) \right) dT$$

- Problems: half-life time must be short enough to release enough energy and long enough to produce energy over the entire lifetime of the mission.
- Low efficiency (< 10%) of the thermocouples.
- Shielding of the electronics.
- Ecological problems (launch…)

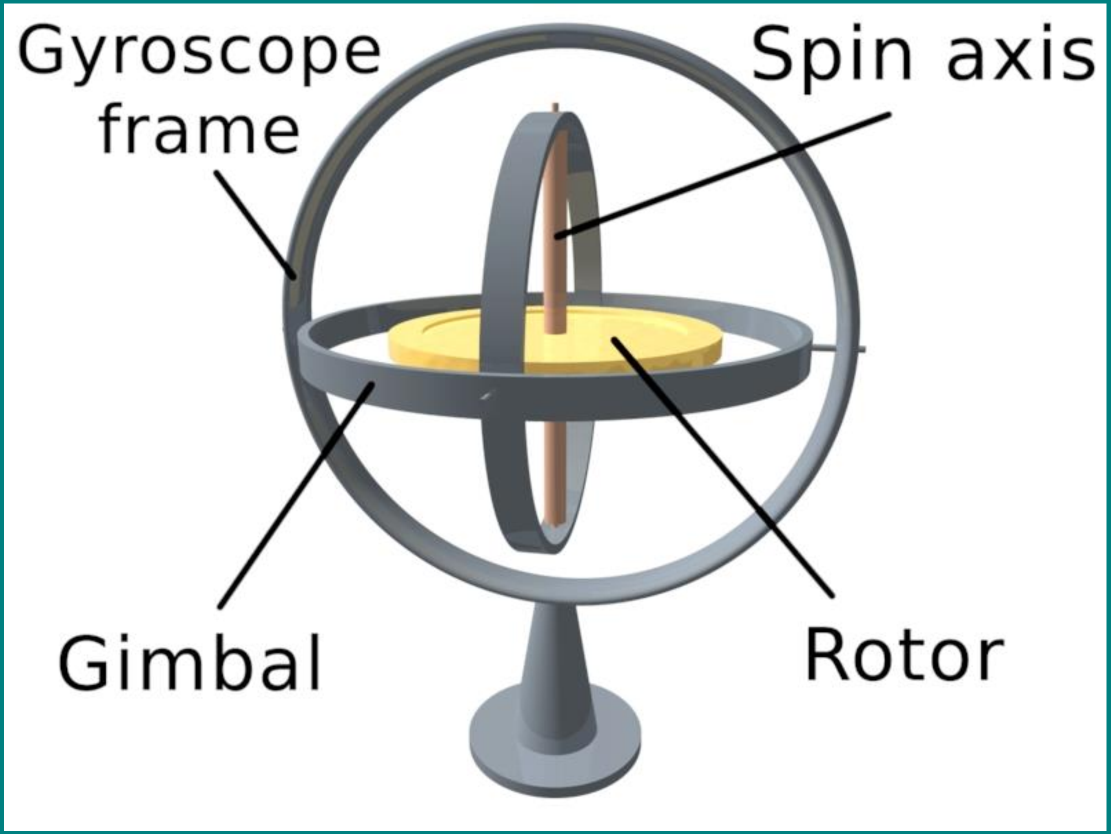
Chapter V: The basic components of a spacecraft

- Attitude and orbit control:

1. Three-axes stabilized satellites
2. Spin-stabilized satellites.

Chapter V: The basic components of a spacecraft

- Attitude control without consumption of fuel using gyroscopic reaction wheels (based on the conservation of angular momentum).



Chapter V: The basic components of a spacecraft

- Classical chemical propulsion is limited. Ideal interplanetary trip: fast and carrying a lot of mass!
- But: limitations due to the rocket equation:

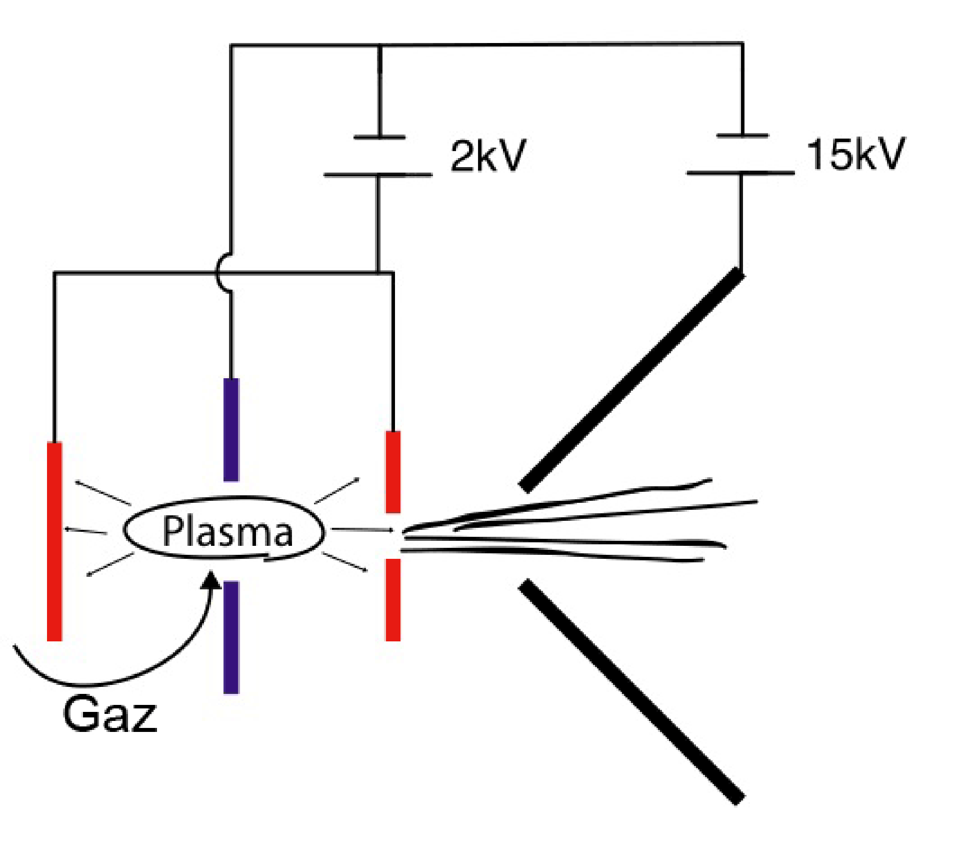
$$\frac{m_{final}}{m_{init}} = \exp\left(\frac{-\Delta v_{\mathrm{total}}}{v_{\mathrm{ej}}}\right)$$

- Possible solution: increase v_{ej} (limited to 3 - 4 km/s for chemical propulsion)?
- Possibilities: ionic propulsion (ions ejected at very high velocity).

Chapter V: The basic components of a spacecraft

- Working principle: use electric or magnetic power to eject ions at 15 –100 km/s.

Gas ionised in a chamber via electrical discharges, confined by a magnetic field, accelerated and focalised by an electrical field (electrodes) and ejected at high velocities. Outside the engines, gas neutralizes at the level of the nozzle via recombination with free electrons.



Chapter V: The basic components of a spacecraft

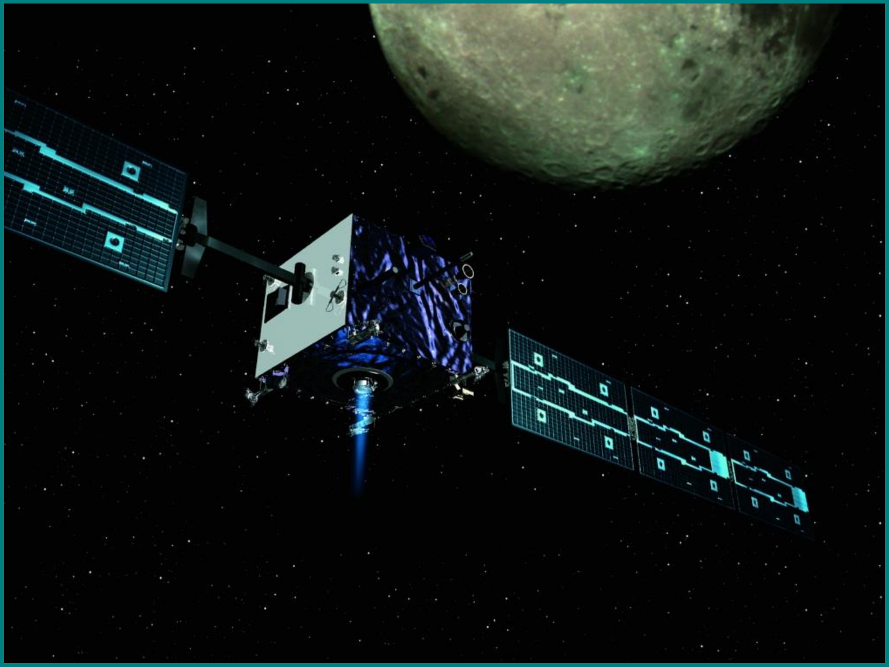
- The thrust of these engines is very low (~ 0.07 N).
- However, they can operate over a very long time (5000 hours in the case of SMART-1).
- Compared to conventional engines, the **integrated** thrust per kg of fuel is about 5 times higher.

	Monopropellant thruster	Fregat Main Engine	SMART 1 Thruster
Propellant	Hydrazine	Nitrogen tetroxide, dimethyl hydrazine	Xenon
Specific impulse v_{ej}/g_0 (s)	200	320	1640
Thrust $\lvert\frac{dm}{dt}\rvert v_{ej}$ (N)	1	1.96×10^4	6.80×10^{-2}
Thrust time (h)	46	0.24	5000
Propellant mass (kg)	52	5350	80
Total impulse (Ns)	1.1×10^5	1.72×10^7	1.2×10^6

Chapter V: The basic components of a spacecraft

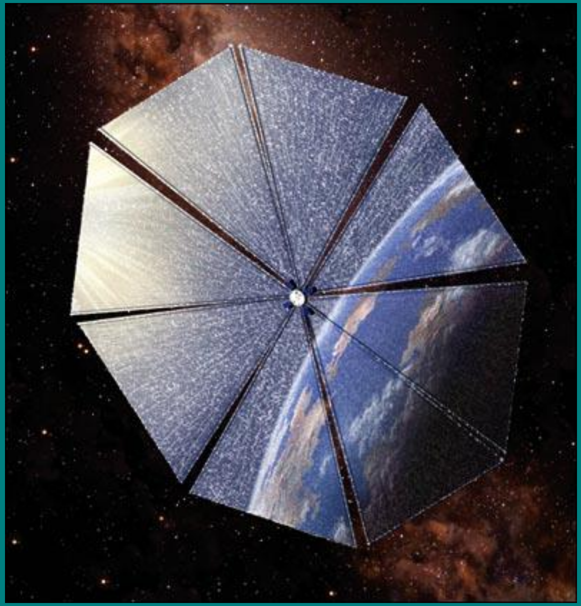
- Problems of the ionic propulsion: electrical power required (14 kW/N of thrust for plasma engines)
- ⇒ Solar arrays can provide this power only in the inner Solar System. Beyond the asteroid belt, other generators are required (RTG, fuel cells…)

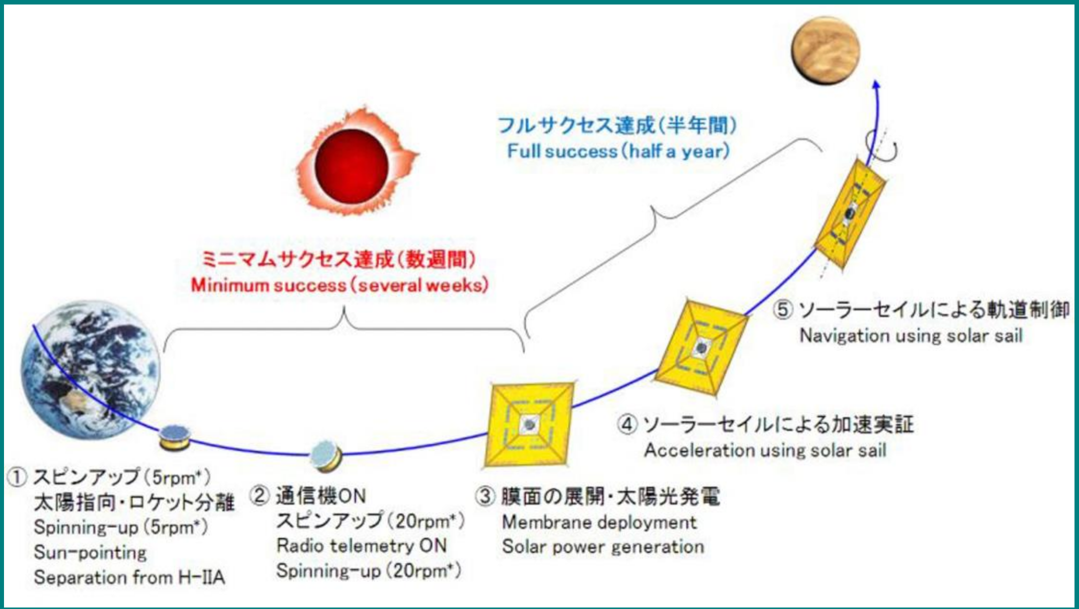
- Example SMART-1 (ESA) has used 80 kg of Xenon gas to travel to the Moon in 13 months.



Chapter V: The basic components of a spacecraft

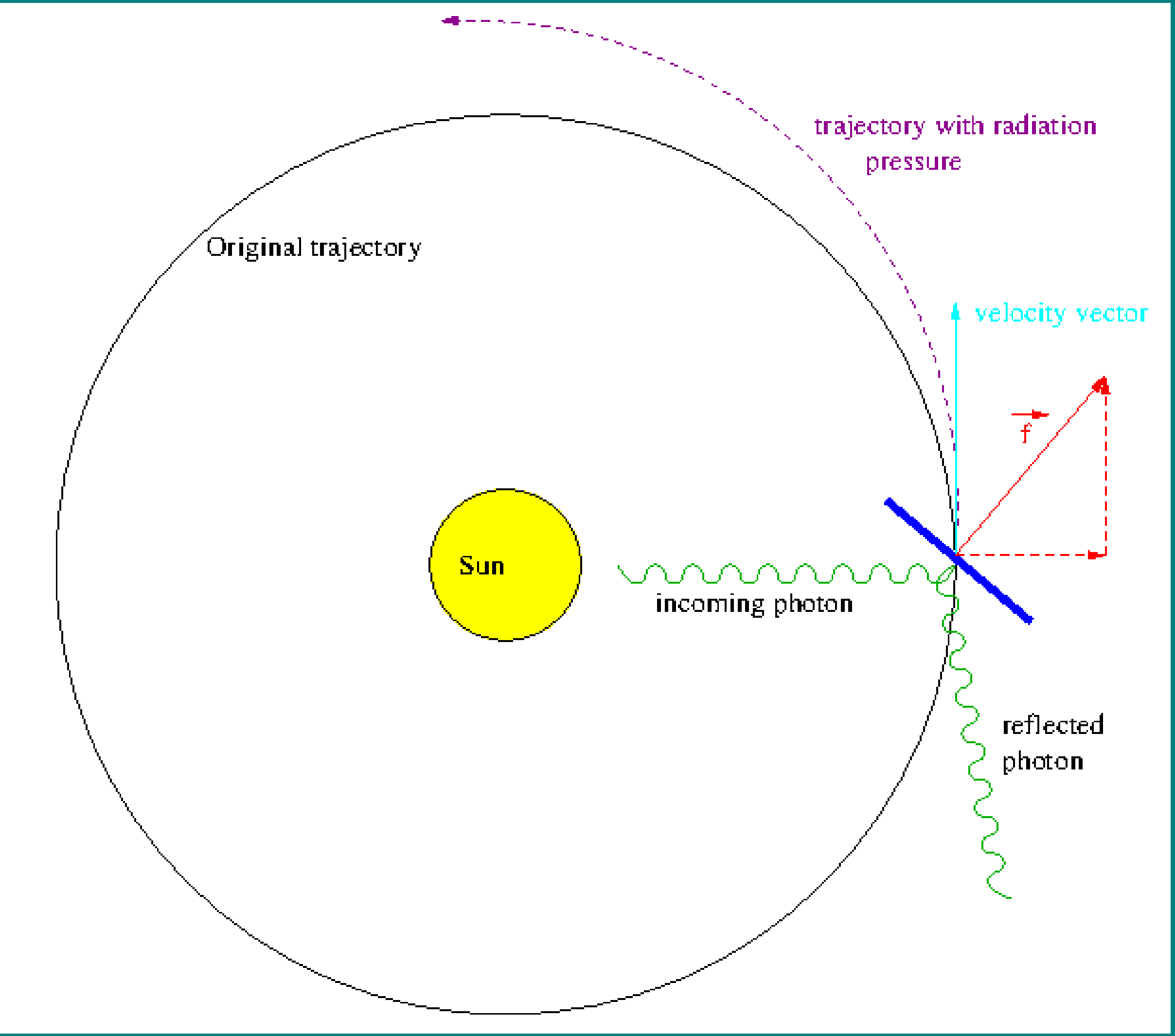
- Solar sails: sail with 100% reflectivity, powered by radiation pressure from the Sun. No fuel required!
- However, to produce a thrust of 1N, one needs a solar sail of 220 000 m^2!
- Ex.: Cosmos 1 (600 m^2) in 2005 (launch failed).
- IKAROS (173 m^2) in 2010, successful flyby of Venus





Chapter V: The basic components of a spacecraft

- How does a solar sail allow travelling towards the outer Solar system?



Chapter V: The basic components of a spacecraft

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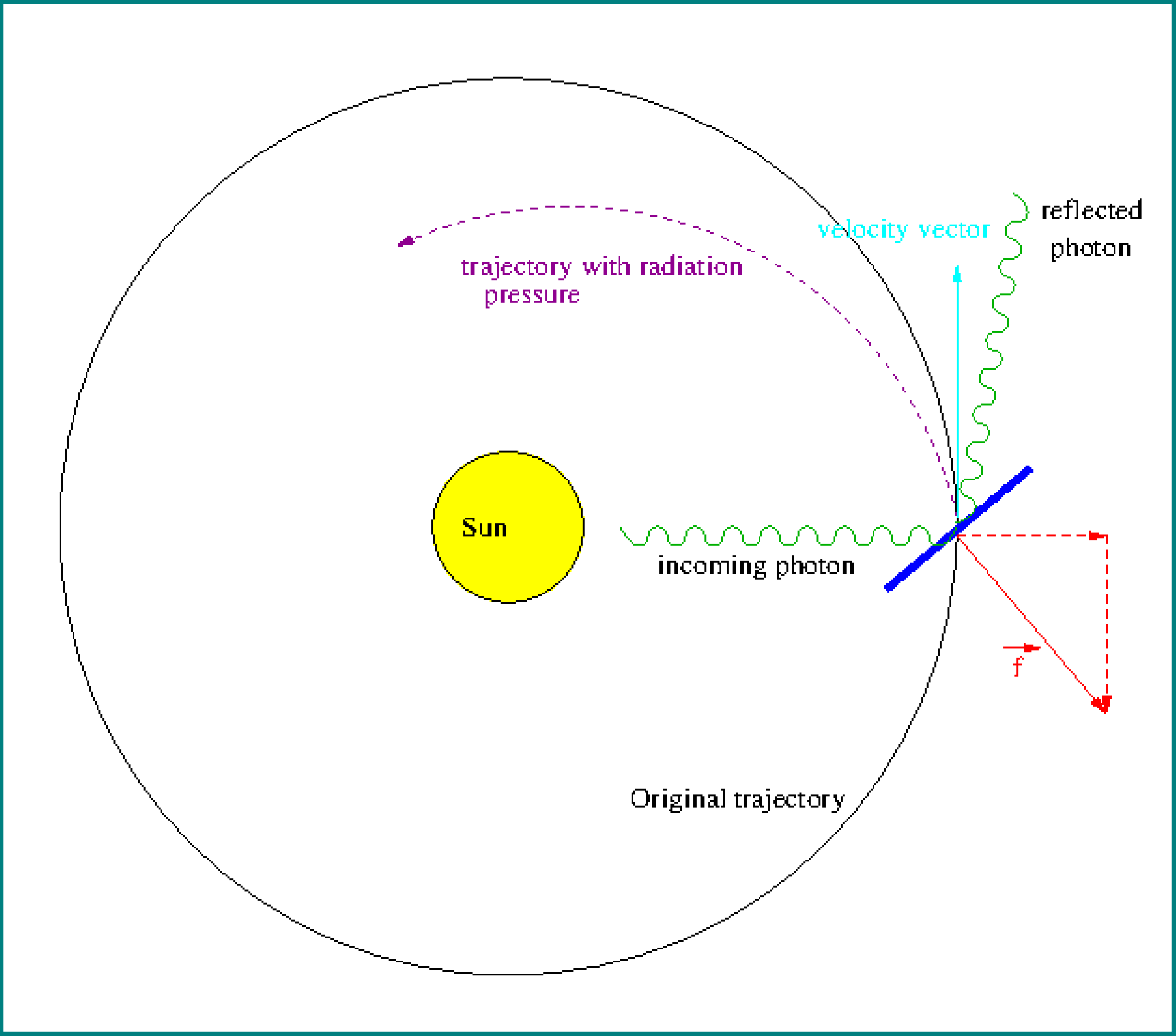


Chapter V: The basic components of a spacecraft

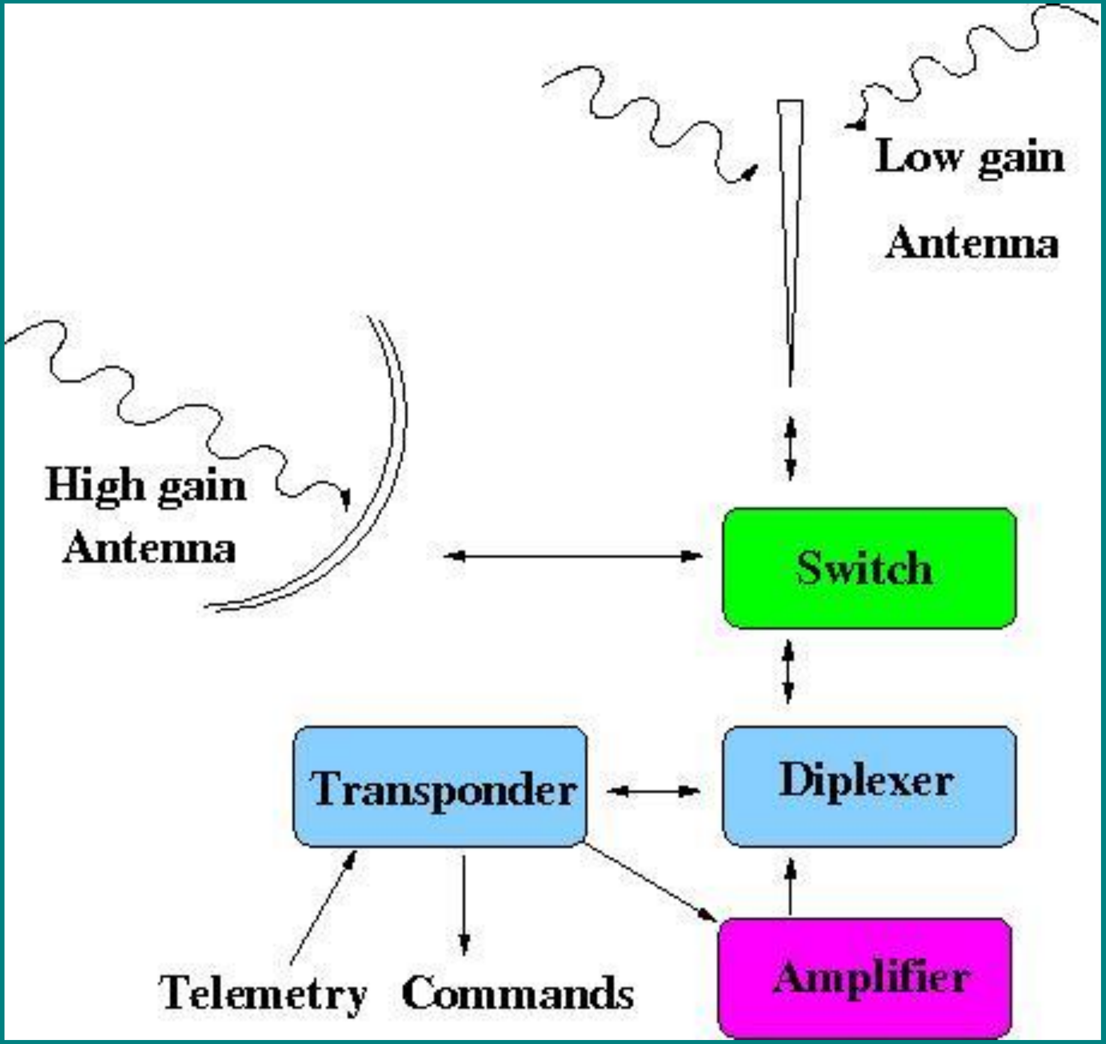
- Telemetry and communications with the ground:

1. Determine the spacecraft's velocity (Doppler effect)
2. Determine its distance (time required for communications at the speed of light)
3. Determine the angular position (triangulation with two ground stations that receive the signal from the satellite simultaneously).

- Telecommunications use certain wavebands in the micro-waves.

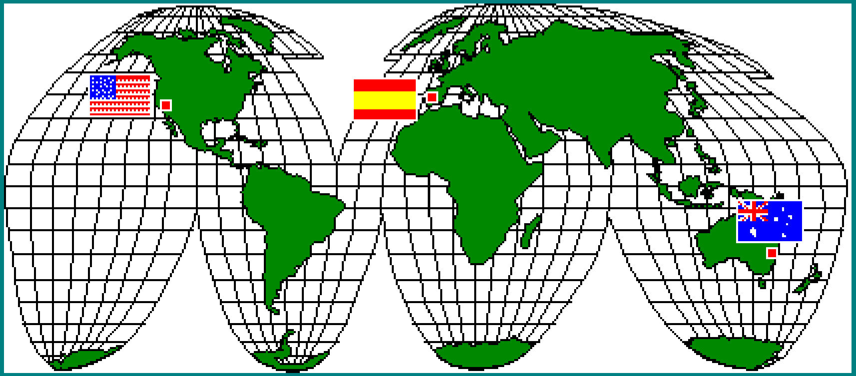
Chapter V: The basic components of a spacecraft

- Satellites feature two antennas: a high-gain directional antenna and a low-gain omnidirectional antenna.



Chapter V: The basic components of a spacecraft

- Ground segment: antennas allowing communication with the spacecraft (e.g. Deep Space Network, DSN):



Chapter V: The basic components of a spacecraft

- Science Operation Centre and Mission Operation Centre: engineers and scientists who take care of the operation of the mission.

Chapter VI: Atmospheric probes and landers

- Atmospheric entry
- Descent to the surface and landing
  1. Celestial body with an atmosphere
  2. Celestial body without an atmosphere
- Balloons
- In-situ measurements:
  1. Fixed platforms
  2. Rovers
- Planetary protection

Chapter VI: Atmospheric probes and landers

- Upon entering a planetary atmosphere, the probe encounters a medium with an exponentially increasing density.

$$\rho = \rho_0 \exp \frac{-z}{H} \qquad H = \frac{k\,T}{m\,g}$$

- The deceleration due to atmospheric drag can be written:

$$\frac{d\,v}{dt} = -\frac{\rho\,S\,C_D\,v^2}{2\,m}$$

- If the probe enters the atmosphere under an angle γ, then:

$$\frac{d\,z}{dt} = -v\,\sin\gamma$$

- One introduces the parameter η:

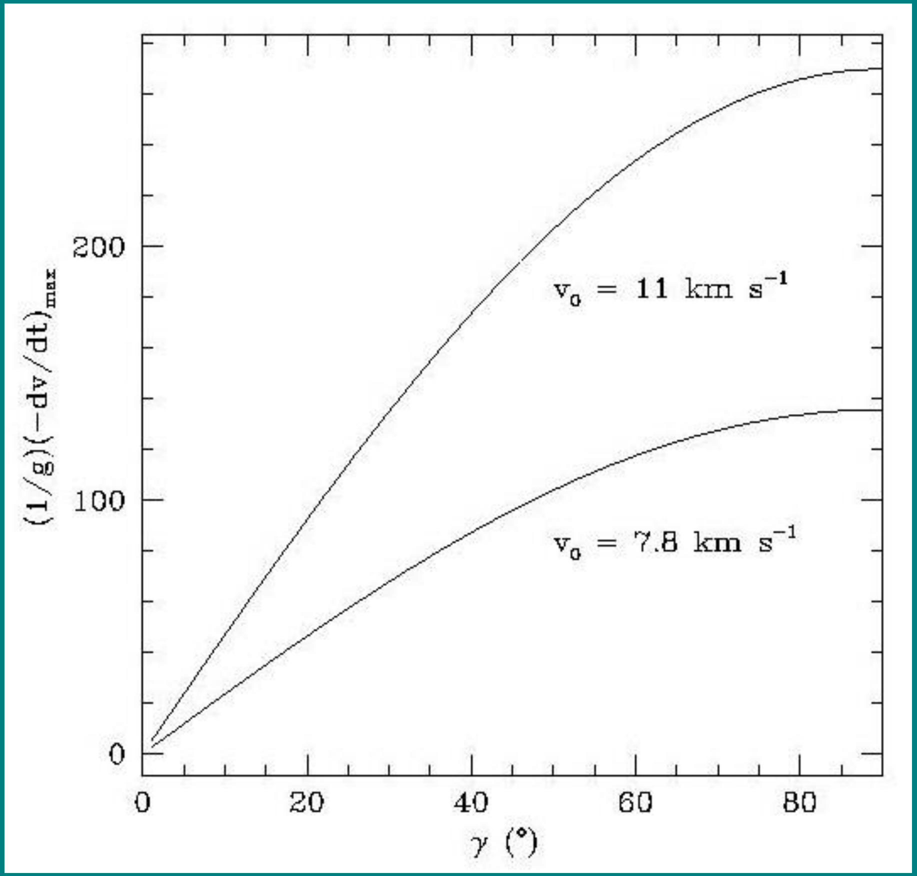
$$\eta(z) = \frac{\rho(z)\,S\,H\,C_D}{2\,m}$$

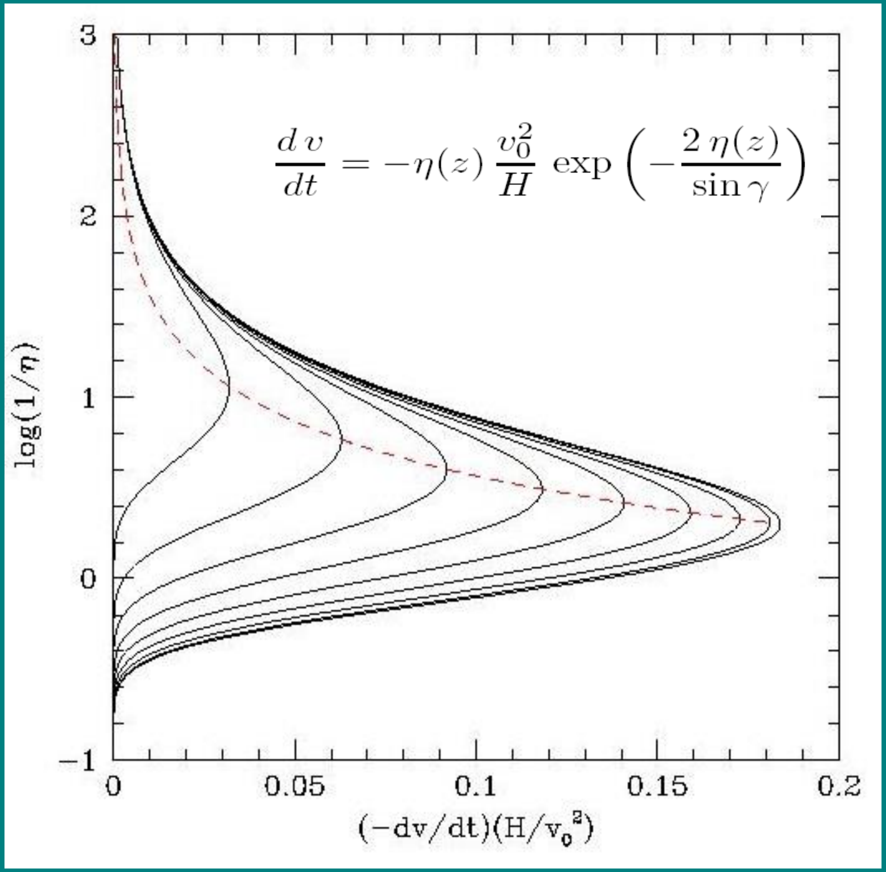
- This then yields:

$$\frac{d\,v}{dt} = -\eta(z)\,\frac{v_0^2}{H}\,\exp\left(-\frac{2\,\eta(z)}{\sin\gamma}\right)$$

Chapter VI: Atmospheric probes and landers

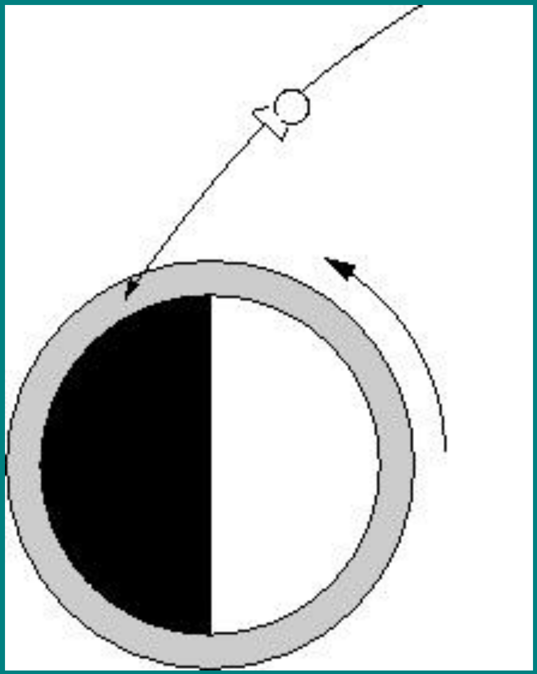
- The maximum deceleration must be limited (< 10 g for manned spaceflight). Deceleration is maximum during a ballistic entry (without aerodynamic lift).





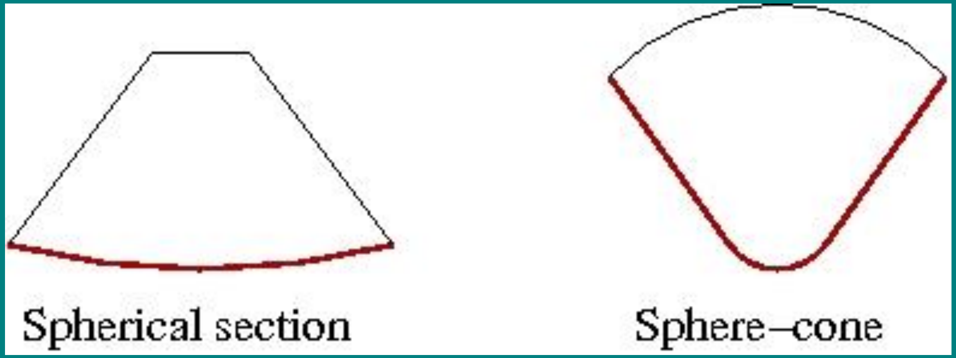
Chapter VI: Atmospheric probes and landers

- During the atmospheric entry, the kinetic energy is dissipated as heat in the gas surrounding the probe/vehicle.
- The heating is proportional to the 3rd power of the relative velocity. One tries to reduce this velocity by entering along the terminator on the “right” side of the planet.



Chapter VI: Atmospheric probes and landers

- The larger the volume of the heated gas, the lower the temperature increase → advantage to have a large C_D (blunt shape) .

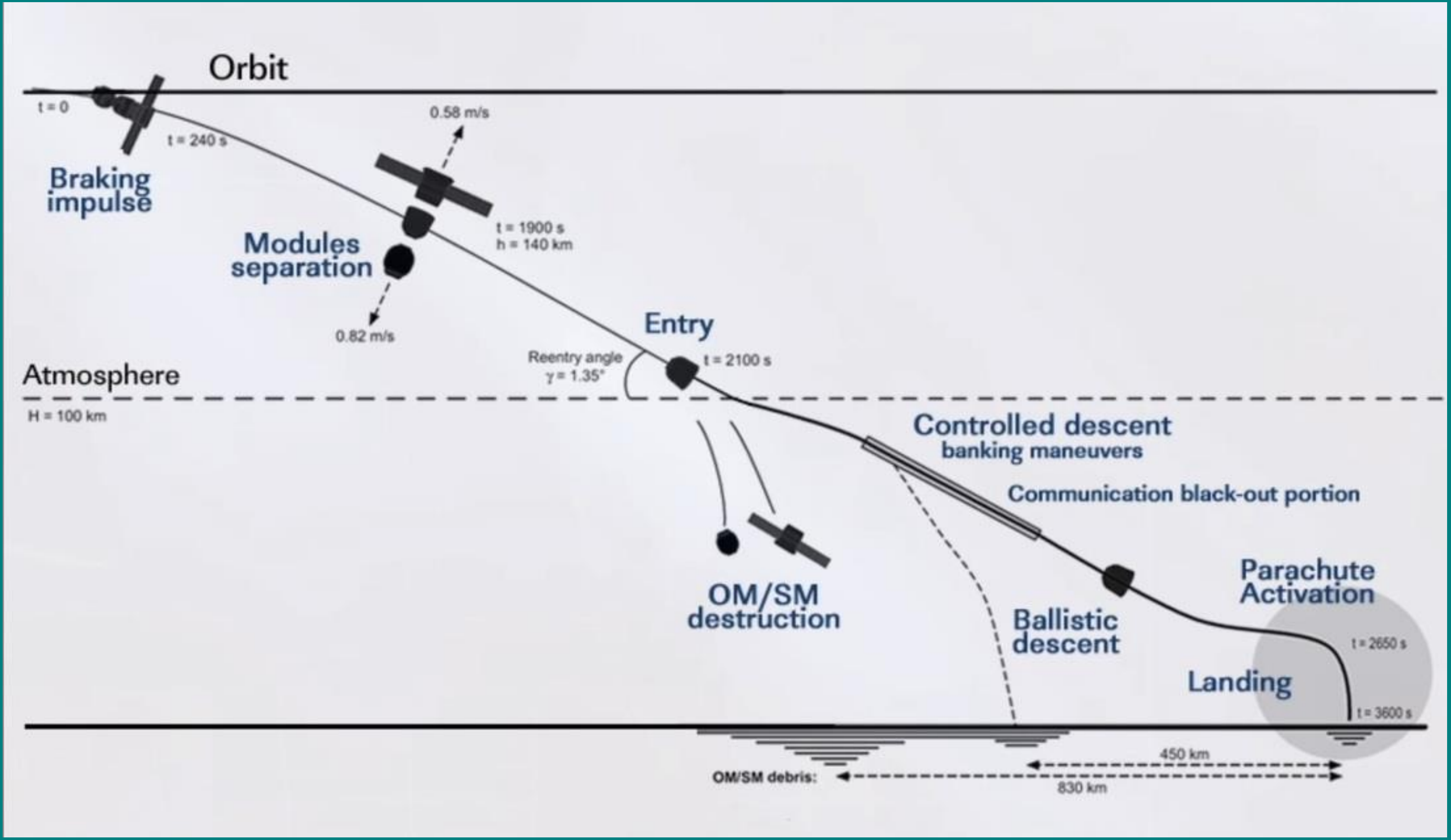


- The lift over drag ratio (L/D) plays an important role:

1. Ballistic entries (e.g. Mercury capsule) have zero lift and undergo the highest peak decelerations.
2. The larger L/D, the lower the peak deceleration, but also the longer the duration of the entry (and thus the longer the duration of the heating).

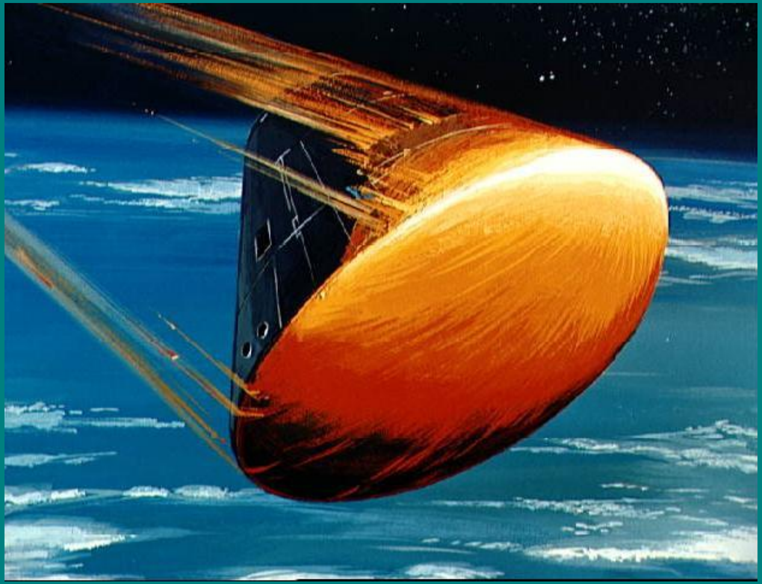
Chapter VI: Atmospheric probes and landers

- Most manned missions use some lift to reduce the peak deceleration (e.g. Soyuz capsule max. deceleration ~ 3.8g)



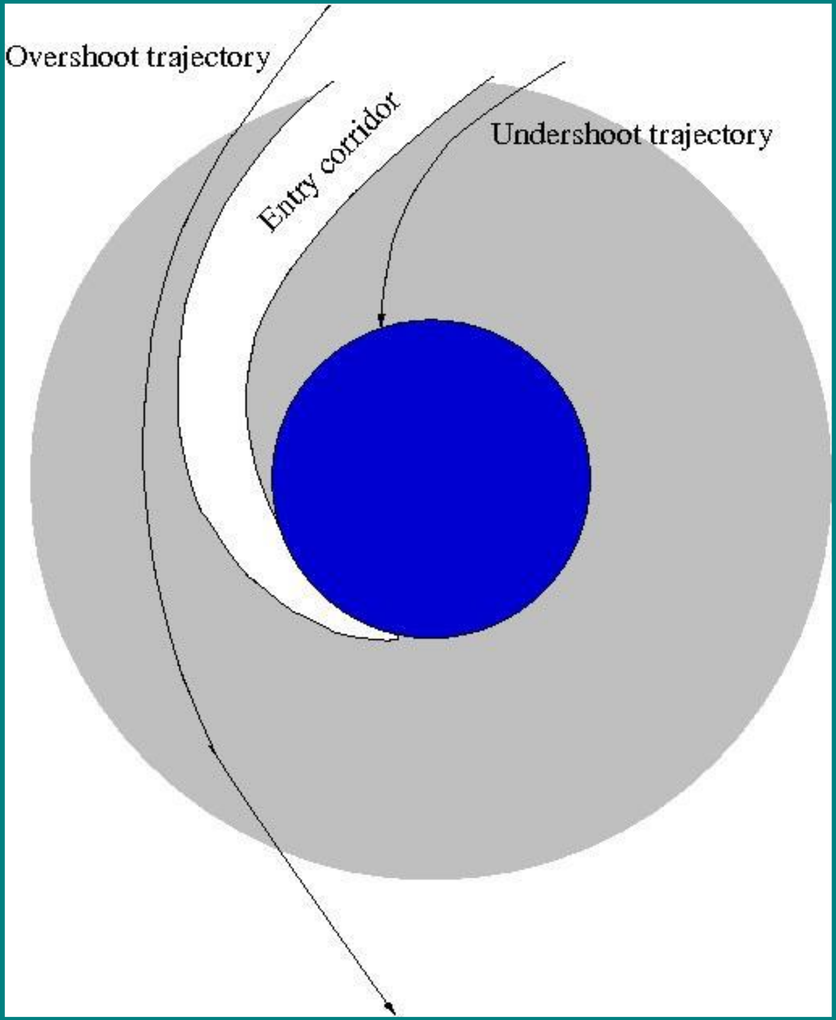
Chapter VI: Atmospheric probes and landers

- The Apollo capsule had a low L/D whilst the Space Shuttle had L/D = 1.
- Peak deceleration of the Apollo capsule was about 7.2 g, whilst it was below 2 g for the Shuttle.



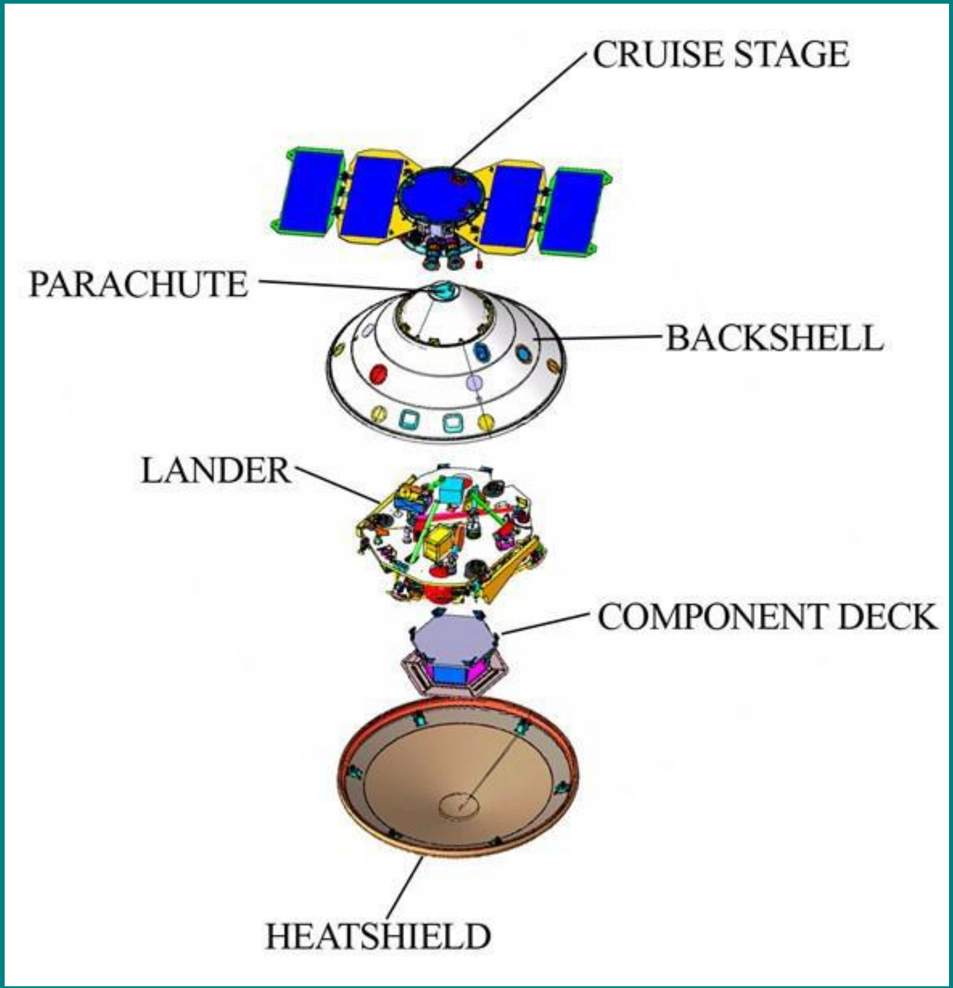
Chapter VI: Atmospheric probes and landers

- A successful entry requires a specific angle γ. If the angle is too large, the deceleration and the heating are too strong and the probe/vehicle disintegrates. If the angle is too small, the vehicle emerges again from the atmosphere.



Chapter VI: Atmospheric probes and landers

- Use an ablative heat shield (honeycomb structure) to dissipate the heat.
- The centre of gravity must be placed correctly with respect to the centre of curvature of the heat shield to avoid rotation of the probe during entry and prevent the unprotected parts of the probe from being exposed to the hot air.



Chapter VI: Atmospheric probes and landers

- Alternative to ablation: radiative heat shield that radiates most of the heat before it reaches the structure.
- The tiles of the Space Shuttle had a high emissivity and a very high insulation power.

Chapter VI: Atmospheric probes and landers

$$\frac{1}{2} S\, C_D\, \rho\, v_t^2 = m\, g$$

& $\beta = \frac{2\,m}{S\,C_D}$ $\rightarrow$ $v_t^2 = \beta \frac{g}{\rho}$

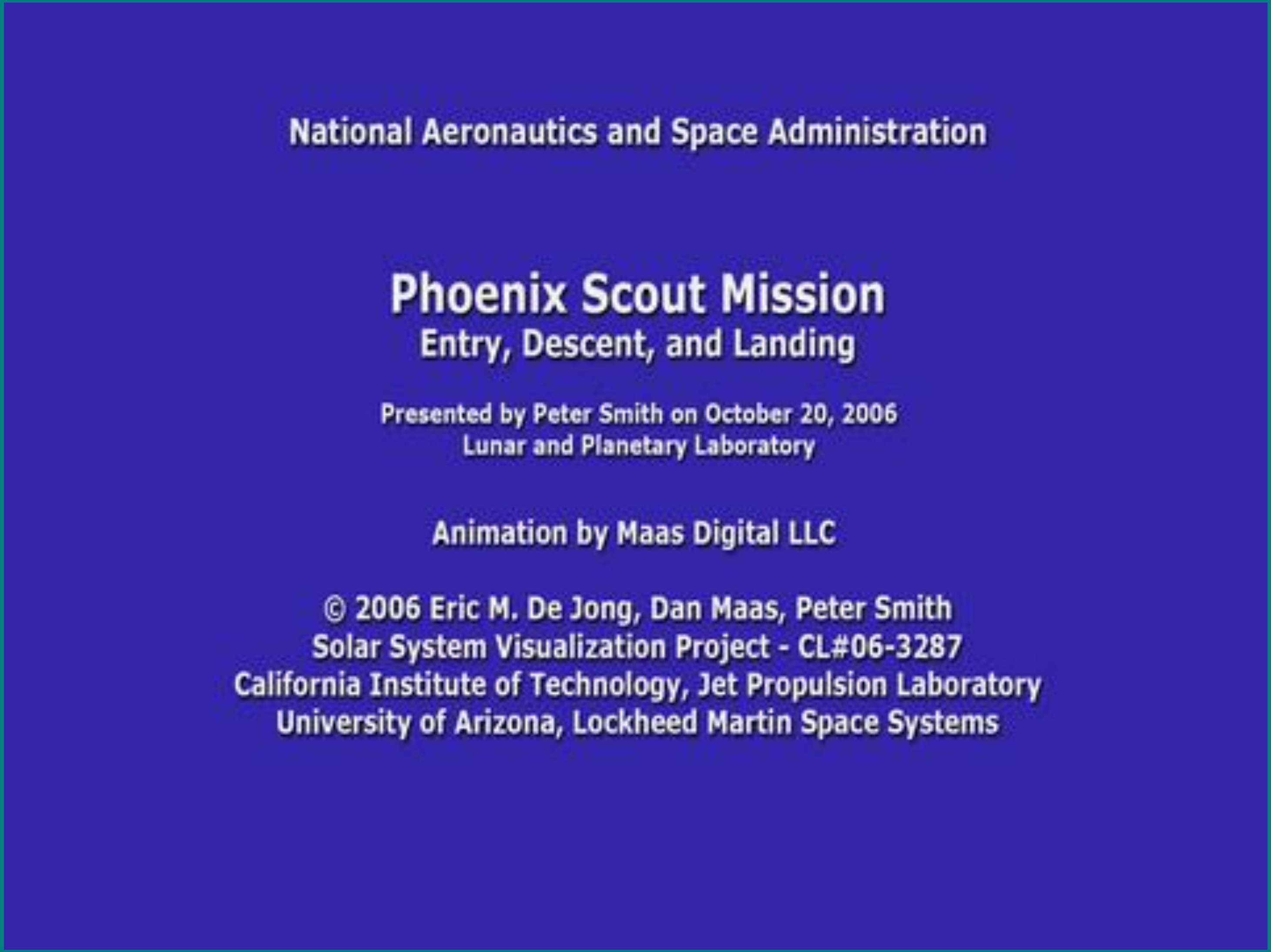
- On a planet with an atmosphere, the final stages of the descent are usually done with parachutes allowing to reduce the terminal velocity.
- For a typical parachute, $C_D \sim 0.5$.
- For planets other than the Earth, the parachutes must be made of non-outgassing, sterilized material and must allow radio communications with an orbiter.

Chapter VI: Atmospheric probes and landers

- One tries to reduce the final descent velocity below 10 m s^{-1}. This often requires firing retrorockets, but these must be used with caution if in-situ measurements are foreseen. The residual energy can be absorbed by airbags (inflated with gas generators) or damped structures in the legs of the lander.

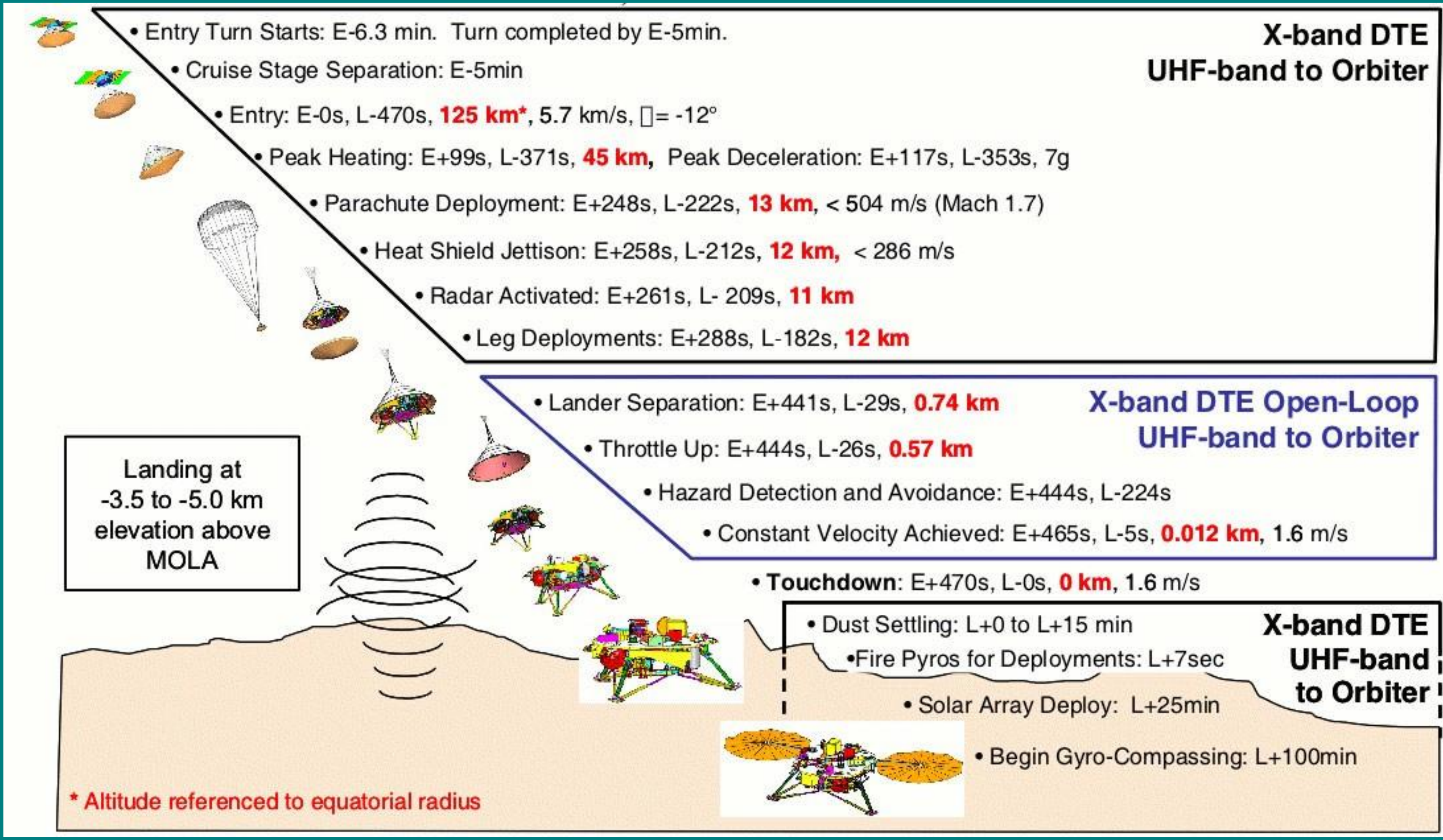
Chapter VI: Atmospheric probes and landers

- E.g.: Phoenix (Animation)



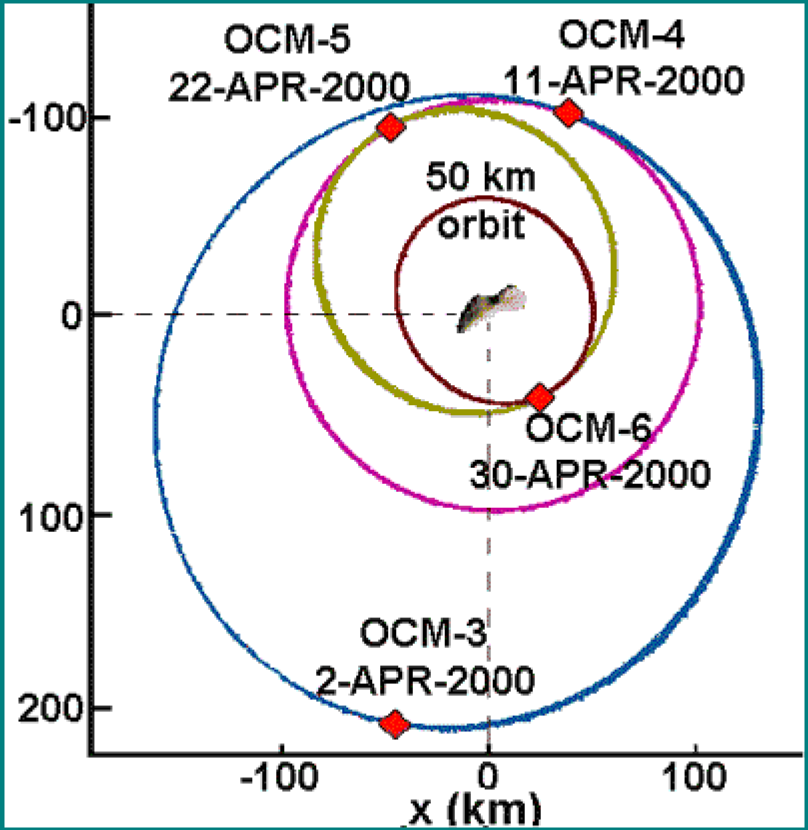
Chapter VI: Atmospheric probes and landers

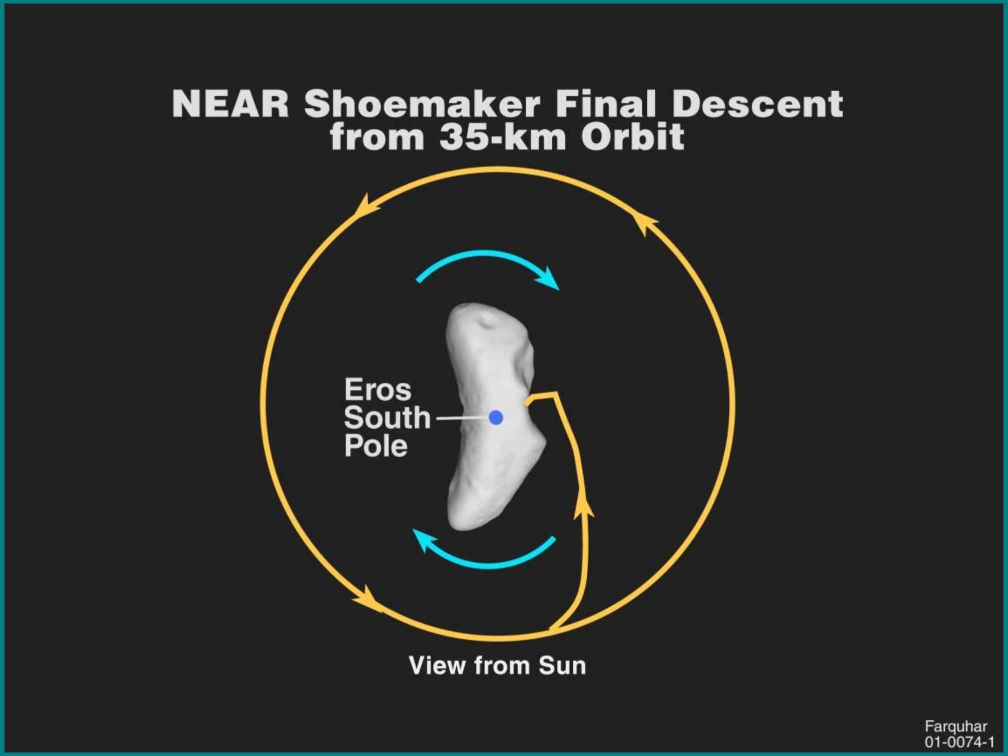
- E.g.: Phoenix



Chapter VI: Atmospheric probes and landers

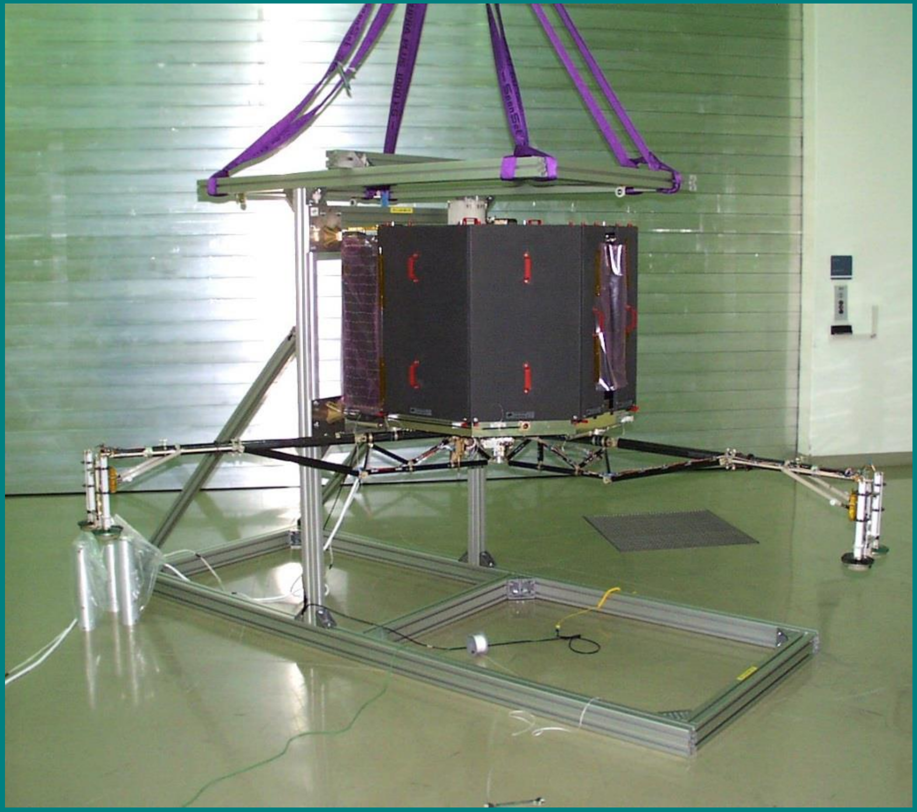
- Airless bodies are often (but not always) minor bodies with a complex geometry (asteroids, comets). Navigating in their (weak and highly non-spherical) gravity field is very complex (e.g. NEAR).





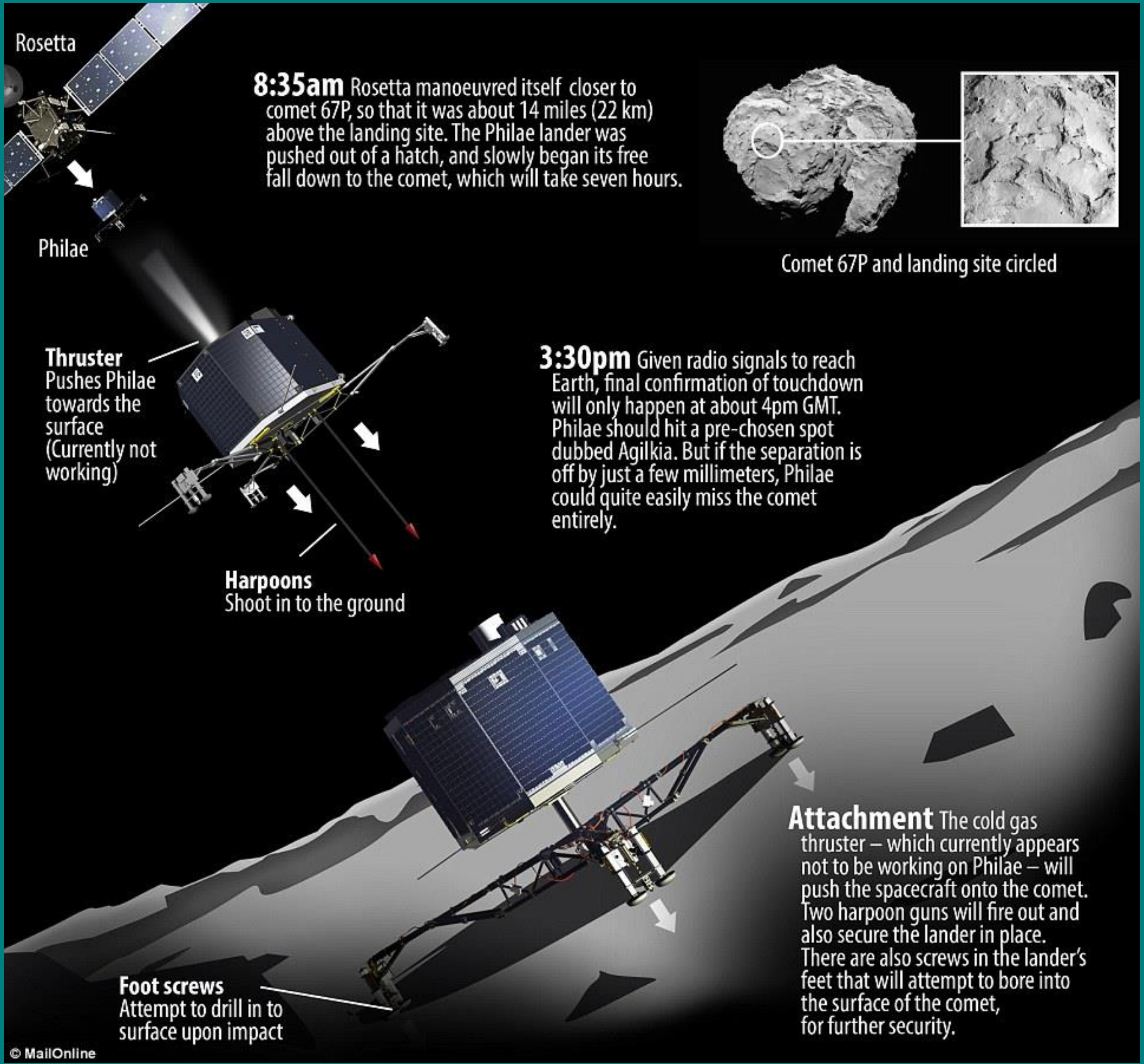
Chapter VI: Atmospheric probes and landers

- Landing and remaining on the ground of minor bodies requires anchoring systems (harpoons, foot screws,...) to avoid rebound or ejection by reaction (e.g. when drilling) or via outgassing of a comet. E.g.: Philae, Rosetta's lander.



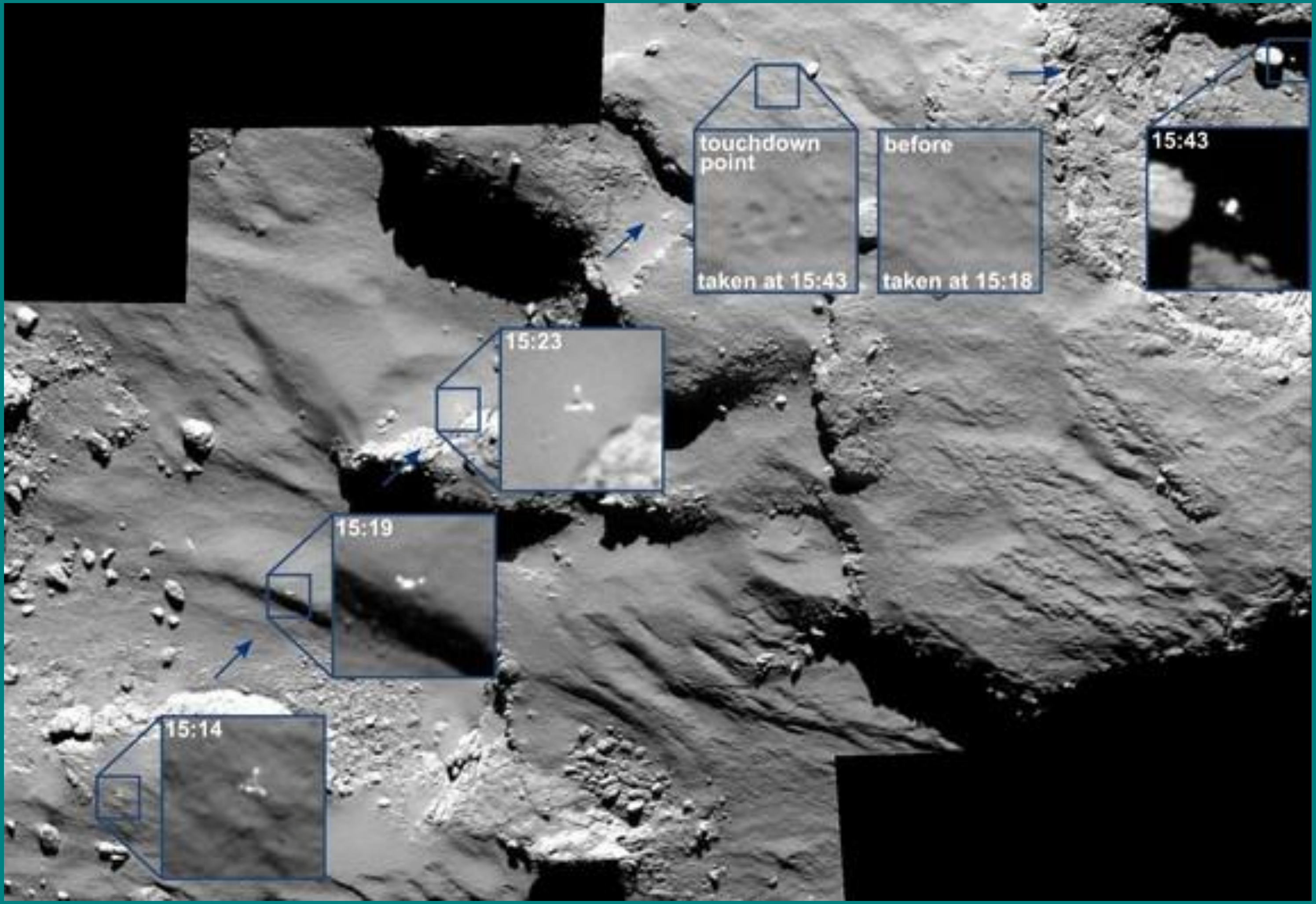
Chapter VI: Atmospheric probes and landers

- The way things should have happened:



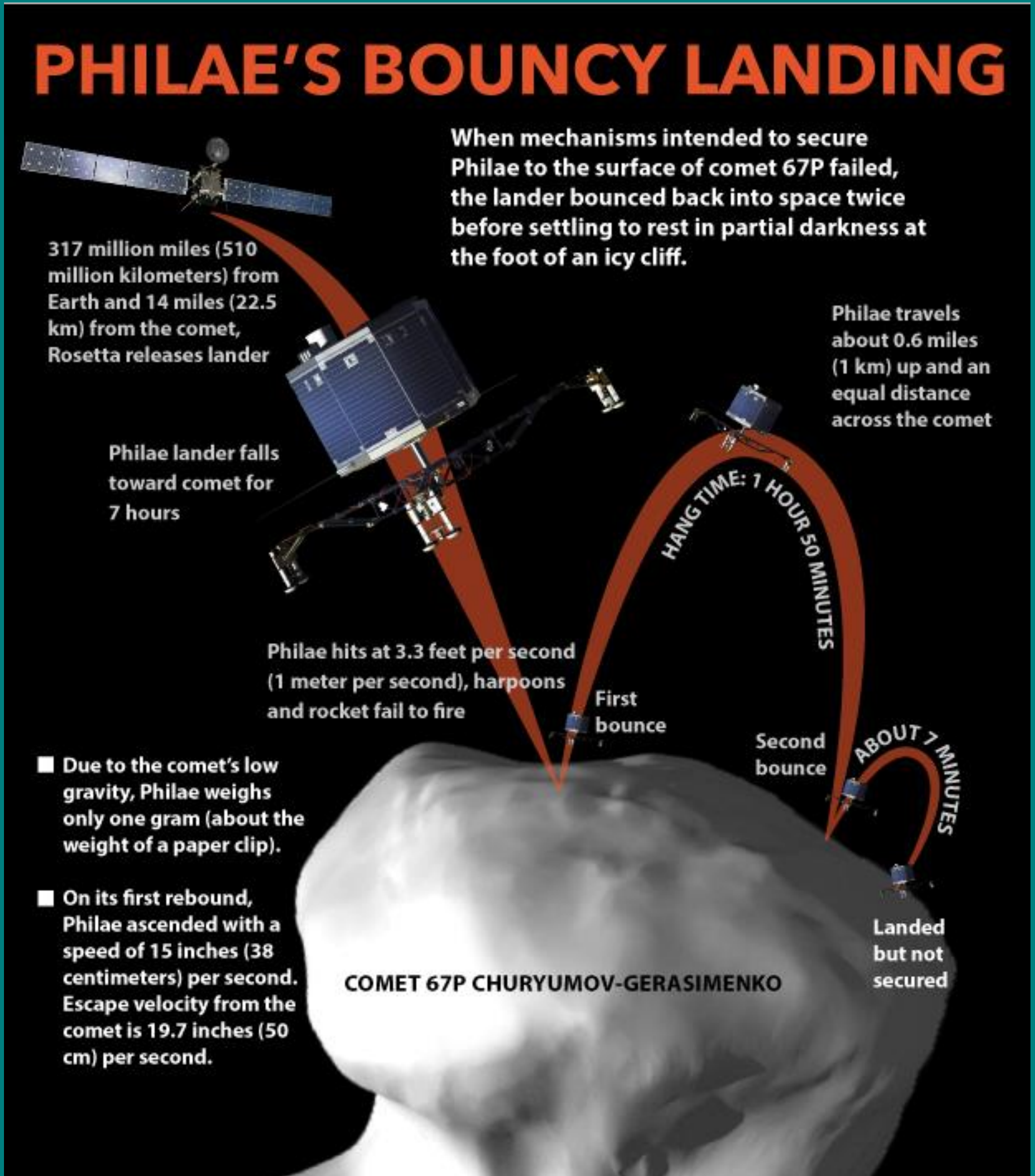
Chapter VI: Atmospheric probes and landers

- Not everything worked as expected for Philae:



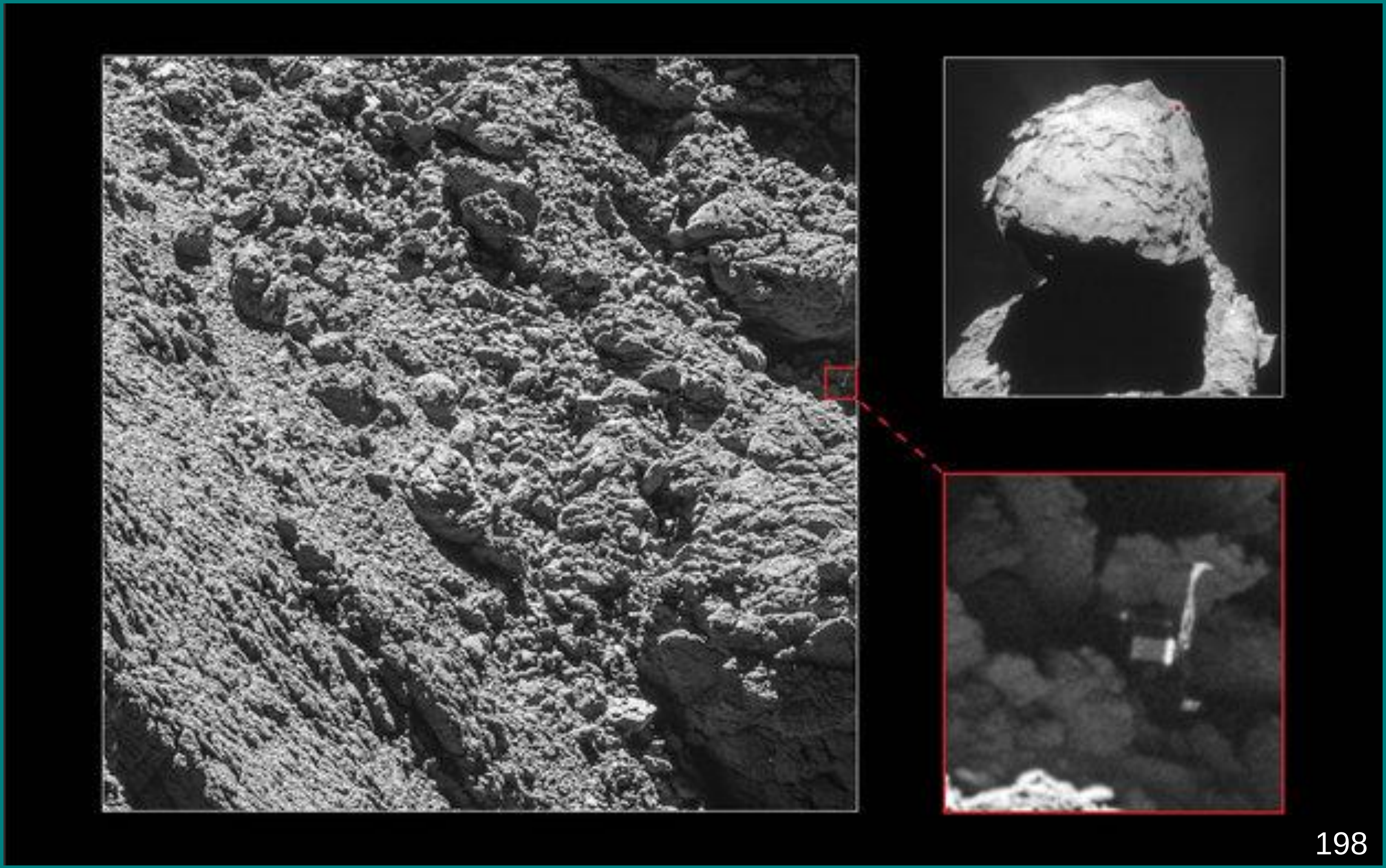
Chapter VI: Atmospheric probes and landers

- Not everything worked as expected for Philae:



Chapter VI: Atmospheric probes and landers

- It took 22 months before Rosetta was able to relocate Philae on the comet's surface.

