Toward an Italian roadmap for lunar exploration. The Italian white paper initiative

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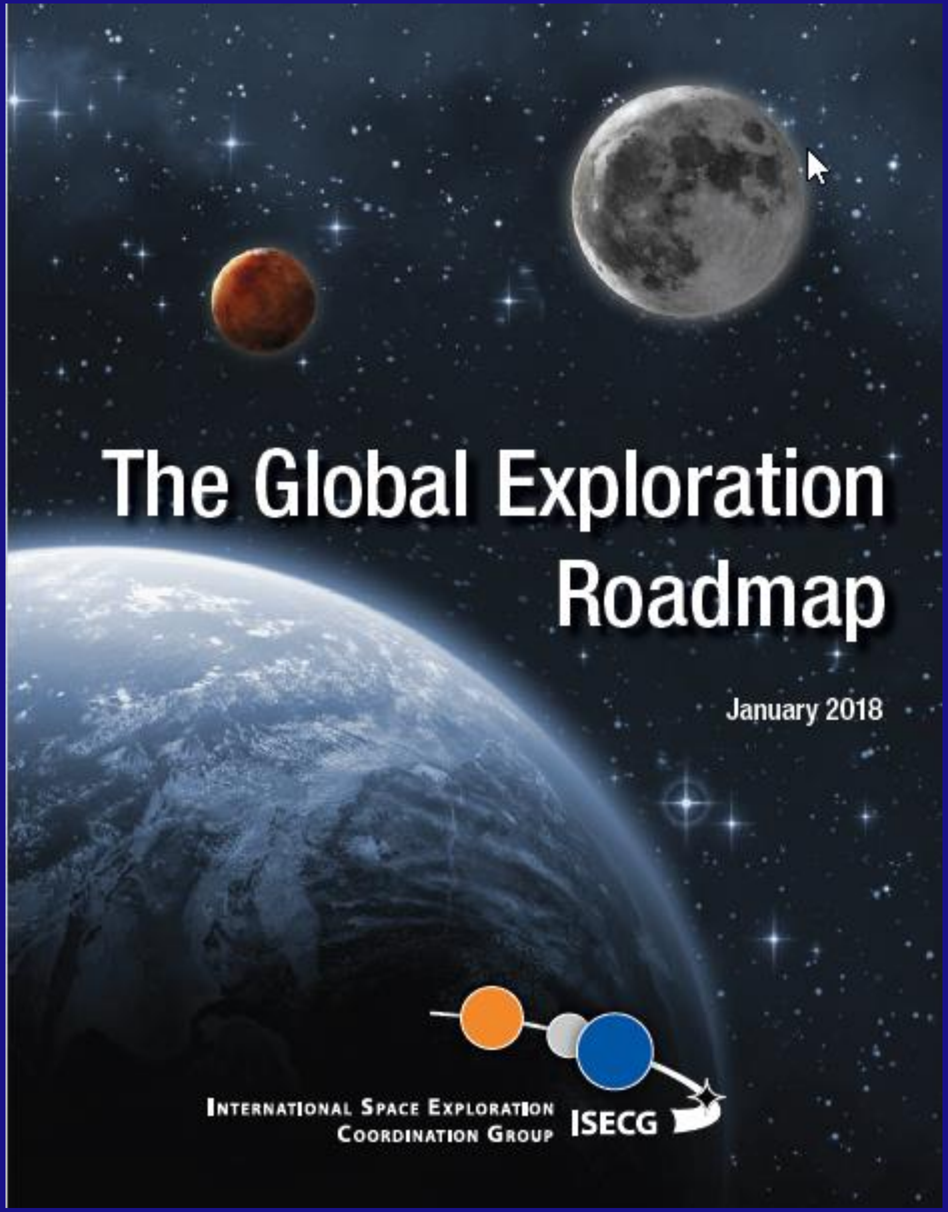
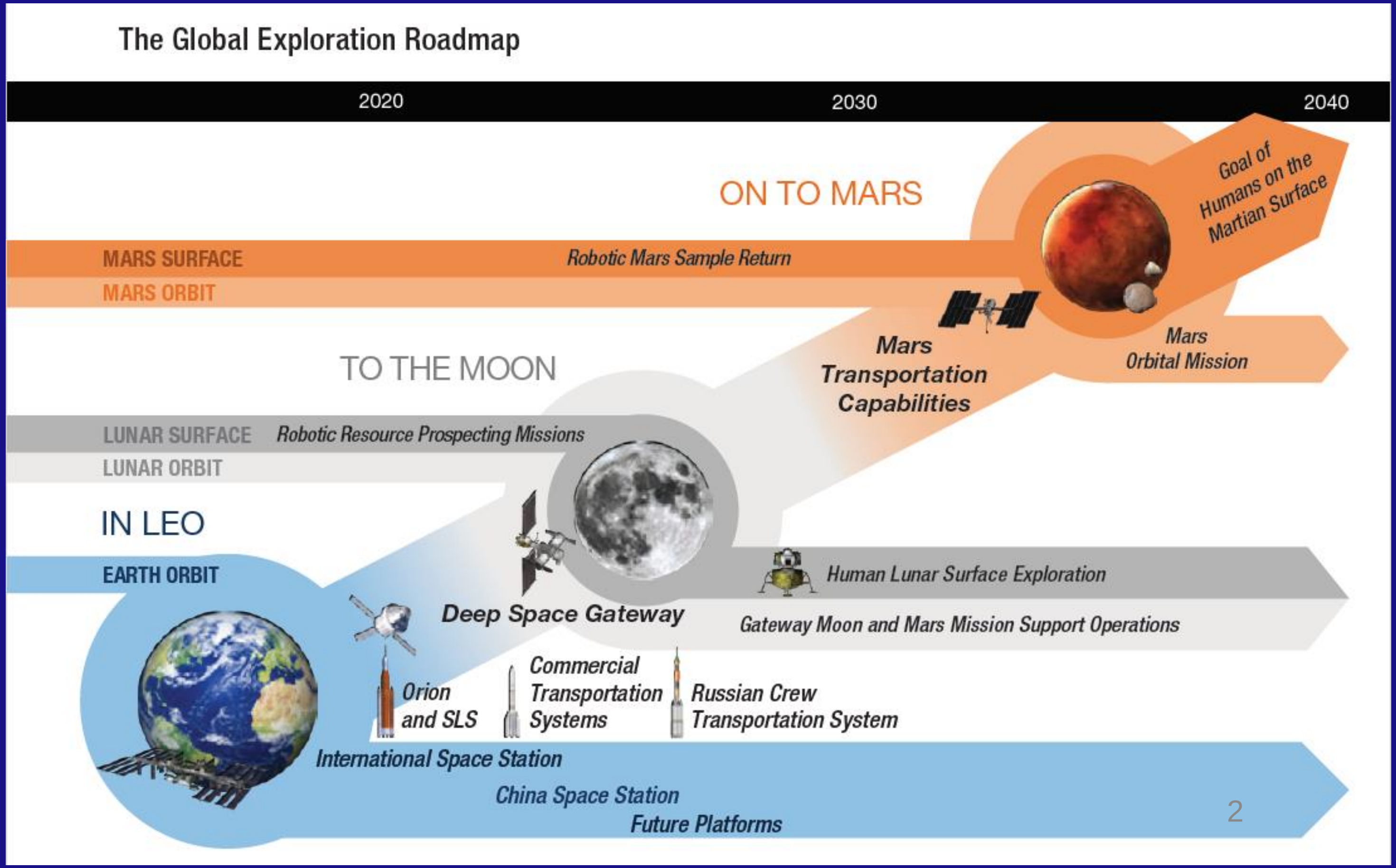
Back to the Moon



