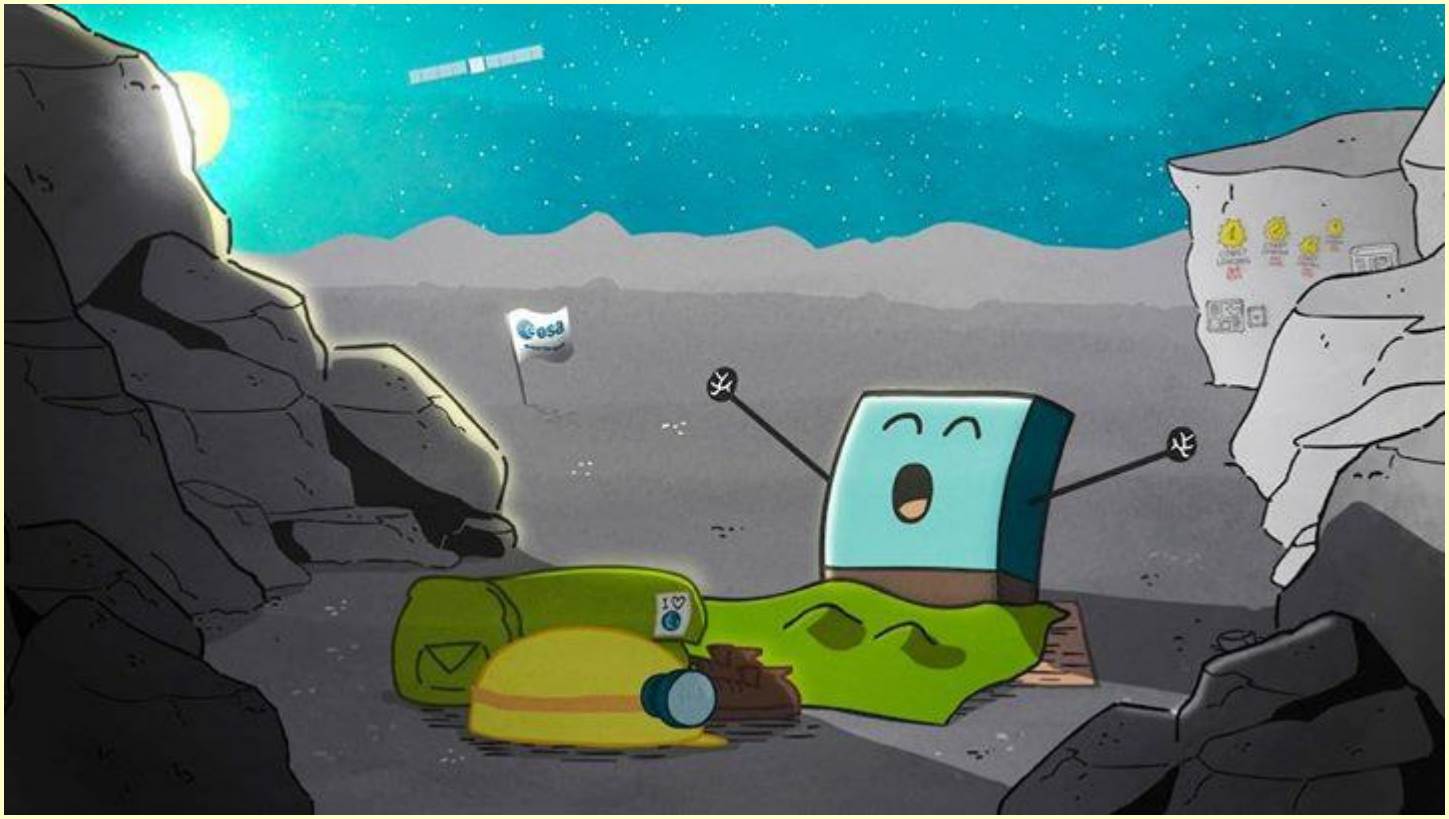
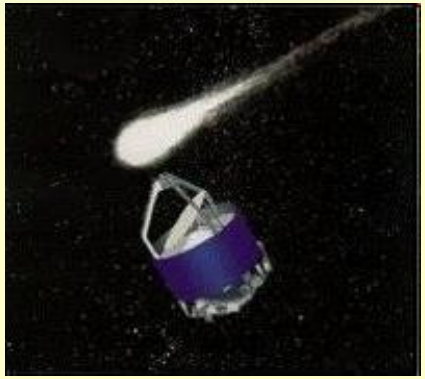
Instrumentation for Planetary Exploration

With thanks to C Erd and D Koschnoy



ESA Planetary Missions



Giotto [1985 - 1992] Flyby at comets Halley (13 March 1986) & Grigg-Skjellerup (1990)

SMART-1 [2003 – 2006]
Solar electric propulsion to moon & lunar observations

Cassini/Huygens [1997]
Huygens landed on Titan (14 Jan 2005)

Mars Express [2003]

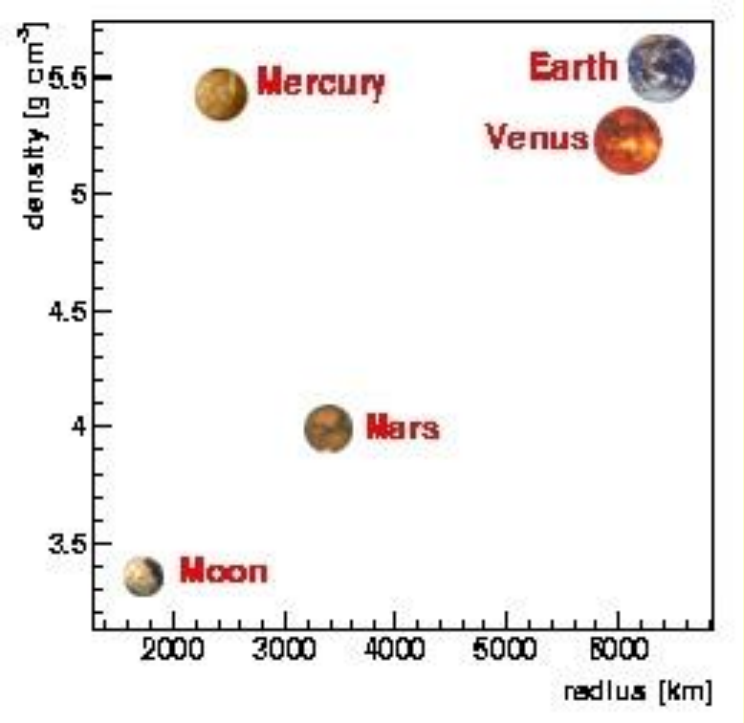
Rosetta [2004]
Steins (2008) and Lutetia (2010)
Churyumov- Gerasimenko (2014)

Venus Express [2005]

BepiColombo [2014]

Motivations for Planetary Exploration

- History and construction of the solar system – constraints on the accretion model
- Origin and evolution of moons
- Evolution of solar system (impact history)
- Water distribution, sub-surface oceans (Europa, Ganymede)
- Atmosphere runaway greenhouse effect (Venus)
- Organic chemistry (Titan, Enceladus)
- Magnetospheric fields and interactions with solar magnetic field
- Etc many others



Issues and Challenges for Space Instrumentation

- **Mass – Power – Volume – Thermal**
  - All equivalent, mass is common invariant
- **Miniaturization**
- **Radiation**
- **Flexibility for coping with unexpected**

Types of Remote Sensing Instrumentation

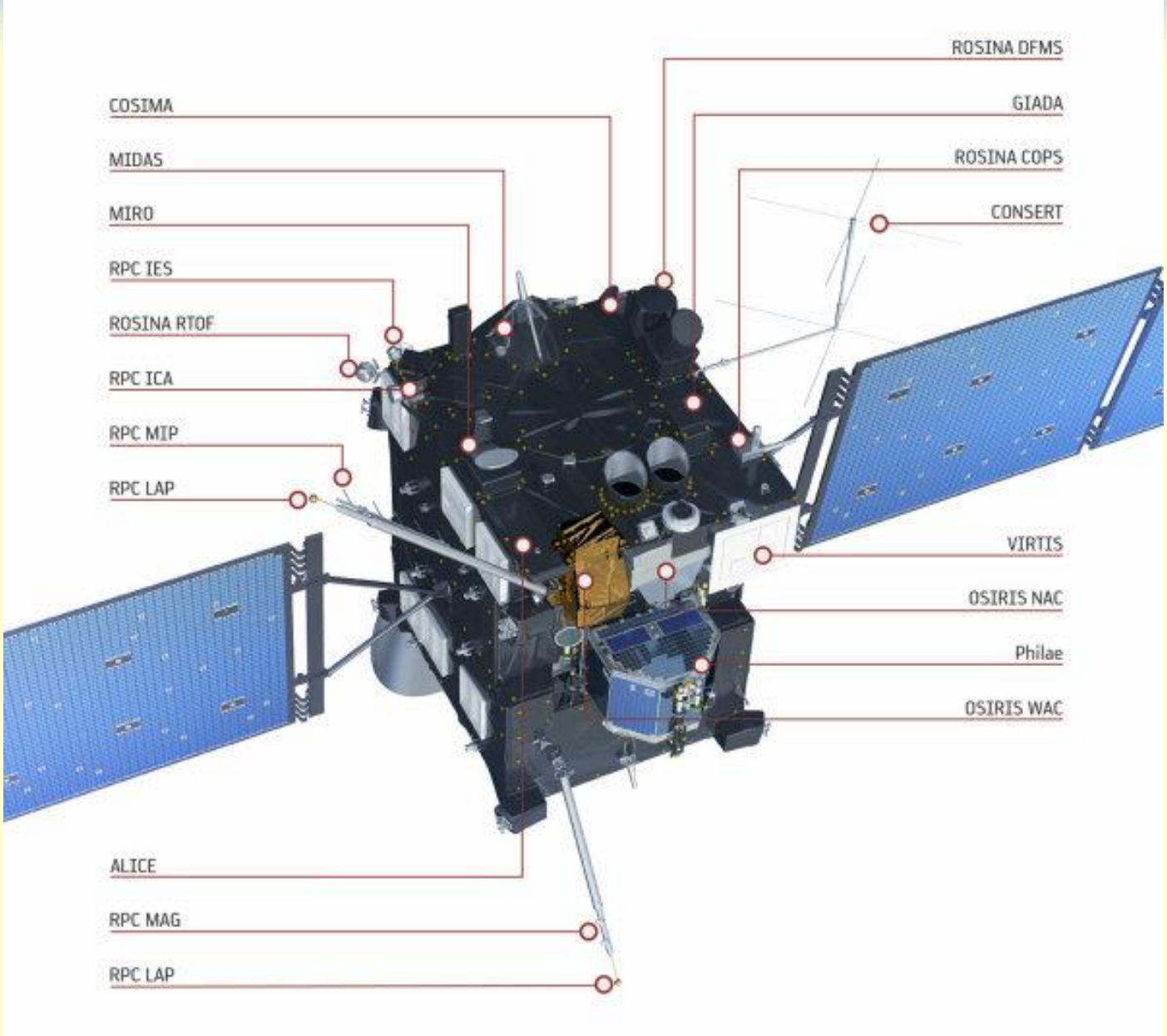
- **Passive**
  - X-ray Spectrometer
  - UV spectrometer
  - Vis/NIR camera
    - Imaging (high, medium resolution)
    - Stereo imaging
    - Hyperspectral imaging
  - NIR spectrometer (hyperspectral imager)
  - Thermal infrared spectrometer
  - Far IR radiometer

Imaging at all wavelengths

- Accelerometer
- Atomic particle spectrometers
- Dust telescope/sampling

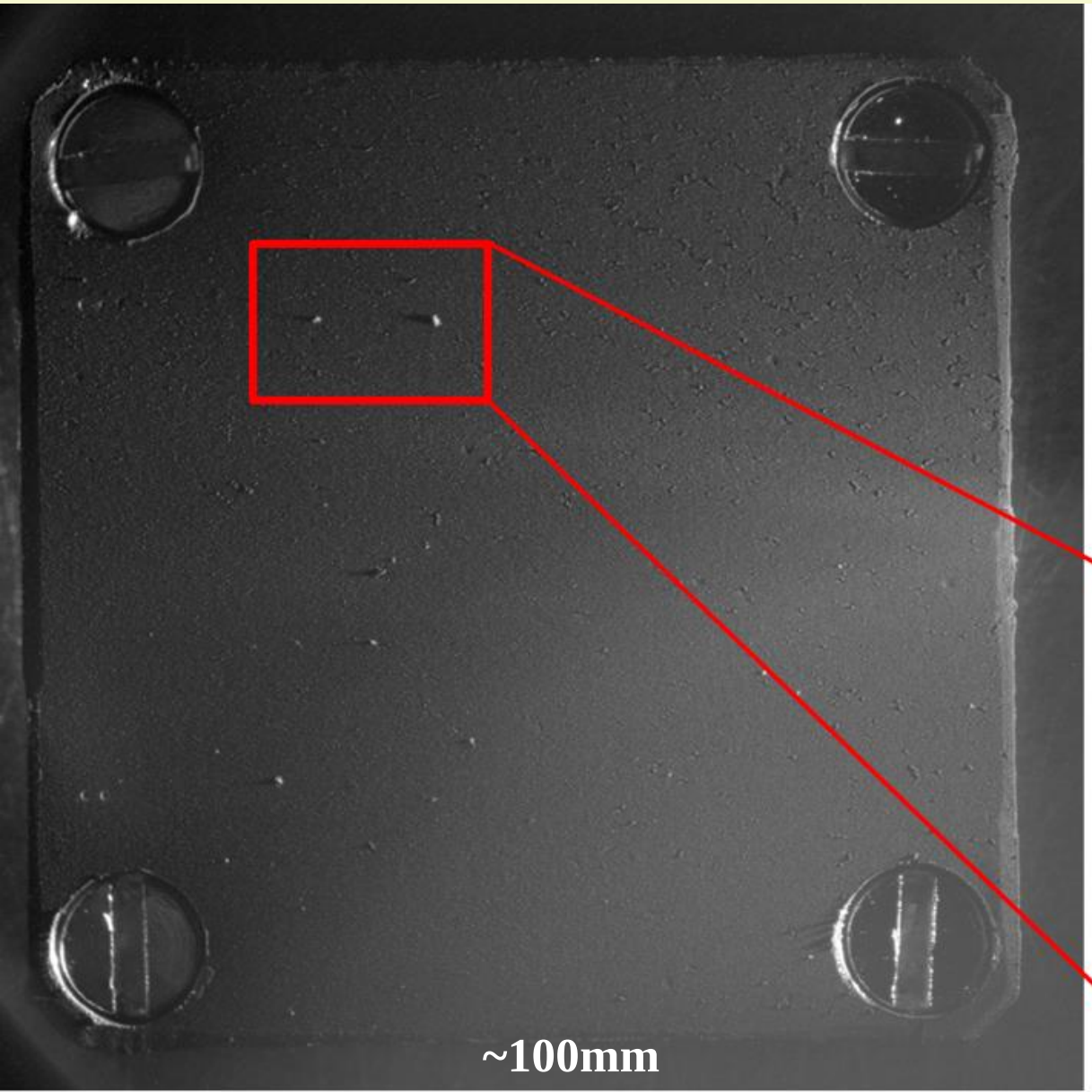
- **Active**
  - Radar reflectometer
  - Altimeter (radar/Laser)
  - Radio-science

Rosetta Science Instruments

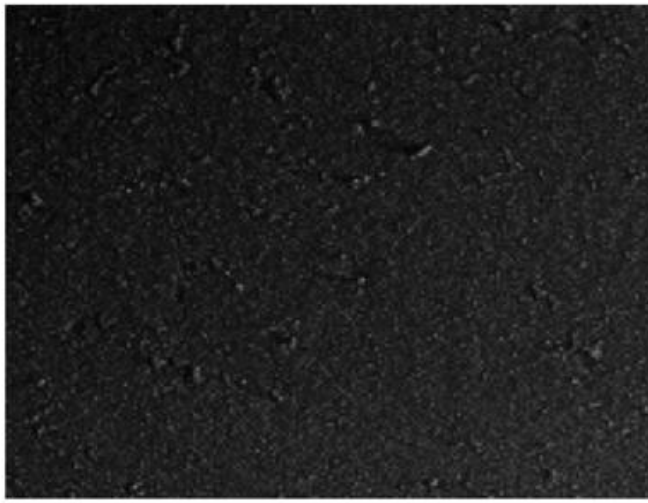


Sampling Dust

- COSIMA instrument is a time-of-flight (TOF) secondary ion mass spectrometer (SIMS) equipped with a dust collector, a primary ion gun, and an optical microscope (COSISCOPE) for target characterization. (19kg 20 W)
- Once one of the targets on the target wheel has been exposed to cometary dust it is moved in front of the microscope and imaged under shallow angle illumination provided by light emitting diodes.
- On-board image evaluation detects the presence and location of dust particles with diameters exceeding a few µm and calculates their position relative to the target reference point. Once the presence of features of interest is established, the target is moved in front of the mass spectrometer.



17/08/2014



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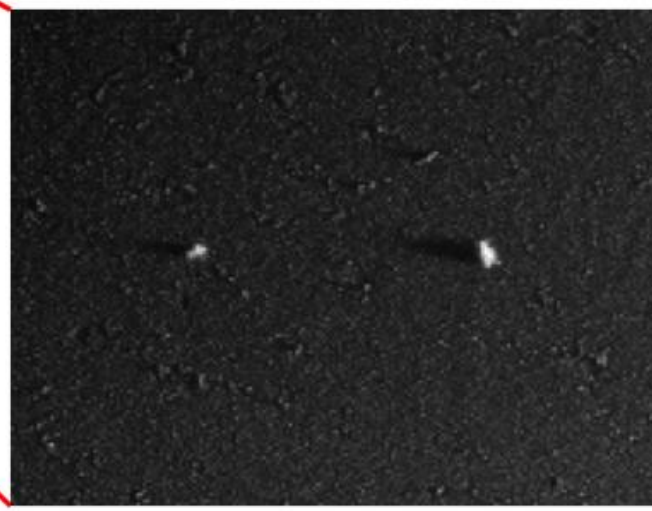
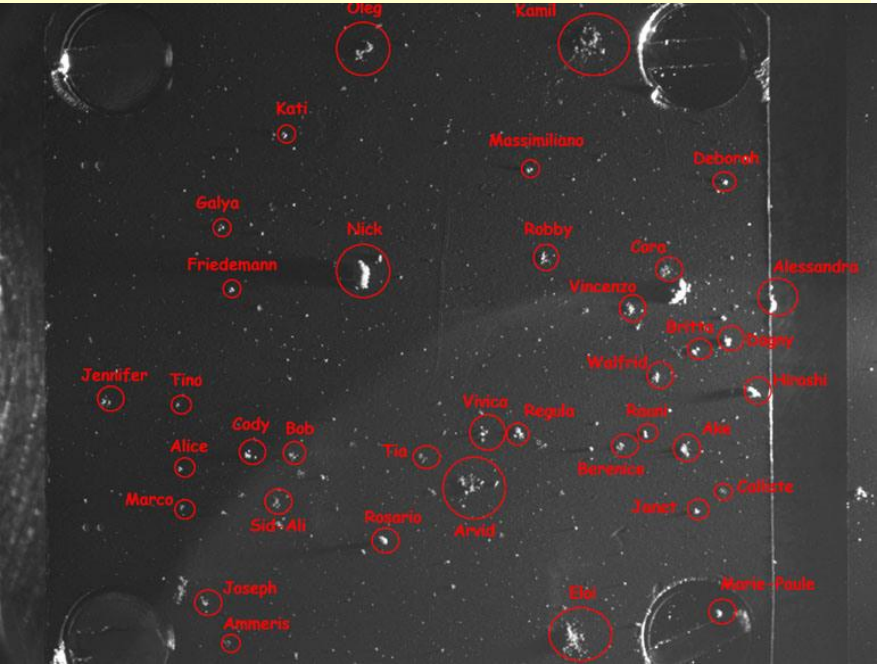
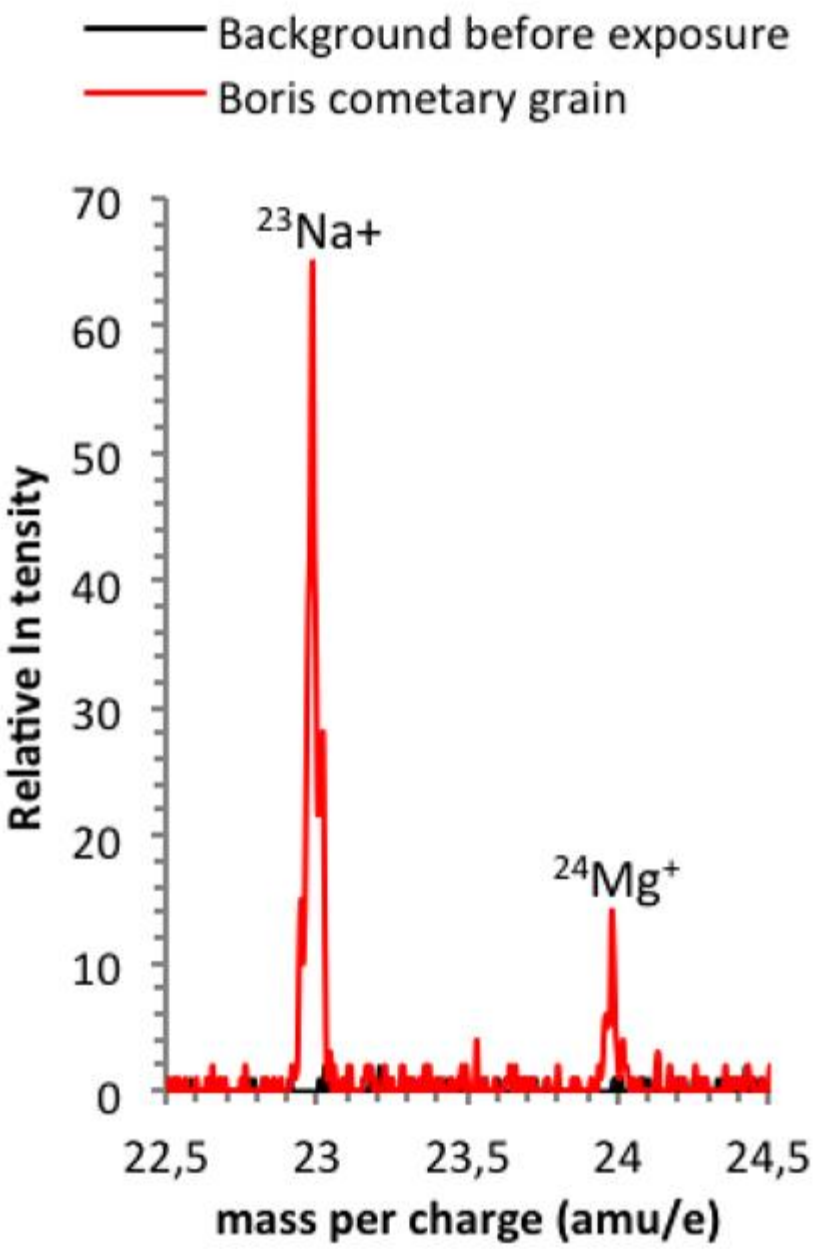