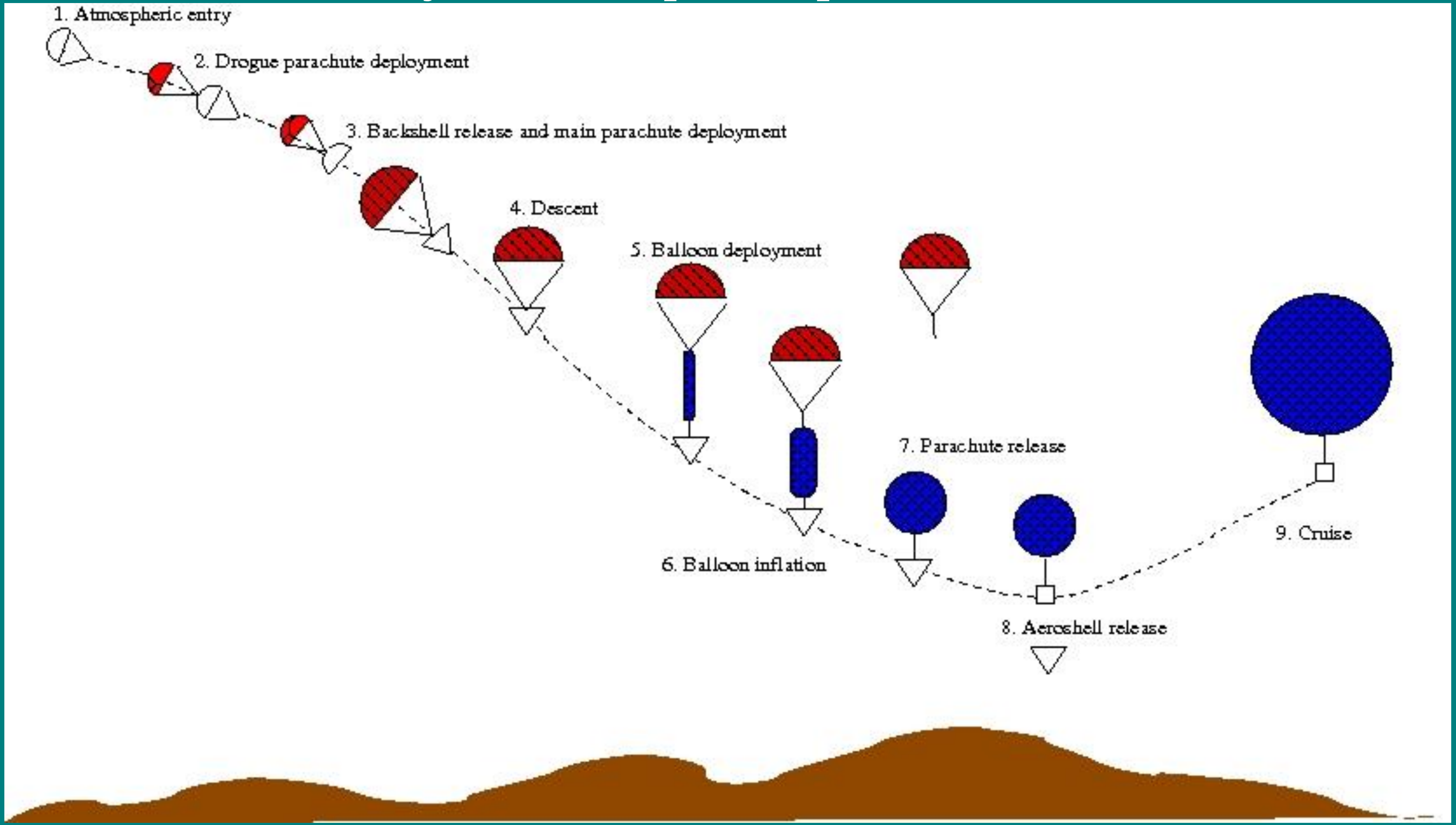


Chapter VI: Atmospheric probes and landers

- Balloons floating through the buoyancy force:

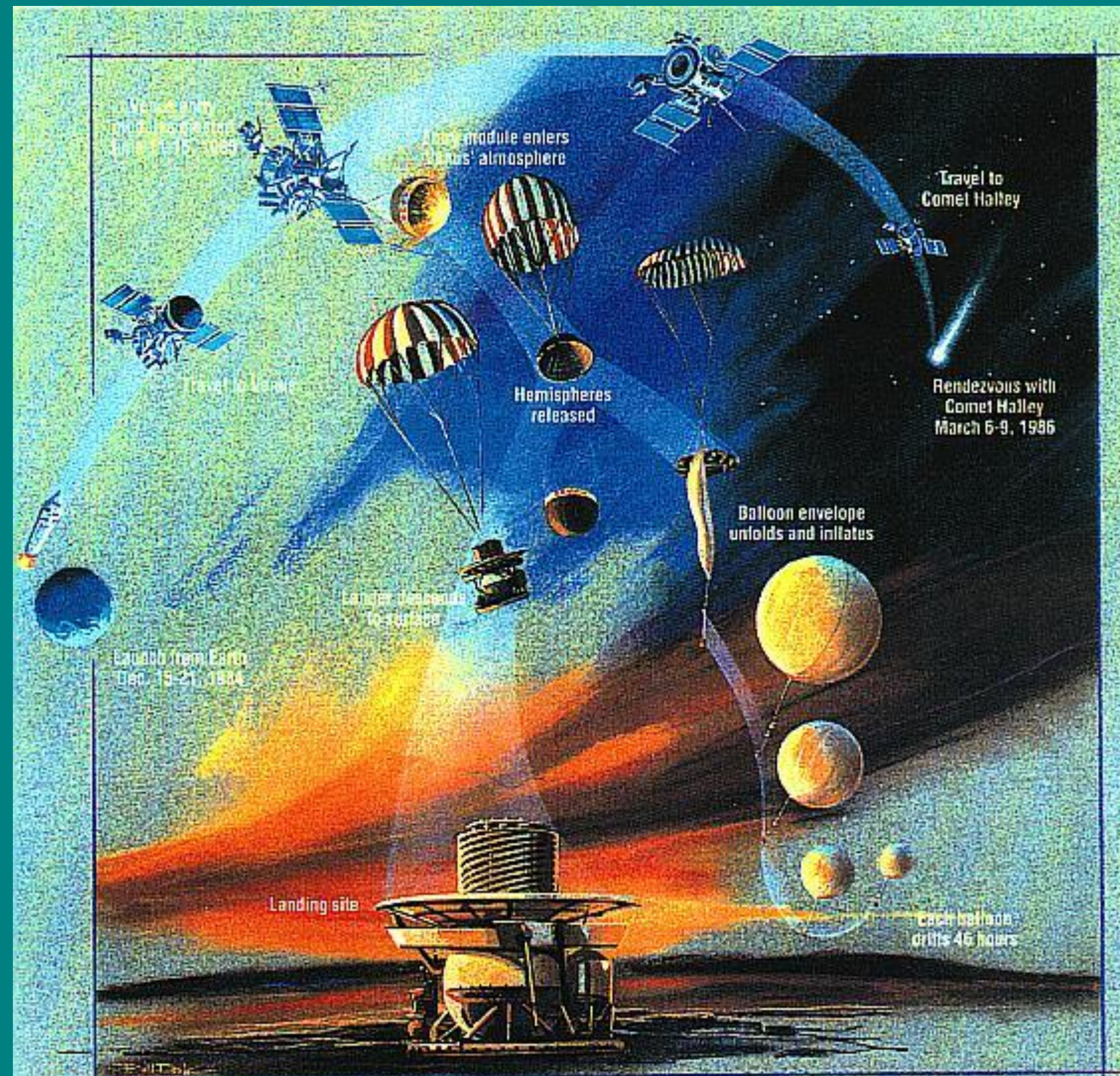
$$m_{\mathrm{probe}} = \rho_{\mathrm{air}}\, V_{\mathrm{balloon}} \left(1 - \frac{P_{\mathrm{gas}}\,\mu_{\mathrm{gas}}\,T_{\mathrm{air}}}{P_{\mathrm{air}}\,\mu_{\mathrm{air}}\,T_{\mathrm{gas}}}\right)$$

can be inflated by an atmospheric probe in the air.



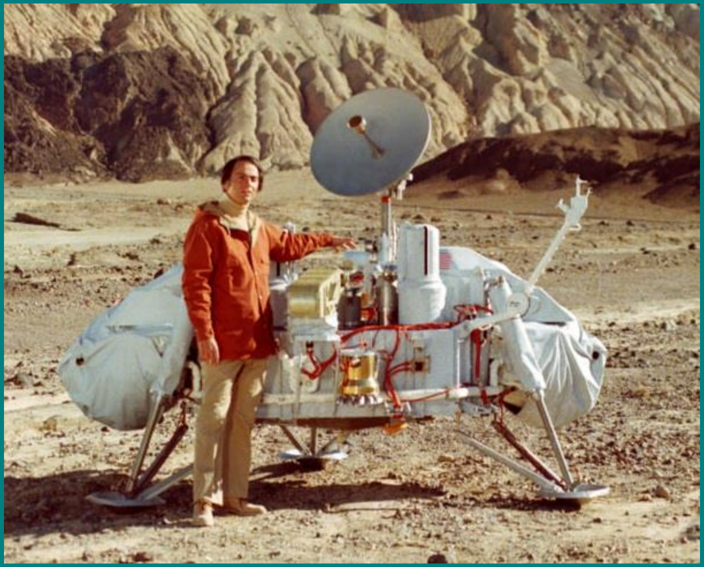
Chapter VI: Atmospheric probes and landers

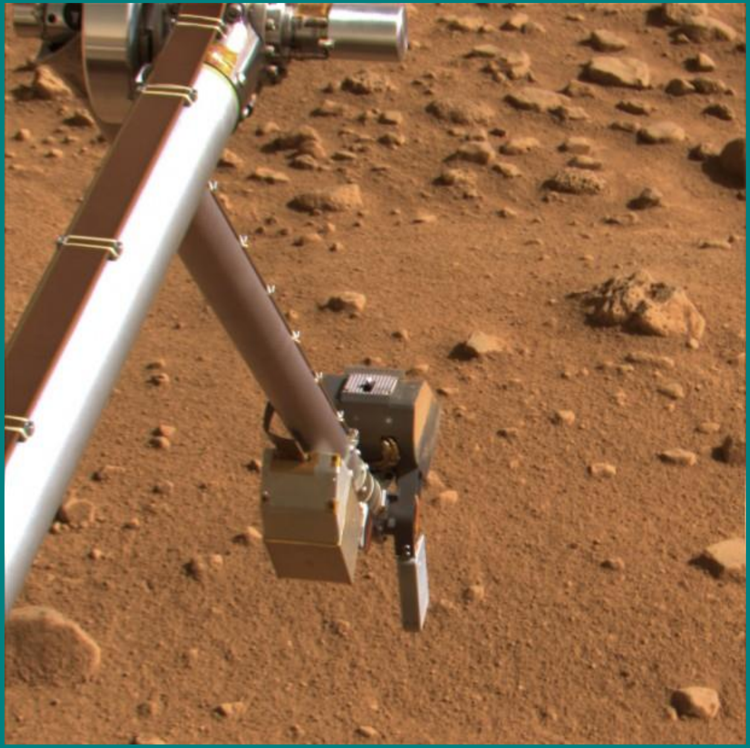
- Balloons are interesting to increase the lifetime of a mission (especially on Venus) and allow to explore a wider area of a planet.
- To date, this concept has only been implemented for the Soviet VeGa missions towards Venus in 1985.

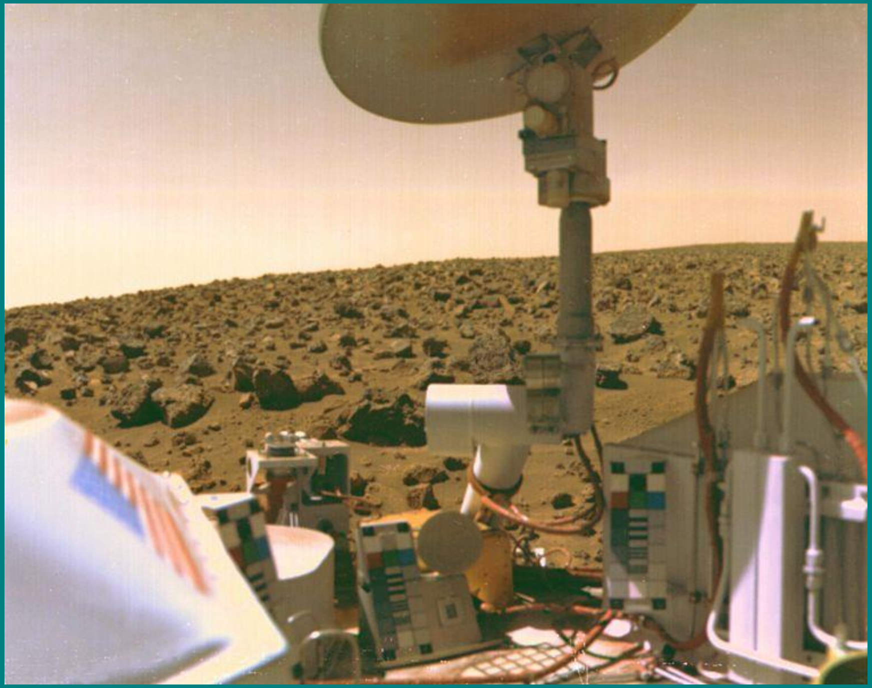


Chapter VI: Atmospheric probes and landers

- In-situ measurements with a fixed platform: collect samples with a robotic arm featuring a scoop (e.g. Phoenix or Viking) to analyse them with the on-board instruments.



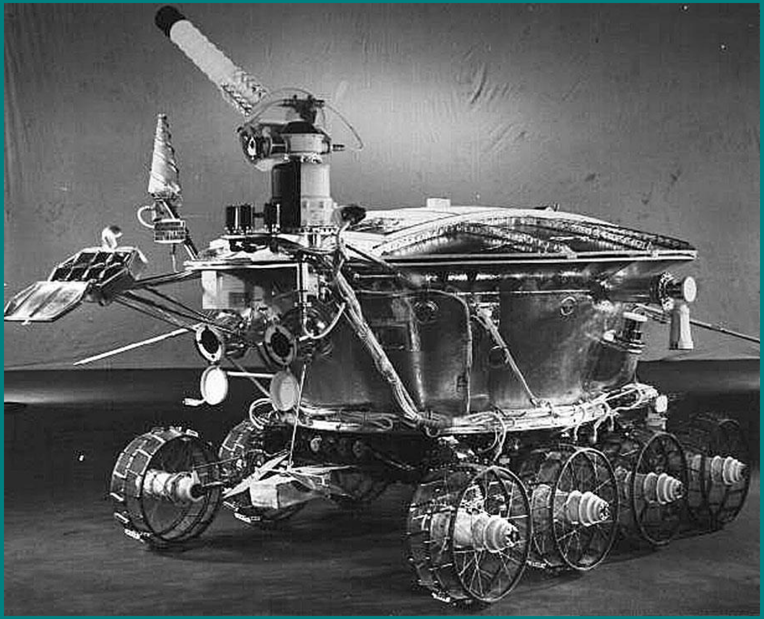


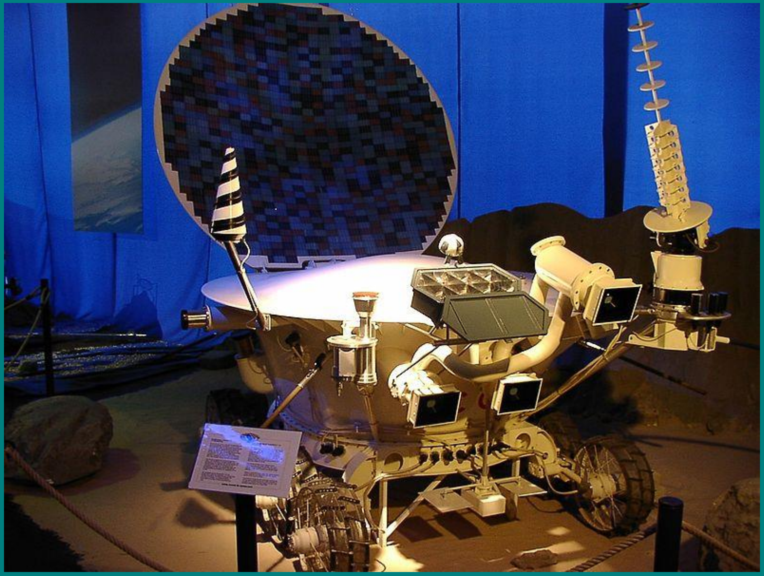


Chapter VI: Atmospheric probes and landers

- In-situ measurements with rovers: 1st implementation Lunokhod 1 & 2 on the Moon.
- Innovating concepts:

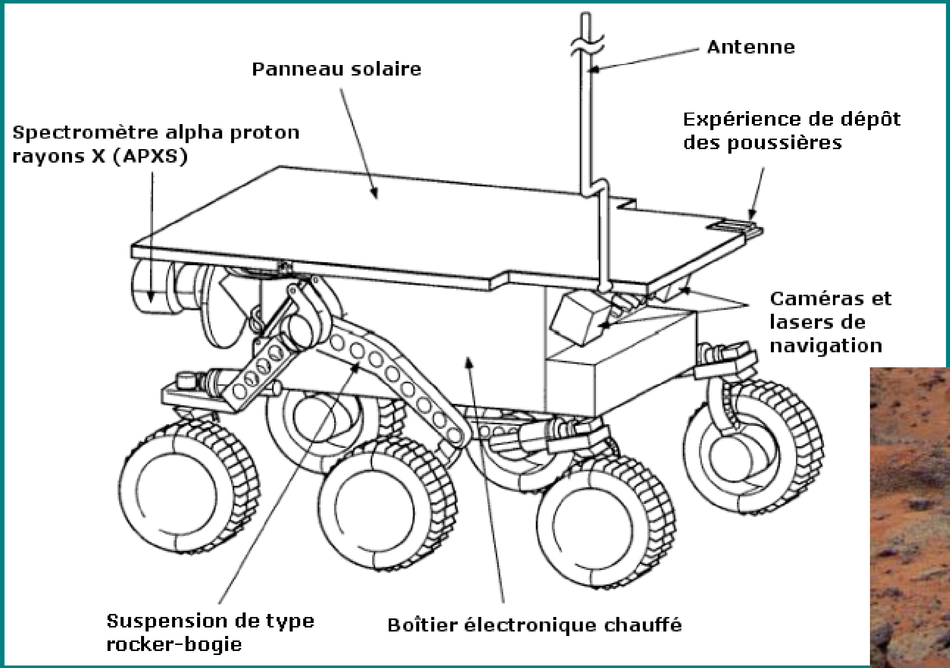
1. 8 wheels each wheel having its proper motor, brake and independent suspension.
2. Solar panels (beneath the lid) used during lunar daytime and heating of the electronics via RTGs during the night.
3. Remote-controlled from the ground in near-real time, thanks to a set of cameras.

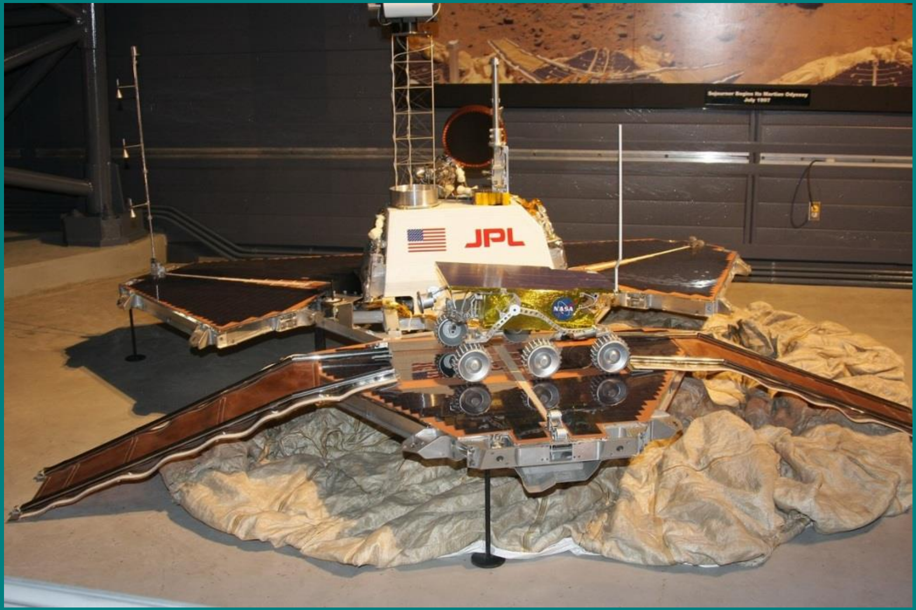




Chapter VI: Atmospheric probes and landers

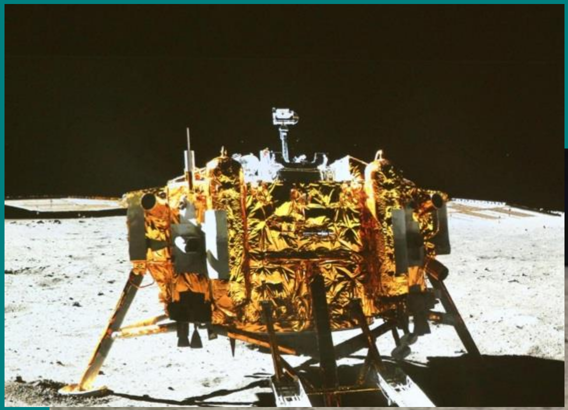
- Mars Pathfinder with its rover Sojourner inspired by the design of the Lunokhod.

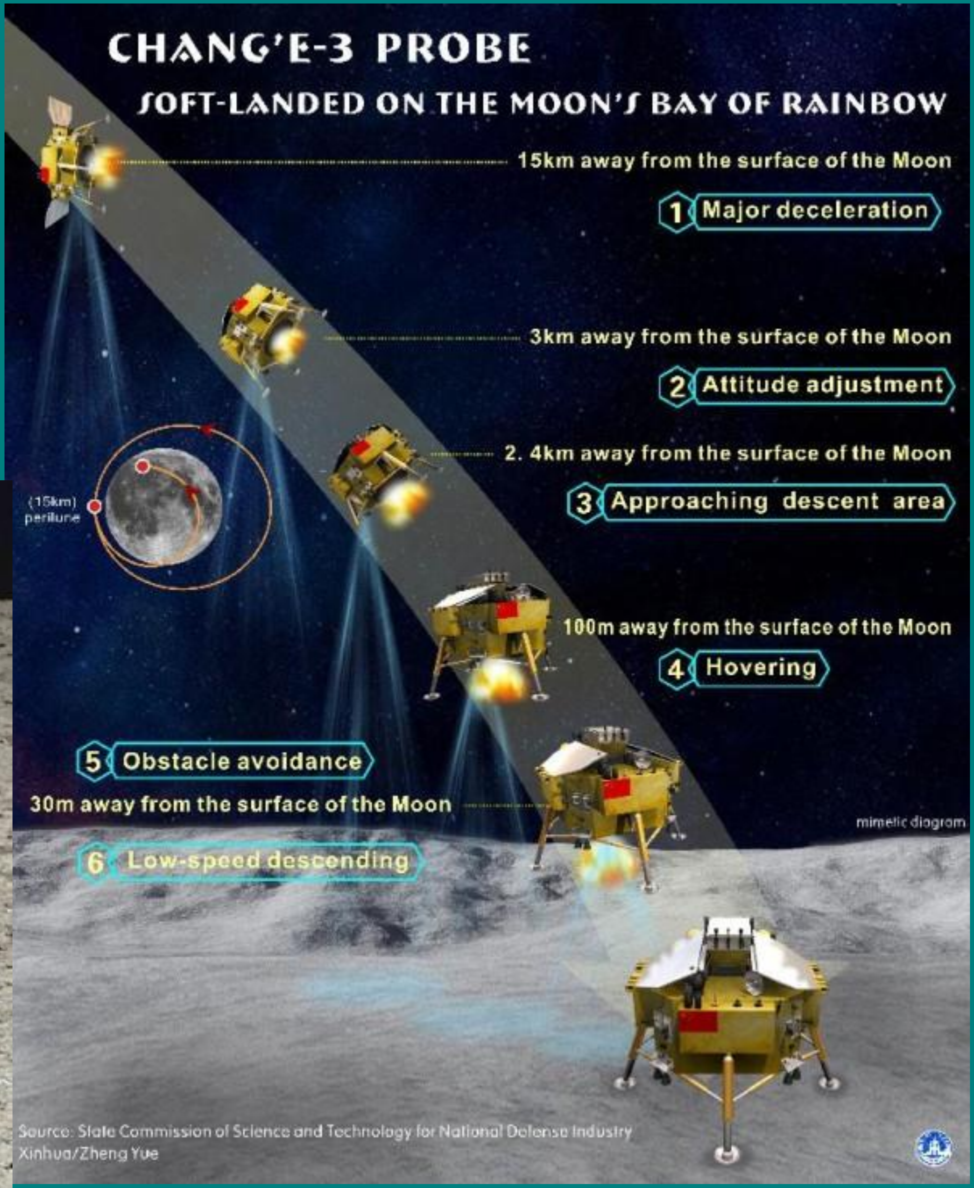




Chapter VI: Atmospheric probes and landers

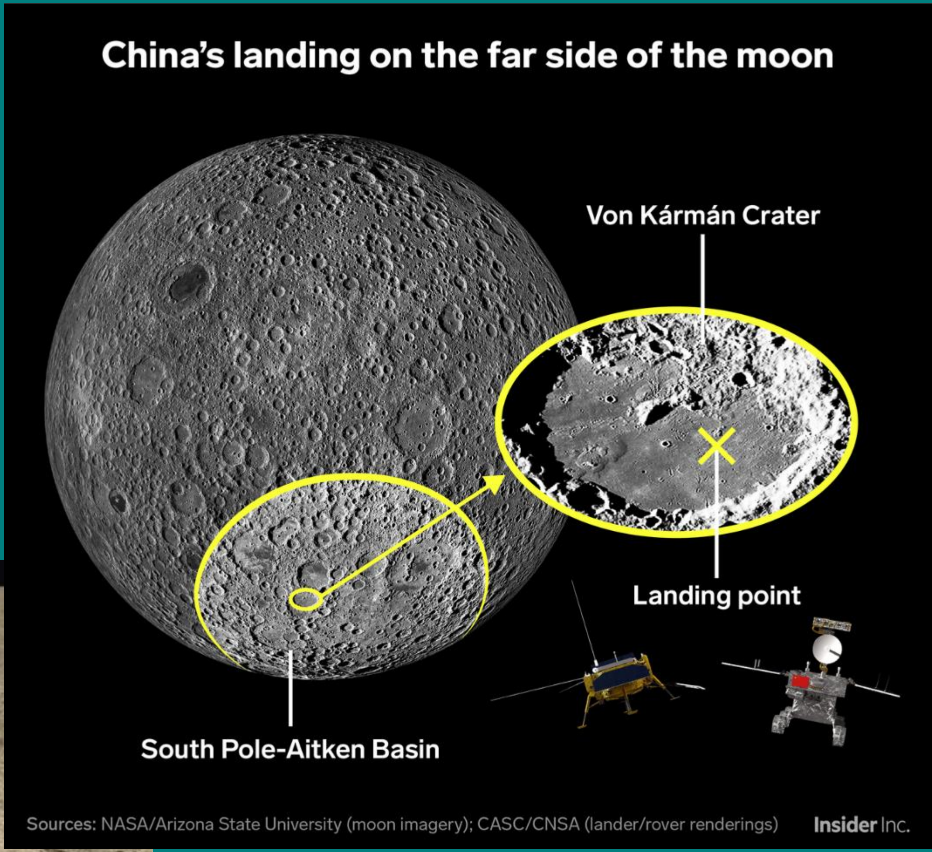
- 40 years after the Lunokhod and the Apollo rovers, China sent Chang'e 3 and its rover Yutu to the Moon.

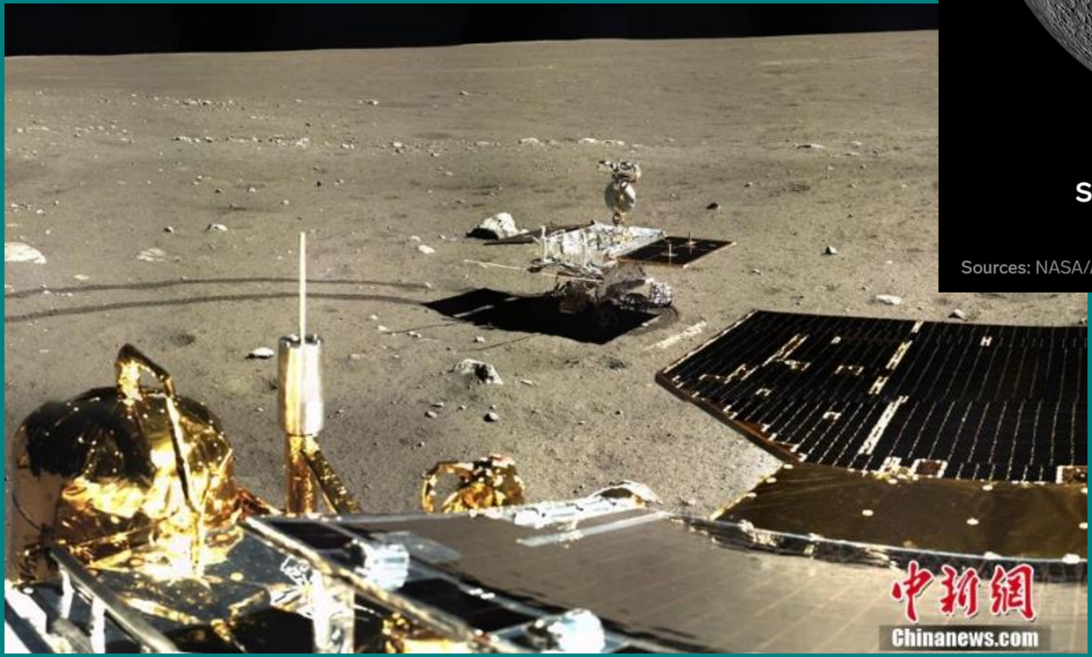




Chapter VI: Atmospheric probes and landers

- In 2019, Chang'e 4 and its rover Yutu 2 landed on the rear side of the Moon.



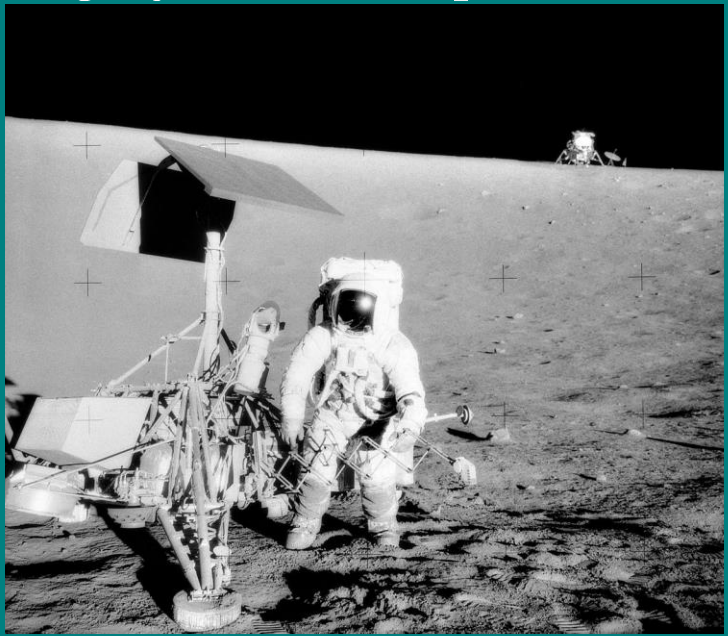


Chapter VI: Atmospheric probes and landers

- Planetary protection:

1. Prevent extra-terrestrial organisms from entering the Earth's biosphere.
2. Avoid contamination of other planets by living terrestrial organisms.

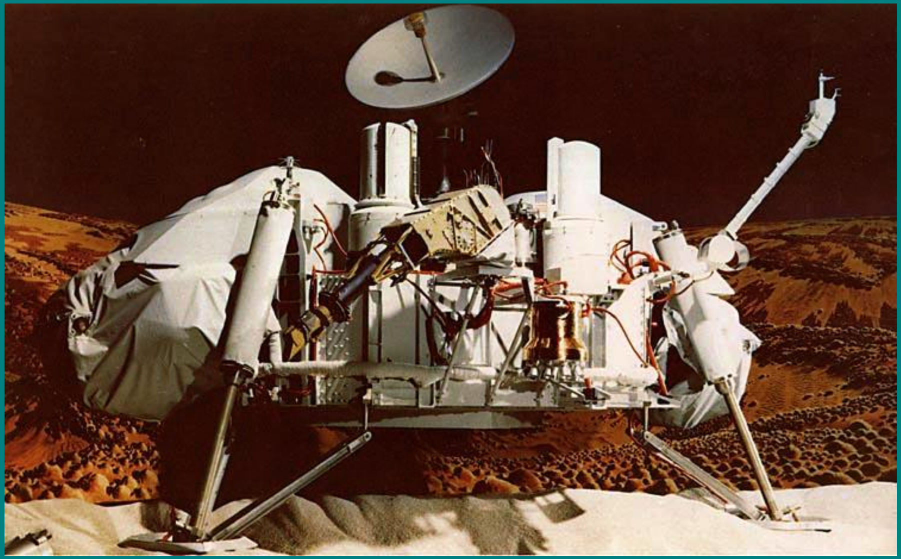
- Amazing problem: how to guarantee sterilization of a probe knowing that bacteria can survive as highly resistive spores as shown by the case of Surveyor 3?



Chapter VI: Atmospheric probes and landers

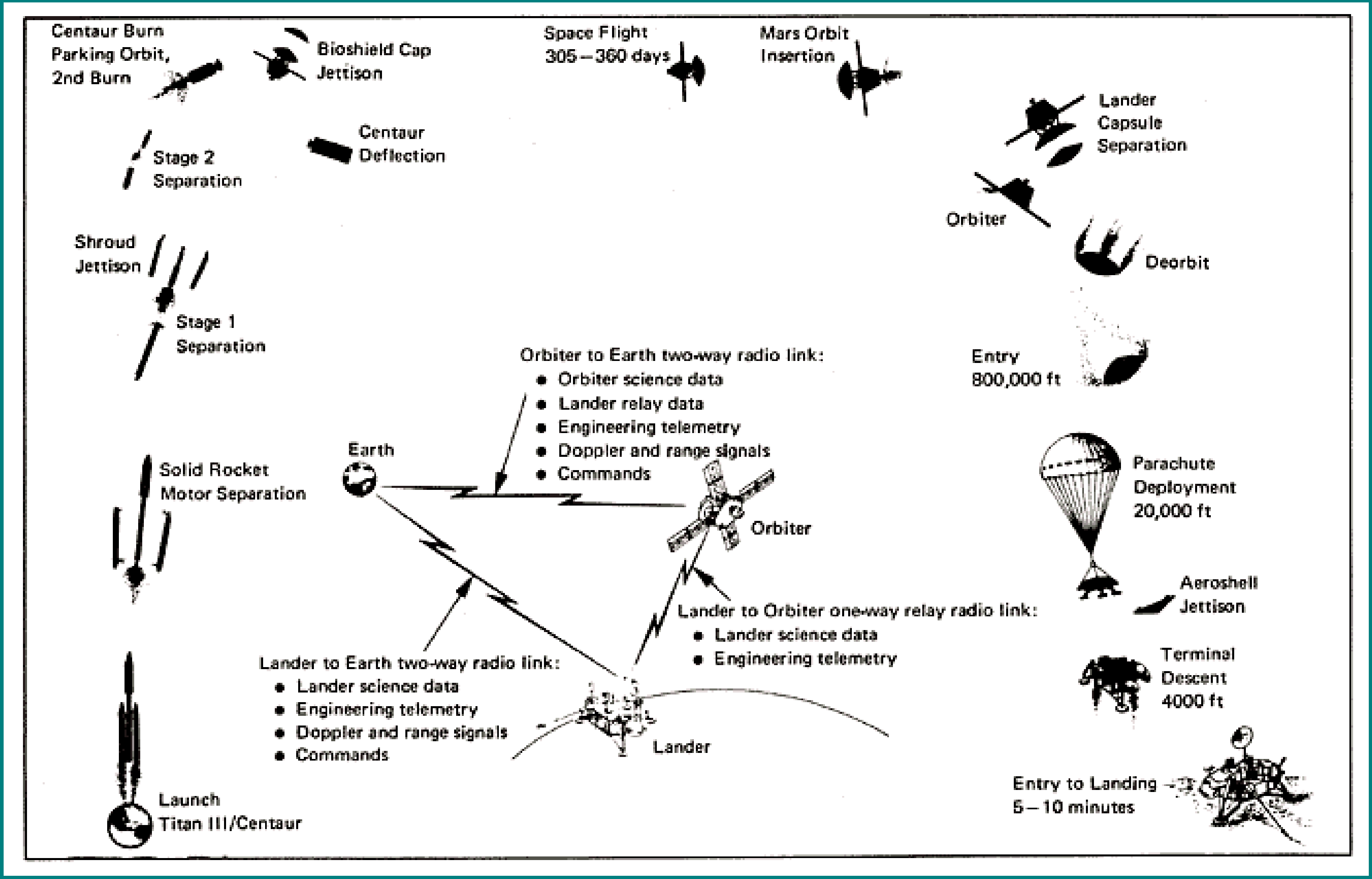
- Protocol used for the Viking landers:

1. Purify the hydrazine of the retrorockets.
2. Bake the assembled lander inside its heat shield at 121°C for 7 days.
3. Place the ensemble in a sealed bio-shield that is only ejected once the probe has left its parking orbit around the Earth.



Chapter VI: Atmospheric probes and landers

- Temporal sequence of the Viking missions:



Chapter VII: Space-borne astrophysics

- Space-borne astrophysics opens new windows on the universe that cannot be accessed from the ground.
- Instrumentation depends on the scientific objectives, the wavelength domains to explore…
- Several examples are addressed in this chapter:

1. Astrometry
2. X-ray astrophysics
3. UV astrophysics

Chapter VIIa: Astrometry

- Astrometry, basic principles
- The Hipparcos satellite
  1. Working principles
  2. Results
- The Gaia mission
  1. Working principles
  2. Expected performances

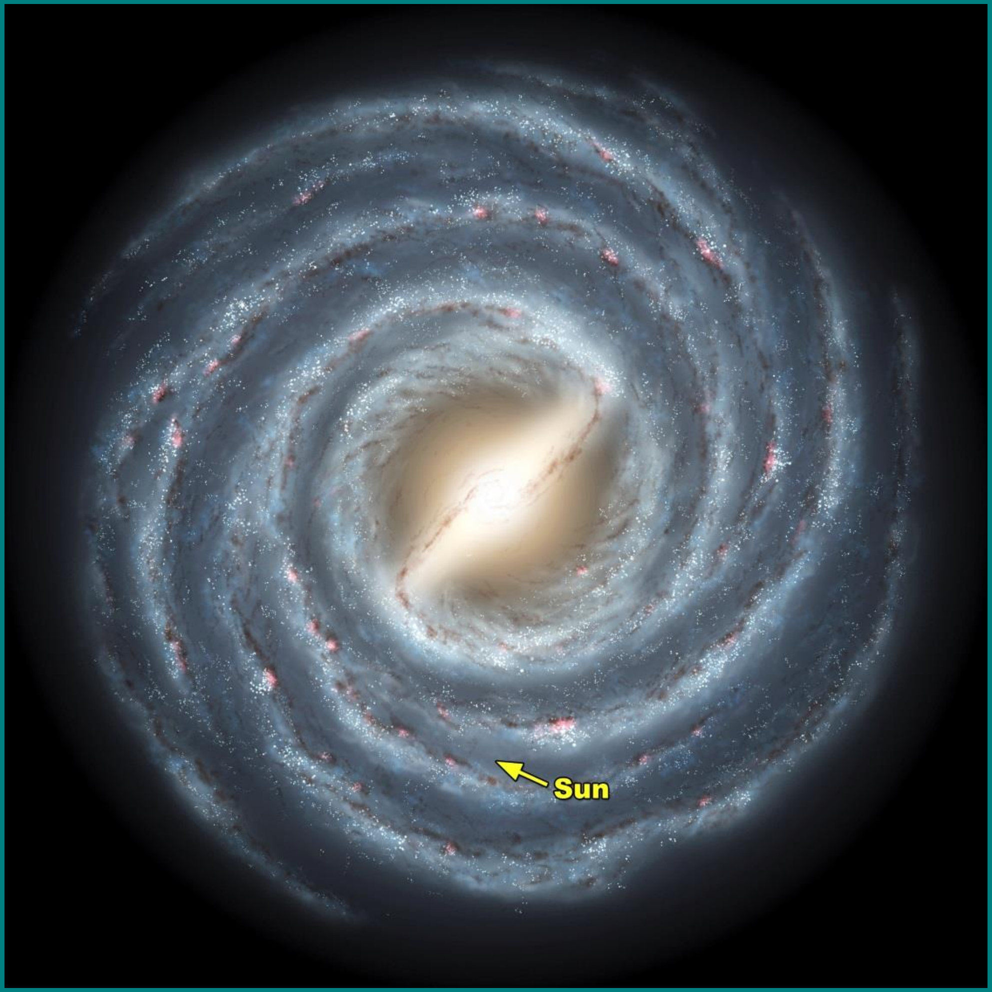
Chapter VIIa: Astrometry

- Astrometry = definition of an "absolute" frame of reference and determination of 5 parameters: angular position (2 parameters), annual parallax, proper motion.
- Very ancient discipline:

1. Catalogue of Hipparchus (around 130 BC) provides the angular position of 1000 stars with an accuracy of 1°
2. Improvements due to Ptolemy.
3. Tycho Brahe (16th century), 1000 stars with a precision of order 1' (no optical instrumentation).
4. Accuracy from the ground in the mid 20th century: up to 0.1''

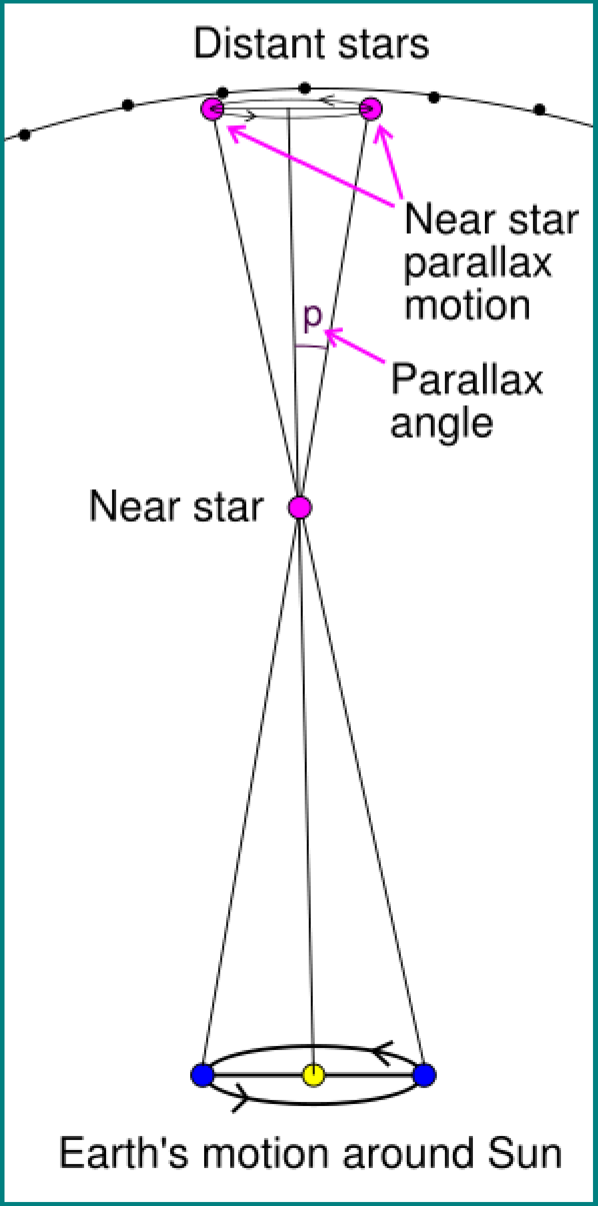
Chapter VIIa: Astrometry

- Astrometry = study of the 3-D structure of our Galaxy and of the different stellar populations that make it up.

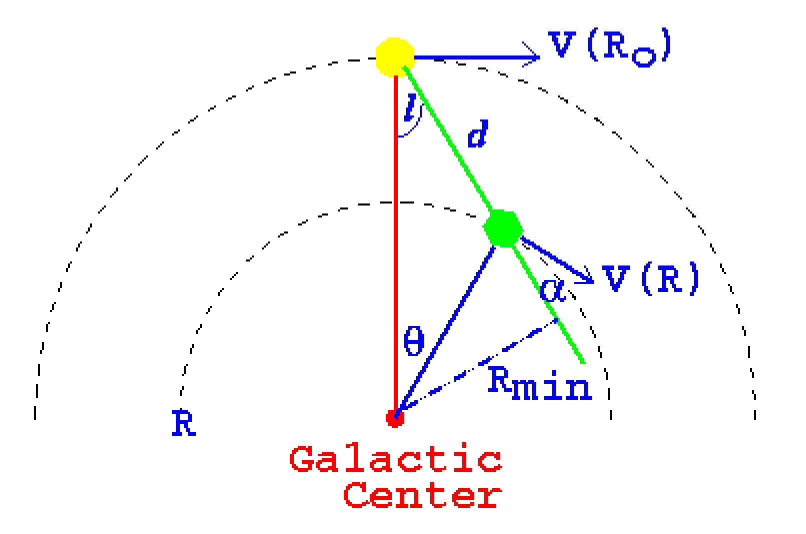


Chapter VIIa: Astrometry

- Annual parallax of nearby stars: due to the Earth's orbital motion around the Sun
- $d = 1/\pi$ (d expressed in parsec = 3.0857 10^{18} cm, π in arcseconds)
- Parallax of the nearest stars: Proxima Centauri 0.772''



Chapter VIIa: Astrometry



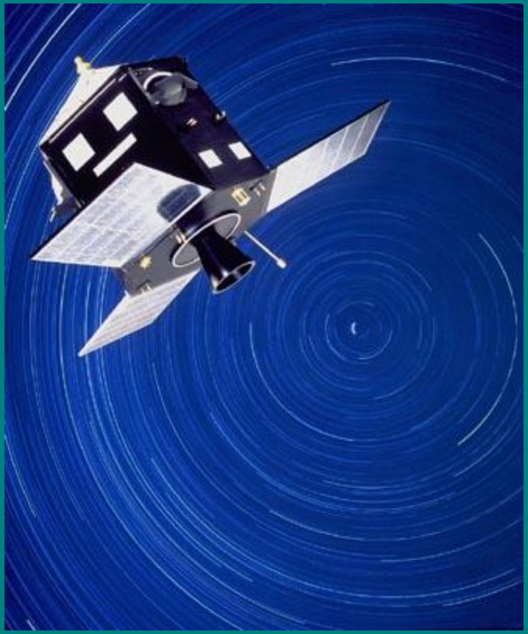
- Proper motion (along 2 directions, declination and right ascension):
  $\mu^2 = \mu^2_\delta + \mu^2_\alpha \cos^2\delta$
- Stars with largest proper motion = nearby stars.
- E.g.: Barnard's stars, μ = 10.3''/year; π = 0.549'' (d = 6 light years)

Chapter VIIa: Astrometry

- Astrometry from the ground: meridian circles

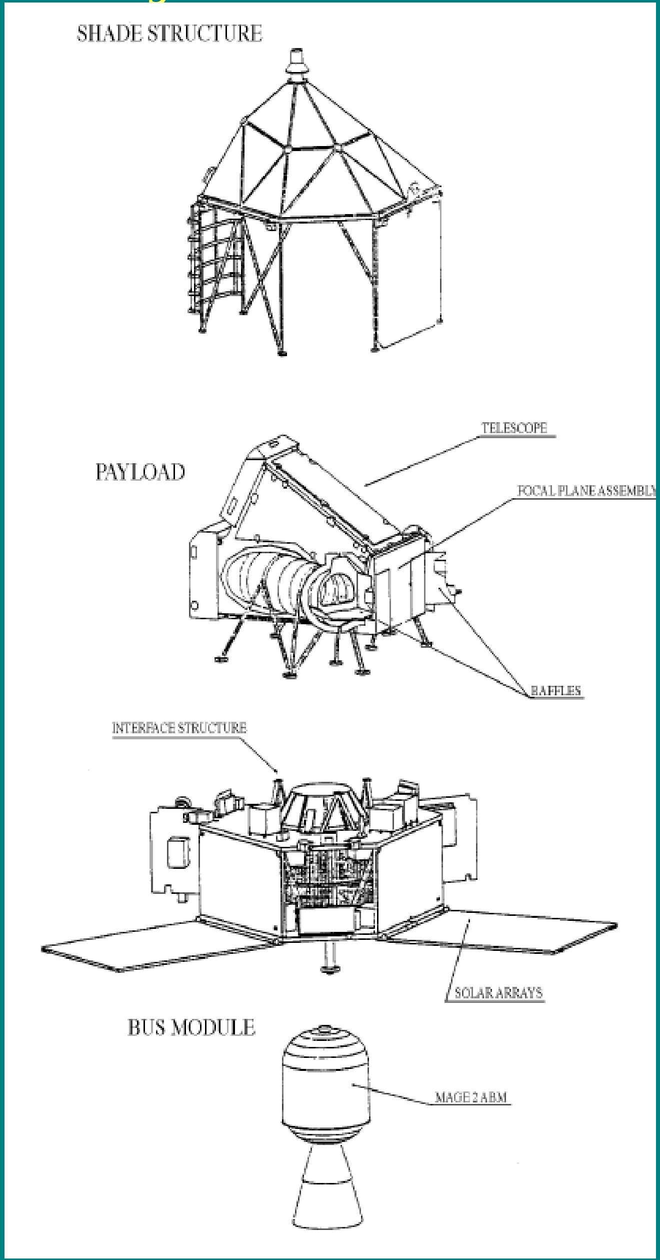
Chapter VIIa: Astrometry

- The Hipparcos satellite: first space-borne astrometric mission (launched in 1989, Ariane 4).
- Intended orbit = GEO, but problem with apogee booster $\Rightarrow$ satellite remained on its highly eccentric transfer orbit.
- Operations until 1993.
- Catalogue published in 1997



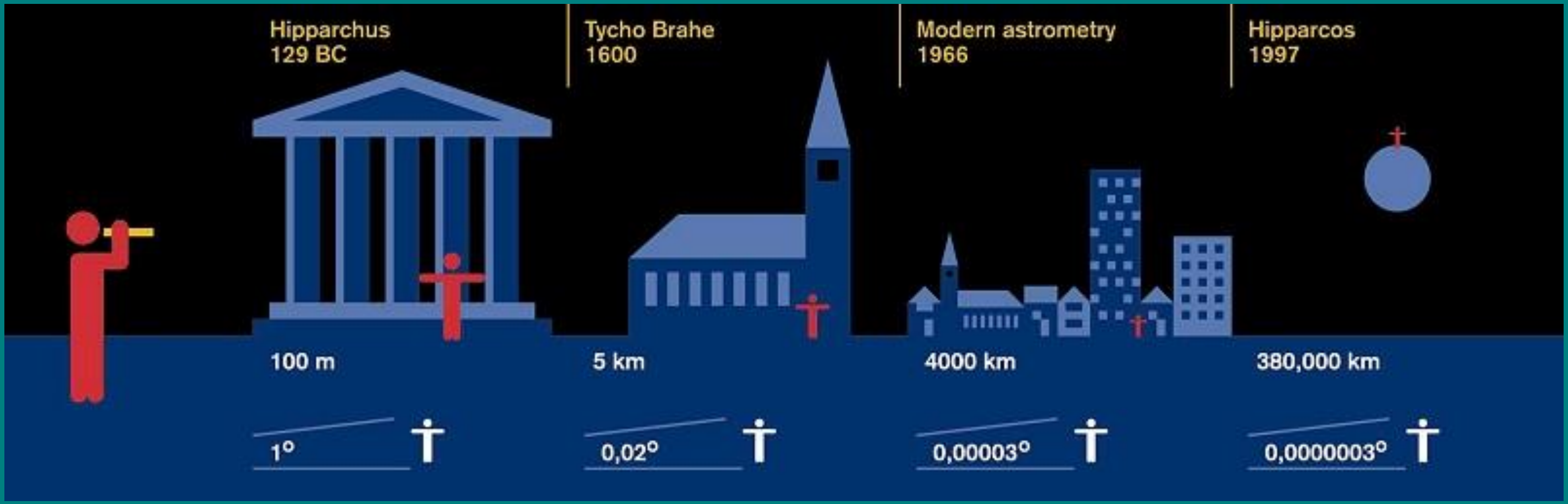
Chapter VIIa: Astrometry

- Hipparcos: Schmidt telescope combining images from two fields of view separated by 58° inside a single focal plane.
- Star light modulated by grid of parallel slits + detector working at 1200 Hz.
- Satellite spinning about its axis + slow precession of the spin axis ⇒ scan the entire sky.
- Each part of the sky is observed on average 100 times.
- Data and spacecraft attitude sent to the ground.



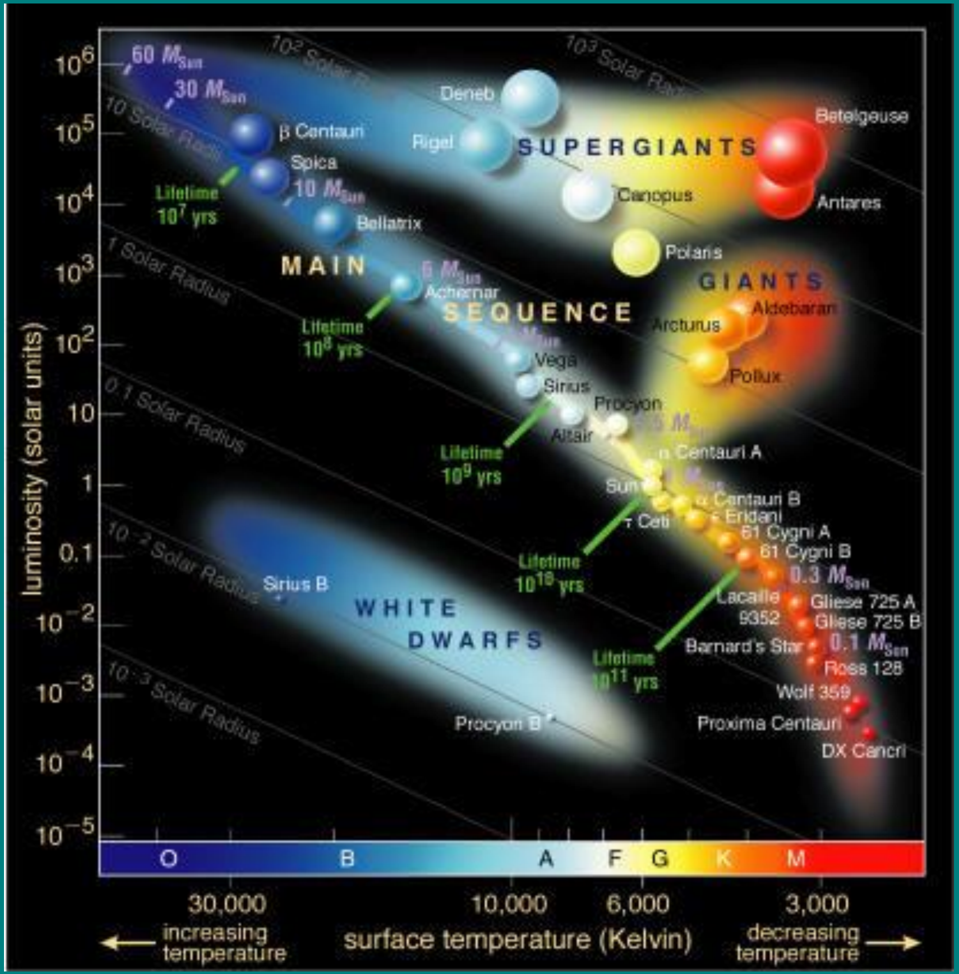
Chapter VIIa: Astrometry

- Hipparcos measured 120 000 stars (up to magnitude 7.3 – 9) with an accuracy of 0.001'' in position, parallax and proper motion (better than anticipated).



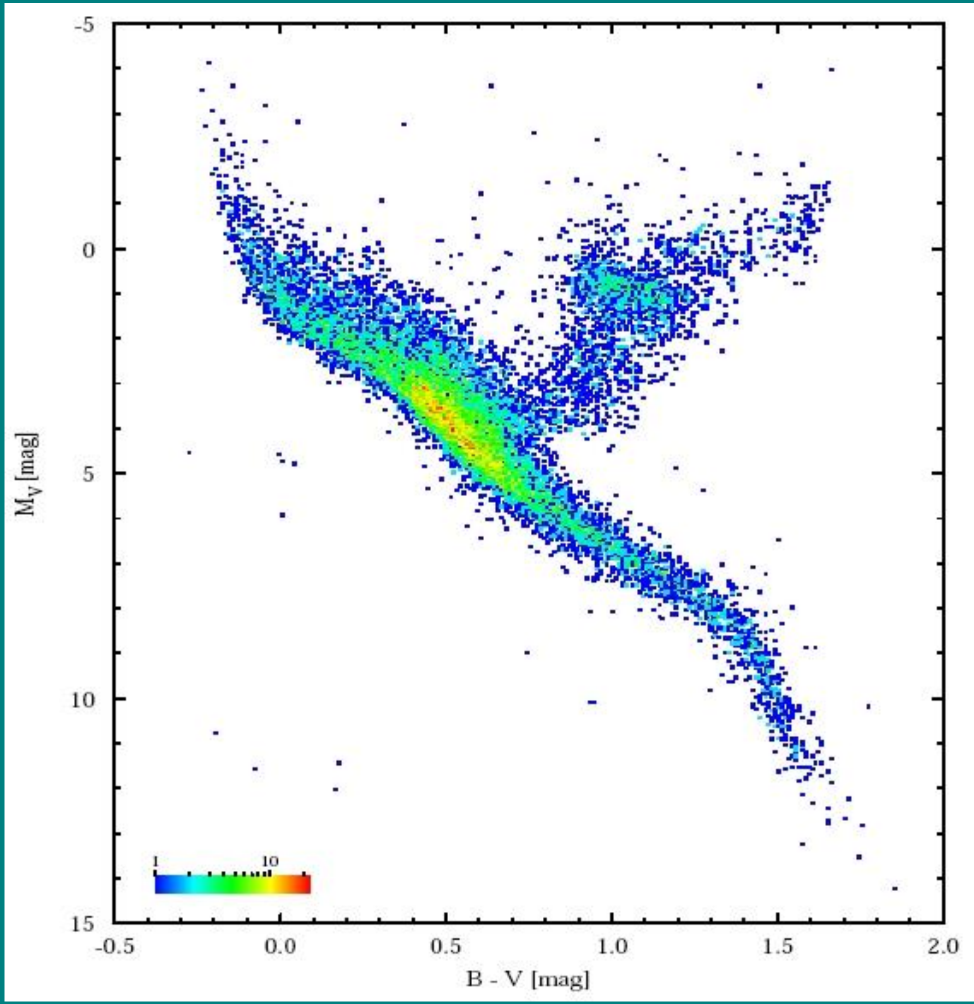
Chapter VIIa: Astrometry

- Hertzsprung-Russell diagram: stellar luminosity vs. effective temperature. Main sequence = most populated part of the H-R diagram.
- Powerful tool for stellar evolution theory.



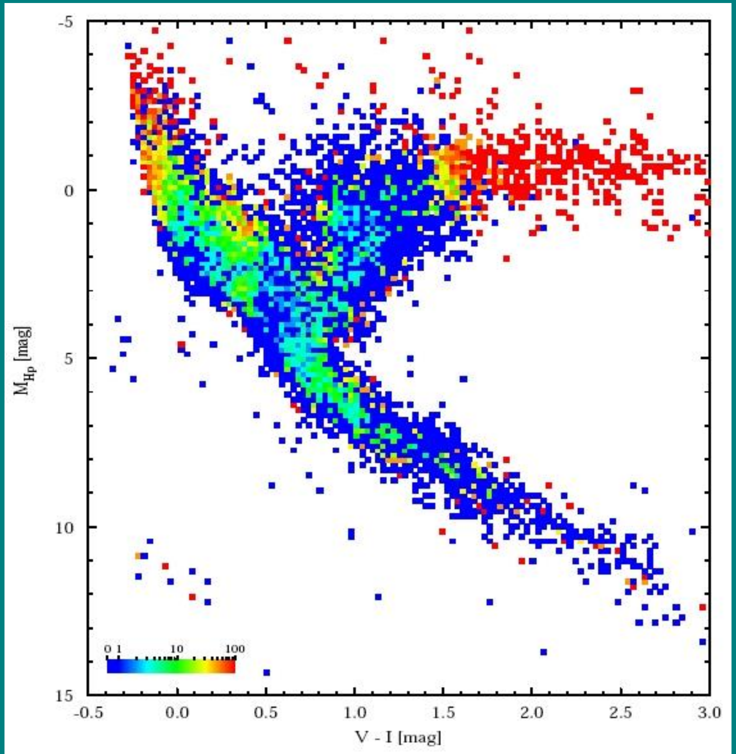
Chapter VIIa: Astrometry

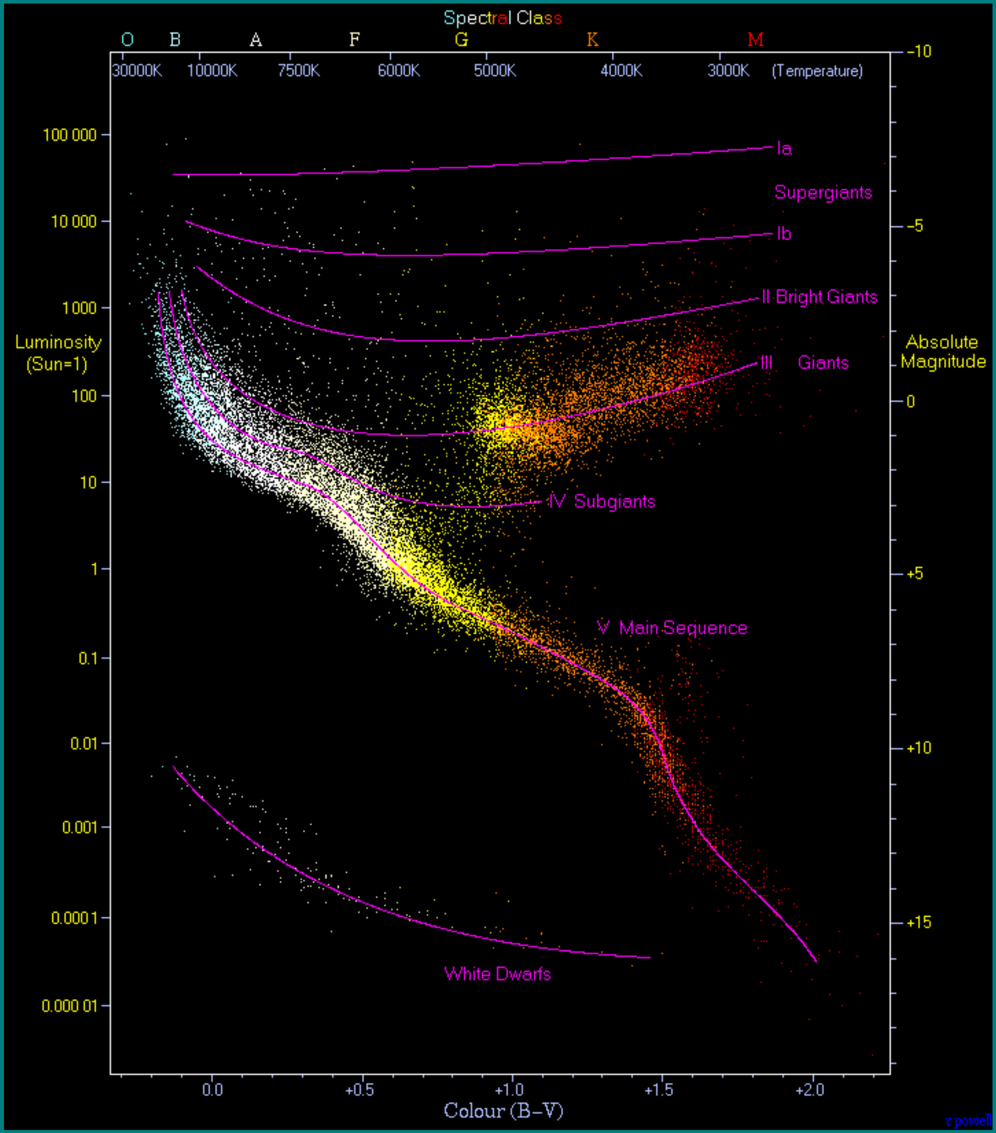
- Observational H-R diagram obtained with Hipparcos: distances up to 100 pc determined with an accuracy of 10%



Chapter VIIa: Astrometry

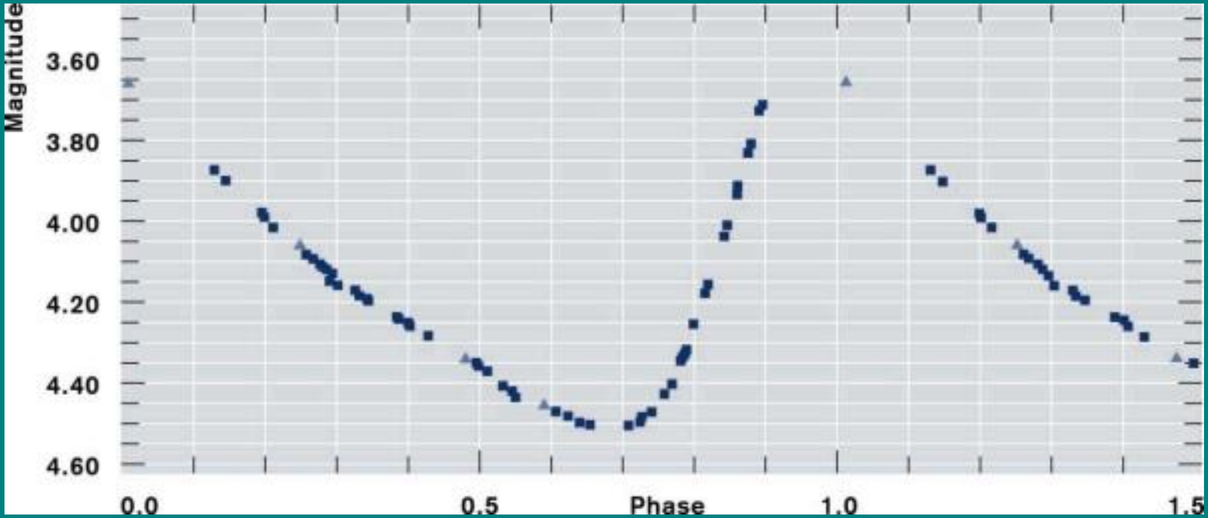
- Observational H-R diagram obtained with Hipparcos: distances up to 100 pc determined with an accuracy of 10%
- Incidence of variability.





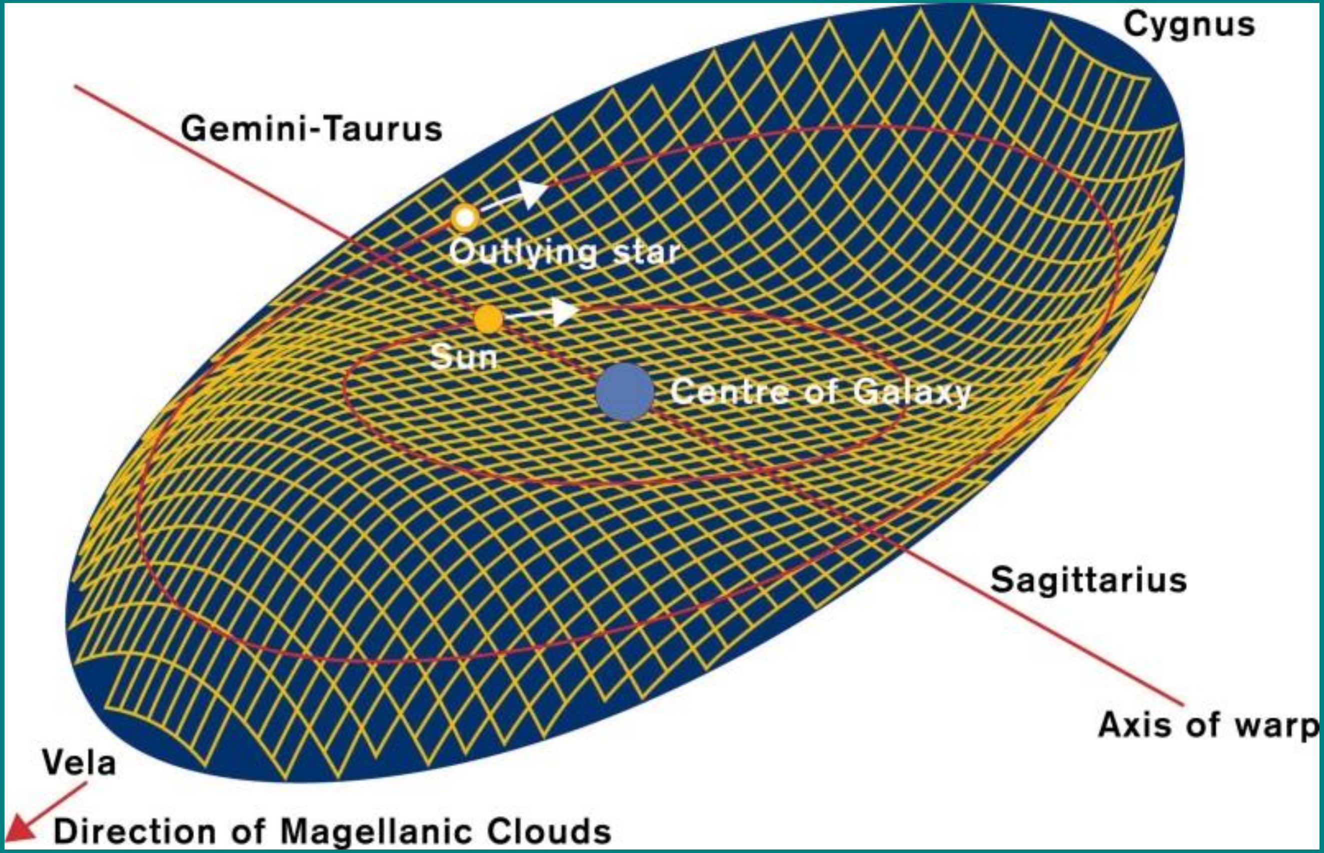
Chapter VIIa: Astrometry

- Determination of the distance of several Galactic cepheids. Pulsating stars that display periodic variations of their brightness.
- Period-luminosity relation: $M_V = - 2.81 \times \log P - 1.43 \pm 0.1$
- Allows to evaluate the distances of extragalactic cepheids (distance ladder).



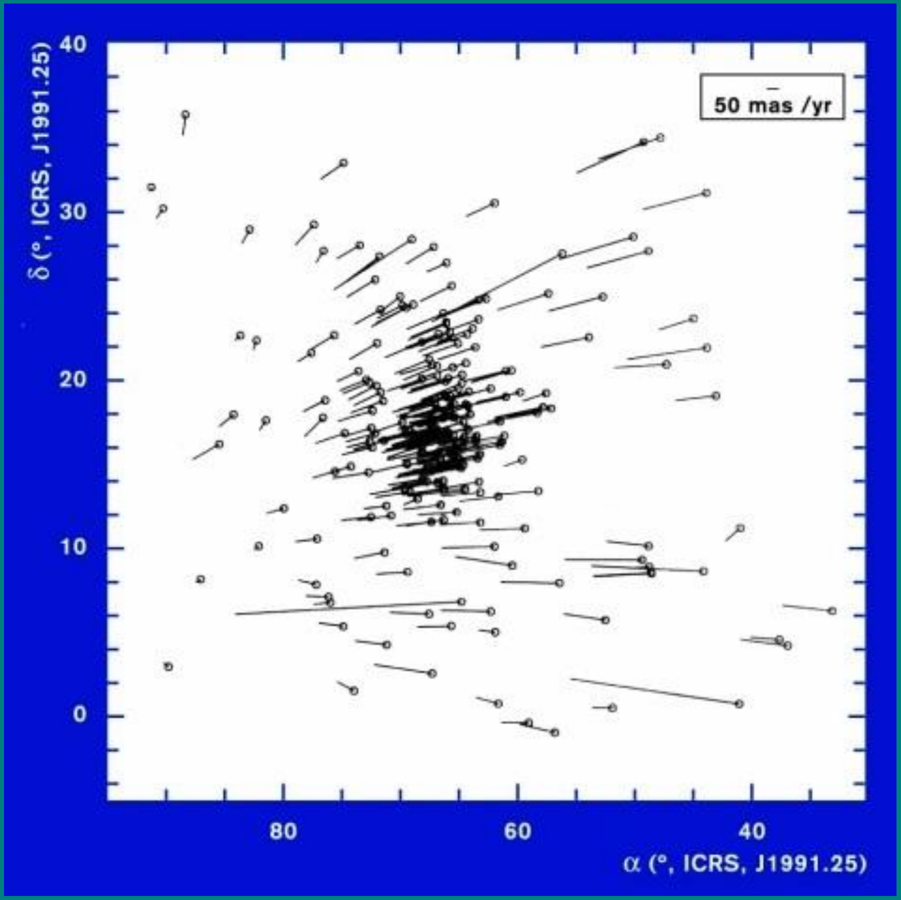
Chapter VIIa: Astrometry

- Disk of the Galaxy is not flat (amplified by a factor 10 in the figure): gravitational pull of the Magellanic Clouds or of dark matter halo surrounding our Galaxy.



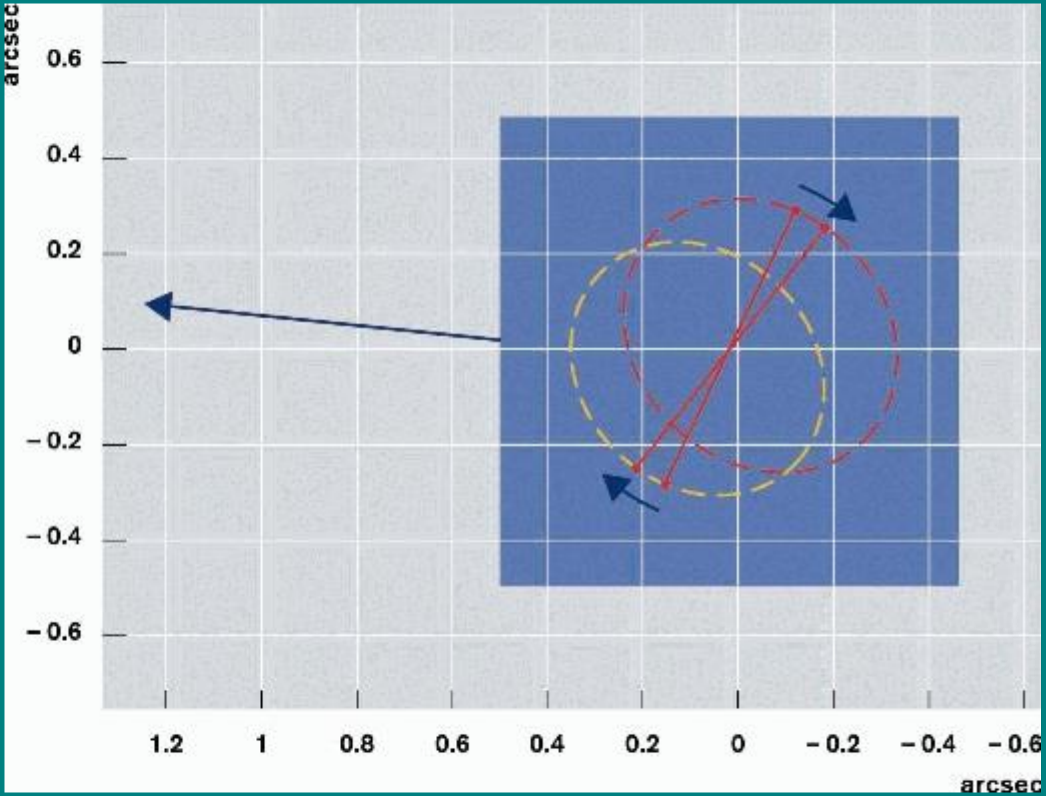
Chapter VIIa: Astrometry

- Proper motion of stars in Galactic open clusters: allows to study the dynamics of clusters and prove the membership of specific stars.



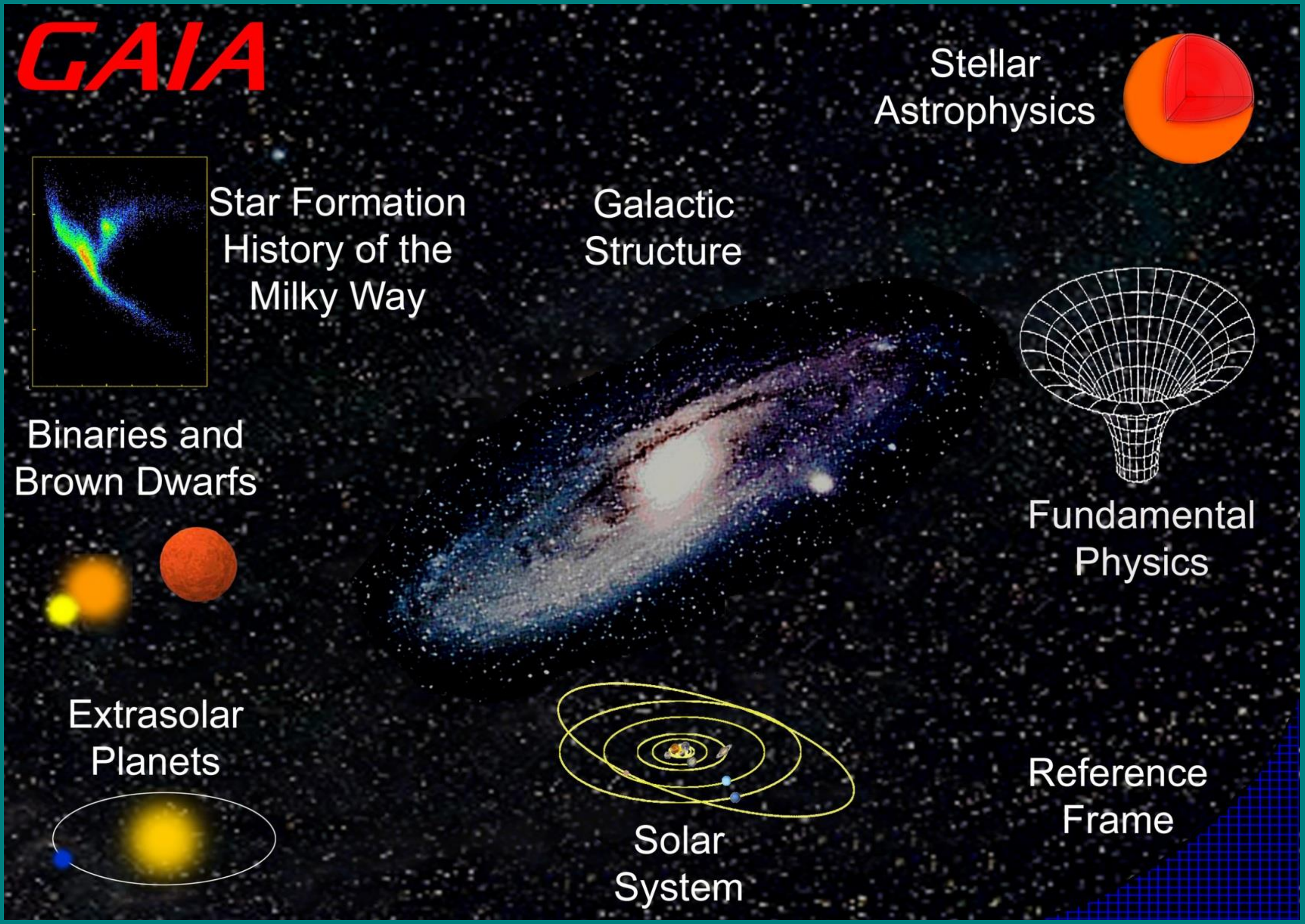
Chapter VIIa: Astrometry

- Astrometric orbits of binary systems allow to determine the masses of the stars that make up these systems (nearby binaries with orbital periods of several years up to several decades).



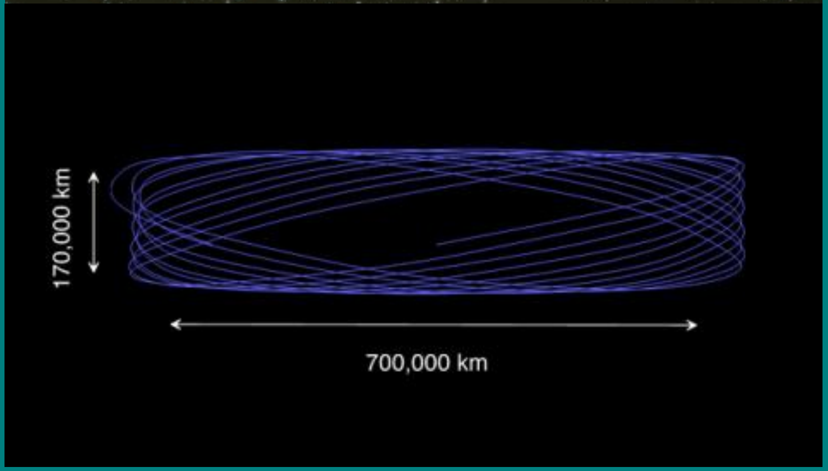
Chapter VIIa: Astrometry

- Gaia: ESA's new astrometry mission, but much more than an improved version of Hipparcos.



Chapter VIIa: Astrometry

- Gaia: launch from Kourou on 19 December 2013 with a Soyuz launcher.
- L2 reached on 8 January 2014.
- Lissajous orbit.