In 2018, the major Space Agencies in the world published the **Global Exploration Roadmap (GER)**, where their share the common intent to expand the human presence into the Solar System with the surface of Mars as driving goal and the Moon as a necessary intermediate step.



Back to the Moon

From GER 2018

This shared roadmap embraces government and private sector strategies for expanding human presence in low Earth orbit, to the Moon and on to Mars. Government investments in space exploration capabilities and missions serve an important role by advancing technologies, reducing risks and identifying new markets where competition can spur innovation that generates further benefits.

- 122 missions from ‘50.
- Success: > 50%
- 8 missions currently operational

> 30 robotic missions to the Moon (from 13 Countries and from both Space Agencies and Private Companies) and 4 crewed already approved and under development in the timeframe 2021 - 2028.

> 20 missions (robotic and crewed) proposed and waiting for evaluation.

New actors:

South Korea, Mexico, United Arab Emirates, Australia, Turkey, Canada, Thailand, Brazil, Israel, South Africa

Public and private engagement

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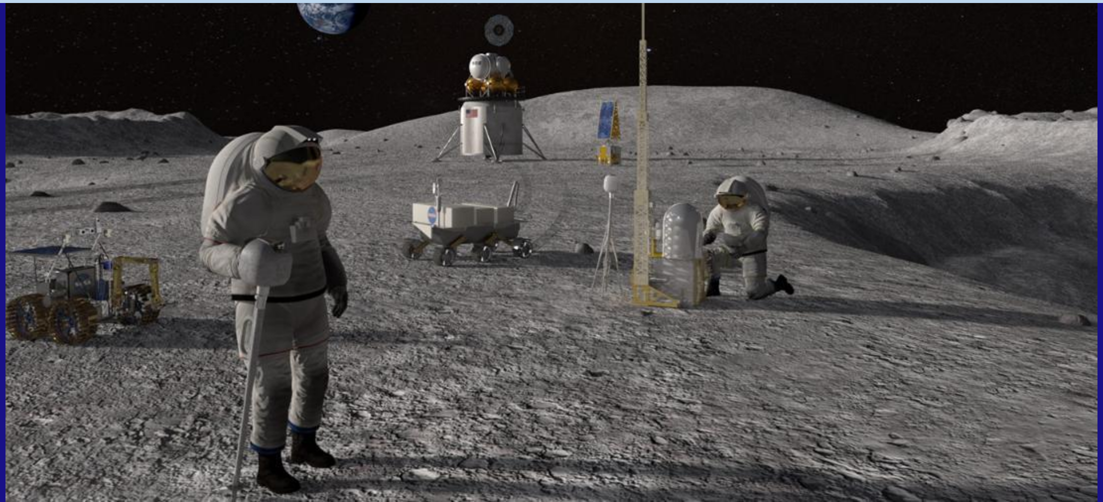
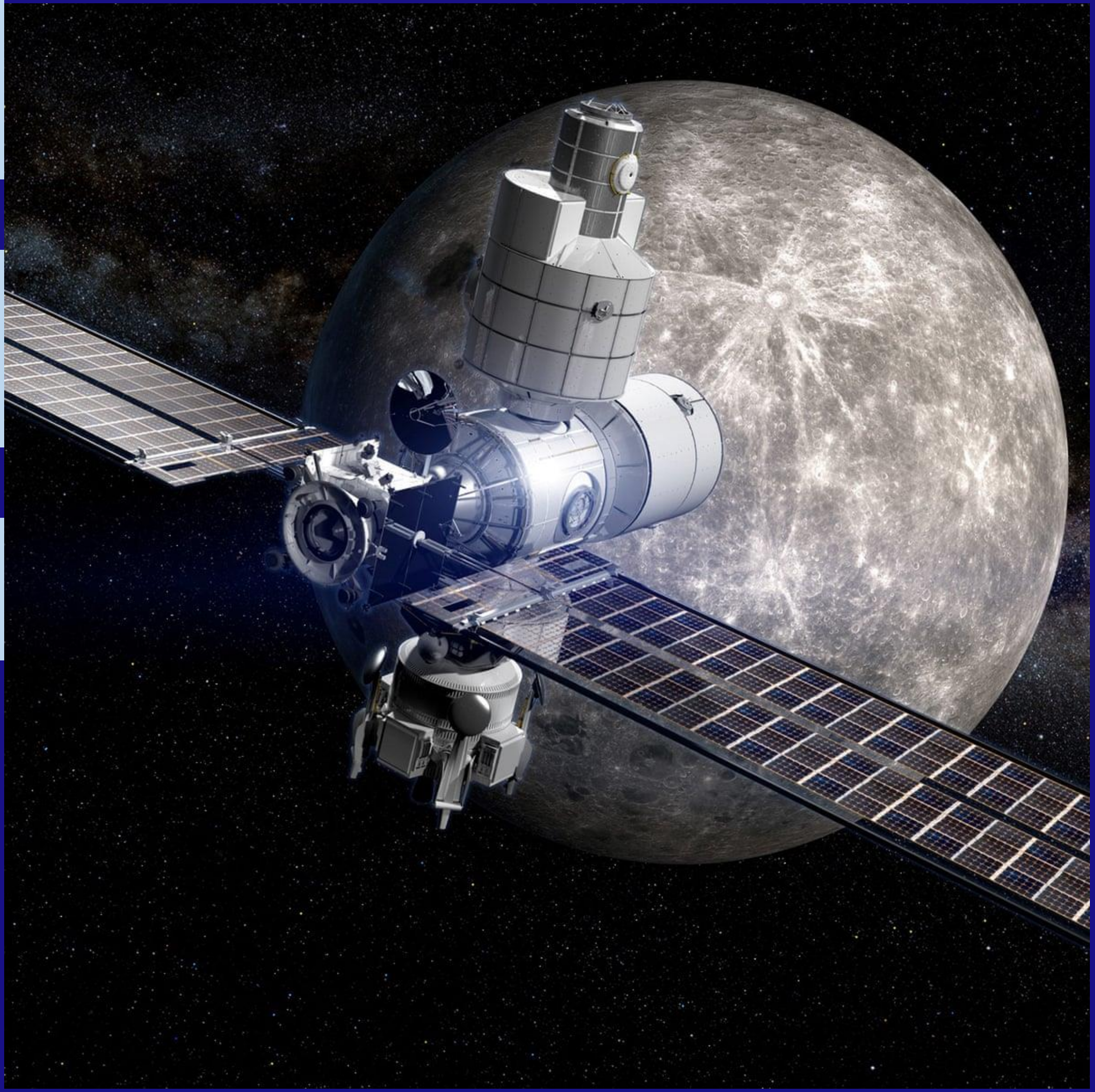
INAF, in agreement with ASI, performed a survey to collect inputs from the Italian scientific community in terms of scientific priorities and needed technologies to get advancement in the field of lunar exploration.