“BORIS”

- Magnesium expected in pyroxenes and olivine
- Sodium only seen before in cometary tail
- Trying to understand presence in refractory minerals





The “Comet Sniffer”

- ROSINA, the **R**osetta **O**rbiter **S**pectrometer for **I**on and **N**eutral **A**nalysis, determines the composition of comet's atmosphere and ionosphere, measure the temperature and bulk velocity of the gas and ions
- 3 sensor approach adopted where each is optimised for a part of the scientific objectives, while at the same time complementing the other sensors.
- the Double Focusing Mass Spectrometer (DFMS),
- the Reflectron Time of Flight Spectrometer (RTOF), and the
- Comet Pressure Sensor (COPS).
- 36 kg 50 W

Physical Structure Investigations

- Measure the mean dielectric properties and, through modelling, to set constraints on the cometary composition (like material and porosity)
- To detect large-scale embedded structures (several tens of metres), and stratifications
- To detect small scale irregularities within the comet
- The CONSERT experiment on the orbiter and on the lander both consist of a transmit/receive antenna and a transmitter and receiver contained in a common box. 3kg box + antenna

CONSERT

- A 90 MHz radio signal, phase modulated with pseudo-randomly encoded data is transmitted from the orbiter towards the comet
- The signal propagates through the comet nucleus and is received on the lander. The transmission cycle is repeated every 200 m seconds.
- The received signal is digitised and accumulated in the lander in order to increase the S:N ratio. The signal compressed to obtain a time/space resolution corresponding to 100 nanoseconds/20m
- Lander signal processing determines the position of the strongest path, then transmits the same pseudo-random code with a delay corresponding to that of the strongest path. The signal propagates back to the orbiter along virtually the same path, (orbiter not travelled far during the measurement cycle). The signal accumulated and stored in the memory in order to be sent to Earth. (cycle ~1 second.)
- Change in propagation delay, phase and amplitude is signature of dielectric changes and tomography

Plasma Measurements – multi sensors and objectives

- an Ion Composition Analyser (ICA)
  to measure the three-dimensional velocity distribution and mass distribution of positive ions
- an Ion and Electron Sensor (IES)
  simultaneously measure flux of electrons and ions in the plasma
- a Langmuir Probe (LAP)
  measure the density, temperature and flow velocity of the plasma
- a Fluxgate Magnetometer (MAG)
  to measure the magnetic field in the region where the solar wind plasma interacts with the comet
- a Mutual Impedance Probe (MIP)
  to derive the electron gas density, temperature, and drift velocity in the inner coma of the comet

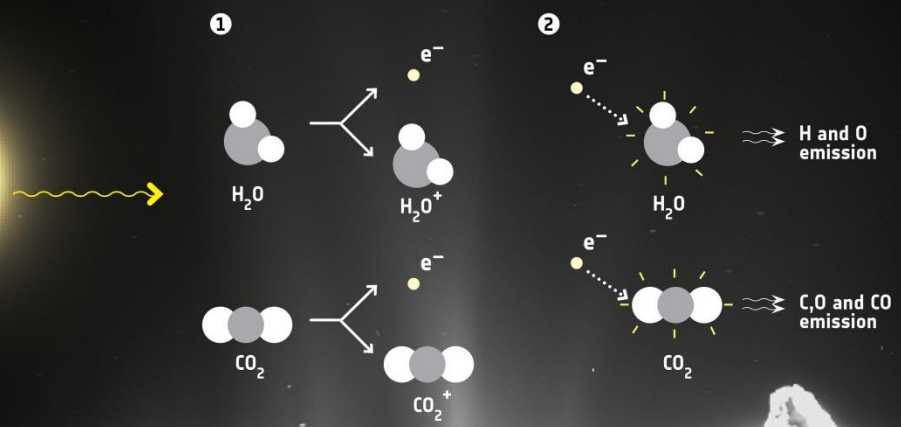
UV spectroscopy (70-200nm)

- Light enters the Alice telescope through a 40 × 40 mm entrance aperture and is collected and focused by an off-axis paraboloidal primary mirror onto the approximately 0.1° × 6° spectrograph entrance slit.
- After passing through the entrance slit, the light falls onto the toroidal holographic grating of a Rowland Circle style imaging spectrograph, where it is dispersed onto a microchannel plate detector. **The 2-D** (1024 × 32 pixel) format MCP detector uses dual, side-by-side, solar-blind photocathodes of potassium bromide (KBr) and cesium iodide (CsI). The spectral resolving power ($\lambda/\Delta\lambda$) of Alice is in the range of 105 - 330 for an extended source that fills the instantaneous field-of-view defined by the size of the entrance slit.
- 3kg / 5 W

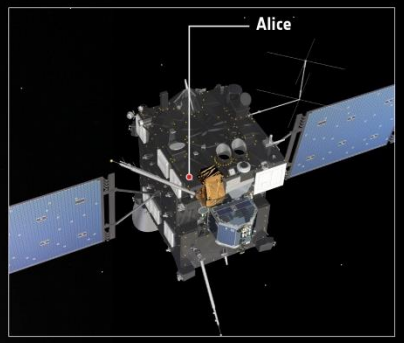
In-situ cf. measurements in tail

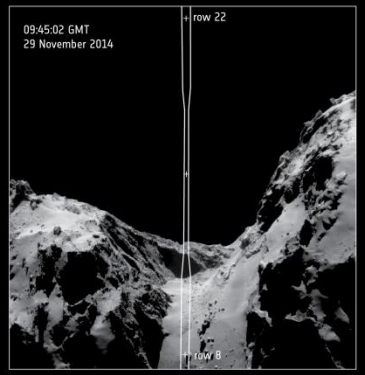
- **Role of electrons near surface instead of sunlight in tail**

Rosetta's close study of Comet 67P/Churyumov–Gerasimenko at ultraviolet wavelengths has revealed that electrons and not photons are responsible for the rapid breakup of water and carbon dioxide molecules erupting from the surface.



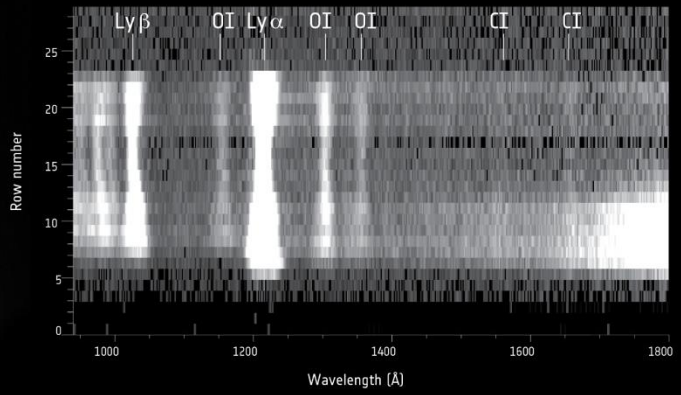
1 Solar photons ionise comet water and carbon dioxide molecules, producing electrons
2 Electrons impact other water and carbon dioxide molecules, creating emission detected by Alice





The data were collected between August and November 2014

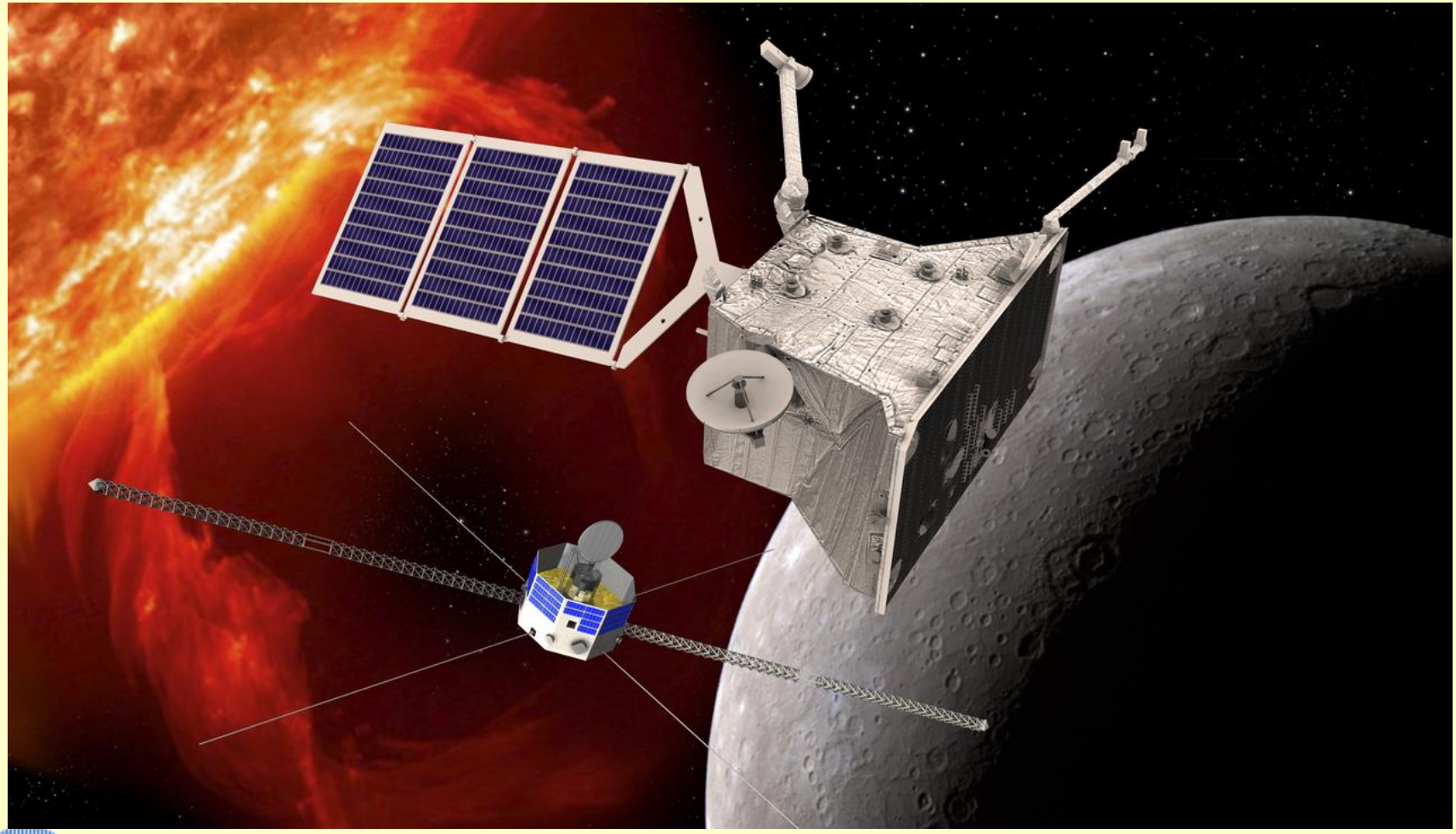
Example of a spectral image (below) obtained by Alice for positions in the comet's coma indicated in the NavCam image (above). The emission by oxygen (OI) and carbon (CI) in the coma are indicated. The bright bands labelled Lyα and Lyβ are due to electron impact on H_2O.



www.esa.int

Spacecraft: ESA/ATG medialab; Comet: MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; ESA/Rosetta/NavCam – CC BY-SA IGO 3.0; data: Feldman et al, 2015

European Space Agency



Example: Science of BepiColombo Mercury Mission

Complete description of Mercury and its environment

Interior ⇔ Surface ⇔ Exosphere ⇔ Magnetosphere

Interior

State of Core
Crust Thickness
-Mass
-Figure & topography
-Moments of inertia
-Magnetic field
-Surface heat flow
Composition of Core

Surface

Composition
-elemental
-mineralogical
Geological History
-geomorphology
-physical properties

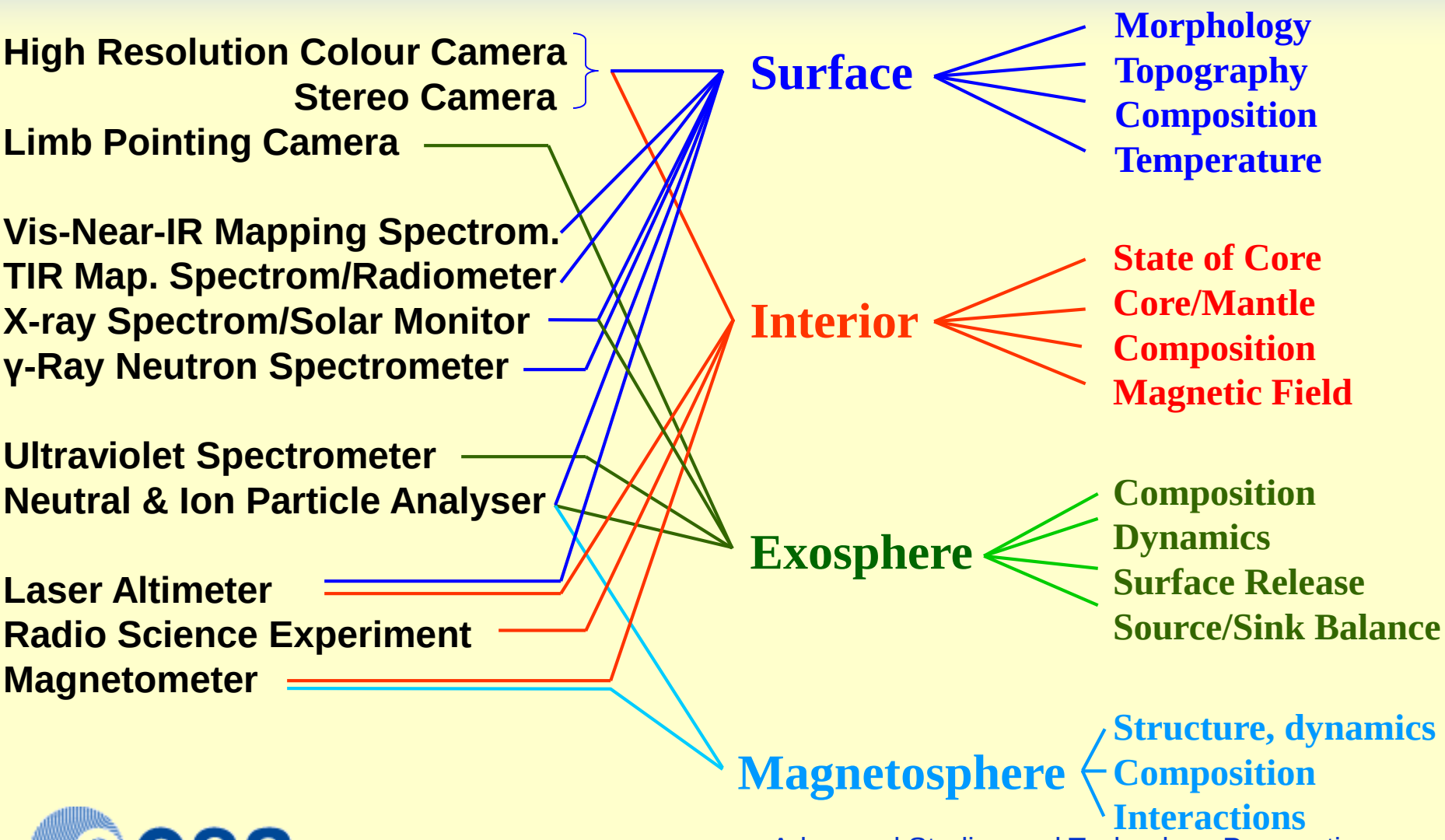
Exosphere

Composition
Vertical structure
Dynamics
Release processes
Source/sink balance

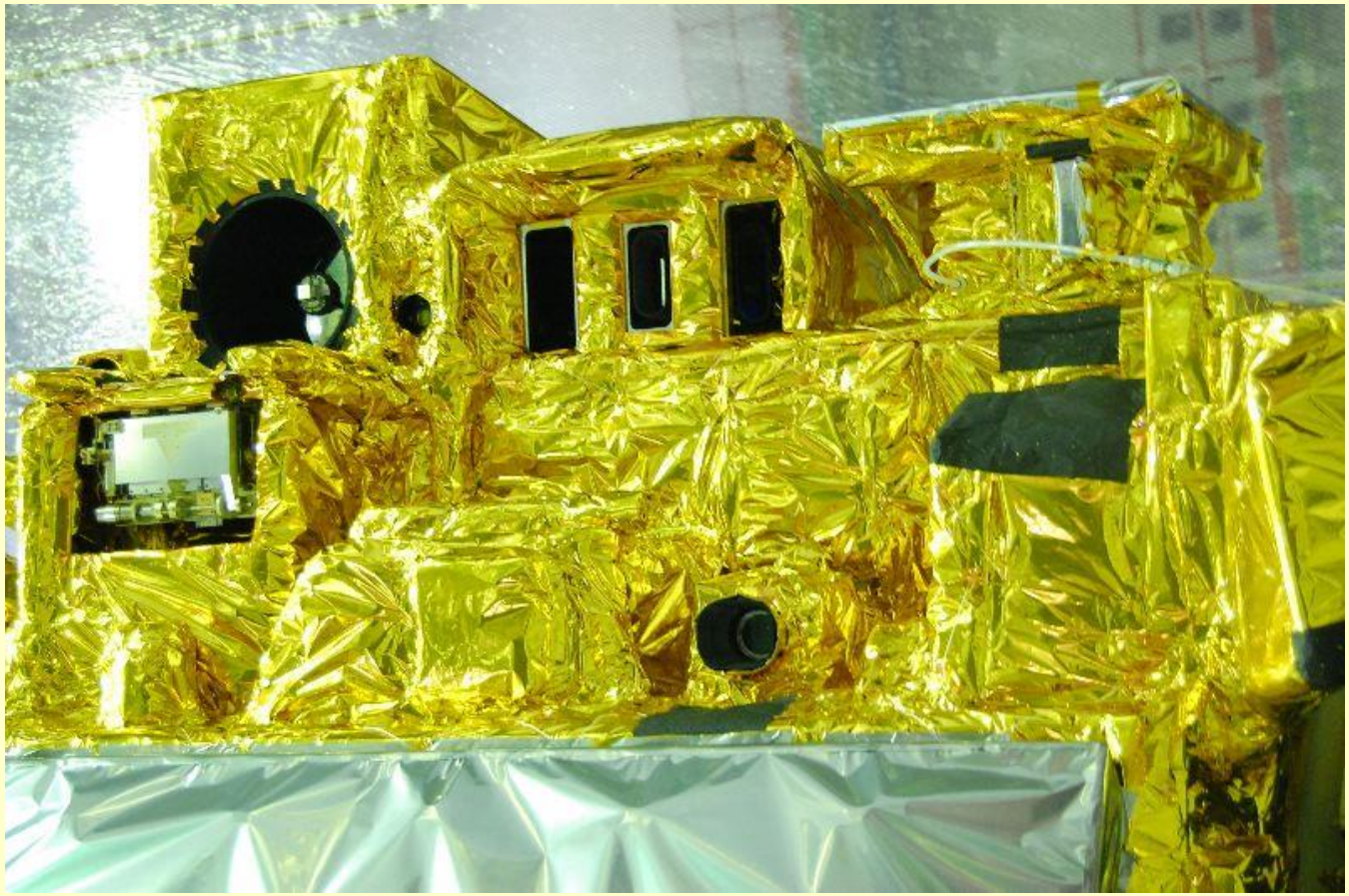
Magnetosphere

Size
Structure & Dynamics
Temporal variability
Interaction with
- Solar wind
- IMF
- Exosphere
- Surface