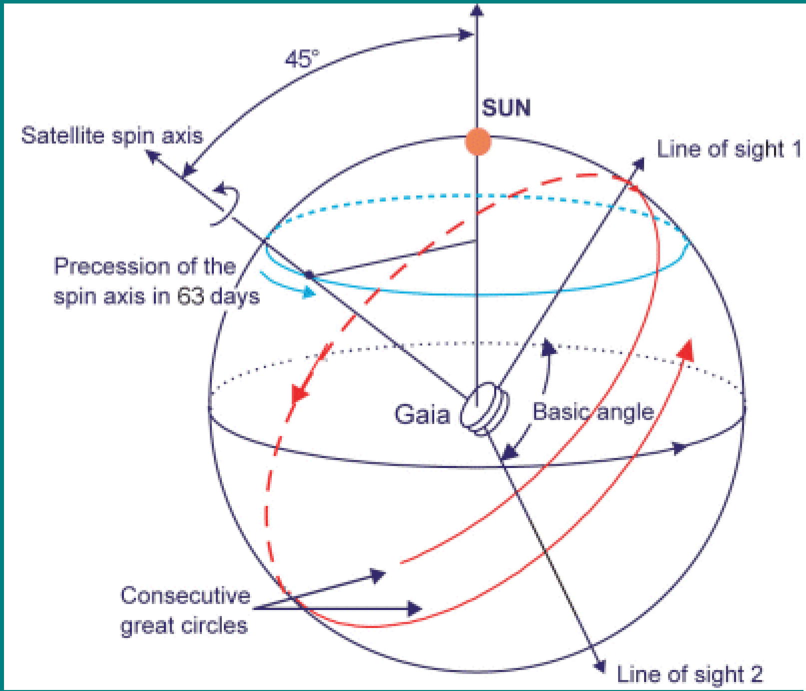


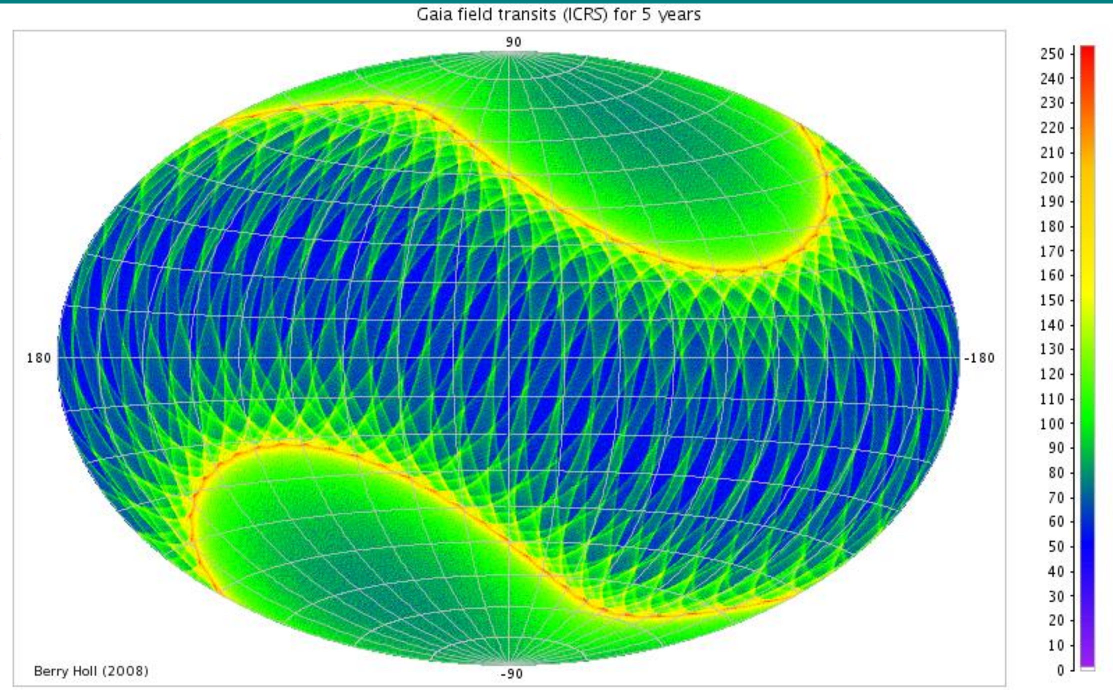
Chapter VIIa: Astrometry

- Gaia: from launch to orbit

Chapter VIIa: Astrometry

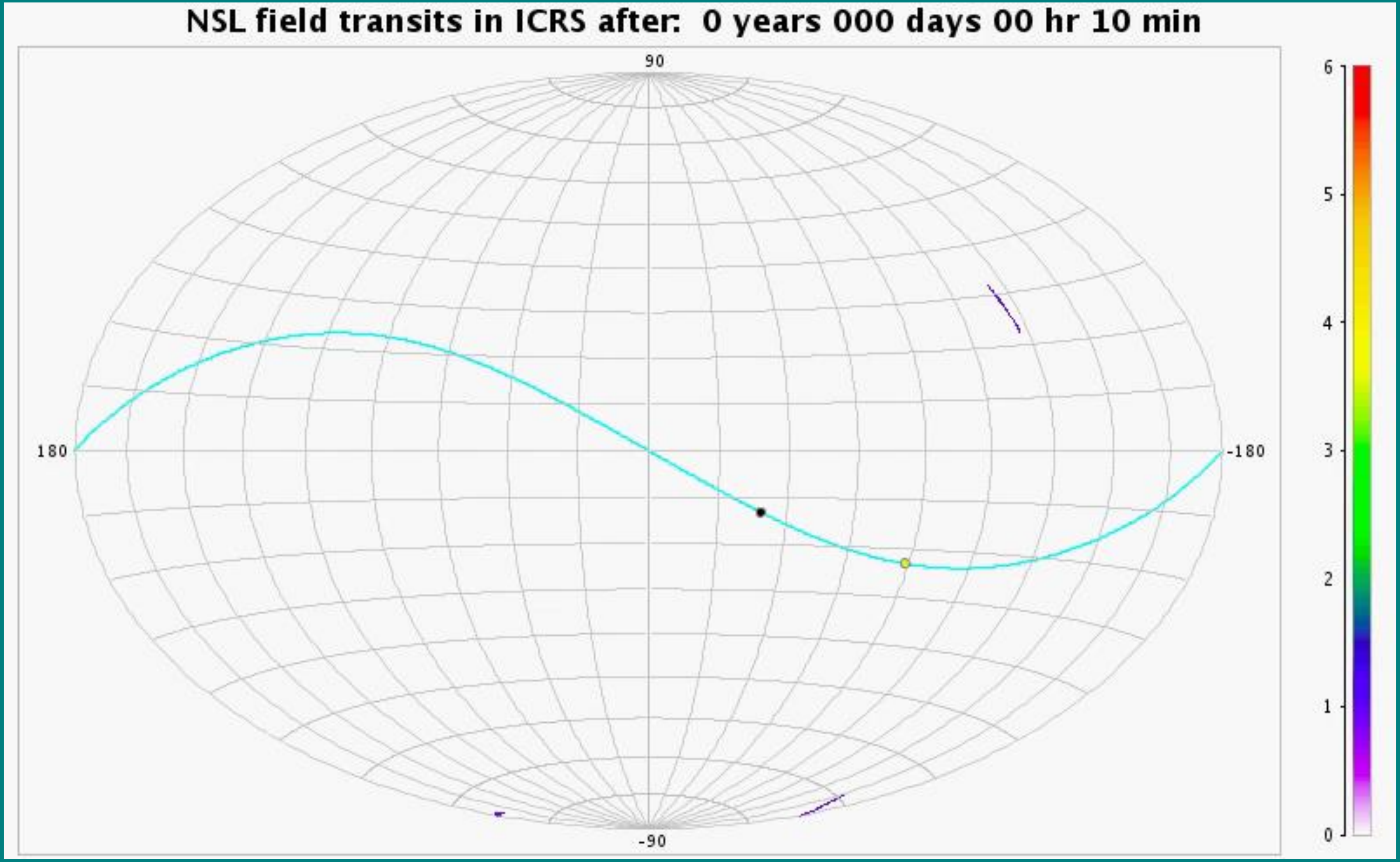
- As for Hipparcos, Gaia spins about its axis which slowly precesses, allowing to observe the whole sky.
- Spin: 60’’/s (6 hours), precession rate: 0.24’’/s (63 days)
- Each position in the sky is observed 70 times on average





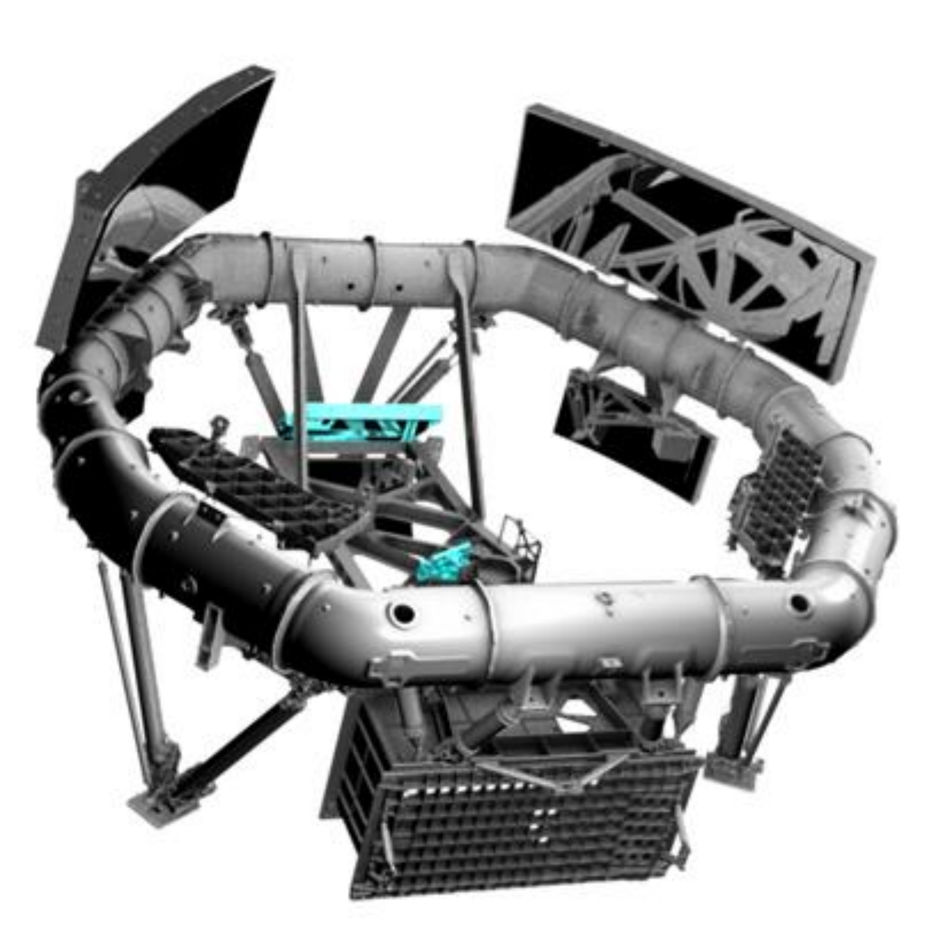
Chapter VIIa: Astrometry

- Gaia operations (Animation)



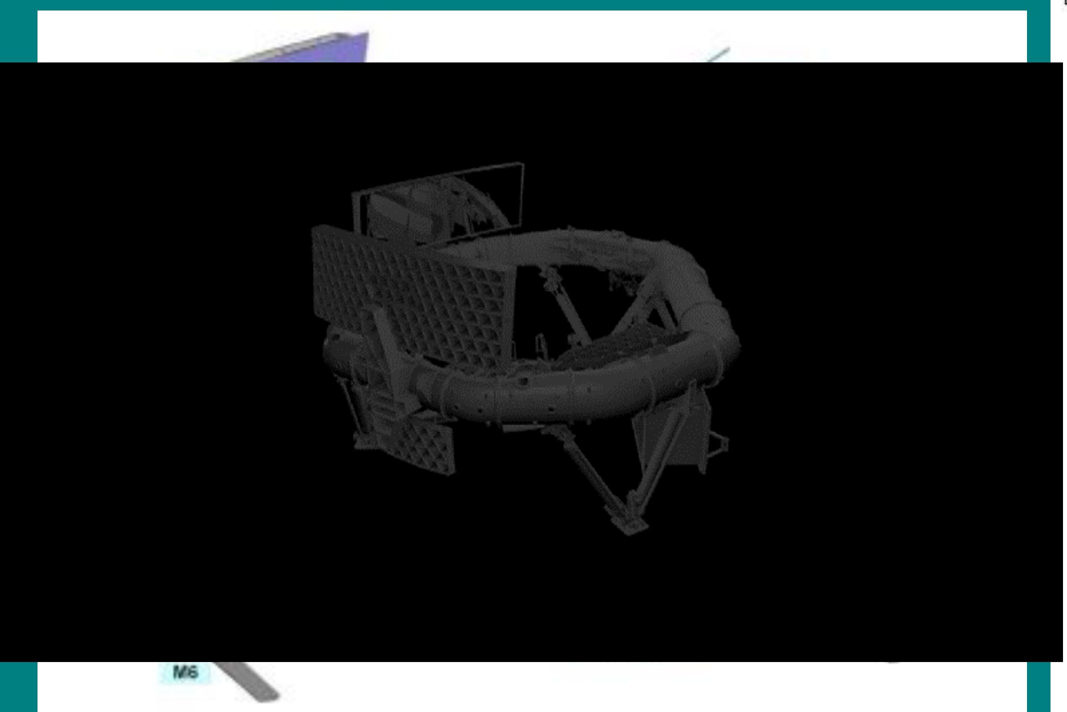
Chapter VIIa: Astrometry

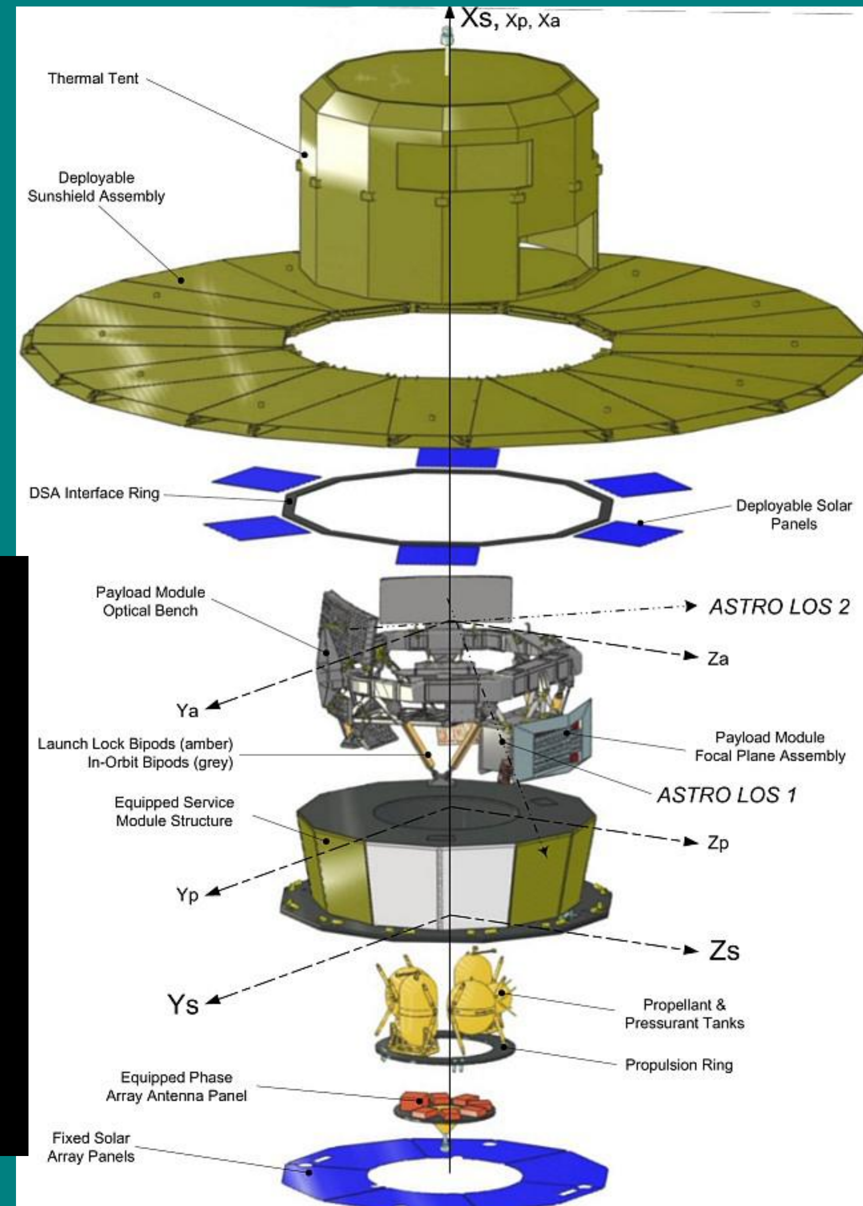
- Payload = two telescopes observing two fields of view separated by 106.5°.
- SiC mirrors



Chapter VIIa: Astrometry

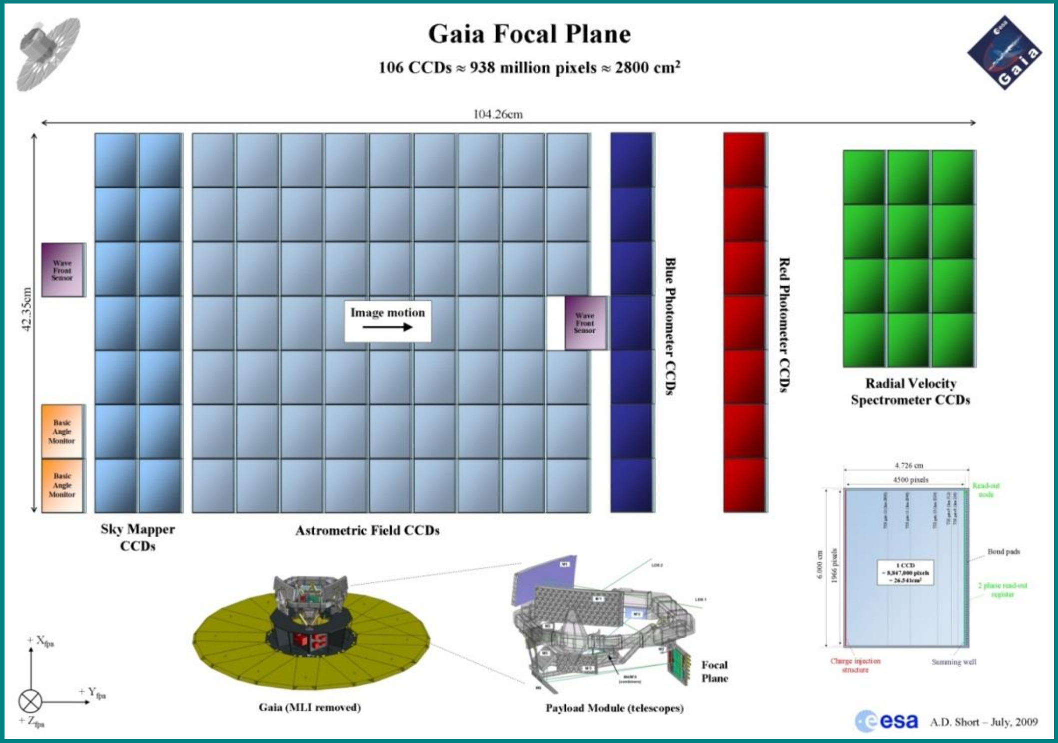
- As for Hipparcos, combination of the images of the two fields of view in a single focal plane.



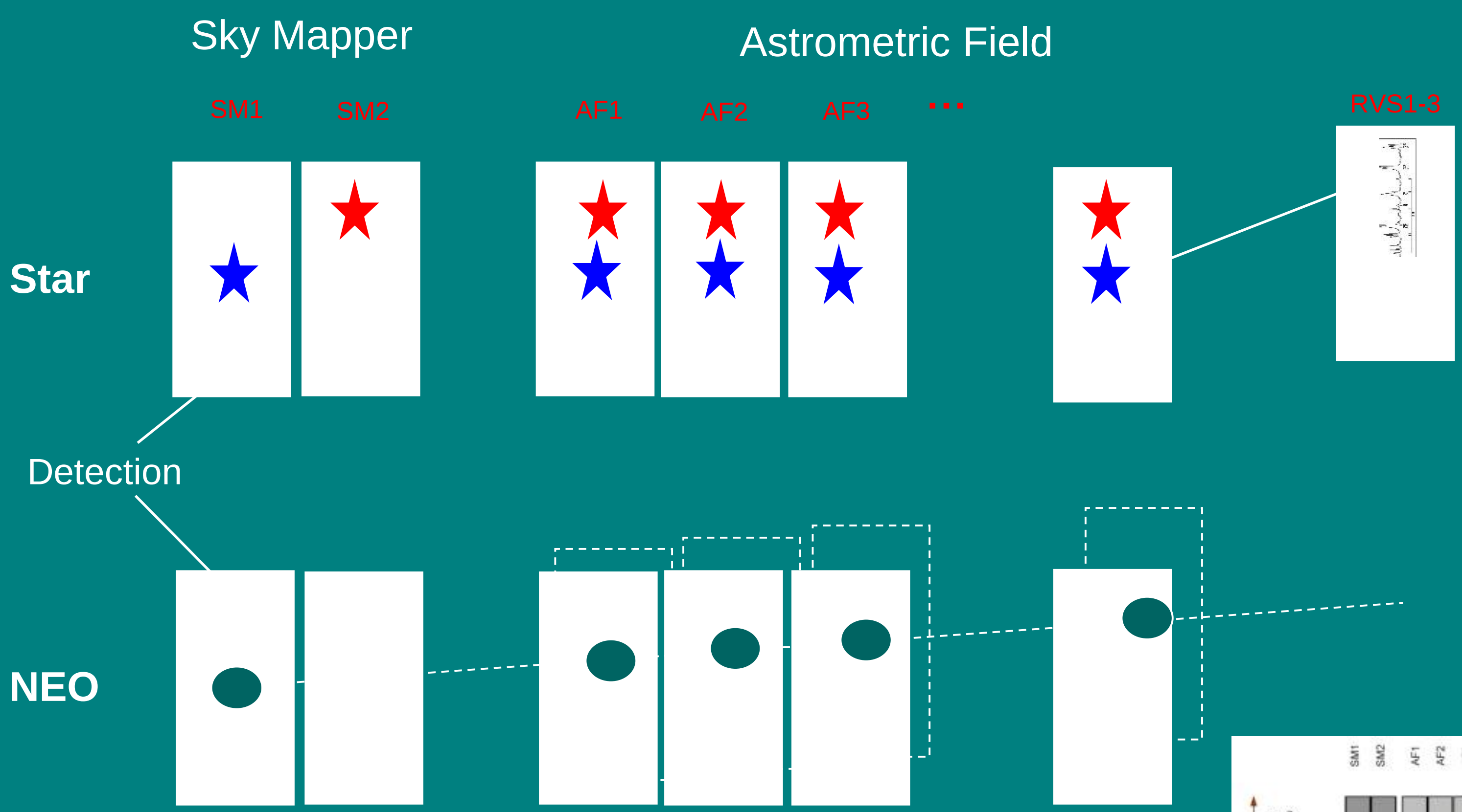


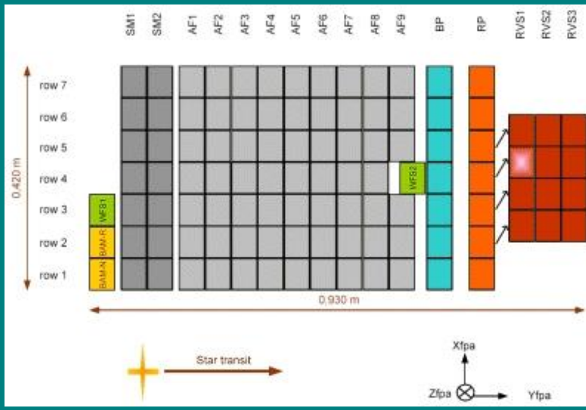
Chapter VIIa: Astrometry

- Focal plane: 106 CCDs, read-out in TDI mode.
- A single instrument, but combining 3 functionalities: astrometry, spectro-photometry (3200 – 10000 Å) and spectroscopy (8470 – 8740 Å, R = 11500)



Chapter VIIa: Astrometry





Chapter VIIa: Astrometry

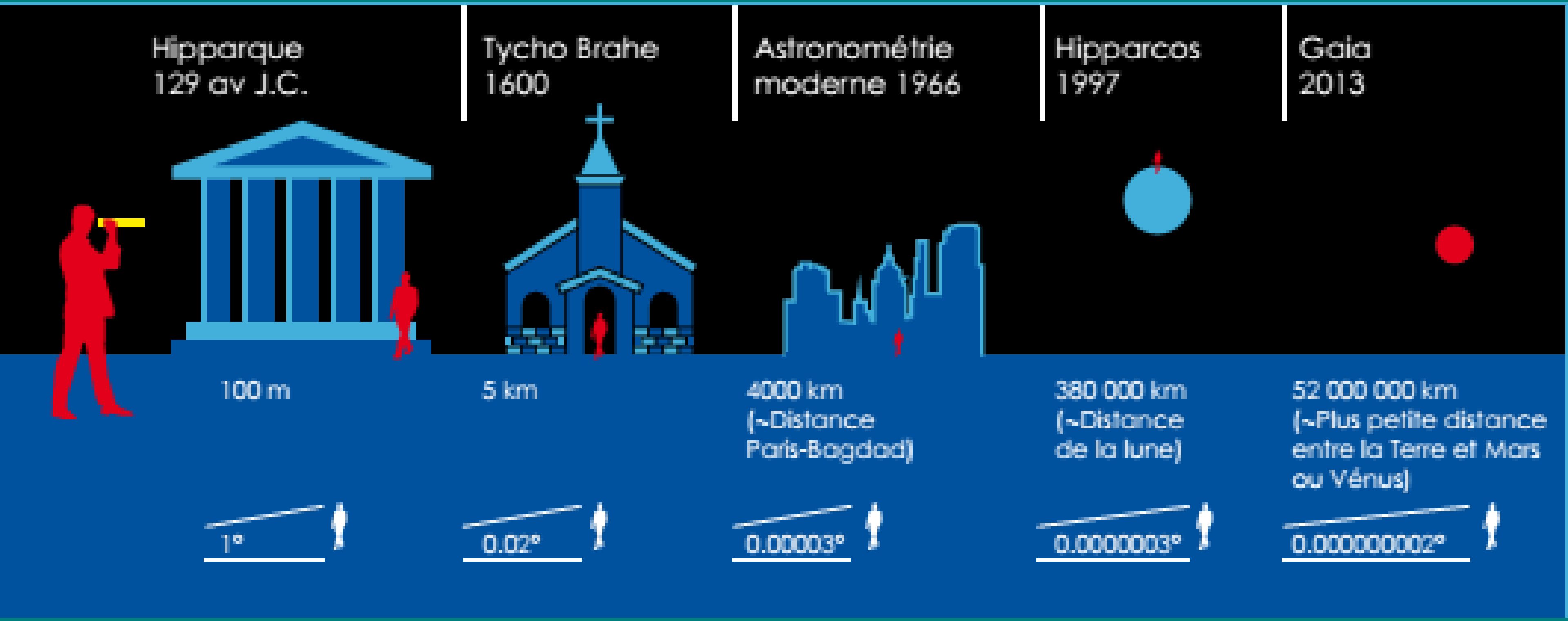
- Ground tests of sunshield deployment

Chapter VIIa: Astrometry

- Sunshield with solar panels deployed in space

Chapter VIIa: Astrometry

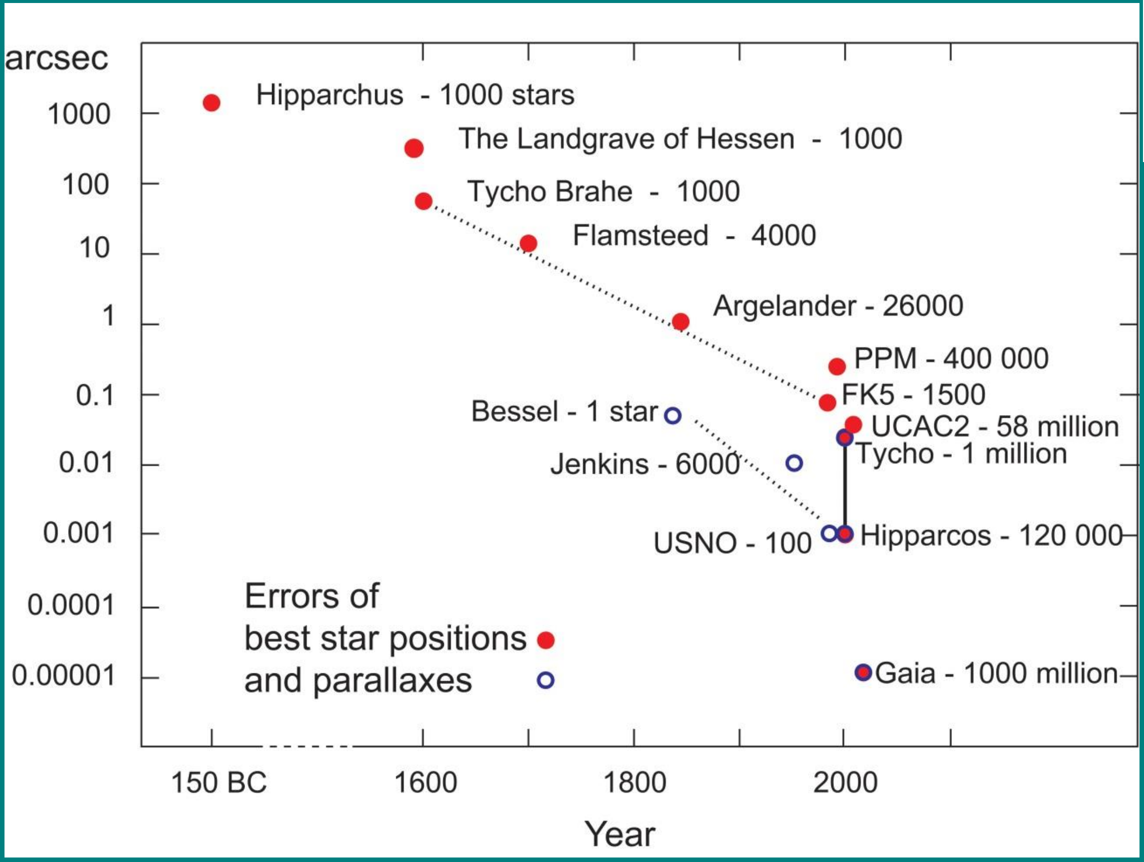
- For stars brighter than V=10, one expects an accuracy of about 10 μarcsec on the parallax = size of a 2 € coin on the Moon (i.e. @ 380 000 km)



Chapter VIIa: Astrometry

- Gaia: expected performances: 10% precision on the distance for 220 million stars.

Spectral type	V (mag)	$\sigma(\Pi)$ (μarcsec)
B1 V	< 10	< 7
	15	< 25
	20	< 300
G2 V	< 10	< 7
	15	< 24
	20	< 300
M6 V	< 10	< 7
	15	< 12
	20	< 100

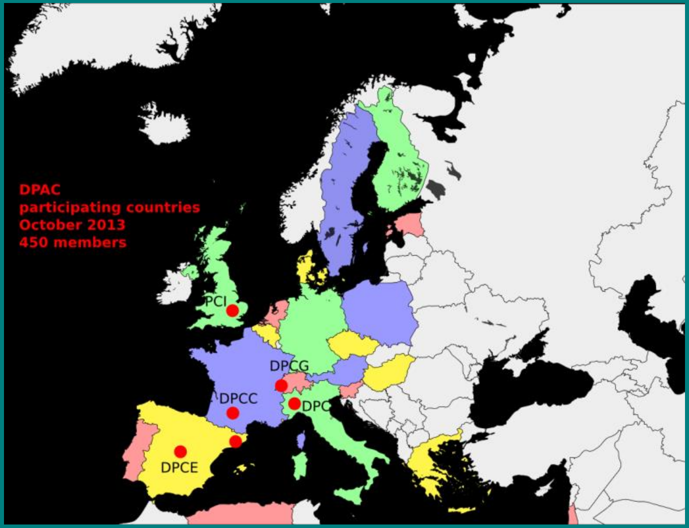


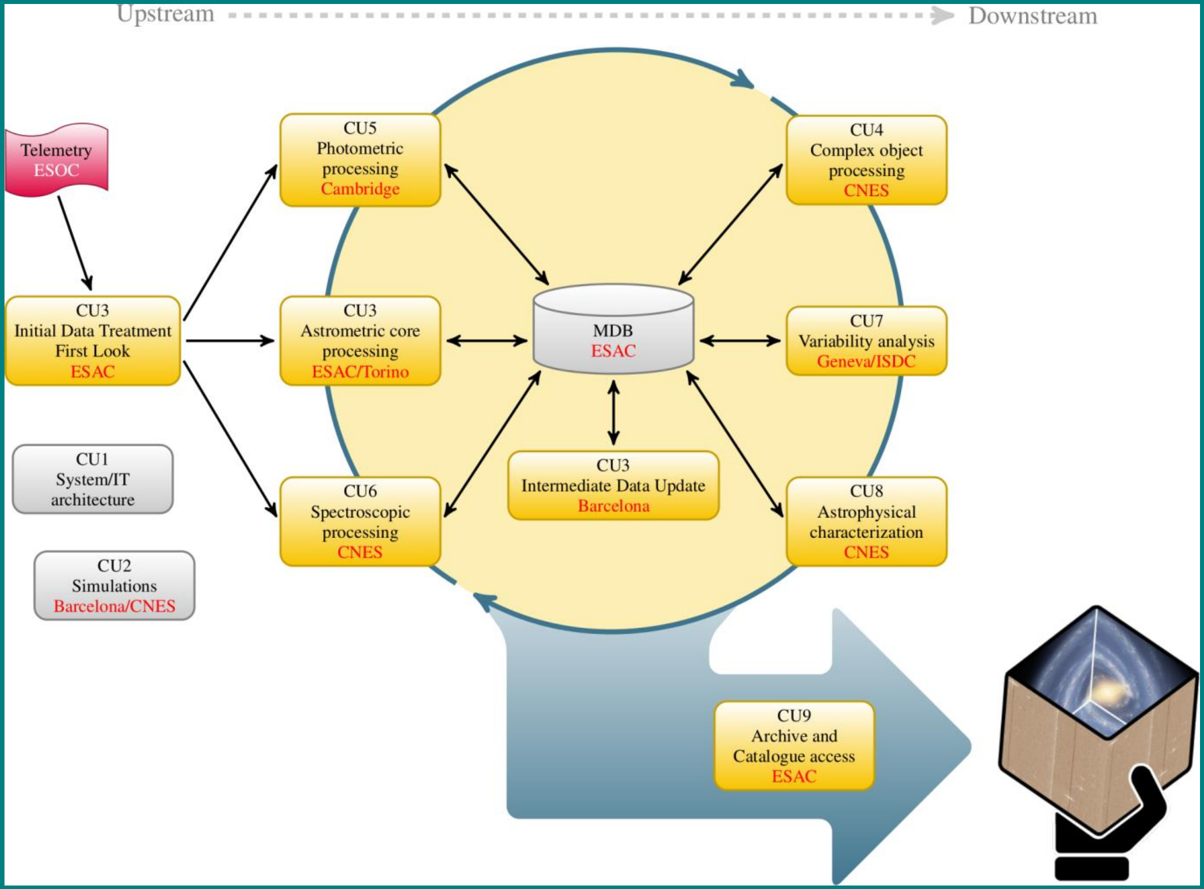
+ Radial velocities, chemical compositions, effective temperatures

Data processing (DPAC)

Chapter VIIa: Astrometry

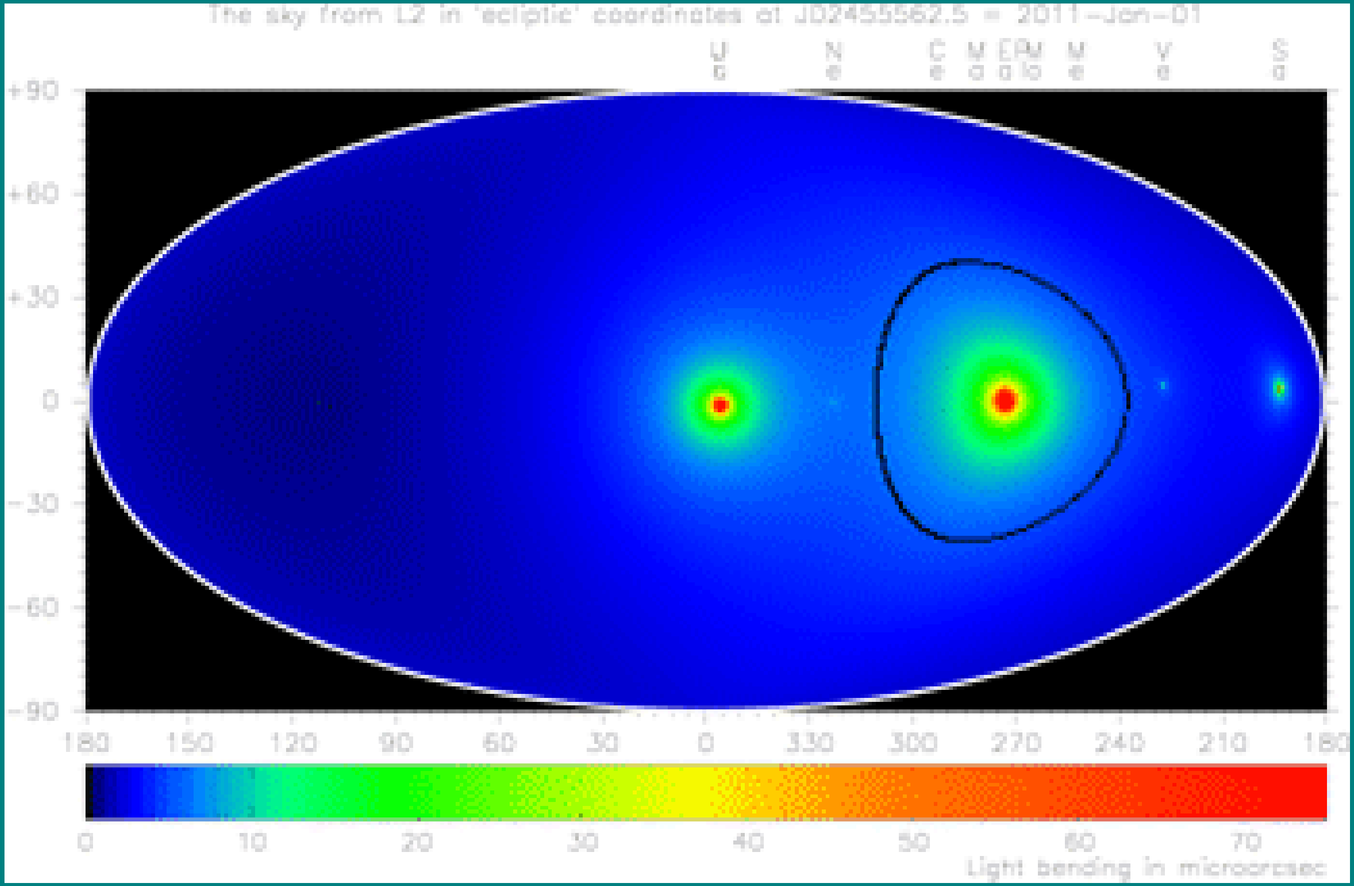
- Data reduction: DPAC (Data Processing and Analysis Consortium).





Chapter VIIa: Astrometry

- Gaia: tests of general relativity

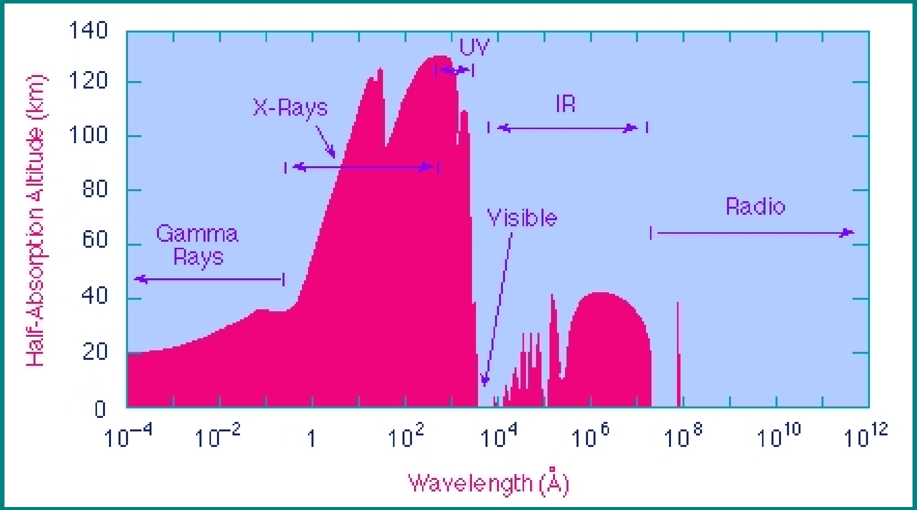


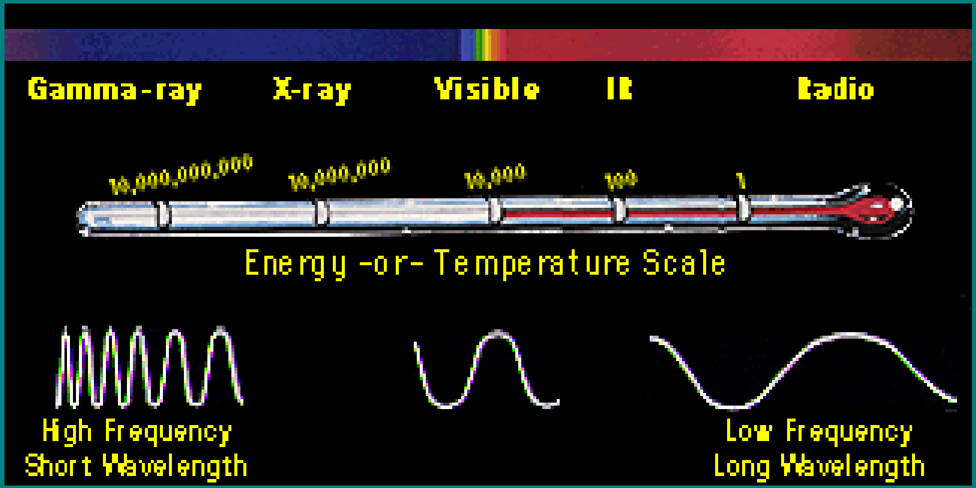
Chapter VIIb: X-ray astrophysics

- X-rays: another view of the universe
- The beginning: the Uhuru satellite
- X-ray telescopes
- The XMM satellite
- Examples of scientific questions: accretion
  1. X-ray binaries
  2. AGN
- The future: Athena

Chapter VIIb: X-ray astrophysics

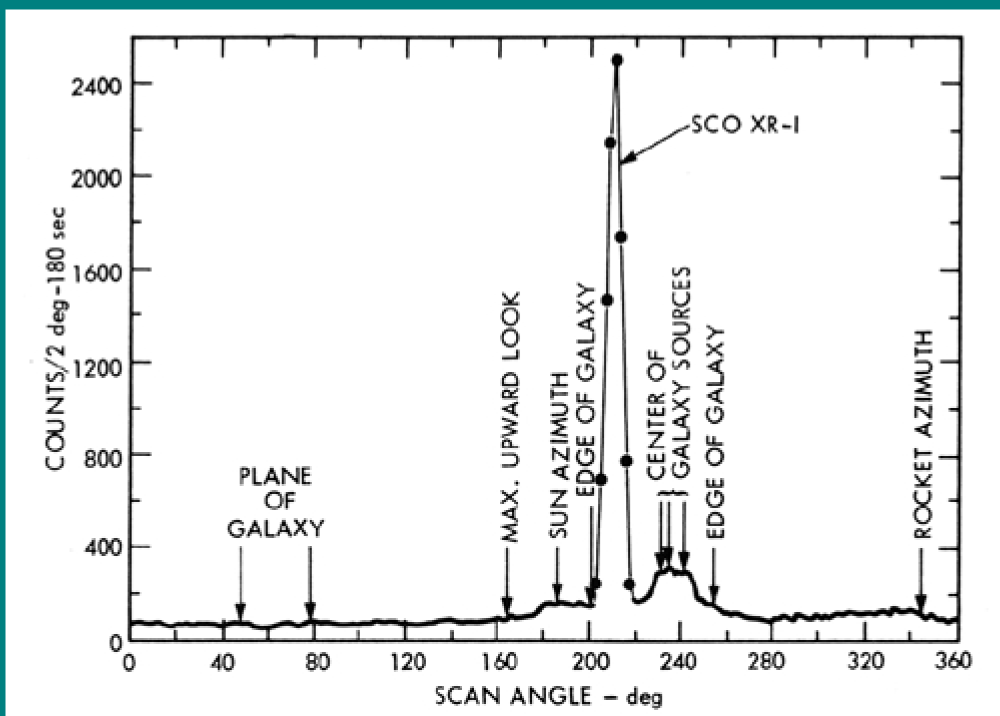
- Observation of X-rays (between about 1 and 100 Å): only from space!
- Violent phenomena (generating plasma at high temperatures)

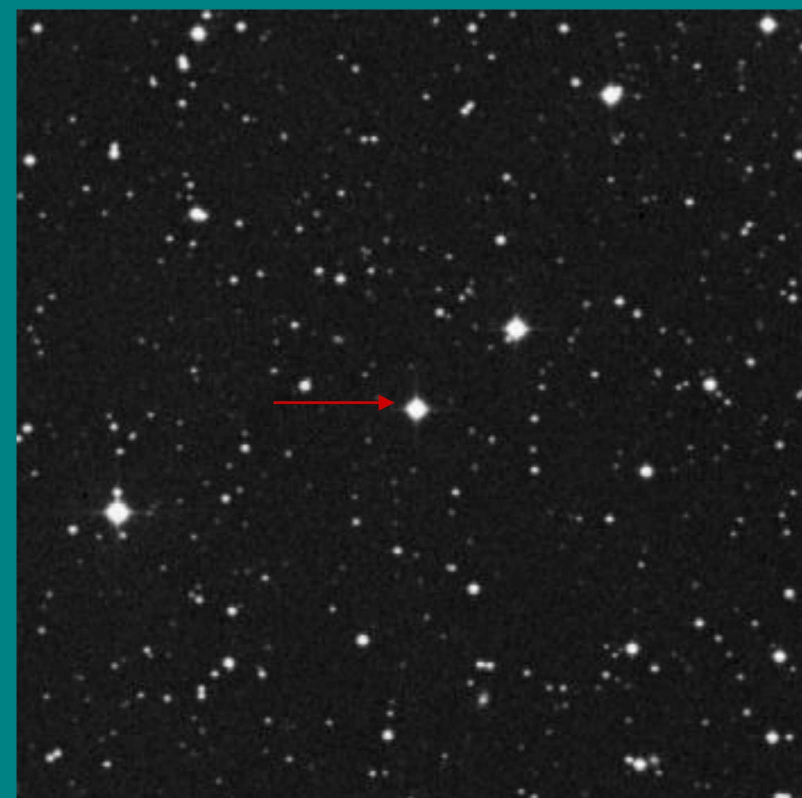




Chapter VIIb: X-ray astrophysics

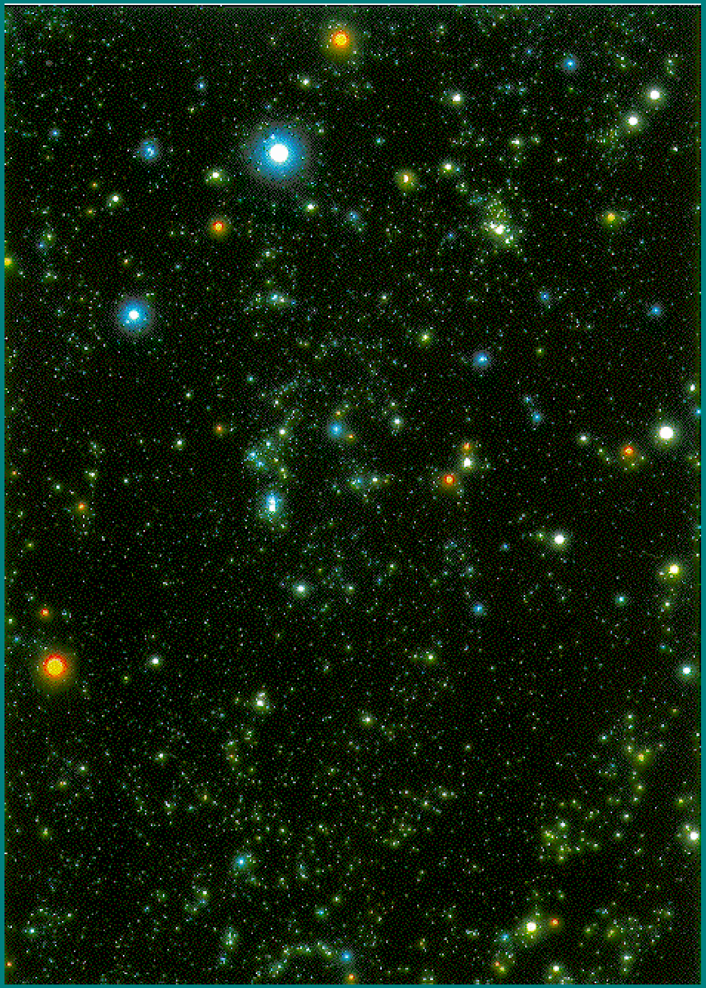
- 1st cosmic X-ray source detected outside the Solar System: Sco X-1 (June 1962, Aerobee rocket) = brightest X-ray source apart from the Sun
- Optical counterpart identified in 1967: 13th magnitude star!

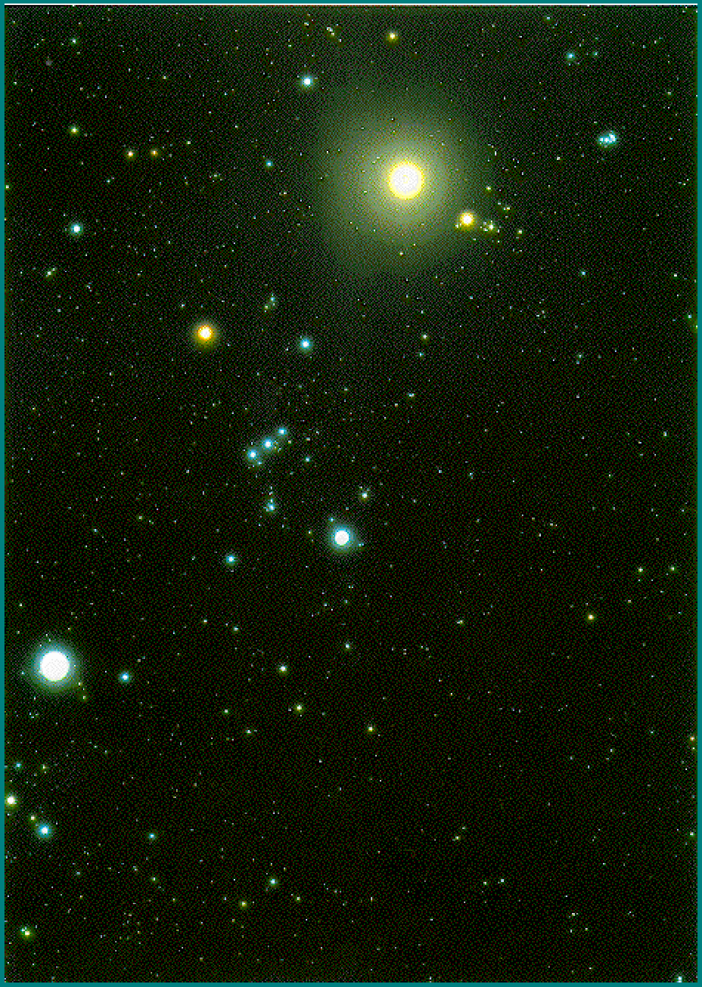




Chapter VIIb: X-ray astrophysics

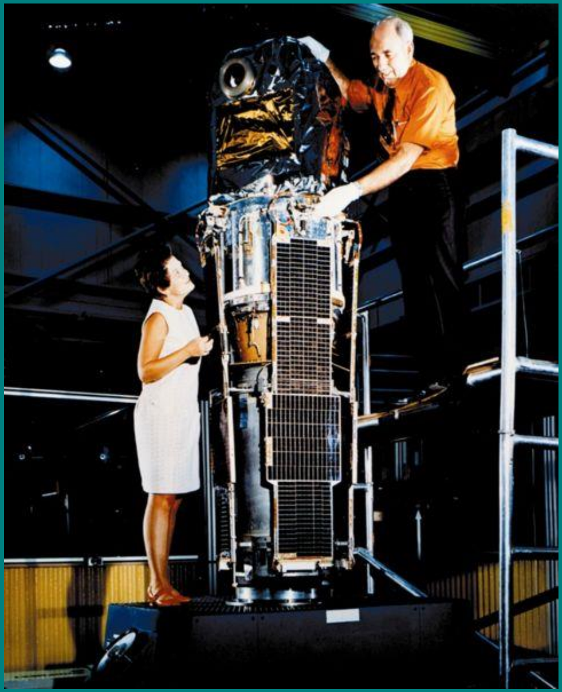
- X-rays reveal an alternative view of the universe.

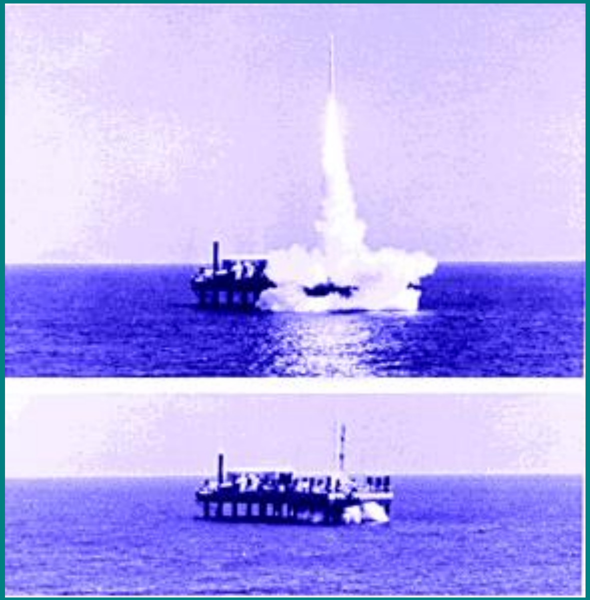




Chapter VIIb: X-ray astrophysics

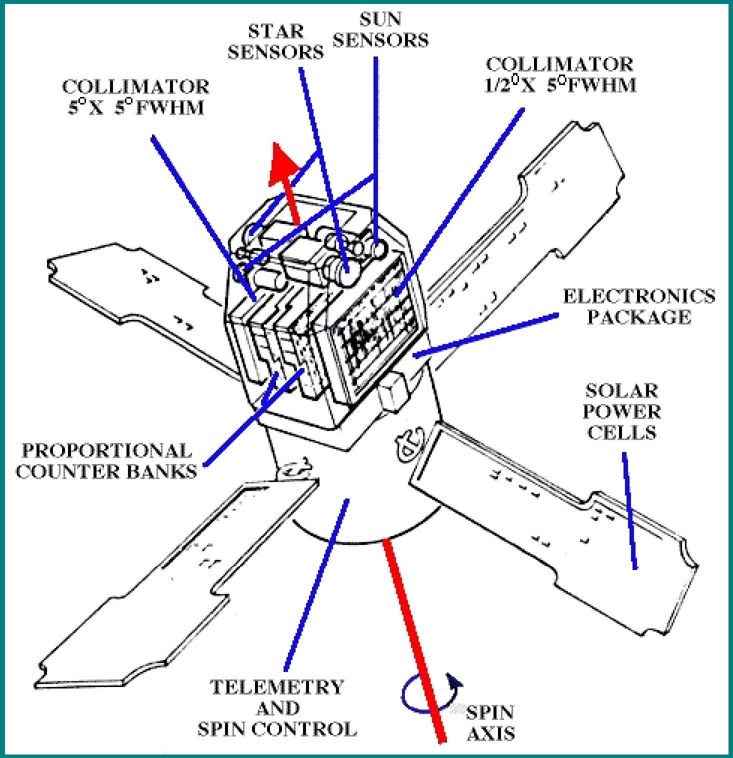
- 1st X-ray satellite: Uhuru launched in 1970
- LEO with inclination of 3°
- Main objective: map the full sky in X-rays (2 to 20 keV)

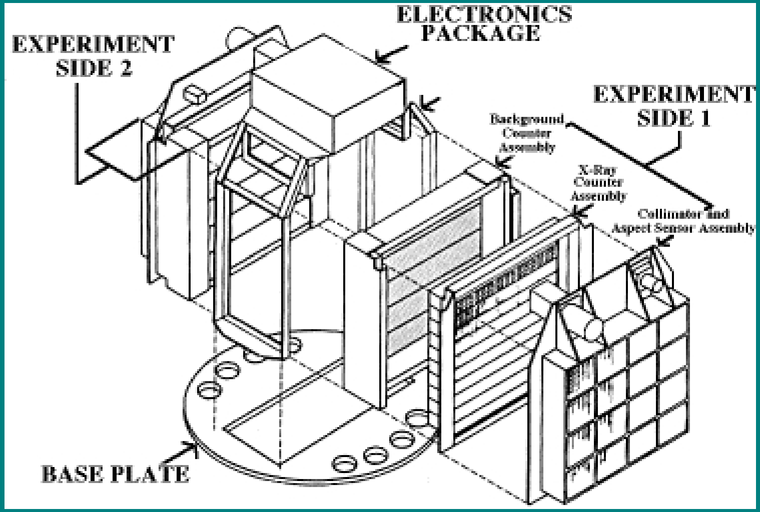




Chapter VIIb: X-ray astrophysics

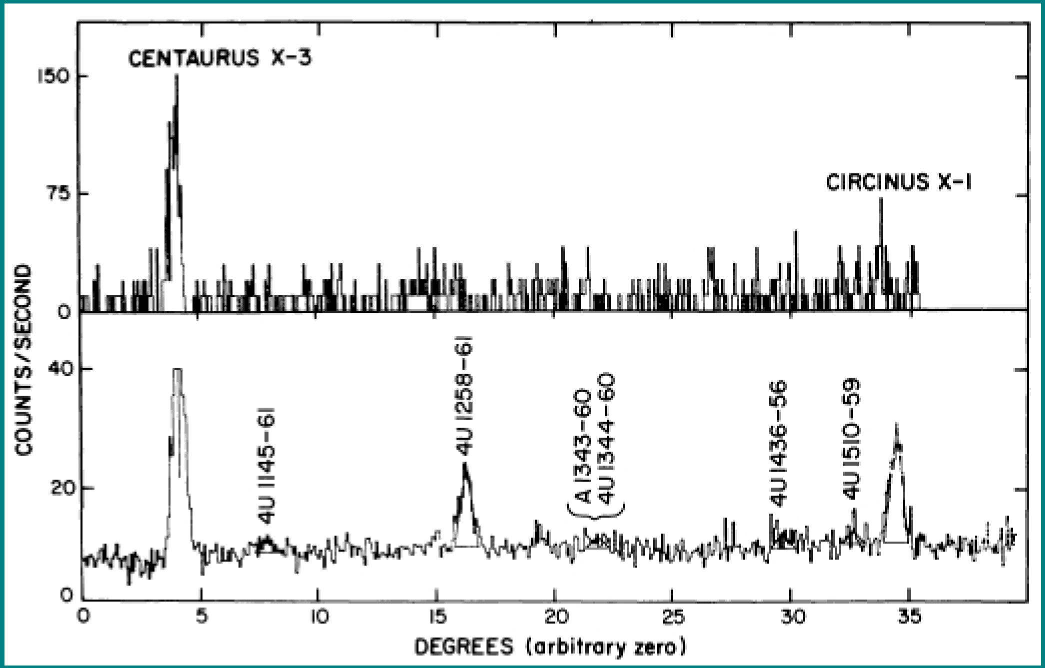
- Uhuru did not feature an X-ray telescope, but two proportional counters with X-ray collimators yielding fields of view of 0.52° × 5.2° and 5.2° × 5.2°
- Satellite spinning to scan the entire sky.





Chapter VIIb: X-ray astrophysics

- Collecting area of Uhuru: about 700 cm^2
- Sensitivity: about 1.5×10^{-11} erg cm^{-2} s^{-1}
- No images!



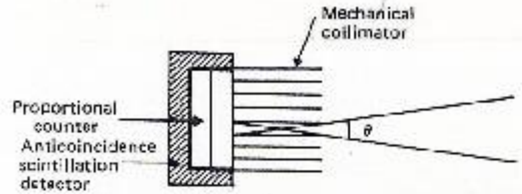
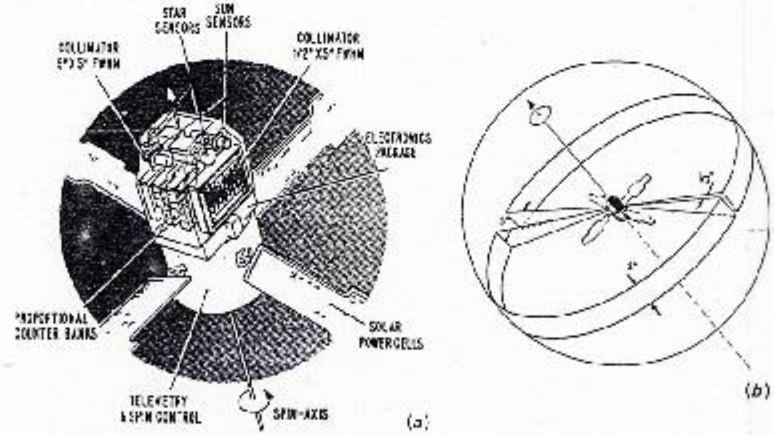
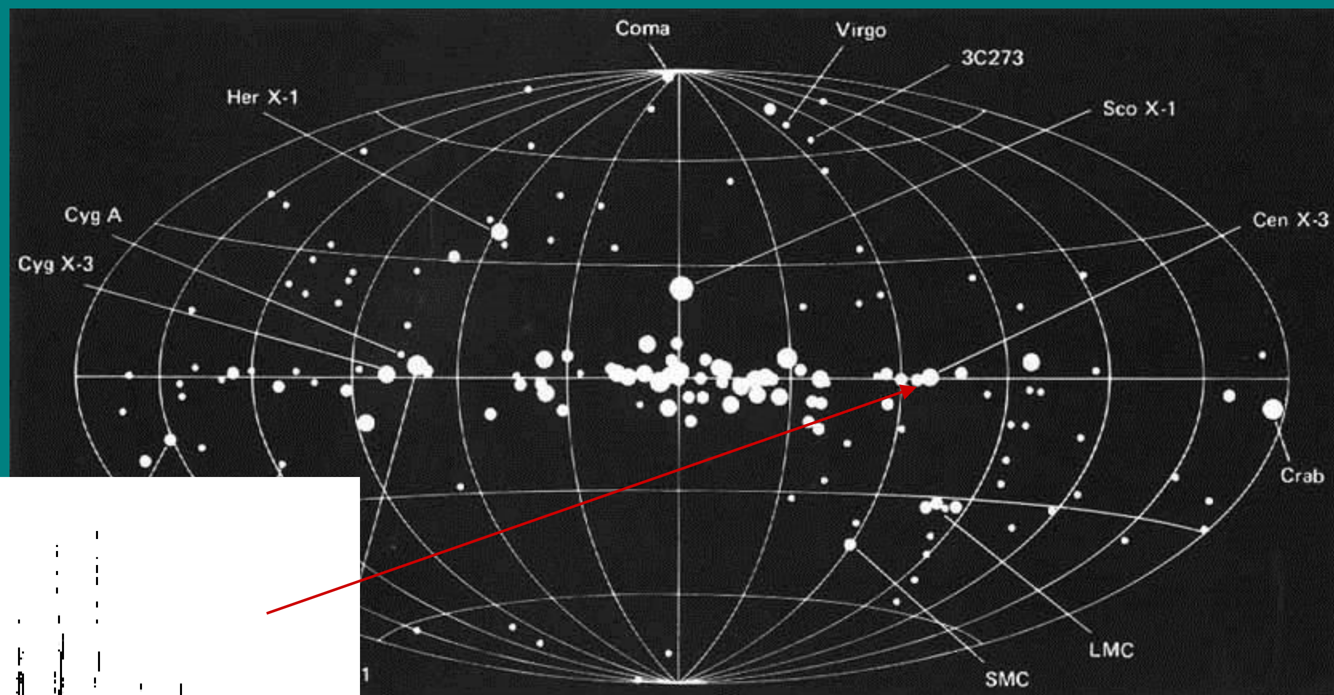


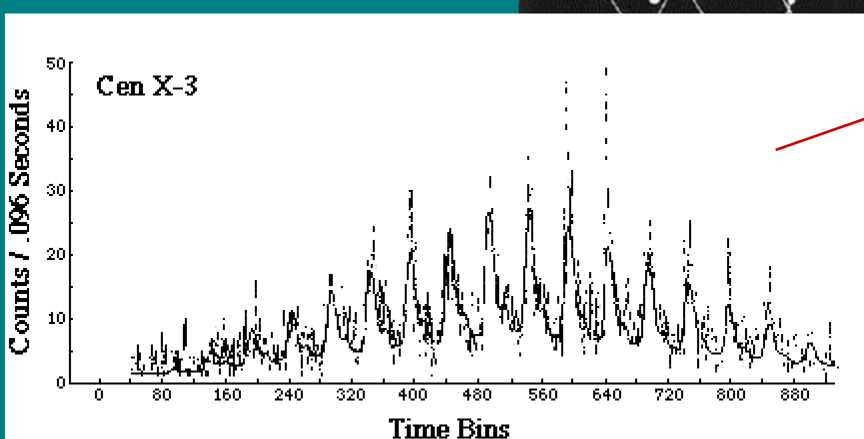
Figure 7.9. The layout of a simple X-ray telescope of the type flown on the UHURU and Ariel-V satellites.



Chapter VIIb: X-ray astrophysics

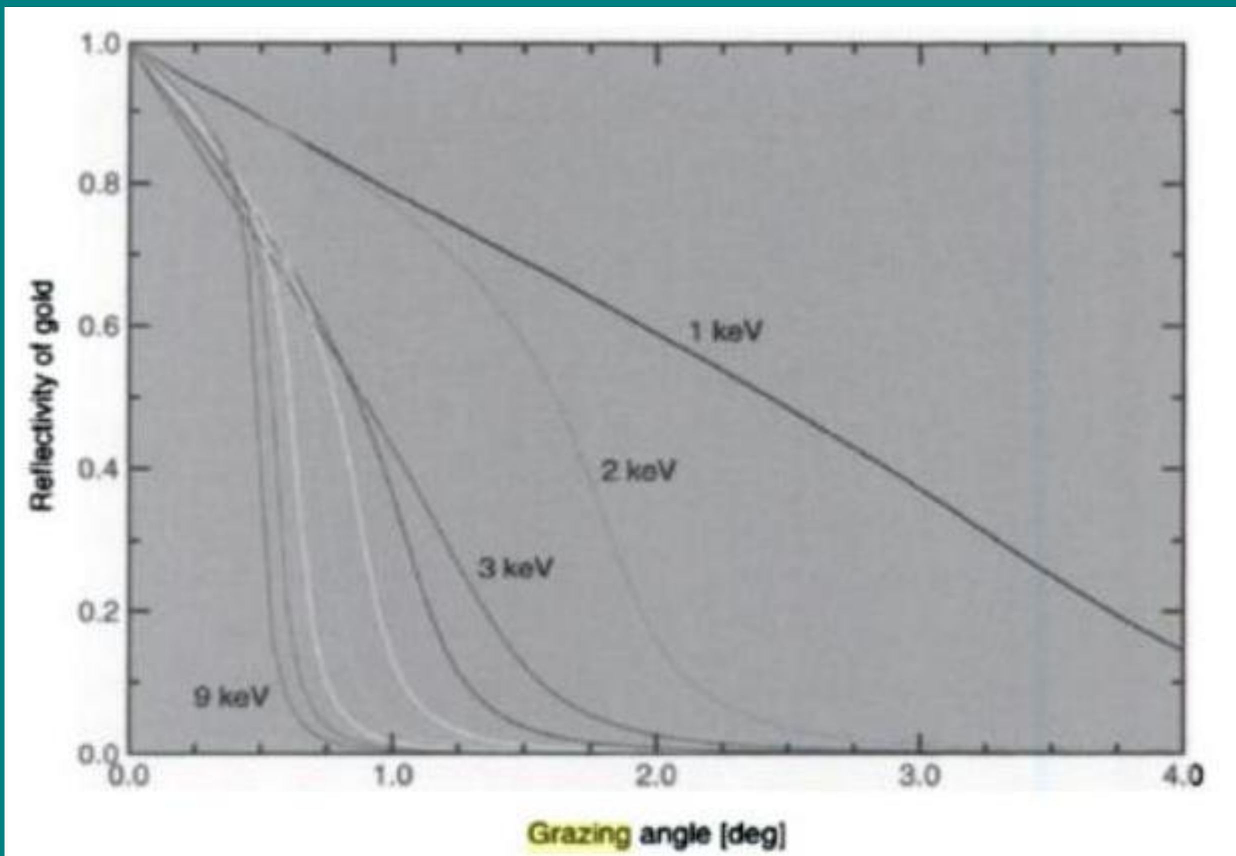
- Final Uhuru catalogue: 339 X-ray sources with their positions (not very accurate), flux, light curve, spectra (8 bins)
- Sources highly concentrated in the plane of the Galaxy.

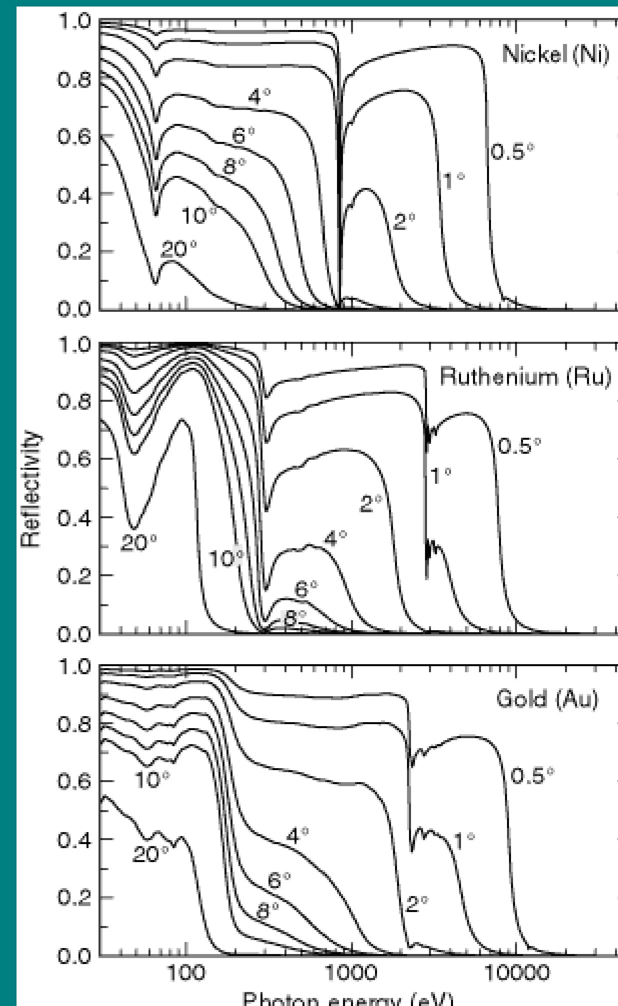




Chapter VIIb: X-ray astrophysics

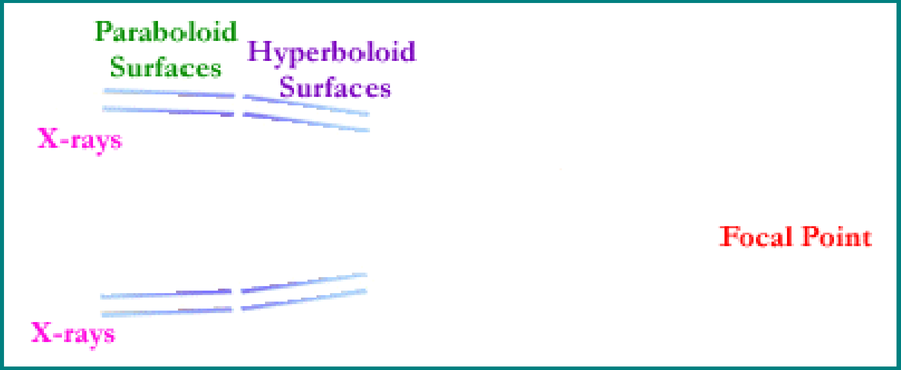
- Reflection of X-rays: grazing incidence.

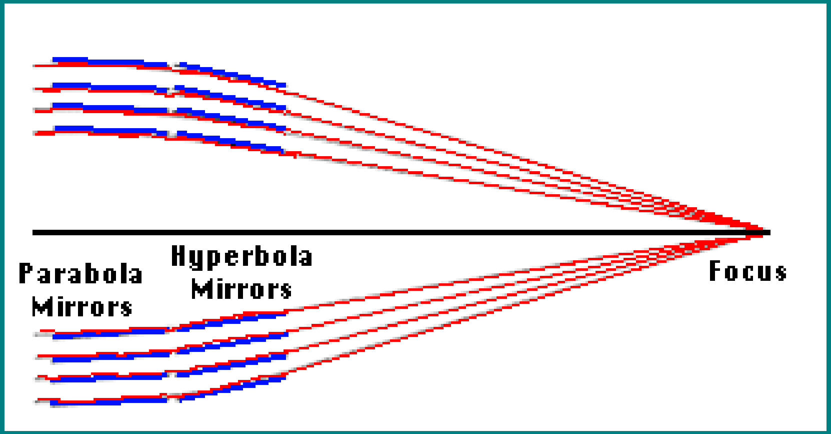


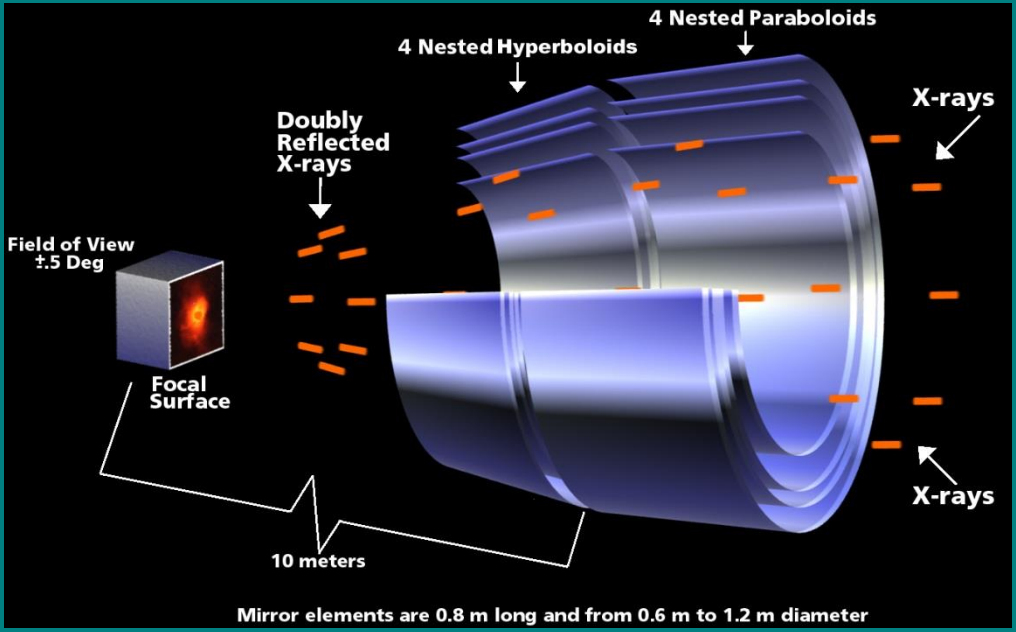


Chapter VIIb: X-ray astrophysics

- Wolter I assembly: combination of paraboloid and hyperboloid surfaces to reduce focal length.

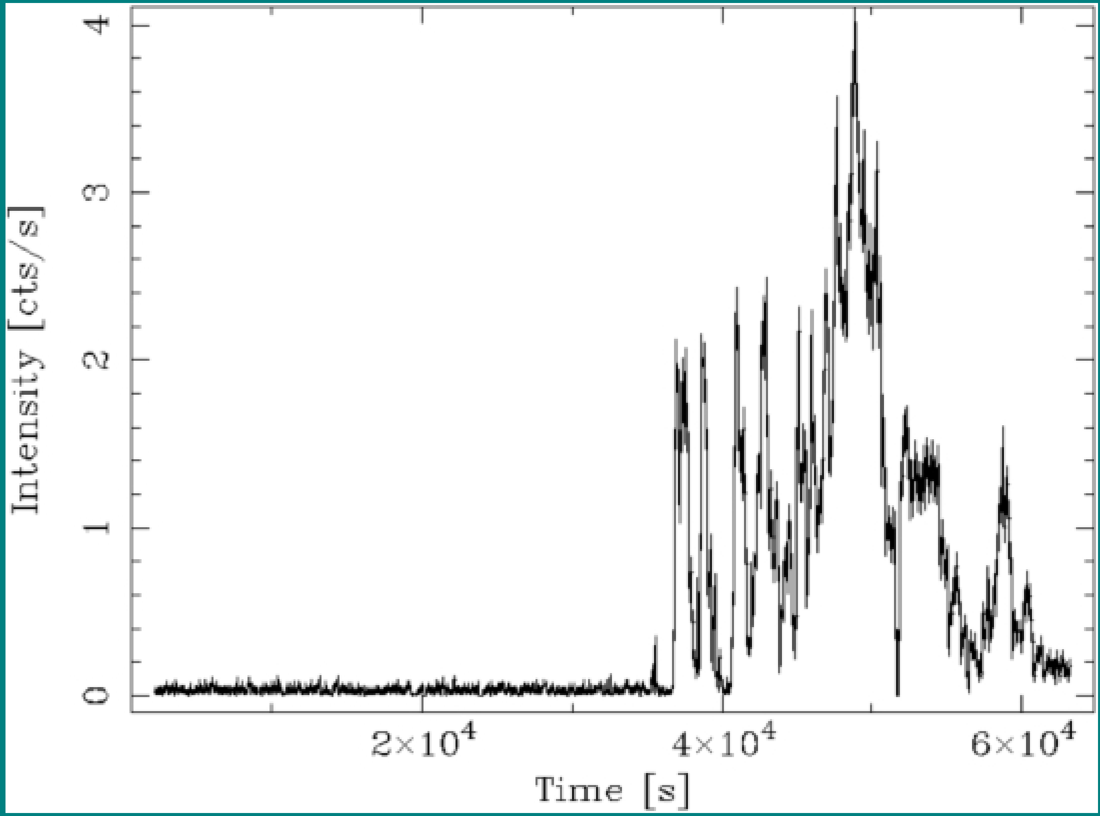






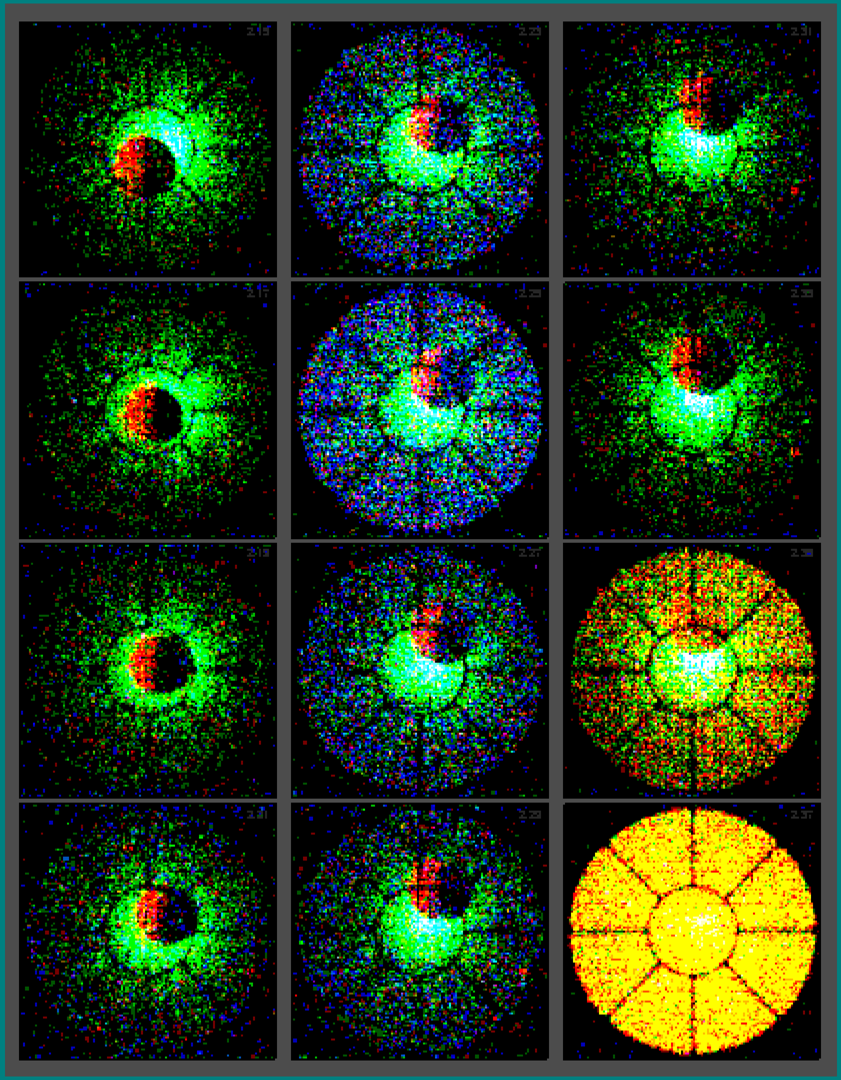
Chapter VIIb: X-ray astrophysics

- Problem with Wolter I type mirrors: not only X-ray photons are reflected under grazing incidence…



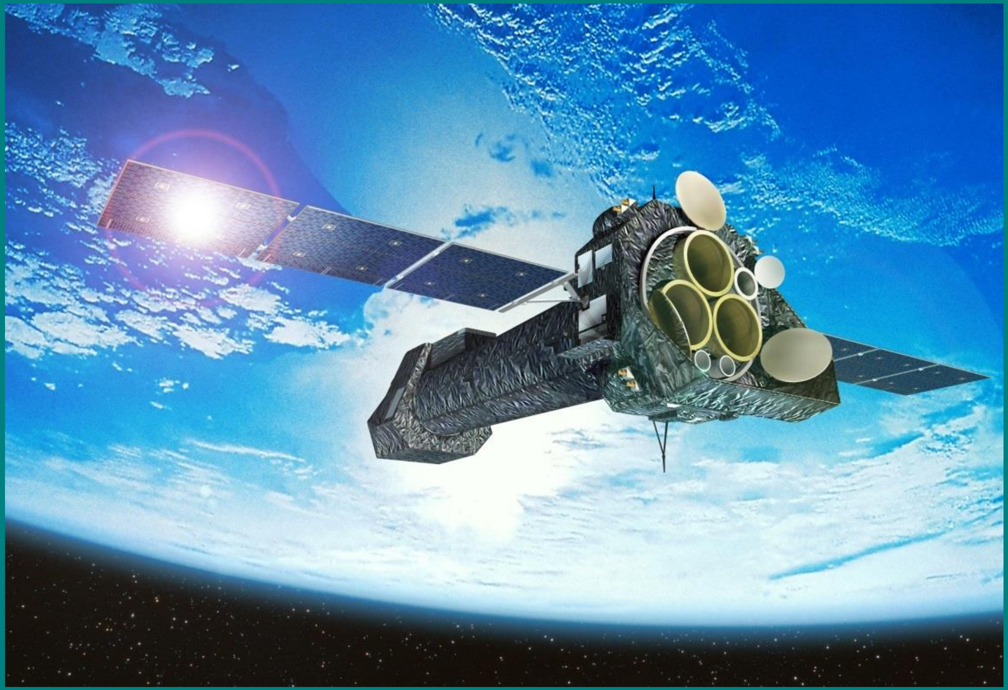
Chapter VIIb: X-ray astrophysics

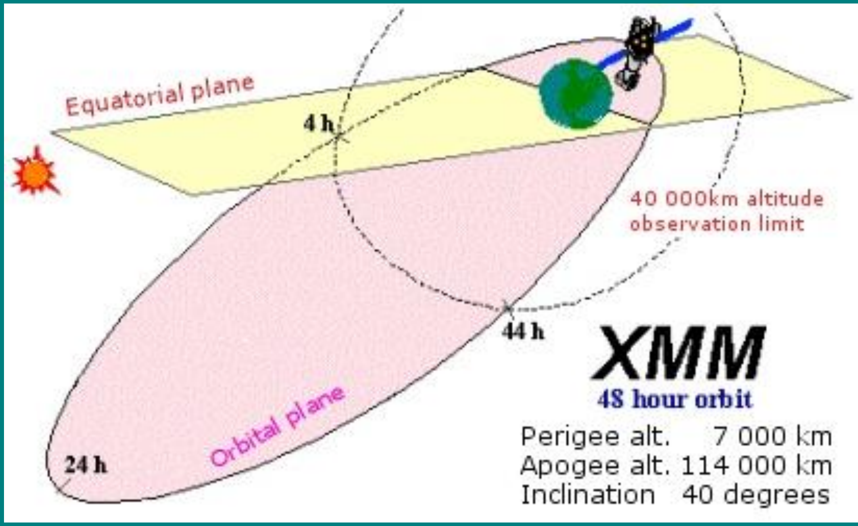
- Imaging capabilities open-up new possibilities: easier identification of the sources, study of their morphology,…
- Einstein, ROSAT, ASCA, Chandra, XMM-Newton, Suzaku, NuStar…



Chapter VIIb: X-ray astrophysics

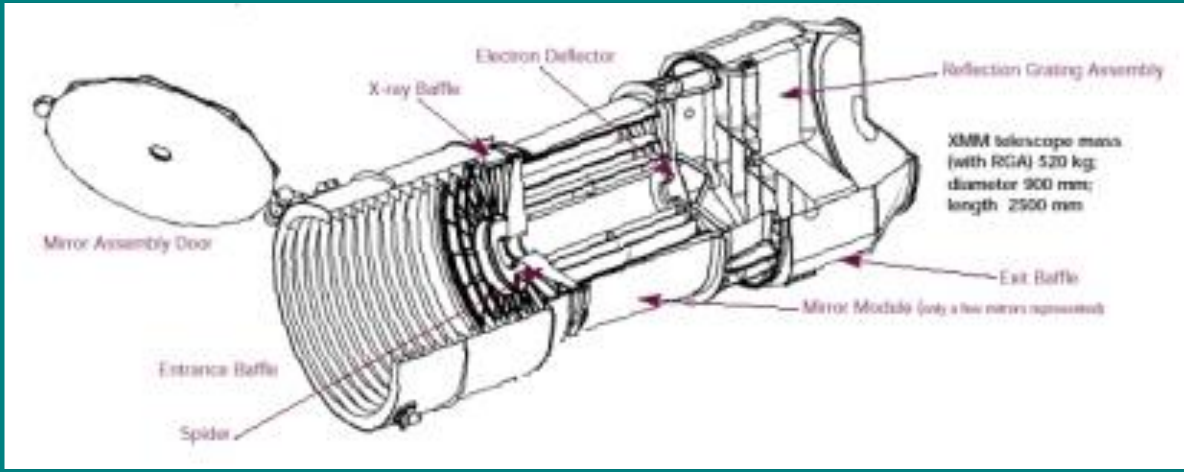
- XMM-Newton: ESA's X-ray telescope





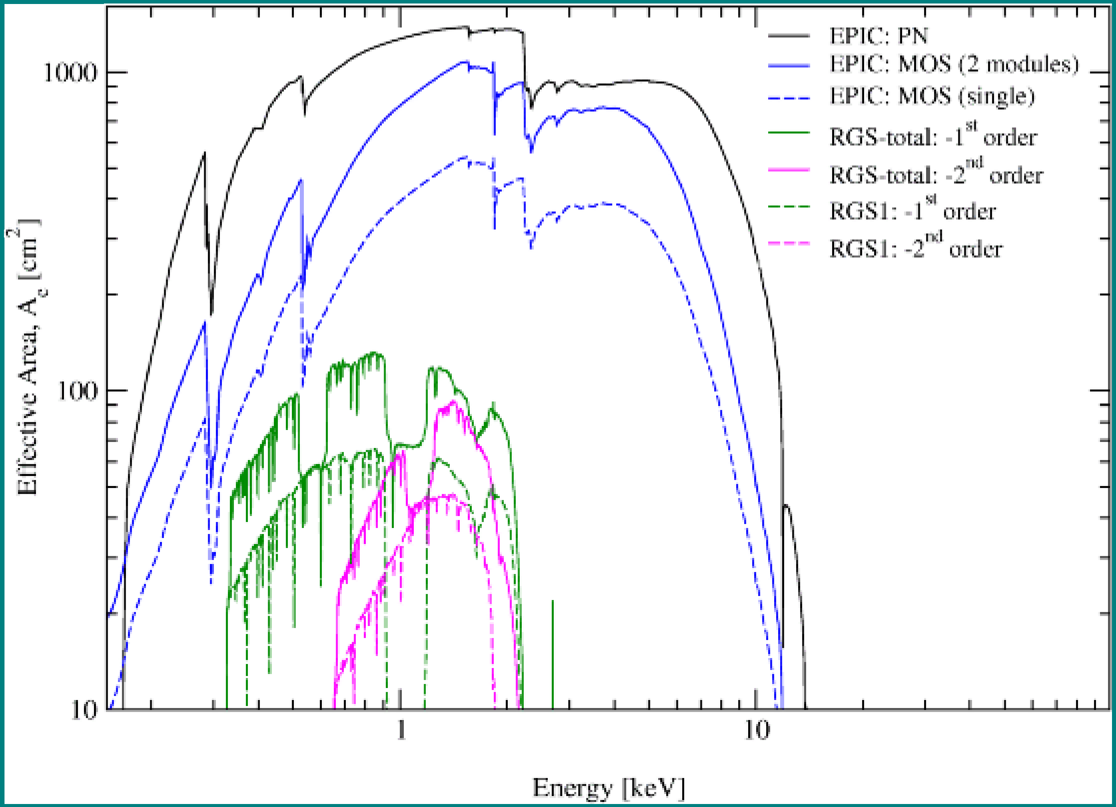
- 48h, highly eccentric (e = 0.79) orbit.