This survey, although not completely exhaustive of Italian interests, collects proposals from most Italian research institutes and universities.

36 proposals of instrumentation have been proposed with Italian leadership





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Survey of laboratory facilities in the Italian research institutes and universities.

SEM, IR-VIS-UV spectrometers, micro Raman, mass spectrometers (ICP-MS, LA-ICP-MS, LCMS), diffractometers, etc.

INAF laboratories (IAPS, OA Naples, OA Catania, OA Arcetri), University of Florence, Pavia, Perugia, Salento, Padua, University of Campania (CIRCE LAB), INGV, ENEA Frascati and Casaccia, CNR Florence, INFN (Frascati, Perugia, Florence), ASI Space Geodesy Center Matera.

Back to the Moon: Scientific objectives

Incredible opportunity to advance in several fields of science.

Of the Moon	On the Moon	From the Moon
Bombardment	Habitability of the Earth through time	Radio astronomy
Structure from core to crust	Life in the Universe	Optical and infrared astronomy
Rock diversity and distribution	Survivability in space	Cosmic ray astronomy
Polar volatiles (e.g. ice)	Physiology and medicine	
Volcanism	Fundamental physics	
Impact processes	Space physics	
Regolith	History of the Sun and Solar System	
Atmosphere, plasma and dust	Impact rate	
Tectonics	Earth-Moon formation	

Table 2 - Science of the Moon, on the Moon, from the Moon as identified by the global scientific community and described in detail in RD3 and Annex 1.