Instrumentation



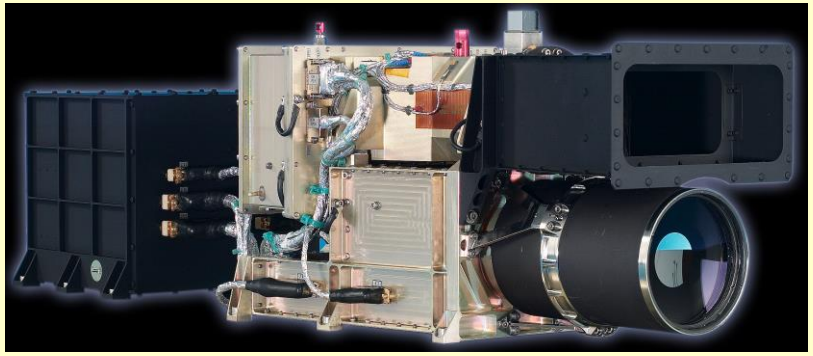
Nadir Looking Instruments on Chandrayaan-1



Visible Camera

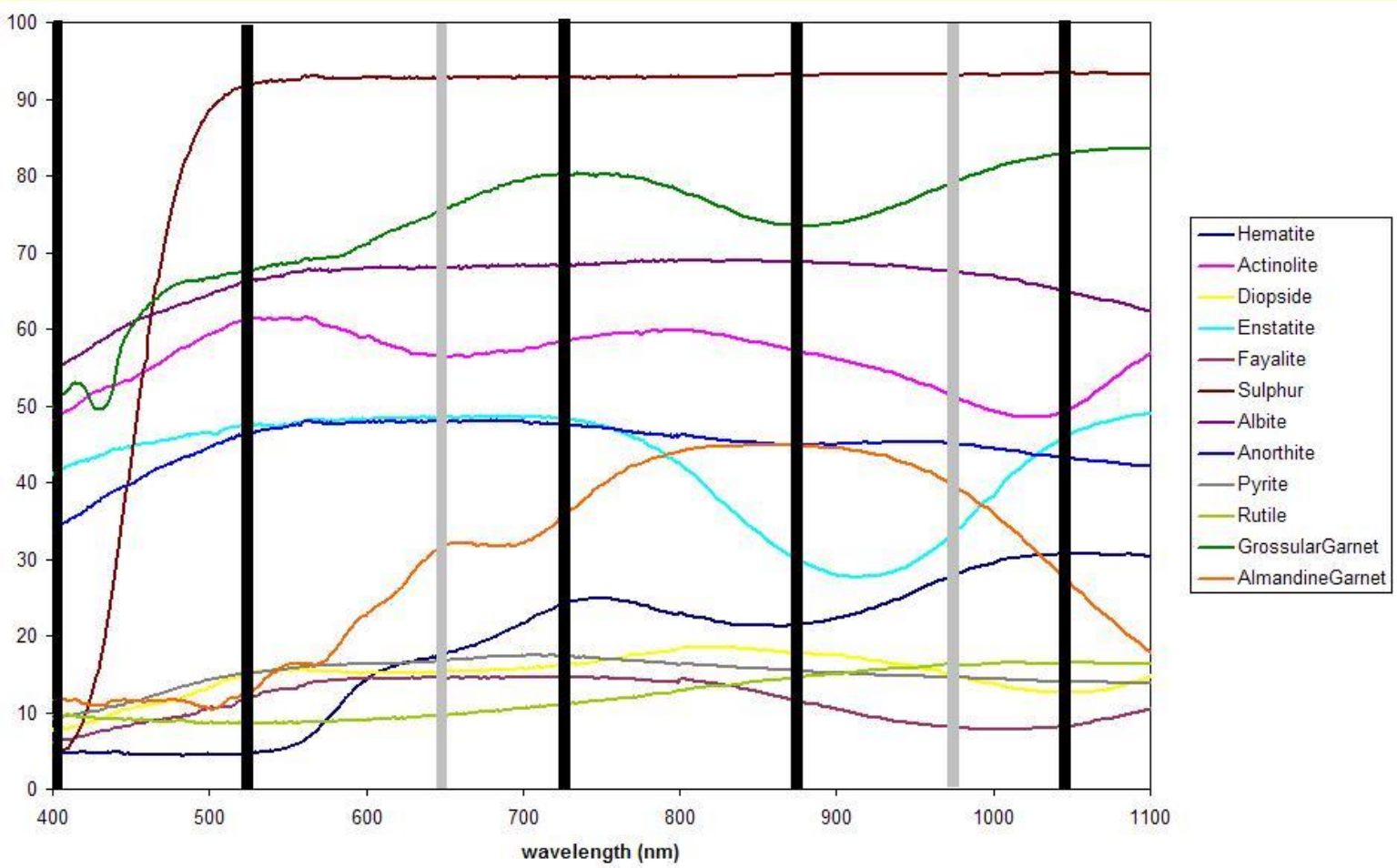
- Mapping
- Surface investigations on morphology, topography, composition
- Spatial resolution as high as possible
- Limited number of filters
- Stereo imaging

AMIE/SMART-1

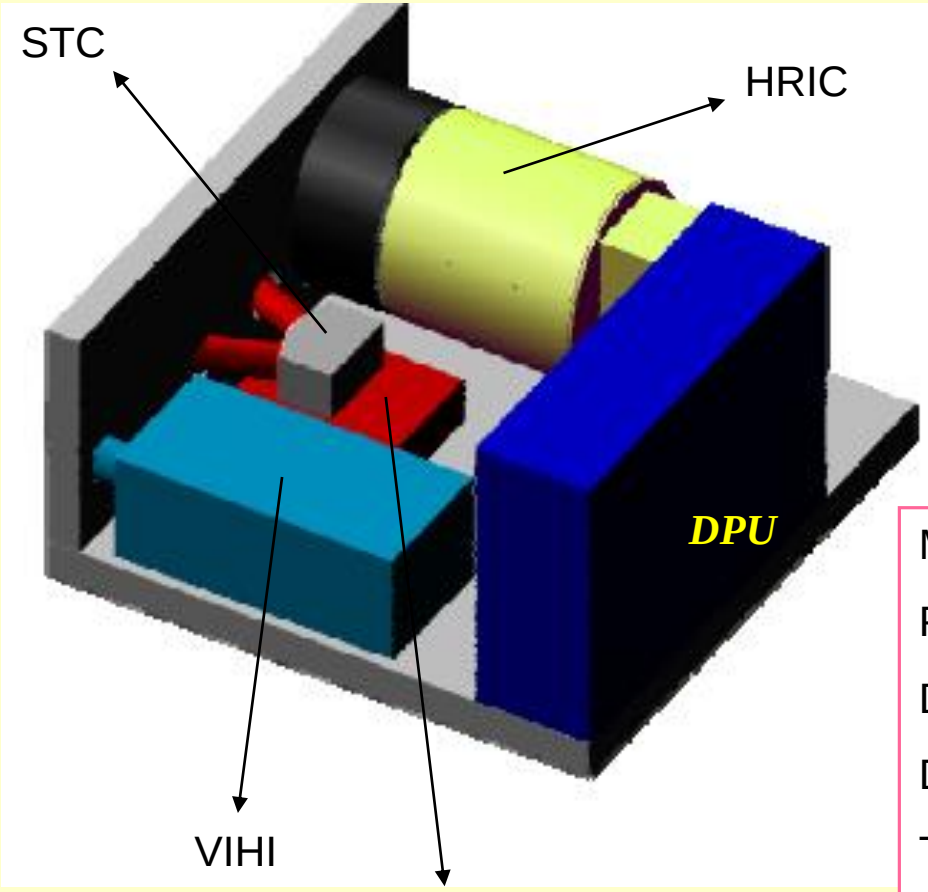


HRSC-SRC/Mars Express 20kg / 40W

Vis Camera Filters



BepiColombo: SIMBIOSYS



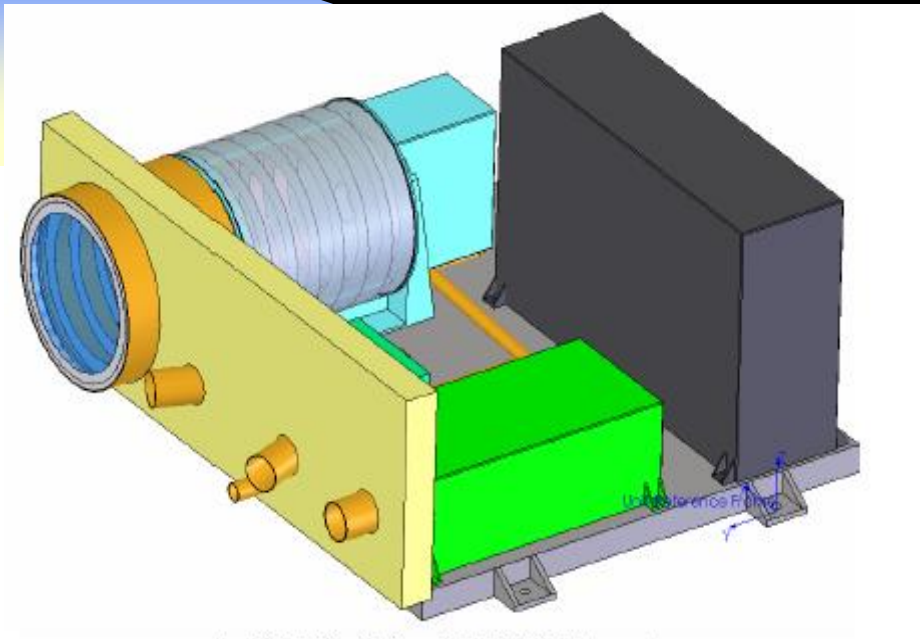


Fig.:3.2.2.1: Overall view of SIMBIO-SYS Instrument

Mass: 9.1 kg including DPU

Power (all on) 33 W

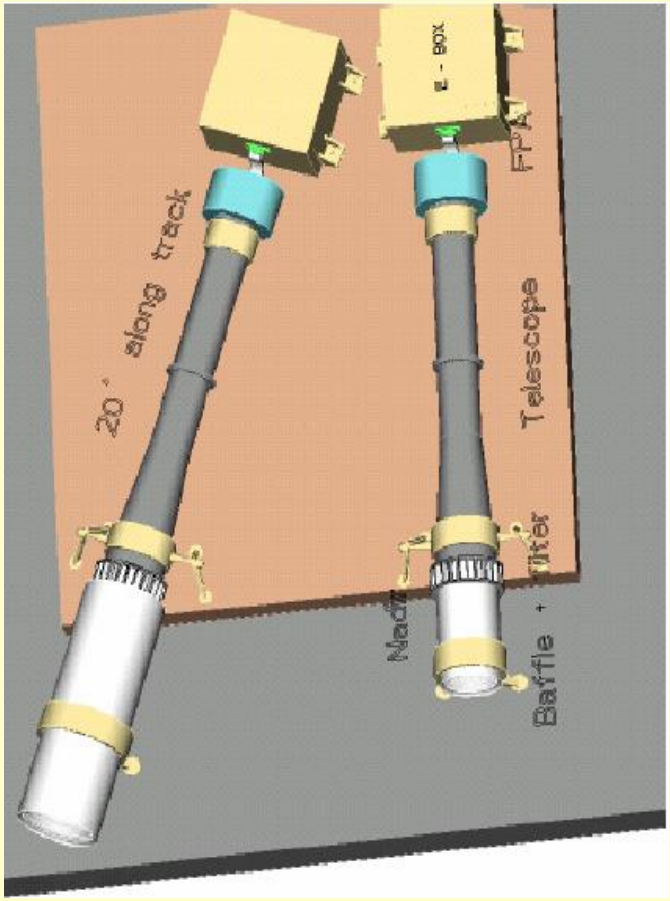
Dimensions: 400 x 400 x 200 mm^3

Data Volume (4 Hermean years)1200Gb

Telemetry 4.2 / 8.2 Mps (ave/peak)

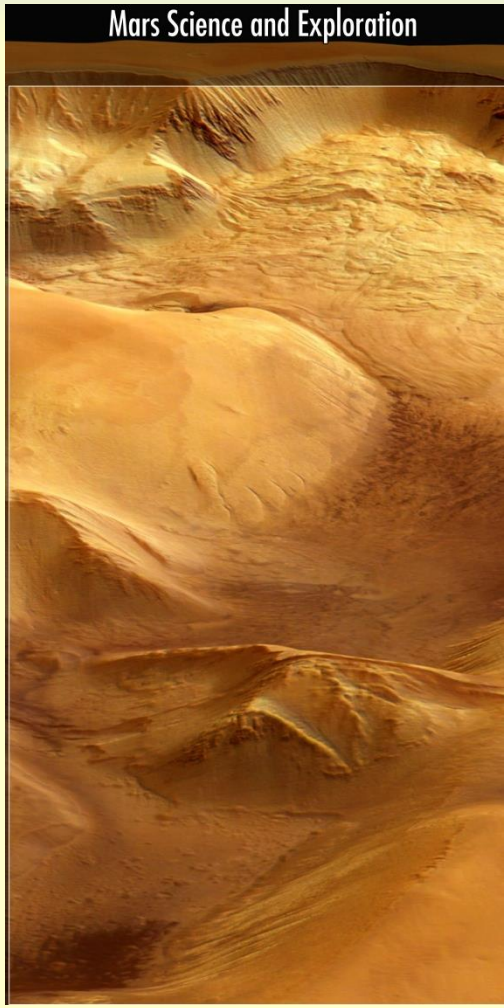
Temperature -50 °C for VIHI, –20 °C /+30 °C

BepiColombo: BEPICAM



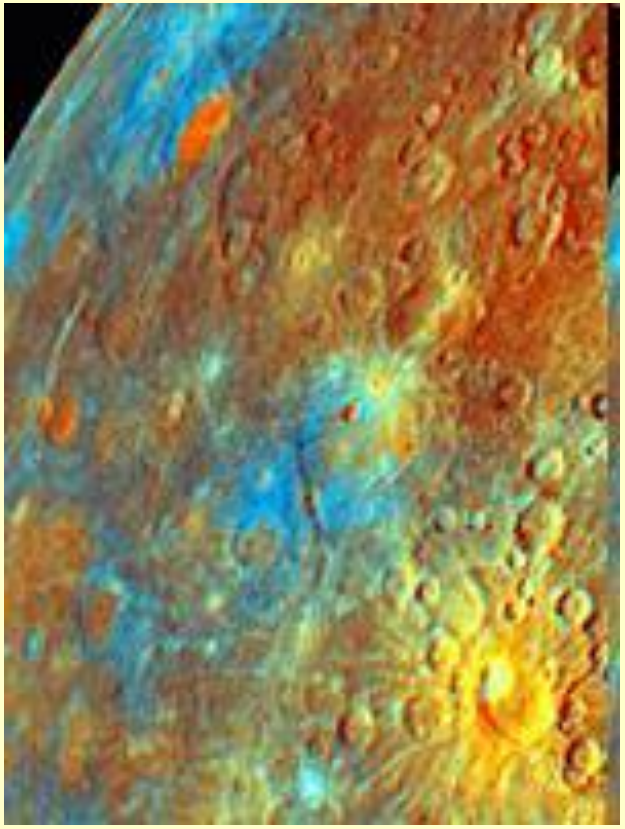
In-flight direction

- **Dual camera system for global and high resolution imaging**
  - High resolution up to 10 m/px, 5m/px
  - 20° tilt angle provide stereo viewing
  - Mass: 4.77 kg, incl. DPU and margin
  - Power 3 / 7 W depending on observation mode
  - One DC/DC for each optical head
  - Dimensions : 600 x 400 x 100 mm^3

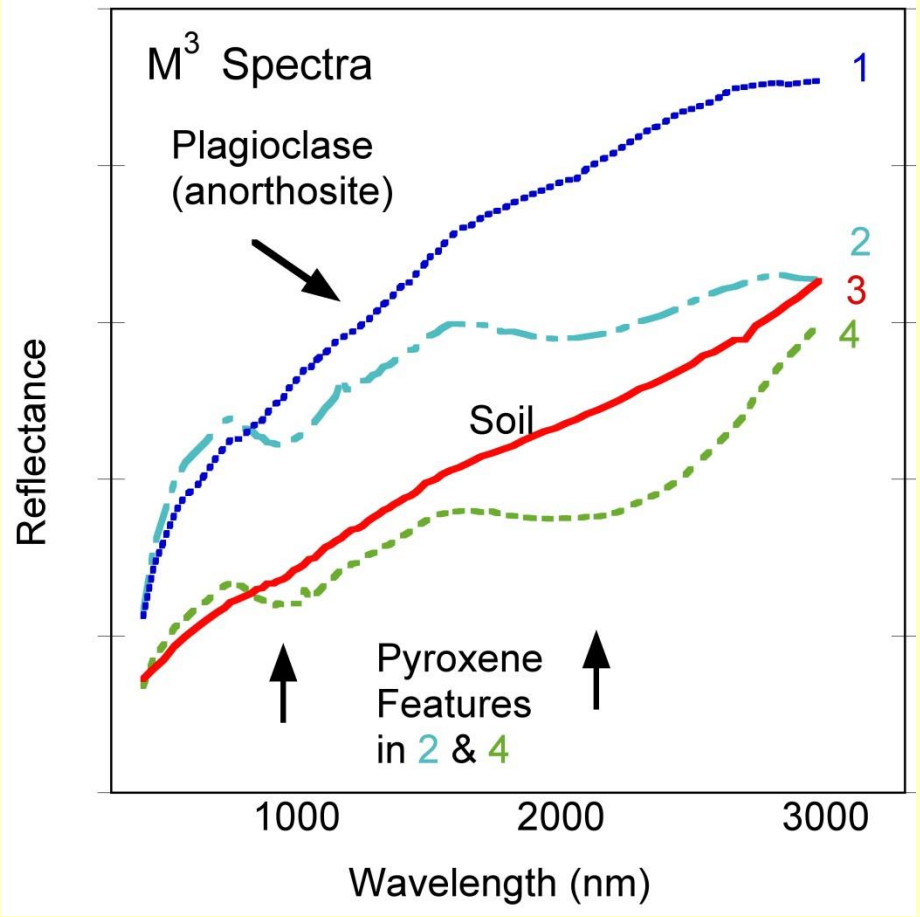


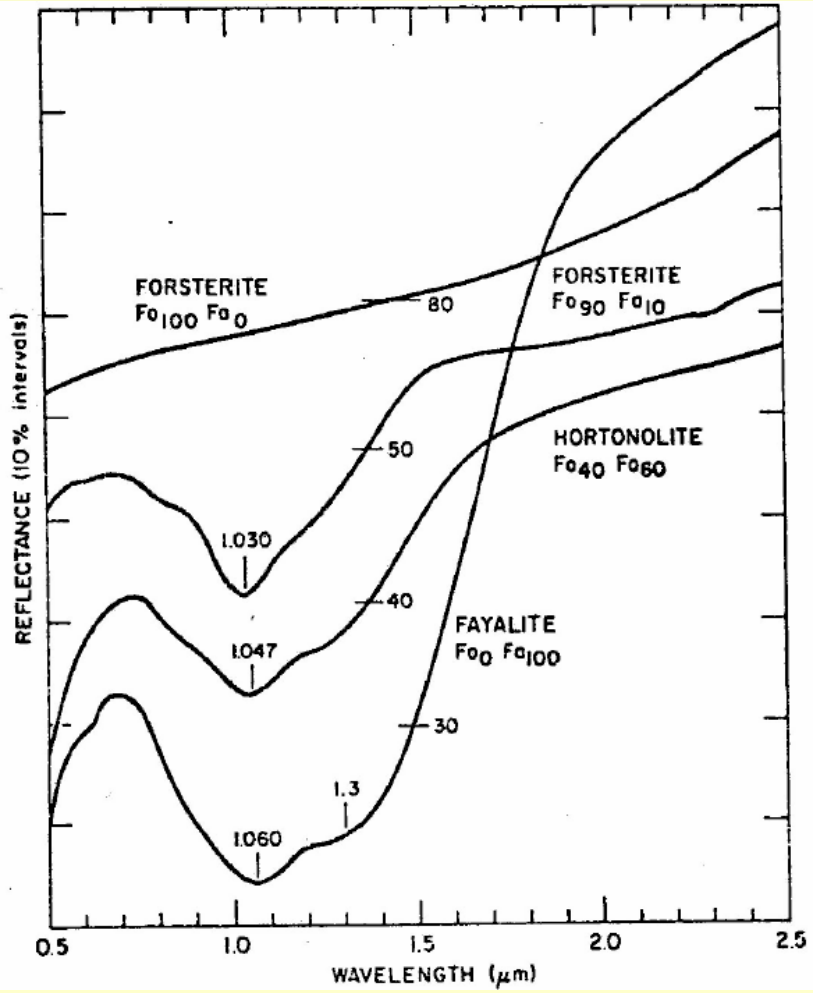
NIR Measurements

- Surface investigations on geology, composition
- Spatial resolution as high as possible
- Surface spectroscopy ($\Delta\lambda \approx 10$ nm)