- XMM-Newton: 3 modules of 58 nested Wolter I mirrors = the largest collecting area to date ~ 4000 cm^2



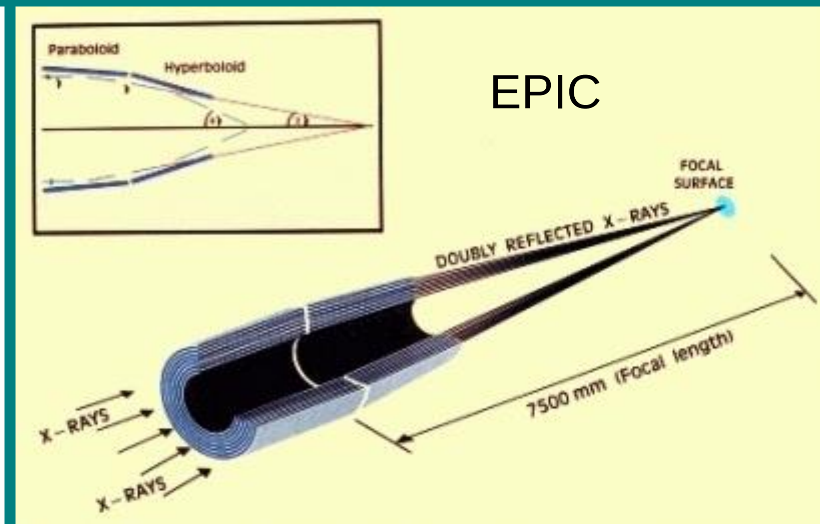
Chapter VIIb: X-ray astrophysics

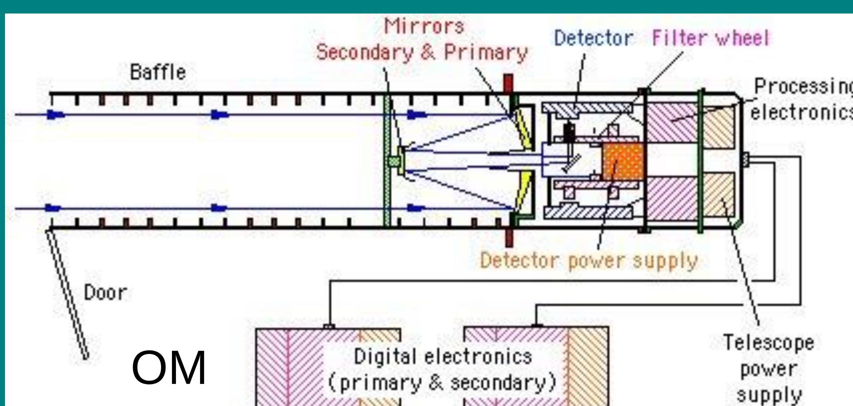
- XMM-Newton: 3 modules of 58 nested Wolter I mirrors = the largest collecting area to date ~ 4000 cm^2

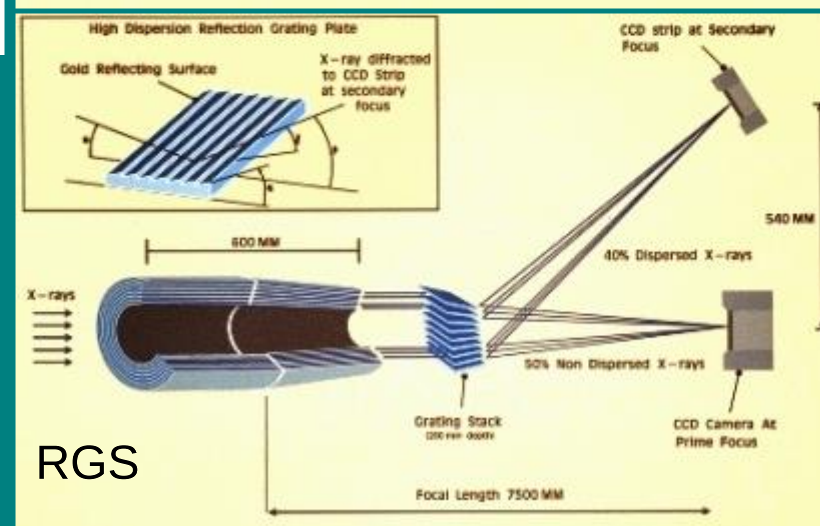


Chapter VIIb: X-ray astrophysics

- 3 EPIC cameras, 2 RGS spectrographs and an Optical Monitor

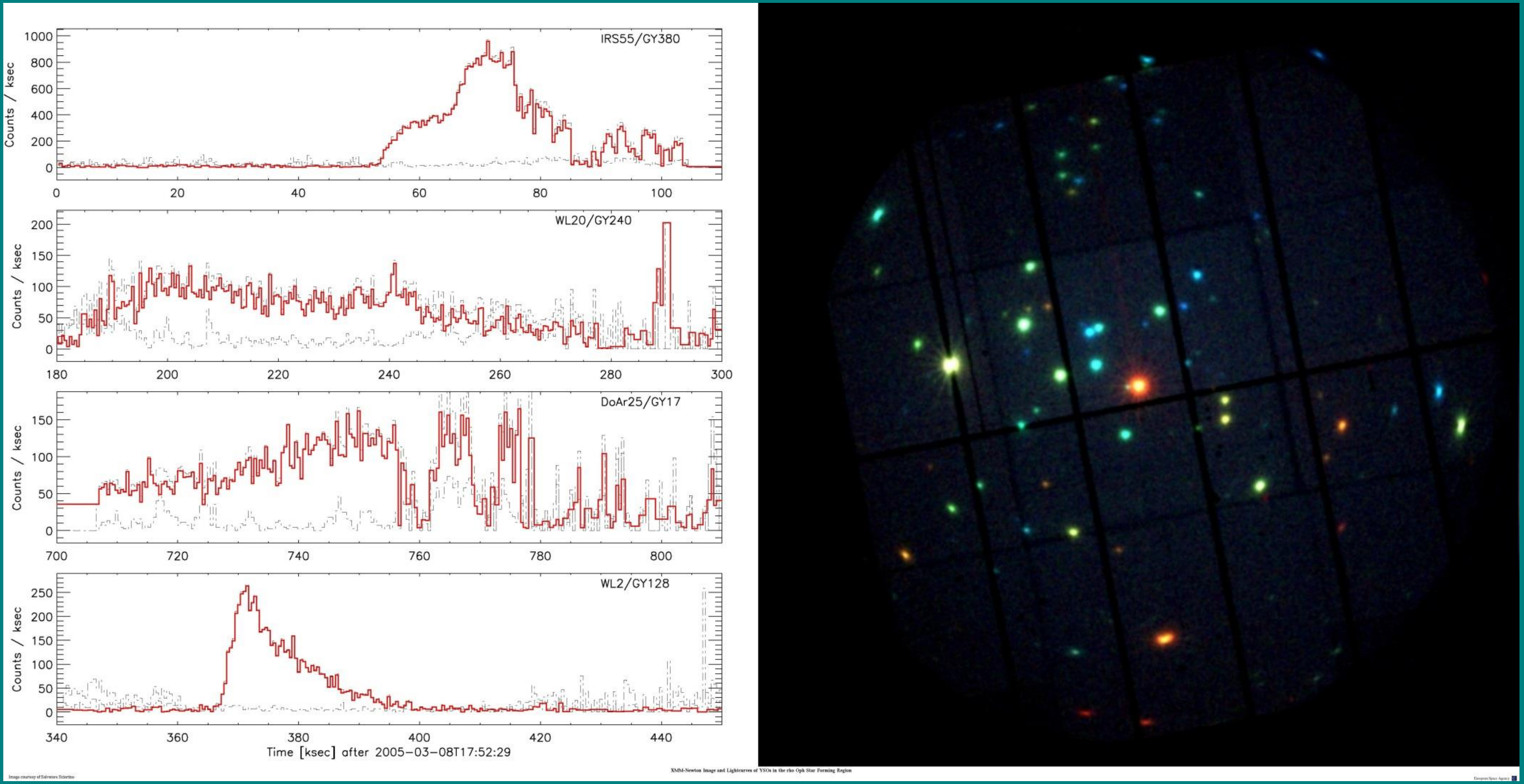






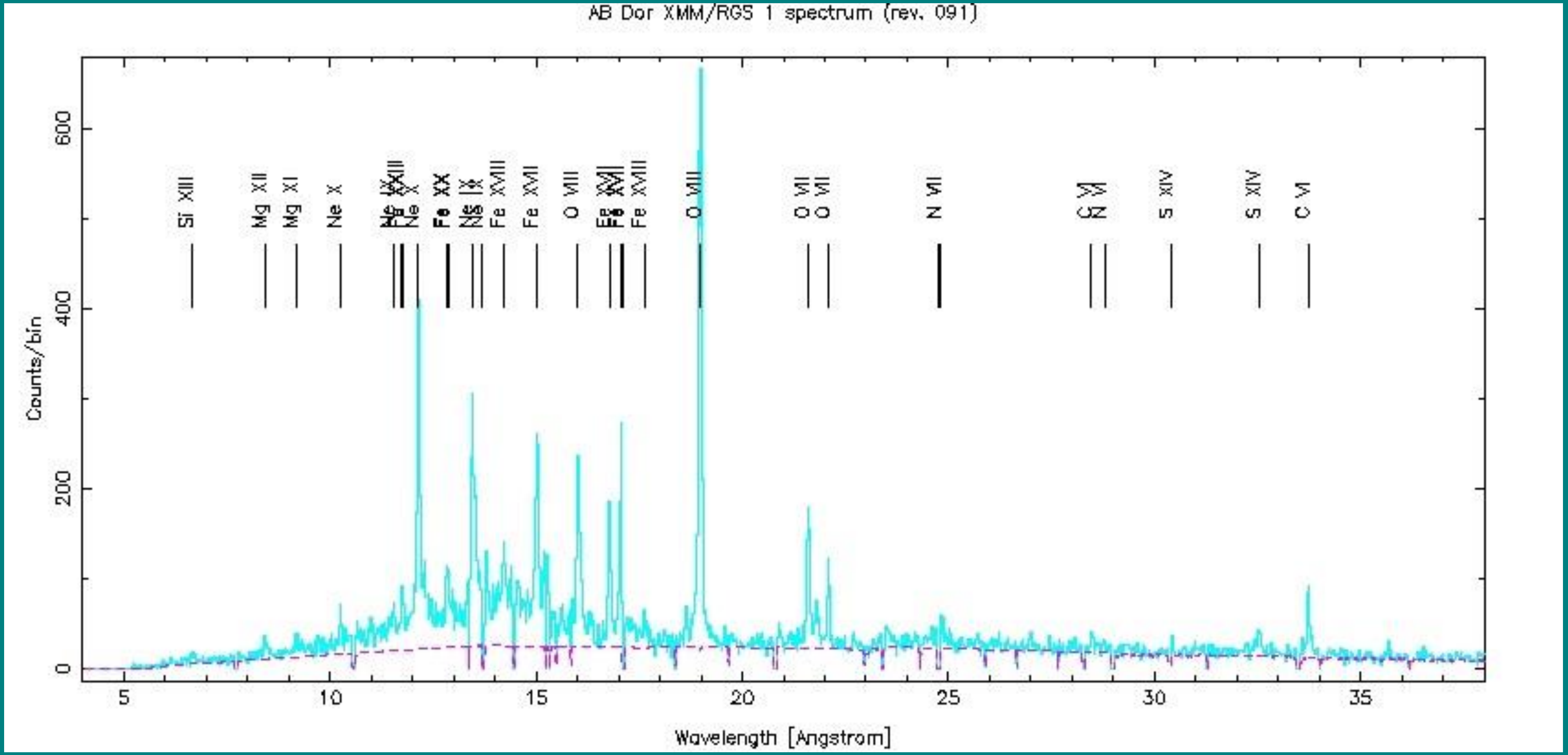
Chapter VIIb: X-ray astrophysics

- 3 EPIC cameras: imaging + medium-resolution spectroscopy and light curves between 0.2 and 12 keV.



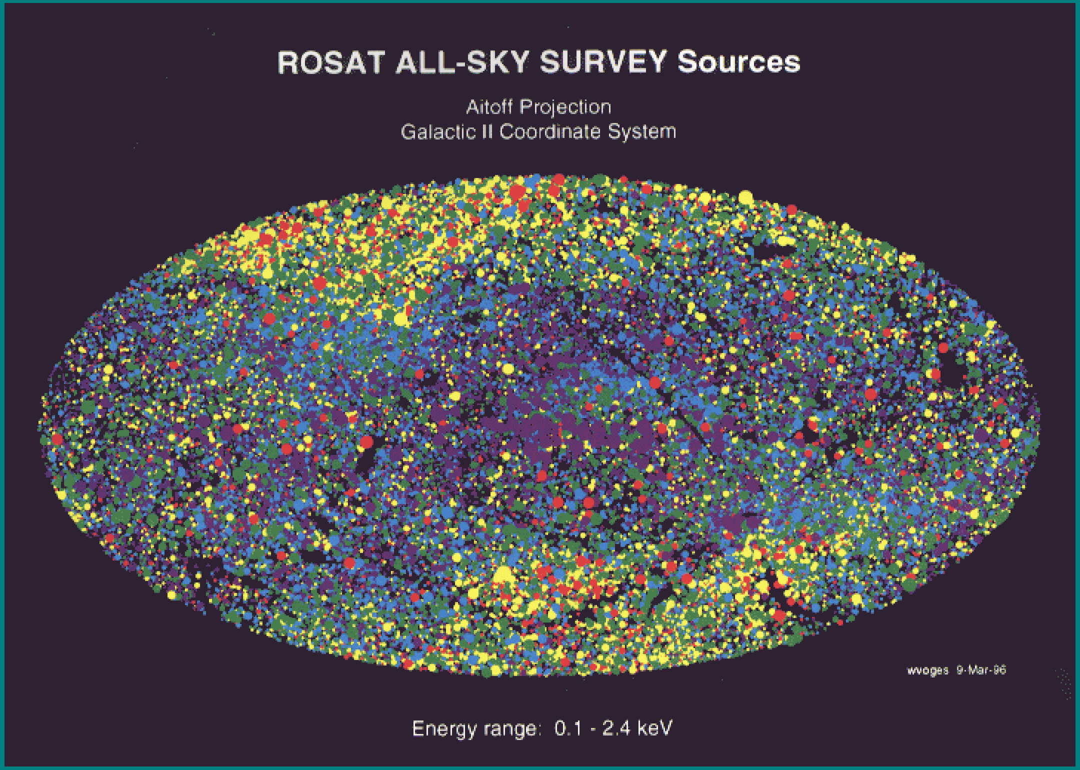
Chapter VIIb: X-ray astrophysics

- RGS: high resolution (R ≤ 800) spectroscopy from 5 – 38 Å.



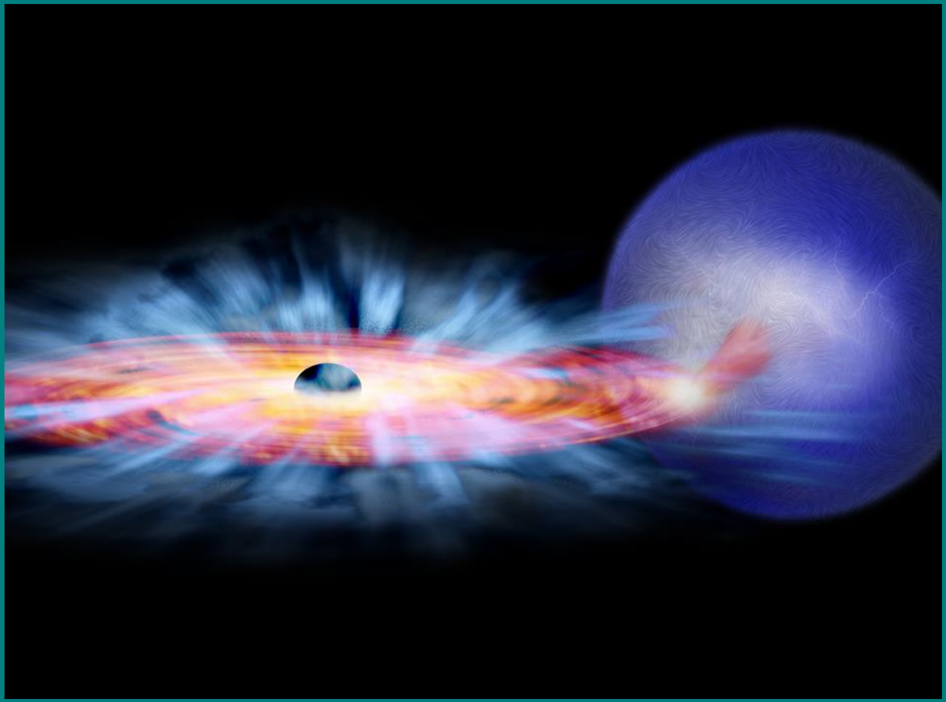
Chapter VIIb: X-ray astrophysics

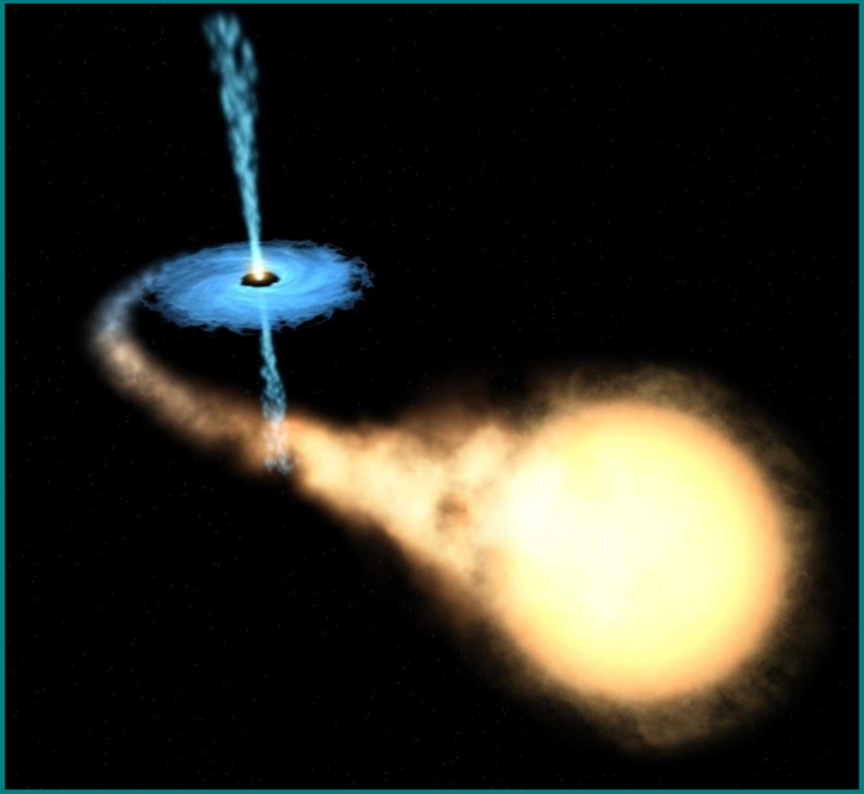
- Some numbers:
  1. Uhuru found 339 sources over the full sky down to 1.5×10^{-11} erg cm^{-2} s^{-1}
  2. ROSAT All Sky Survey: 125 000 point-like sources
  3. 3XMM catalogue: 370 000 sources over 794 square degrees with a median flux of 2.4×10^{-14} erg cm^{-2} s^{-1}



Chapter VIIb: X-ray astrophysics

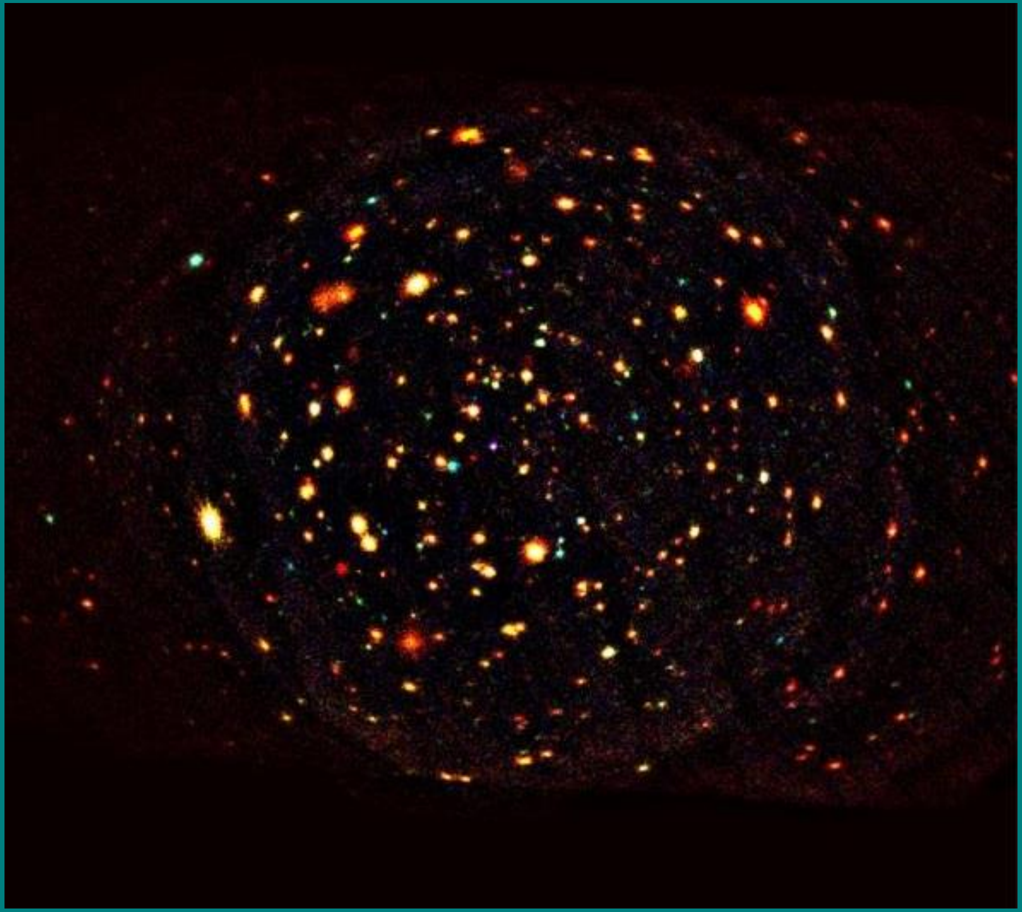
- The accretion phenomenon: X-ray binaries (Sco-X1,…) = binary system hosting a compact object (neutron star or black hole) accreting material from a normal star (that fills up its Roche lobe)

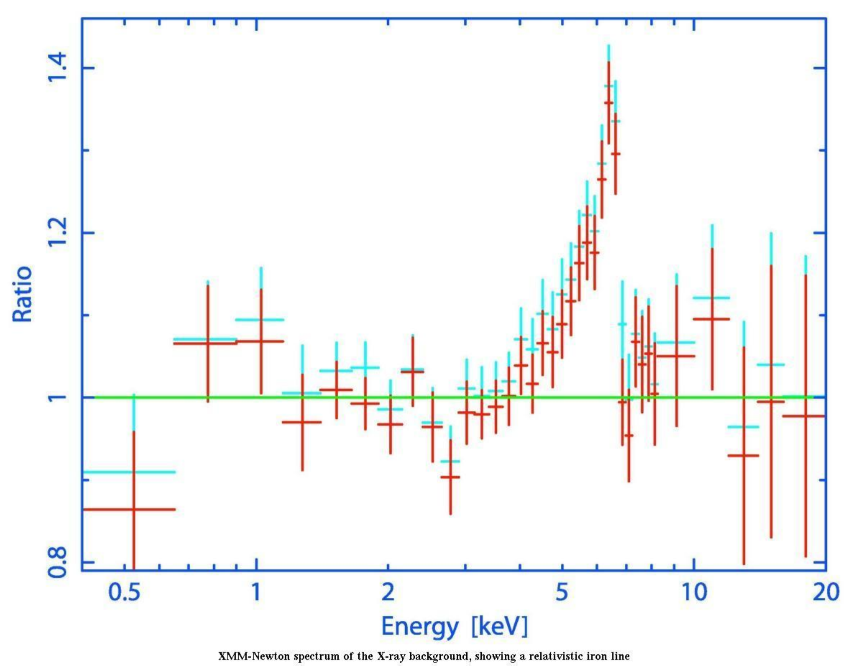




Chapter VIIb: X-ray astrophysics

- Accretion: nuclei of active galaxies (AGN): supermassive black hole accreting material from its host galaxy.

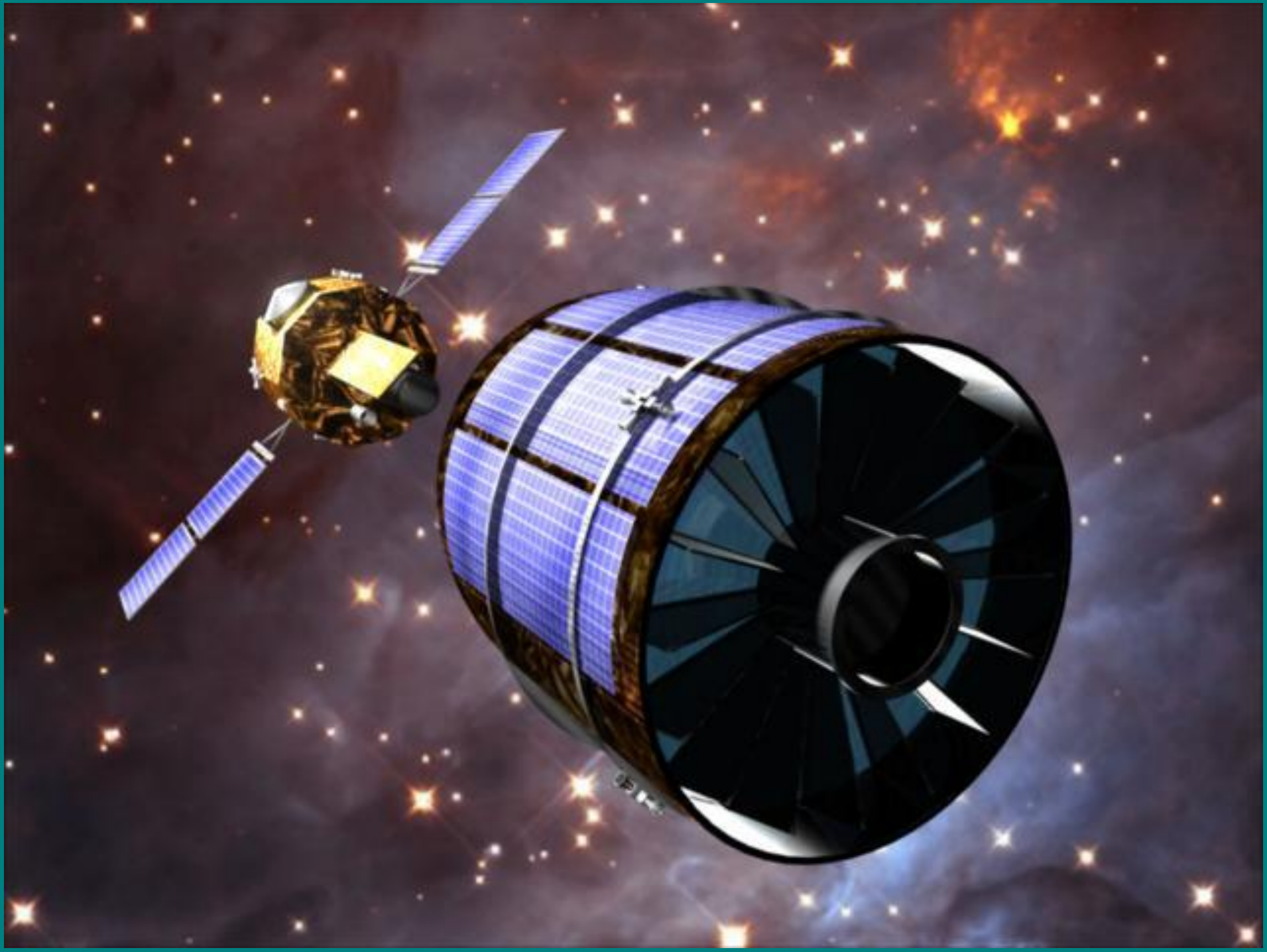




XMM-Newton spectrum of the X-ray background, showing a relativistic iron line

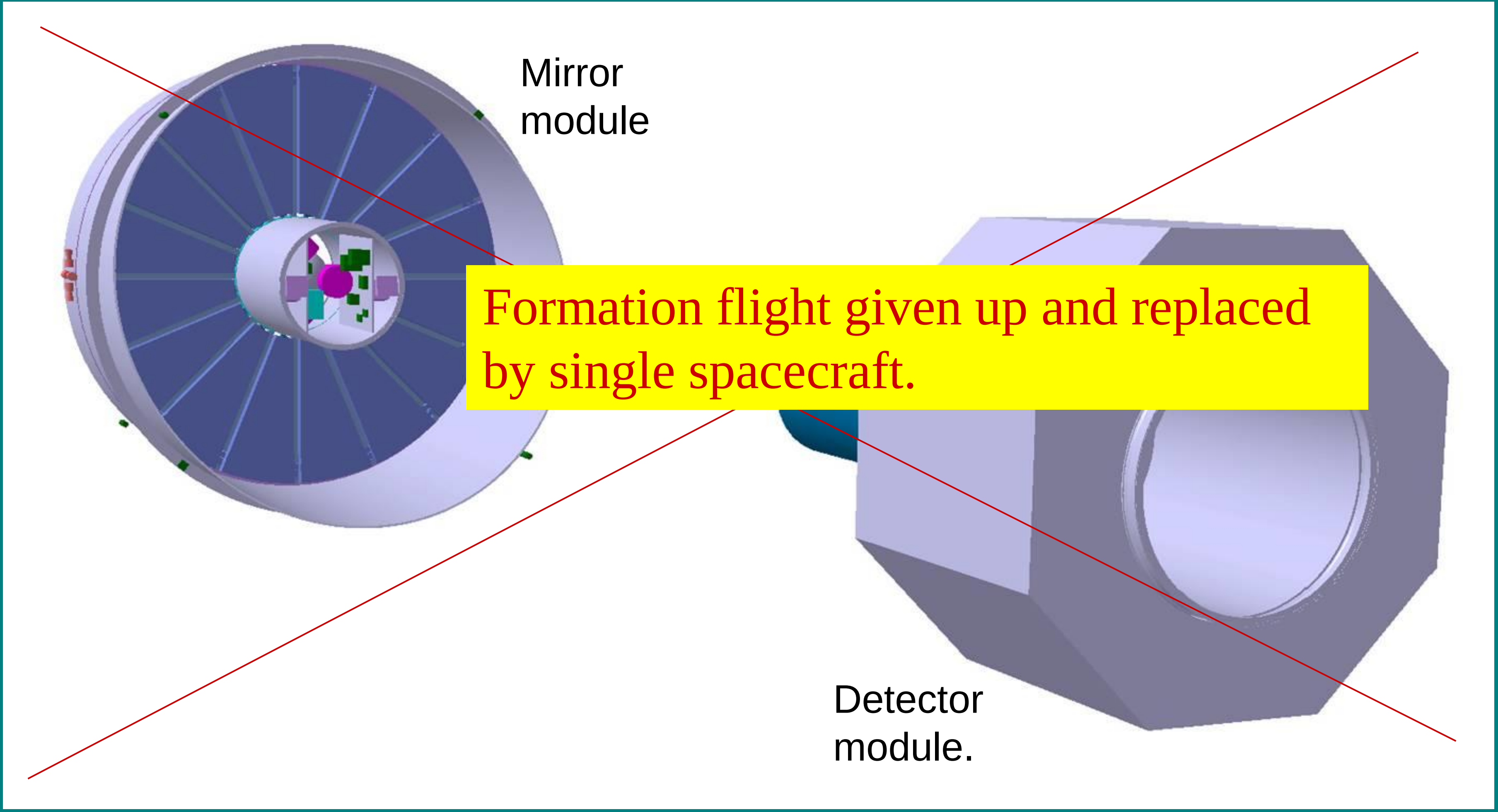
Chapter VIIb: X-ray astrophysics

- The future? The XEUS project…
- Formation flight about L2, collecting area of 5 m^2



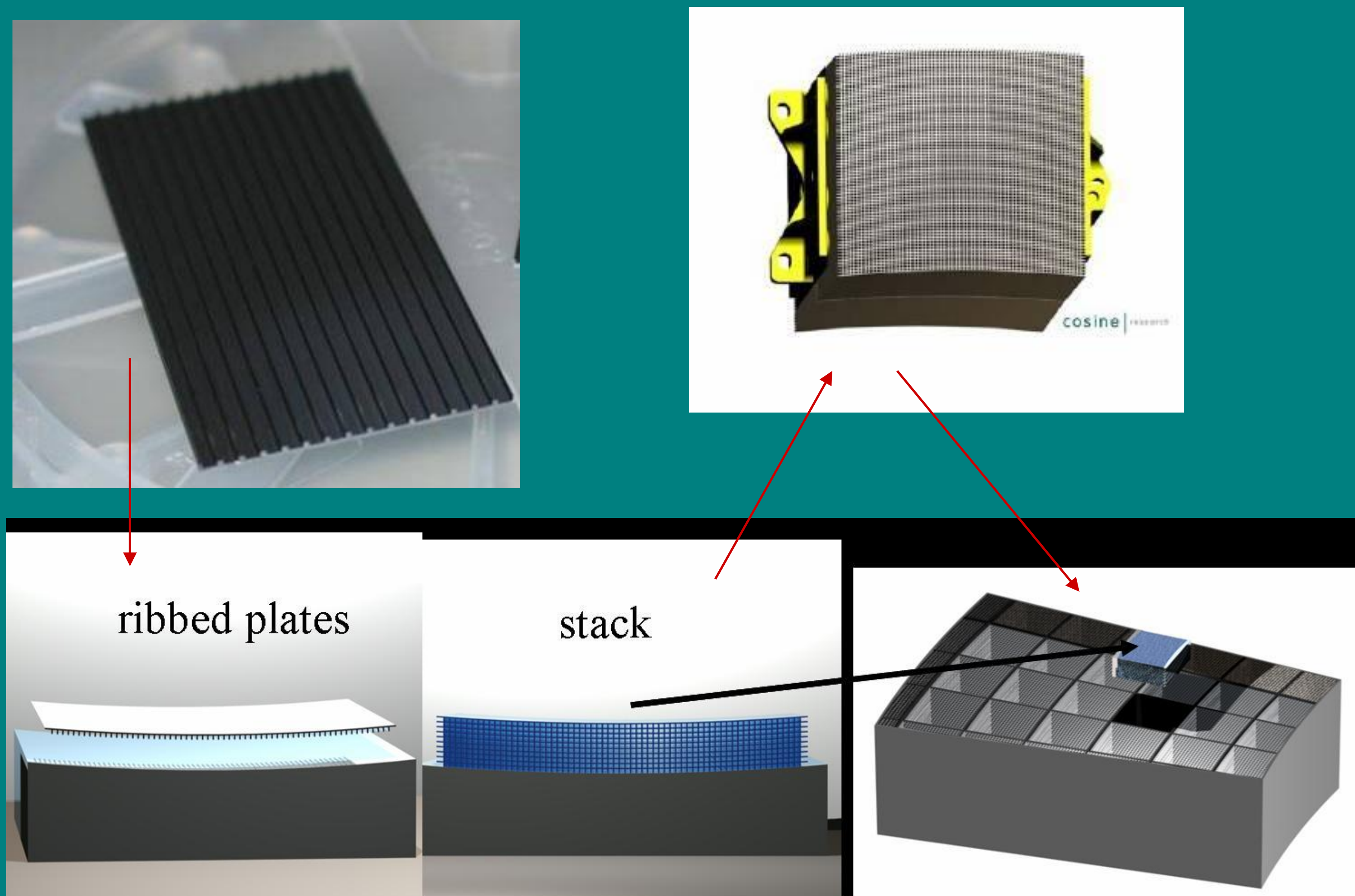
Chapter VIIb: X-ray astrophysics

- Formation flight: separation of 35 m with an accuracy of 1 mm[3]



Chapter VIIb: X-ray astrophysics

- New technologies for ultra-light weight mirrors:

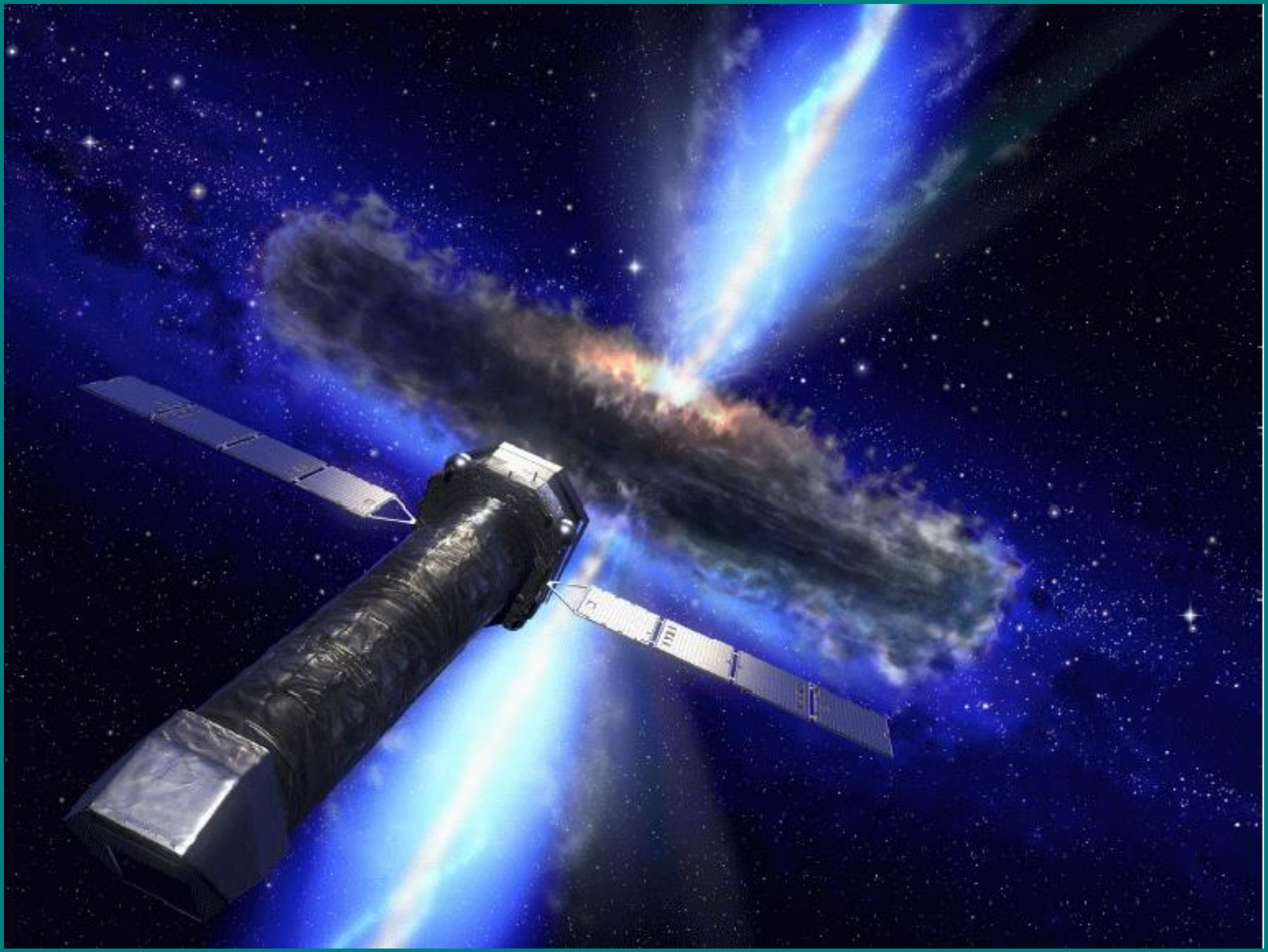


Chapter VIIb: X-ray astrophysics

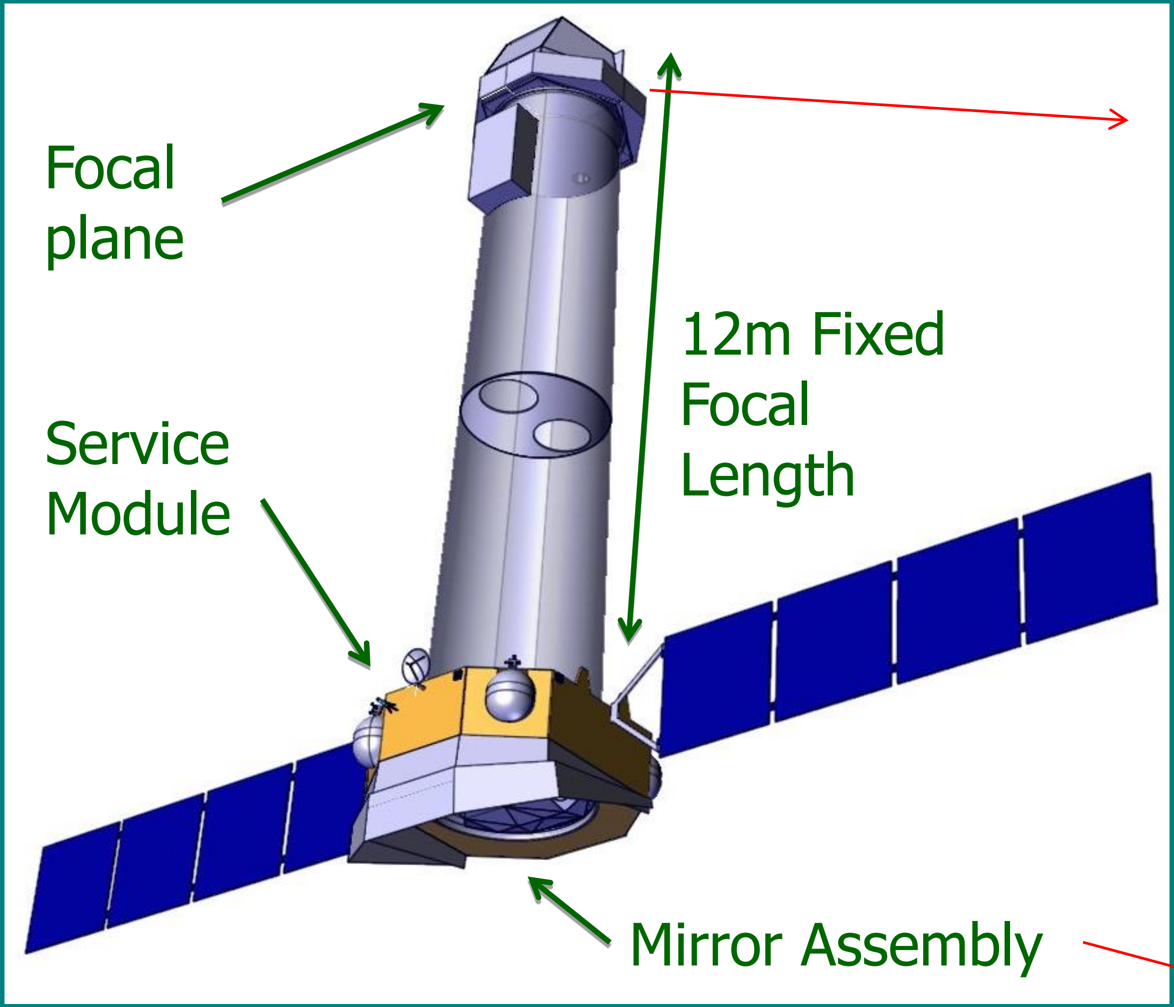
- Because of the complexity of XEUS, ESA decided to collaborate with NASA and JAXA on the IXO (International X-ray Observatory) project: a single spacecraft.
- Following hesitations by NASA, ESA gave up IXO and focused on Athena, a reduced version of IXO to be built by Europe only.
- However, in spring 2012, Athena was not selected as ESA's first L-class mission.
- Uncertain future for X-ray astrophysics in Europe following this decision.
- In the spring 2013: ESA call for 2nd and 3rd L-class mission: Athena+ was proposed…and selected as second L-class mission of Cosmic Vision.

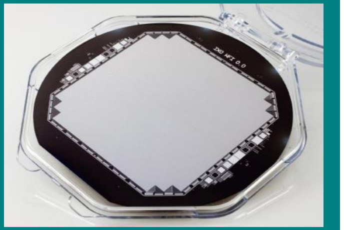
Chapter VIIb: X-ray astrophysics

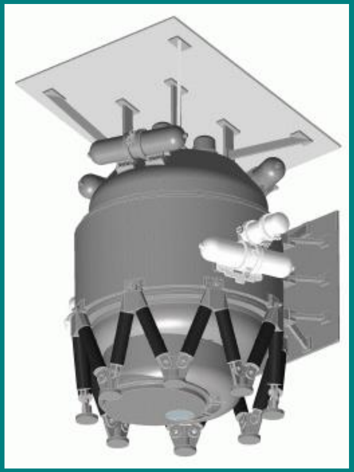
- Athena: un quantum leap in sensitivity.



Chapter VIIb: X-ray astrophysics







- Instruments : Wide Field Imager (WFI), X-ray Integral Field Unit (X-IFU) microcalorimeter.

Collecting area: $2m^2$ @ 1 keV. Sensitivity ~ 30 times higher than XMM, angular resolution 5” (3”)

Orbit around L2 or L1, 5 years nominal lifetime (launch 2030)

Chapter VIIc: UV astrophysics

- Fundamental concepts
- IUE: a spectroscopic mission
- GALEX: an imaging and spectroscopic mission
- Examples of scientific questions addressed:
  1. Massive stars and their stellar winds
  2. Star formation activity
  3. Aurorae in the Solar System

Chapter VIIc: UV astrophysics

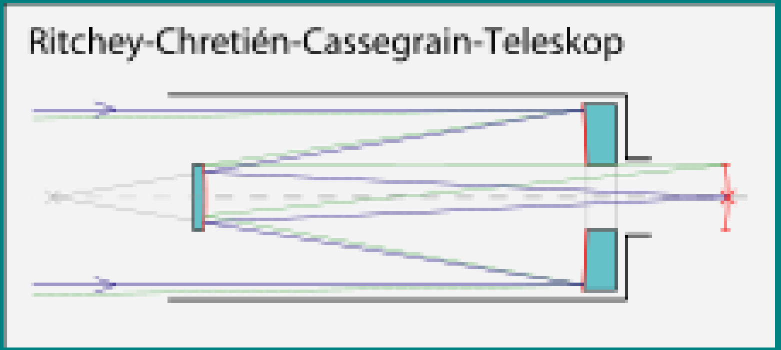
- The UV domain: rich in resonance lines (between the fundamental level and an excited level) $\Rightarrow$ important diagnostics of the physical conditions.
- $\lambda \leq 3000$ Å absorbed by the Earth's atmosphere $\Rightarrow$ need to go to space
- EUV radiation shortwards of the Lyman limit ($\lambda \leq 912$ Å) strongly absorbed by interstellar hydrogen.

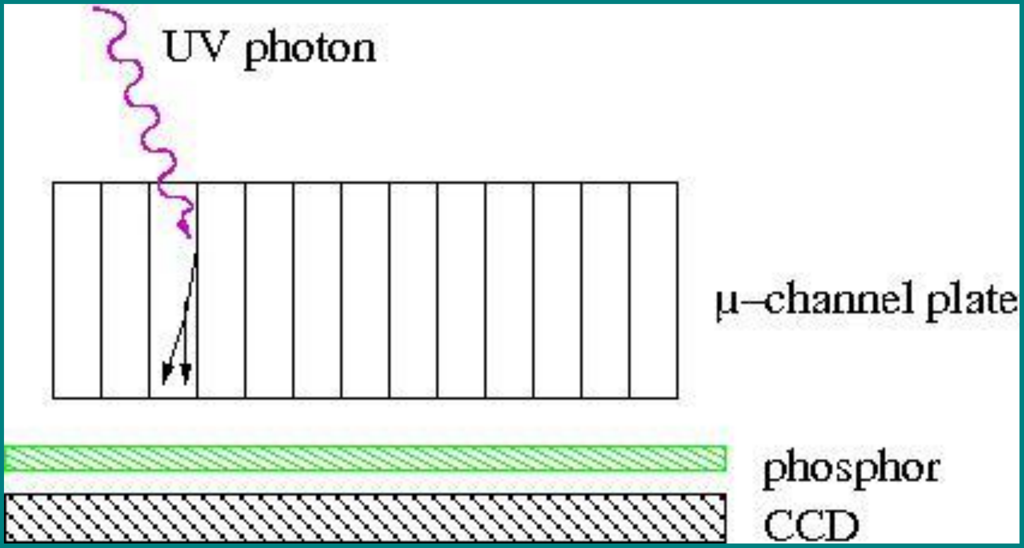
	Wavelength (Å)
Near-UV	3000 – 4000
Middle-UV	2000 – 3000
Far-UV	1000 – 2000
Extreme-UV	100 – 1000

Chapter VIIc: UV astrophysics

- Near UV into far UV: Ritchey-Chrétien design (hyperbolic primary and secondary mirrors) with special coatings (Au or SiC).
- EUV: grazing incidence.
- MCP detectors:

  photocathode + CCD



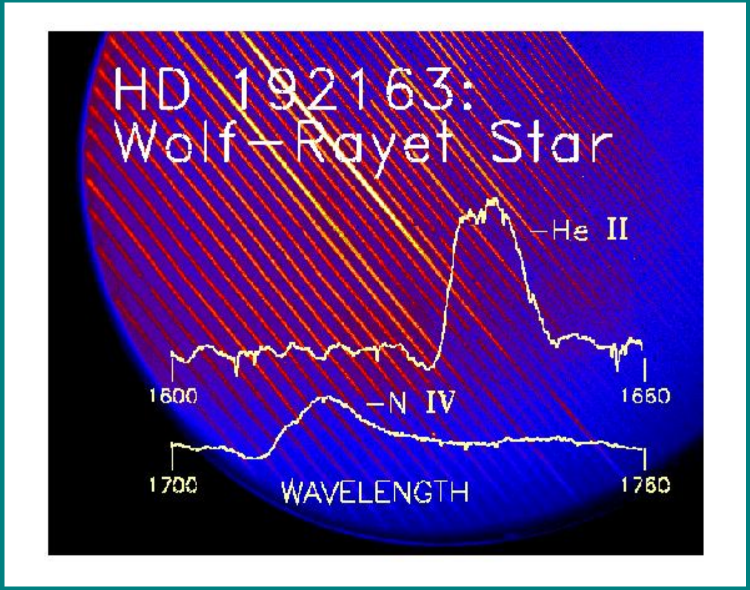


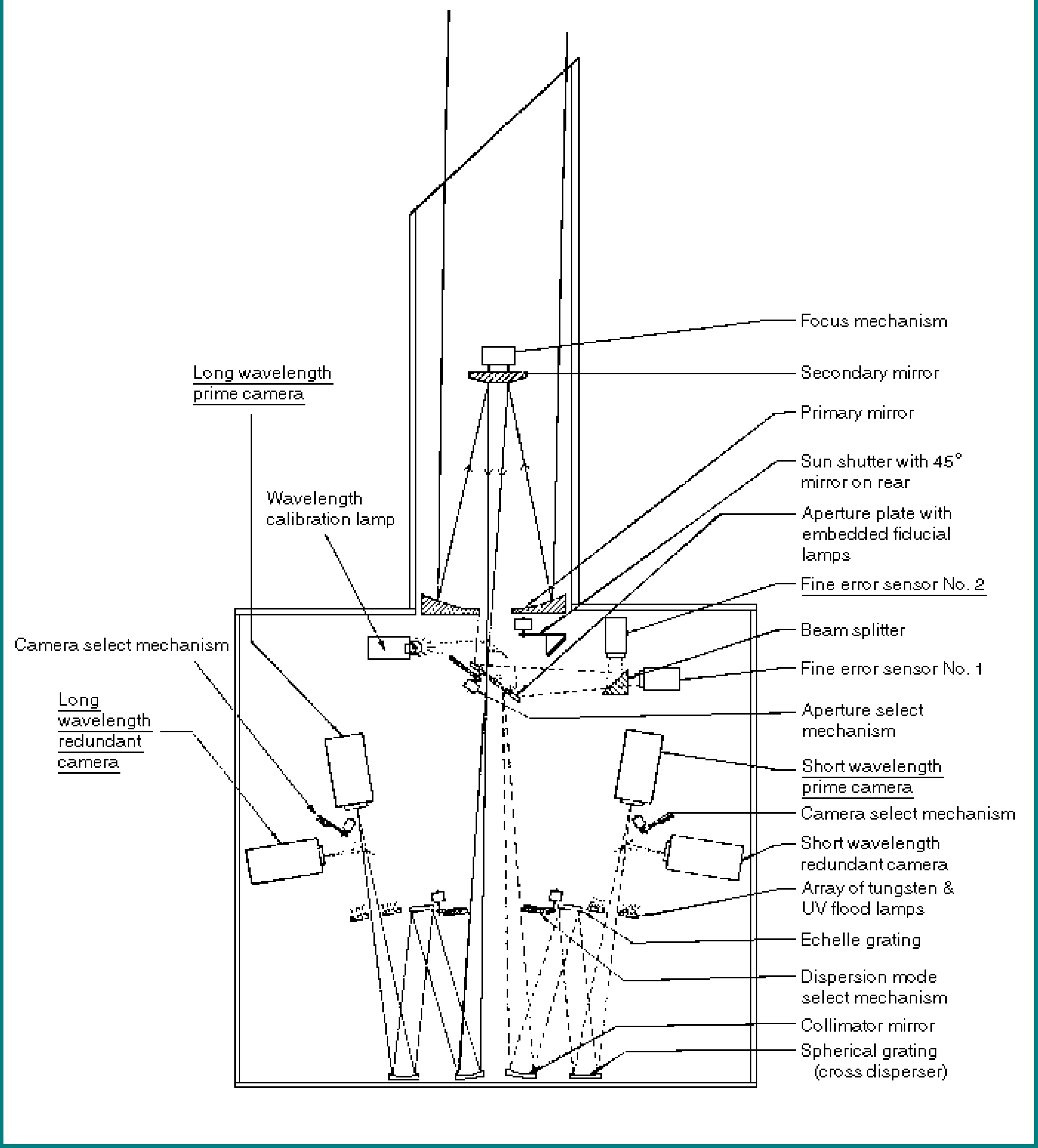
Chapter VIIc: UV astrophysics

- International Ultraviolet Explorer (NASA+ESA+PPARC)
- Geosynchronous orbit (24h), slightly eccentric (e = 0.24) and inclined by 28.6°.
- Launched in 1978, stopped in 1996.
- Spectroscopy mission (R ≤ 18 000).

Chapter VIIc: UV astrophysics

- Ritchey – Chrétien telescope
- Echelle spectroscopy over two domains: 1150 – 1980 and 1800 – 3200 Å
- 104 000 observations of about 10 000 different objects.



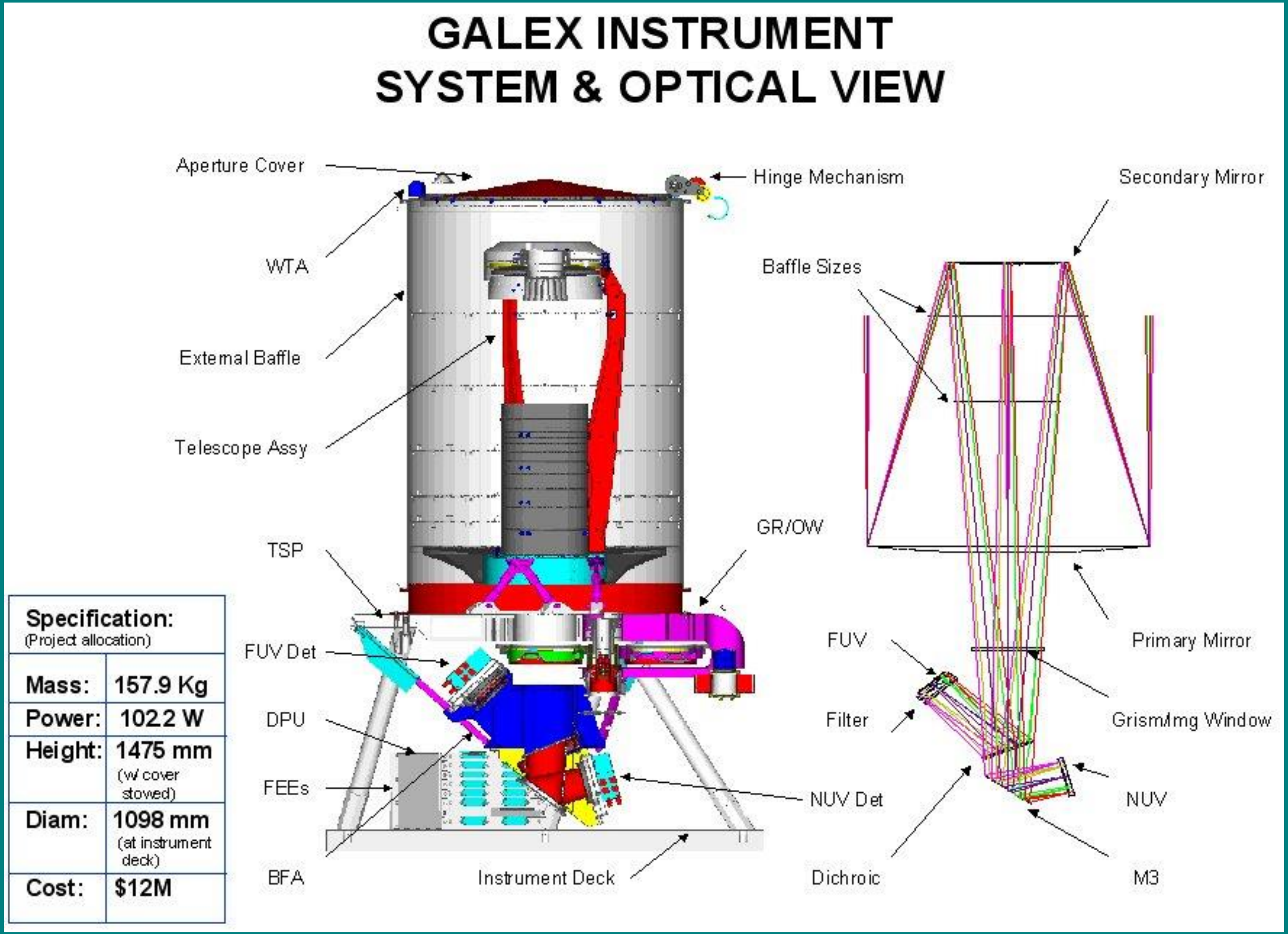


Chapter VIIc: UV astrophysics

- GALEX (Galaxy Evolution Explorer, April 2003 – June 2013)

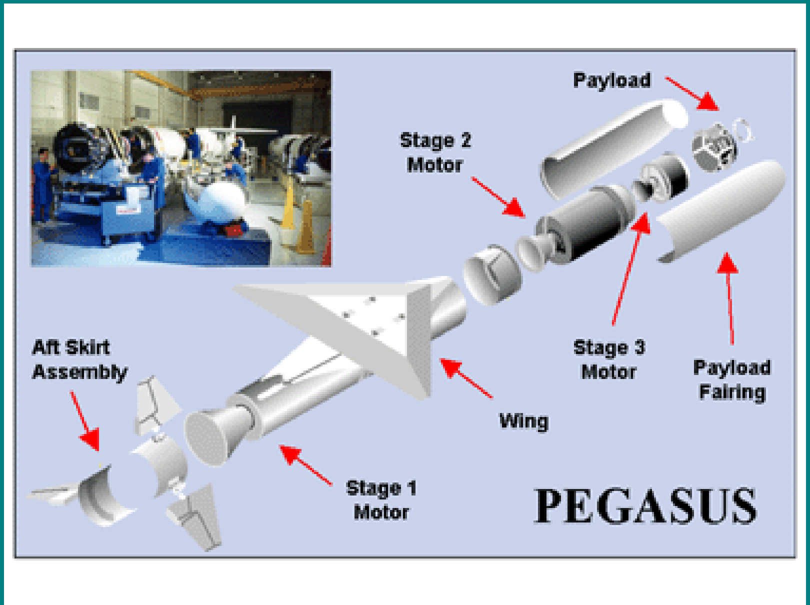
Chapter VIIc: UV astrophysics

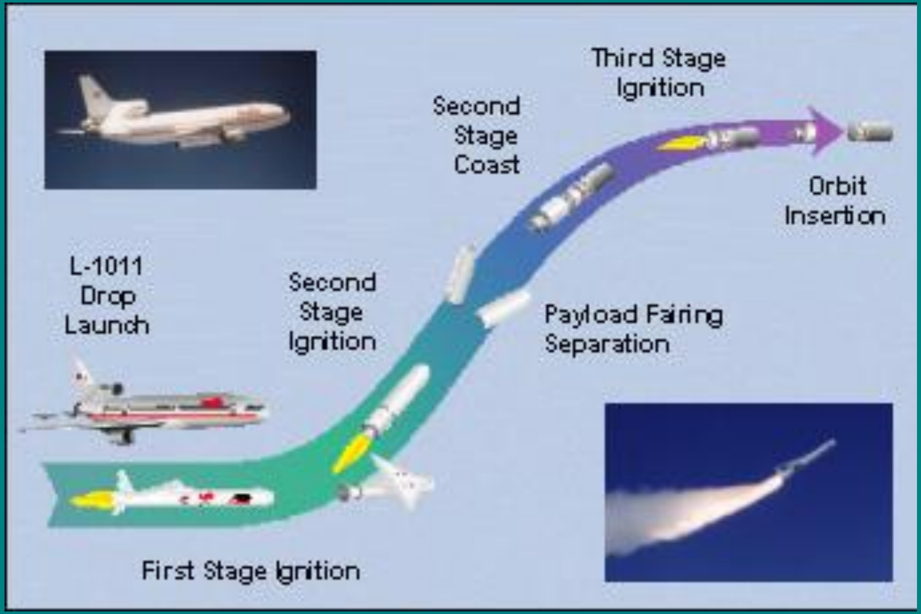
- GALEX: imaging and spectroscopy in the far and mid-UV.



Chapter VIIc: UV astrophysics

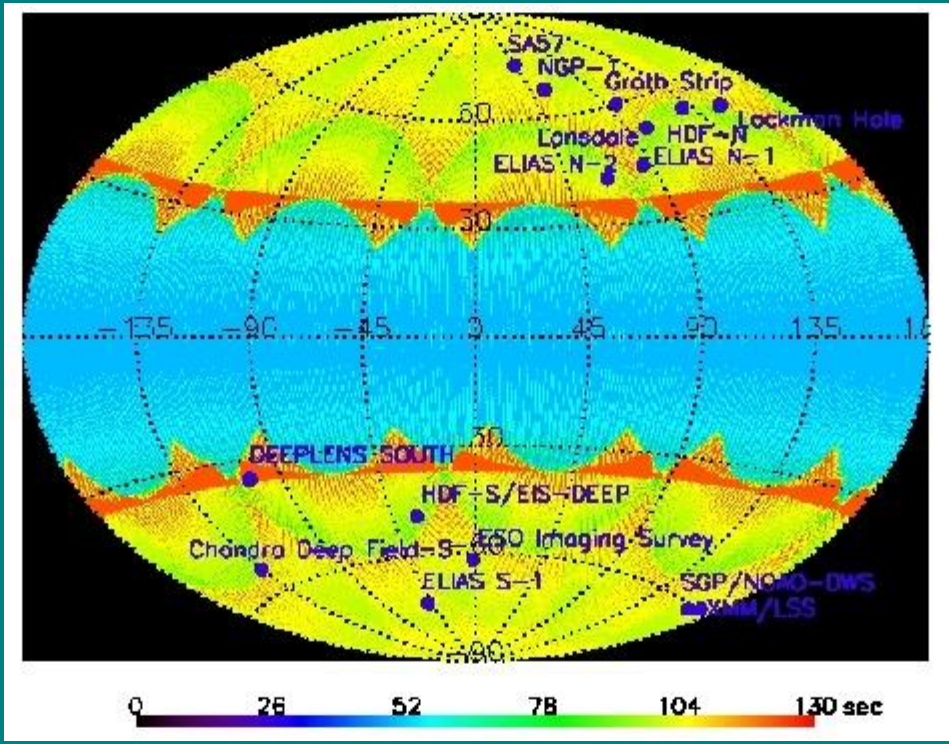
- GALEX: launch into LEO (inclination of 29°) by airborne Pegasus rocket.

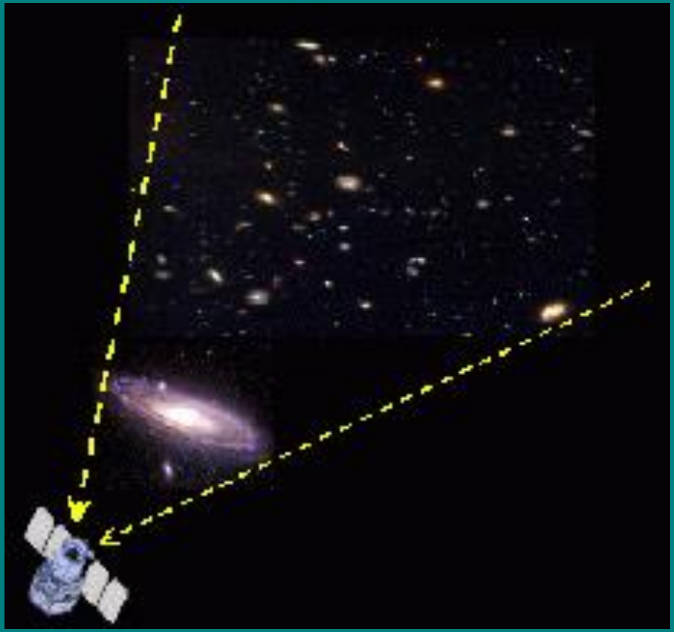


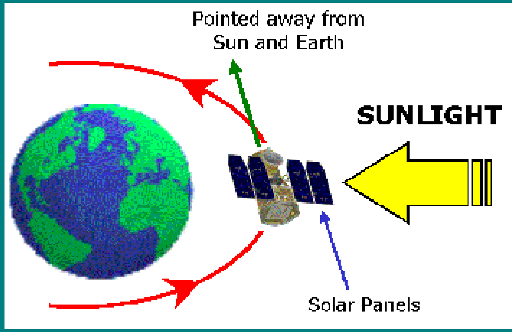


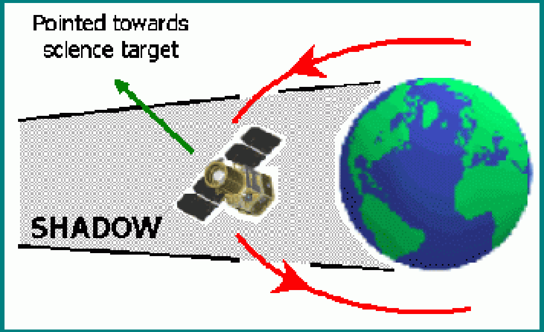
Chapter VIIc: UV astrophysics

- GALEX: survey of the full sky to investigate the evolution of the star formation activity with redshift.









Chapter VIIc: UV astrophysics

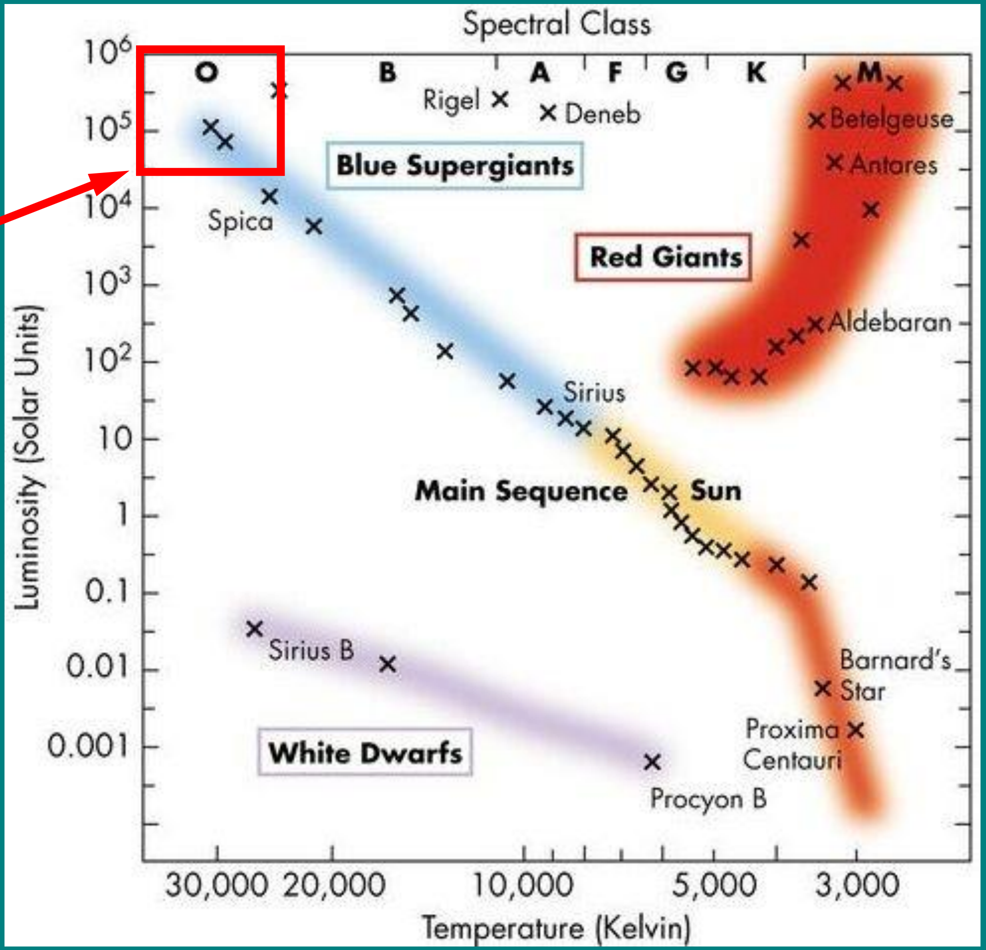
- UV astronomy: ideal for the study of hot objects.
- OB or Wolf-Rayet stars

$$M_{\rm init} \geq 15\, M_\odot$$

$$T_{\rm eff} \simeq 30\,000 - 90\,000\,{\rm K}$$

$$L/L_\odot \simeq 3 \times 10^4 - 3 \times 10^6$$

- Typical lifetime: 10^7 years.

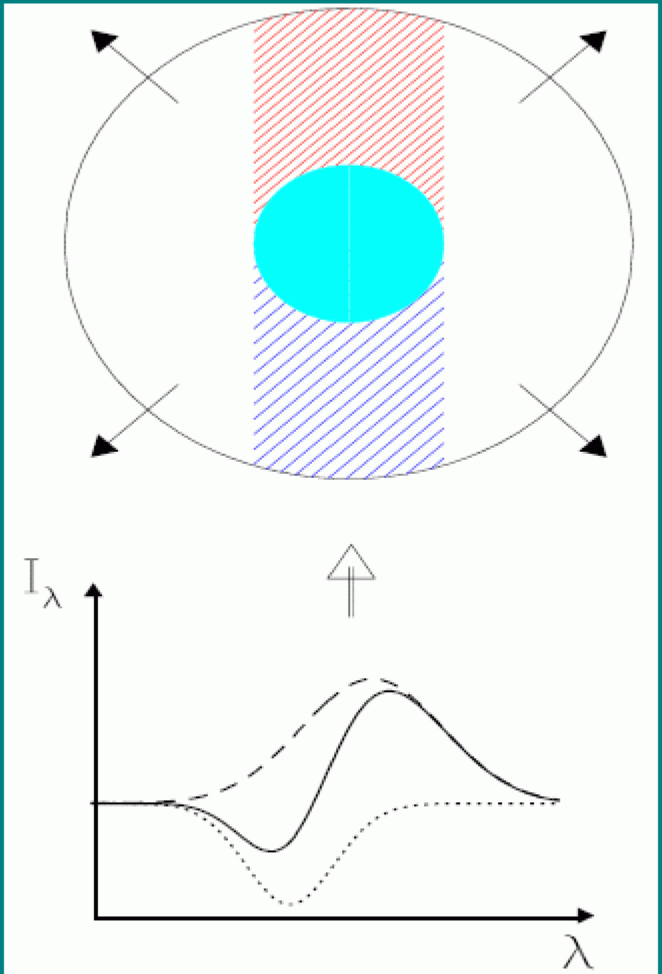


Chapter VIIc: UV astrophysics

- Stellar winds of massive stars discovered through P Cygni profiles seen in the UV domain:

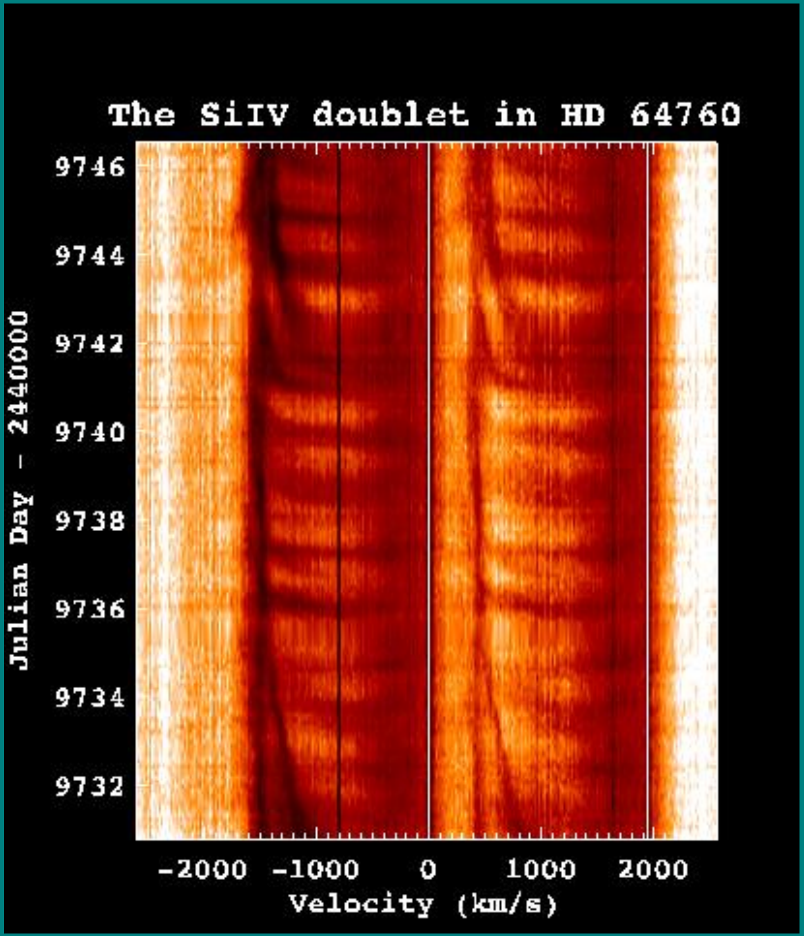
$$\dot{M} \simeq 10^{-6} - 10^{-4}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$$

$$v_{\infty} \simeq 1000 - 5000\,\mathrm{km\,s}^{-1}$$



Chapter VIIc: UV astrophysics

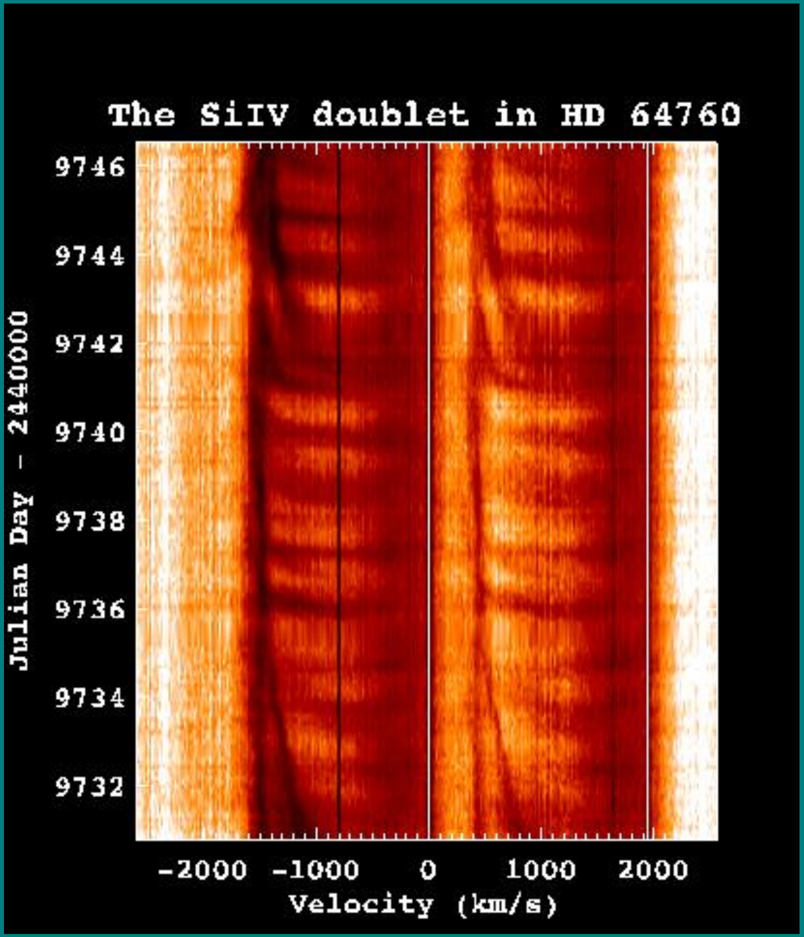
- IUE: spectroscopic studies of massive stars (OB and Wolf-Rayet)
- Variability: in some cases monitored on timescales of several hours up to several days.