Extracted from the document "*ESA Strategy for Science at the Moon*"

Science of the Moon

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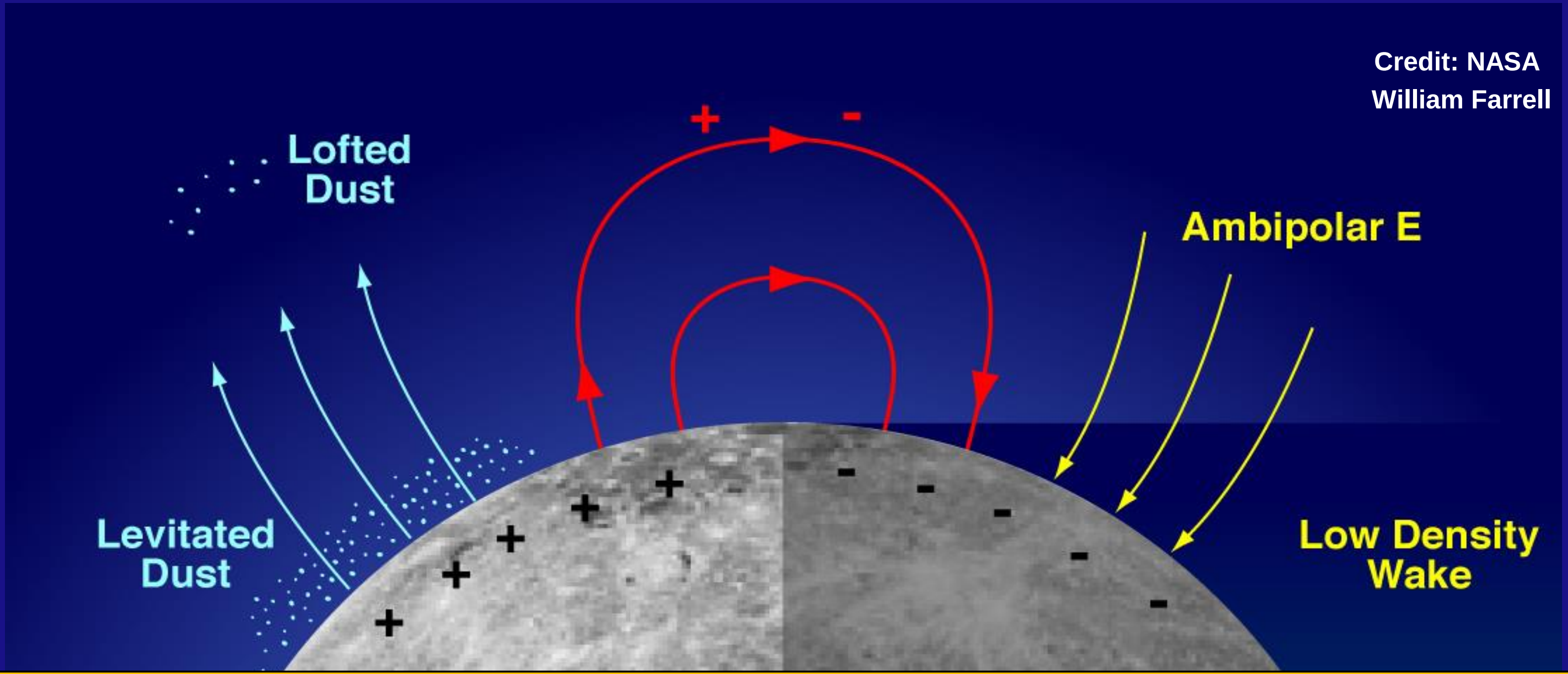
Science of the Moon – Atmosphere, Plasma and Dust

Apollo mission detected the presence of lunar dust (glows or streamers) up to 100 km above the surface.

The ejection of dust from the surface is caused by the impact of fast meteoroids and by the electrostatic forces at the lunar surface causing dust levitation and/or ejection.

Dust transport over the lunar surface: triggered by the different surface potentials of the lunar surface in the bright (positively charged due to photoelectron emission) and dark (negatively charged due to plasma sheath currents) sides.



Needs to explore the near-surface electrostatic lofting of dust associated with plasma anomalies/voids in locations like polar craters, magnetic anomalies, and the night-side terminator.

Needs to deploy **neutral and ion spectrometers, plasma instrumentation** (e.g. Langmuir probes), **magnetometers** and **dust instrumentation** to the surface should be taken to any location.

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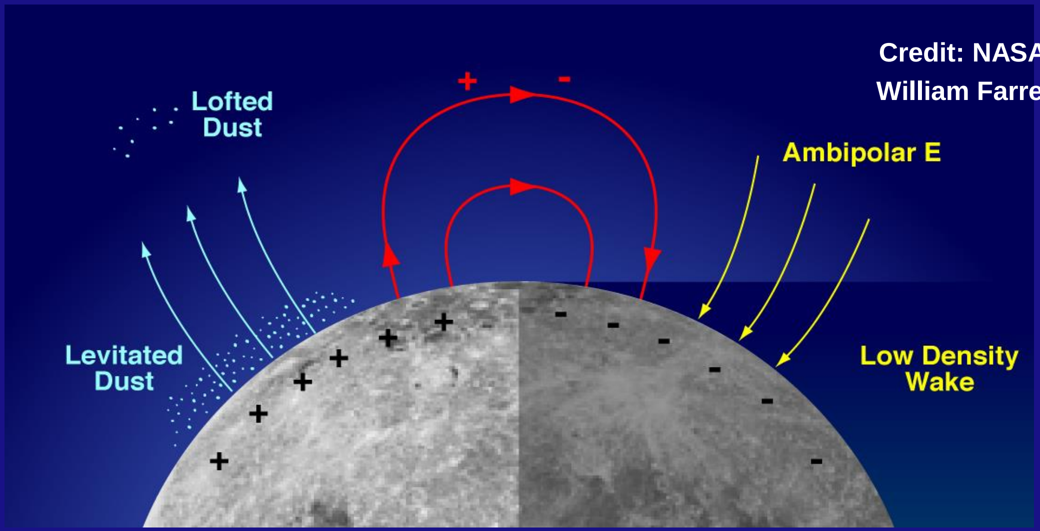
Science of the Moon – Atmosphere, Plasma and Dust

Dust in the lunar environment

- Characterization of lunar dust environment is key for planning a safe exploration of the Moon and for preparing for in-situ resource utilization (ISRU) efforts.
- The understanding of the mobilization mechanism of micron sized dust particle above the lunar surface is of great engineering importance for future lunar missions and lunar-based observatories since the lunar dust environment poses significant problems to both equipment and astronauts.
- Models predict dust is electrical charged → need of direct verification → development of mitigation strategies.
- Needs to explore the near-surface electrostatic lofting of dust associated with plasma anomalies/voids in locations like polar craters, magnetic anomalies, and the night-side terminator.