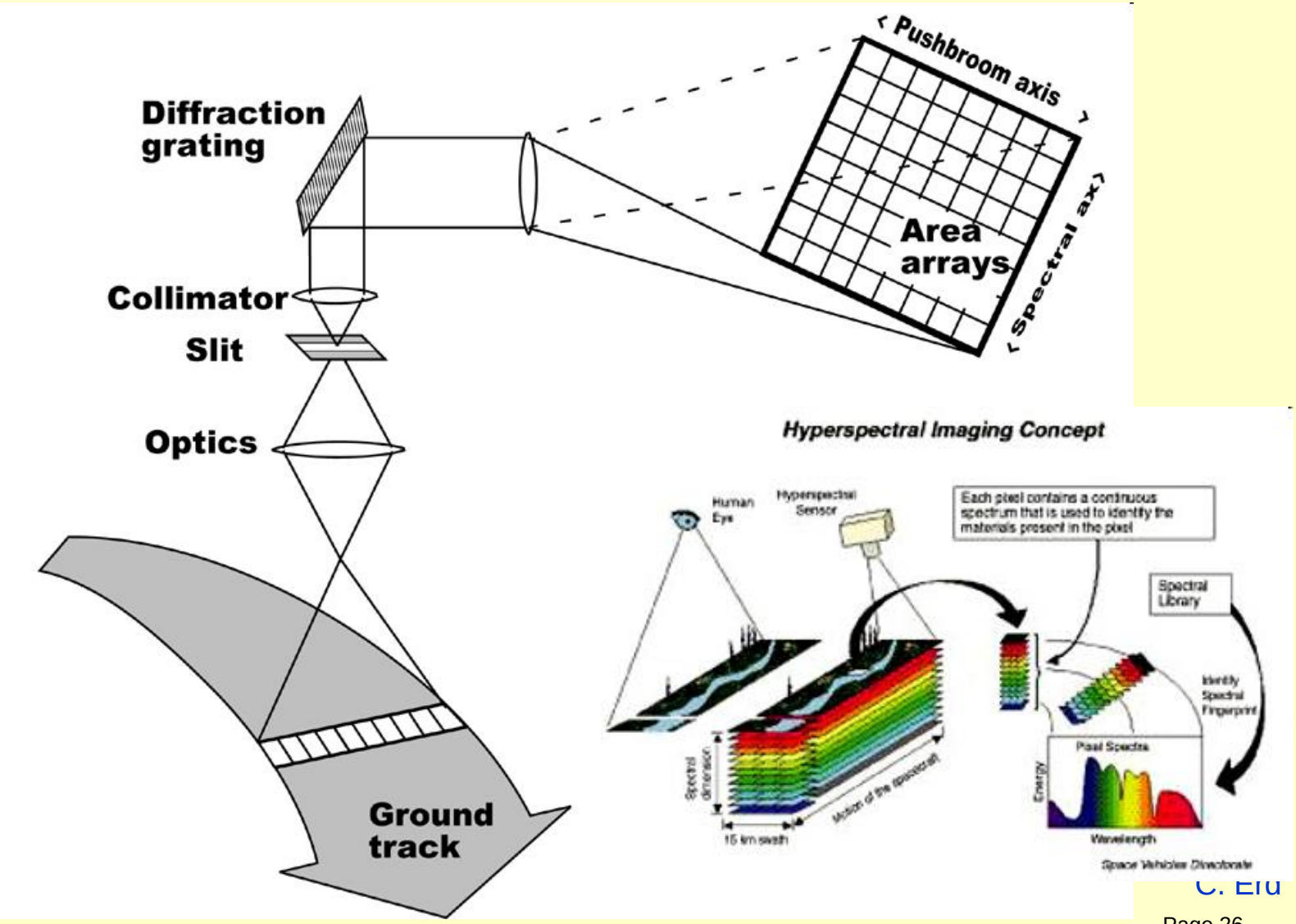


NIR Spectroscopy Requirements

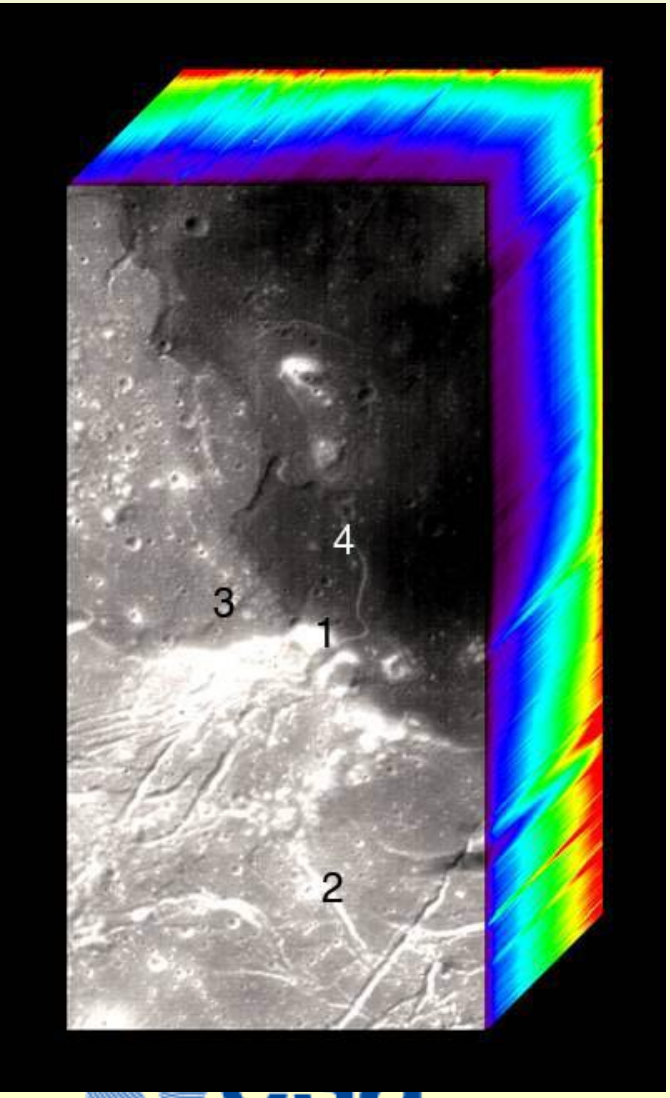


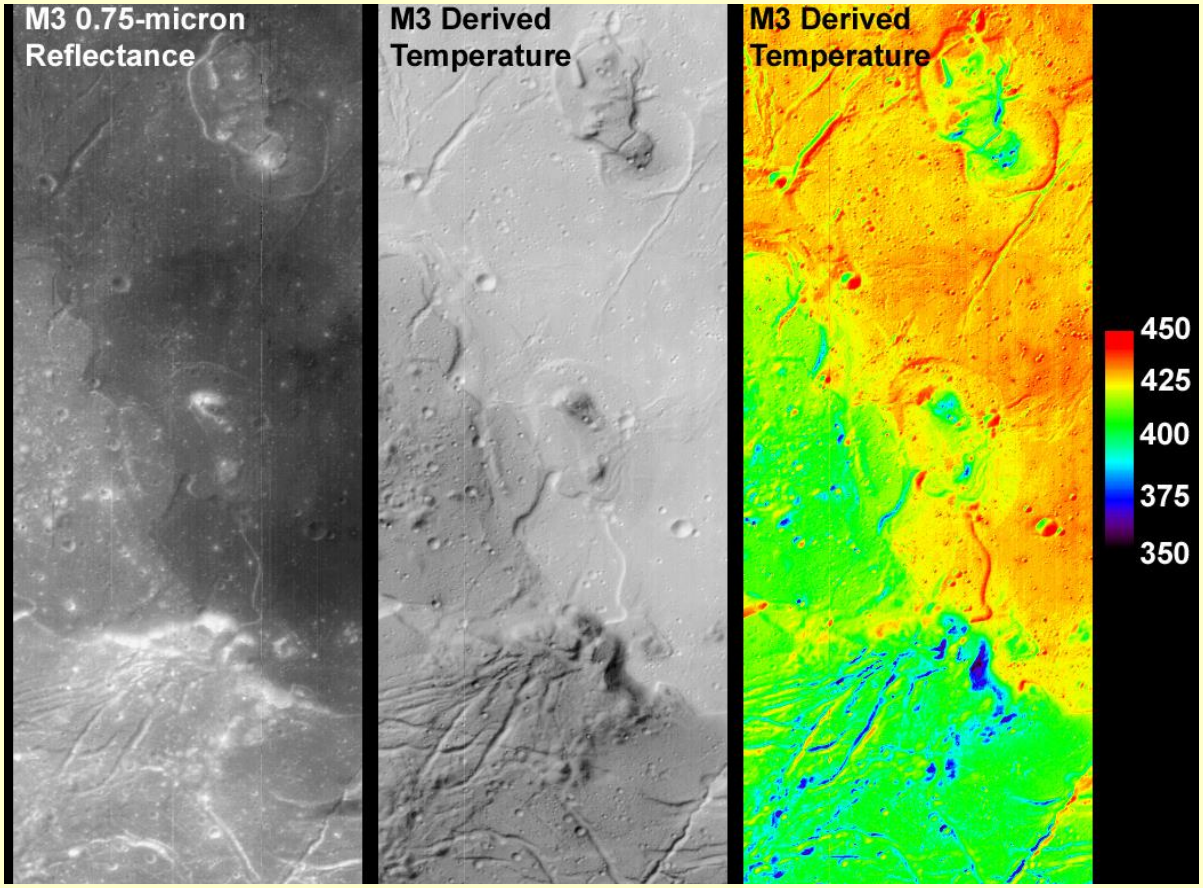


Hyperspectral Imaging – “Push Broom”

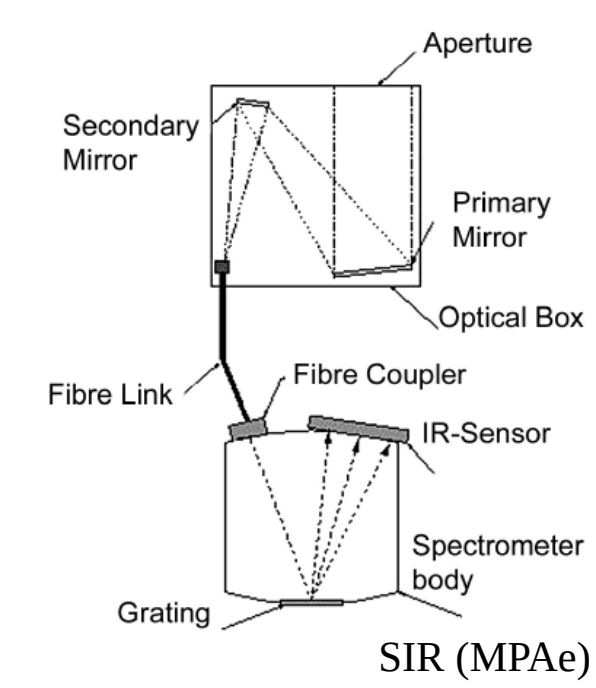


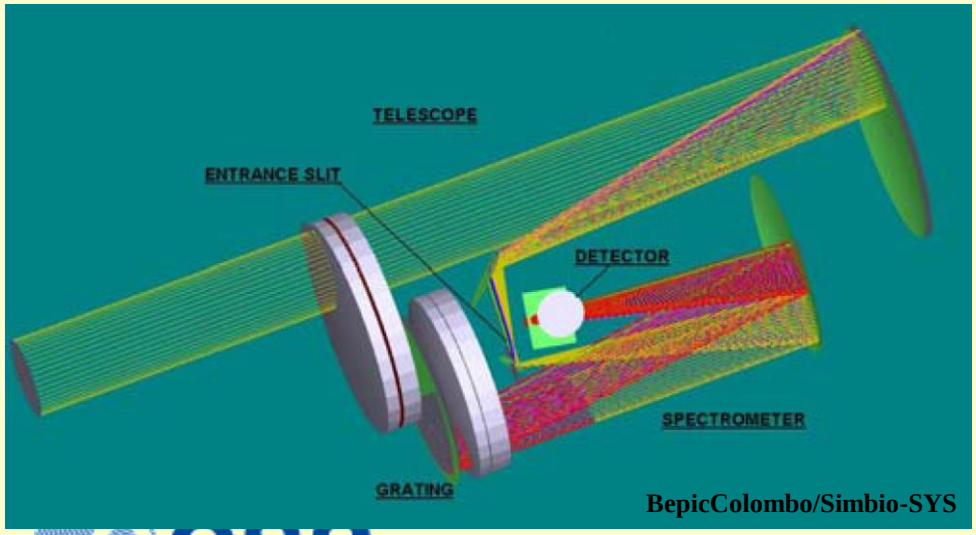
Hyperspectral Imaging

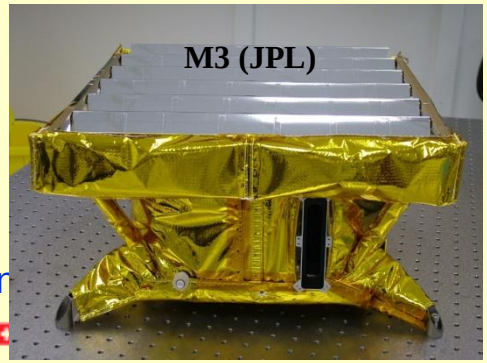




NIR Instruments

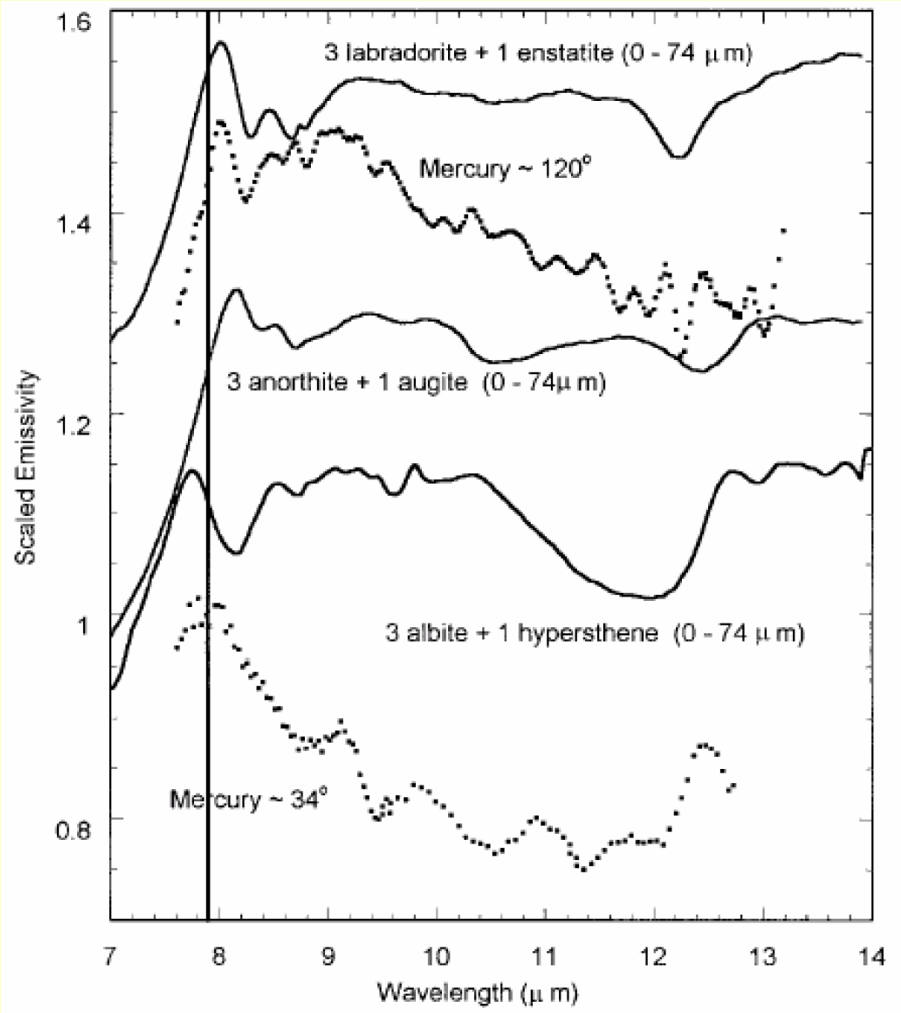






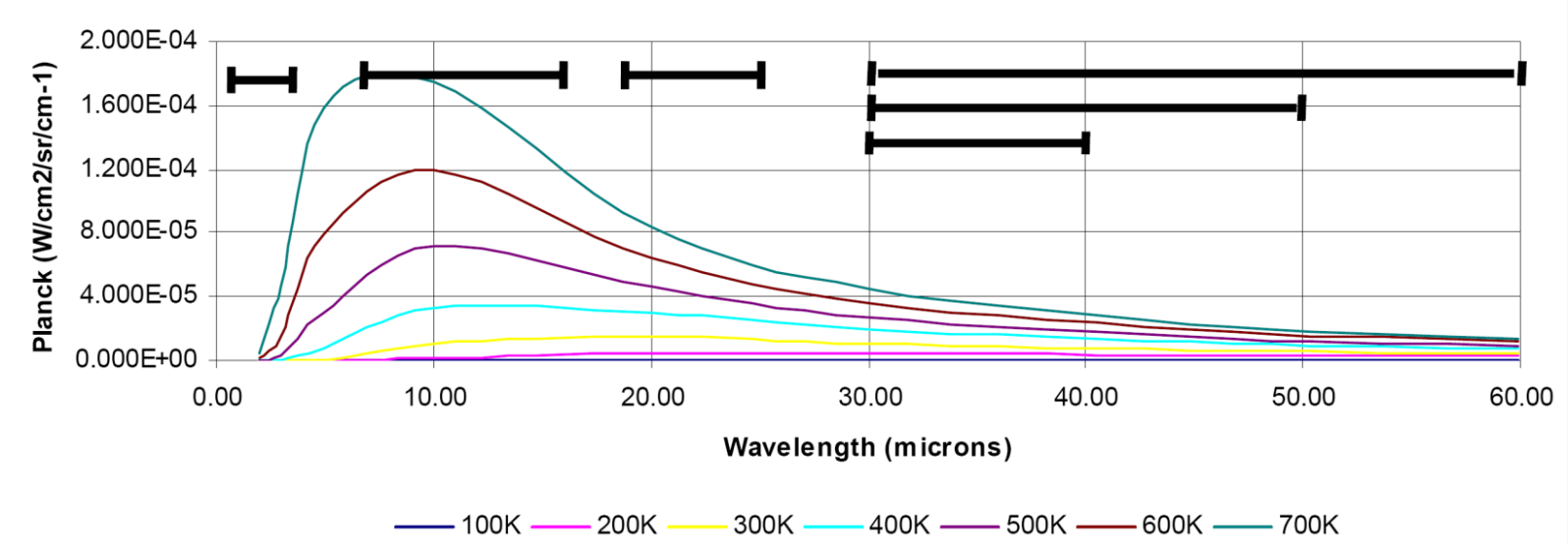
Thermal IR Spectrometer

- Geology, structure of surface materials
- Thermal IR range 7 – 15 µm
- Spectral resolution $\Delta\lambda \approx$ 100 – 200 nm (variable)
- Uncooled microbolometer and grating



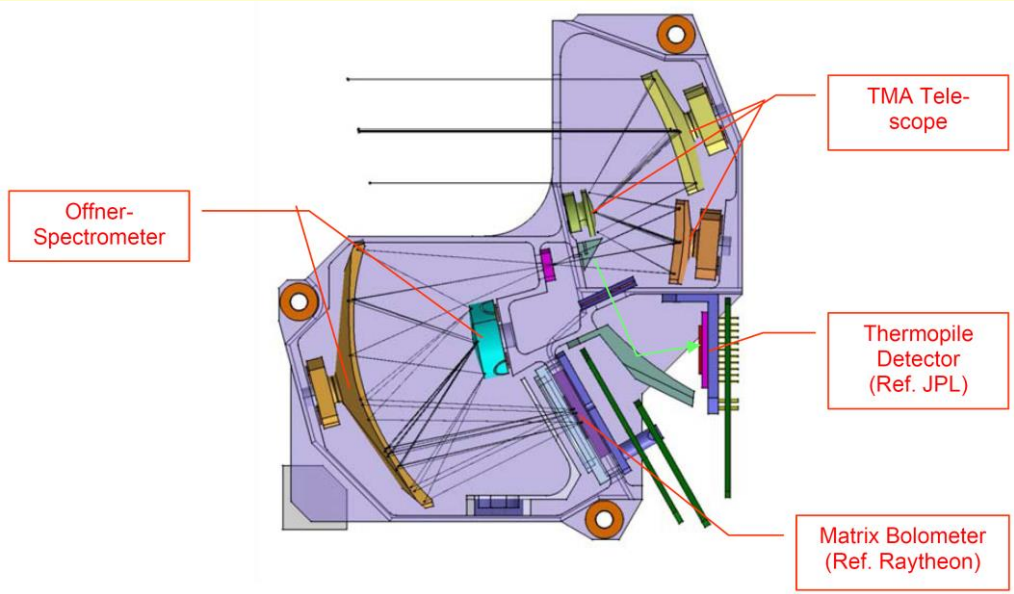
Thermal IR Radiometer

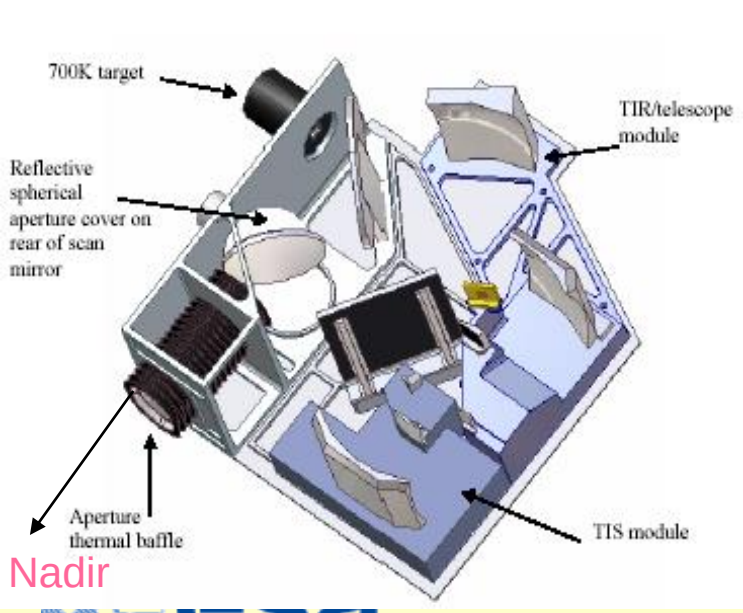
- Thermal conductance and capacitance measurements
- Characterization of bulk body or atmosphere
- Typically 15 – 40 (60) µm, $\Delta\lambda \approx 5 – 20$ µm
- Broad spectral range
- Low resolution