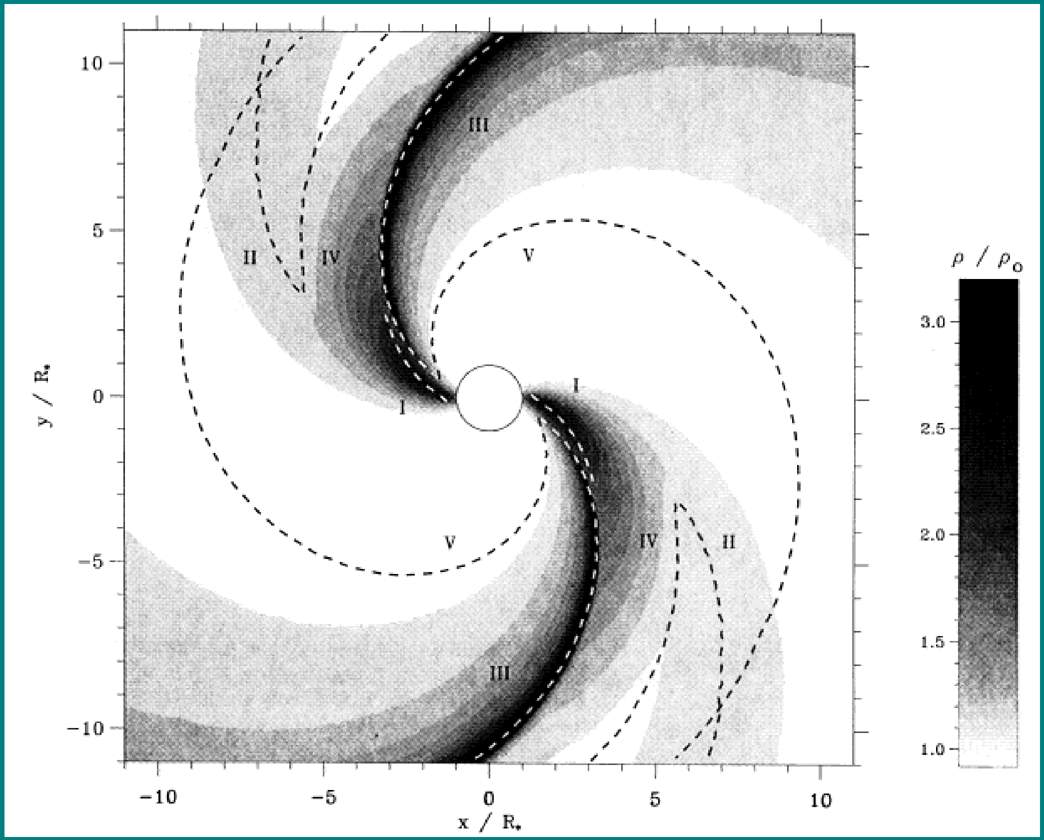


Animation HD 64760

Chapter VIIc: UV astrophysics

- IUE: spectroscopic studies of massive stars (OB and Wolf-Rayet)
- Variability: in some cases monitored on timescales of several hours up to several days.





Chapter VIIc: UV astrophysics

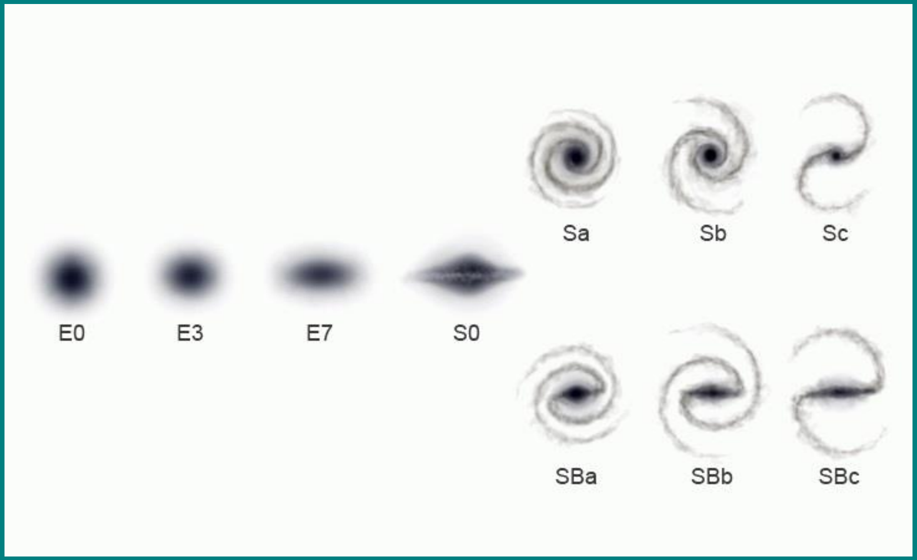
- Star forming regions host massive and hot stars that emit copious amounts of UV radiation.

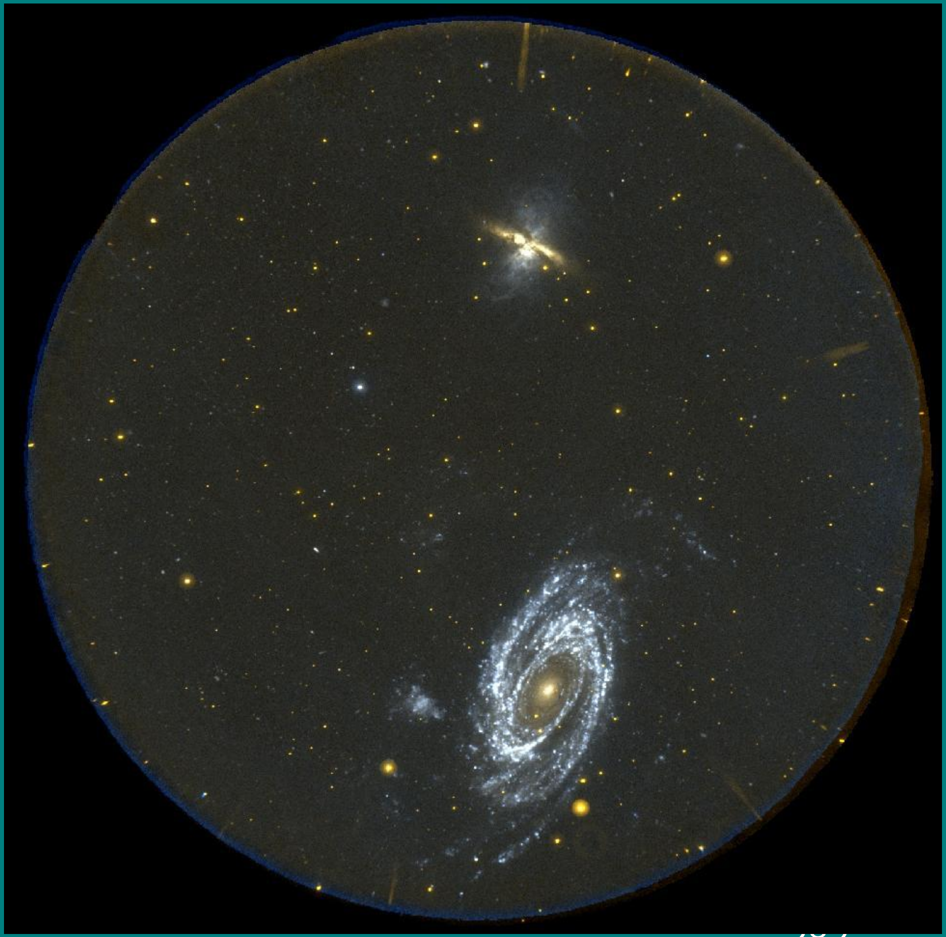
Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)

Chapter VIIc: UV astrophysics

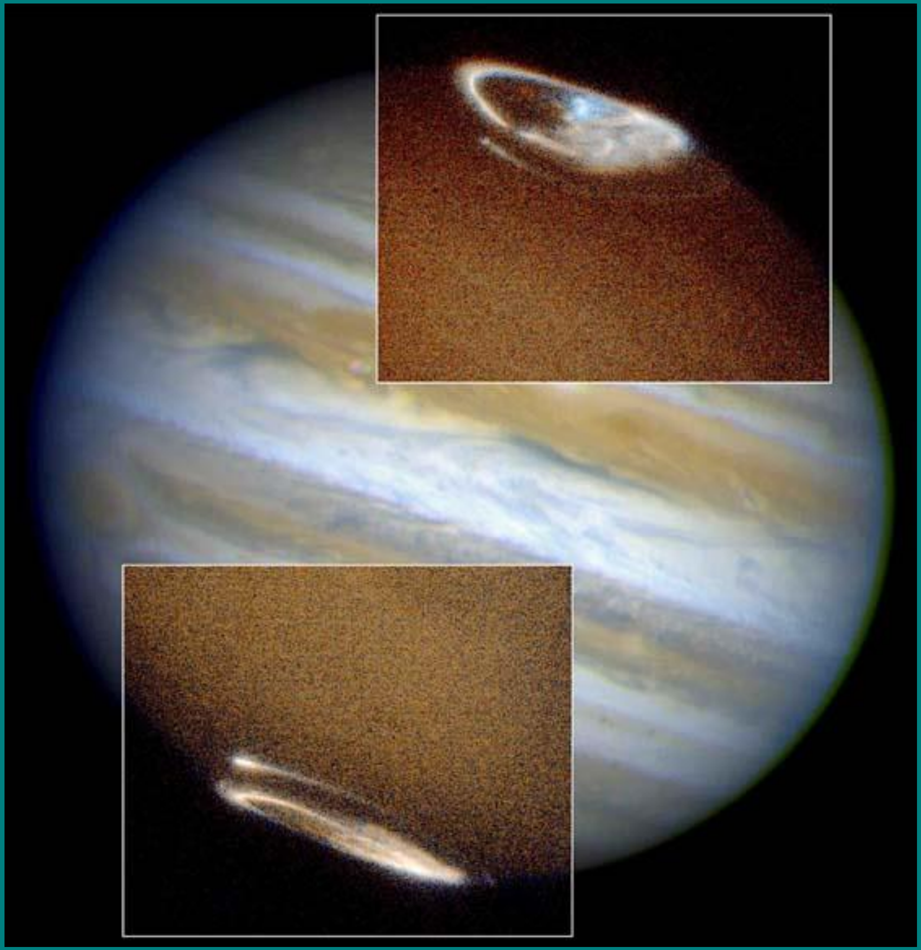
- Spiral galaxies: the most active ones in terms of star formation.

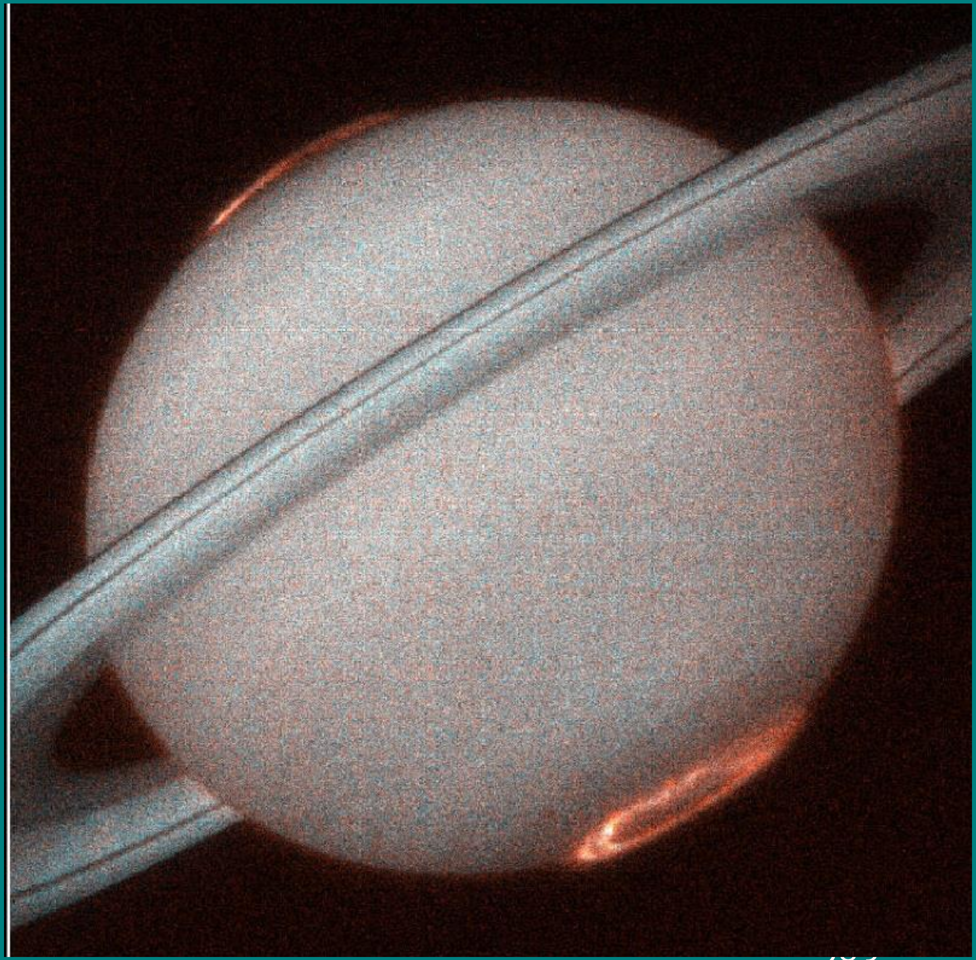




Chapter VIIc: UV astrophysics

- Inside the Solar System: STIS (HST) observations in the UV reveal aurorae on Jupiter and Saturn.





Chapter VIII: The exploration of the Solar System

- Space exploration has deeply changed the study of the bodies of the Solar System.
- « In situ » measurements; observations from orbiters; landing on bodies of the Solar System; robotic missions, sample return; manned missions…
- Examples addressed in this Chapter:

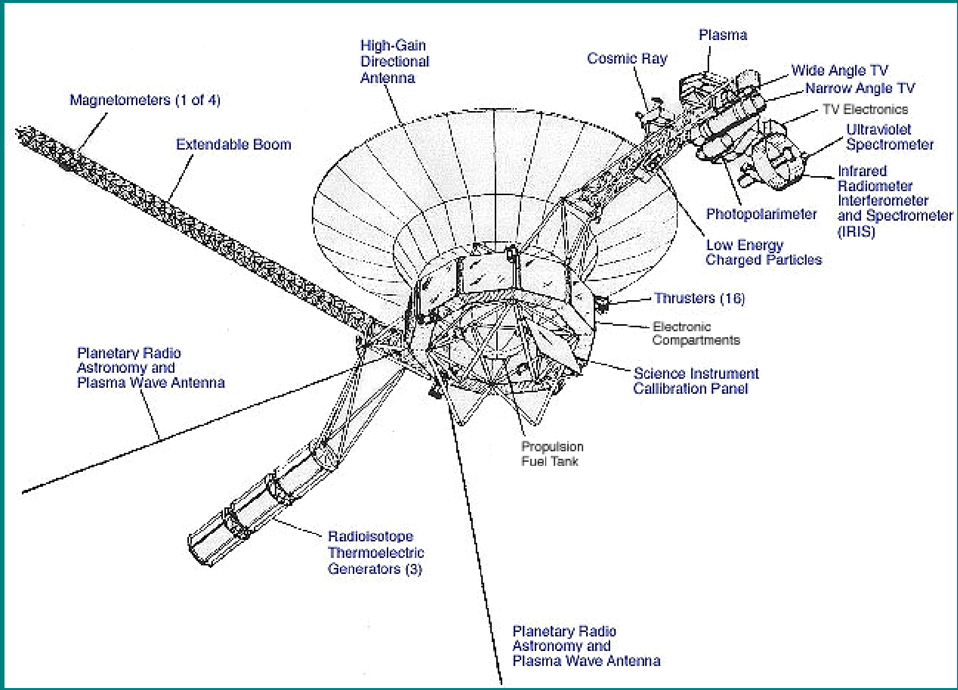
1. Observations of the Sun and measurements of plasma properties
2. Missions to Mars
3. The study of Saturn and its satellites

Chapter VIIIa: Solar observations and plasma measurements

- The basic principles of measuring plasma properties in space.
- Multi-wavelength observations of the Sun and helioseismology
- The present: SOHO and Cluster II
- The future: Solar Orbiter

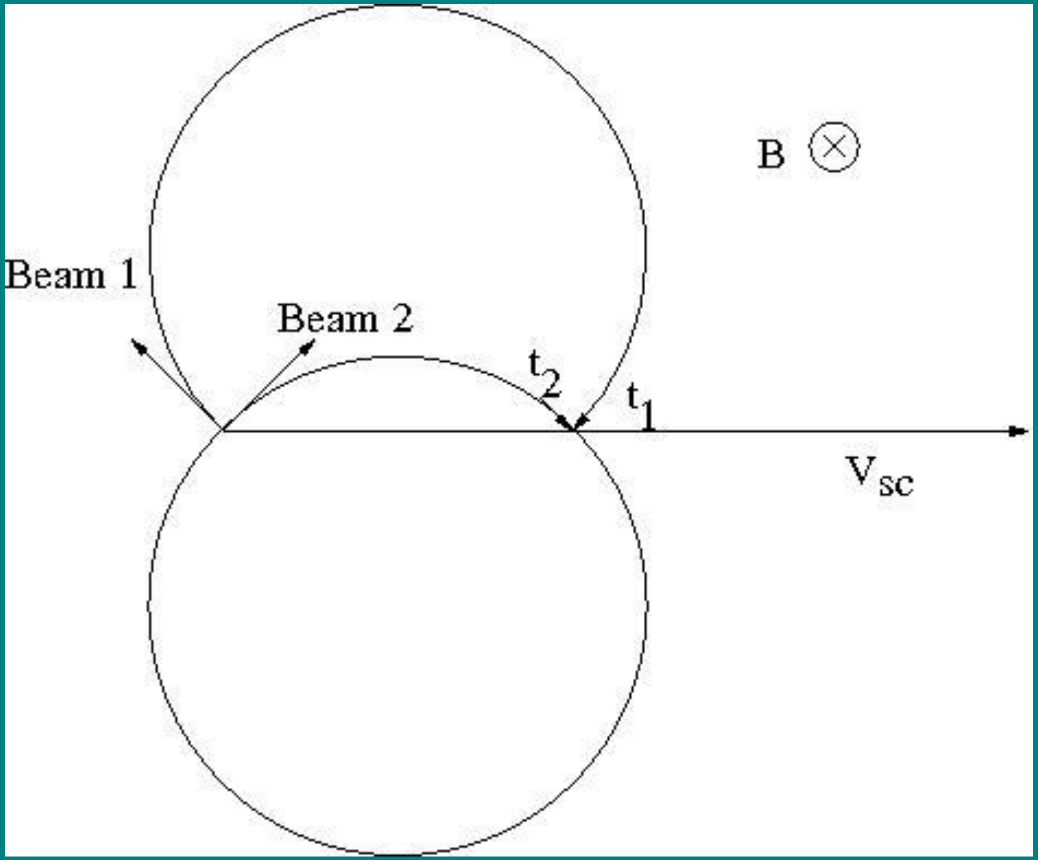
Chapter VIIIa: Solar observations and plasma measurements

- In-situ measurements of the properties of the plasma of the solar wind or created via interaction with the magnetosphere
- Measure magnetic and electrical fields, chemical compositions, velocities, temperatures,…
- Magnetometers are placed on deployable booms to reduce the perturbations by the spacecraft.



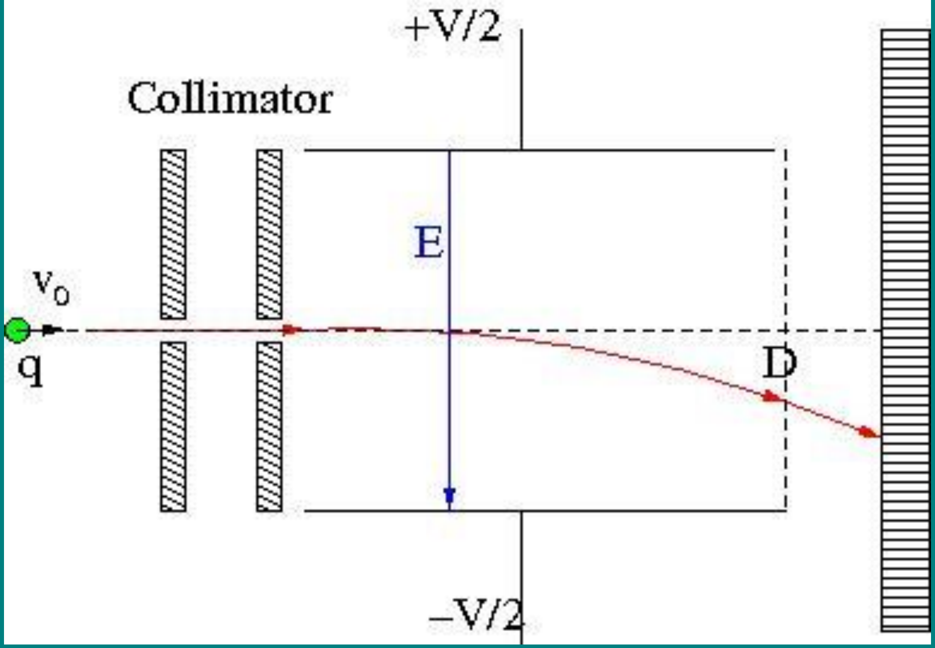
Chapter VIIIa: Solar observations and plasma measurements

- "Fluxgate" magnetometers on rotating spacecraft (e.g. Cluster)
- "Electron drift" magnetometers



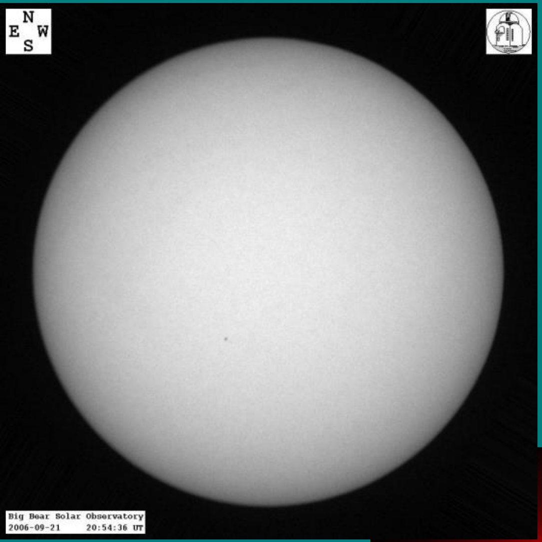
Chapter VIIIa: Solar observations and plasma measurements

- Electric fields are measured using pairs of spheres attached to very long (60 – 100 m) deployable booms. Rotation of the satellite creates a variable tension.
- Measure the energy per unit electric charge: deflection of the ions under the influence of an electric field + time of flight between two positions ⇒ determination of the energy, charge, mass, bulk velocity and temperature of the ions.

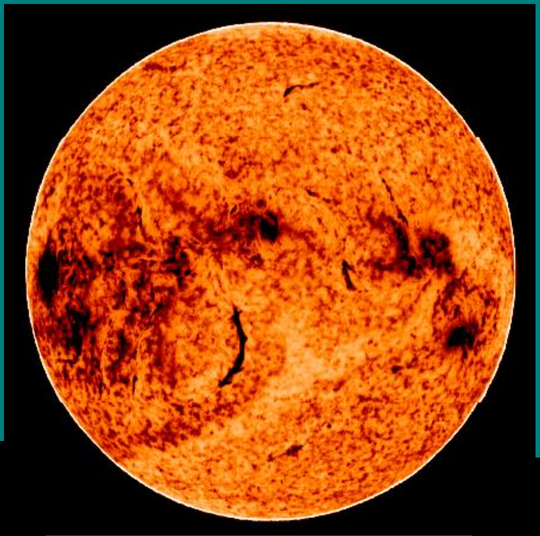


Chapter VIIIa: Solar observations and plasma measurements

- Multi-wavelength observations allow to study phenomena that cannot be observed in the optical domain.

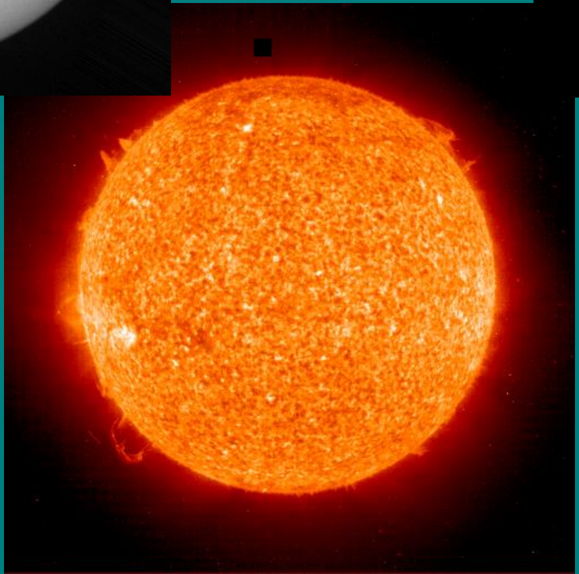


visible

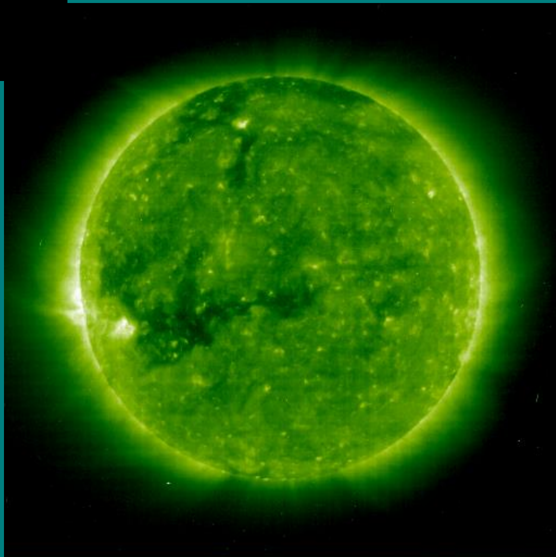


radio

EUV



X-ray



Chapter VIIIa: Solar observations and plasma measurements

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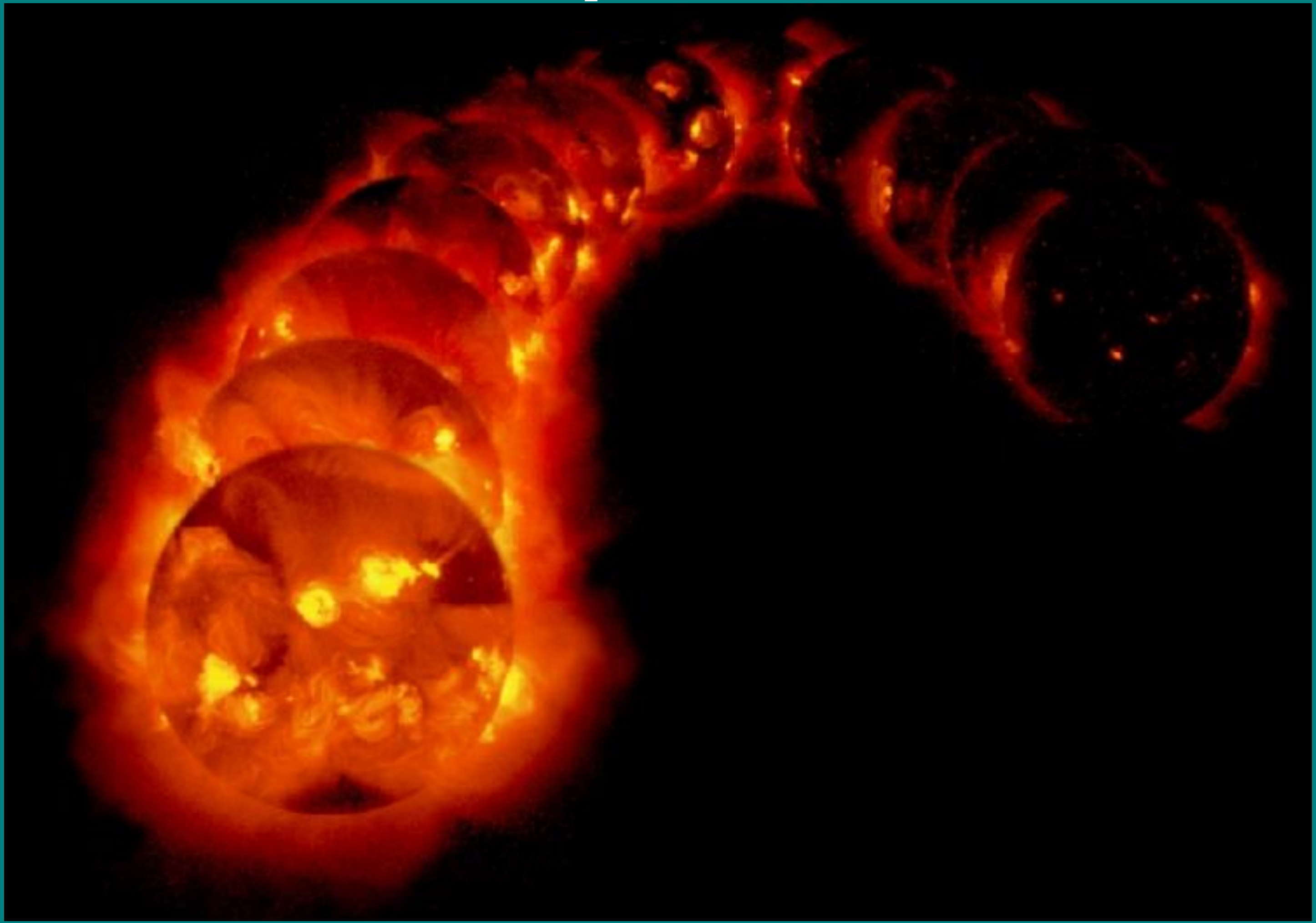
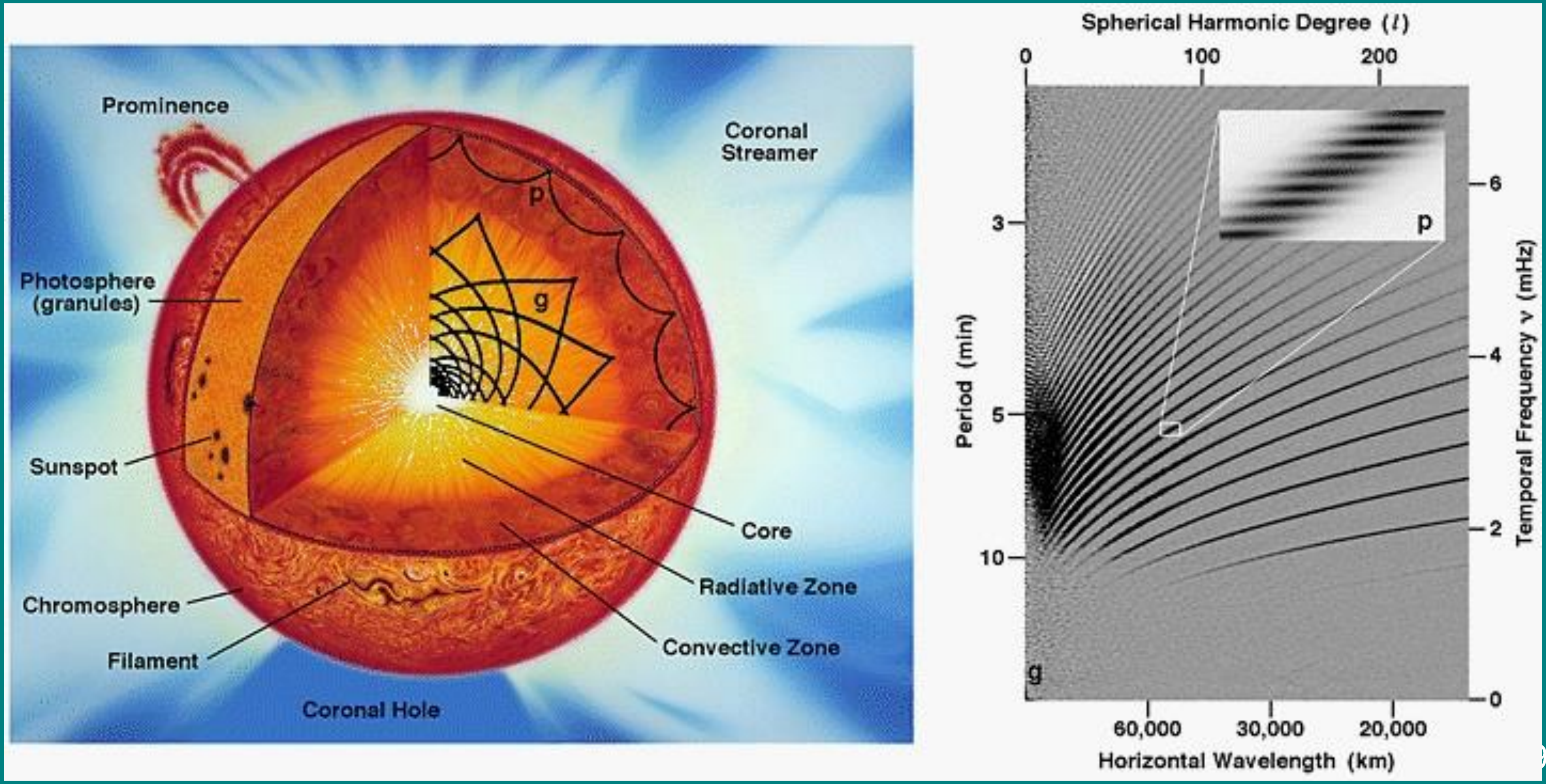


Chapter VIIIa: Solar observations and plasma measurements

- High-precision studies of the “5 minutes” oscillations of the Sun (helioseismology) to investigate the Sun’s internal structure.
- Pressure (*p*) and gravity (*g*) modes

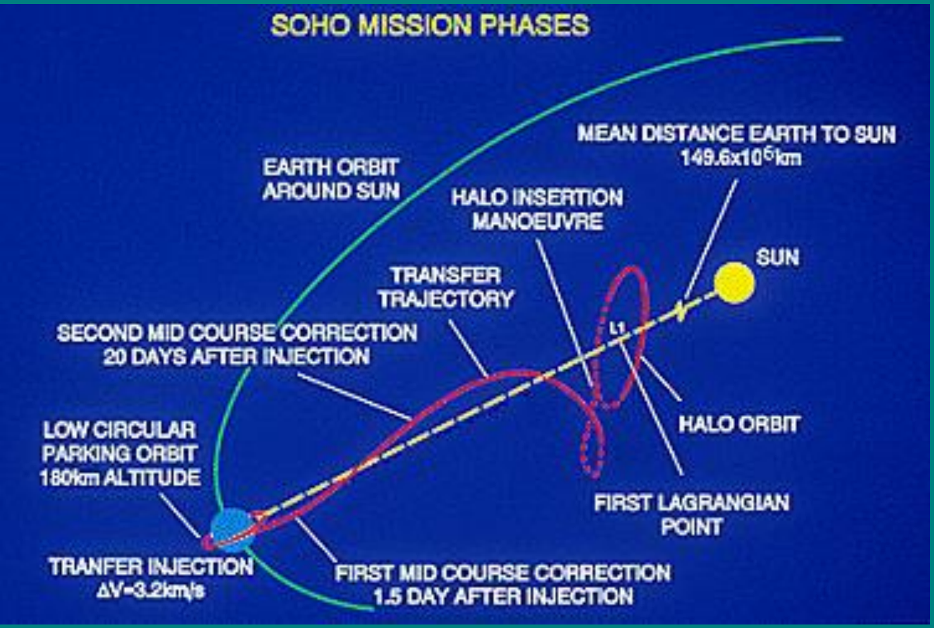


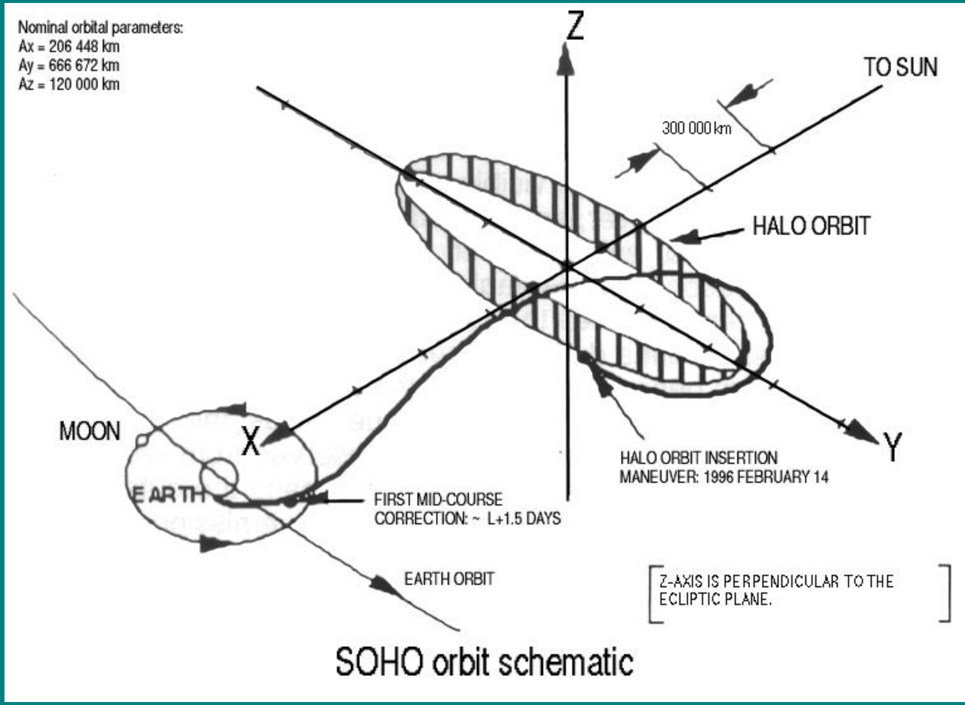
Chapter VIIIa: Solar observations and plasma measurements

- SOHO (Solar and Heliospheric Observatory): cornerstone mission of ESA's Horizon 2000 programme, collaboration between ESA and NASA
- Operations approved until end of 2020.

Chapter VIIIa: Solar observations and plasma measurements

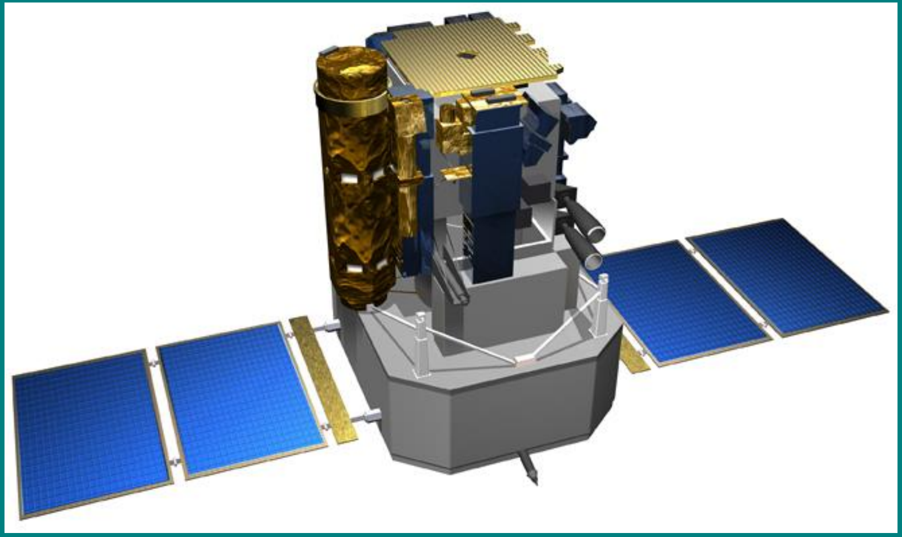
- Launched in 1995 from Cape Canaveral towards L1.
- Halo orbit around L1⇒ continuous access to the Sun + radio communications not disturbed by the Sun.

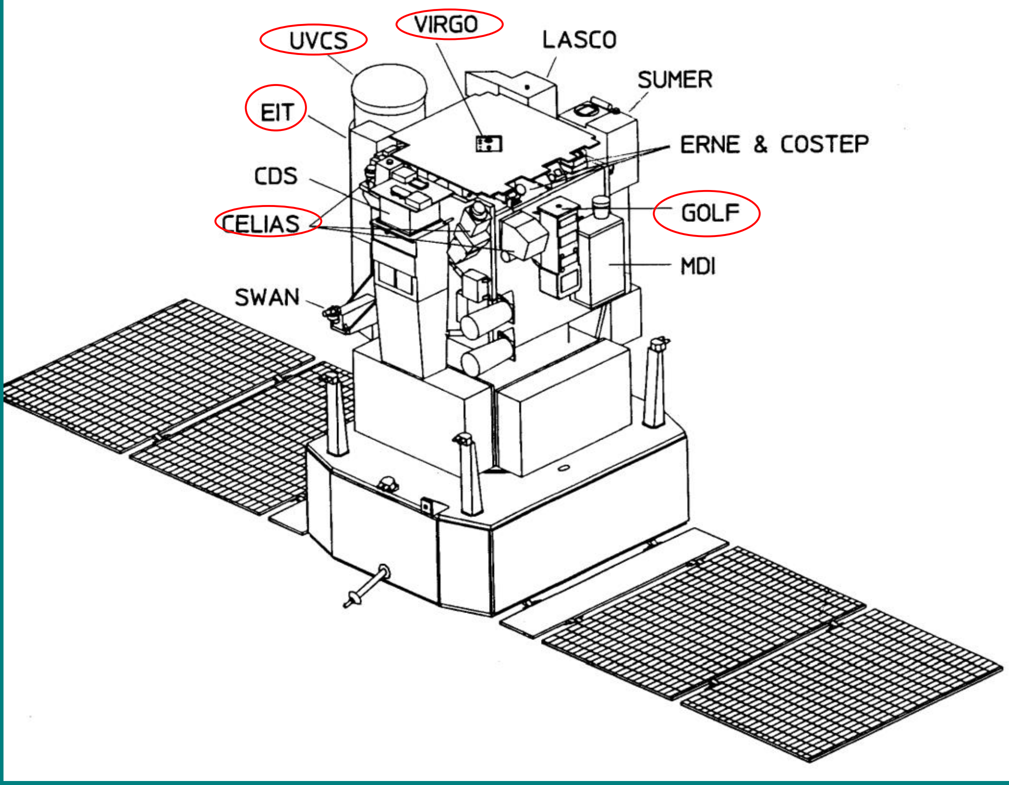




Chapter VIIIa: Solar observations and plasma measurements

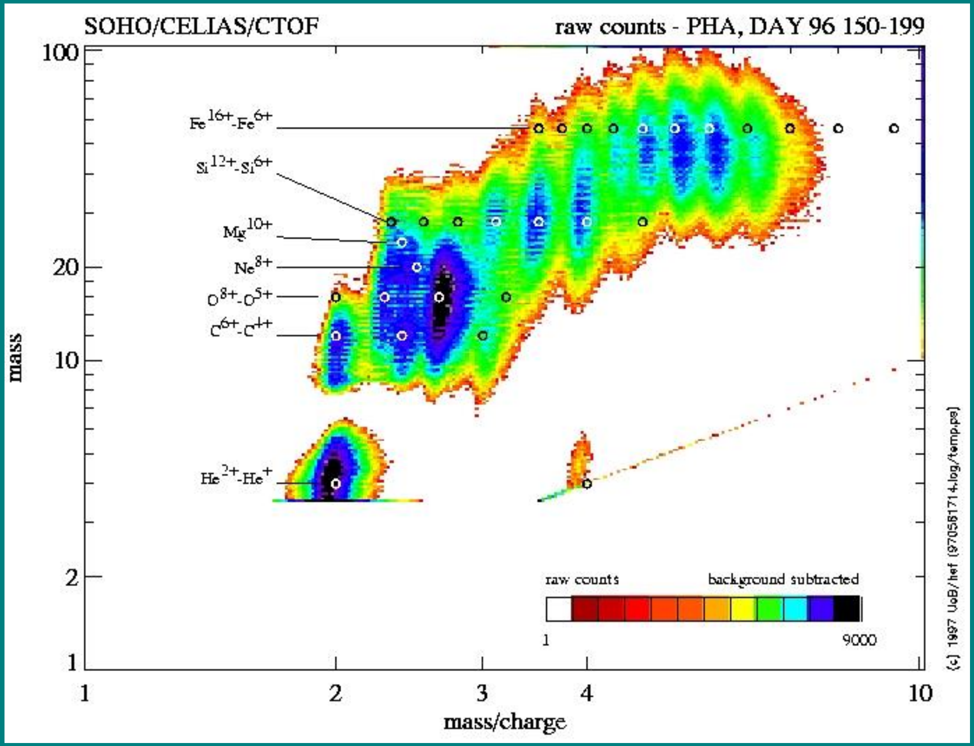
- SOHO was temporarily lost in 1998 (bad manoeuver by the spacecraft operators). The mission is currently operated without gyroscopes, but remains 3-axes stabilized.
- The probe features 12 scientific instruments.

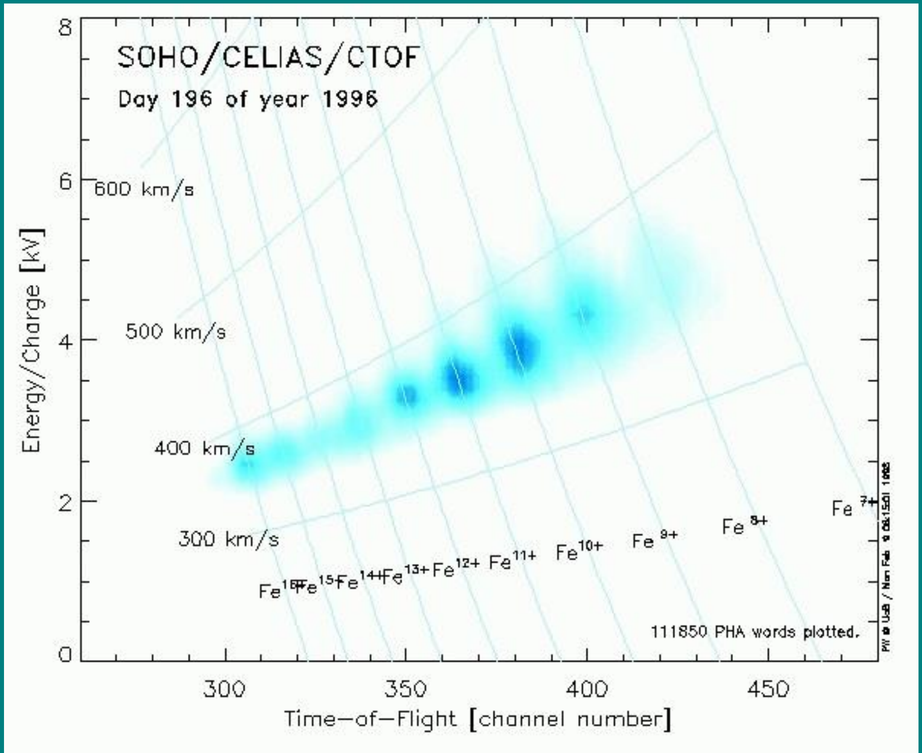




Chapter VIIIa: Solar observations and plasma measurements

- CELIAS (Charge Element and Isotope Analysis System): study of the composition of the Solar wind and of the energetic particles through deflection in an electric field (E_k/q) + time of flight (τ) and residual energy (E_r).





Chapter VIIIa: Solar observations and plasma measurements

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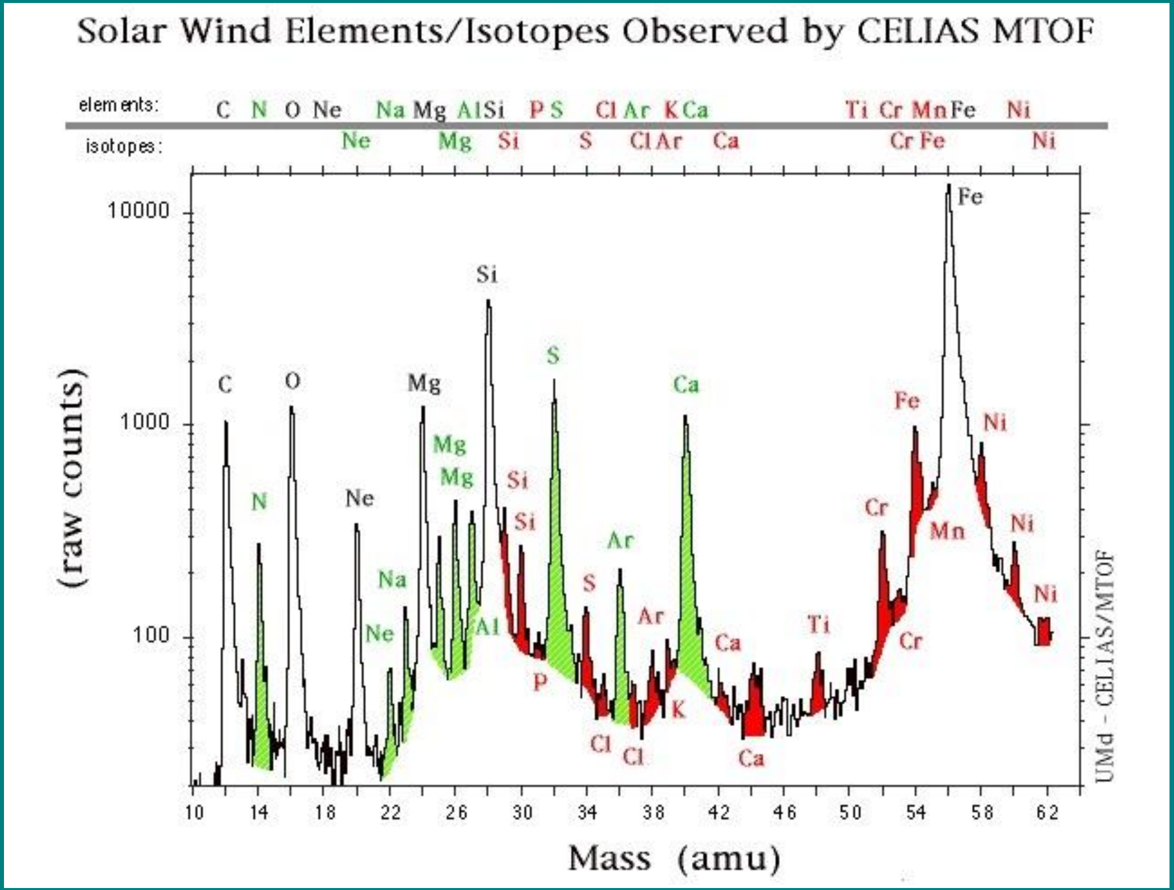
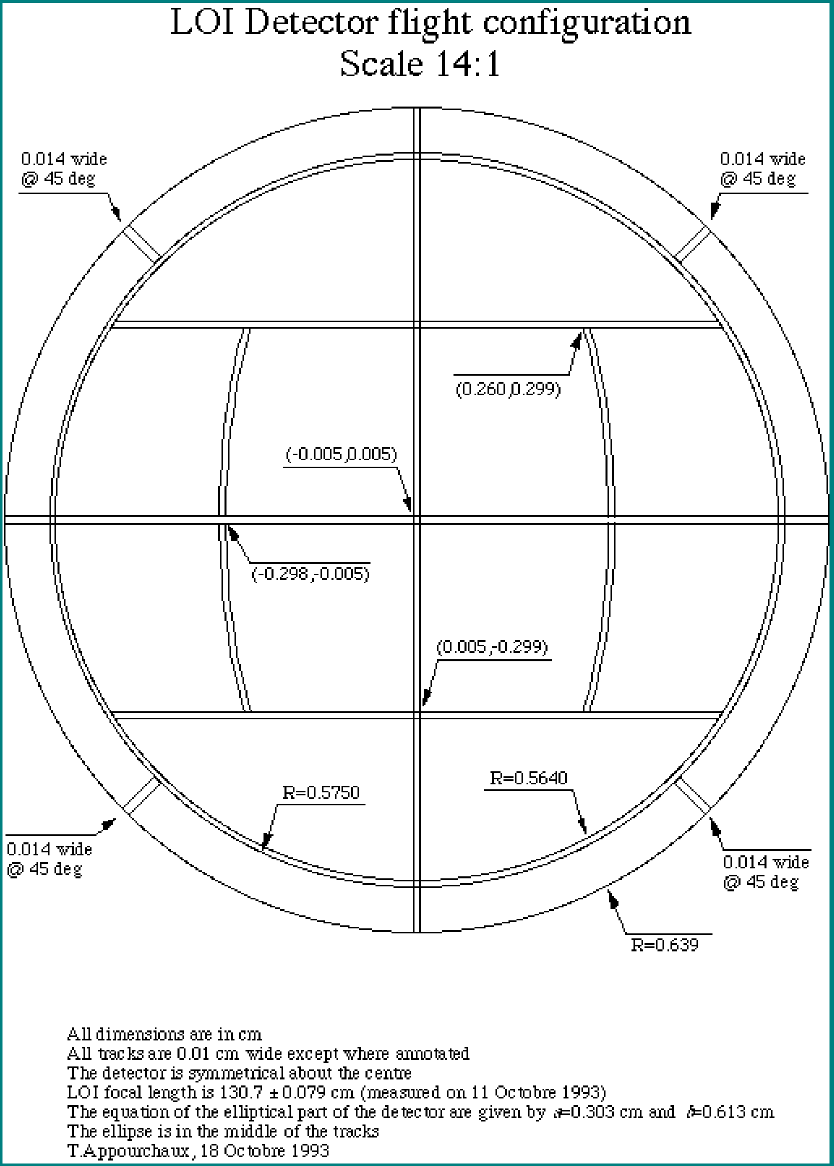


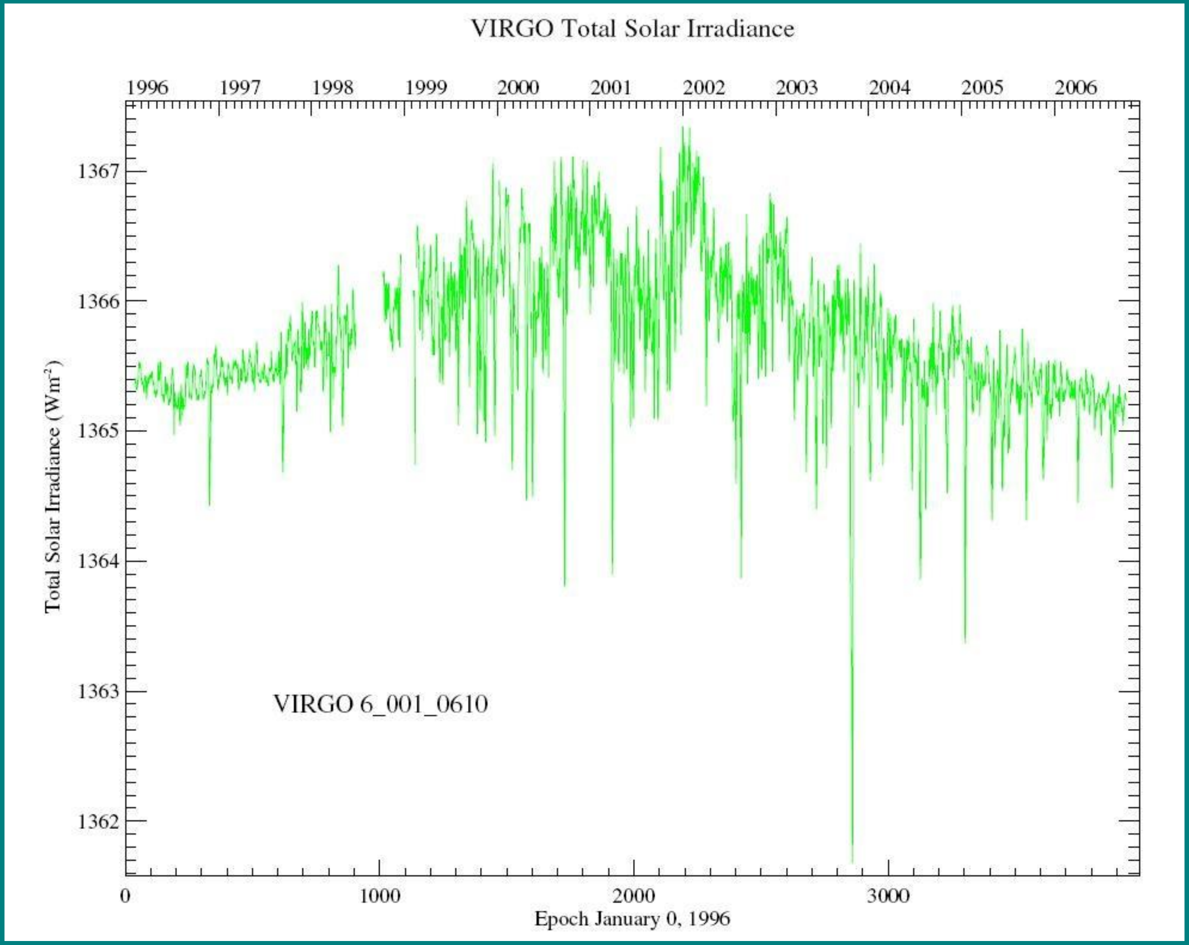
Chapter VIIIa: Solar observations and plasma measurements

- VIRGO (Variability of Solar Irradiance and Gravity Oscillations) instrument: precise determination of the solar flux with a detector adapted to the size of the Sun as seen from L1. One of the objectives: detect *g* mode pulsations.



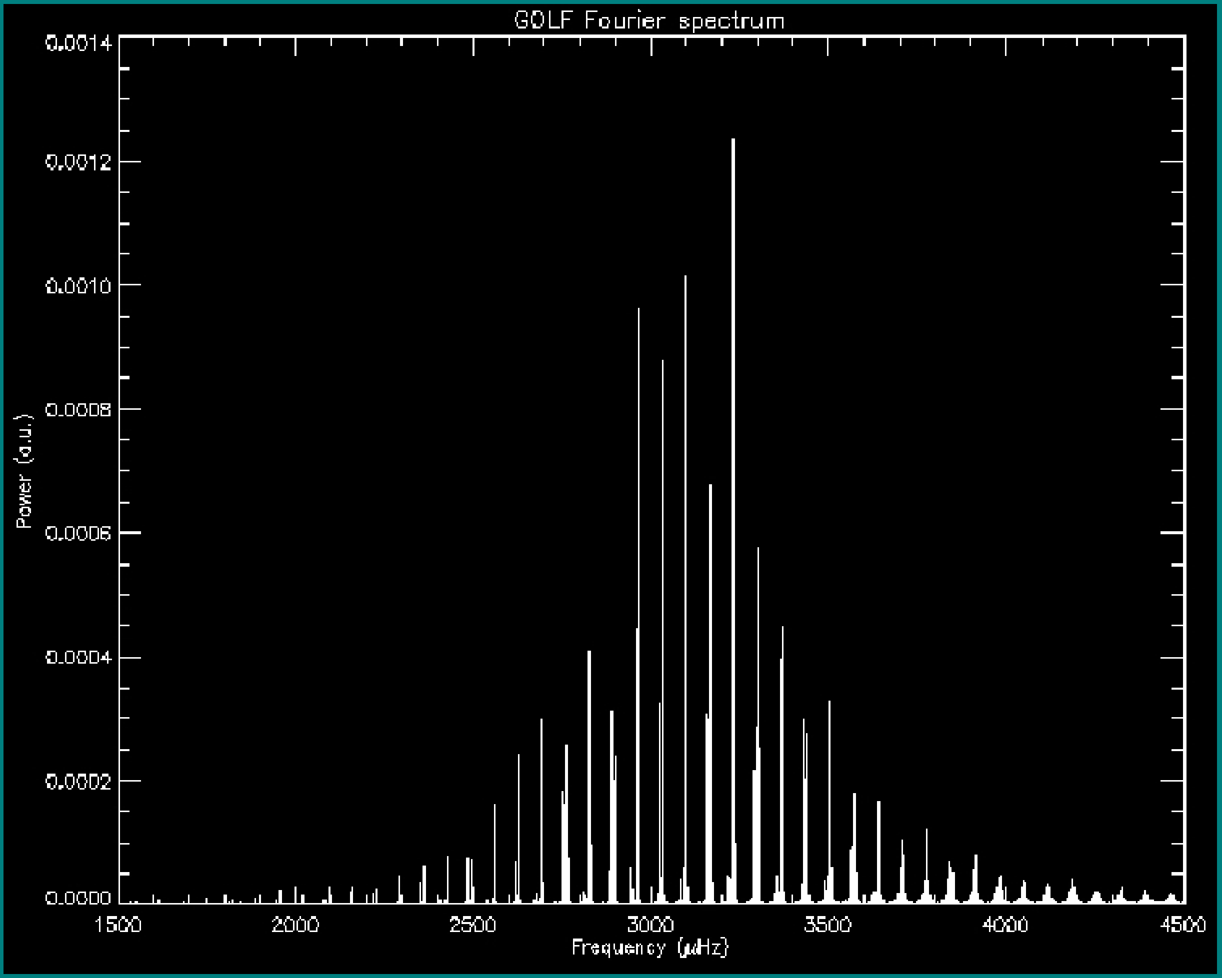
Chapter VIIIa: Solar observations and plasma measurements

- VIRGO instrument: variations of the solar flux with the 11-year solar cycle. No reliable detection of *g* modes to date.



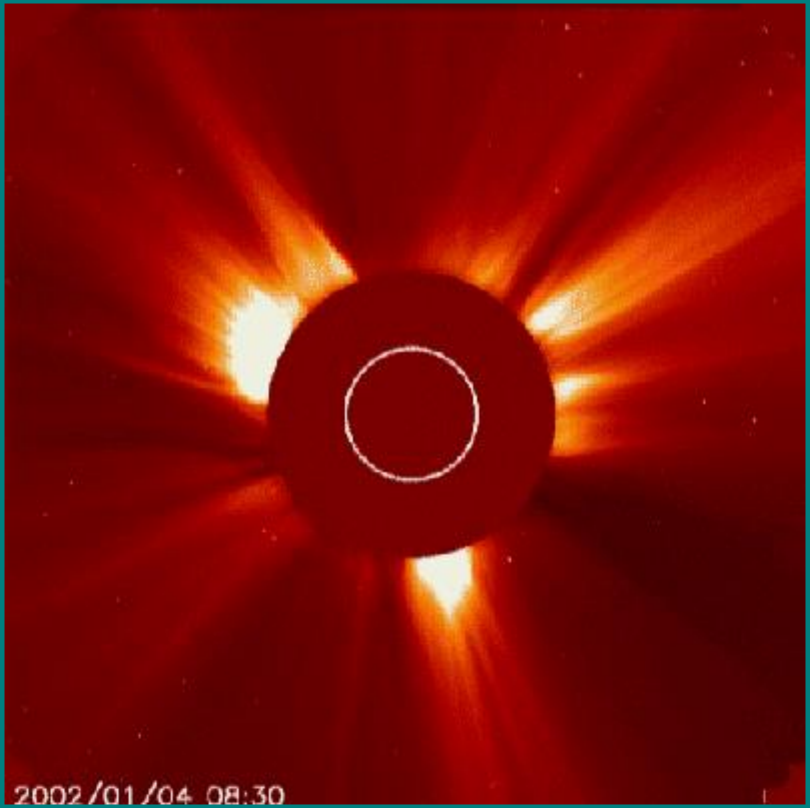
Chapter VIIIa: Solar observations and plasma measurements

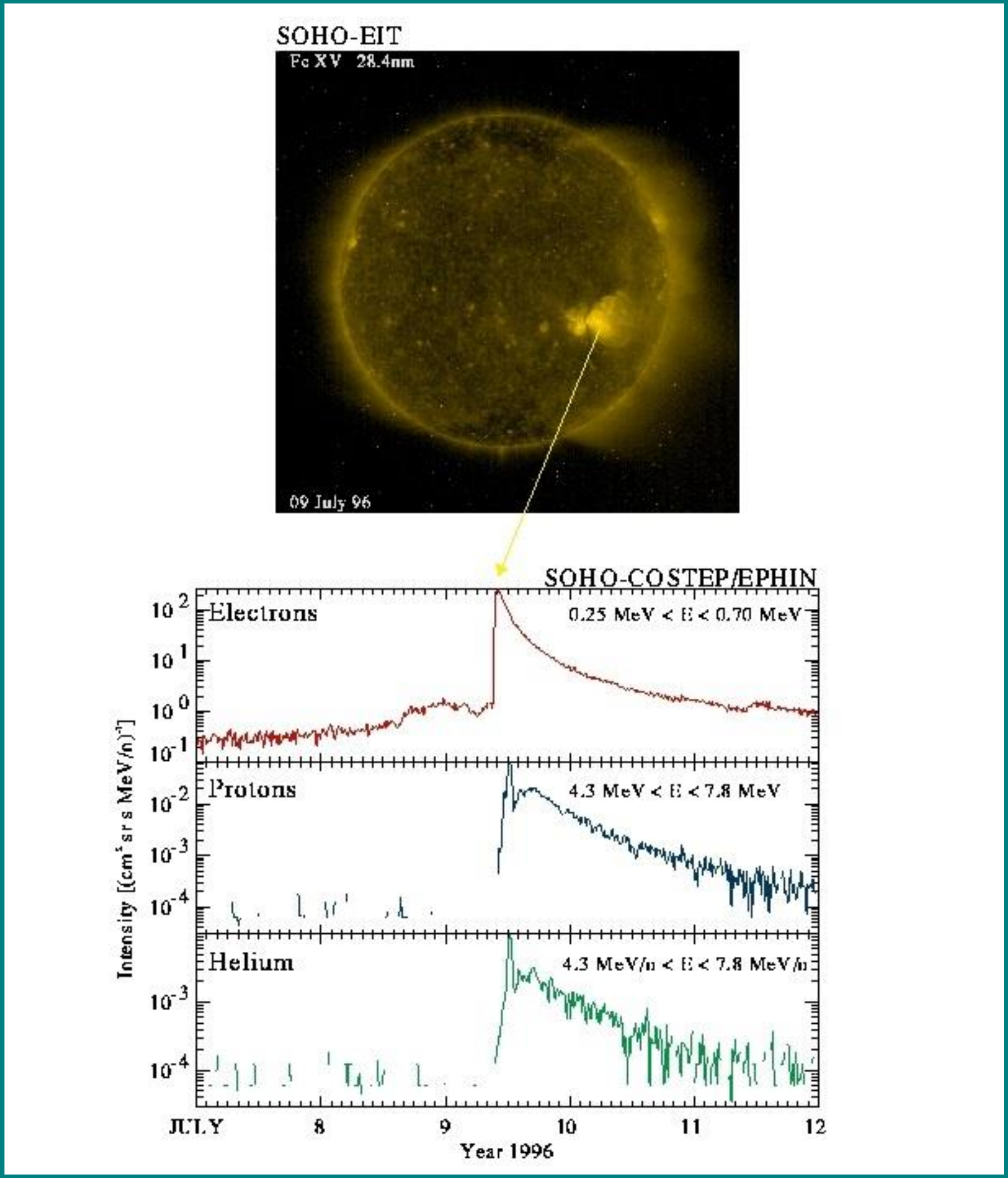
- Other important results of the SOHO mission: Fourier spectrum of the solar oscillations measured with GOLF



Chapter VIIIa: Solar observations and plasma measurements

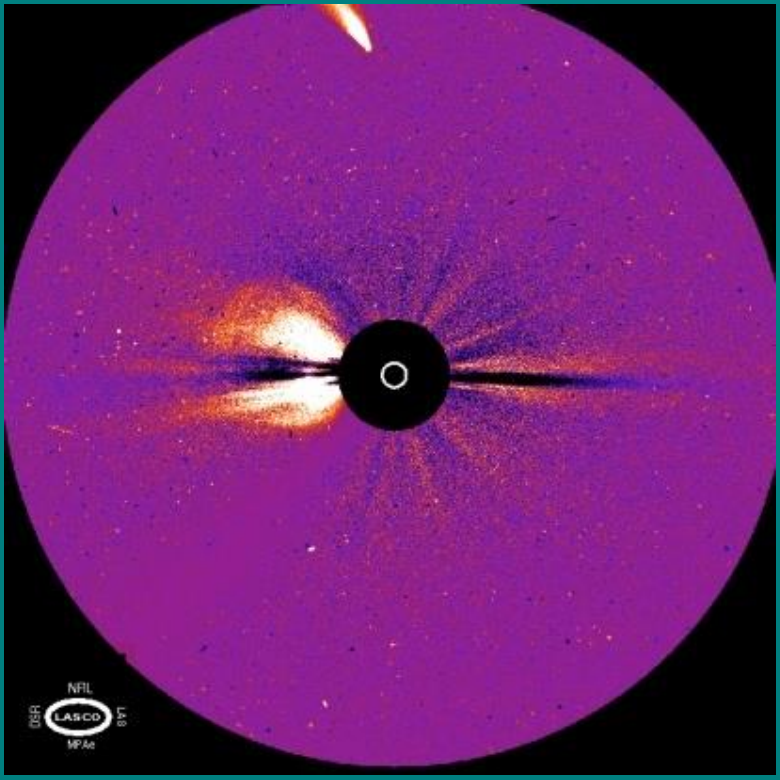
- Other important results of the SOHO mission: coronal mass ejections and eruptions studied with LASCO, EIT, COSTEP,…

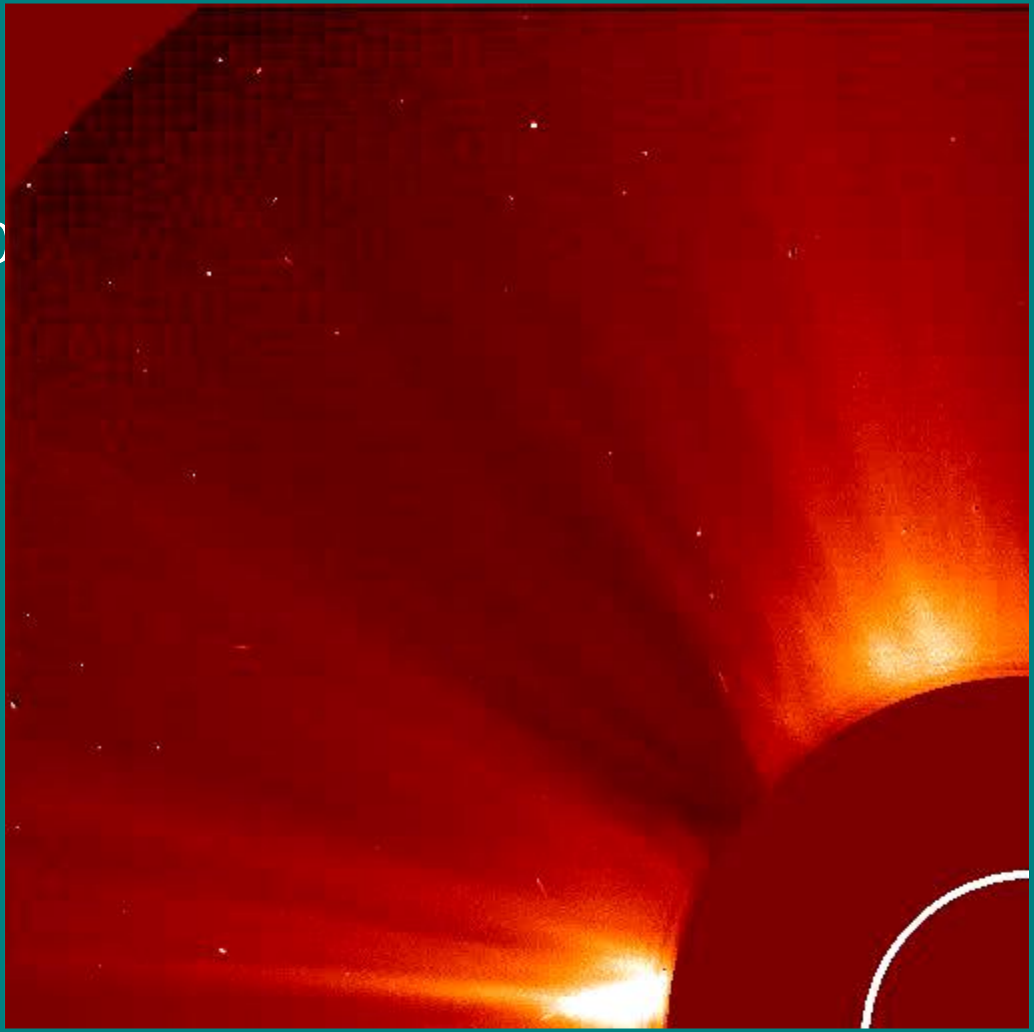




Chapter VIIIa: Solar observations and plasma measurements

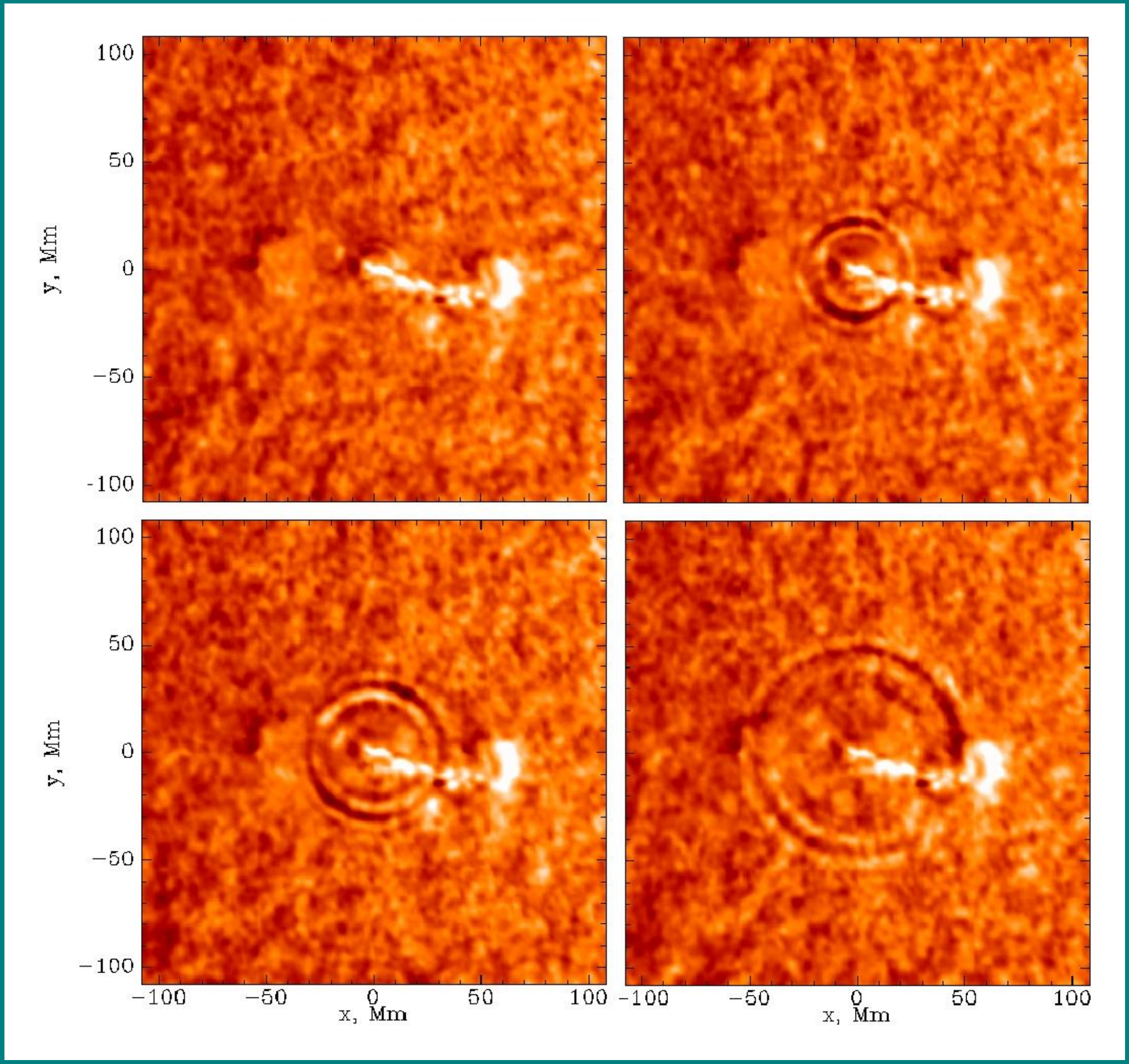
- Other important results of the SOHO mission: discovery and observation of new comets with LASCO (e.g. Machholz)





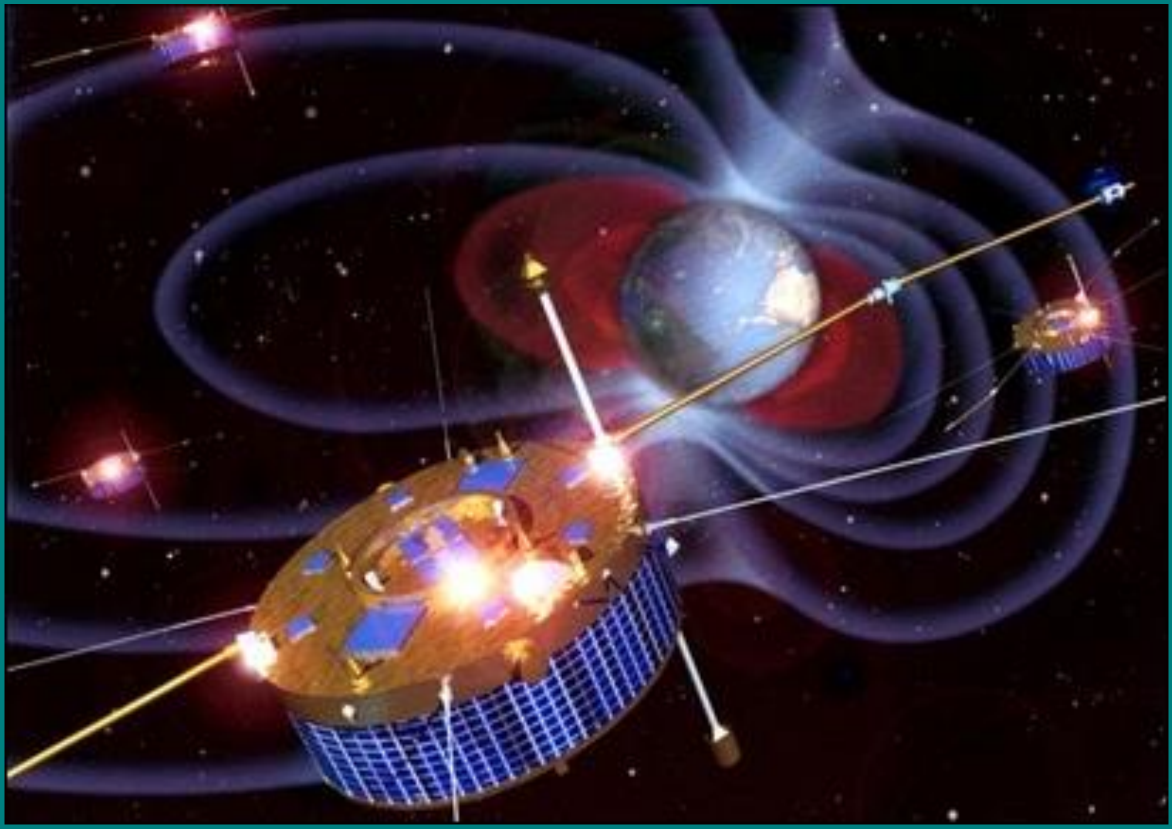
Chapter VIIIa: Solar observations and plasma measurements

- Other important results of the SOHO mission: discovery of “Sun quakes” with MDI.



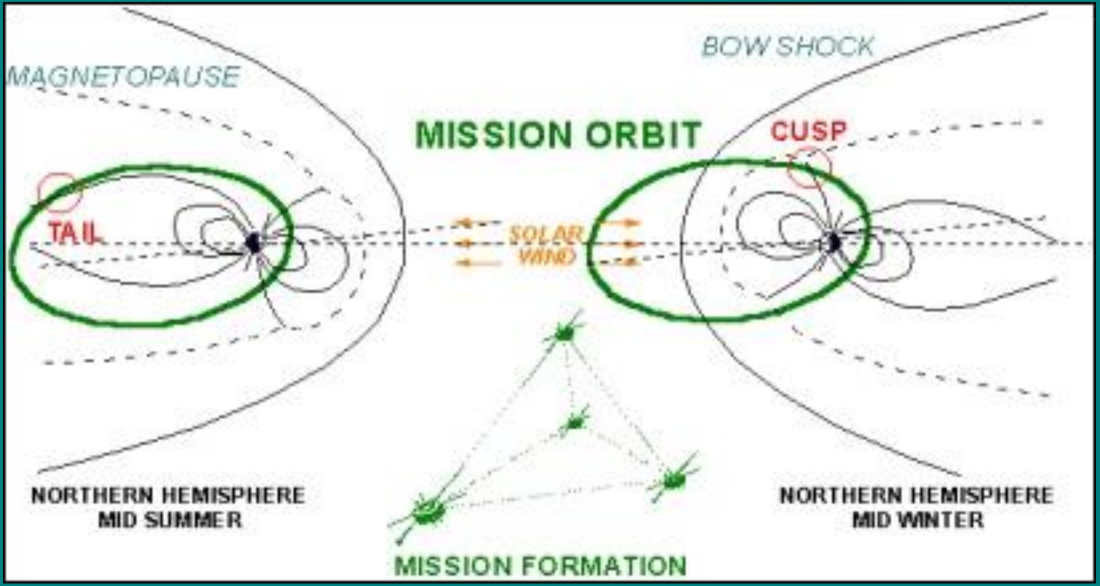
Chapter VIIIa: Solar observations and plasma measurements

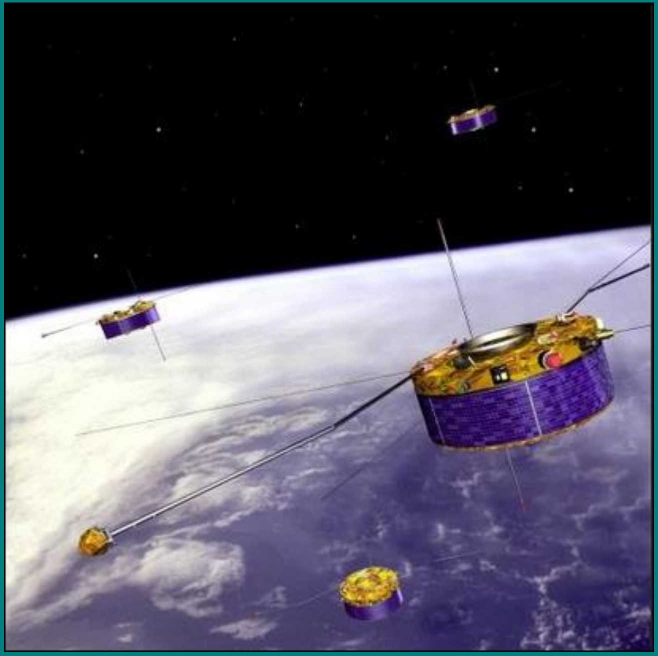
- Cluster: first attempt failed (explosion of Ariane V launcher in 1996).
- Cluster II launched from Baïkonour in 2000 (Soyuz launchers).