- **Microbalance based-device**. It is aimed to the measurement of volatiles' abundance in dust particles that deposit over its surface, the grain cumulated mass and charge through thermogravimetry.
- **Dust sensor** for the measurement of mass, speed, electrical charge of suspended dust. It couples two sensing grids of electrodes and a PVDF sensor. Monitoring of both slow (< 100 m/s) and fast (> 1 km/s) particles → overcome of the limits of Apollo's LEAM.
- Simultaneous monitoring of dust from shadowed and illuminated areas through the utilization of **swarm of micro-rovers.**

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Moving platforms – Robotic exploration

Set of micro-rovers with reduced weight, size (300 x 200 x 100 mm^3), and cost, working with a swarm logic. Able to perform simultaneous measurements from different positions or areas. Merging of independent measurements will enhance the scientific return in e.g.: 1) Polar exploration; 2) Identification of cold traps for water and other volatiles; 3) HD Photogrammetry & cartography; 4) Investigation of dust environment.

Micro-rovers are cheaper, flexible, replaceable, and well suited to investigate areas that are considered too risky for a traditional rover (e.g., bottom of craters). With multiple elements managed by a single central “brain”, the loss of one unit would have a limited impact on the success of the overall mission, which ensures redundancy in functions and scientific objectives.

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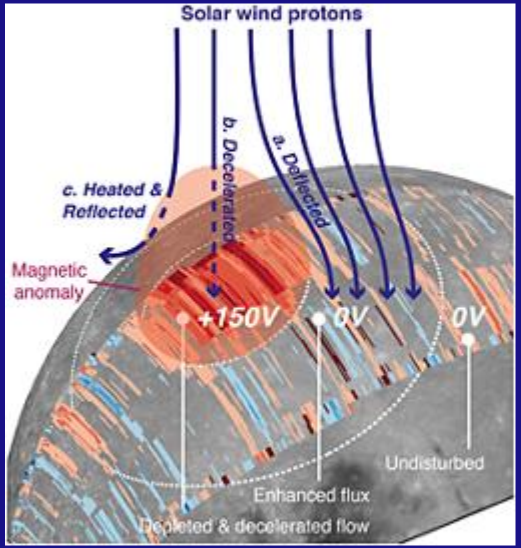
Science of the Moon – Atmosphere, Plasma and Dust

Exosphere and plasma environment

The lunar surface is directly exposed to solar wind or Earth's magnetospheric plasma due to the Moon's lack of a magnetosphere or a dense atmosphere. → intense space weathering of the regolith.

Such continuous ion precipitation could create inhospitable conditions for future human outposts on the Moon, → it is crucial to investigate the close-to-surface environment to determine the safest areas.



Investigation of magnetic anomalies, areas where mini-magnetospheres are formed and the solar wind is deflected.

- **ENA detector** (heritage from BepiColombo-SERENA): a neutral particle imager, based on the state-of-the art of Micro-Channel Plate (MCP) detectors. High angular resolution (4°). Study of: 1) Interactions between the Moon and its environment (Earth's magnetosphere, solar plasma, solar wind, dust and meteorites); 2) interaction of the solar wind with the mini-magnetospheres at the magnetic anomalies; 3) effectiveness of the 'space weathering'; 4) help in the identification of safer areas for human colonization.

- **Multichannel EUV/FUV imaging spectrometer** working in 55- 350 nm spectral range.- Spectroscopic observation of the Moon exosphere and water/ice detection; space weather

- **Multi sensor package** for in situ measurements of the electrical properties of soil/dust and interaction exosphere-surface by means of **permittivity, relaxation and Langmuir probes**. Heritage from Cassini-Huygens.