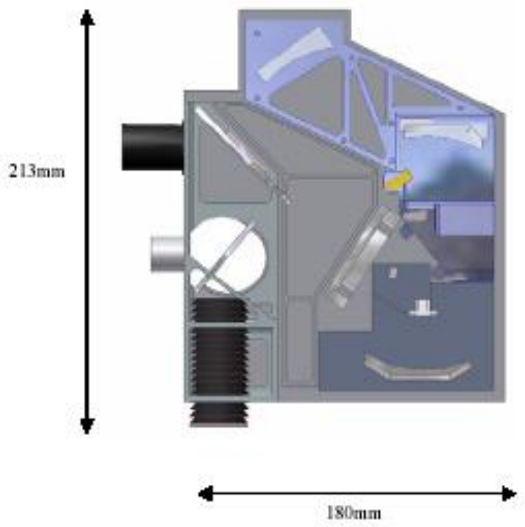


BepiColombo: MERTIS TIR & TIS

Mercury Thermal Infrared Spectrometer Suite





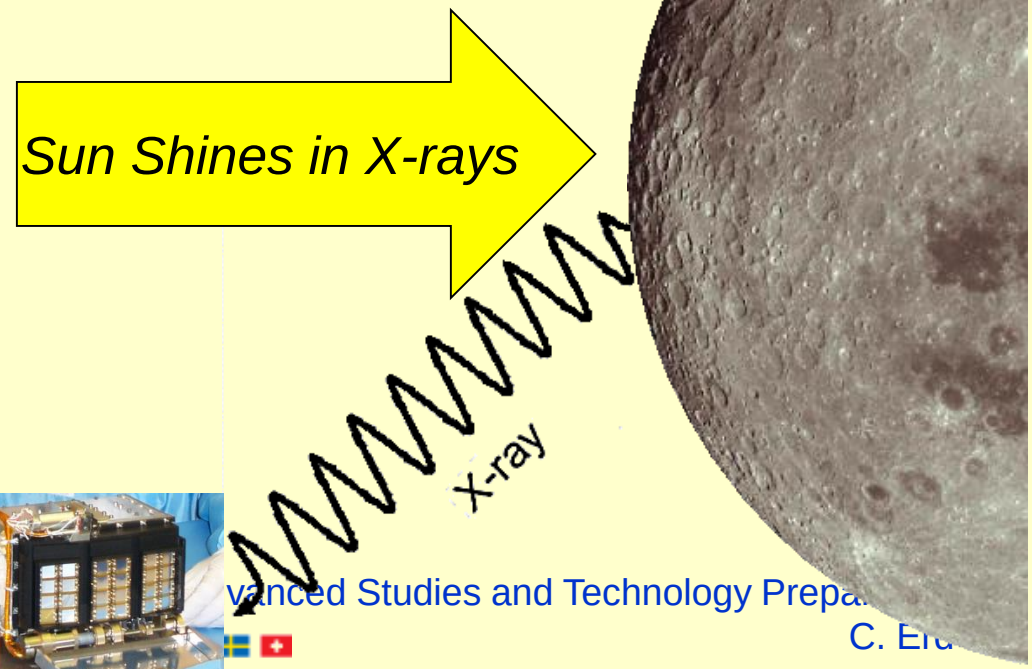


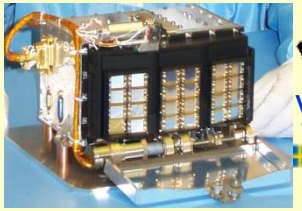
Technology Preparation
C. Erd

X-Ray Spectrometer

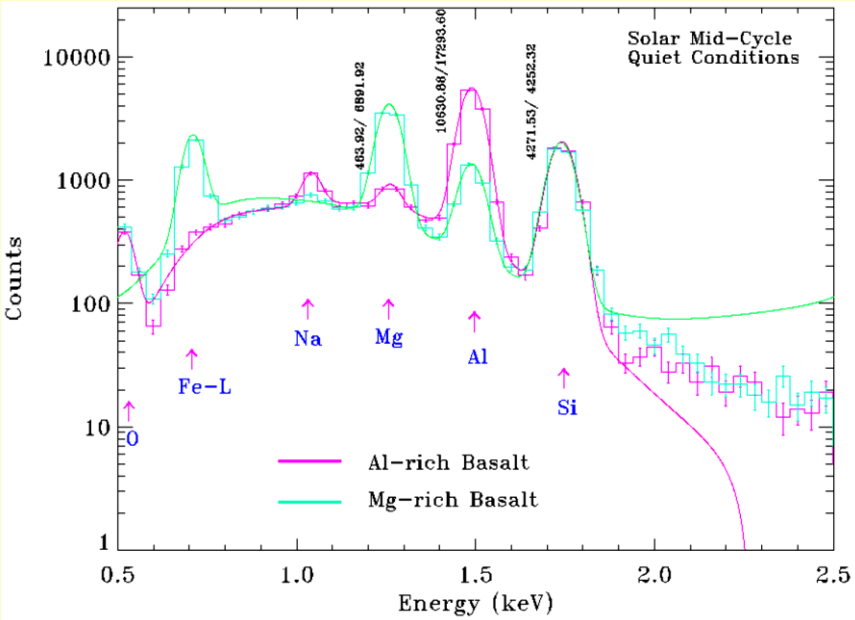
- Elemental composition of surface material
- Good complement to NIR (cristallography/geology observations)
- Main application for atmosphere-less bodies

1. The Sun shines on the Moon (in X-rays)
2. The Moon fluoresces (in X-rays)
3. Each X-ray energy indicates unambiguously the presence of a particular element
4. C1XS detects these X-rays
5. Solar Monitor for Solar Input required for absolute abundances





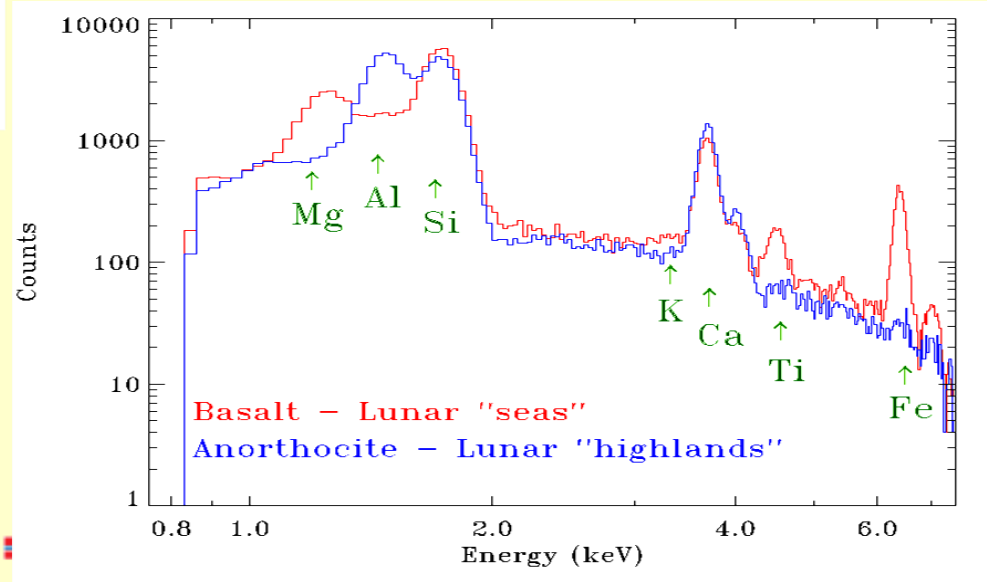
X-ray spectrum



(quiet conditions)

Simulated spectra
for D-CIXS onboard Smart-1

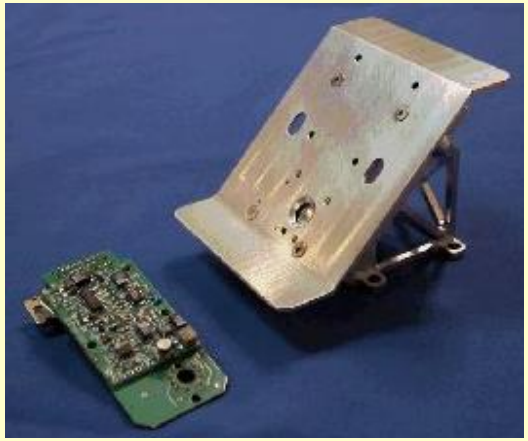
(flare conditions)

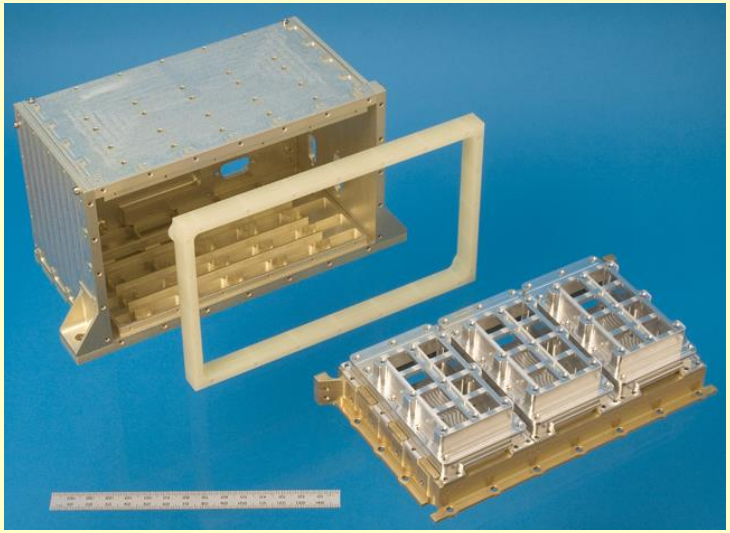


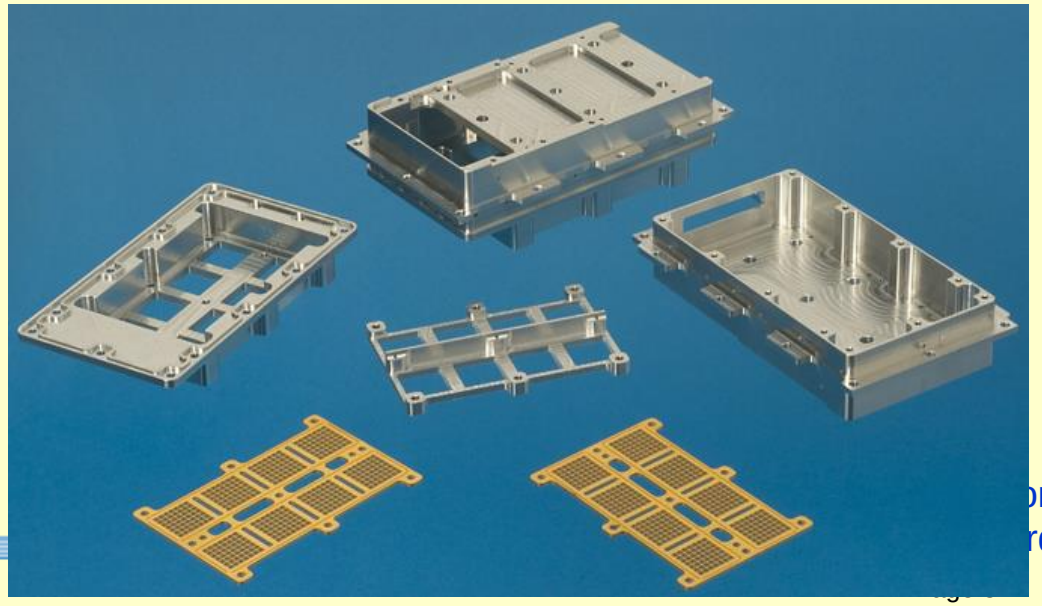
(Grande et al)

CIXS (SMART-1, Chandrayaan-1, BepiColombo)

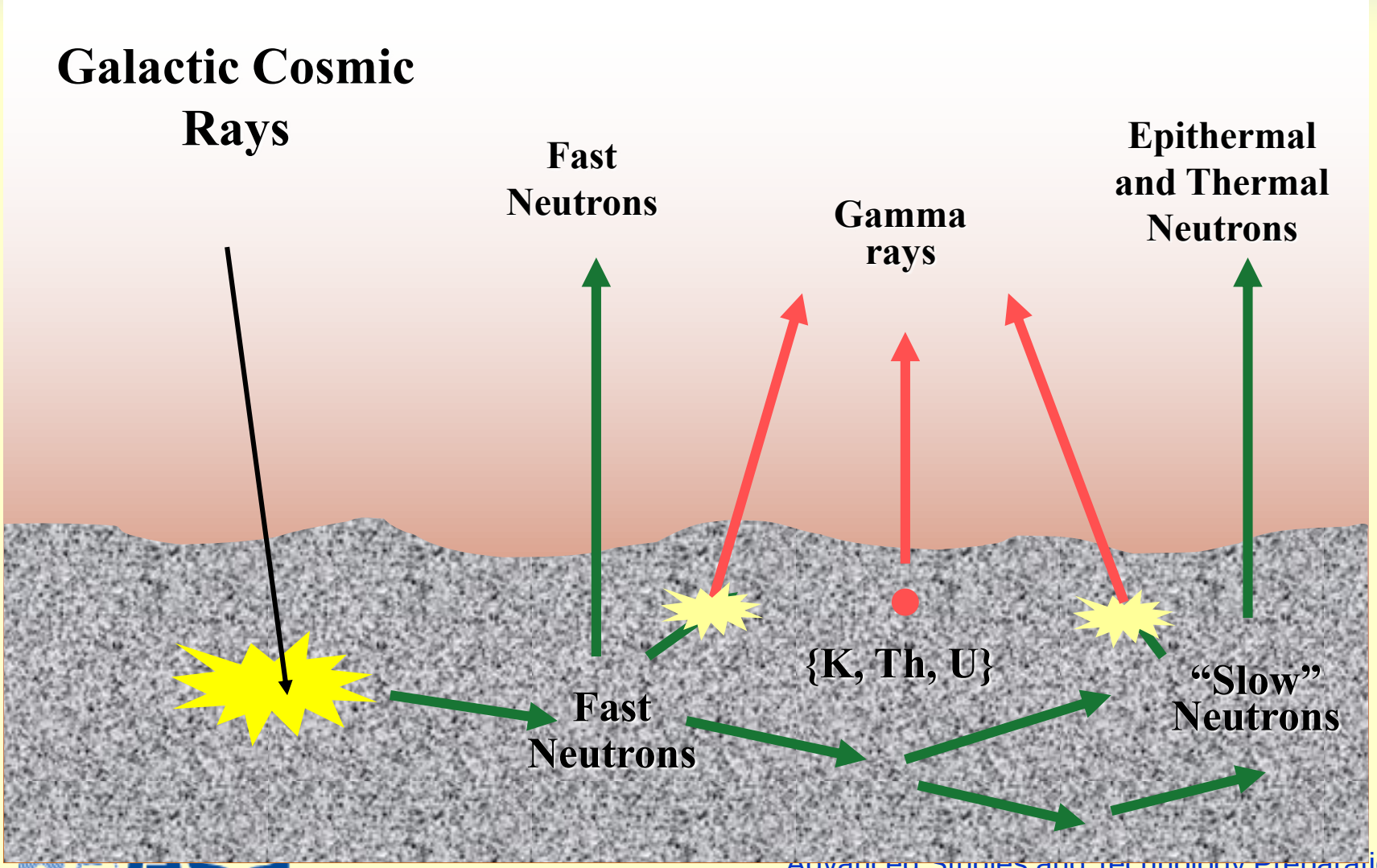
X-Ray Solar Monitor







Planetary Gamma Rays



BepiColombo Baseline Gamma-ray Detector

Central detector: Lutetium aluminium perkovskite (LuAP)

Efficiency	Total	99% @ 662 keV
Photopeak		96% @ 662 keV
Total		91% @ 6.13 MeV
Photopeak		65% @ 6.13 MeV
Energy resolution		7% @ 662 keV

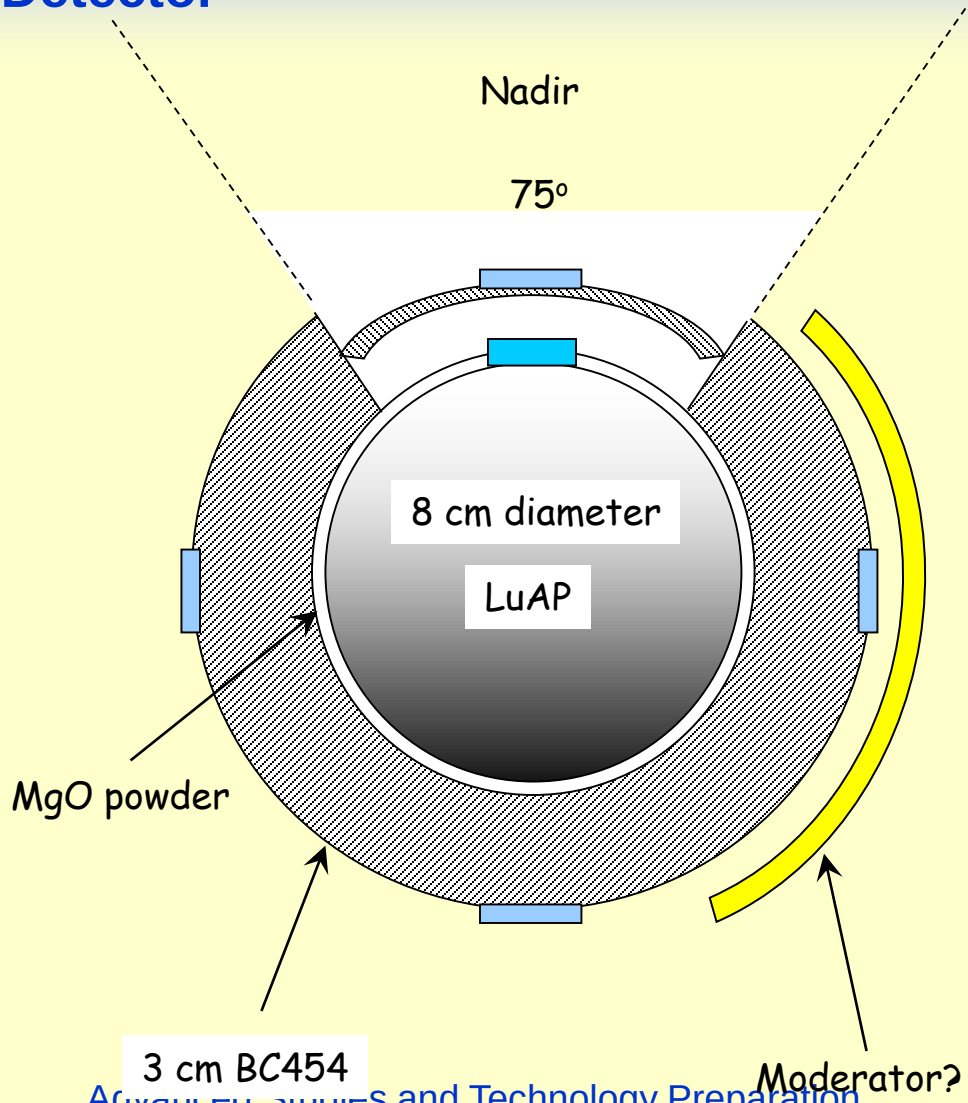
Anticoincidence shield: BC454

Efficiency	100% charged particles
Energy resolution	6% @ 662 keV

41 Photodiodes (Hamamatsu)

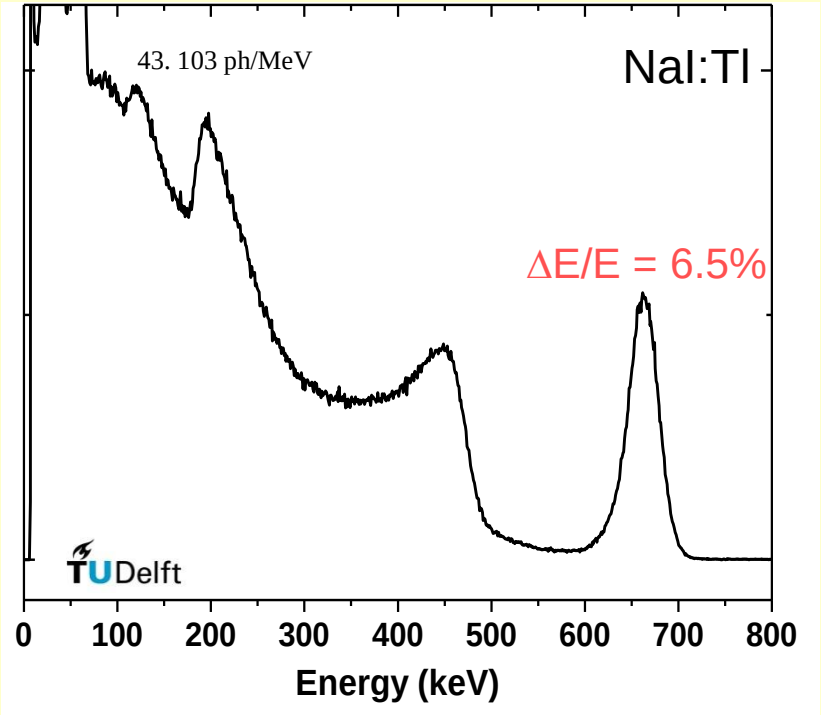
1	Central detector (cooled)	S3590-08
6	Anti-coincident shield detectors	S3590-08