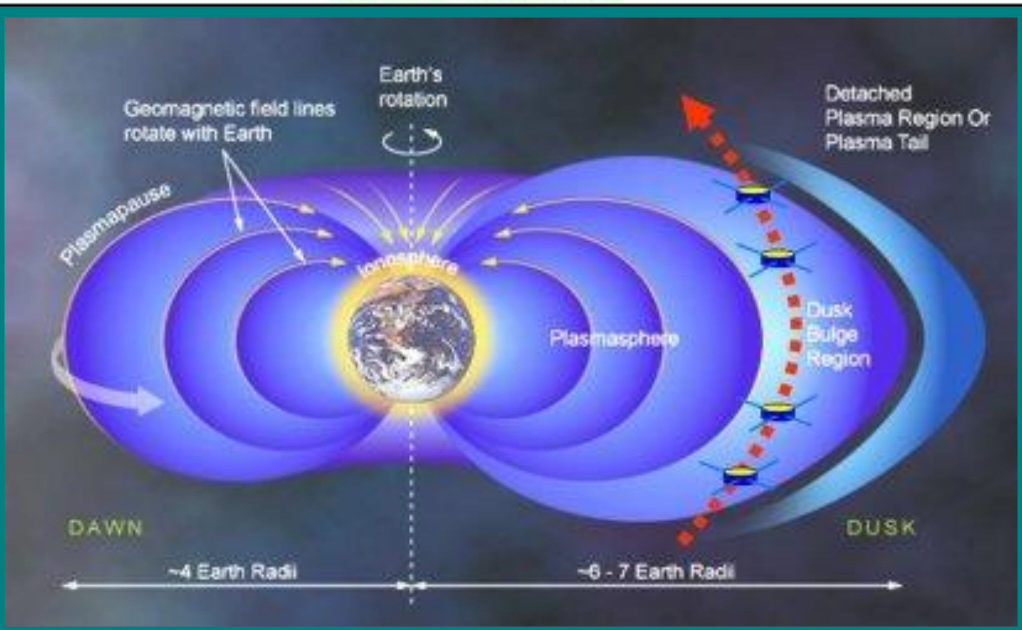


Chapter VIIIa: Solar observations and plasma measurements

- Cluster: 4 satellites flying in formation of a tetrahedron on eccentric polar orbits to explore different regions of the magnetosphere.

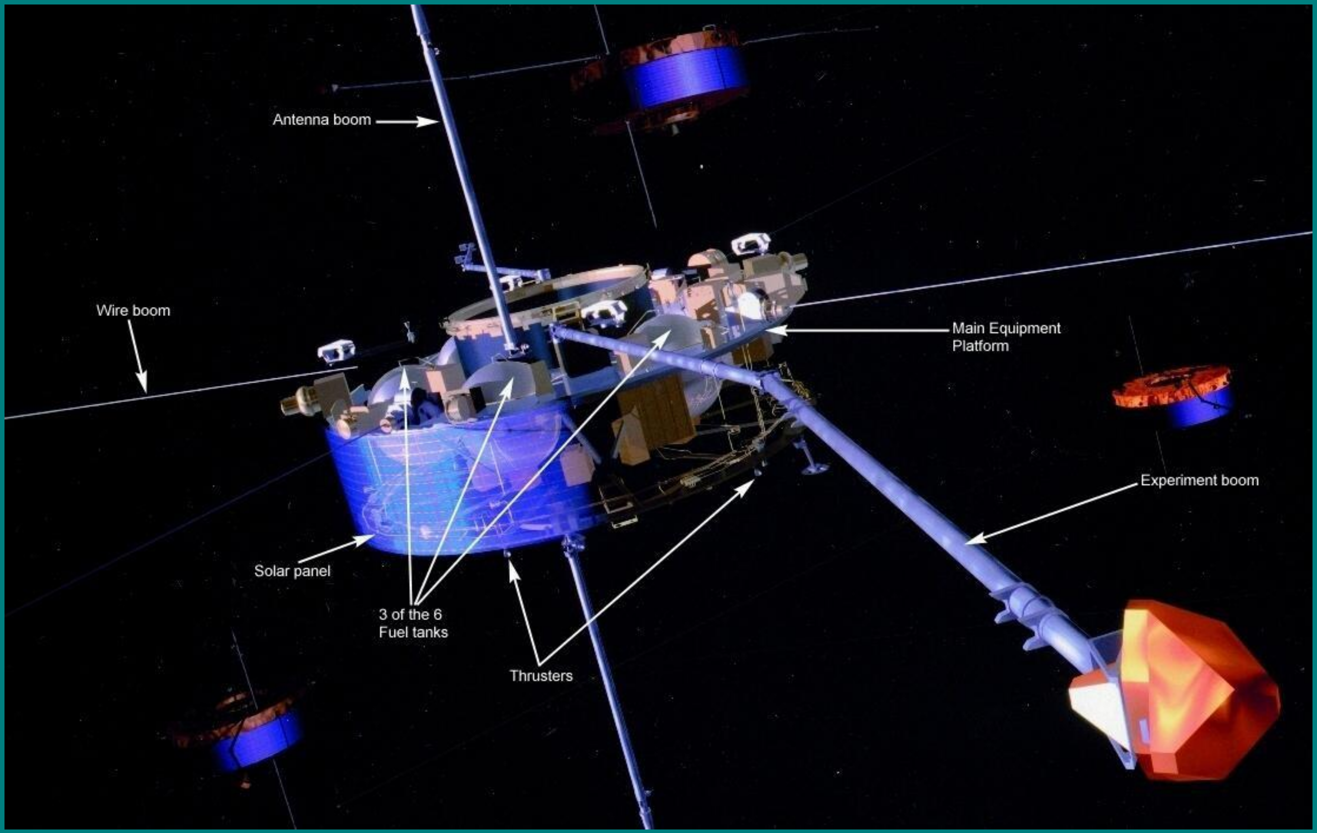


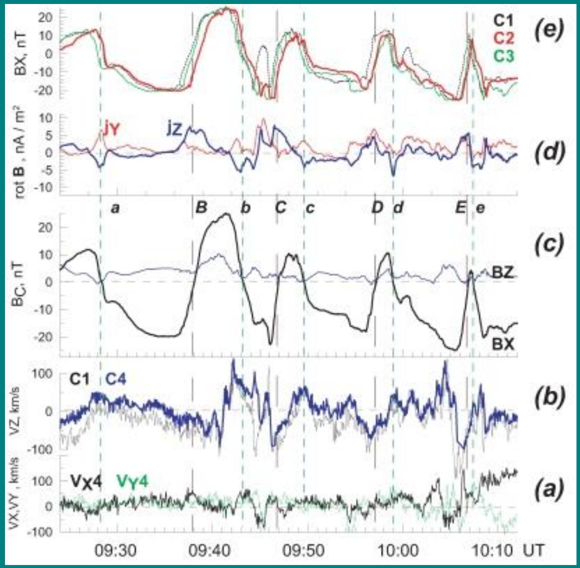




Chapter VIIIa: Solar observations and plasma measurements

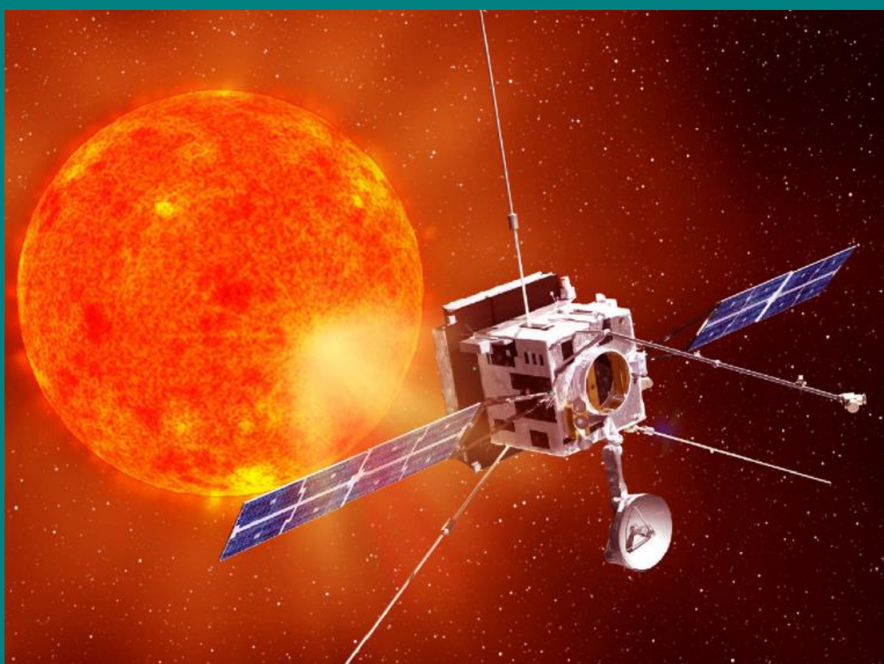
- 4 identical spin-stabilized satellites at the summits of a tetrahedron ⇒ allows distinguish temporal variations of the plasma properties from variations due to the orbit.

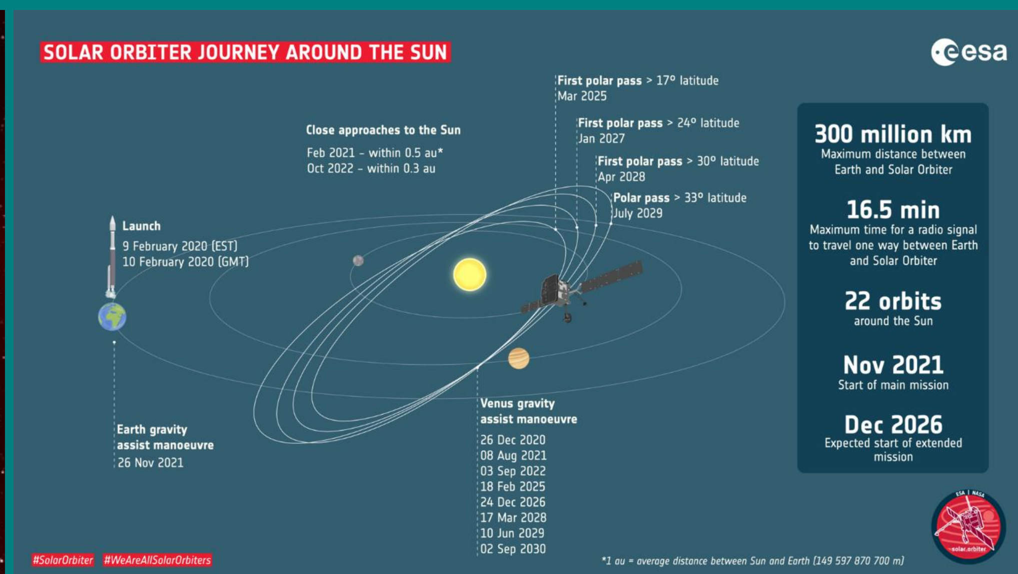




Chapter VIIIa: Solar observations and plasma measurements

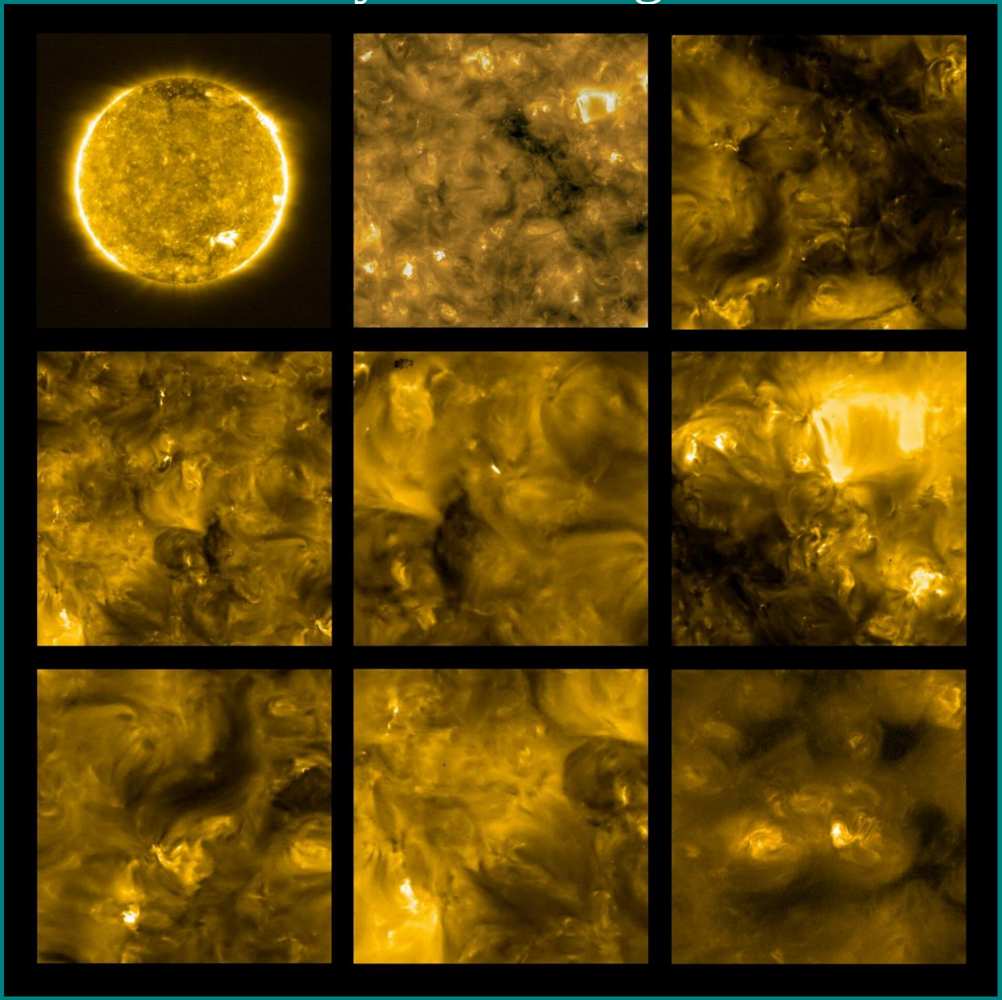
- The future: Solar Orbiter (ESA). Approach the Sun to 0.28 AU and observe it from latitudes above 30°. Orbital motion at perihelion in near resonance with solar rotation.
- How to get out of the plane of the ecliptic? Gravity assist encounters with Venus.





Chapter VIIIa: Solar observations and plasma measurements

- Solar Orbiter launched on 10 February 2020.
- First images released in July 2020. Regular observations start in 2022.

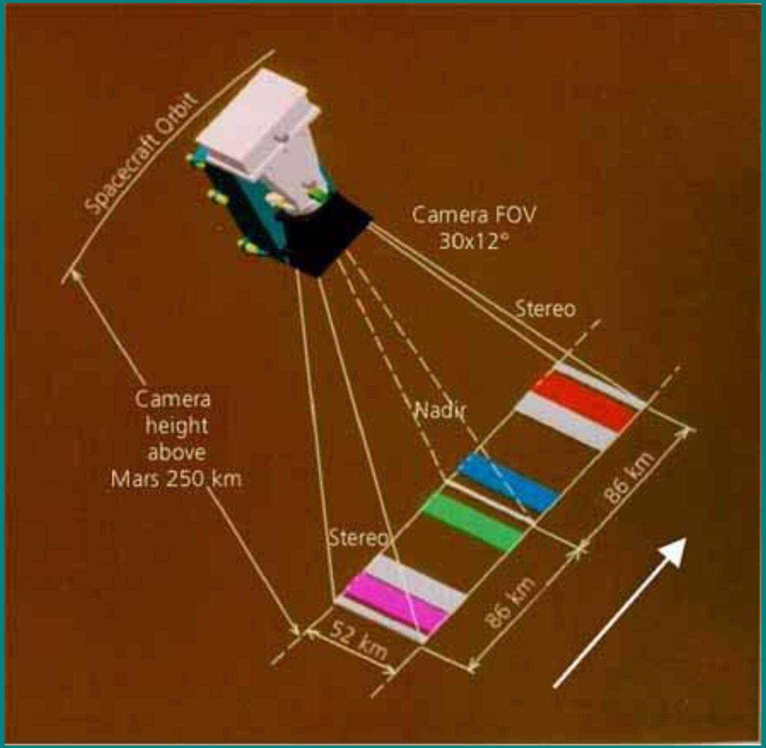


Chapter VIIIb: Missions to Mars

- Some general considerations.
- The NASA rovers Spirit, Opportunity and Curiosity.
- The ESA mission Mars Express
- 2030+: humans on Mars??

Chapter VIIIb: Missions to Mars

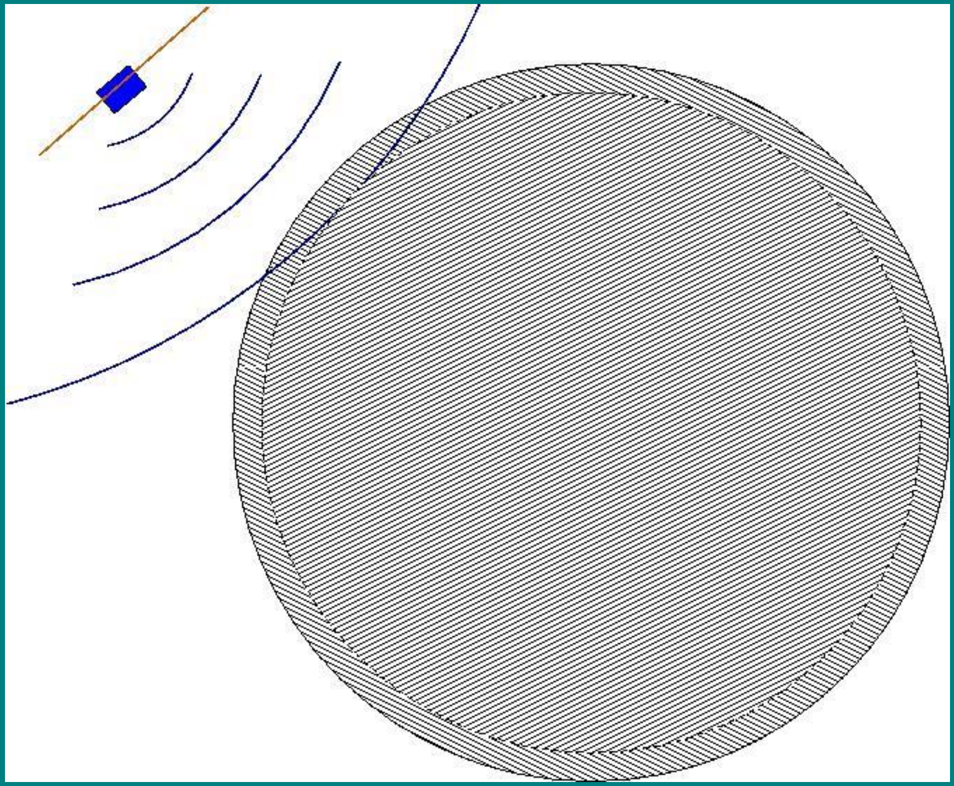
- Planetary missions: observations from an orbit, landers,…
- Each orbiter is equipped with an imaging camera: old missions (Mariner, Viking) used vidicon cameras, recent missions use CCD cameras.

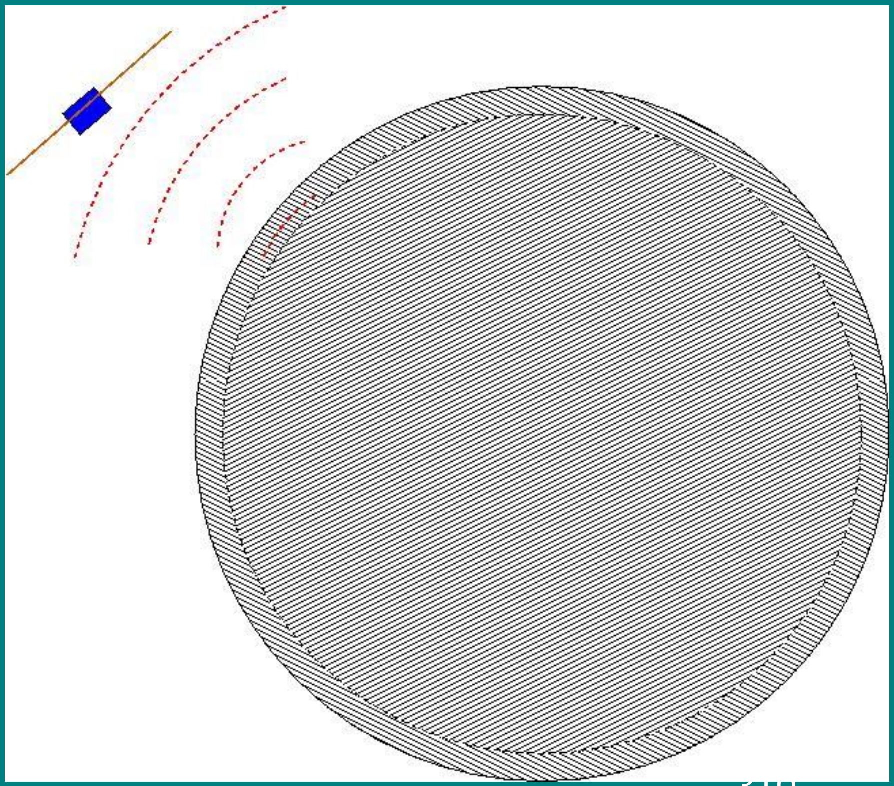


- Stereo cameras (such as the HRSC aboard Mars Express) allow to build 3-D images.

Chapter VIIIb: Missions to Mars

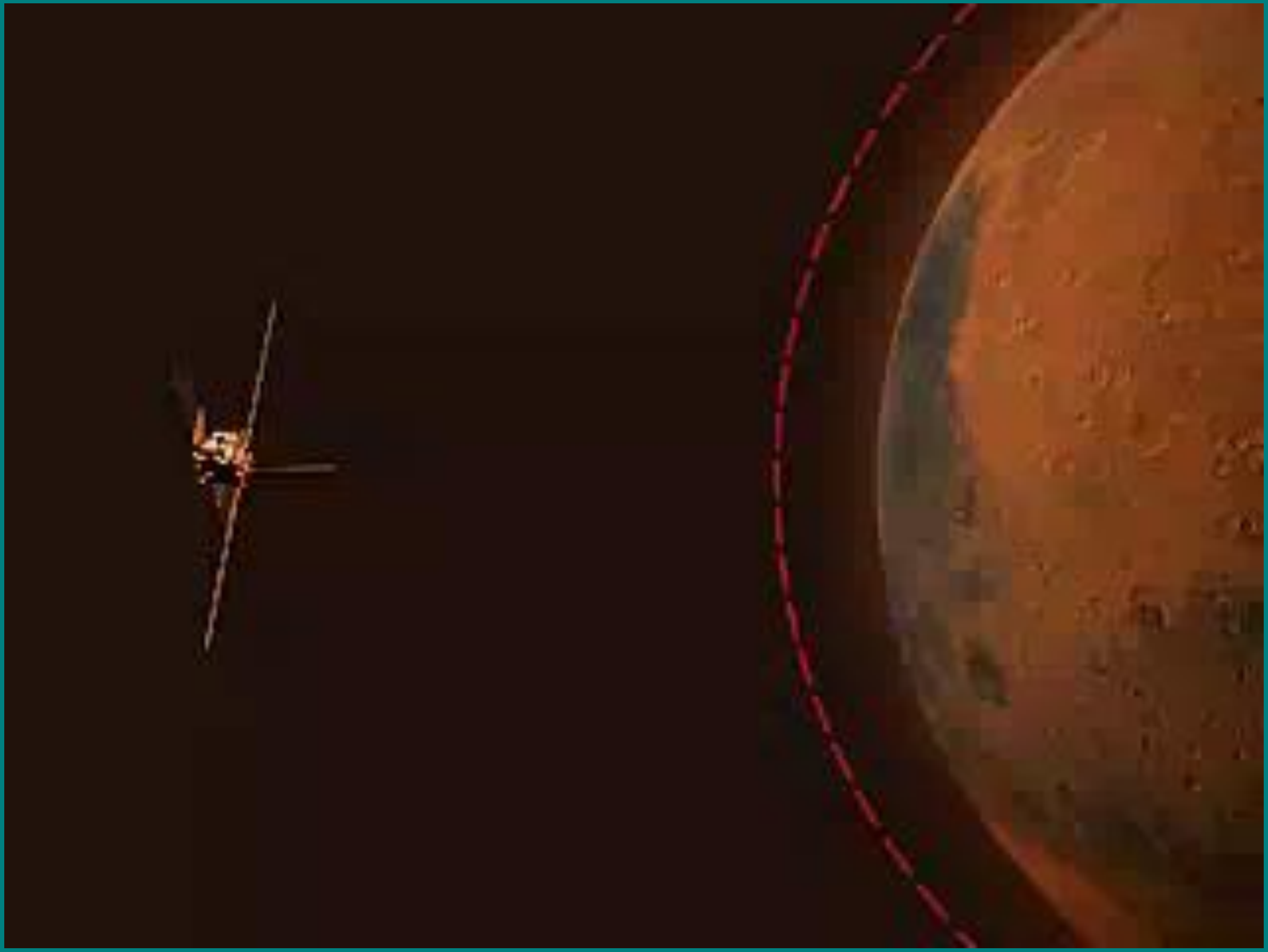
- Ground penetrating radars (GPR): radio waves penetrate into the soil and their reflection at different interfaces depends on the properties (dielectric constant) of the materials encountered.





Chapter VIIIb: Missions to Mars

- Example of ground penetrating radar: the MARSIS instrument aboard Mars Express



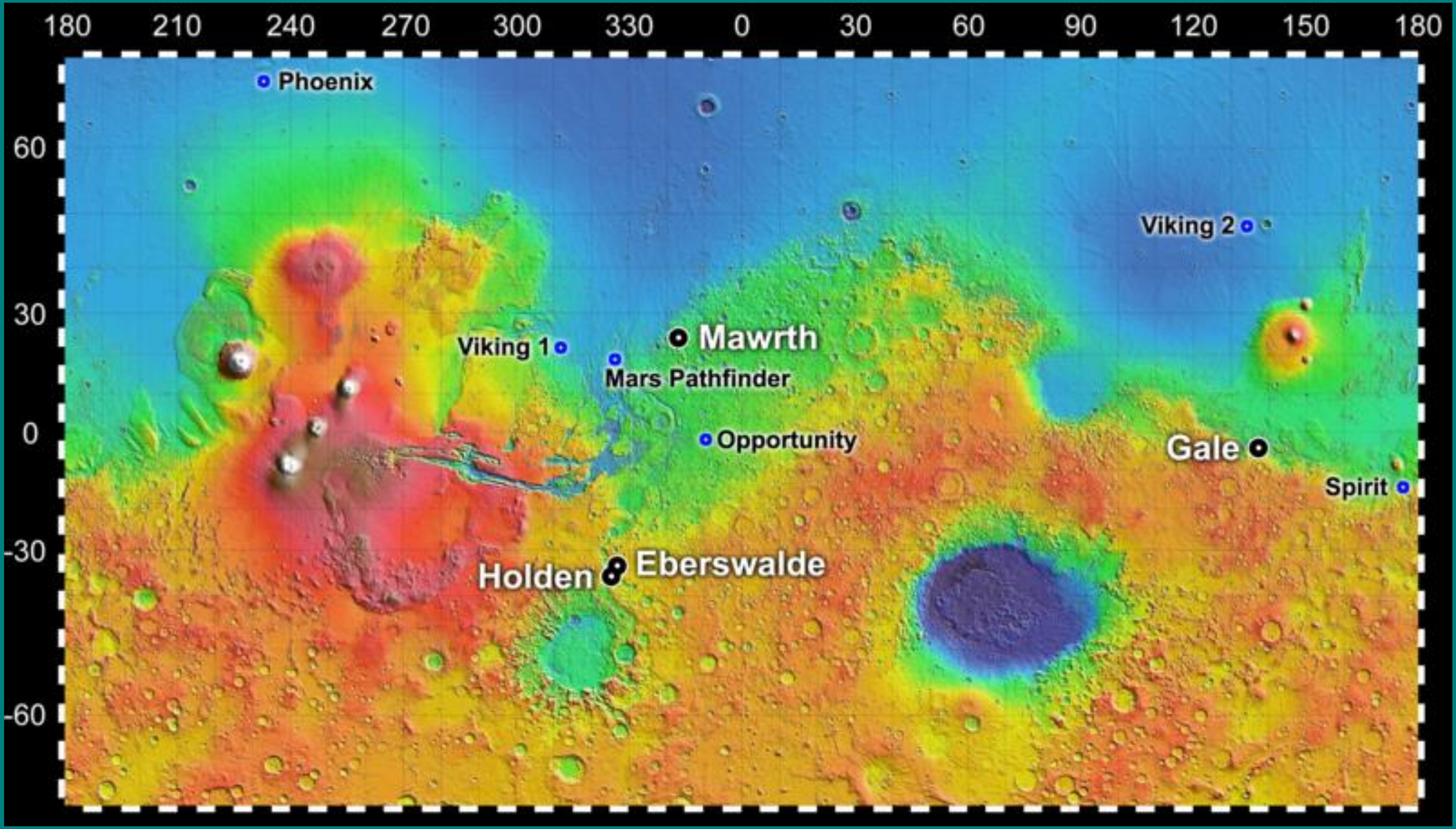
Chapter VIIIb: Missions to Mars

- Landers: choice of the landing site?

1. Scientific considerations: old lakes (exo-biology), volcanic sediments (geology), polar caps (climatology)…
2. Technical considerations: near the equator (thermal environment, solar irradiation on solar panels), landing sites not at high altitude (parachutes), flat and smooth landing sites.
3. Uncertainty ellipse on the impact point (uncertainty on descent velocity and trajectory of the probe, uncertainties on the atmospheric density, wind direction,…).

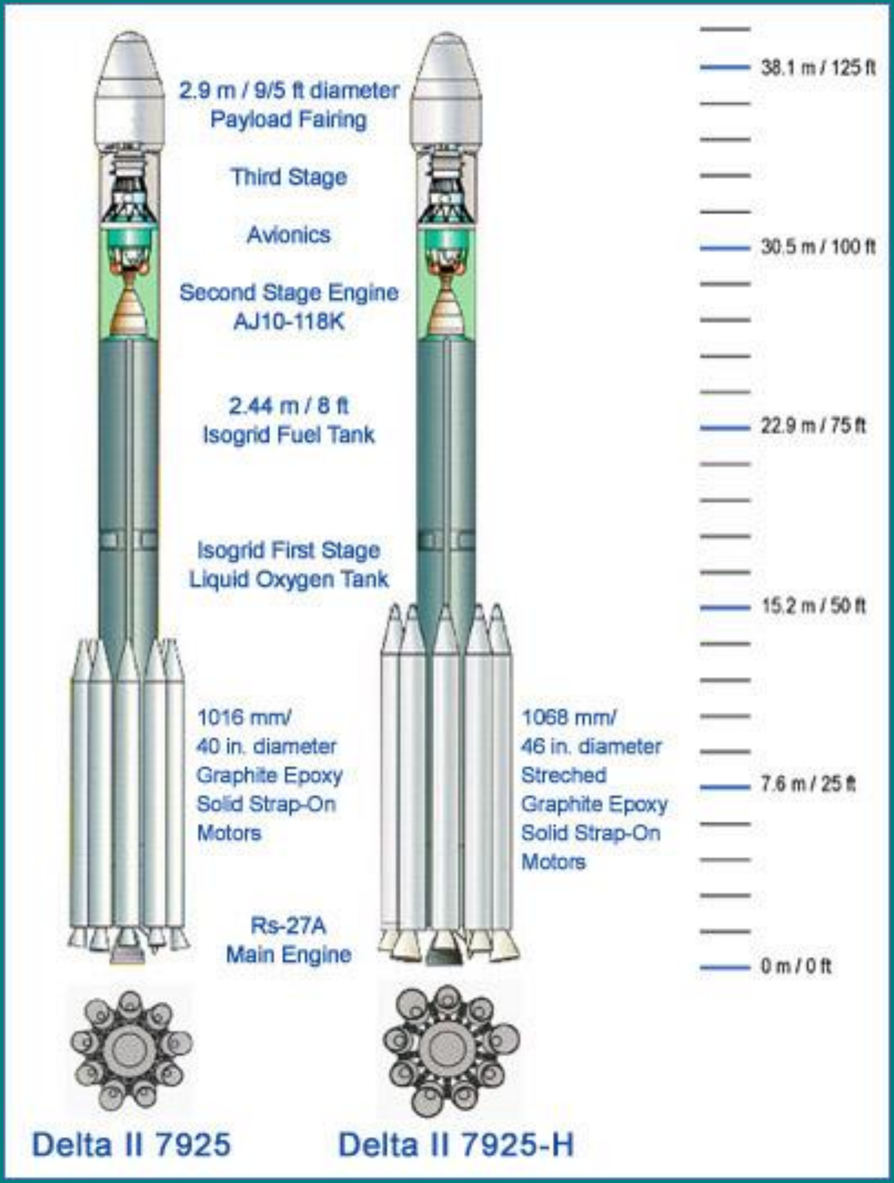
Chapter VIIIb: Missions to Mars

- Landers: choice of the landing site?



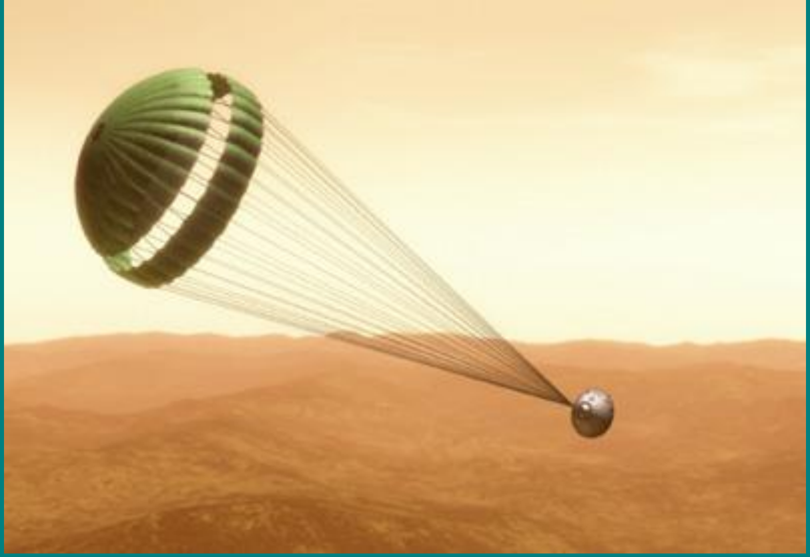
Chapter VIIIb: Missions to Mars

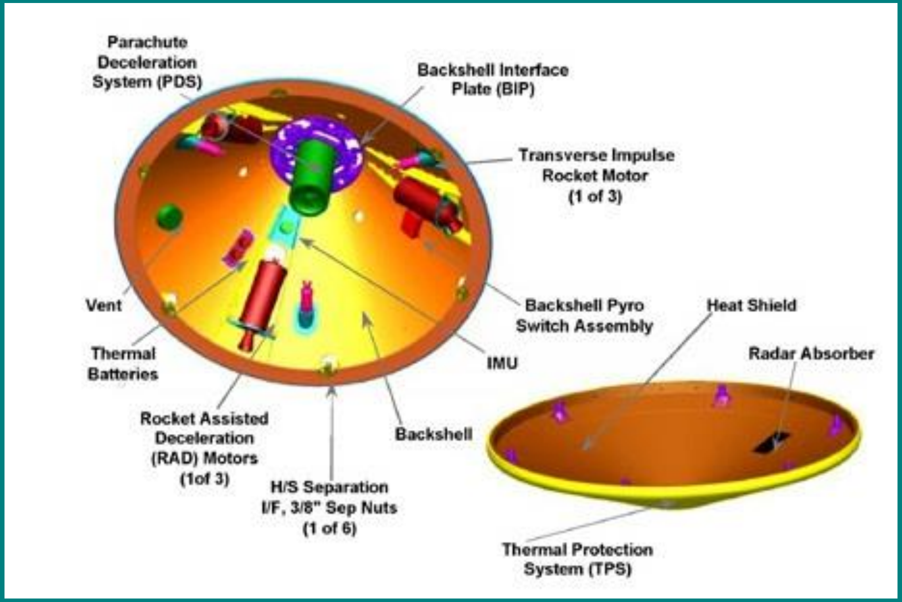
- Mars Exploration Rover mission: 2 identical rovers (Spirit and Opportunity).
- Launch in June and July 2003 by Delta II and Delta II Heavy launchers.
- Spirit: last contact in March 2010
- Opportunity: contact lost in Summer 2018 (officially terminated in February 2019).

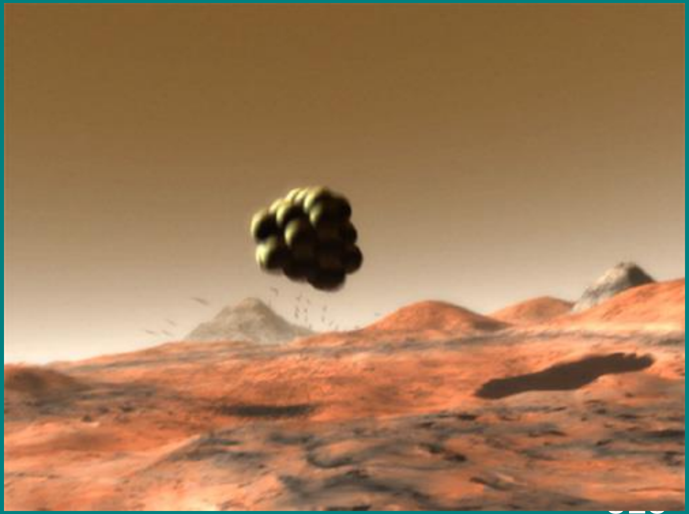


Chapter VIIIb: Missions to Mars

- Entry into the Martian atmosphere and landing: parachutes and airbags.

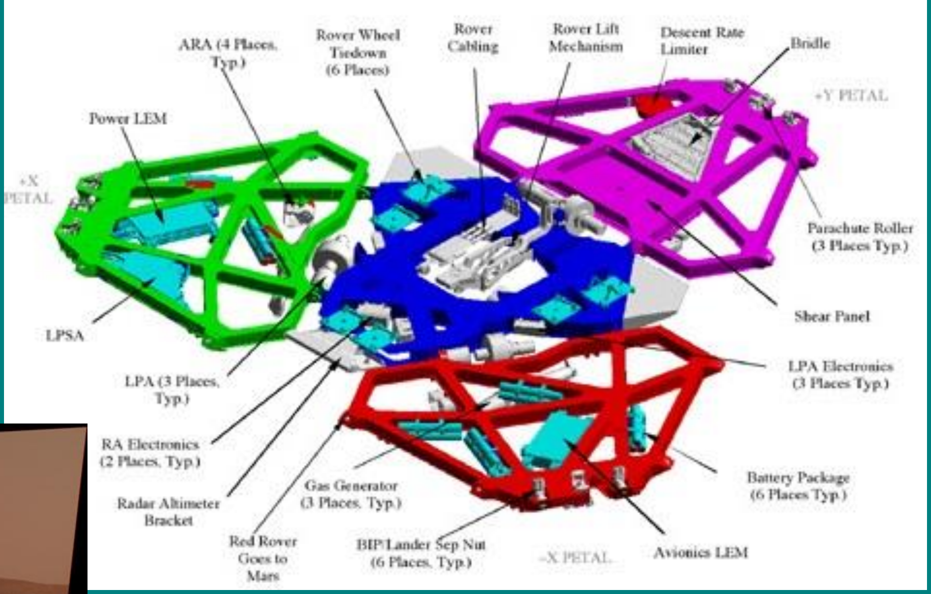


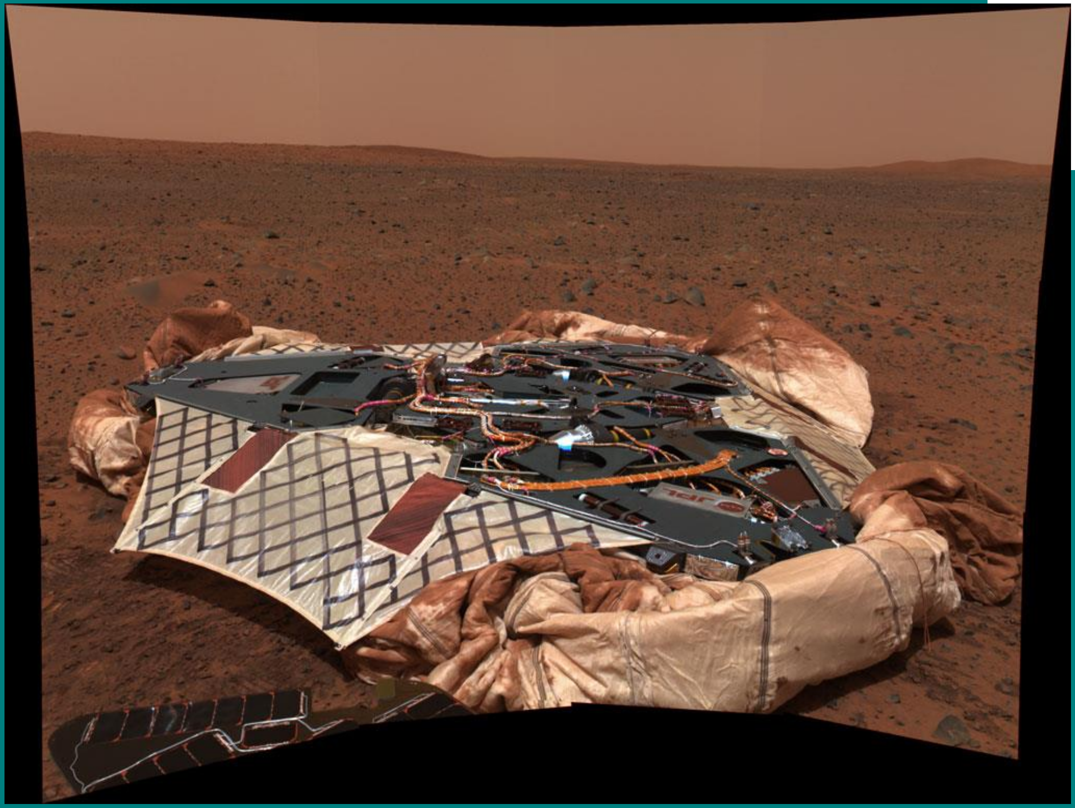




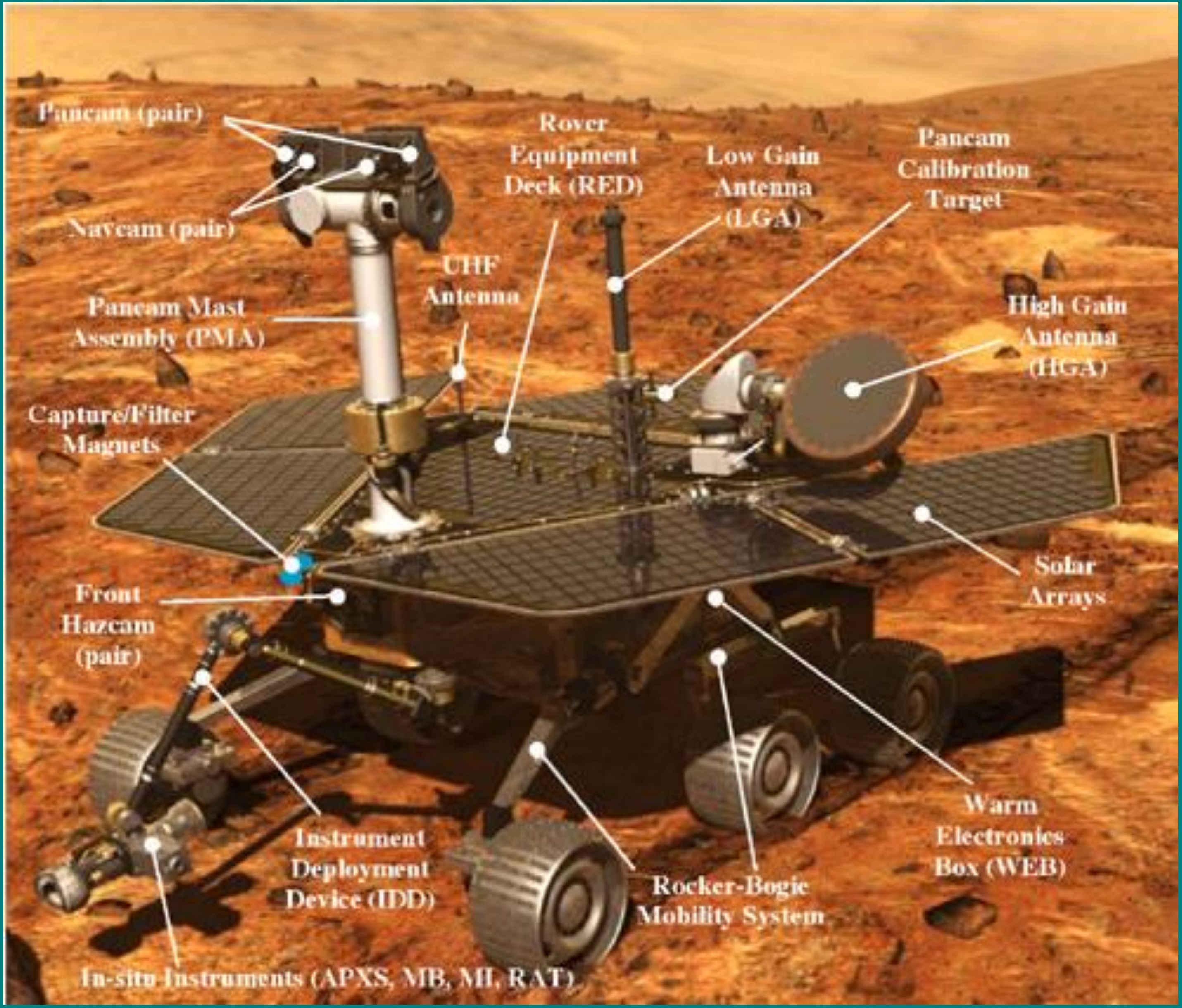
Chapter VIIIb: Missions to Mars

- Rover protected by landing module.



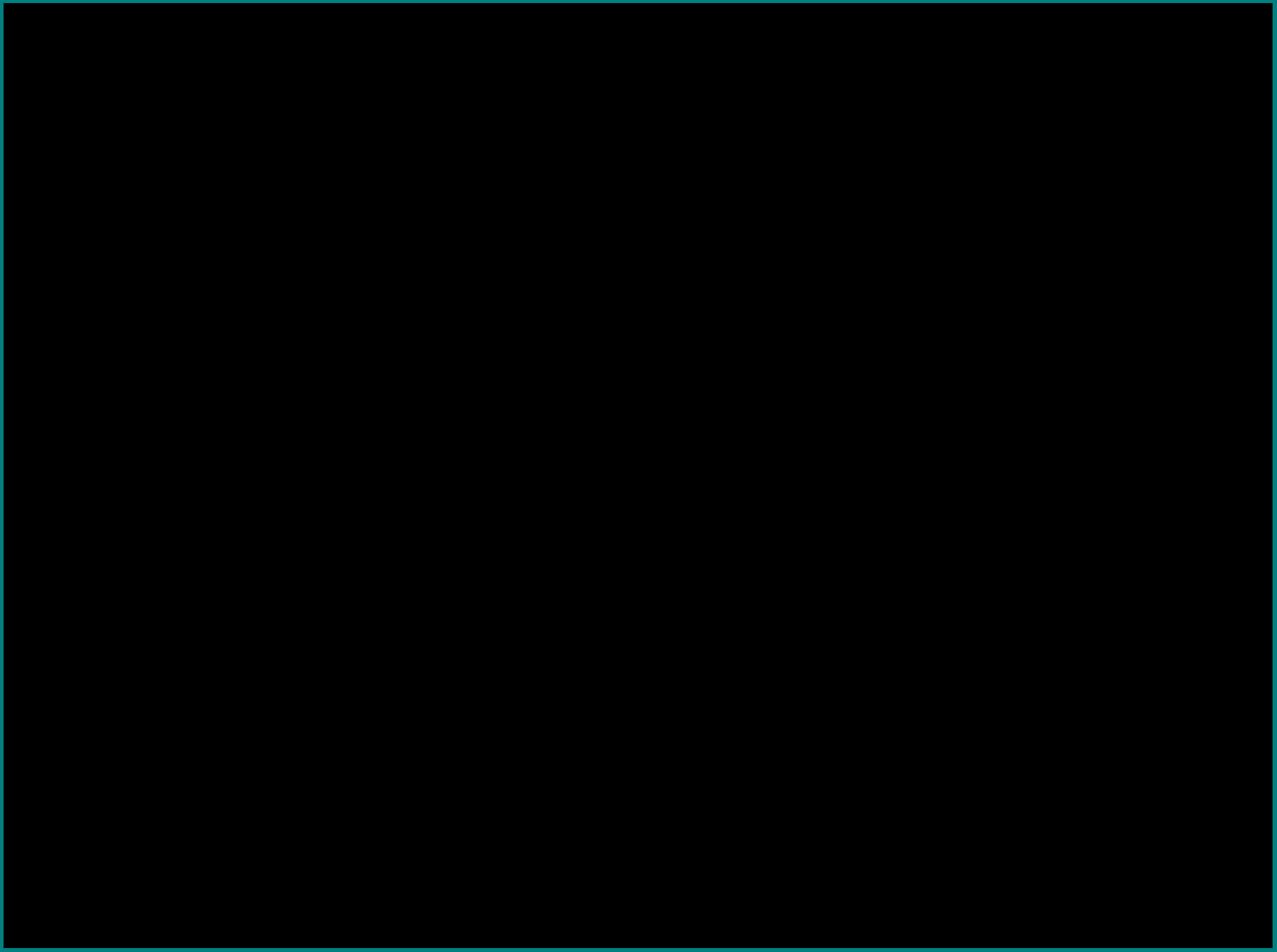


Chapter VIIIb: Missions to Mars

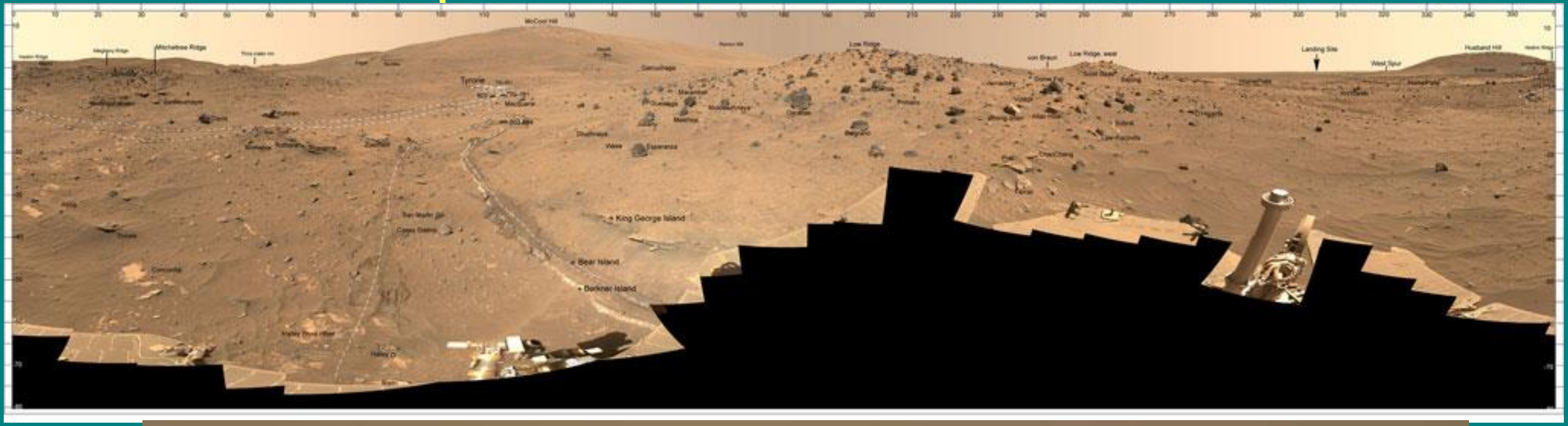


Chapter VIIIb: Missions to Mars

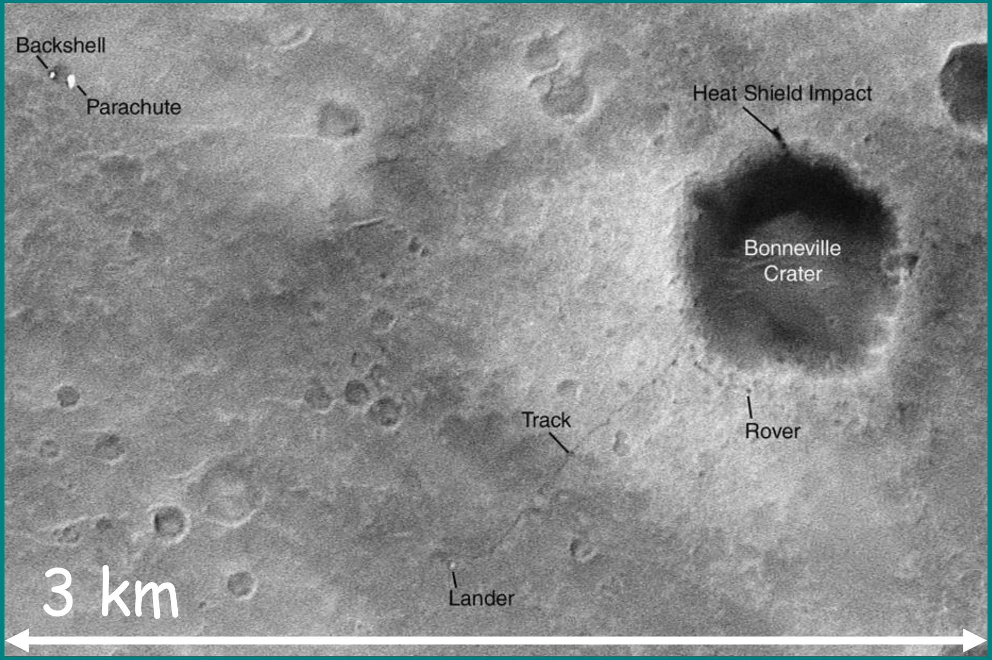
- Animation of the journey, landing and operations of the rovers.



Chapter VIIIb: Missions to Mars

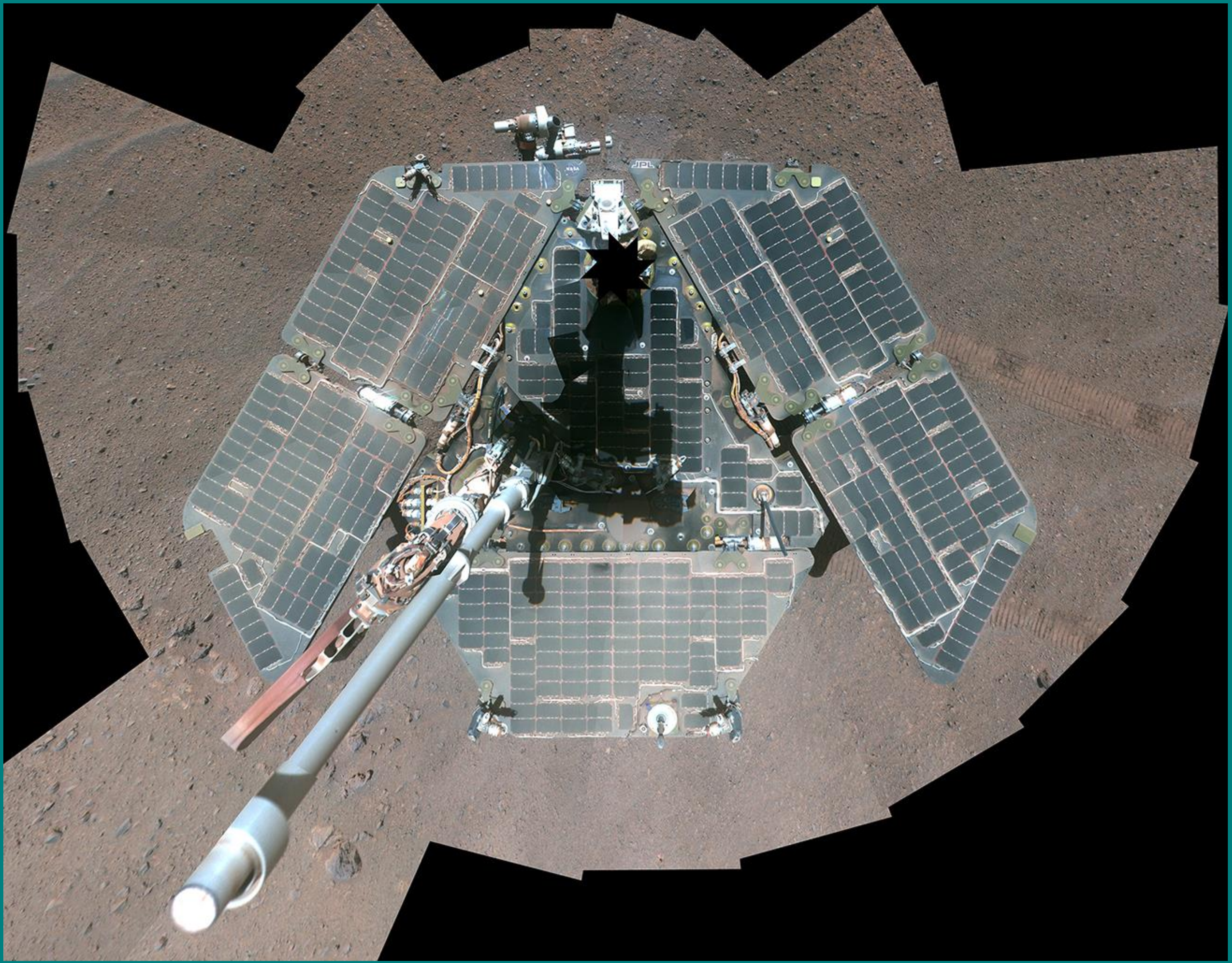


Chapter VIIIb: Missions to Mars



Chapter VIIIb: Missions to Mars

- ‘Selfie’ allows checking the status of the solar panels (dust layer)

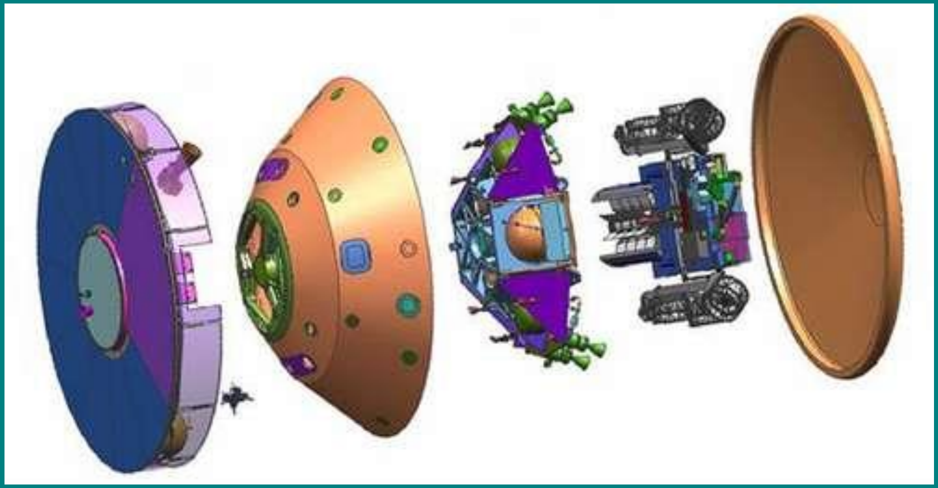


Chapter VIIIb: Missions to Mars

- Mars Science Laboratory (MSL) launched in November 2011 by an Atlas Centaur V launcher.

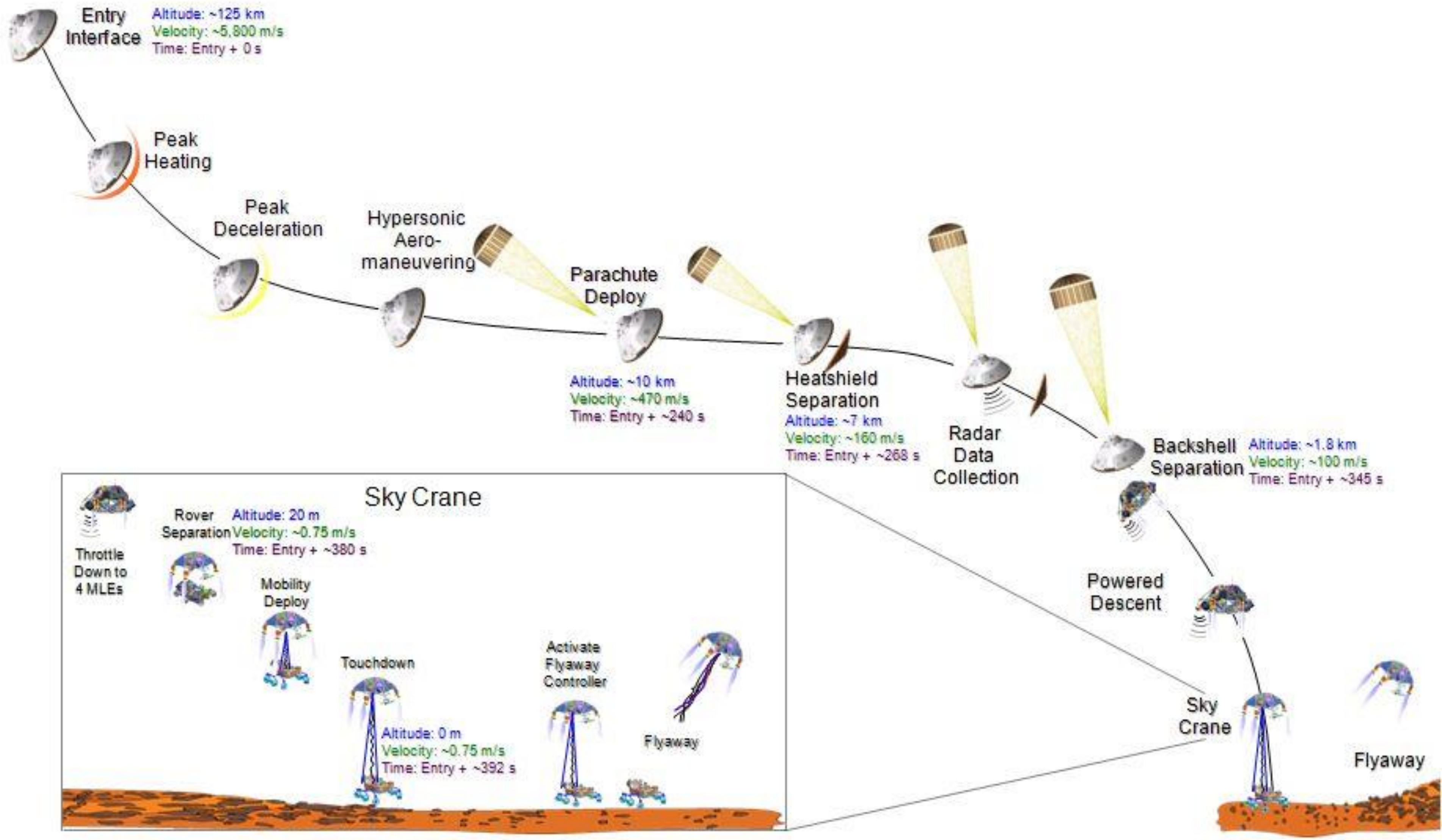
Chapter VIIIb: Missions to Mars

- Spacecraft composed of cruise stage, backshell, descent module, Curiosity rover and the heat shield.



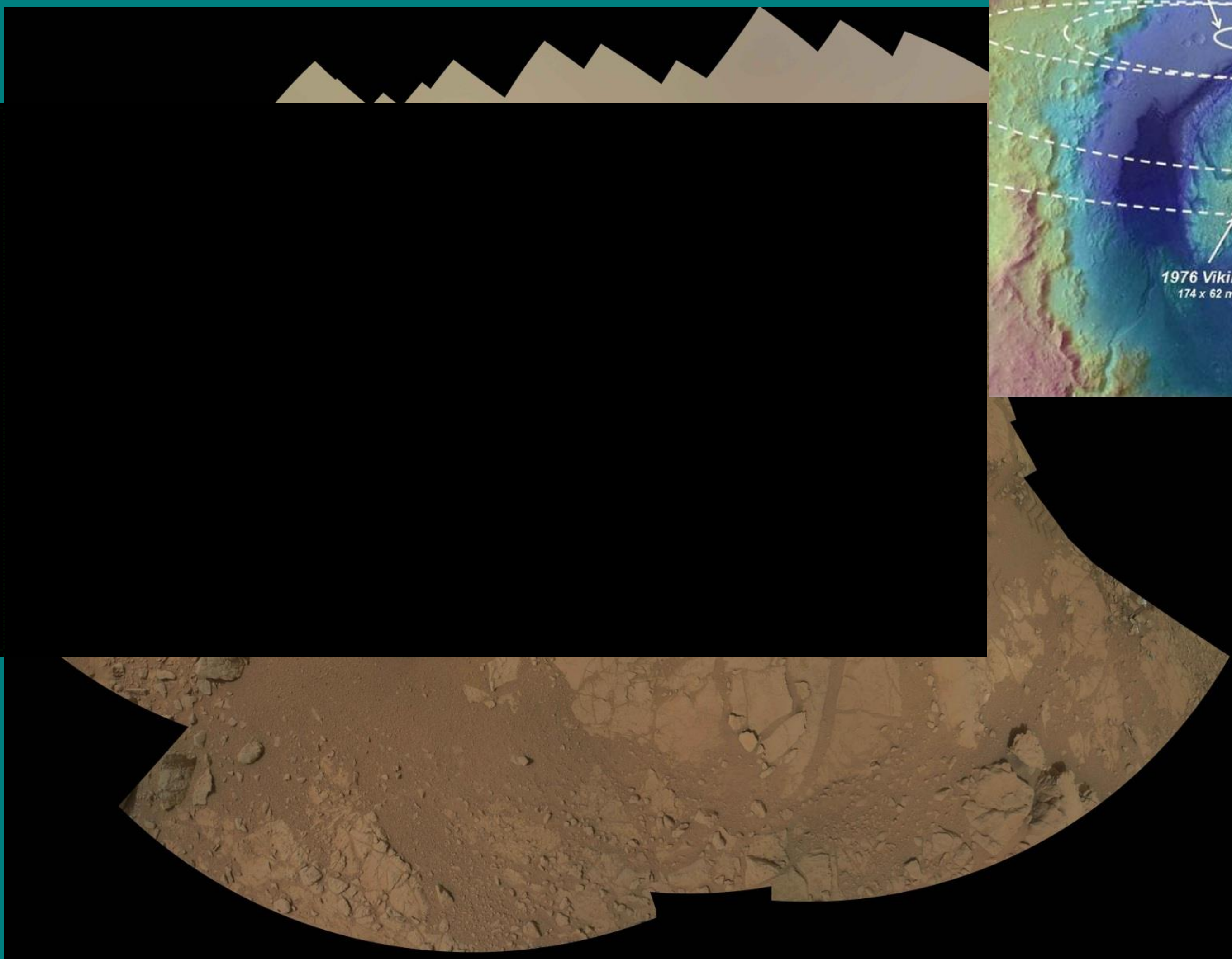
Chapter VIIIb: Missions to Mars

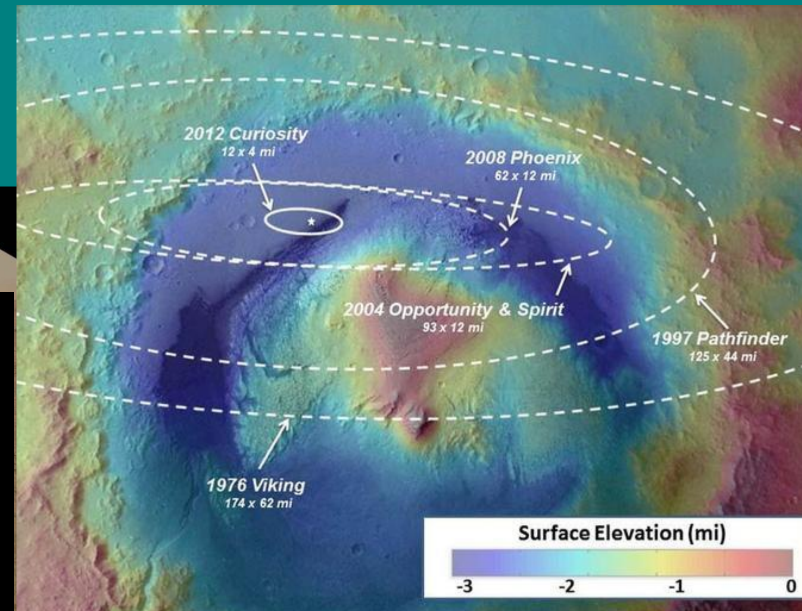
- 6 August 2012: unprecedented landing sequence



Chapter VIIIb: Missions to Mars

- Start of the ground operations





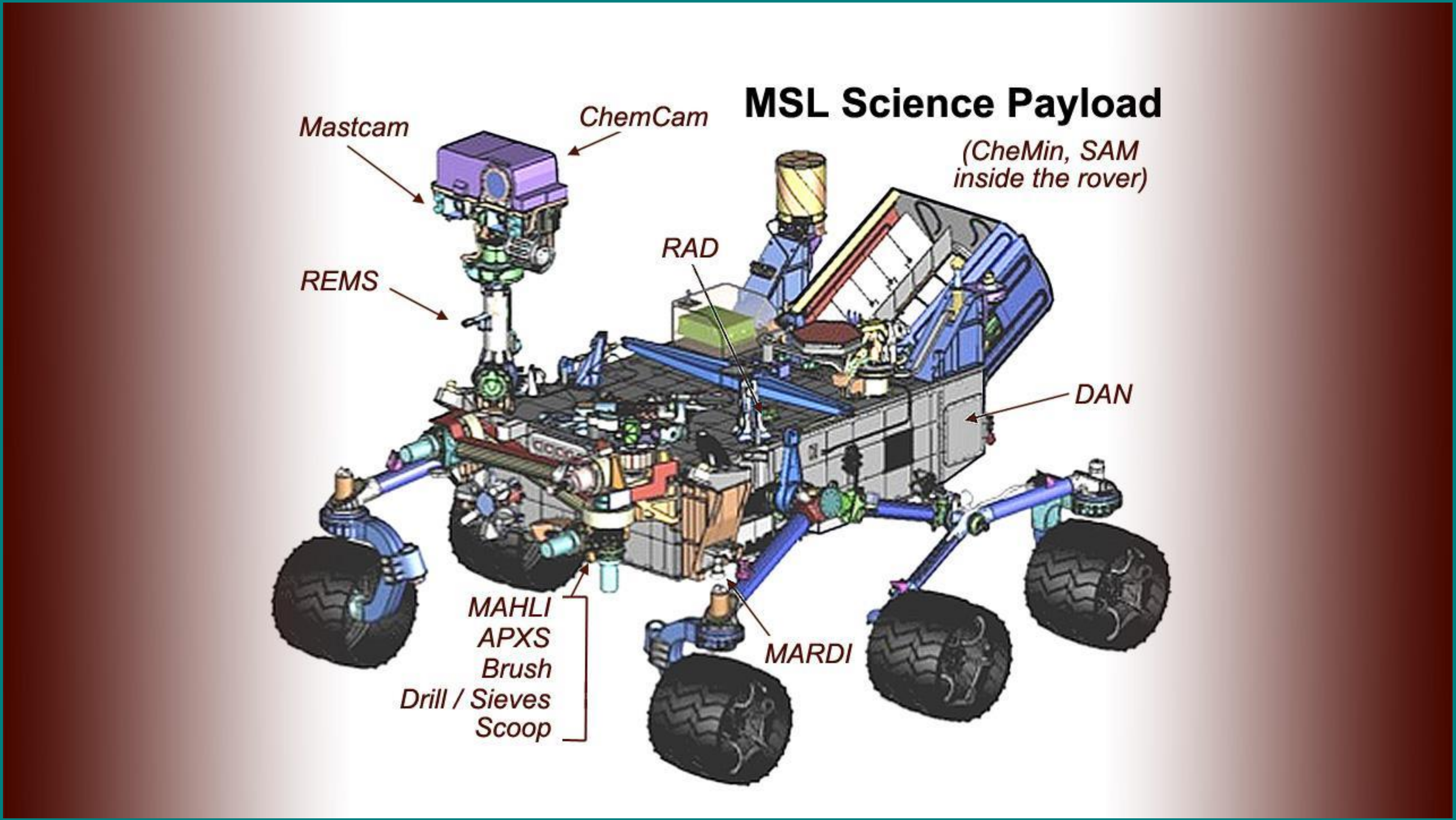
Chapter VIIIb: Missions to Mars

- Curiosity = biggest rover sent to Mars hitherto.

- Wheels allow to climb Mount Aeolis (Mount Sharp)

Chapter VIIIb: Missions to Mars

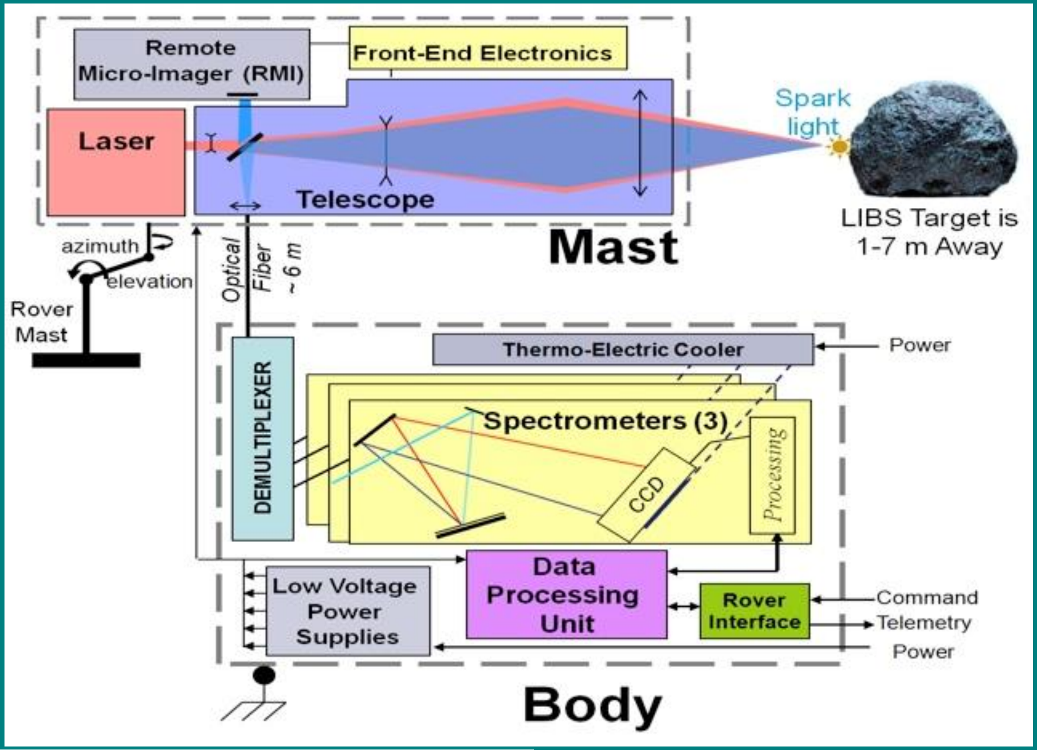
- Curiosity = laboratory equipped with 10 different experiments to search for conditions for the emergence of life.

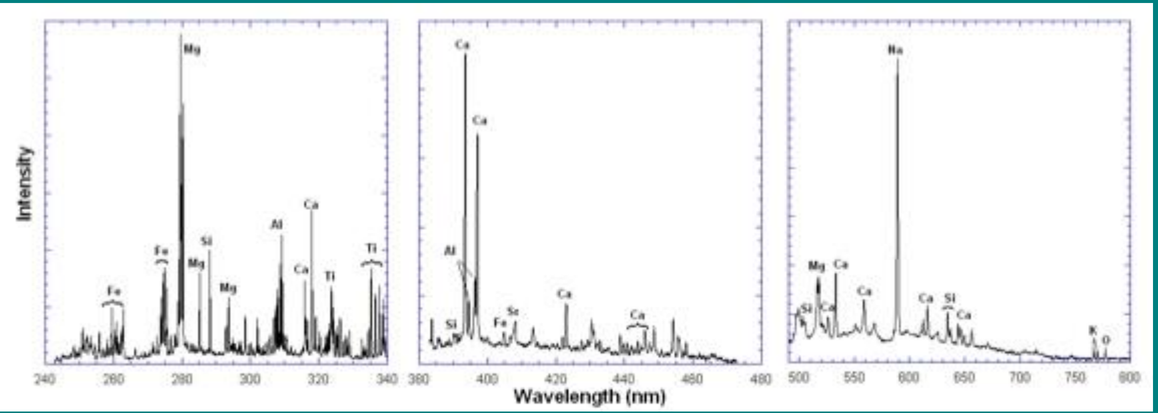


Chapter VIIIb: Missions to Mars

Example: ChemCam instrument:

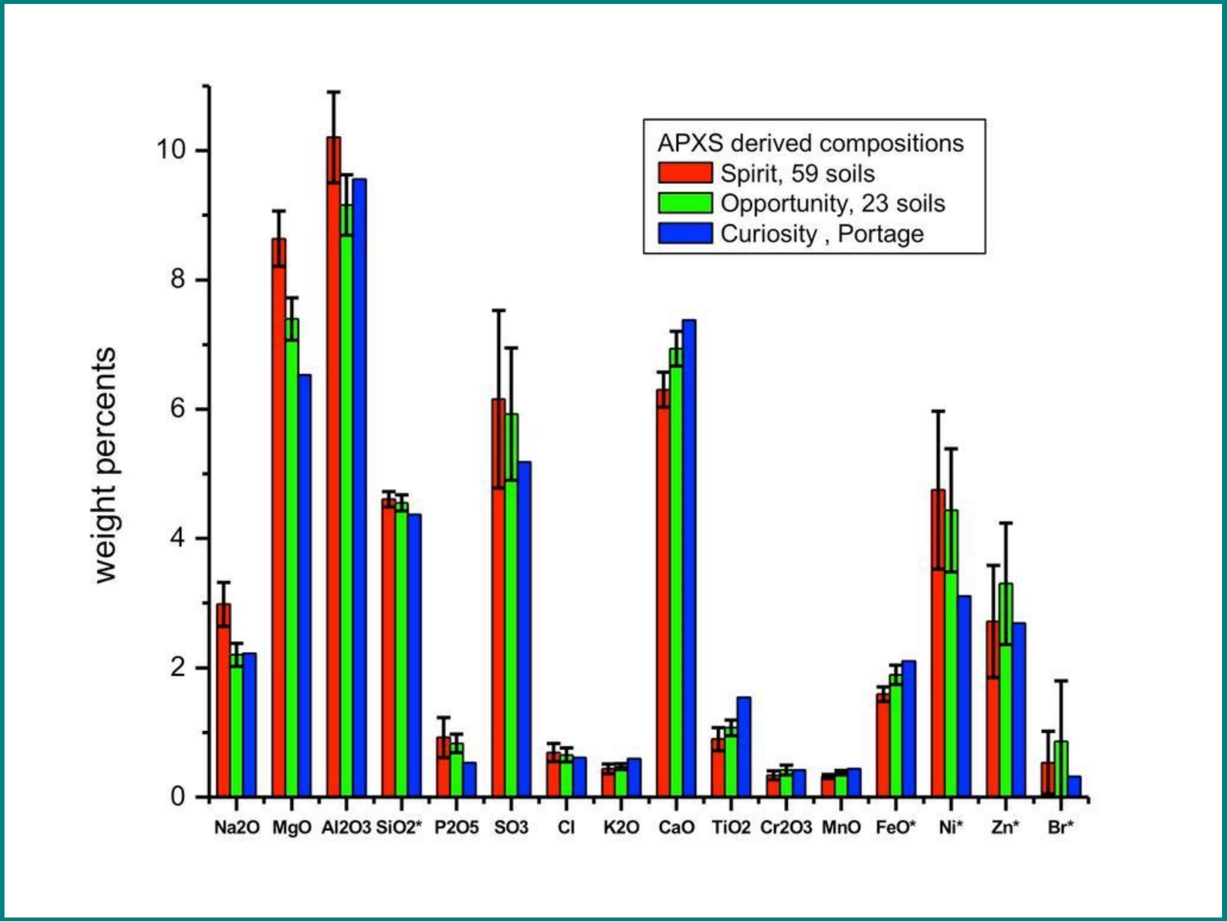
- Evaporate sample with a laser beam.
- Collect the light emitted by the resulting plasma.
- Analyse this light by means of 3 different spectrographs.





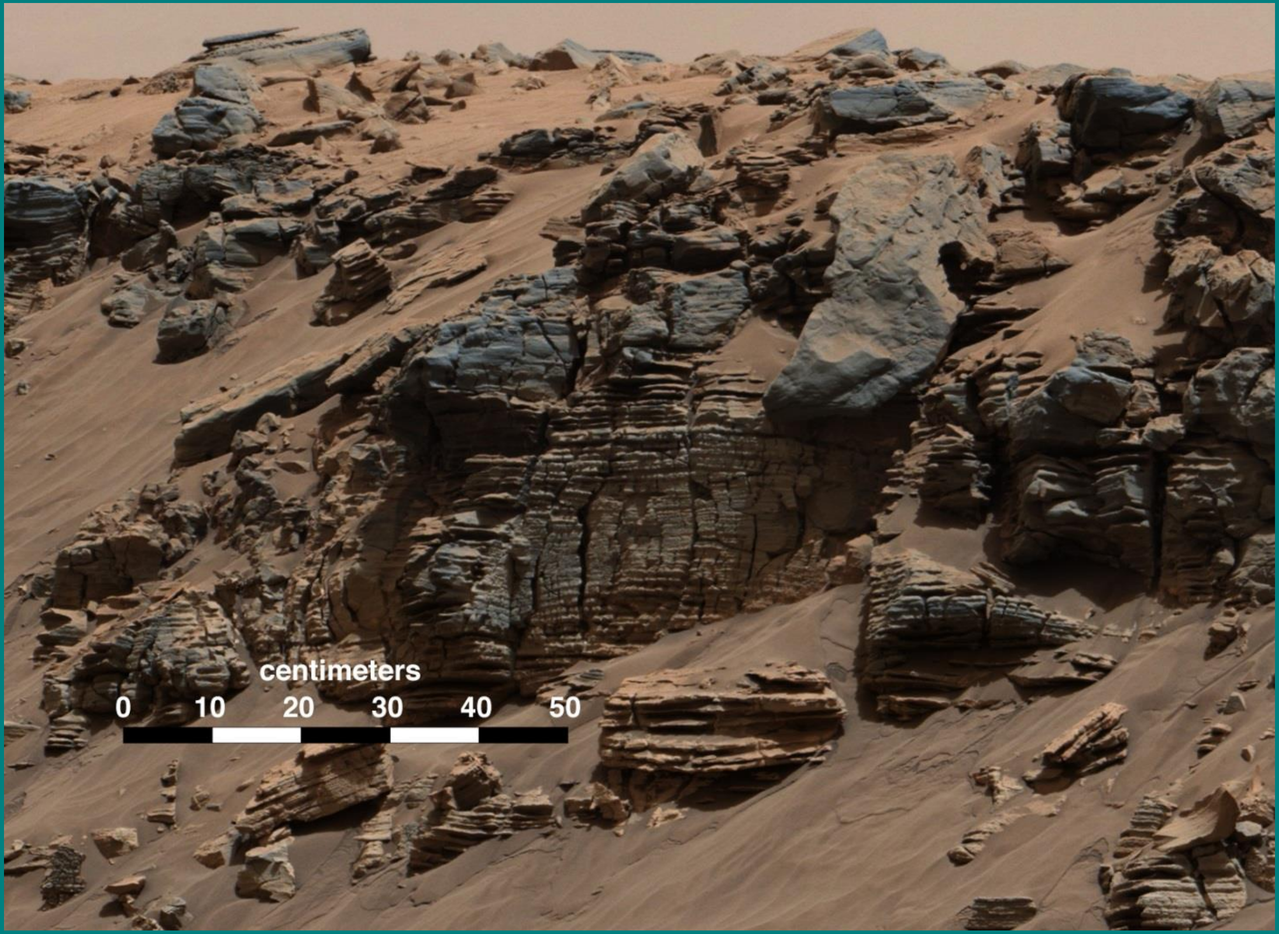
Chapter VIIIb: Missions to Mars

- Other instrument: APXS (α particle X-ray spectrometer), already present on Sojourner, Spirit and Opportunity.