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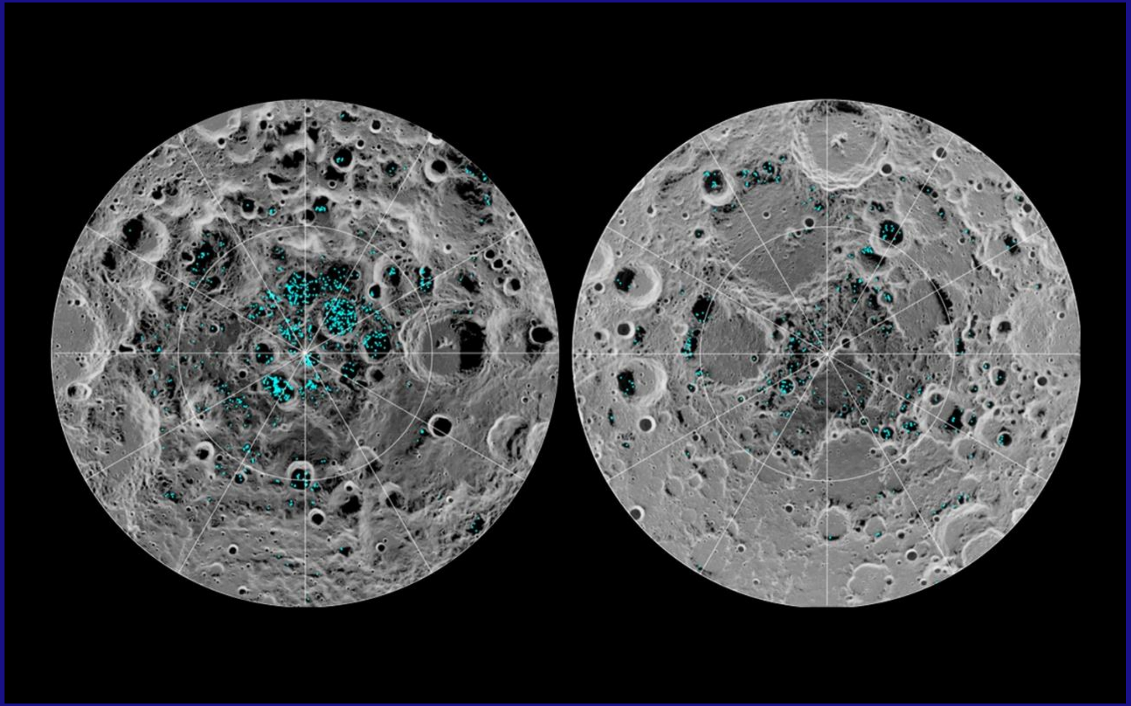
Science of the Moon – Polar volatiles / Lunar volatile cycle

Very small obliquity (1.5 degree) → topographic depressions near the poles are permanently shaded from sunlight → extremely low temperatures (25 – 80 K) → cold trapping of volatiles.



Lunar poles may record a history of volatile flux through the inner solar system over the lifetime of the traps.

The polar regions may provide critical resources, such as high concentrations of hydrogen and water, for future human exploration.

NIR detection of OH features at low and high lat and larger abundances in colder regions near the terminator. →
Diurnal volatile cycle?

Relationship among primordial and surficial volatiles with those that are cold-trapped to be understood.

Observations indicate that water ice has a heterogeneous distribution both laterally and with depth on large spatial scales. The distribution at 1-100 m spatial scales, critical for in situ resource utilization (ISRU) implementation, has not been measured.

Instruments of interest for compositional measurements during surface missions include **evolved gas analysers**, **mass spectrometers, neutron spectrometers,** and **infrared spectrometers**. Other instruments providing additional geological context measurements include **gamma ray spectrometers** and **ground penetrating radars**.
Return of cryogenically preserved samples.

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Science of the Moon – Near surface geology

The Moon is a small body with a limited renovation of its surface → preservation of information of the early evolution of the Solar System and the first stages of Terrestrial bodies development.

Geological information stored on the Moon crust are related to:

1) the development of crusts on terrestrial bodies,
2) Earth-Moon system formation and evolution,
3) the basin related volcanism,
4) the small bodies' tectonism,
5) the hypervelocity impact processes and products;
6) the impact record during the Solar system evolution,
7) the regolith production,
8) the water and hydrated minerals production on airless bodies,
9) the in-situ resource materials for future sustainability.

Despite plenty of data provided by the orbiters, the still unanswered questions are becoming to future human exploration → need to get more details of the surface increasing the spatial and spectral resolutions of the collected data.

Obtaining compositional information at higher spatial resolutions, the **return of samples** from high-priority targets, **in situ elemental and mineralogical analyses** as well as **regional seismic networks** to determine vertical structure, **subsurface sounding**, geologic fieldwork by astronauts. Mobility is a benefit if available.

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Science of the Moon – Instruments for geology and ice mapping/characterization (1/3)

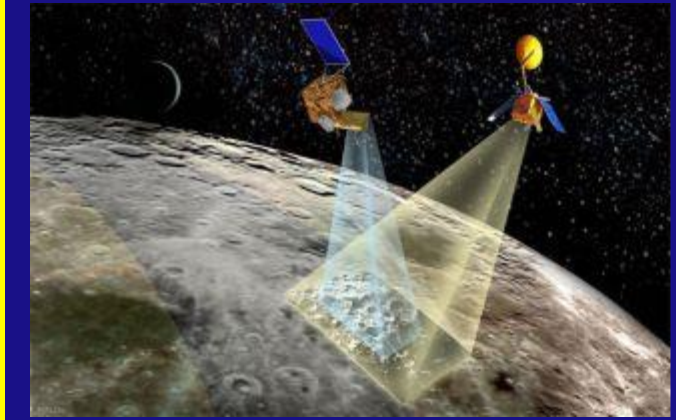
Radars:

- **Subsurface sounding radar** (from orbit) (heritage: MRO-SHARAD). It transmits a 10 MHz bandwidth pulse centered at 20 MHz. It is particularly well suited for the study of the upper few hundred meters of the Lunar subsurface and for the detection and mapping of subsurface voids such as lava tubes.

- **Inteferometric Synthetic-Aperture Radar (In-SAR)** (from orbit). Characterization of small-scale surface roughness and near-surface regolith density, with a horizontal resolution of several tens of cm and a vertical res. of the order of several cm that are relevant to human exploration.

  Because SAR is capable of imaging areas in permanent shadow such as polar craters, this information would also help characterizing the distribution of volatiles at depths that are accessible to human explorers.