Bias voltages 30 V to 70 V



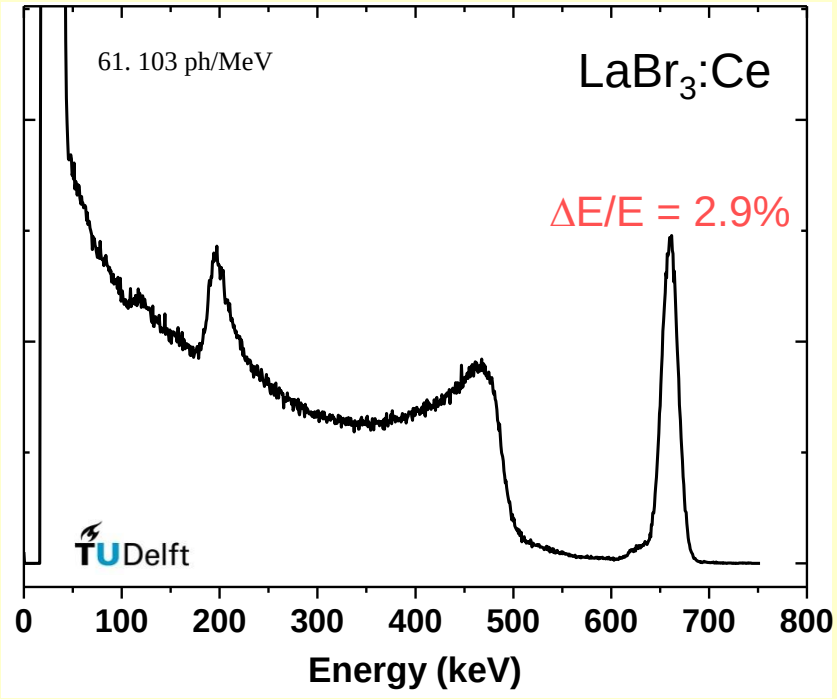
LaBr3:Ce resolution

Pulse-height spectra (662 keV gamma rays) from ^{137}Cs source



τ_s= 230 ns

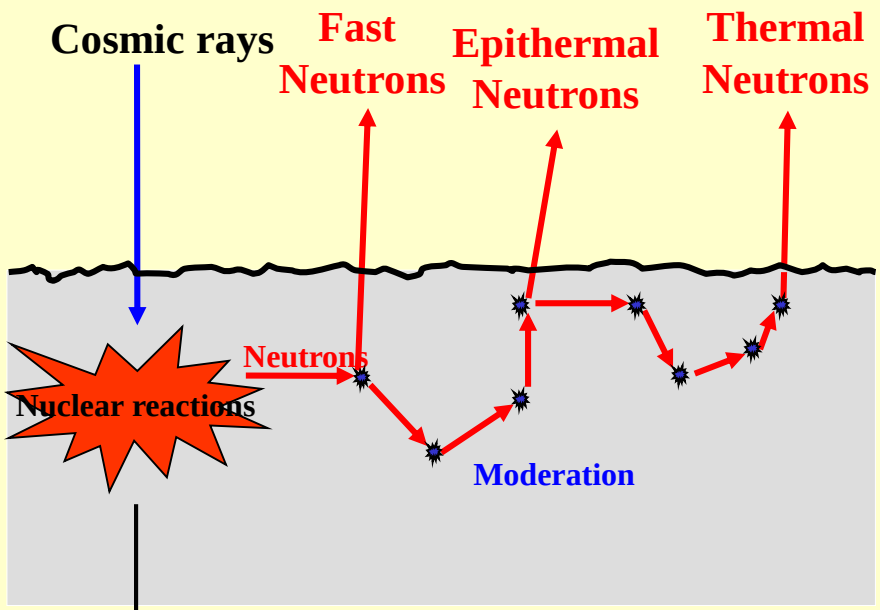
ρ=3.7 g/cm³



τ_s = 18 ns

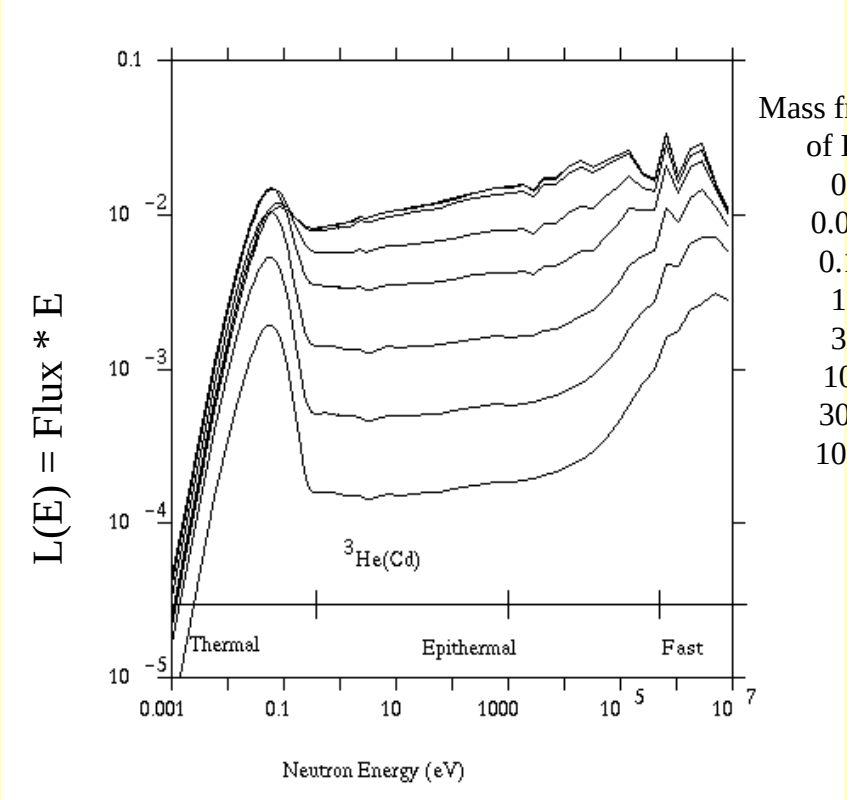
ρ = 5.3 g/cm³

Neutrons



- Direct interactions and spallation collisions
- Evaporation from an excited residual nuclei

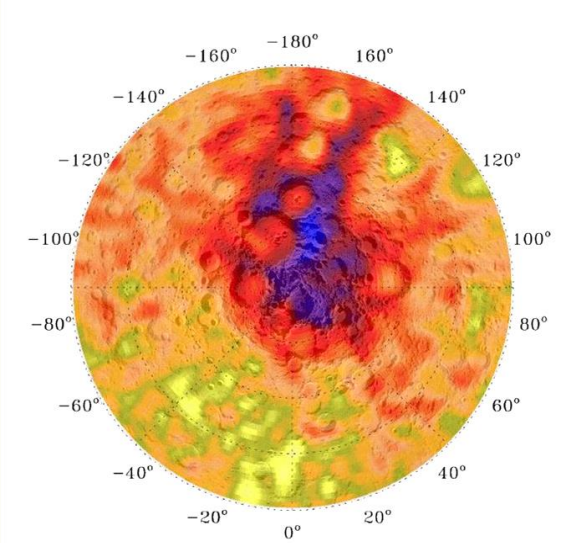
Search for Water

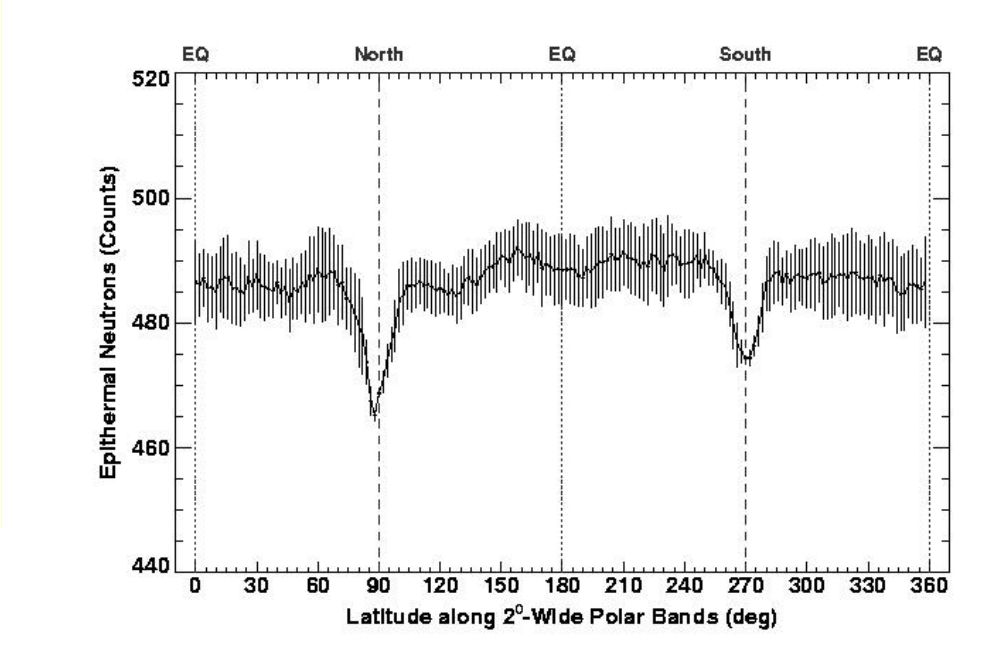


Mass fractions of H_2O
0%
0.01%
0.1%
1%
3%
10%
30%,
100%

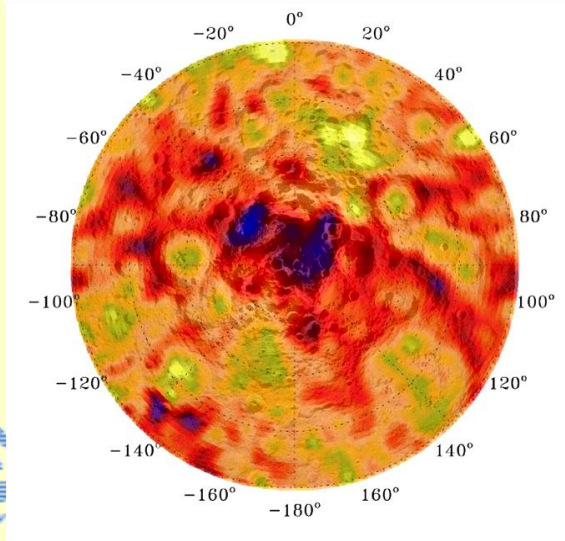
Epithermal Neutrons : Search for water

North Pole (>70°)





South Pole (<-70°)



[H] ~ 1700 ± 900 ppm

i.e. $[H_2O] = 1.5 \pm 0.8\%$

→ Solar wind cannot account for such amount

(Feldman et al, 2000, 2001)

BepiColombo MGNS

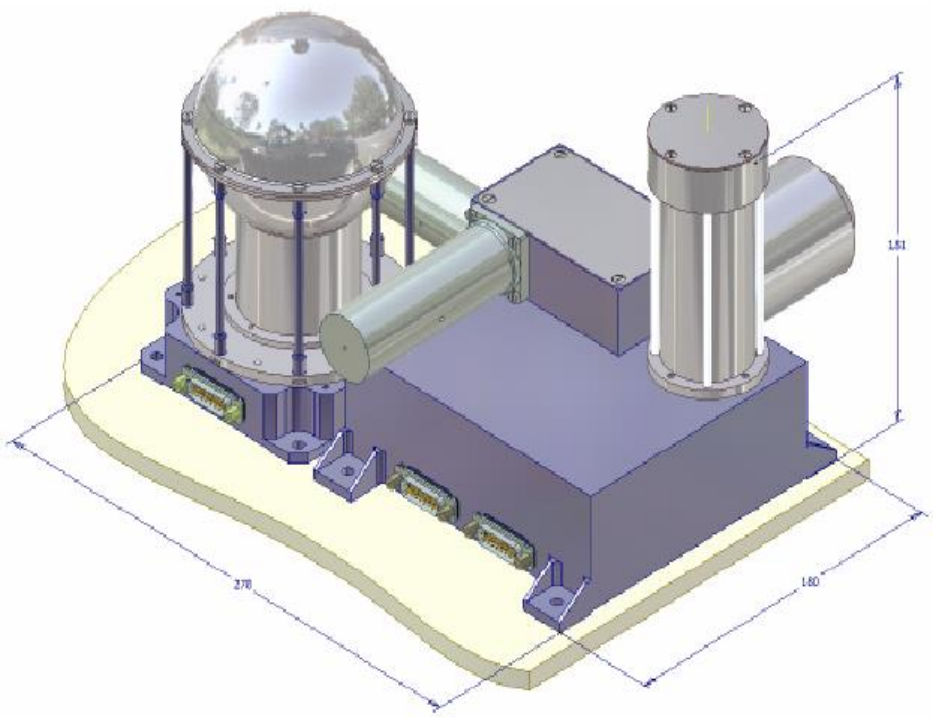


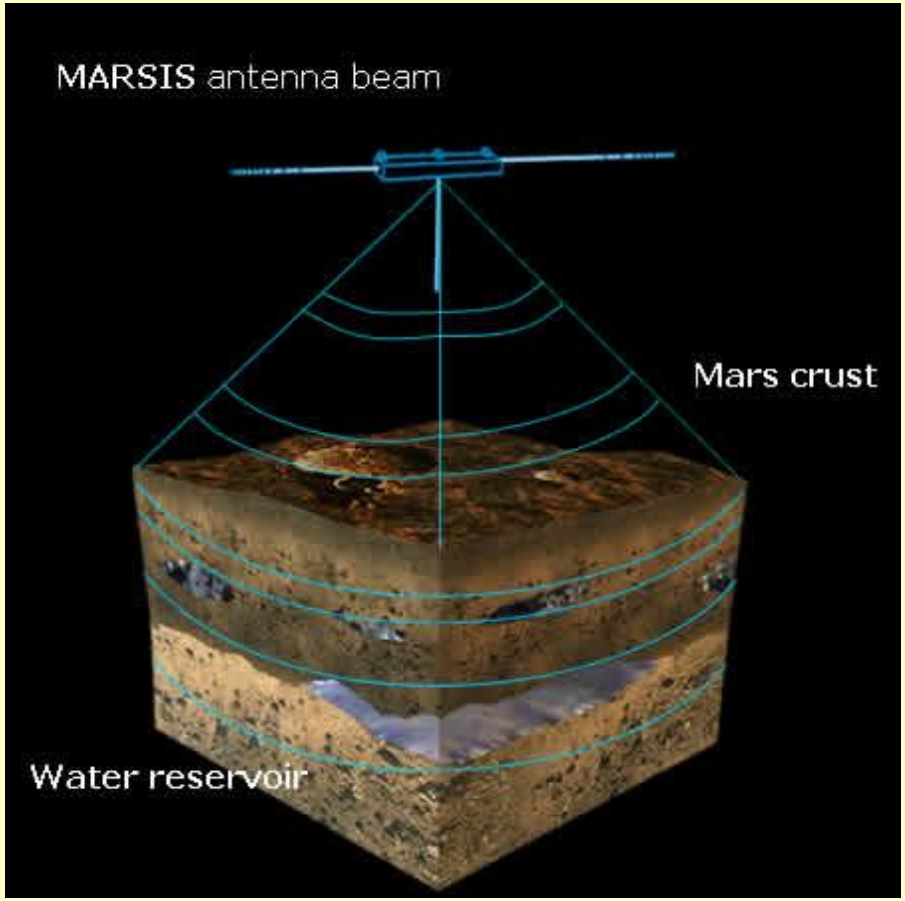
Figure 4.1. Mechanical design and interfaces of MGRS segment of MGNS

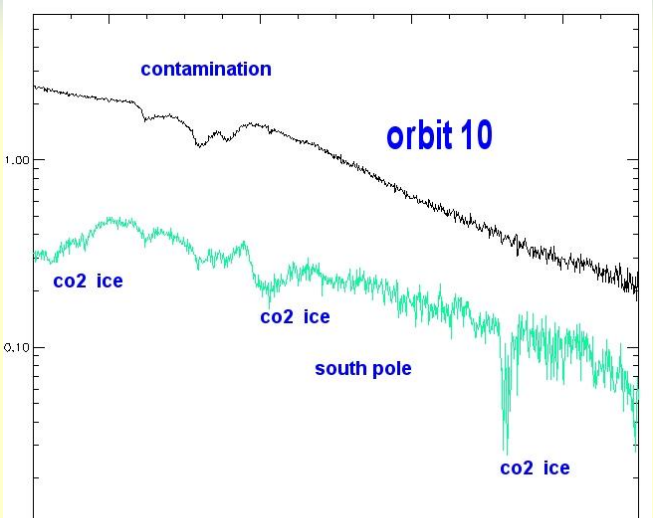
- **Gamma rays and neutrons detector**
- **New Scintillation technique based detector**
- **γ: $LuAlO_3$:Ce**
- **n: Stilbene for neutrons**
- **Spectral Resolution 4% at 662 keV**
- **Spatial resolution 400 km at pericenter**
- **^{3}He proprtional counter with/without Cd shielding One has polyethylene moderator**
- **High energy neutrons with sthylbene scintillator**
- **Choice dictated by high resolution req. (3 KeV at 1 MeV)**
- **Resources:**
  - Mass: 4.35 kg
  - Power: 3 W average
  - Data volume 9 Mbit/day
  - Ops T –10 °C to +20 °C
  - No heater

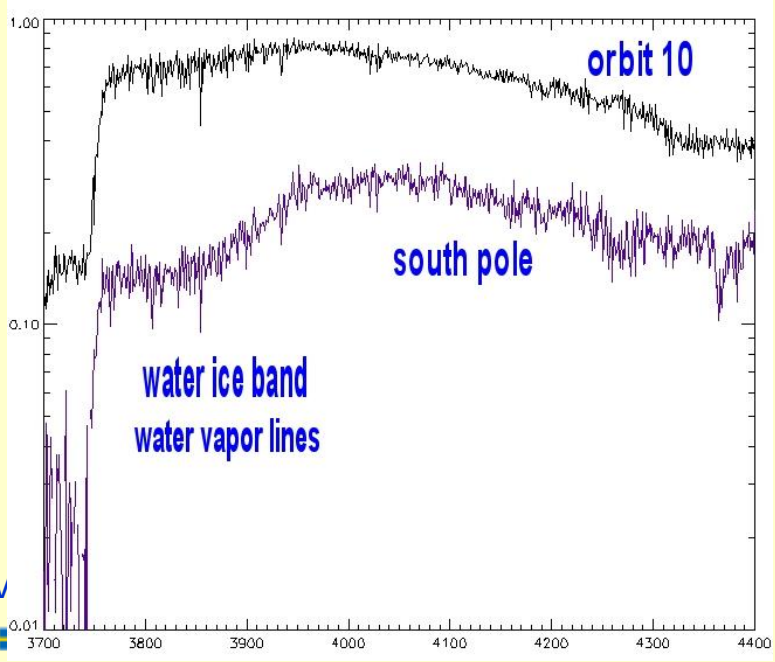
Ground Penetrating Radar

- **Measures reflection of layers with changes in dielectric constant**
- **Penetration depth depends on electric conductivity of soil, centre frequency (few 100 MHz to few GHz), and power (20 – 30 W)**
- **Penetrations of 10s to 100s m possible**
- **Typical applications**
  - Underground water
  - Ice thickness
  - Liquid surfaces when surface is not accessible (Titan)
- **Mars Express: 40 m antenna, 5 km depth**