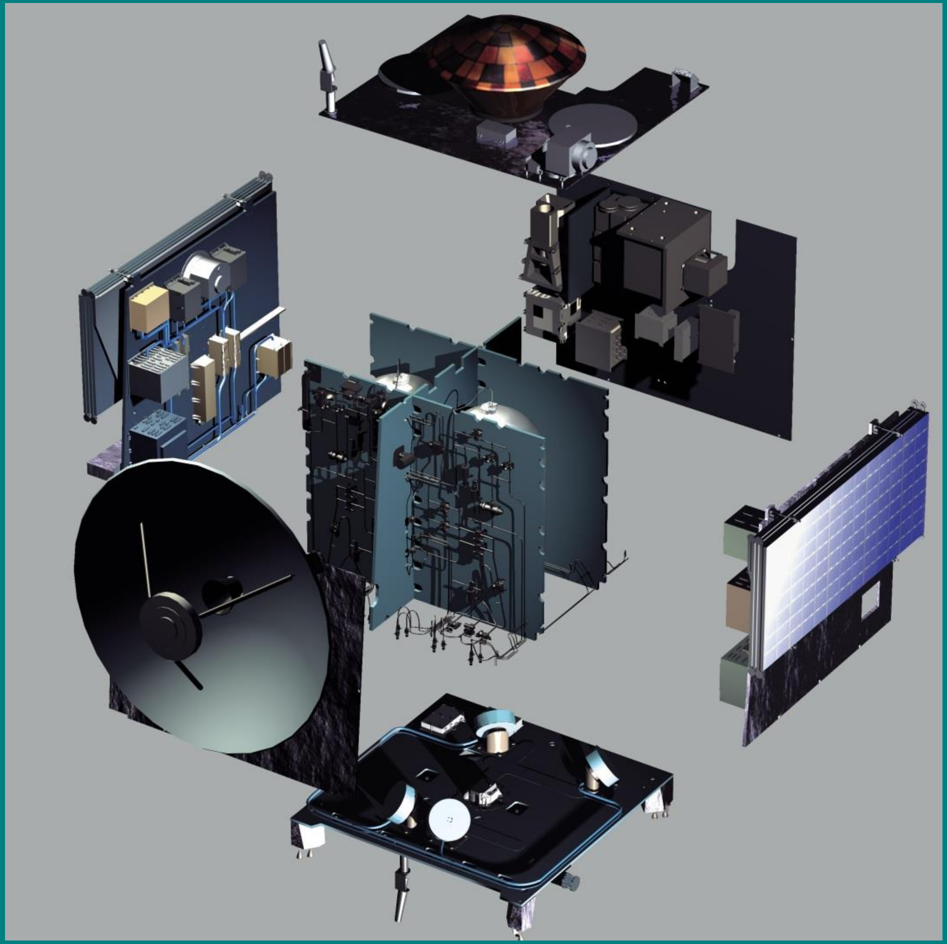
Chapter VIIIb: Missions to Mars

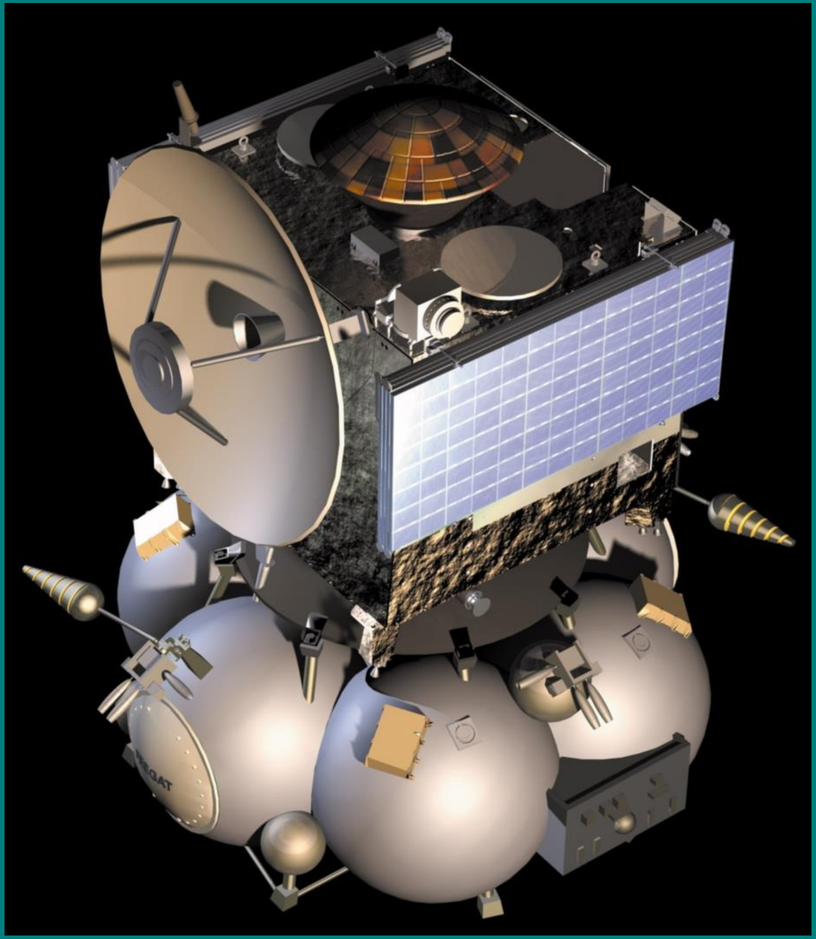
- Other instrument: sedimentary signs of a Martian lakebed photographed by the MastCam.



Chapter VIIIb: Missions to Mars

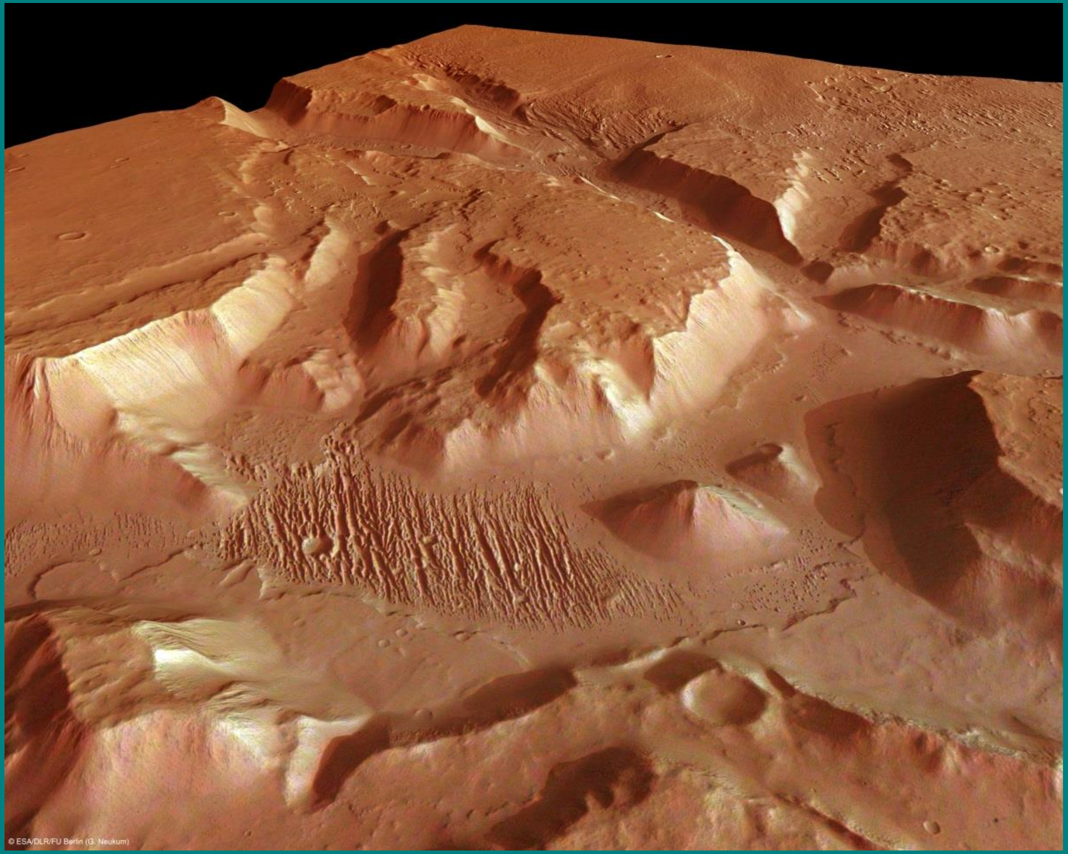
- Mars Express launched in June 2003 by a Soyuz Fregat launcher.
- Orbiter and lander (Beagle 2)

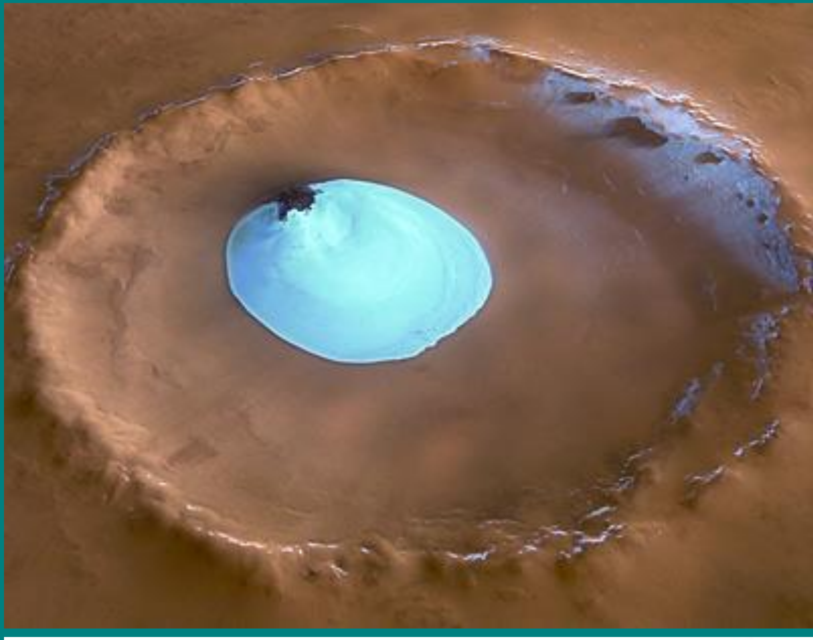


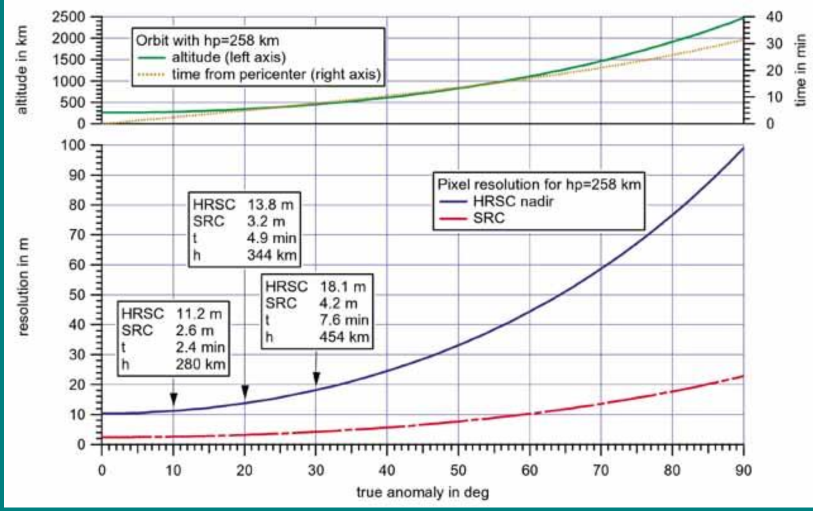


Chapter VIIIb: Missions to Mars

- HRSC: stereo images (3-D) of the Martian surface.



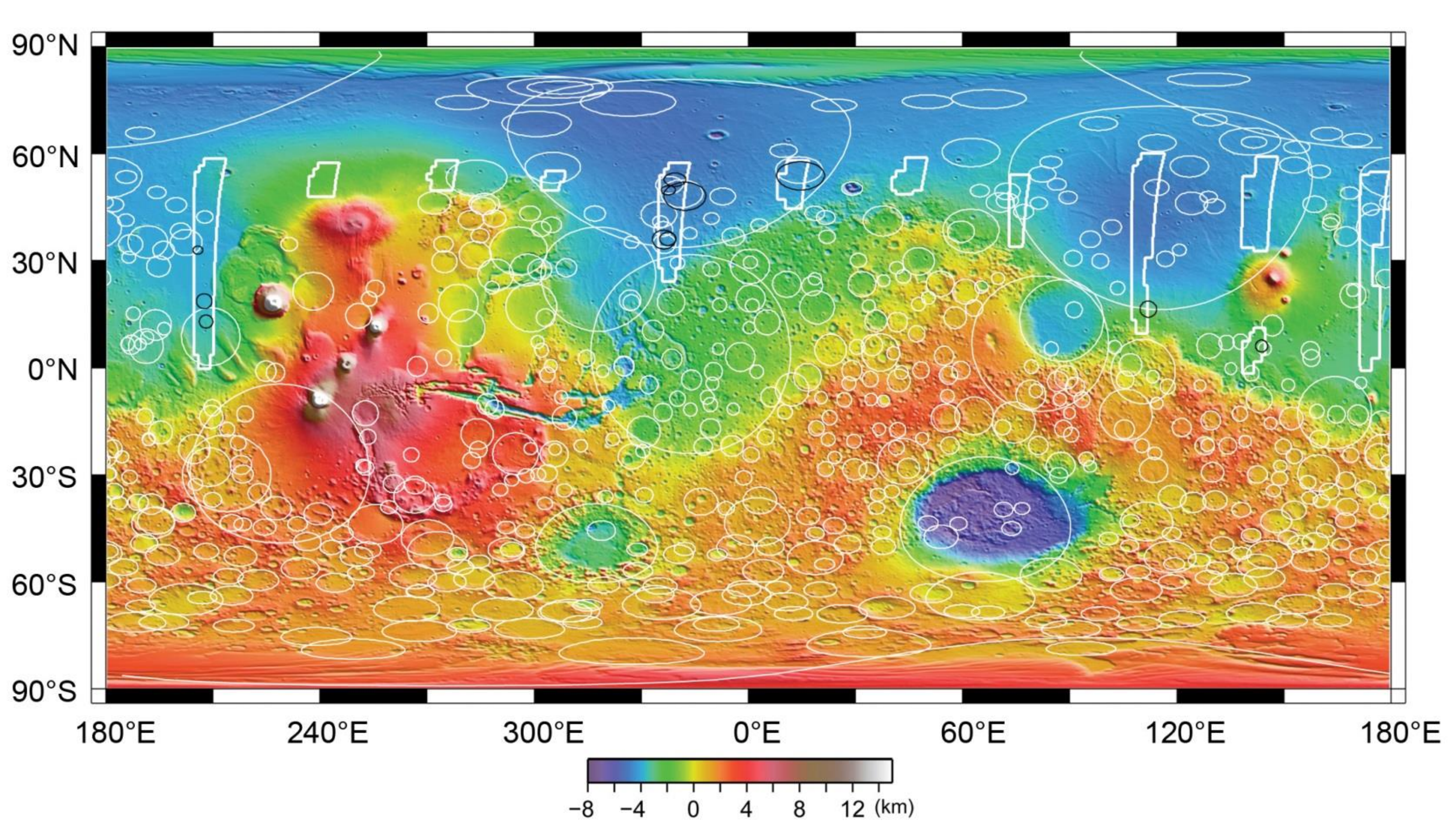




- HRSC: images taken when the spacecraft is at pericentre.

Chapter VIIIb: Missions to Mars

- MARSIS: radar that explores the sub-surface layers down to several km.



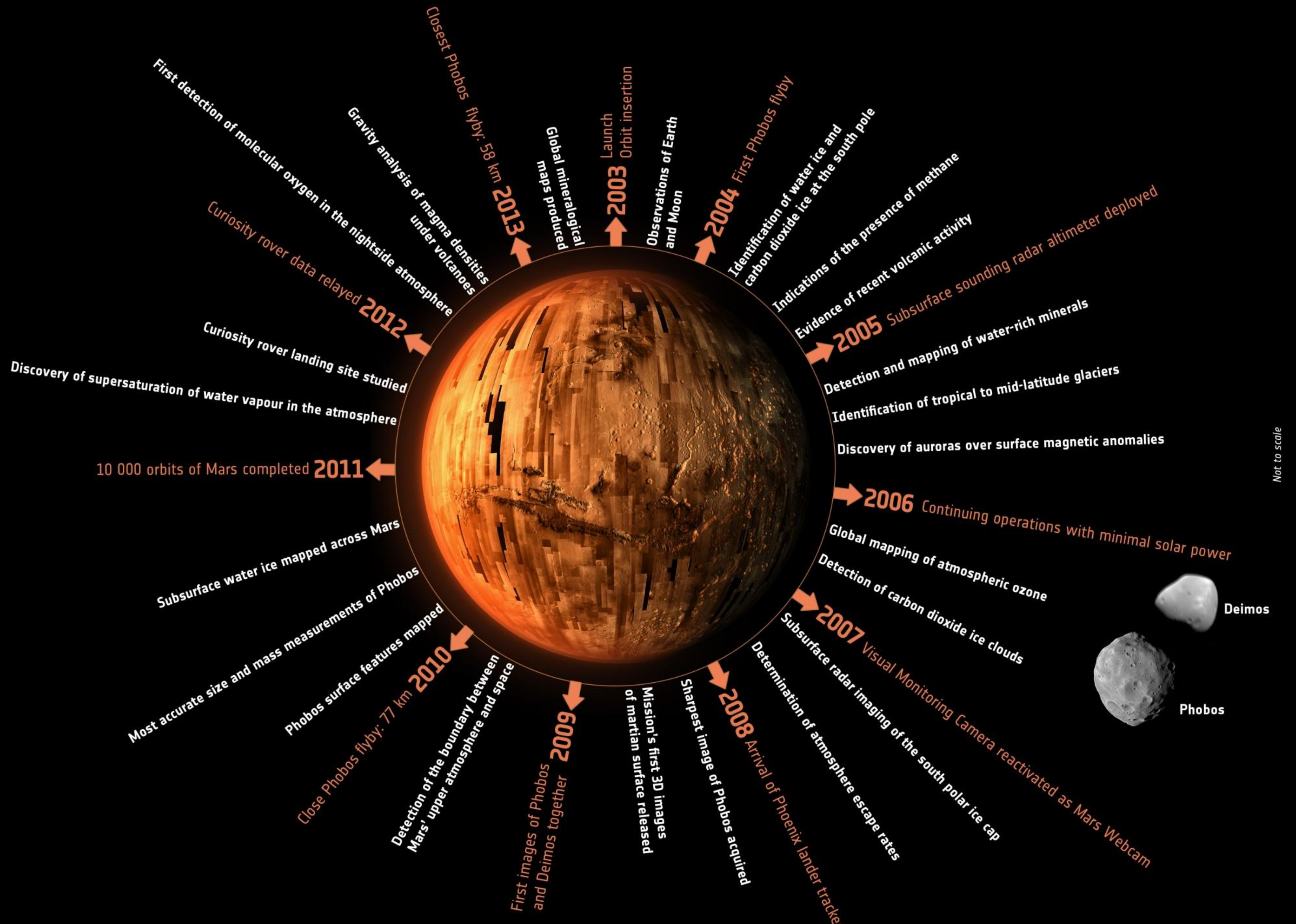
Chapter VIIIb: Missions to Mars

- Film « Water on Mars »

→ MARS EXPRESS MISSION HIGHLIGHTS

mars express

esa



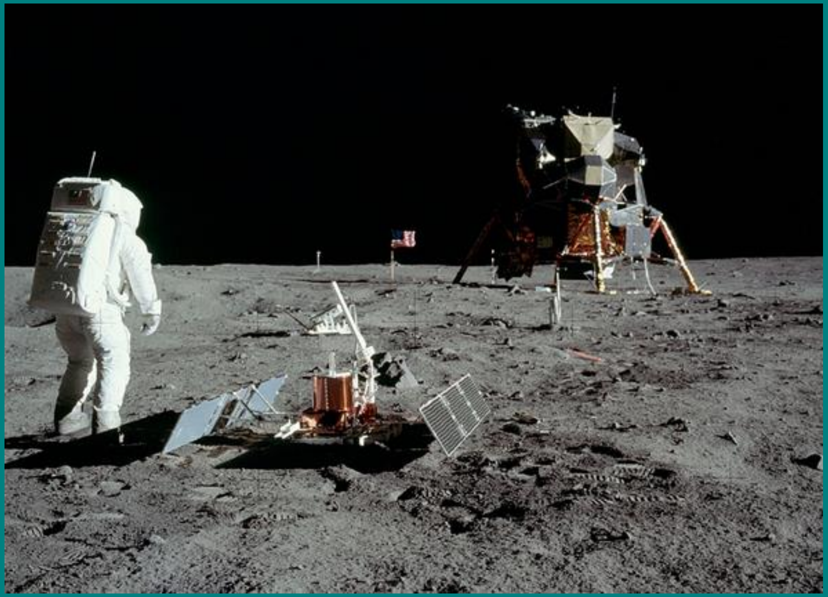
Images of Mars, Phobos & Deimos: ESA/DLR/FU Berlin (G. Neukum)

Chapter VIIIb: Missions to Mars

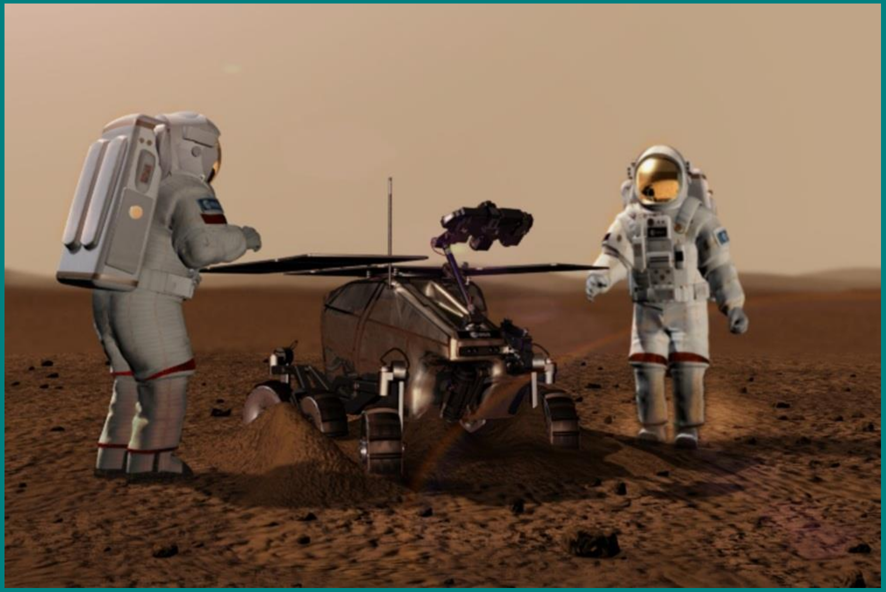
- Phoenix (5 – 11/2008) uncovered water ice by grinding the surface around its landing site (+68.2° N, 125.7° W).
- However, the amount of residual water (ice) remains uncertain (estimates based on Omega – Mars Express data and Phoenix data disagree).

Chapter VIIIb: Missions to Mars

- Mars is the destination of projects of future manned missions.
- As well as Dutch reality TV shows…



Apollo missions 1969 –72



Aurora 2030+?

Chapter VIIIb: Missions to Mars

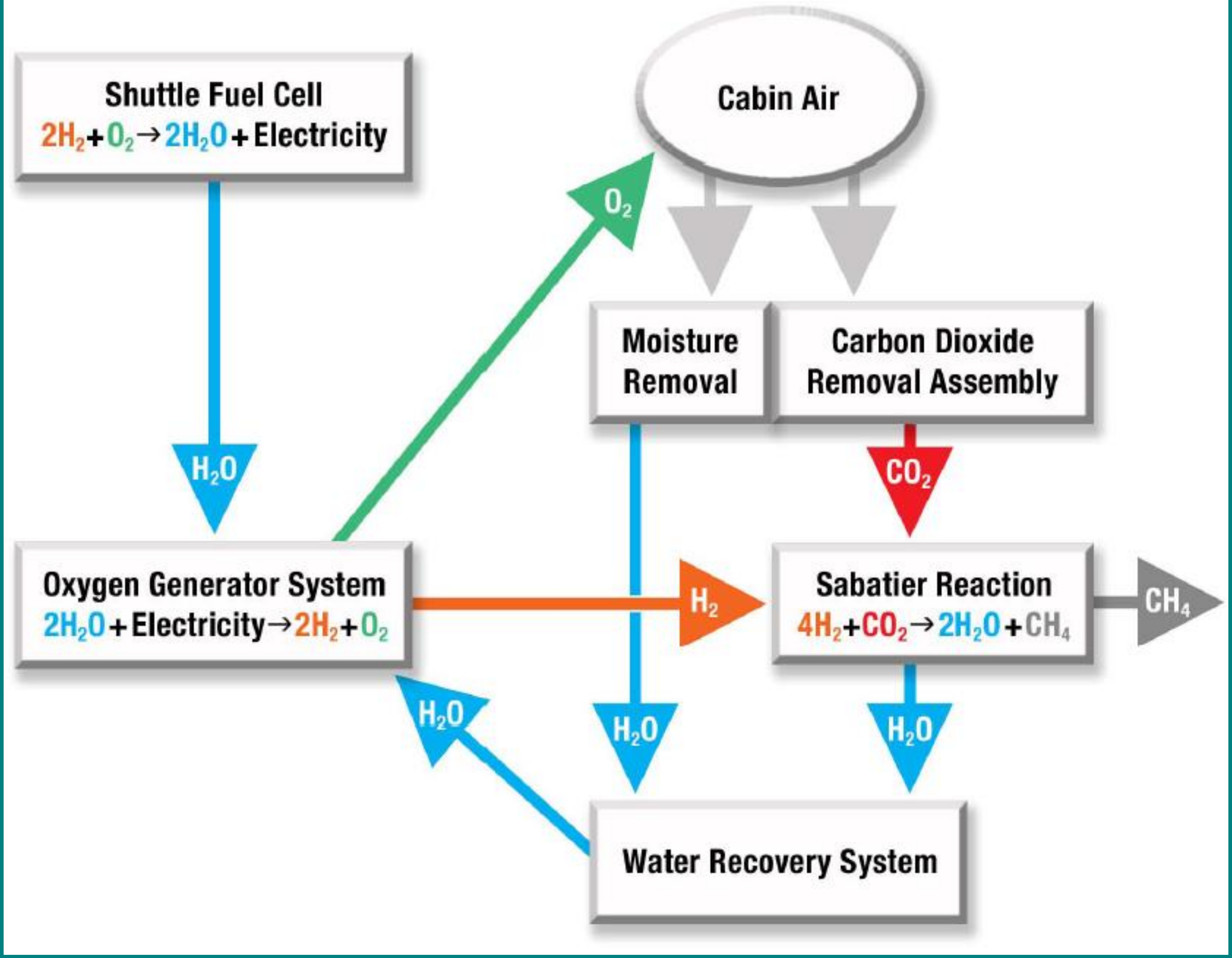
- However,
  - To date, no manned mission left the Earth's sphere of influence and moved to a distance of more than 385 000 km from the Earth.
  - No manned space mission of more than 10 days duration has been done outside the Earth's magnetosphere.

- With current technologies, a round trip to Mars lasts about 3 years.
  - Problems for the human organism (absence of gravity, radiations) and psychological load ⇒ shorten the duration of the trip.
  - Need to achieve a nearly 100% autonomy of the spacecraft (recycling of waste, medical equipment,…) ⇒ needs a lot of mass.

- ⇒ Need to develop new propulsion systems!

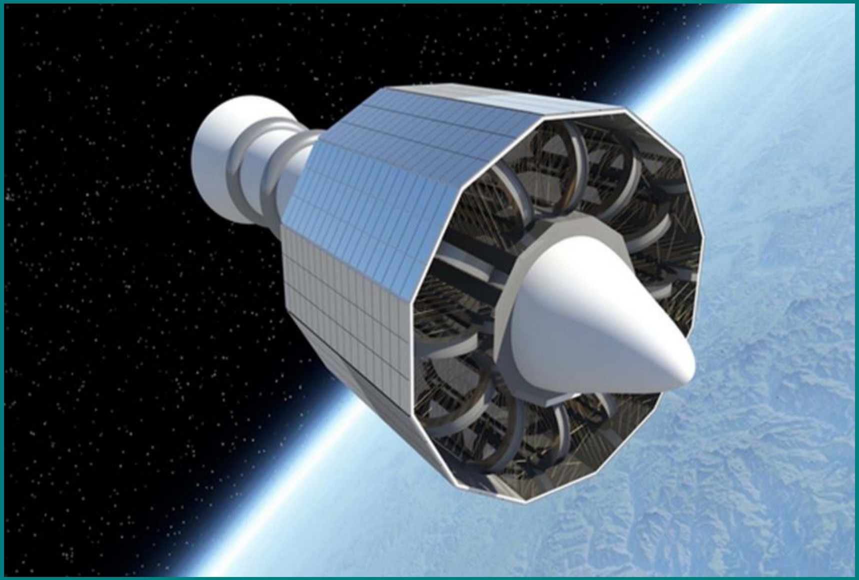
Chapter VIIIb: Missions to Mars

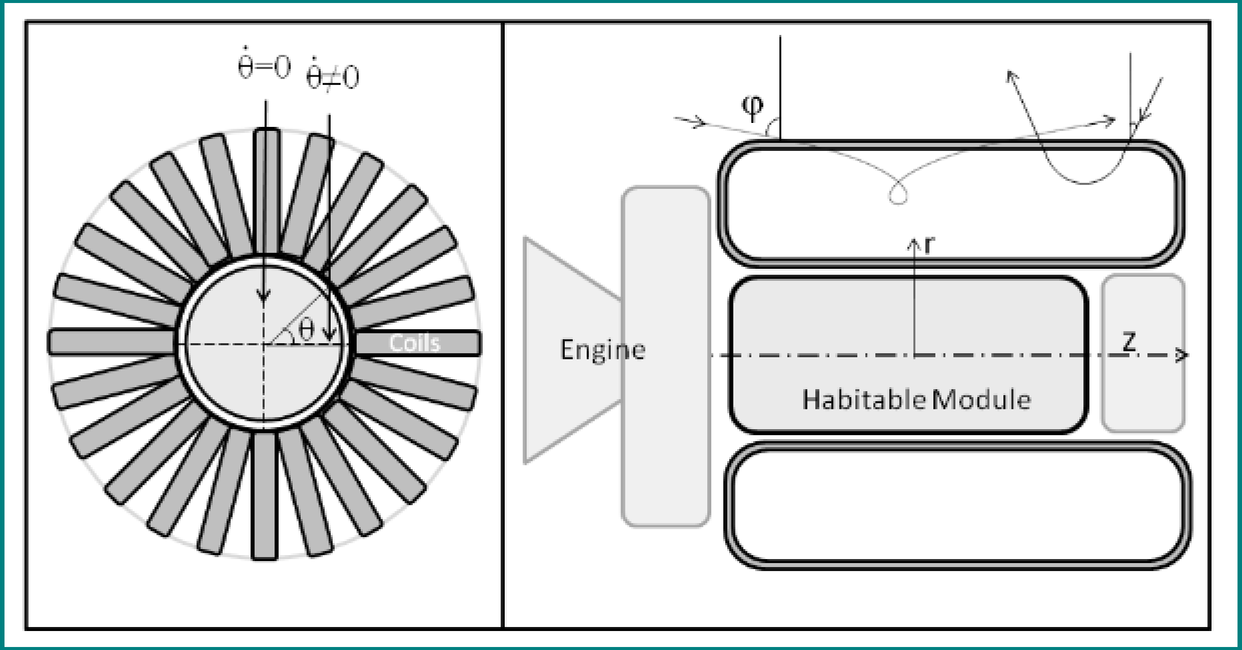
- Example: development of techniques to recycle the cabin air and water.



Chapter VIIIb: Missions to Mars

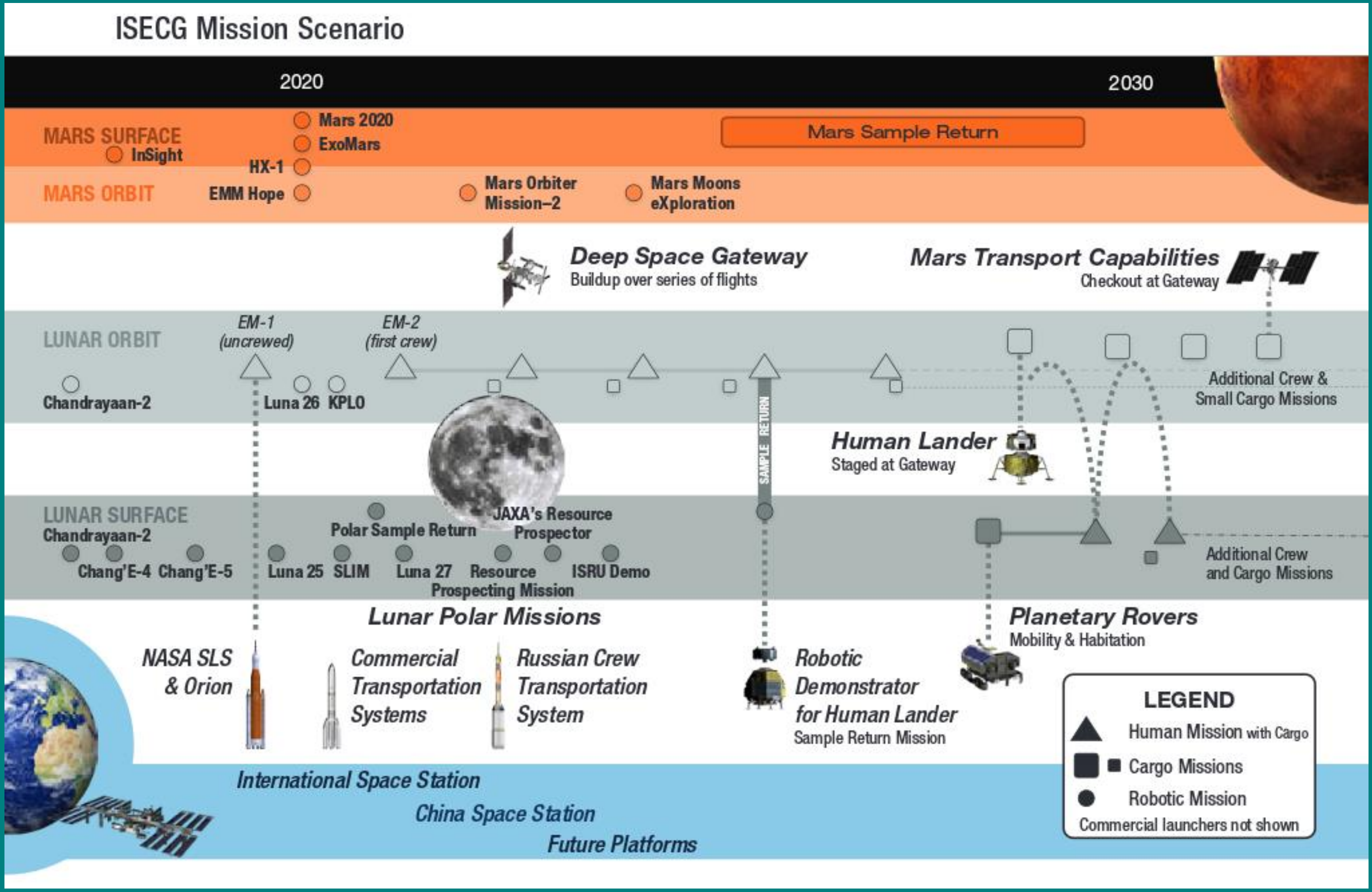
- Example: shielding against cosmic rays: Space Radiation Superconducting Shield (SR2S) project.





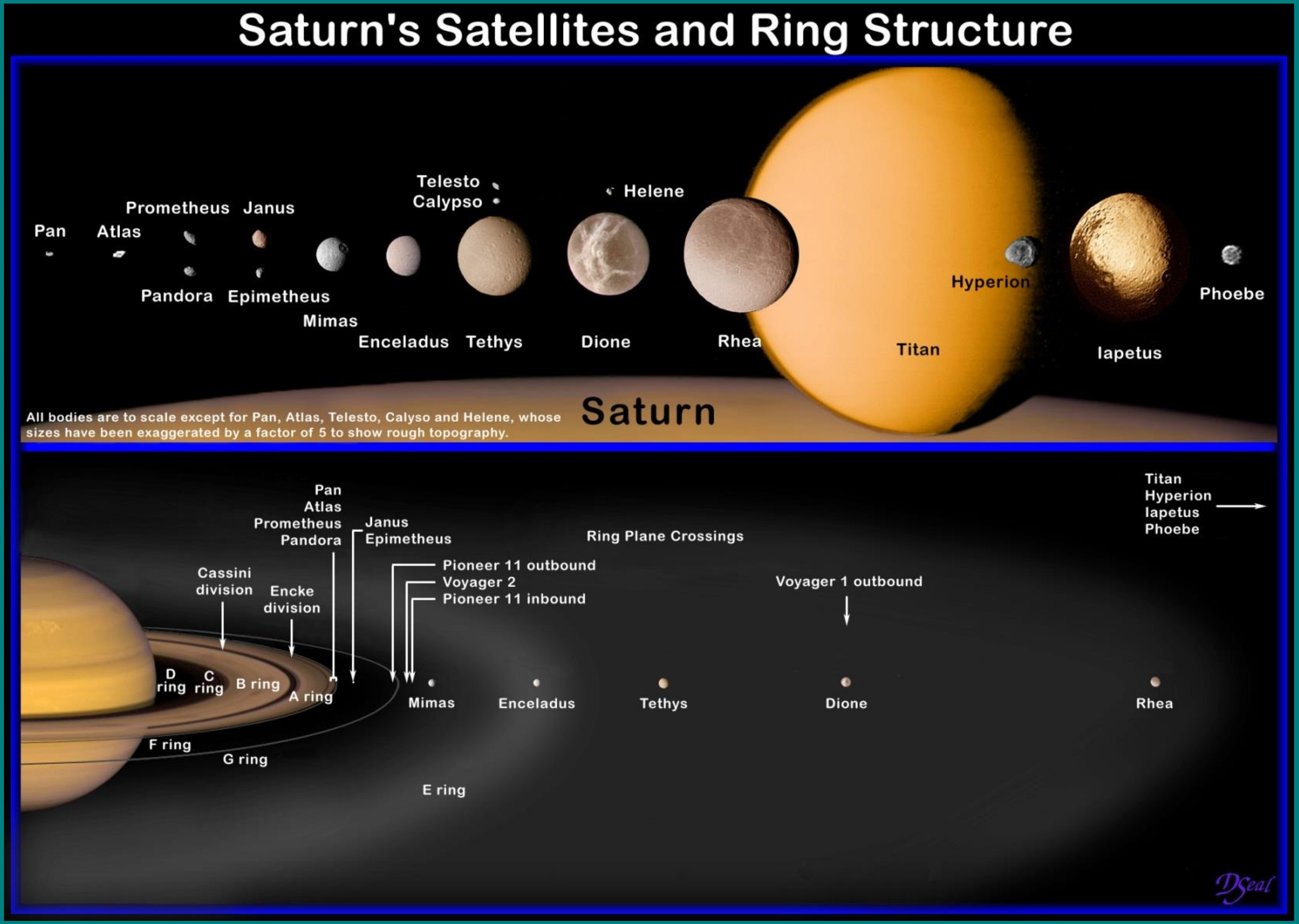
Chapter VIIIb: Missions to Mars

- When will the first humans land on Mars?
- Roadmap of the ISECG (updated in 2018) does not provide any binding schedule, but identifies several steps to be accomplished and stresses the role of preparatory robotic exploration.



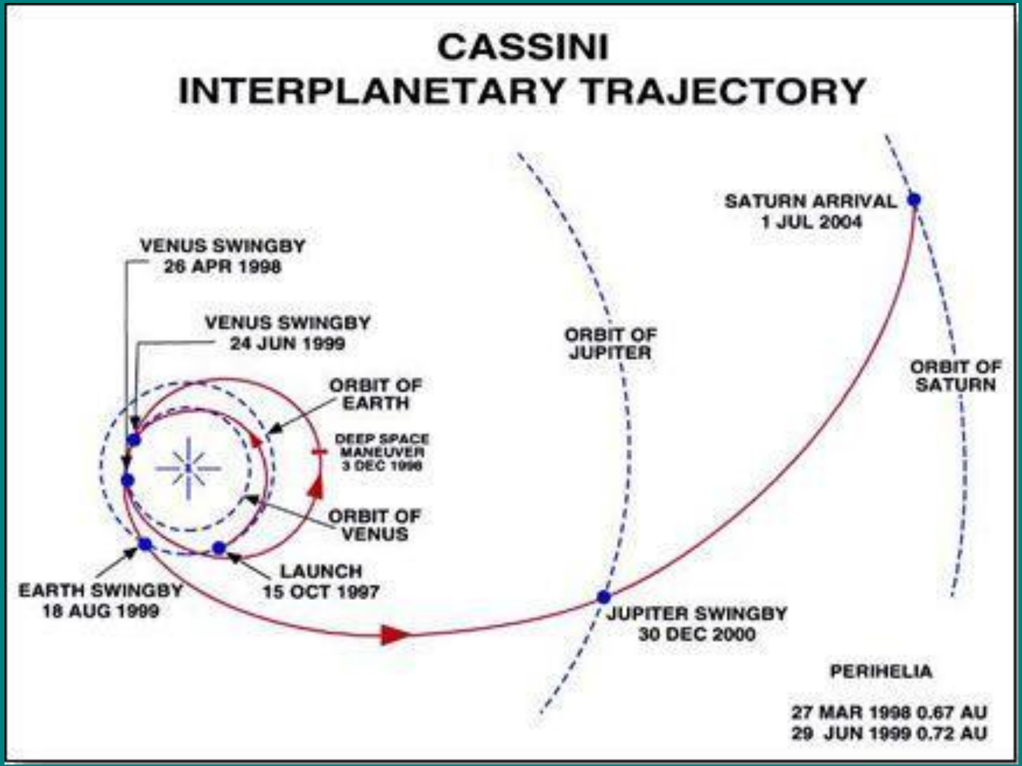
Chapter VIIIc: The Cassini-Huygens mission

- Cassini-Huygens: joint NASA/ESA mission to explore Saturn and its moons (mainly focussing on Titan).



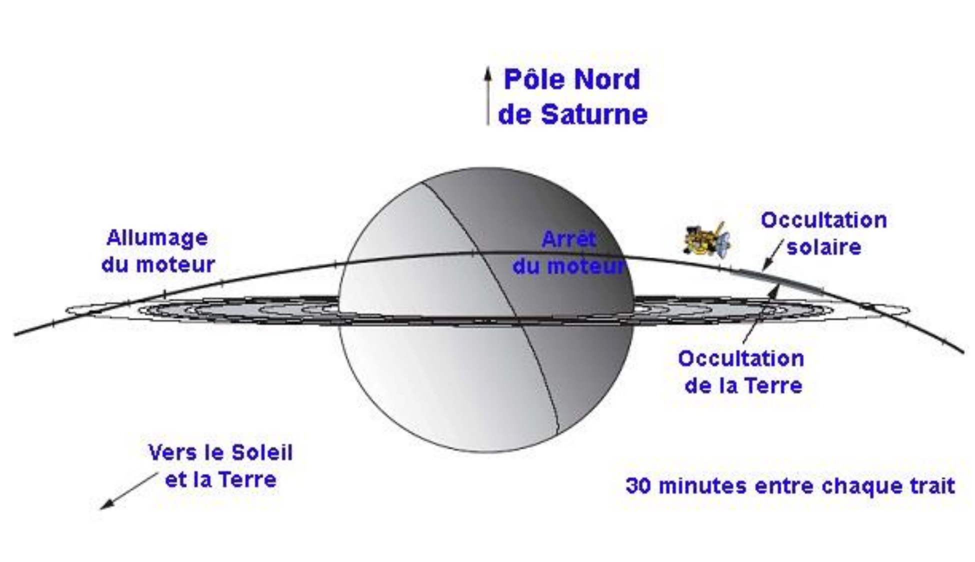
Chapter VIIIc: The Cassini-Huygens mission

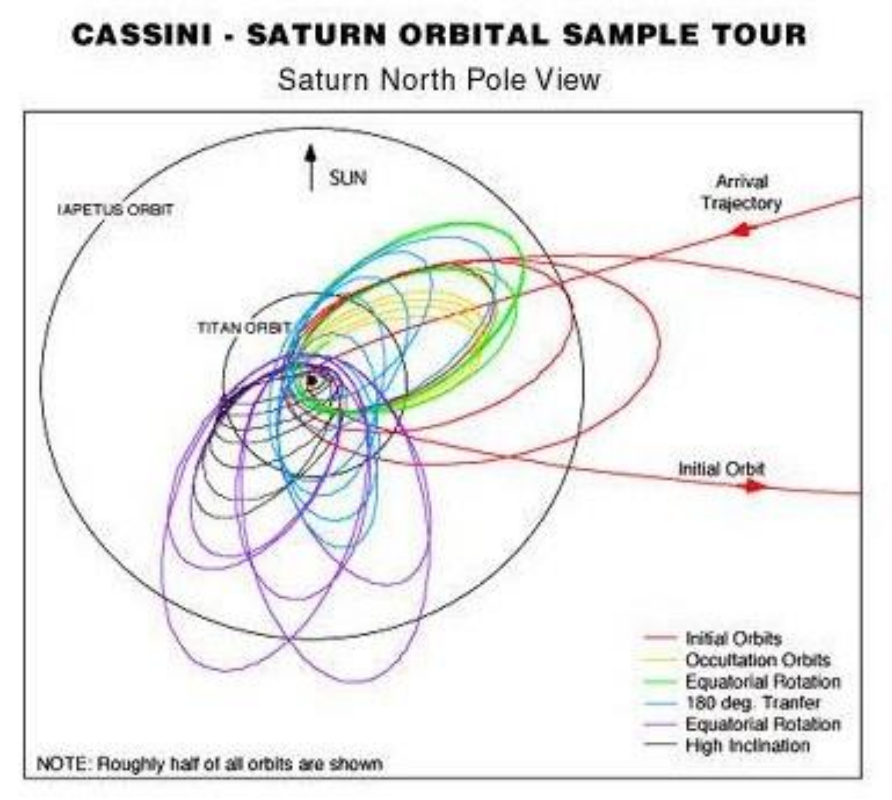
- Launch in October 1997 with a Titan IV-B/Centaur rocket.
- Total mass of the spacecraft: 5650 kg, impossible to launch via Hohmann orbits ⇒ gravity assist (VVEJ) ⇒ 7 years journey with unusual thermal constraints.



Chapter VIIIc: The Cassini-Huygens mission

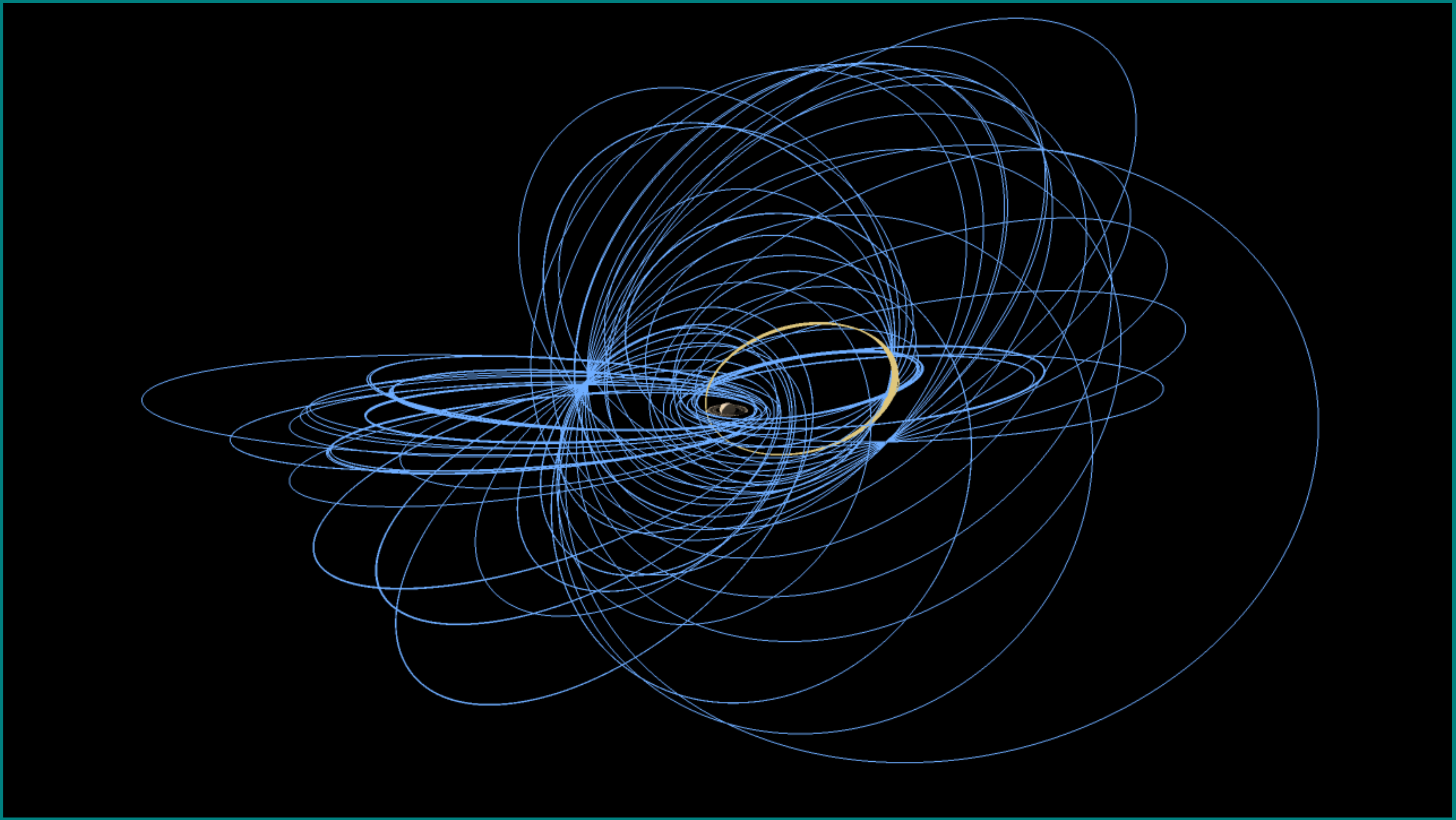
- Arrival near Saturn in July 2004, crossing the rings at an altitude of 20 000 km.
- Gravity assist of Titan used to regularly modify the trajectory and visit different objects of Saturn's system.





Chapter VIIIc: The Cassini-Huygens mission

- Over the 13 years of operation in orbit around Saturn, orbital inclination was changed several times from near 0° to ~ 64°.



Chapter VIIIc: The Cassini-Huygens mission

- Instruments aboard Cassini:

1. Remote optical sensing: infrared spectrograph, imaging systems (CCD cameras), narrow spectral band imager…
2. Synthetic aperture radar and radio system…
3. In-situ measurements of fields, waves, and particles.

Mission ended on 15/09/2017 (plunge into Saturn’s atmosphere).

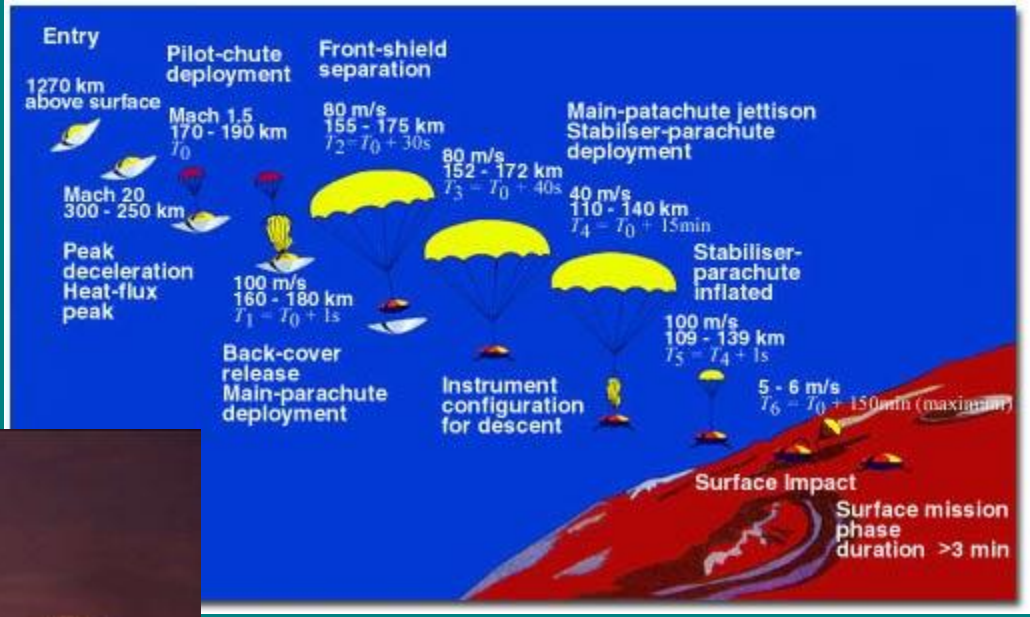
Chapter VIIIc: The Cassini-Huygens mission

- The Huygens probe:

1. 17/12/2004: Cassini-Huygens put on collision course with Titan.
2. 25/12/2004: Huygens separates from Cassini at a velocity of 0.35 m/s.
3. 28/12/2004: Cassini's trajectory is corrected to ensure a flyby of Titan at altitude of 60 000 km.
4. 14/1/2005: Huygens enters Titan's atmosphere and lands.

Chapter VIIIc: The Cassini-Huygens mission

Entry of the Huygens probe in the atmosphere of Titan.



Chapter VIIIc: The Cassini-Huygens mission

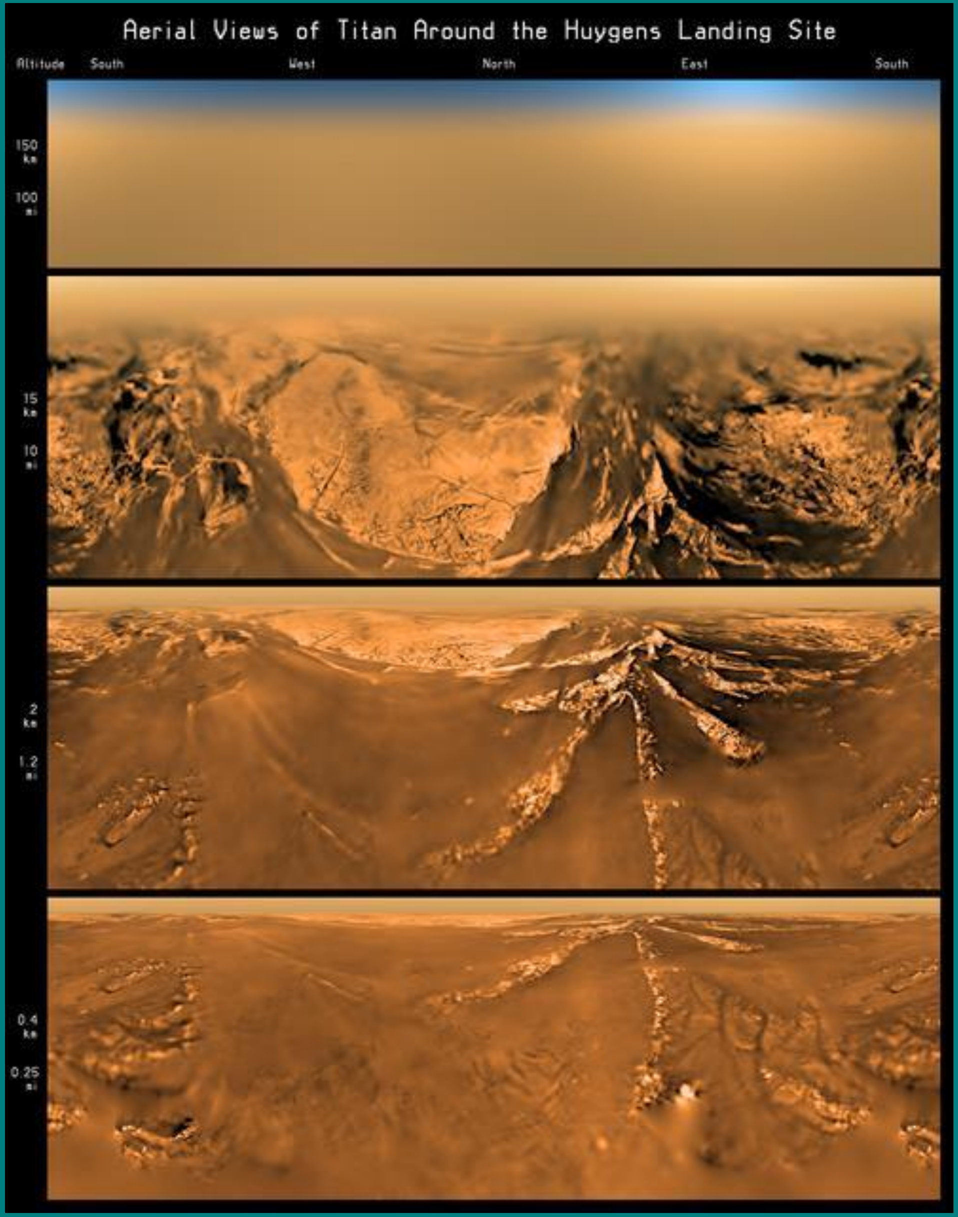
- Instruments aboard Huygens:

1. Instrument to collect aerosols and analyse them via pyrolysis.
2. Photometers, imaging cameras looking aside and towards the ground.
3. Wind velocity determination through the Doppler effect.
4. In-situ measurements of the properties of the atmosphere.
5. Analysis of the surface properties at the landing site.

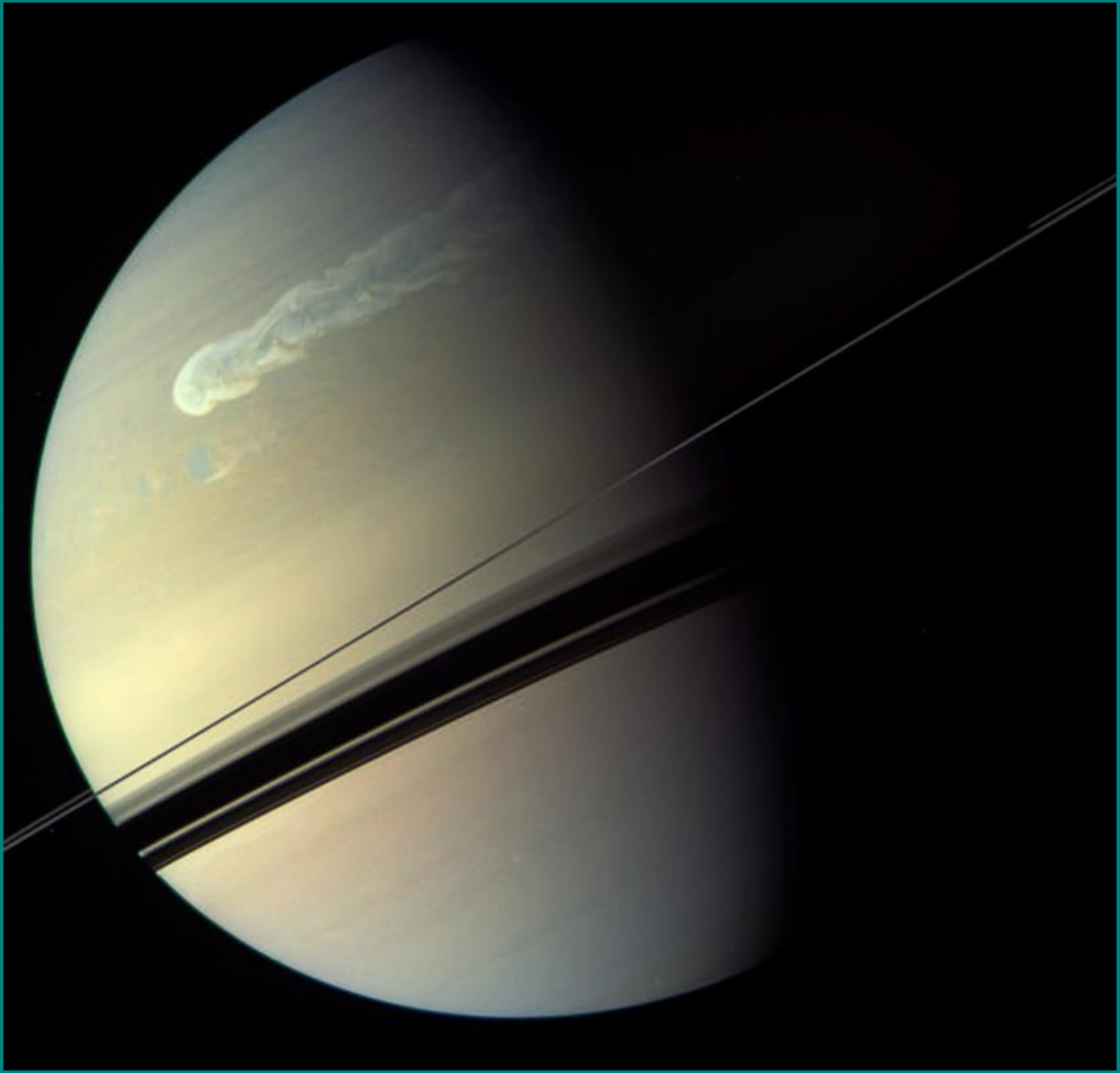
Movie: Huygens/huygens.exe

Chapter VIIIc: The Cassini-Huygens mission

Images of Titan's surface:



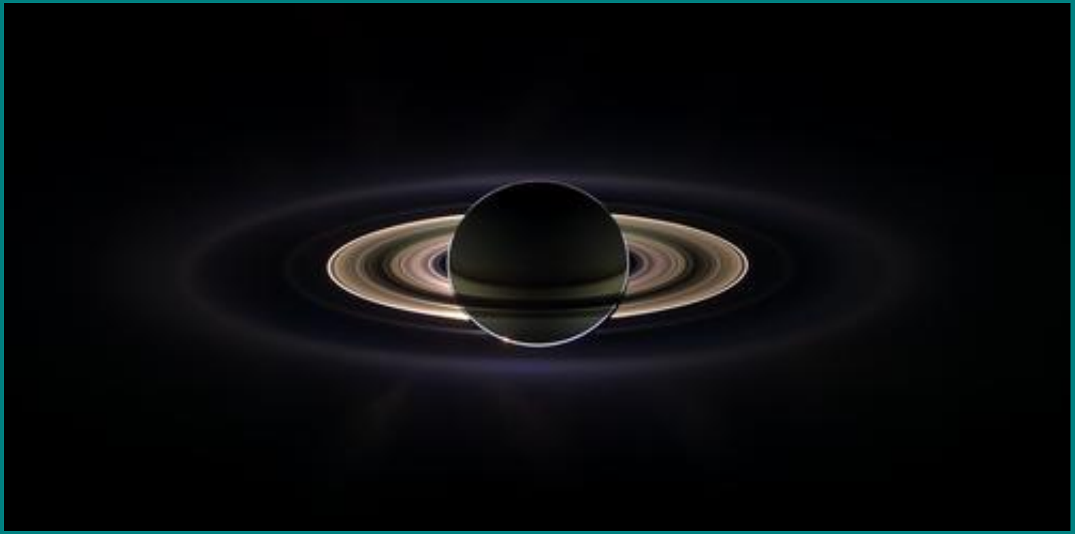
Chapter VIIIc: The Cassini-Huygens mission

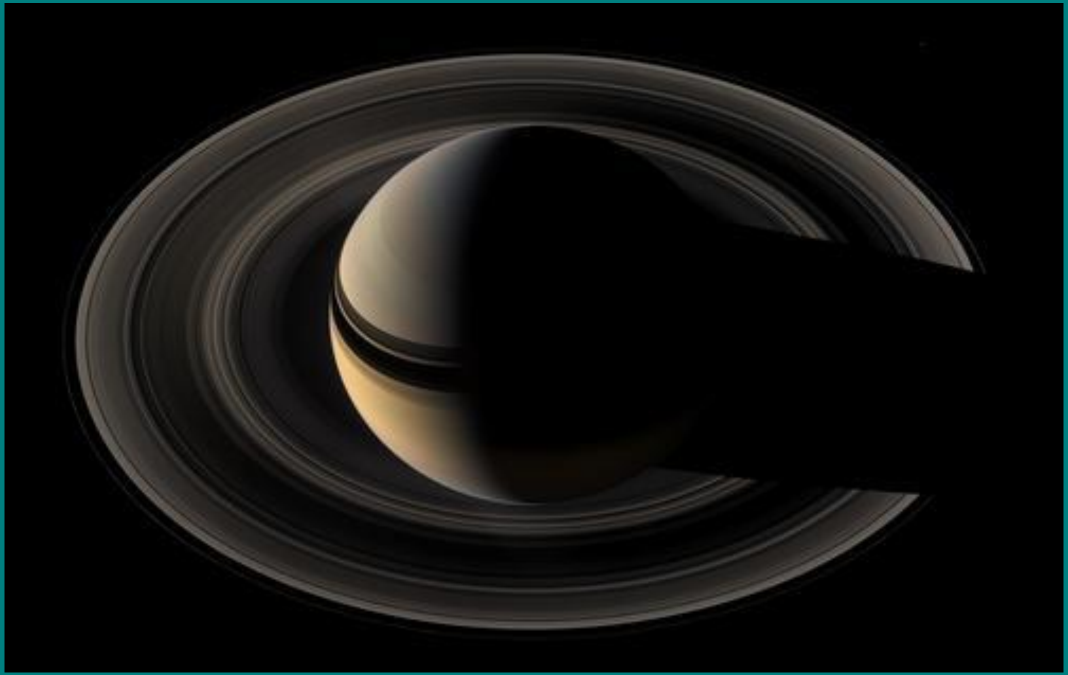


Giant storm in Saturn's northern hemisphere (2010 – 2011)

Chapter VIIIc: The Cassini-Huygens mission

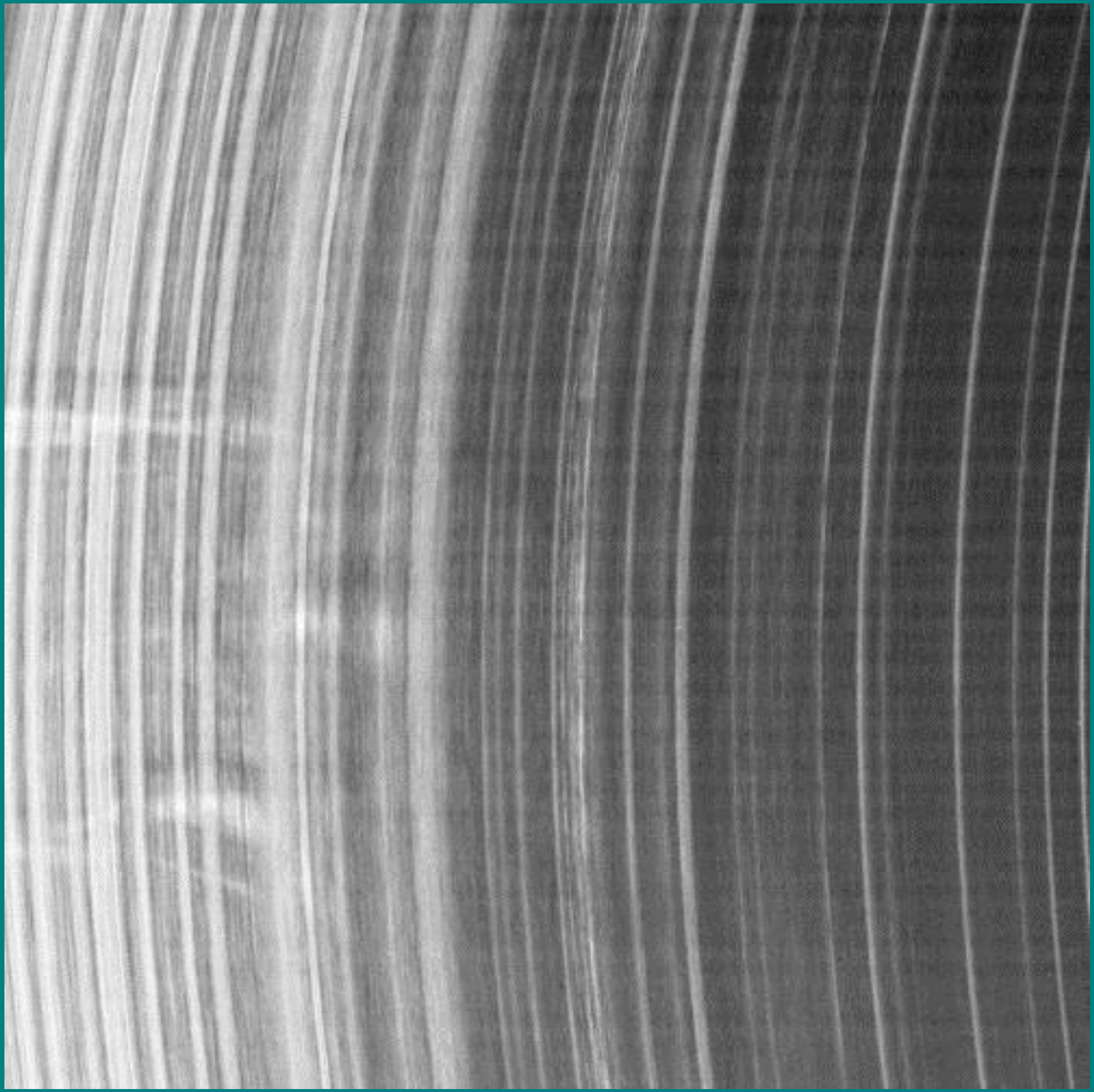
Images of Saturn and its rings from very diverse positions:





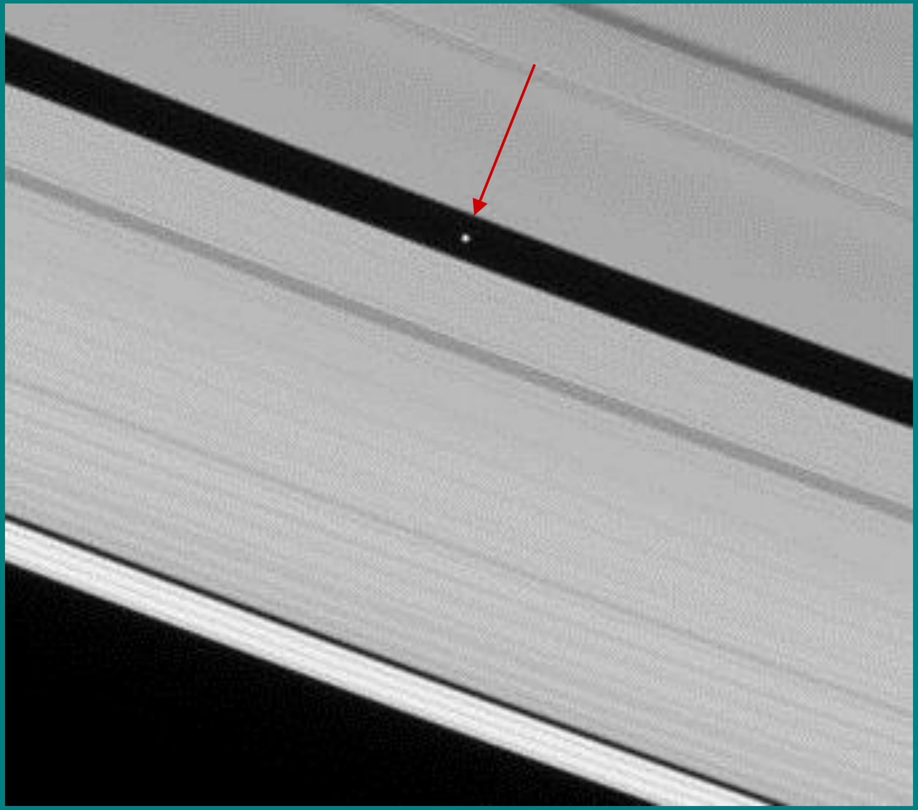
Chapter VIIIc: The Cassini-Huygens mission

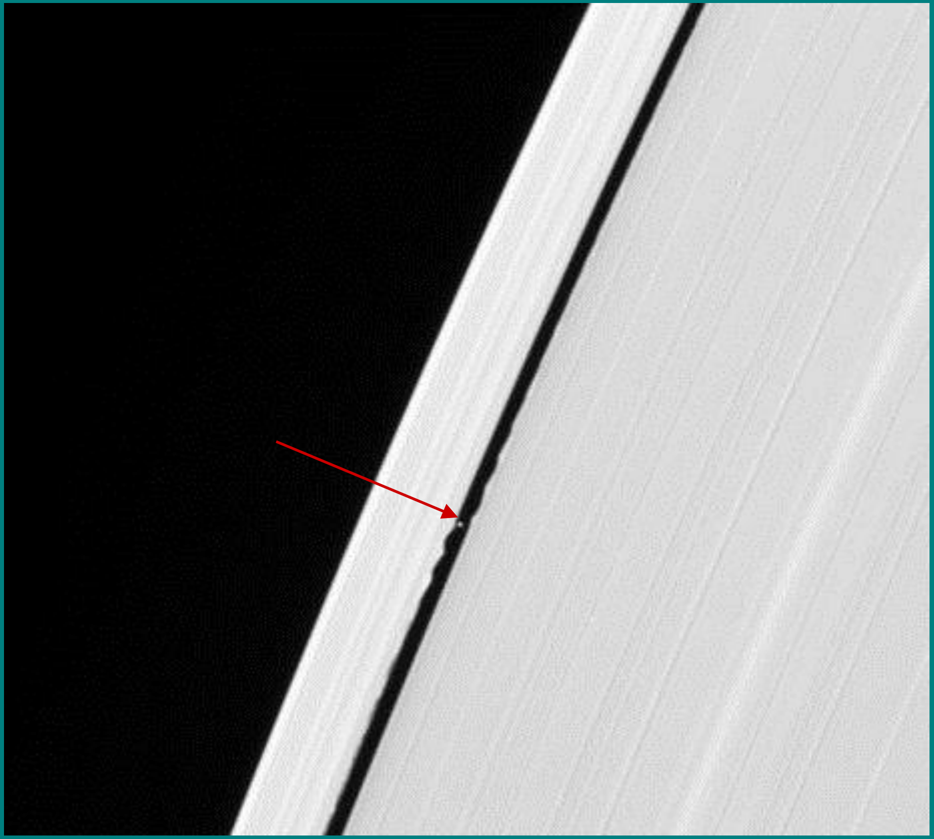
Images of Saturn and its rings: the “spokes”



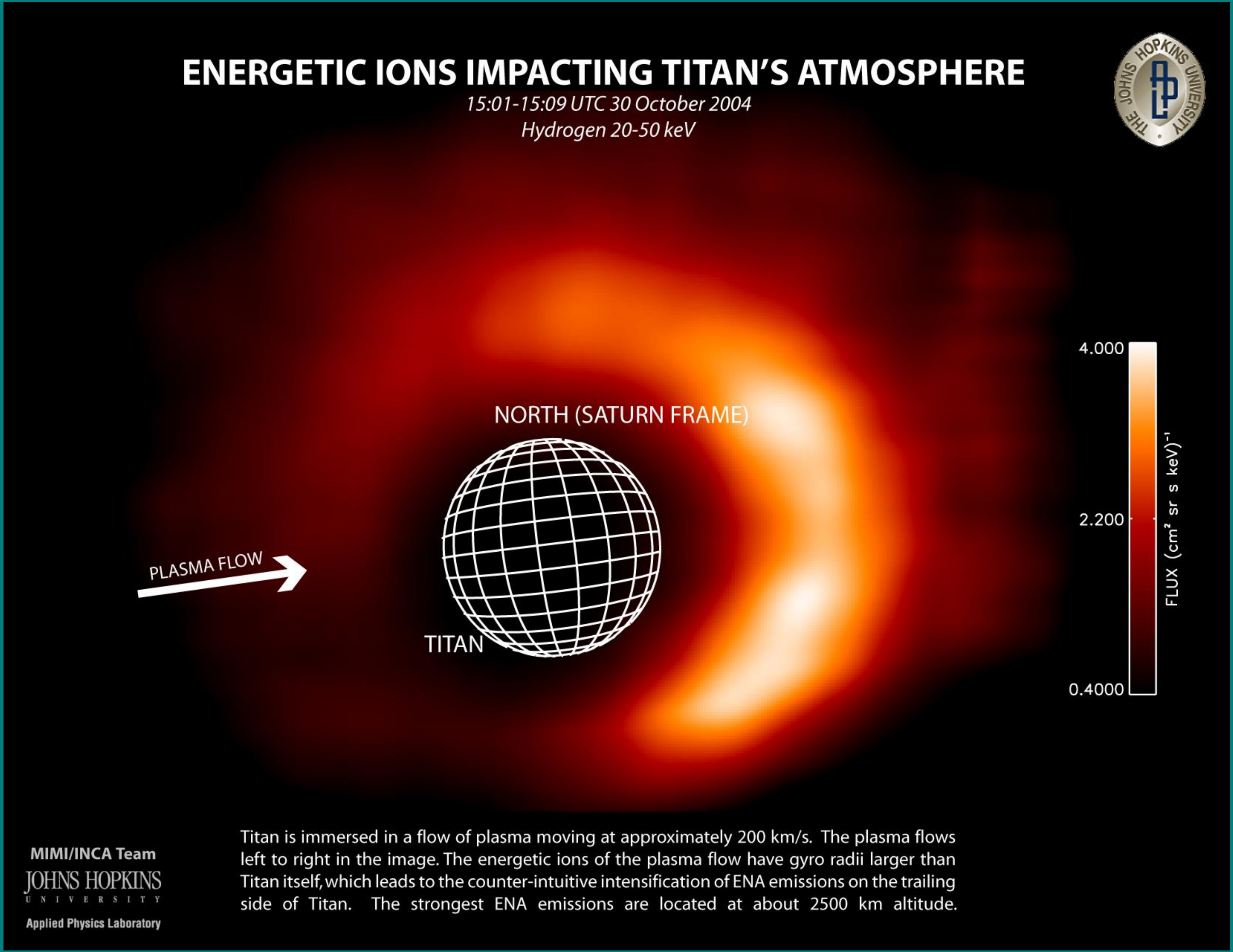
Chapter VIIIc: The Cassini-Huygens mission

Images of the "shepherd" satellites of Saturn:

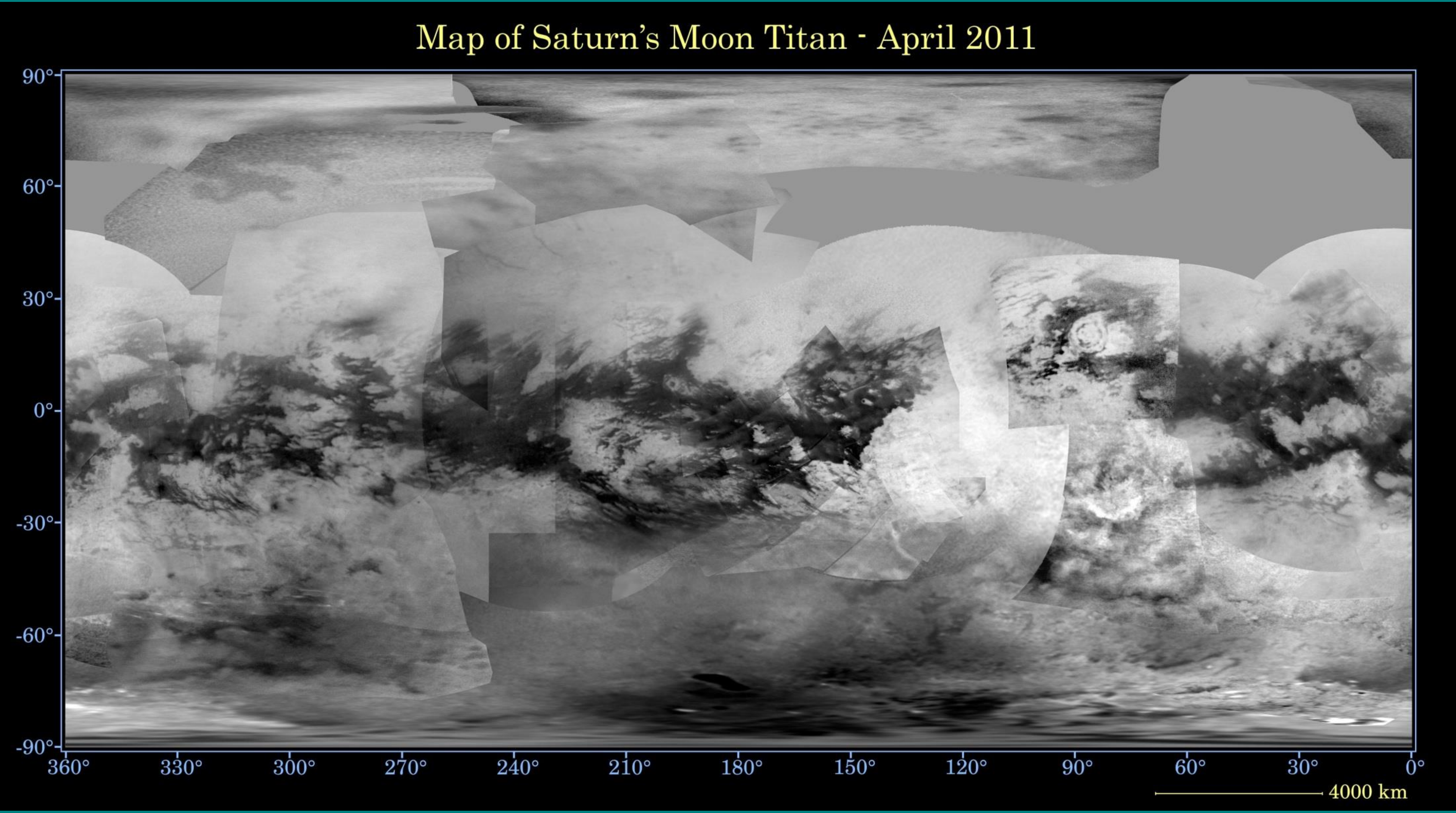




Chapter VIIIc: The Cassini-Huygens mission

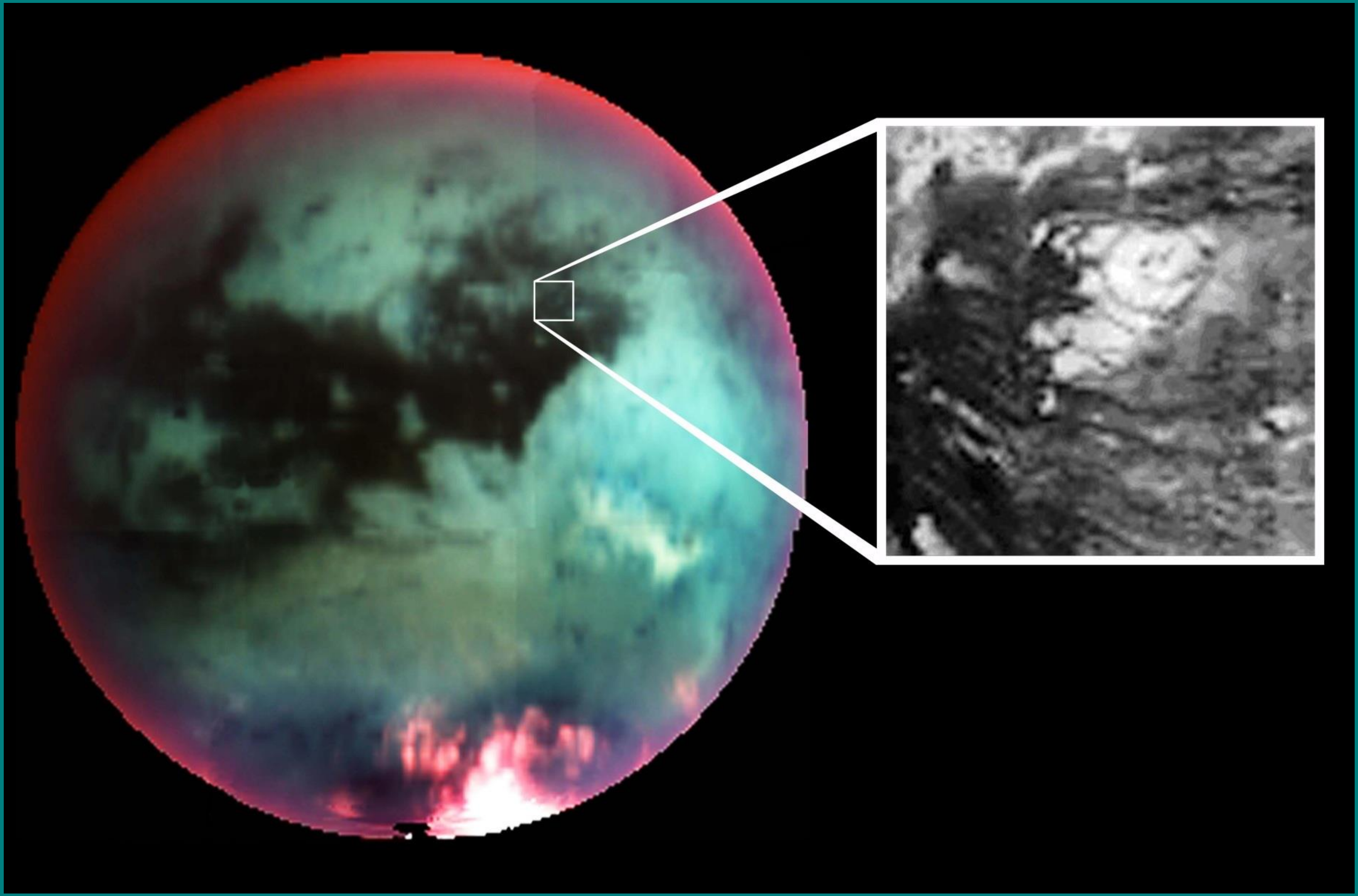


Chapter VIIIc: The Cassini-Huygens mission

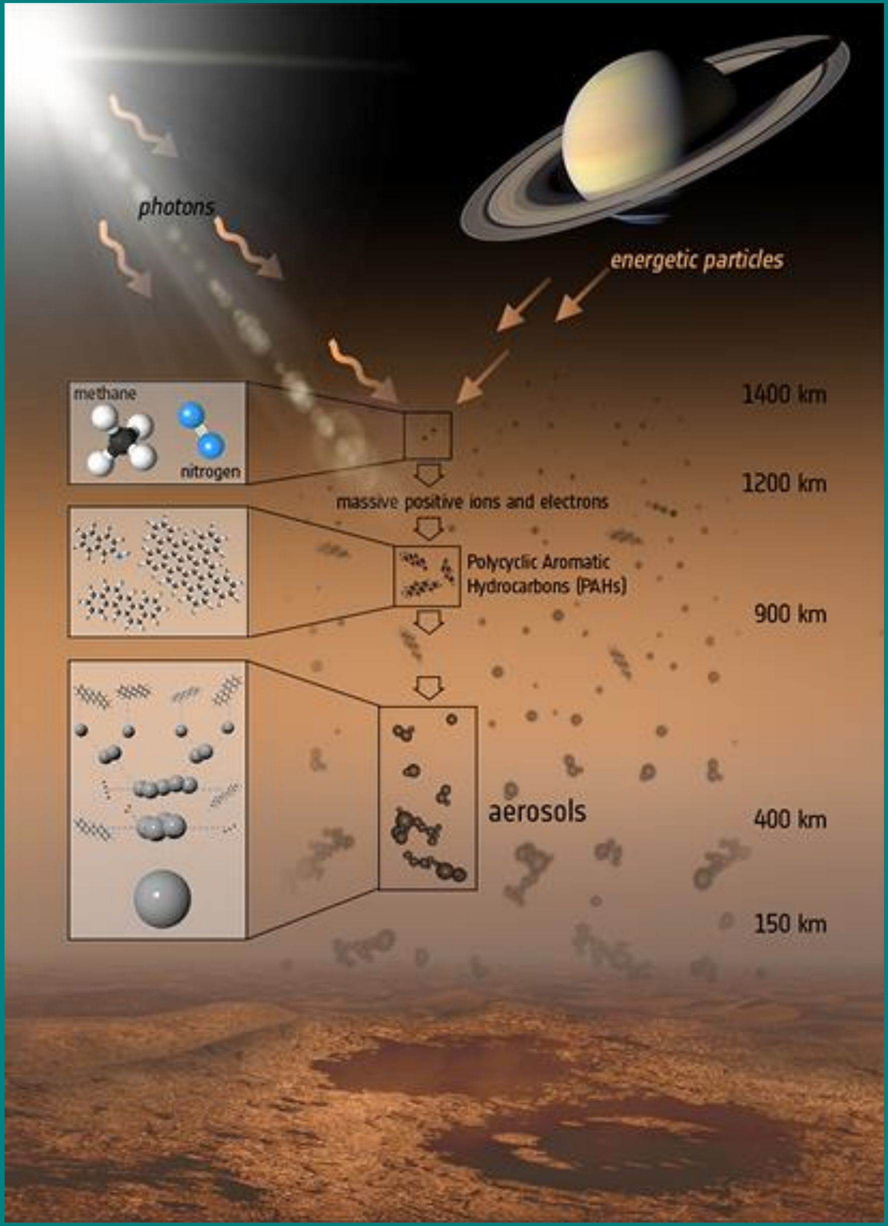


Mapping Titan

Chapter VIIIc: The Cassini-Huygens mission



Chapter VIIIc: The Cassini-Huygens mission



Chemical processes in the atmosphere of Titan

Chapter IX: From exploration to exploitation?