- **Ground penetrating radar** for shallow (~50 m) subsurface investigations (from rover/lander). Light, non-destructive, and low power consumption. A GPR system equipped with an antenna array could be tuned at different frequencies in the range from 500 to 2000 MHz to optimize the trade-off between vertical resolution and depth.



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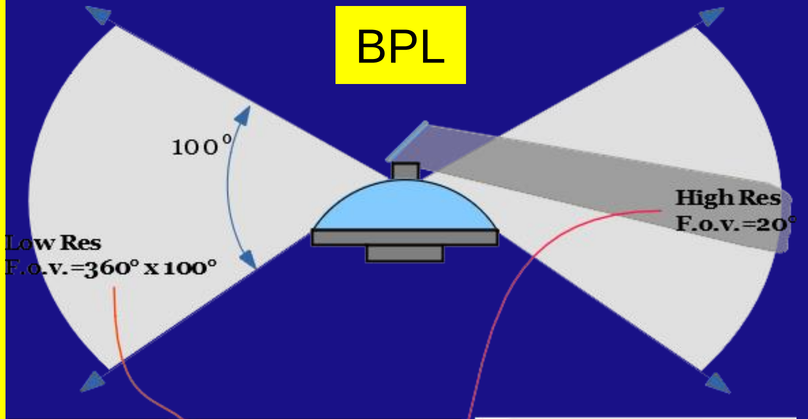
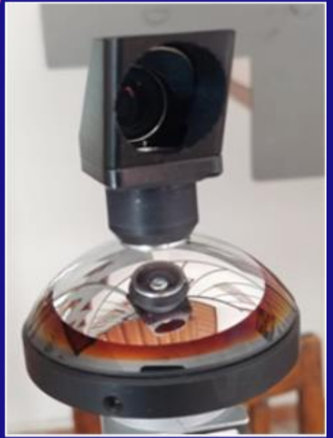
Science of the Moon – Instruments for geology and ice mapping/characterization (2/3)

Cameras and spectrometers:

- Novel (and patented) **Bifocal Panoramic Lens** (BPL) which is able to acquire, simultaneously, a panoramic image (360°x100°) and an higher resolution one. (On Rover, drone, lander, astronauts).
- **Stereo camera + spectrometer in a single instrument** (heritage BepiColombo - SIMBIO-SYS), providing stereo pair for each spectral sampling of the spectrometer. 4D data will be generated: each pixel of the DTM will has the spectral information. (From orbit)
- **Hyperspectral imaging spectrometer** operating on the surface in the range 0.4 - 3.0 μm. Characterization of surface mineralogy at spatial scales (cm to m) inaccessible even from low lunar orbit. Valid support for astronauts for a rapid reconnaissance of the surface composition. Characterization of samples in terms of level of hydration, content of volatile compounds, degree of space weathering, etc (heritage: JUICE/MAJIS, ExoMars/Ma_MISS, Rosetta/VIRTIS, …)
- **Compact Fourier spectrometer** (orbiter-based) (heritage: ExoMars-MIMA). For prospecting of lunar resources and surface science from orbiter, addressed by the characterization of the lunar surface composition, including water ice abundance, in the 2-100 μm spectral.





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Science of the Moon – Instruments for geology and ice mapping/characterization (3/3)

LIBS/Spectrometers and Diffractometers:

- **Instrument based on hyperspectral imaging and LIBS spectroscopy, combined with a context camera**. Spectral range: 200-900 nm. Analytical tool for astronauts and rovers dedicated to sample selection, able to assess chemical and mineralogical composition of rocks. (On Rover and/or portable analytical tool for human exploration).

- **Diffractometer** based on ExoMars – XRD instrument. It combines X-ray fluorescence spectroscopy (XRF) and X-ray diffraction (XRD) to simultaneously analyze the chemical and mineralogical composition respectively. (Robotic arm of the lander to put the instrument in touch with the sample. It requires a tool to clean and flatten the rock surface before the analysis.)

- **Gamma-rays instrument** for the detection of chemical abundances on the lunar surface. Heritage from HERMES Pathfinder, to be tested in LEO starting from 2023.