Radar Sensing



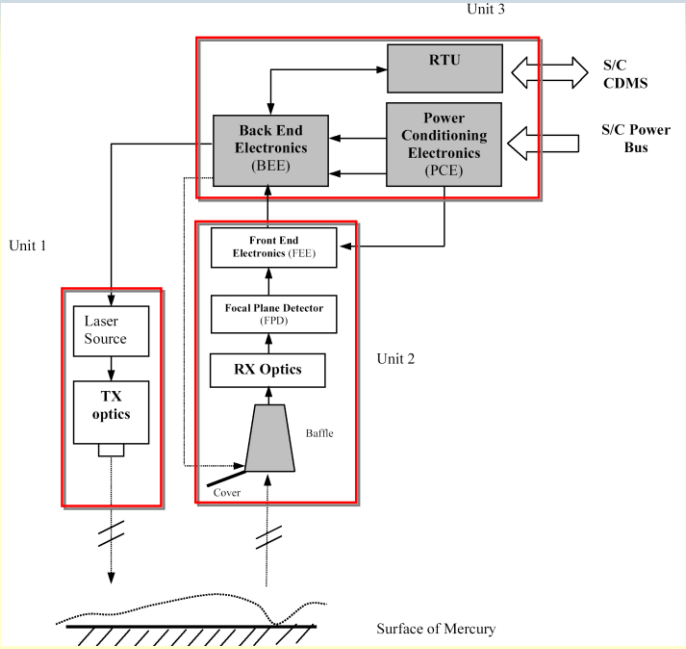


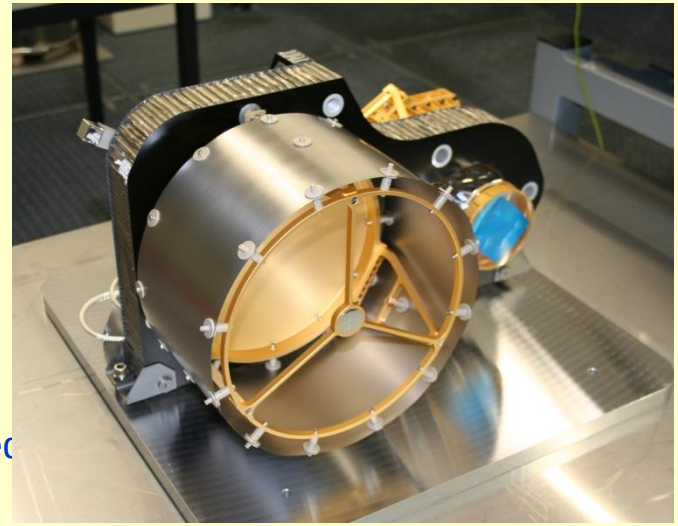


Adv

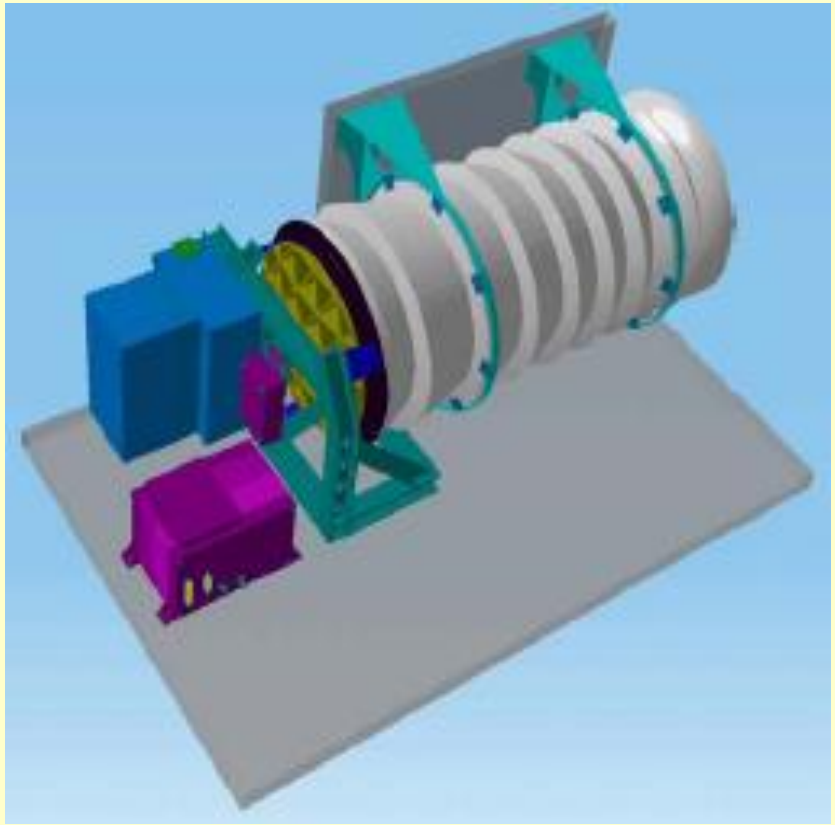
Laser Altimeter

- **Using spacecraft as test mass – assuming geodetic orbit**
- **Absolute attitude measurement to ~1 m**
- **Determination of shape of planetary body**
- **Two implementation options**
  - Light pulse measurement
    - Continuous pulsing of laser
    - Measurement of peak intensity in arrival pulse
  - “Photon counting mode
    - Emission of shorter lower light levels
    - Photon counting and gating on expected arrival times



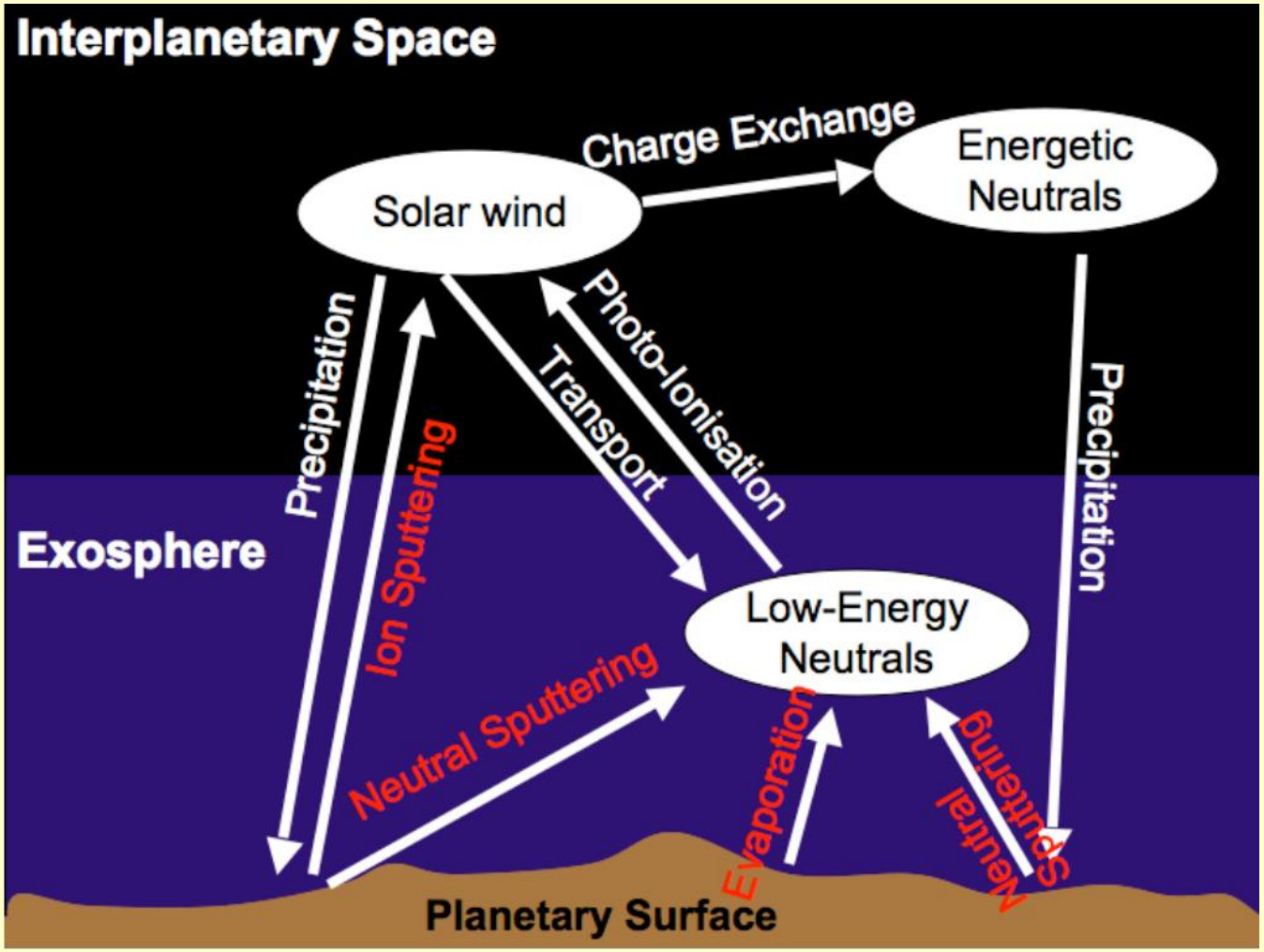


BepiColombo BELA



- **LASER ALTIMETER**
  - Principle of operation Direct Detection approach (high energy: 50 mJ and low frequency 10 Hz) with Si-APD for return signal detection
  - Mass: 13.9 kg (with margin)
  - Power 43.5 W
  - Dimensions: 900 x 340 x 350 mm^3
  - Requires continuous (also dayside) operations
  - Operations for altitudes between 400 – 1000 km
  - On-ground co-align. wrt medium res camera required to 100 µrad

Exosphere


Interplanetary Space
Charge Exchange
Solar wind
Energetic Neutrals
Precipitation
Ion Sputtering
Transport
Photo-Ionisation
Precipitation
Exosphere
Low-Energy Neutrals
Neutral Sputtering
Evaporation
Neutral Sputtering
Planetary Surface

UV Measurements of Hermean Exosphere (1/3)

Species	λ(nm)	H(km)	t_{aph}(s)
H	121.6	2300	3
He	*58.4*	*575*	*≈10*
O	130.2	145	5
Na	330.3 268.1	101	0.05 1
K	404.5 321.8	59	1 60
Ca	422.7 239.9	58	0.03 110

Calculations by F. Leblanc, 2003
(except for He)

- **Vertical/ geographical/ seasonal mapping of already detected species (H, He, O, Na, K, Ca)**
- **From Mariner 10 results : I(He) ≈ I(O) ≈ 70 R (Hunten et al, 1988)**
- **Detection of Na possible at 268 nm (where 200M photocathode may be used).**
- **Ca marginally detectable at 239 nm.**
- **Na and K also measurable at longer wavelengths : resp. 589 nm and 766-770 nm**

UV Measurements of Hermean Exosphere (2/3)

Species	λ(nm)	H(km)	t_{aph}(s)
Si	251.5	82	0.2
Mg	285.3 202.6	96	0.003 0.8
Al	308.3 213-215	85	0.04 8
Fe	297-298 216.7	41	0.5 10
S	180.7	72	13.9
C	165.6 156.0	193	11.5 35
N	120.0	165	0.2
OH*	308.5	140	2

*Inferred from Morgan and Killen (1997)

- **Searching for elements expected, but not still observed (Si, Mg, Al, Fe, S, C, N, O, OH), and vertical/ geographical/ seasonal mapping**
- **According to current modelling, metallic elements easy to detect and map.**
- **S, C, N more difficult to measure (longer integration time required).**
- **Coverage, sampling : as complete as possible (as for Na, K, Ca).**

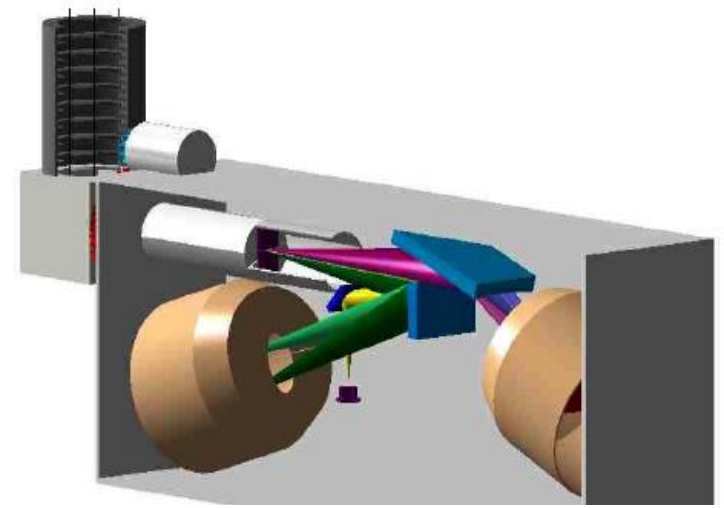
UV Measurements of Hermean Exosphere (3/3)

Species	λ (nm)	t_{perih} (s)	t_{aph} (s)
Ca^+	393.4	10	24
Fe^+	260.0	40	93
Si^+	126.0	29000	67600
C^+	133.4	1240	2900
Al^+	167.0	2800	6500
Mg^+	279.5 280.2	0.6 1.0	1.3 2.4
S^+	125.9	1.1E06	2.8E06

Calculations by F. Leblanc, 2003

- **Searching for ions (He^+, Na^+, O^+, Mg^+, Al^+, Ca^+, C^+, N^+, S^+, …) and mapping/monitoring**
- **Ionospheric density unknown.**
- **Working assumption: $X^+/X=1/100$.**
- **Ions of Ca, Fe and Mg realistically detectable on Mercury (but Ca^+ ouside 200M range).**
- **C^+ and Al^+ only marginally detectable.**

BepicColombo: PHEBUS



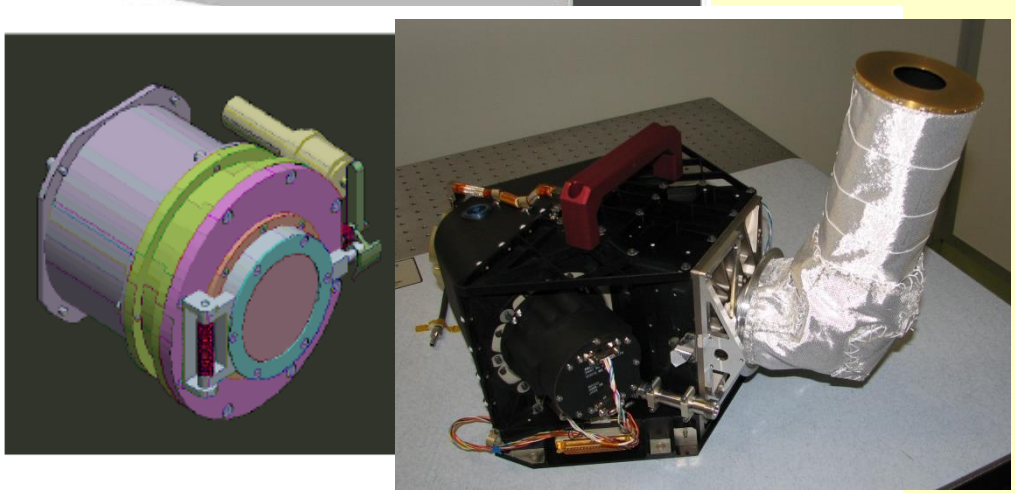


Figure 11 : EUV Detector housing

- **Probing exosphere by UV spectroscopy**
  - 2 spectro-photometers based on Micro Channel Plates detectors in the 50 nm – 330 nm range plus 1 deg rotation scanning mirror
  - Double channel system, FUV and EUV, each of which equipped with its own MCP
  - Mass: 3.77 kg
  - Power 4 W (up to 12 W)
  - Dimensions: 380x 250 x 150 mm^3
  - Scanning mirror for limb viewing

Measurement Principle of Atomic Spectrometer

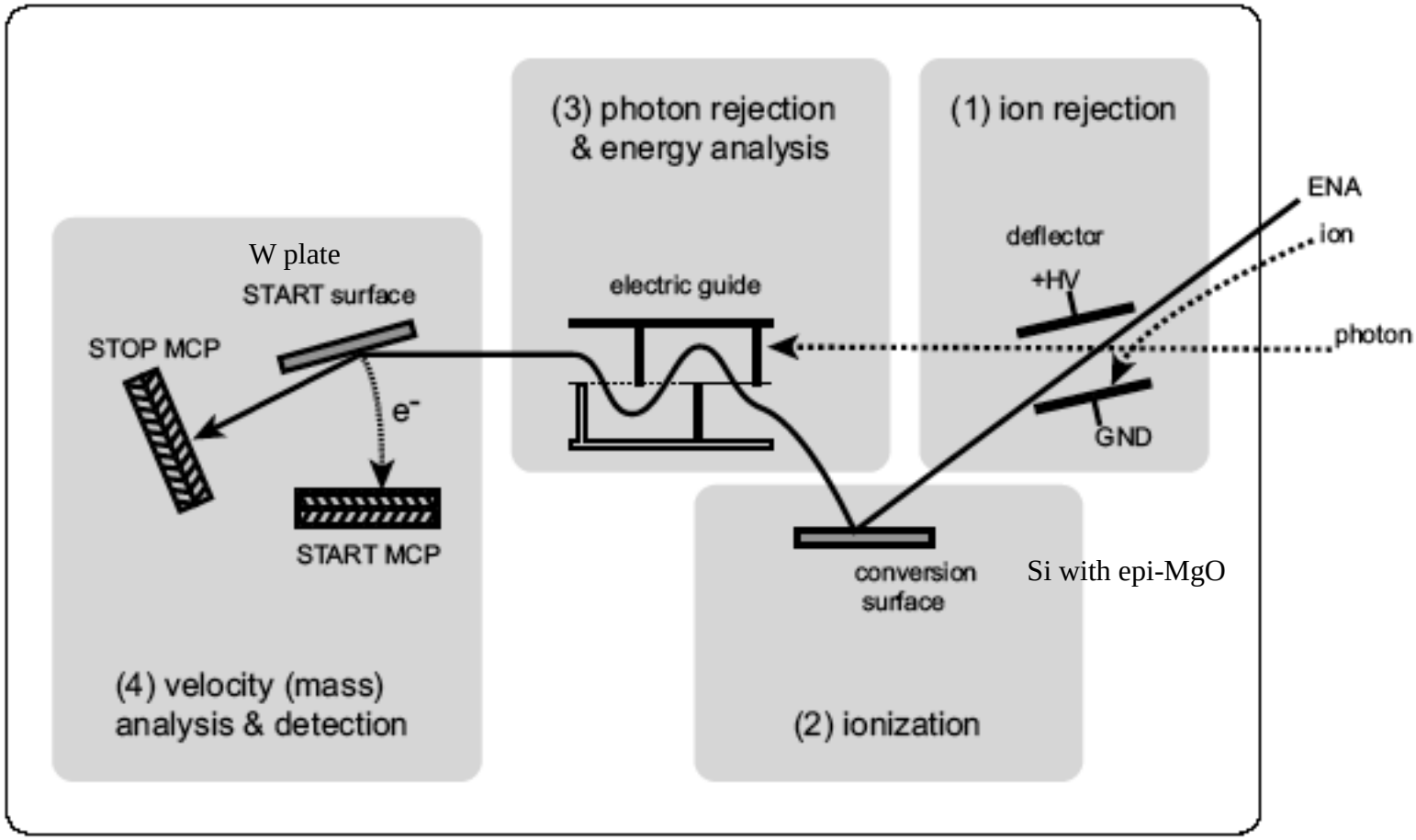
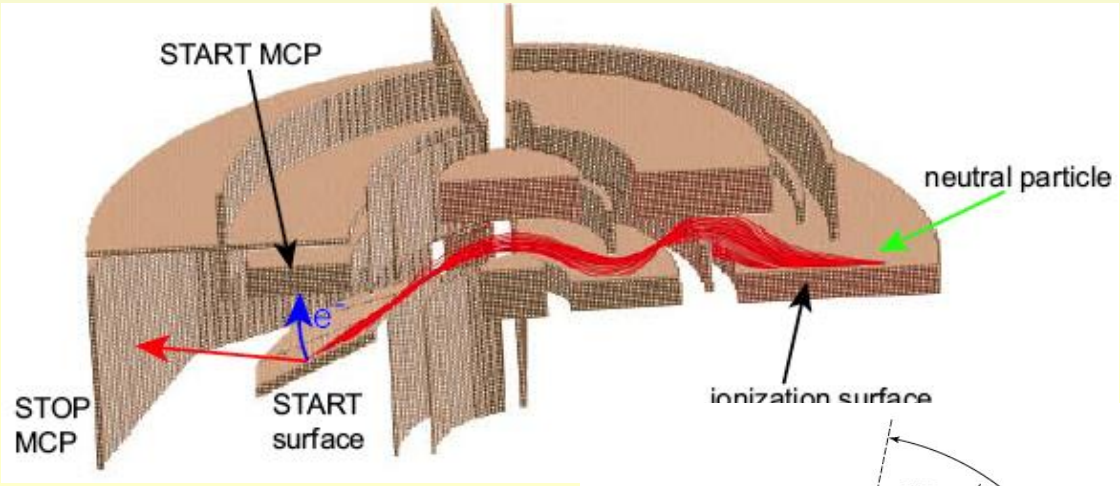
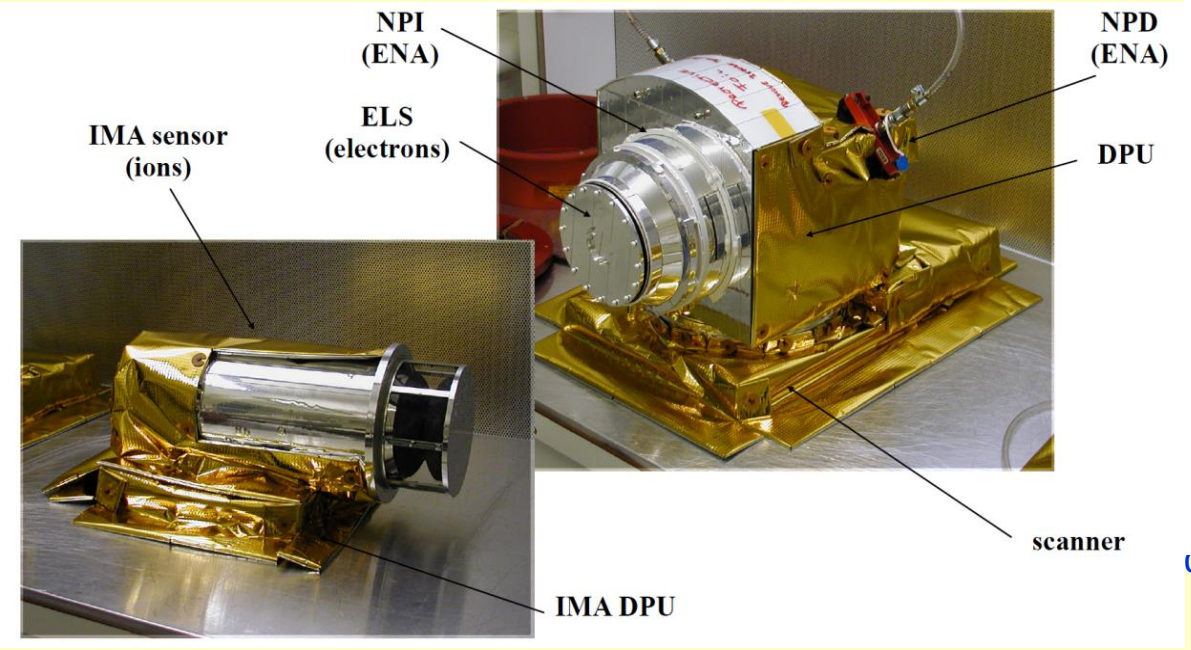


Fig. 1. Schematic diagram for detecting a LENA by the instrument.