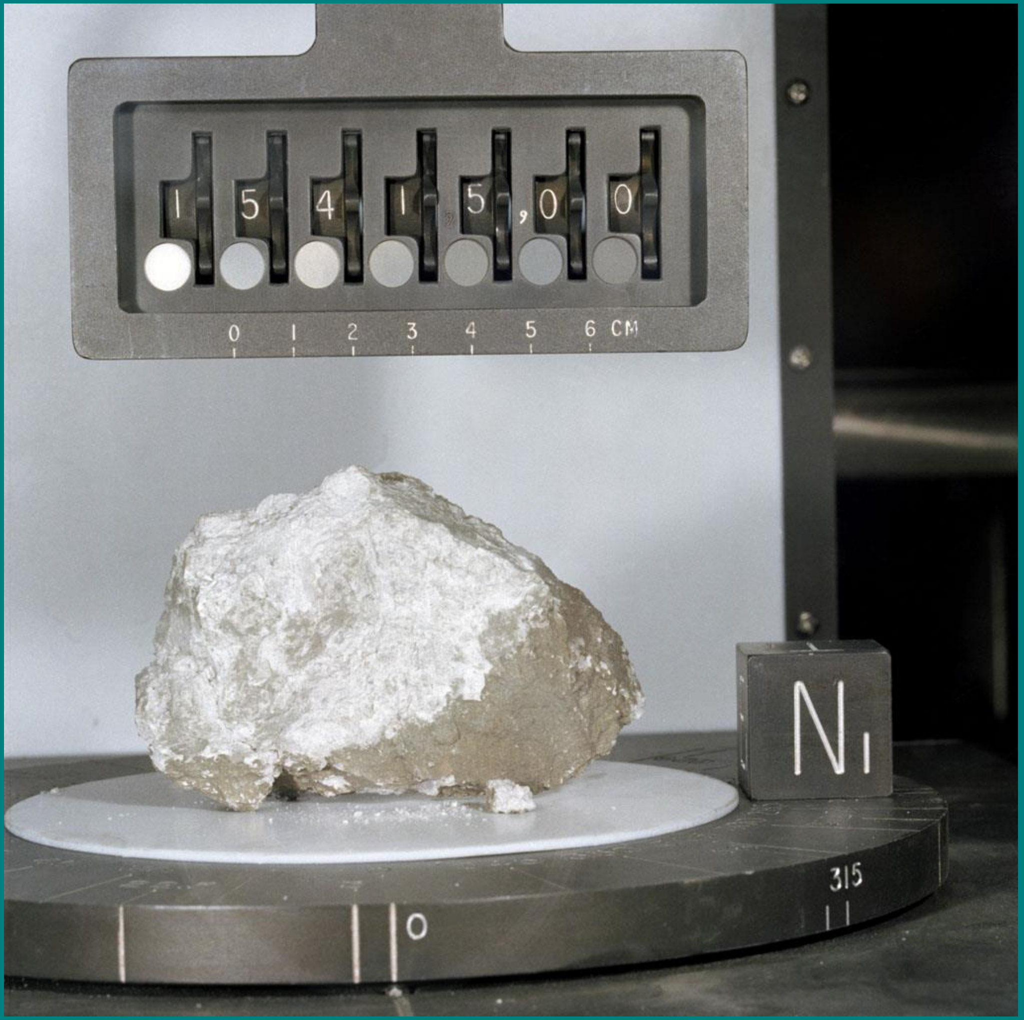
- The Moon and the legacy of the Apollo missions
- 50 years later: return to the Moon?
- The Moon: a giant fuel reservoir??
- The new Eldorado?
- Do we have the right...?

Chapter IX: From exploration to exploitation?

- Between July 1969 and December 1972, twelve astronauts walked on the Moon in the context of the Apollo programme.
- Important technological developments!
- Politically motivated programme (Cold War)…

Chapter IX: From exploration to exploitation?

- Scientific impact of the Apollo programme, quite modest...
- 382 kg of lunar rocks.
- The Moon formed following the collision between the Earth and another celestial body.

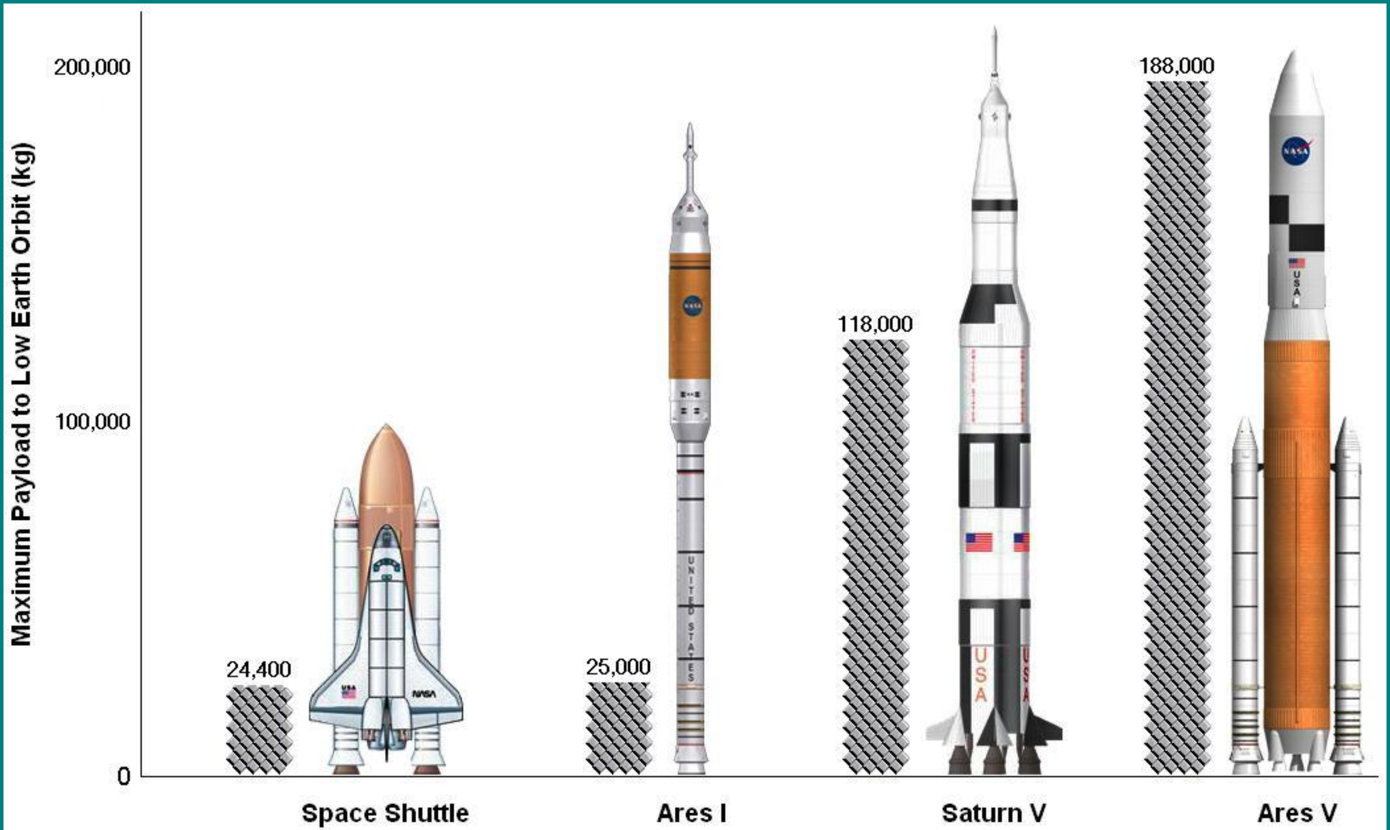


Chapter IX: From exploration to exploitation?

- First tentative of a remake: 40 years later, speech of G.W. Bush in January 2004...
- But making a human survive on the Moon costs about 1 million USD each minute!

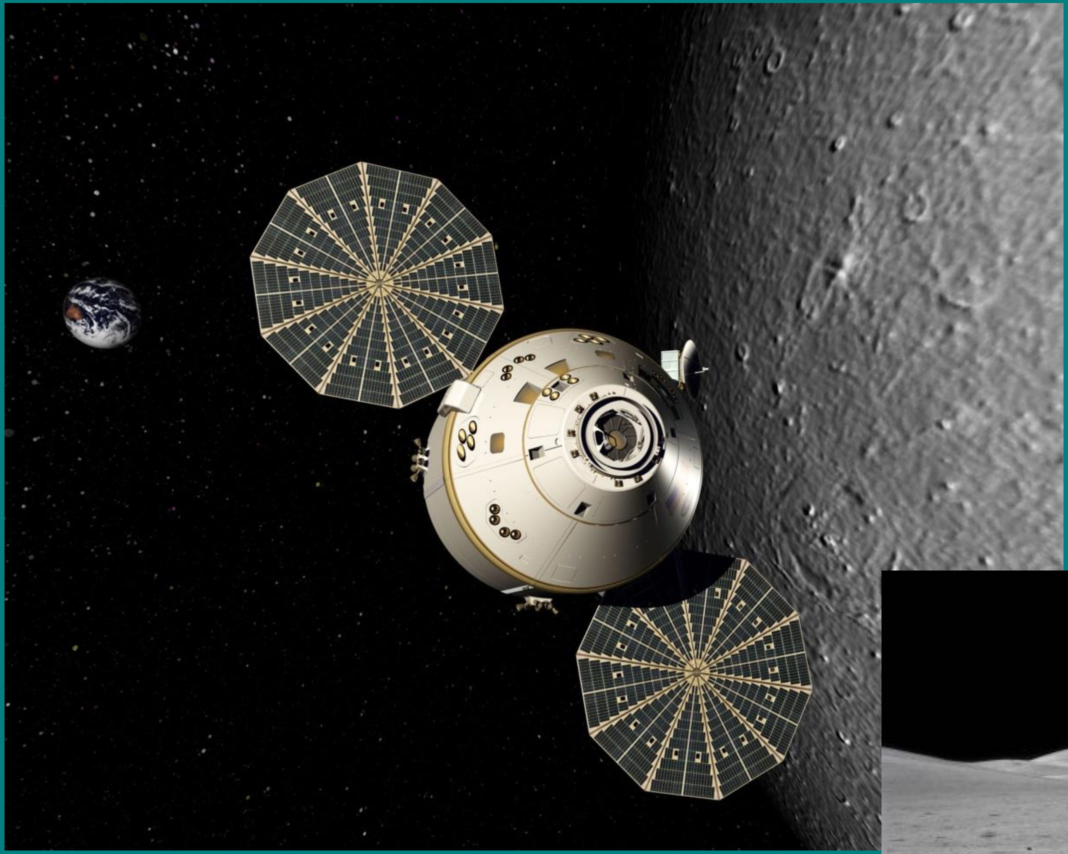
Chapter IX: From exploration to exploitation?

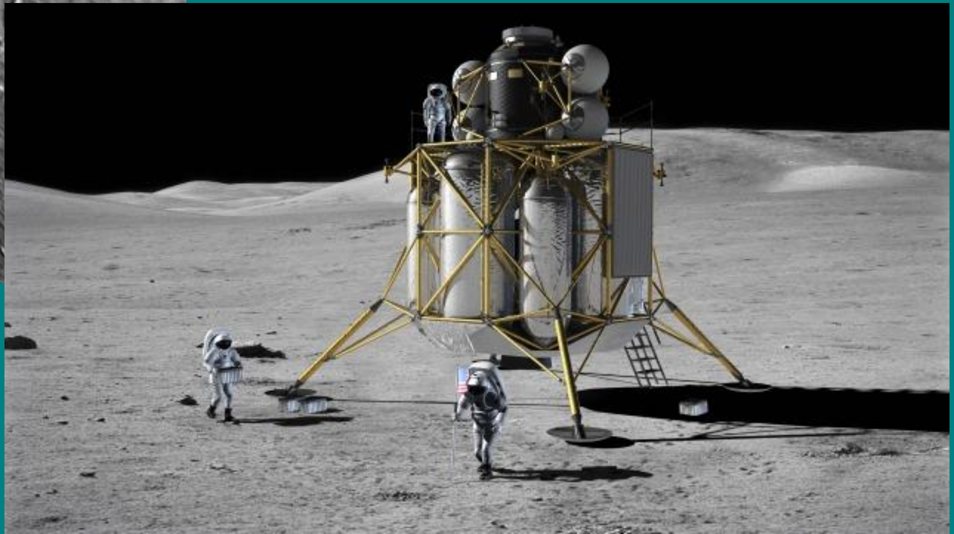
- Constellation programme: replacement of the Space Shuttle (decided following the losses of Challenger and Columbia) and develop vehicles to go to the Moon (stopped by the Obama administration).
- Development of new launchers: Ares I and Ares V



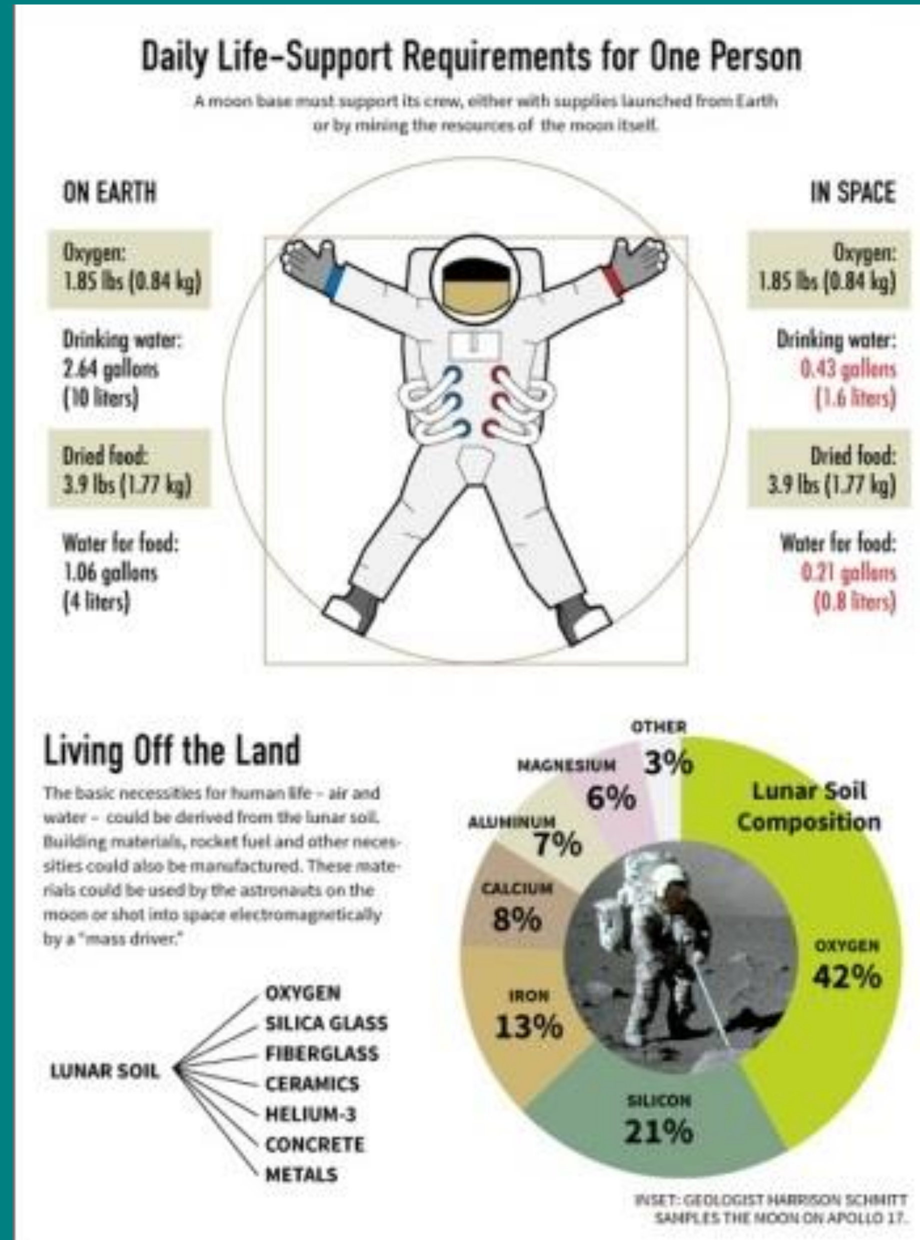
Chapter IX: From exploration to exploitation?

- Development of new spacecraft: Orion and Altair



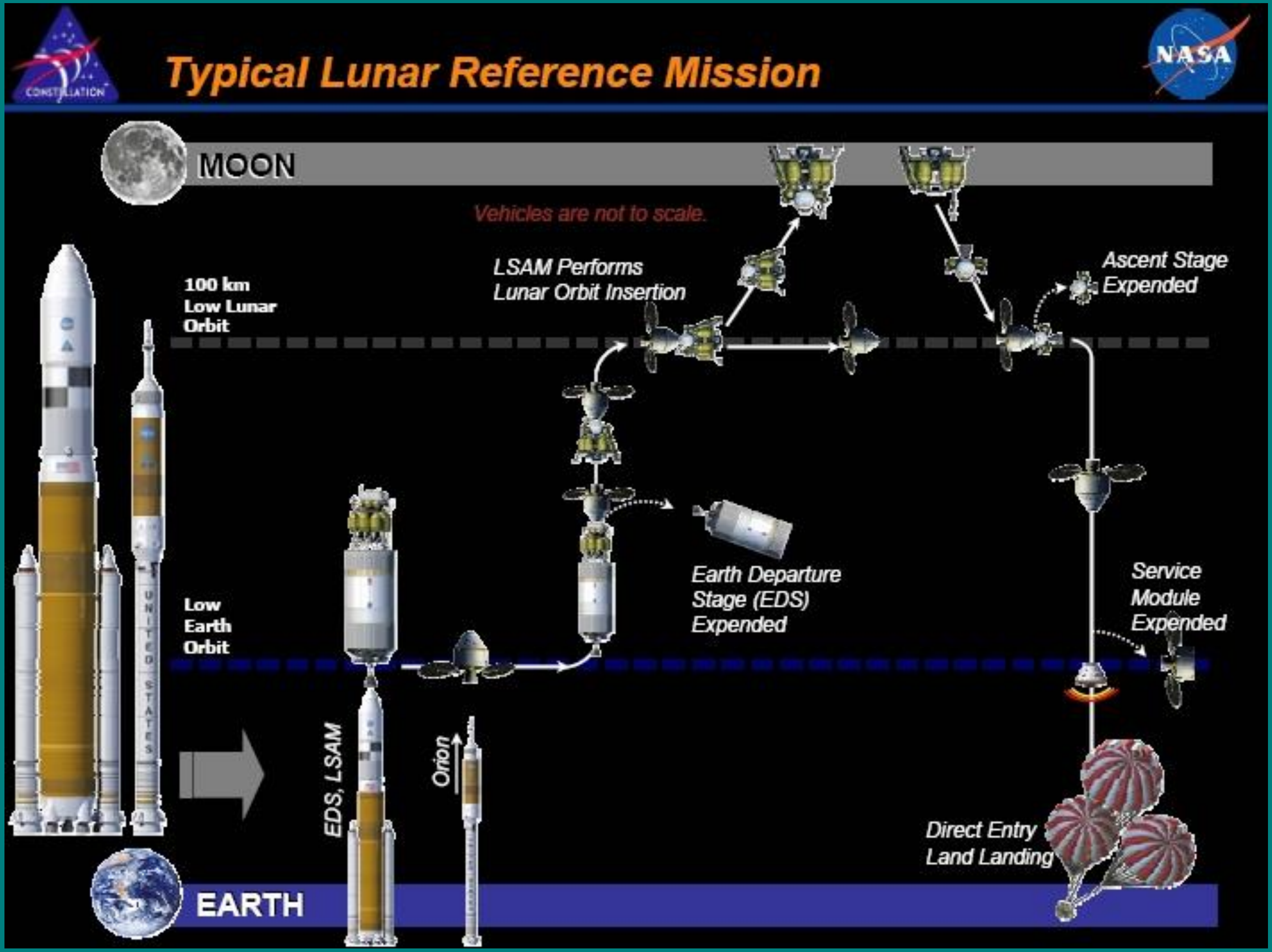


Chapter IX: From exploration to exploitation?



Chapter IX: From exploration to exploitation?

- A trip to the Moon

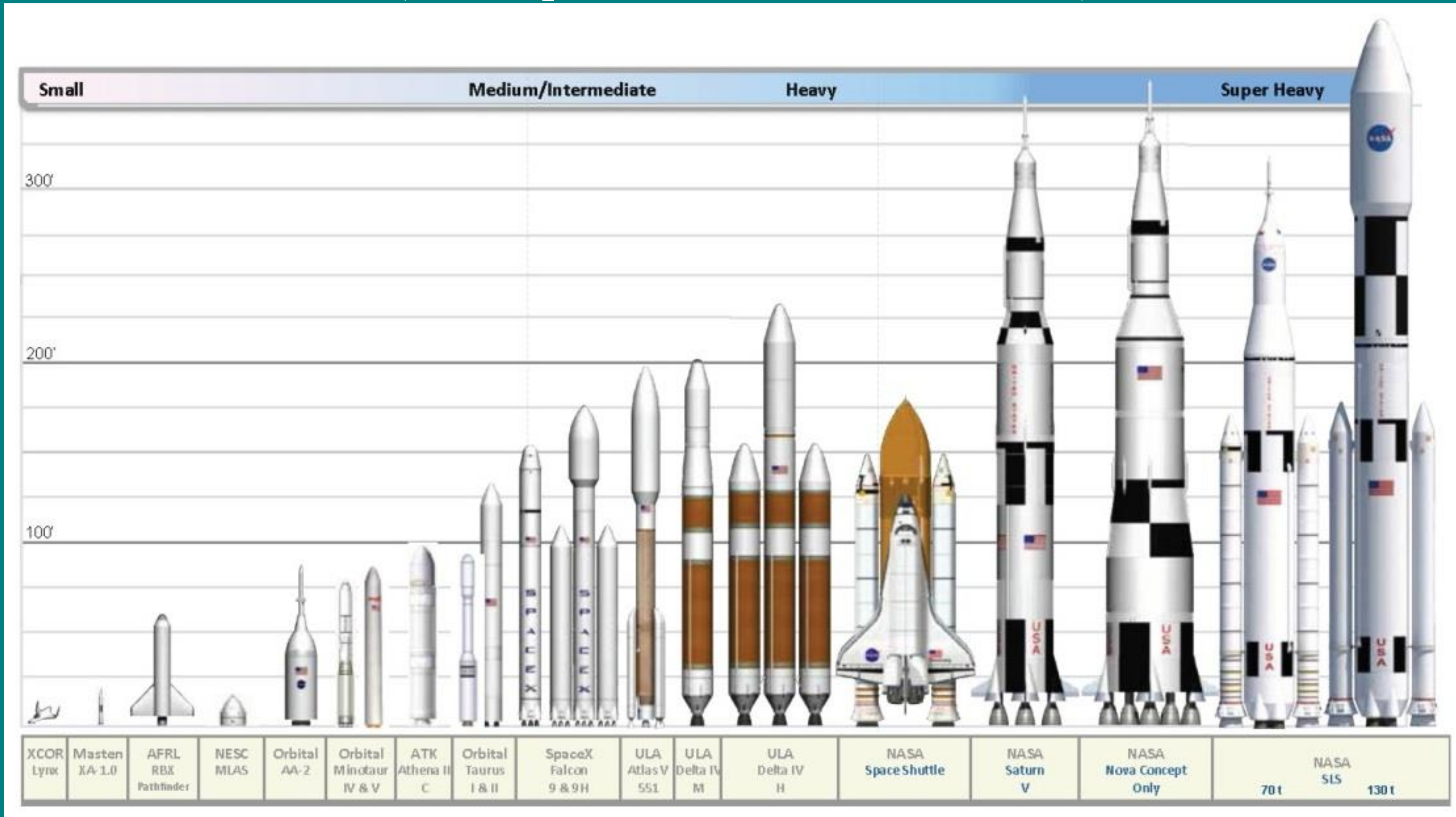


Chapter IX: From exploration to exploitation?

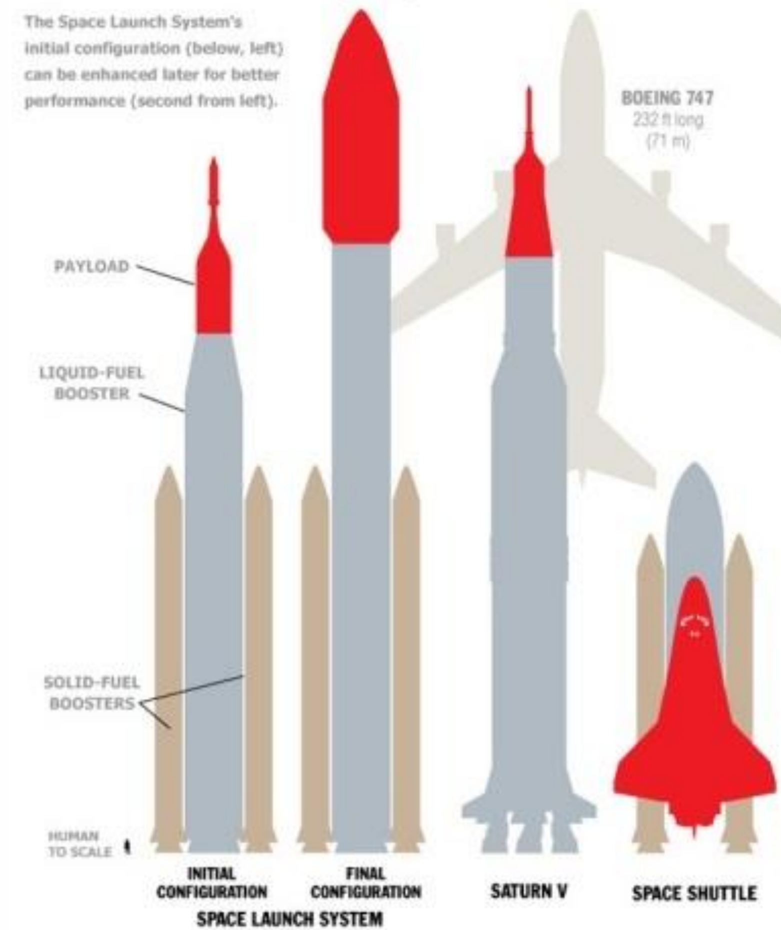
- Following the withdrawal of the Constellation programme: NASA continues developing the Orion capsule (first unmanned test in December 2014).

Chapter IX: From exploration to exploitation?

- Following the withdrawal of the Constellation programme: NASA continues developing the Orion capsule and a new launcher SLS (that replaces the Ares launchers)



How SLS Stacks Up Against Other Rockets



	SLS Initial Configuration	SLS Final Configuration	Saturn V	Space Shuttle
Country	United States	United States	United States	United States
Years of operation	first launch planned for 2017	to be determined	1967-1973	1981-2011
Destinations	Earth orbit, deep space	Earth orbit, deep space, asteroids, moon, Mars	Earth orbit, moon	Earth orbit
Fuel type	solid fuel, LH2/LOX	solid fuel, LH2/LOX	kerosine, LH2/LOX	solid fuel, LH2/LOX
Height	320 ft (97.5 m)	400 ft (122 m)	363 ft (110 m)	184 ft (56.1 m)
Lift capability	70-77 metric tons	up to 130 metric tons	130 metric tons	24.4 metric tons
Thrust	8.4 million lbs (3.8 million kg)	9.2 million lbs (4.2 million kg)	7.5 million lbs (3.4 million kg)	7.8 million lbs (3.54 million kg)

LH2 = liquid hydrogen fuel
LOX = liquid oxygen oxidizer
Solid fuel = aluminum perchlorate composite mixture

SOURCES: NASA, LOCKHEED MARTIN

KARL TATE / © SPACE.com

Chapter IX: From exploration to exploitation?

- New attempt due to Trump administration: SLS will be used to build Deep Space Gateway, a platform for Moon exploration, but also to outer space + human landing by 2024?

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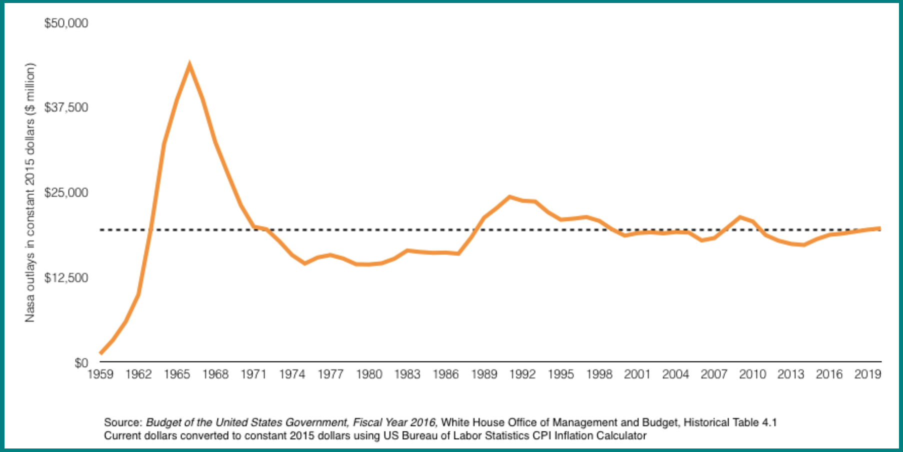
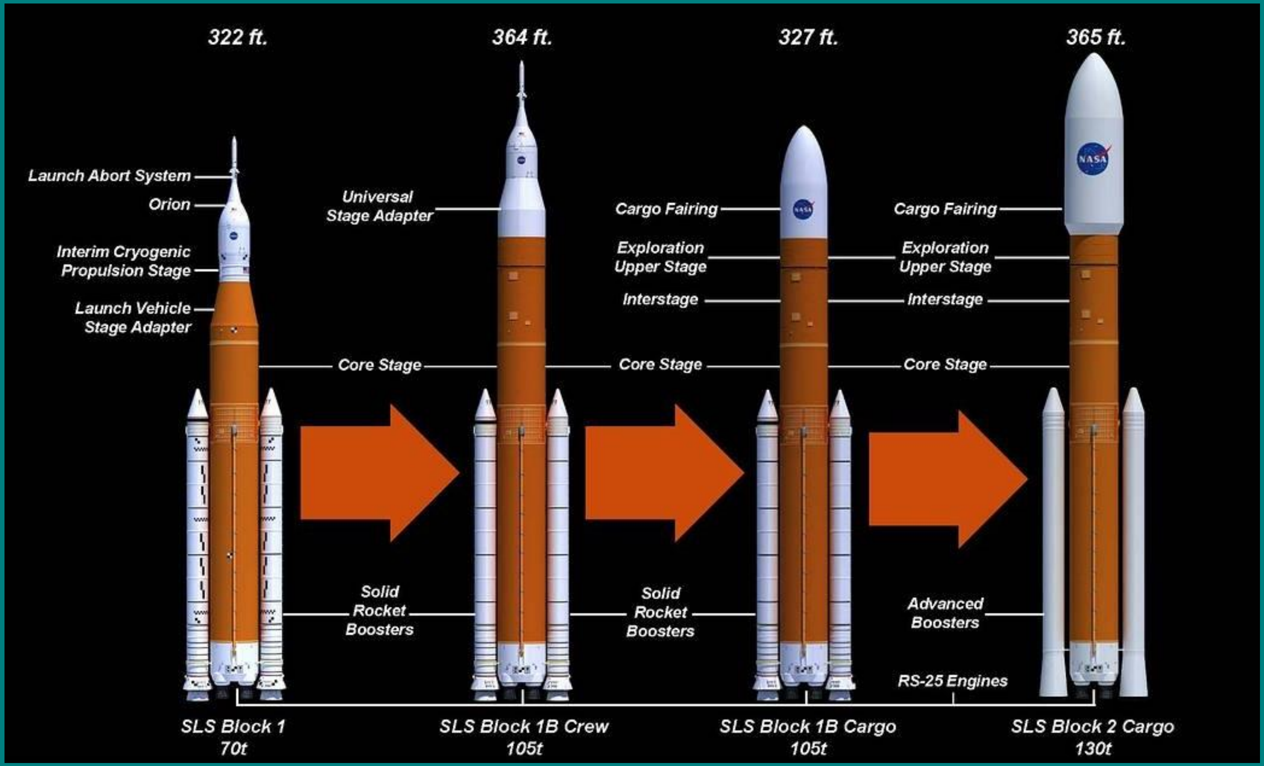
Chapter IX: From exploration to exploitation?

- But US Space Policy not clear and SLS development behind schedule.
- Funding sufficient???





Chapter IX: From exploration to exploitation?

- What are the motivations to return to the Moon?
- Helium-3?
- Helium-3 could make nuclear fusion more accessible and open up new avenues for generation of electric energy in the future: *15 to 20 tons are enough to secure the yearly production of electricity in the USA.*

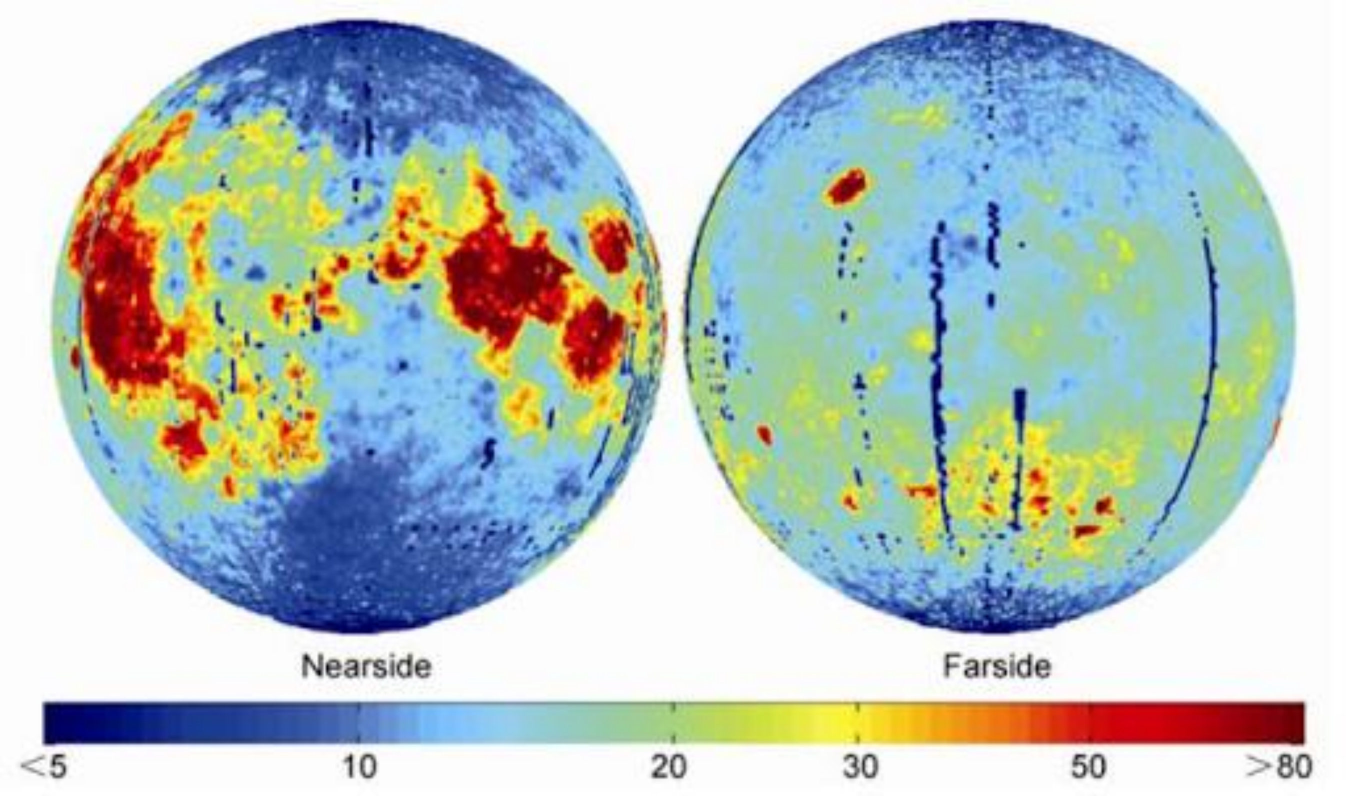
$$
\begin{aligned}
{}^2\mathrm{H} + {}^2\mathrm{H} &\rightarrow {}^3\mathrm{He} + \mathrm{n} \\
{}^2\mathrm{H} + {}^2\mathrm{H} &\rightarrow {}^3\mathrm{H} + \mathrm{p} \\
{}^2\mathrm{H} + {}^3\mathrm{H} &\rightarrow {}^4\mathrm{He} + \mathrm{n}
\end{aligned}
$$

$$
\begin{aligned}
{}^2\mathrm{H} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + \mathrm{p} \\
{}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + 2\,\mathrm{p}
\end{aligned}
$$

- Problem: helium-3 is only marginally present on Earth.

Chapter IX: From exploration to exploitation?

- But helium-3 is much more abundant on the Moon (about 1 million tons) due to the direct impact of the Solar wind on the lunar surface.



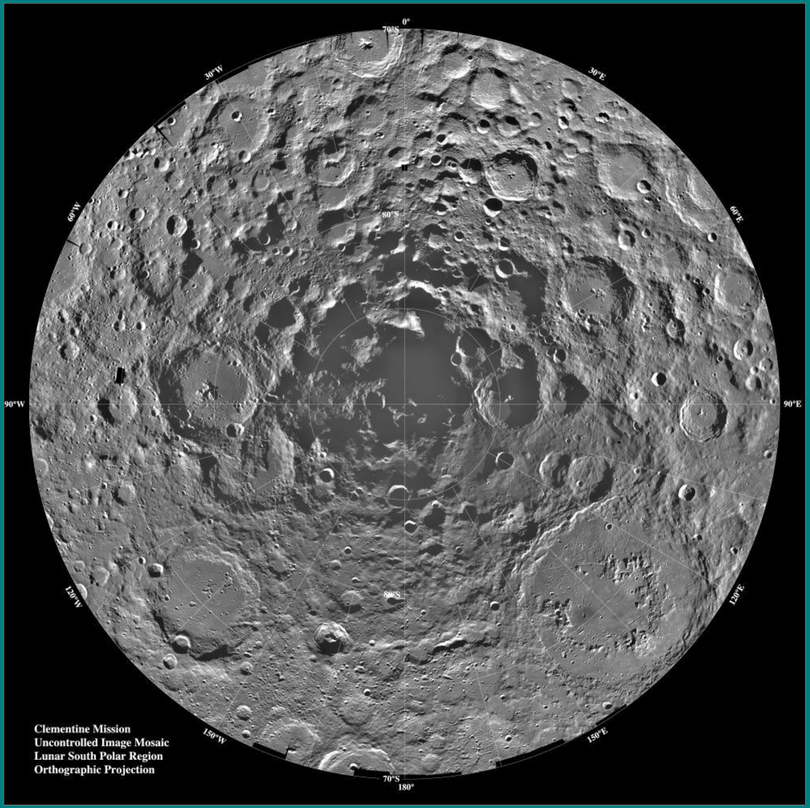
Chapter IX: From exploration to exploitation?

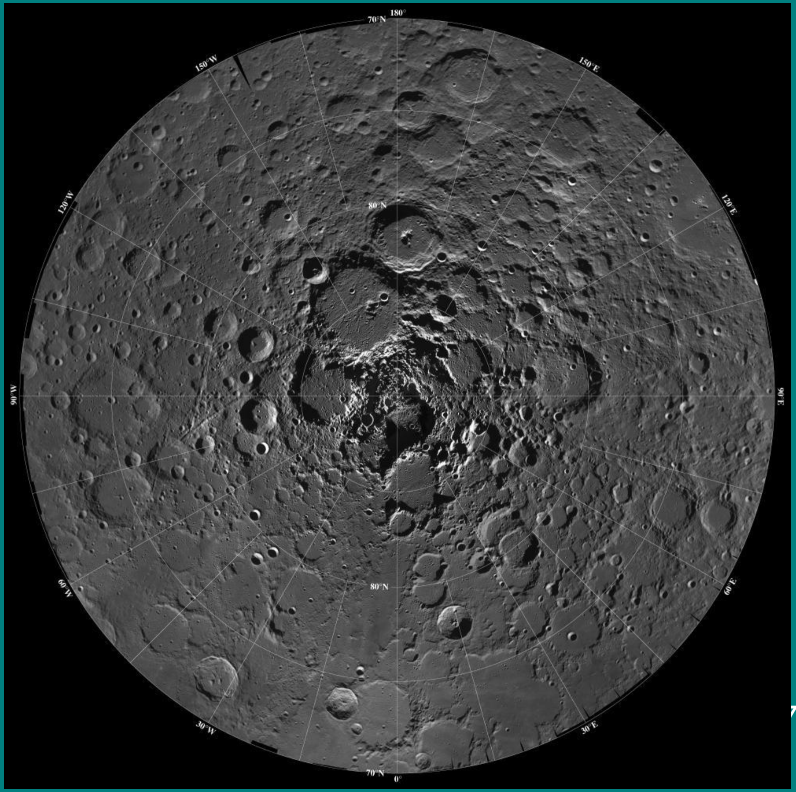
- Extraction of lunar helium-3 would imply to transform the Moon into a giant mining site: one needs to process millions of tons of regolith to extract a single ton of helium-3!
- Economic interest very uncertain!

- What about other lunar resources?

Chapter IX: From exploration to exploitation?

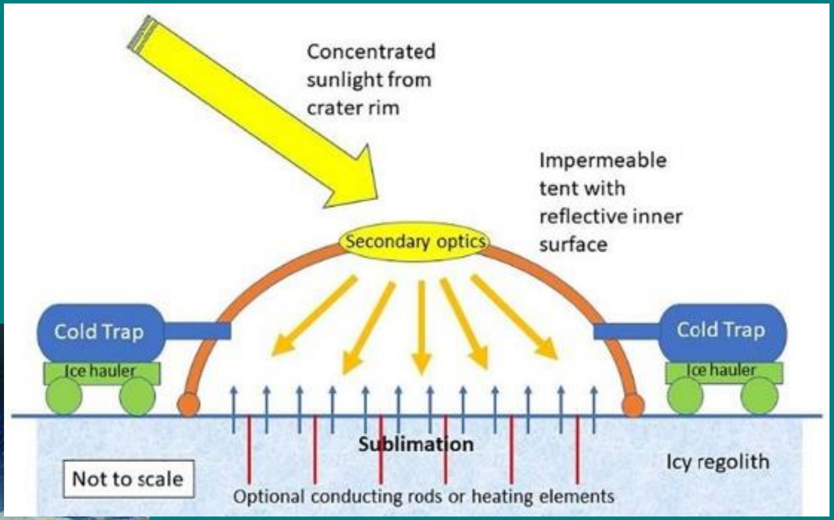
- Moon: temperature varies between -173 and +127°C at the equator; no atmosphere; no water in the regolith...
- But: Clementine, Lunar Prospector and other probes found water ice in deep, shady craters in the polar regions.

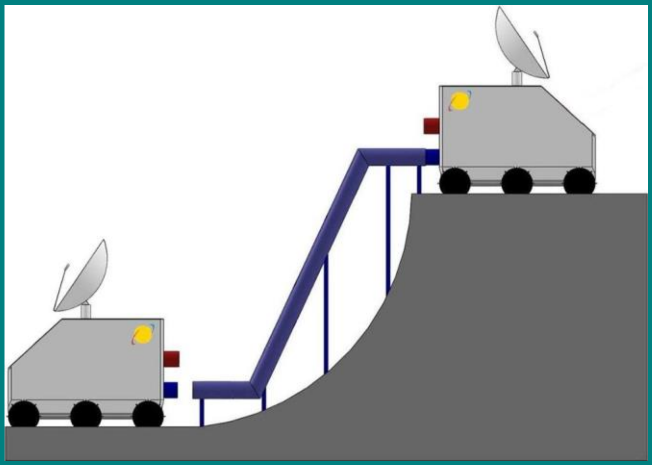




Chapter IX: From exploration to exploitation?

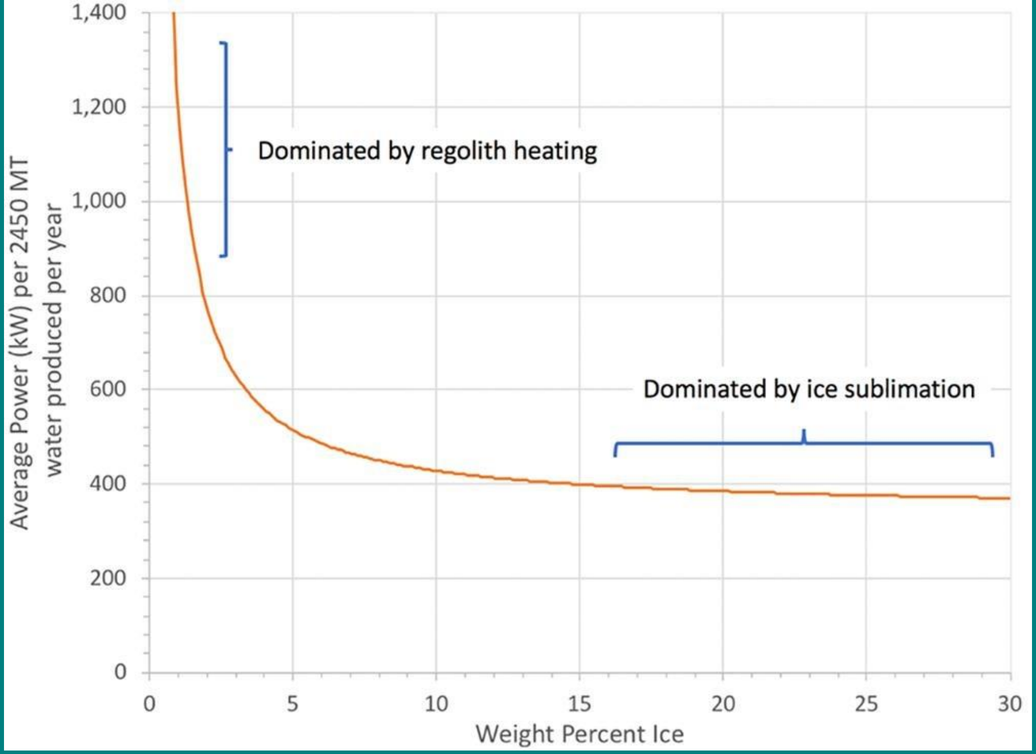
- Water can be extracted via sublimation and can be decomposed into liquid H_2 and O_2 (propellant for deep-space exploration)!
- Fully robotic extraction?





Chapter IX: From exploration to exploitation?

- Economic interest depends upon (highly uncertain) water abundance and upon (even more uncertain) demand for lunar fuel.

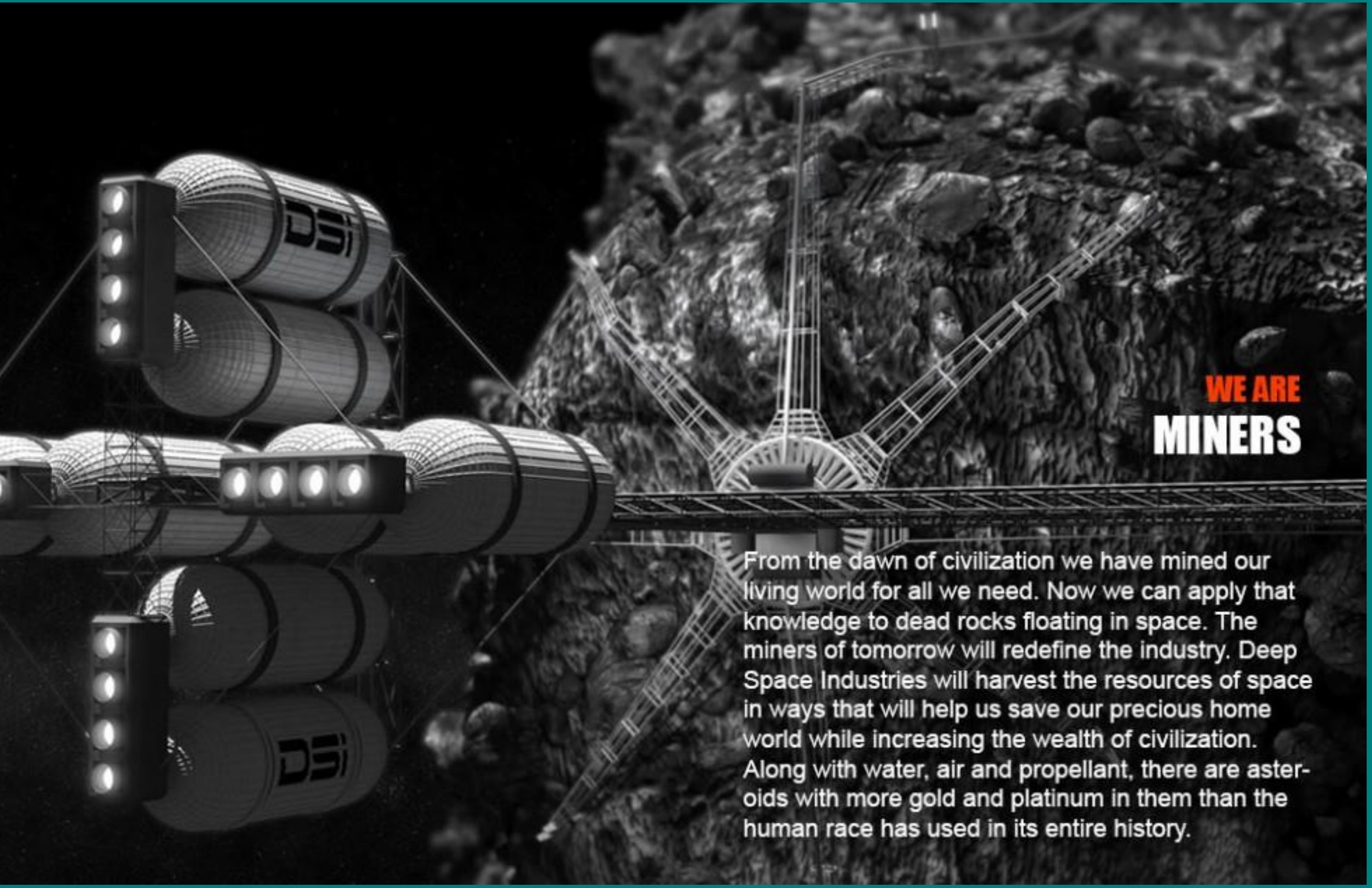


Chapter IX: From exploration to exploitation?

- Private companies are interested in the exploitation of asteroids, with promises such as "Harnessing valuable minerals from a practically infinite source will provide stability on Earth, increase humanity's prosperity, and help establish and maintain human presence in space." (http://www.planetaryresources.com/ http://deepspaceindustries.com/).
- The objective is to develop robotic probes at low cost (nano-satellites), allowing to explore thousands of nearby asteroids and then to develop the technologies to exploit their resources (water, hydrocarbons and rare metals) and sell them to clients either in the orbit or on the ground.

Chapter IX: From exploration to exploitation?

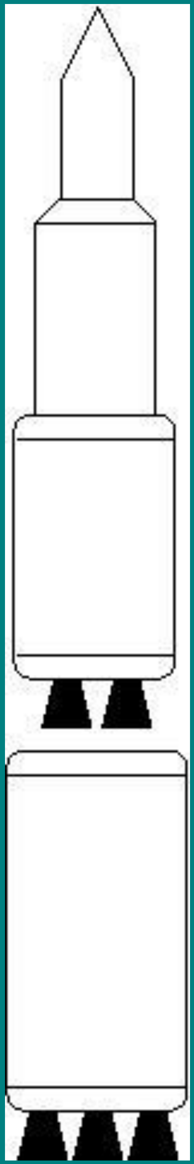
Chapter IX: From exploration to exploitation?



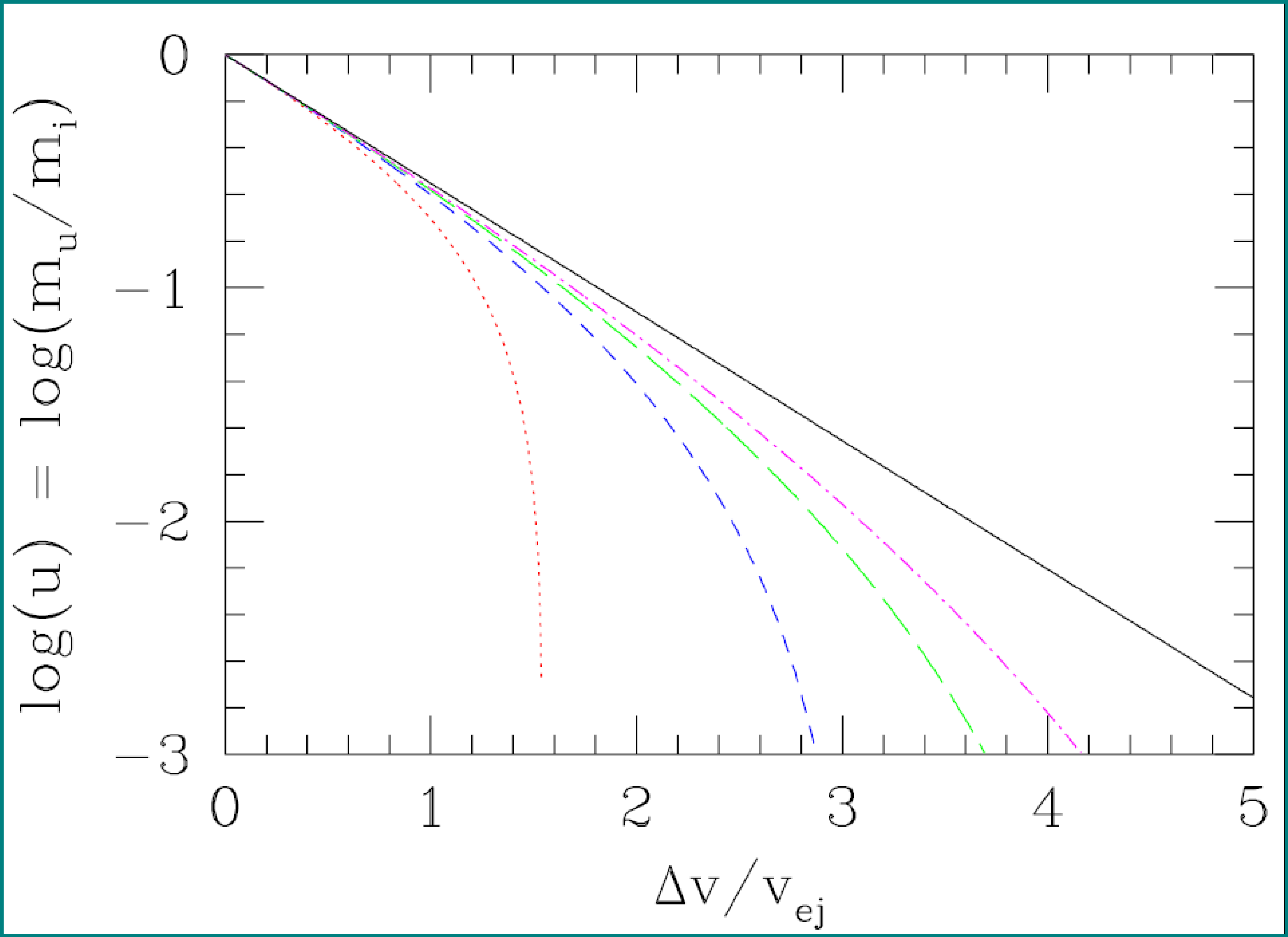
Chapter IX: From exploration to exploitation?

- The UN outer-space treaty sets the rules for space activities and prohibits the nations who signed the treaty (including all leading actors in space exploration) from claiming sovereignty over any celestial body.
- USA, Luxembourg, Japan and UAE have adopted national legislations to circumvent the restrictions of the outer-space treaty.
- But what about private companies? Will the Moon and the asteroids become the Wild West of the 21^{st} century?
- The US policy (Artemis Accords, “safety zones”, Space Force) violates the Outer Space Treaty
- Will private companies observe the same security standards especially regarding space debris?
- But most of all: do we have the moral right to exploit other celestial bodies to solve man-made terrestrial problems?

Chapter X: Exercises

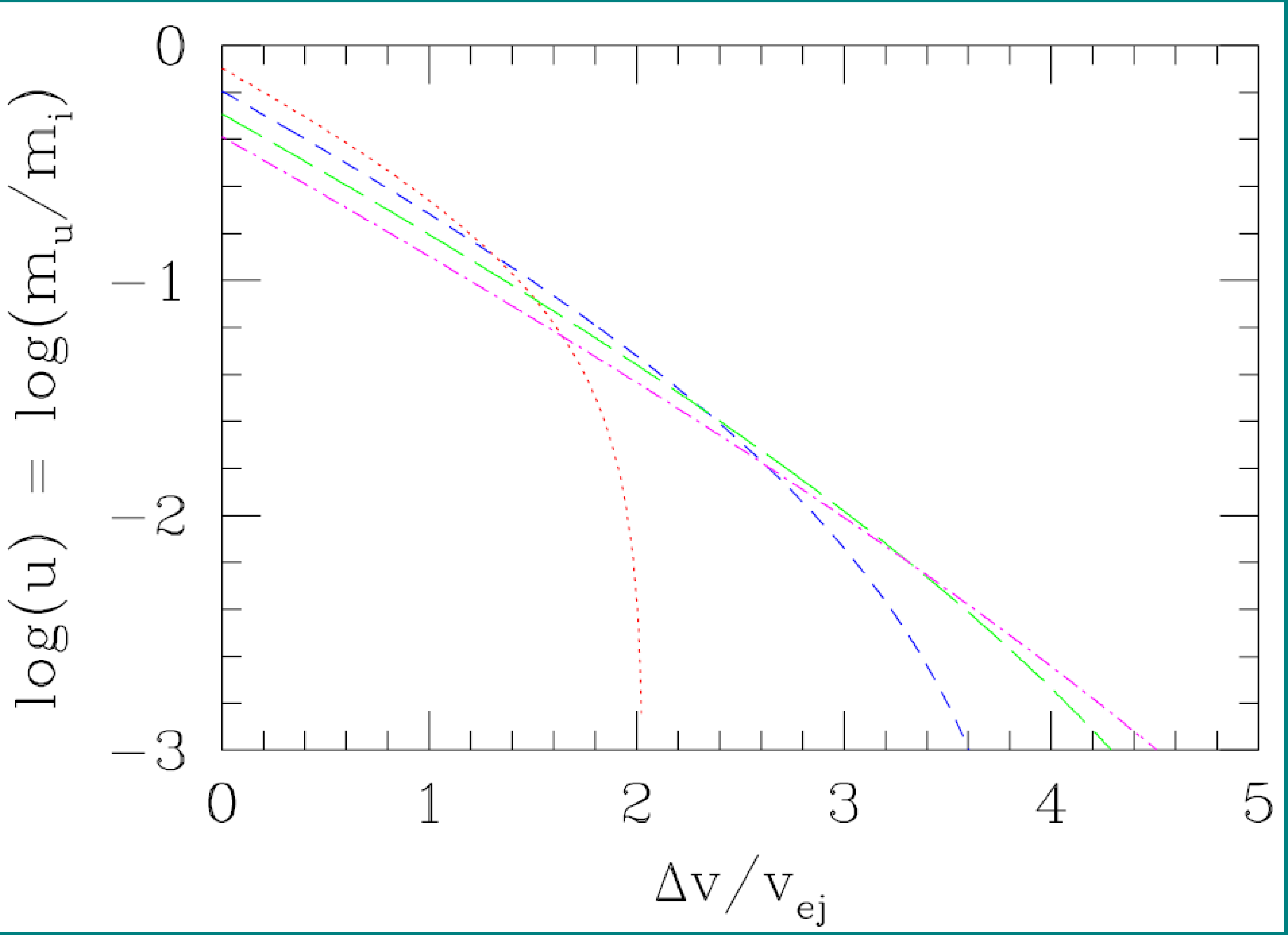


- Exercise 1: multi-stage rocket



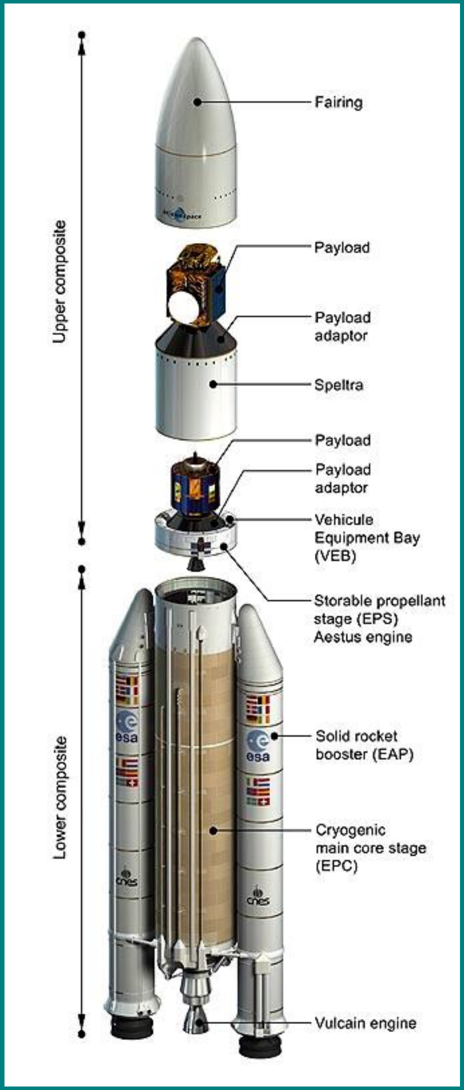
Chapter X: Exercises

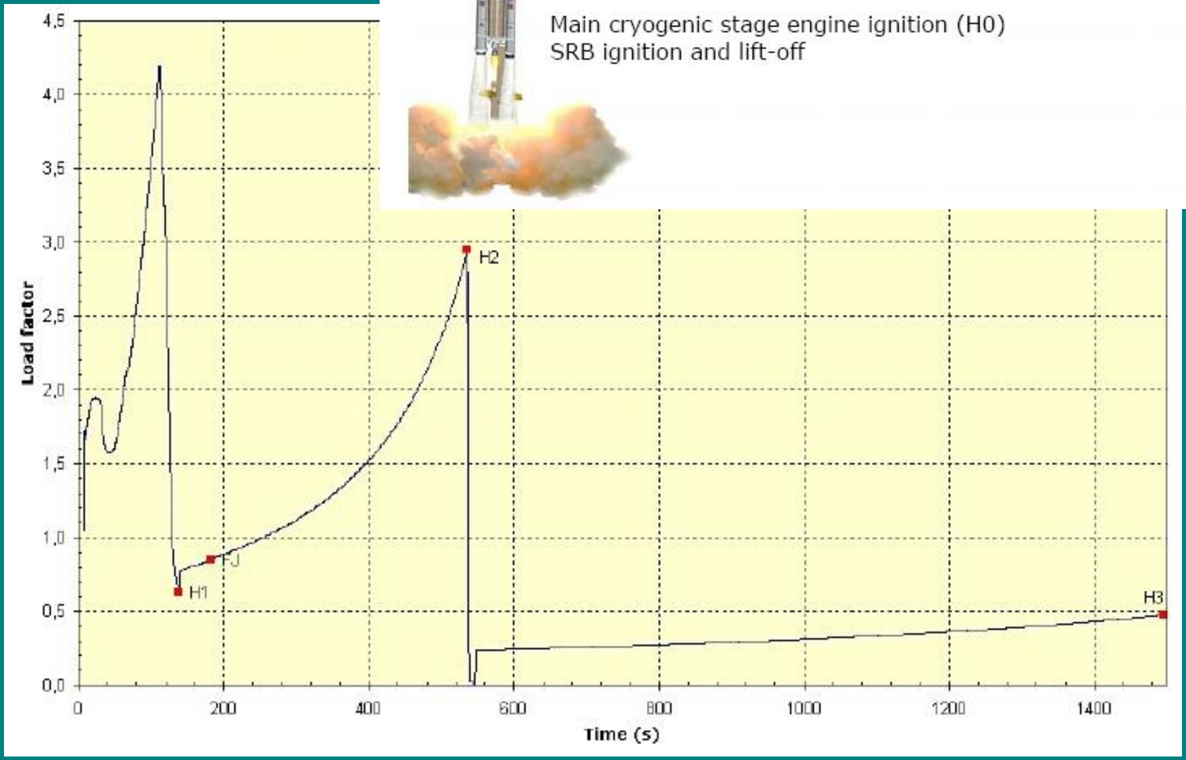
- Exercise 1: multi-stage rocket

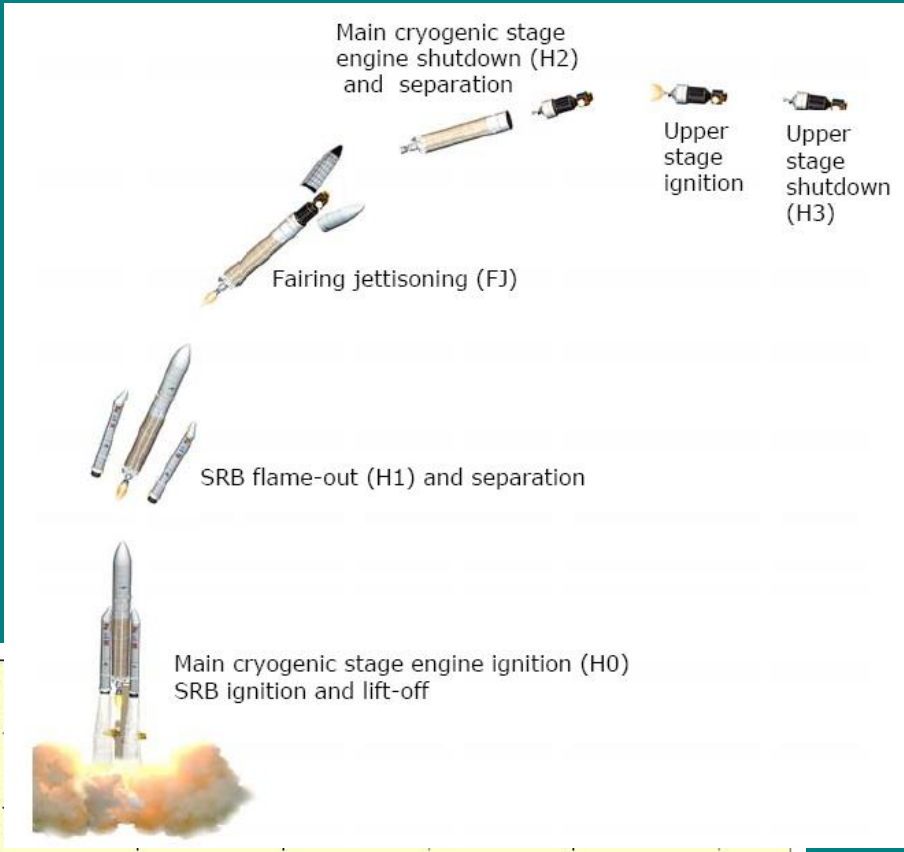


Chapter X: Exercises

- Exercise 2: Ariane V

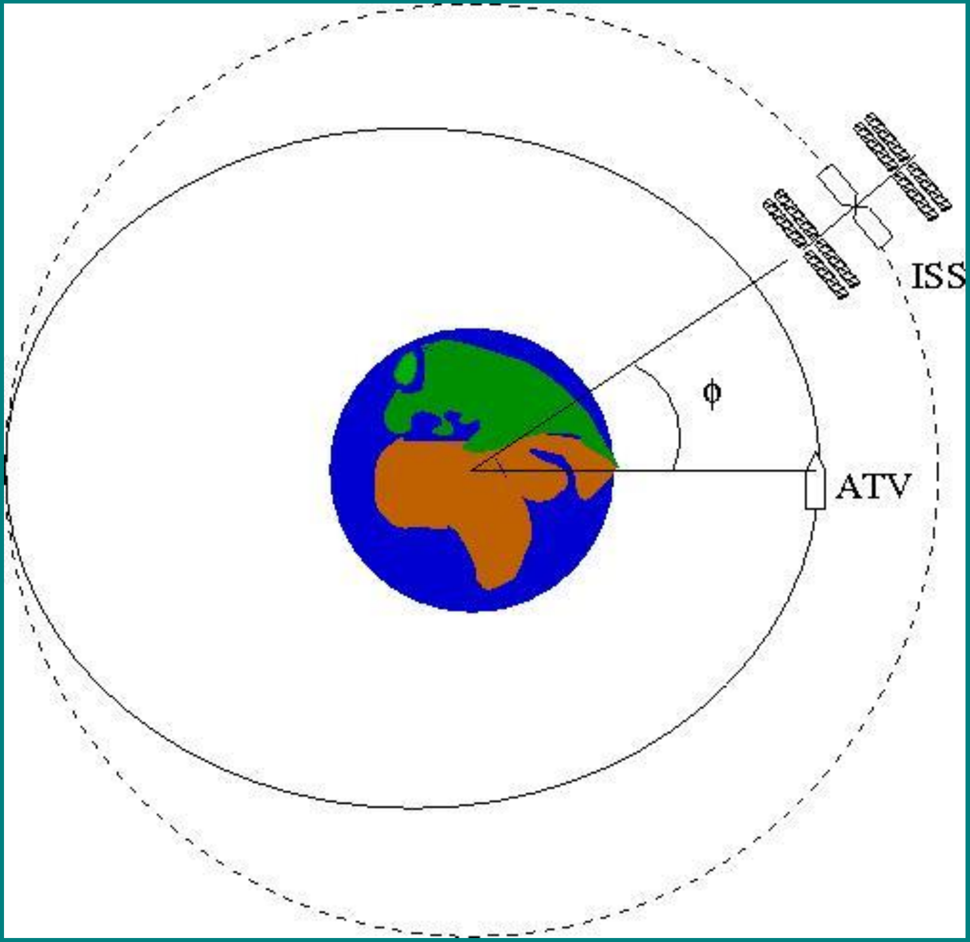






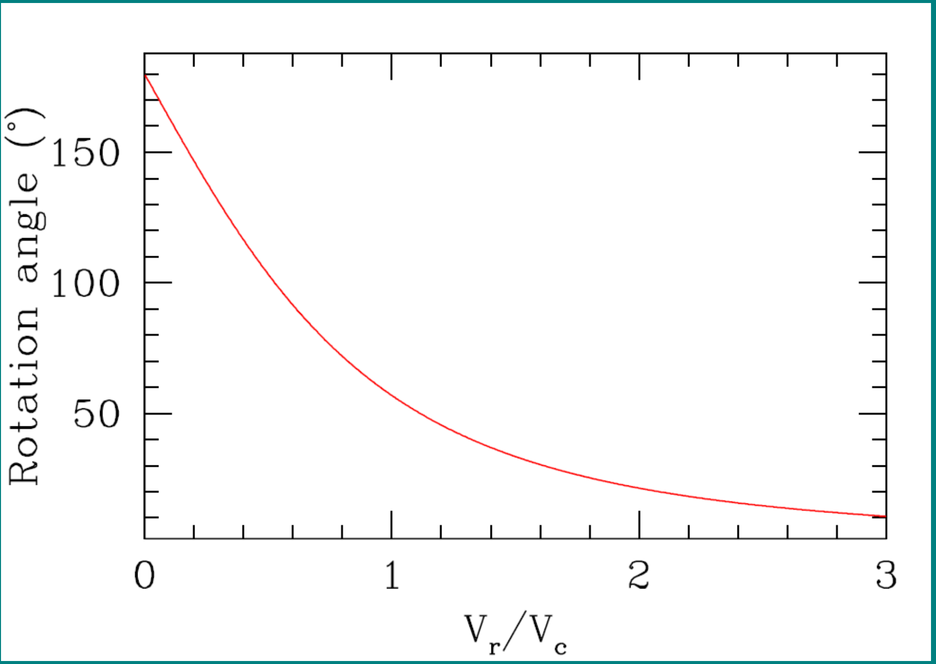
Chapter X: Exercises

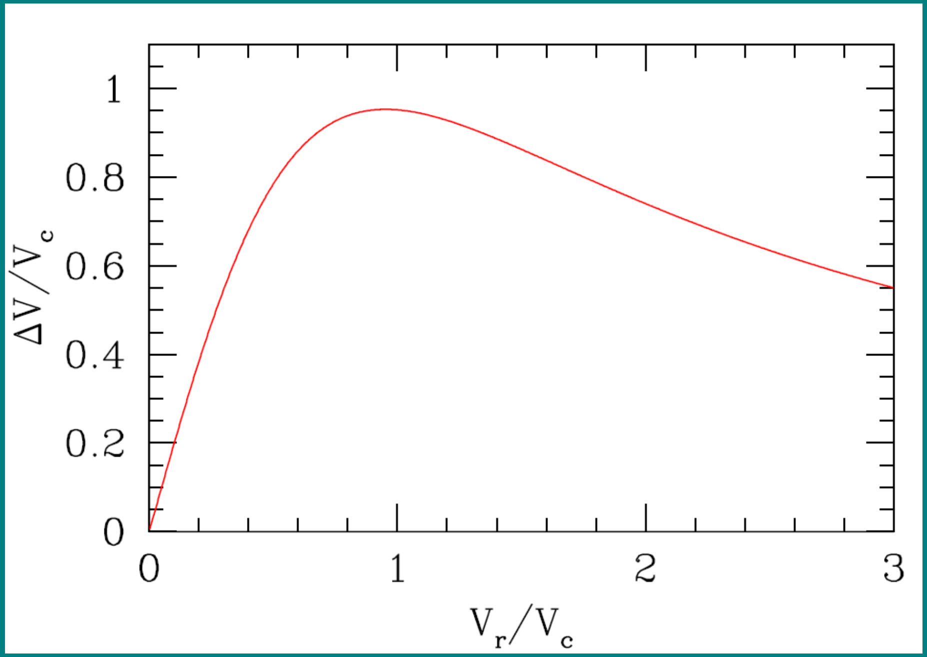
- Exercise 4: orbital manoeuvres



Chapter X: Exercises

- Exercise 4: orbital manoeuvres





Chapter X: Exercises

- Exercise 6: remote-sensing mission to Mars