Chandrayaan-1: SARA/CENA





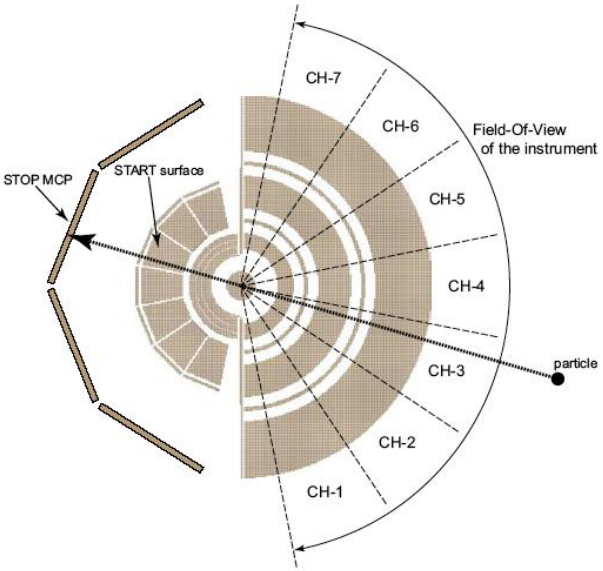


Fig. 3. Azimuthal field of view of the instrument. Seven sectors (CH-1 to CH-7) cover approximately 160 deg in the azimuthal direction.

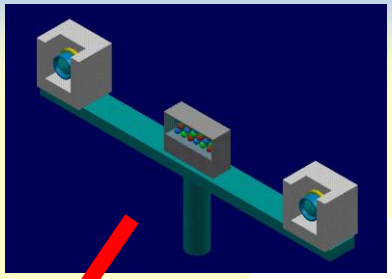
Lander

- **Ground truth**
- **Surface investigations and active sampling**
- **Sample selection**
- **High mass amplification (factors 20 or more)**
- **Miniaturization**
- **Sharing of resources: mass memory, power converter, access**
- **Power provision**
  - Battery: thermal insulation and heating
  - Radioactive Power Generator: excess heat during interplanetary transfer

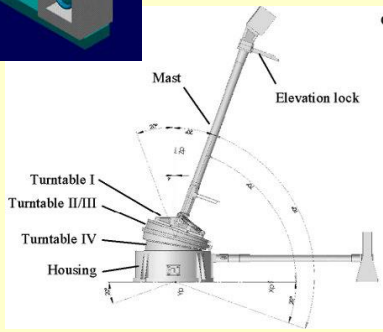
Lander Elements

Rover

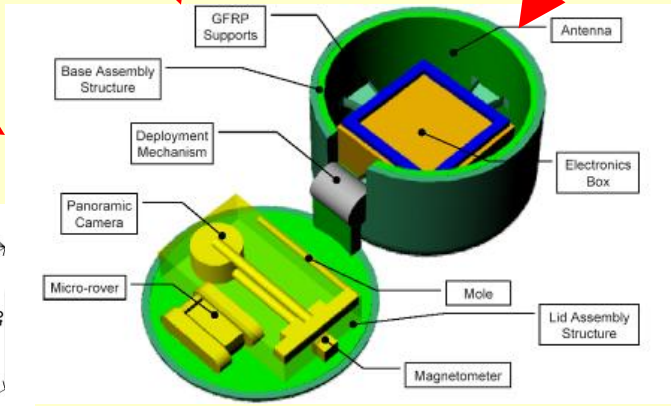
APX



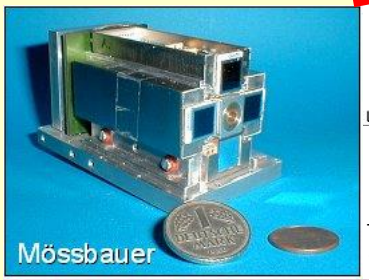
Pan-Cam

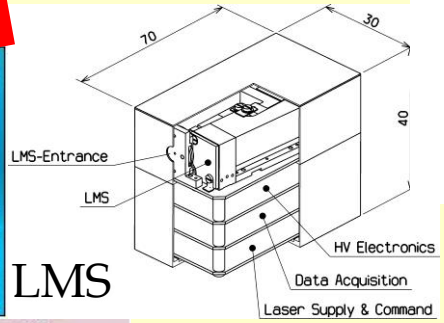


Lander



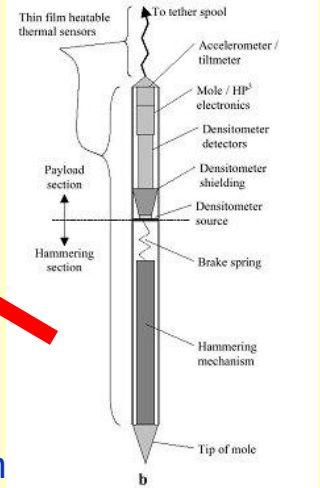
Geochemistry Package





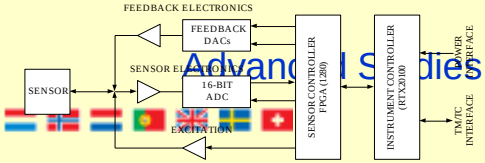
LMS

Mole

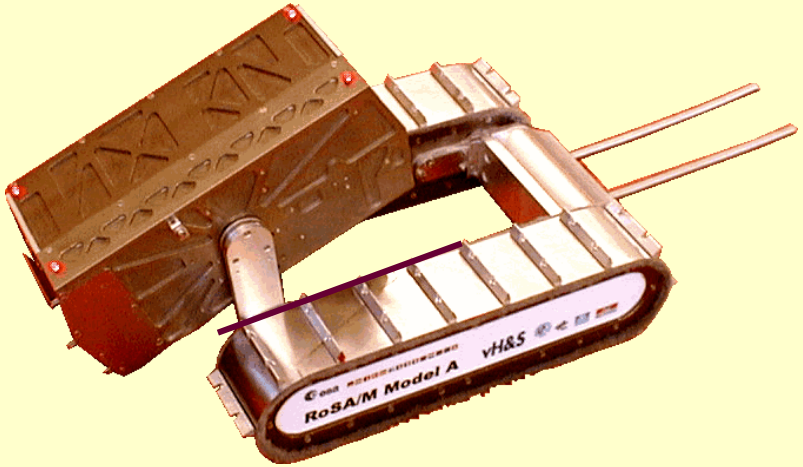


CPPS

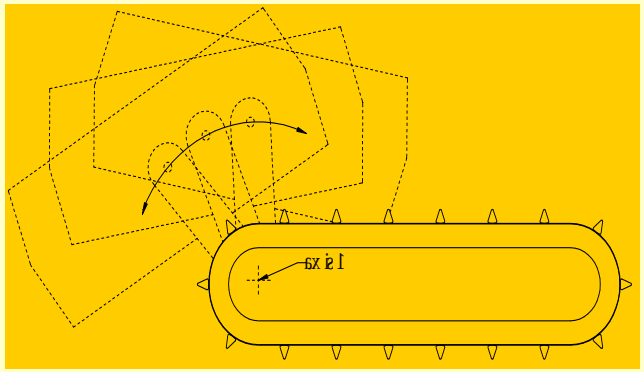
MAG-ASIC

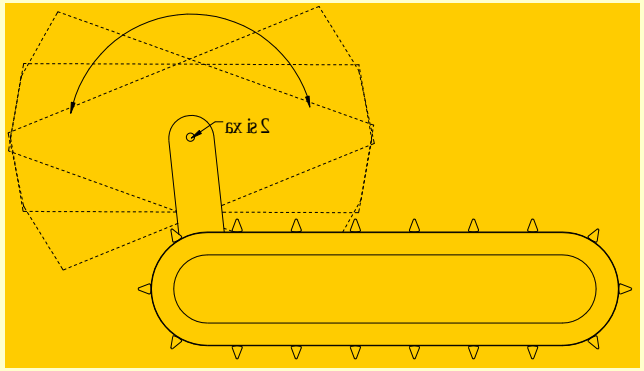


Miniaturized Lander “Nanochod”

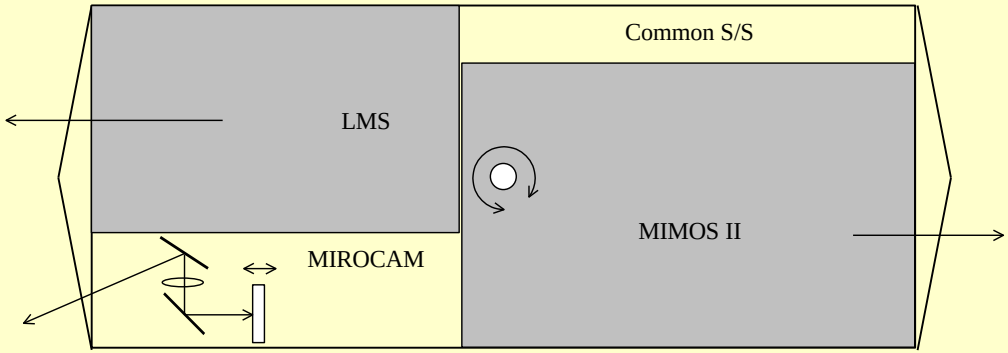


2 axis of flexibility



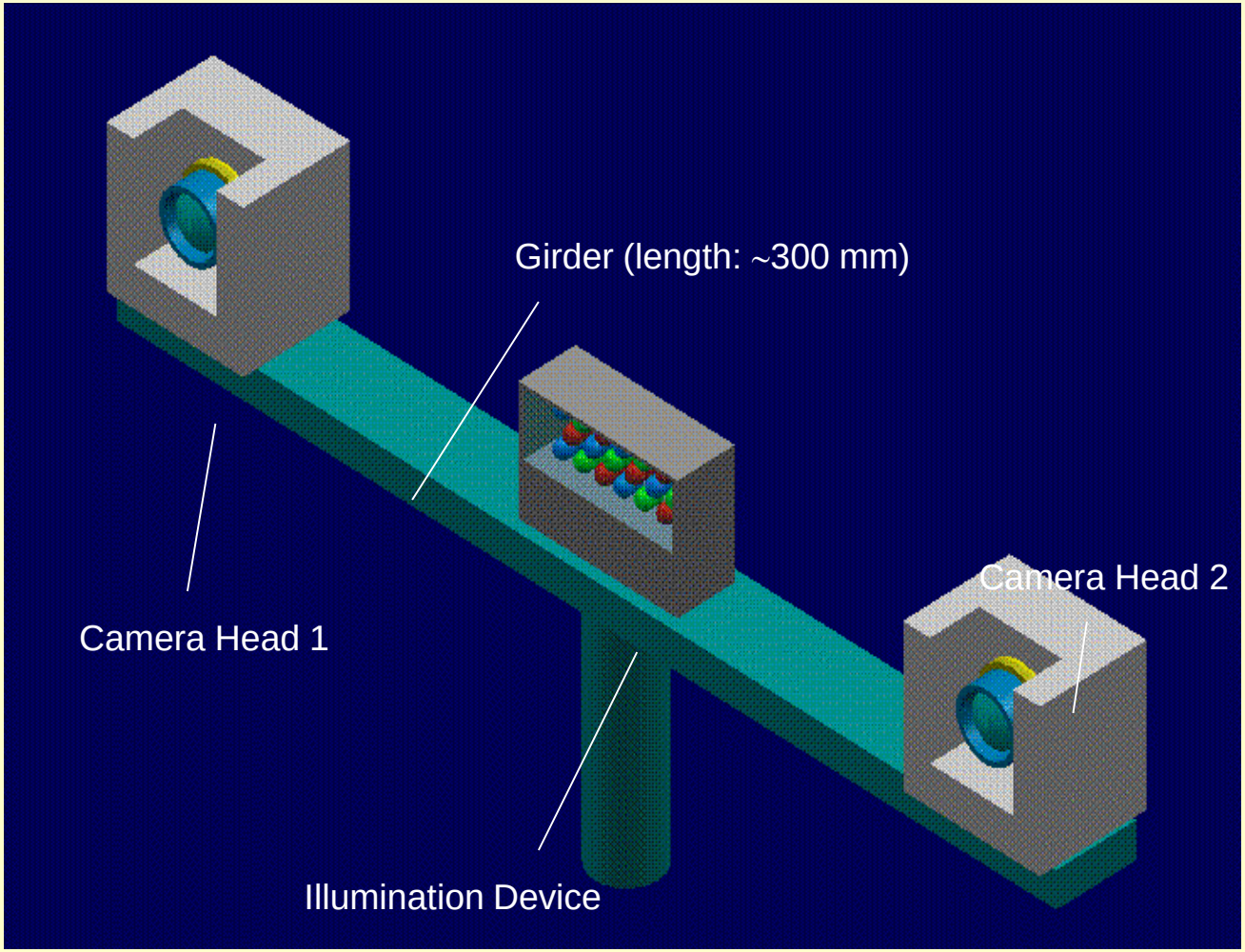


Equipment Bay



Large Class Rover

PlanetMicroCam: Camera Heads & Illumination Device

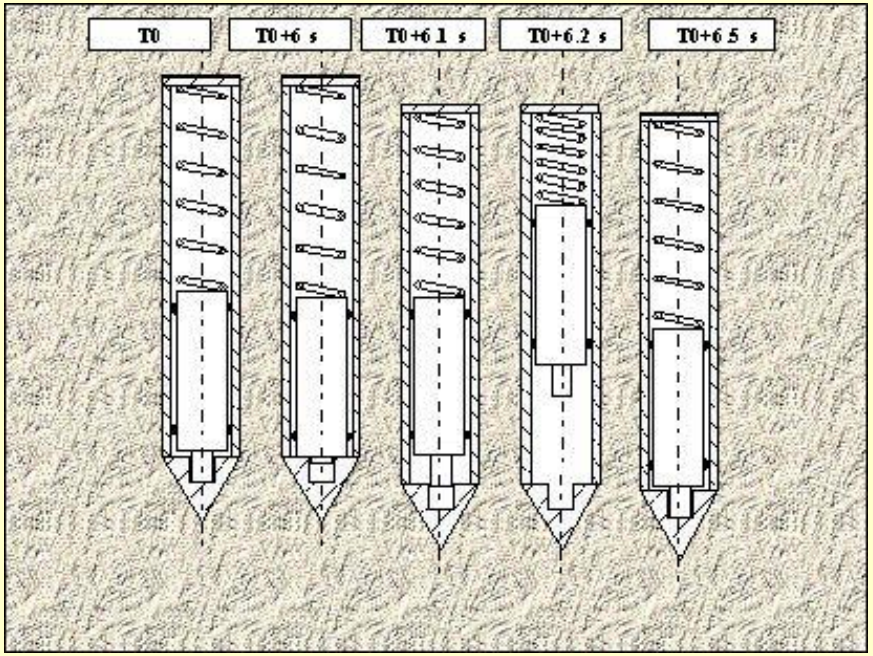


Mounting Arm of Camera System

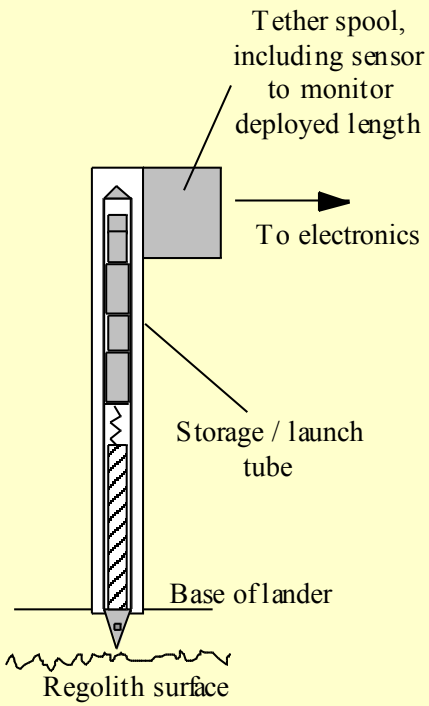
- Rigid boom concept with mast deployment after landing
- Lander inclination compensation up to 20 °
- 3 Actuators (stepper motors) in total
- All MSS electronics inside housing, no E-Box
- Capacitive azimuth sensor
- Total mass: 1024 g
- Total power:
  - 200 mW (standby)
  - 3350 mW (operational)

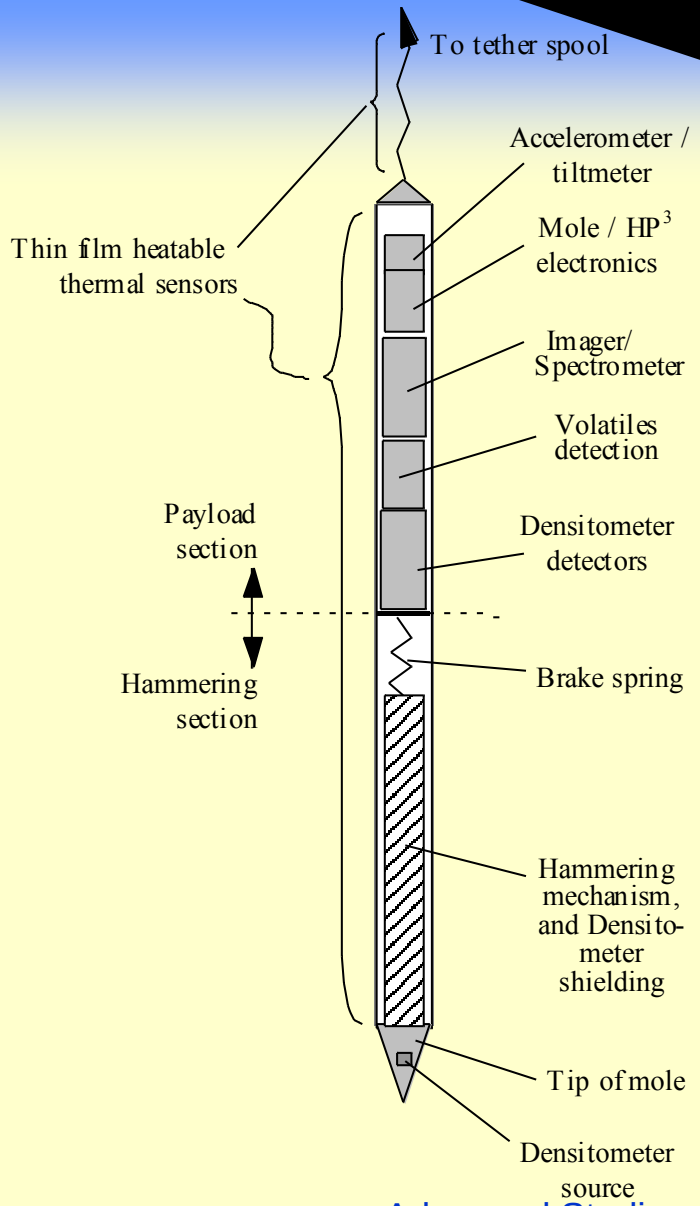
Subsurface Element: Drill

- Measure heat distribution of mantle
- Search for sub-surface water
- Mounting of accelerometer for tidal motions
- Radio beacon for libration measurements



Drill/Mole


Tether spool, including sensor to monitor deployed length
To electronics
Storage / launch tube
Base of lander
Regolith surface


To tether spool
Accelerometer / tiltmeter
Thin film heatable thermal sensors
Mole / HP3 electronics
Imager/ Spectrometer
Volatiles detection
Payload section
Densitometer detectors
Hammering section
Brake spring
Hammering mechanism, and Densito-meter shielding
Tip of mole
Densitometer source

Summary and Conclusion

- **Large variety of instrumentation to cover all aspects of planetary science**

- **Higher level of integration and sharing of common functions such as**
  - Data processing, compression, and storage
  - Interface to s/c bus
  - Power conversion and conditioning

- **More reading http://sci.esa.int/**