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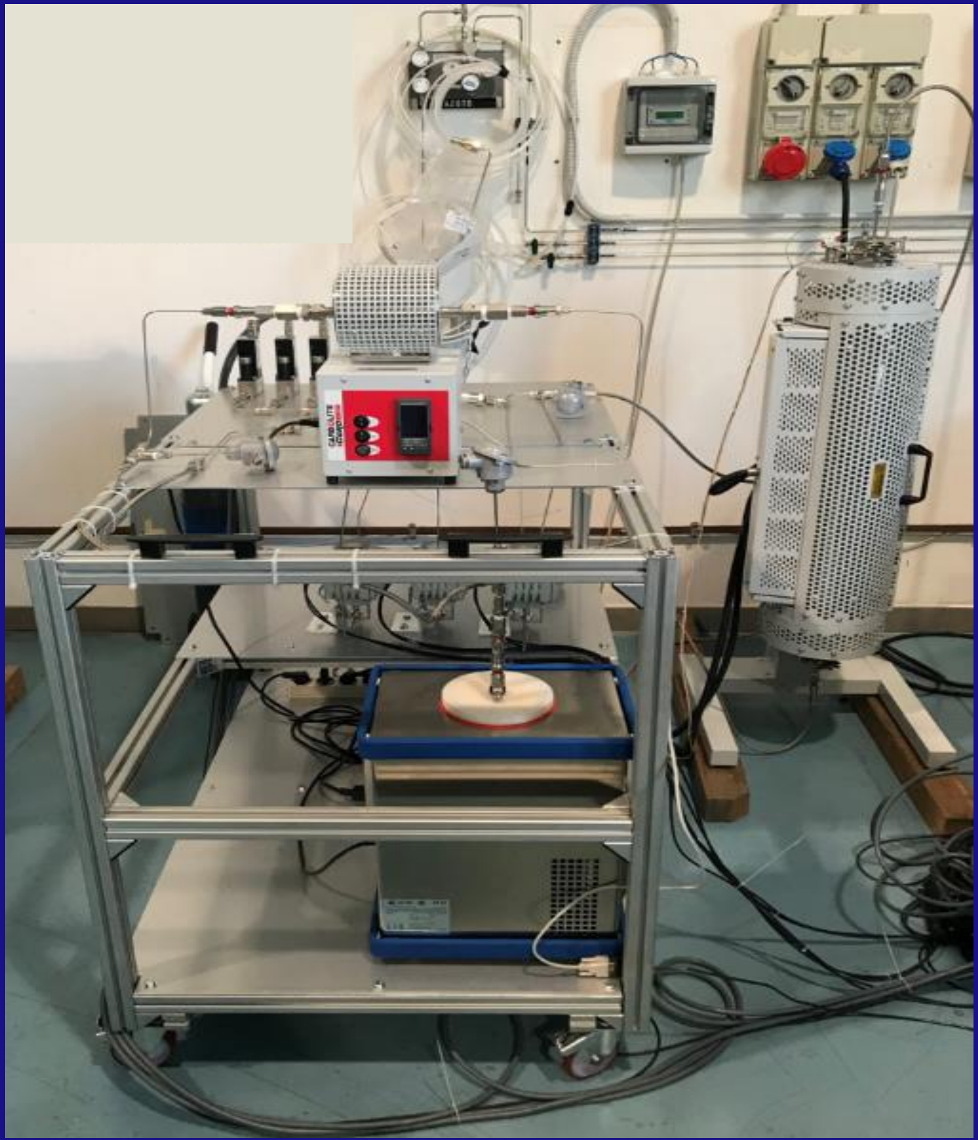
ISRU experiments

ISRU: experiment for Water\Oxygen extraction from dry regolith: thermo-chemical reactors are exploited for water\oxygen production from the regolith minerals. The experiment is based on the reduction of oxides present in the lunar feedstock, by means of carbon injected as methane in a warmed reactor. The reduction stage produces CO CO 2 syngas which are manipulated through a following Sabatier reaction stage to obtain water and recycle the methane\Hydrogen reactants. A gas chromatographer quantifies the produces species; water is regularly produced with NU-LHT-2M simulant and a solid-gas bed with no molten feedstock.

The process is landing site mineralogic composition independent.



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Science of the Moon – Structure from core to crust

- The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.
- Important information on the structure and composition of the lunar interior came from Apollo seismic data and NASA GRAIL mission.
- Open scientific questions would require a more detailed knowledge of its interior and the collection of high-quality geophysical data.

Need of a simultaneous, **globally distributed seismic and heat flow network** and/or **an expanded retroreflector network**, and strategic **collection of samples** from terrains of different ages.

Seismological data:

- **Ultra stable laser interferometry with optical fiber cables** which guarantees very high-sensitivity of the methodology.
- **Passive Lunar Seismic antenna** for moonquake high-resolution sensing: array of seismic sensors
- **Broad-band seismometer** measuring the three orthogonal components of the ground accelerations with sensitivity better than $10^{-10} \frac{m}{s^2}/\sqrt{Hz}$, in the frequency range $10^{-3} - 20\ Hz$ and + array of closely spaced 6-8 vertical sensors.
- **Dosimeter Seismometer and 3-axial Magnetometer** for the MOON: sensors package

Lunar Laser Ranging (LLR): ML100, the unprecedented single, large, 100 mm next generation lunar laser retroreflector.

Science from the Moon and on the Moon

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Science on the Moon – Experiments on the lunar surface

Biological and physiological effects of the lunar environment

Measurement in situ or on return to Earth of the biological impact of the lunar environment associated with the lunar surface (e.g. radiation and gravitational) to inform human risk modelling and mitigation.

Life Science - chips for the identification and assessment of organic compounds at parts-per-billion sensitivity from samples extracted from the surface of the Moon. The technique will combine liquid microfluidics and chemiluminescence to detect biomolecules in a broad range of molecular sizes, verifying their stability when exposed to lunar environmental conditions (UV and particles radiation).

Survivability in space – UVC disinfection in future lunar habitation modules: Light collector and radiometer. Test 'on site' of the performance of a scaled-down prototype, a 2 mirror telescope with a tracking mechanism, collecting the solar UV light. The telescope concentrates the solar UV germicidal light, while discarding all other bands. Validation of the system performance and of filters and coatings efficacy and stability over time.

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Science from the Moon – Cosmic rays

Experiments for Cosmic-rays measurements:

Moon-based detectors would provide a significant contribution to the cosmic-ray physics, with the most precise measurement of the time-dependent spectra below few tens of GeV, a permanent monitor for radiation hazards and an unprecedented contribution to indirect detection of dark matter.

The would benefit from the absence of an atmosphere and of an almost negligible planetary magnetic field.

- The absence of an atmosphere would allow the detection of primary CRs directly from the Lunar surface.
- A negligible planetary magnetic field will also ensure no energy cutoff, allowing a nearly 100% duty cycle for cosmic-ray measurements of all energies.

Italian technologies:

- **Plastic scintillator** Time of Flight + Magnetic spectrometer + LYSO calorimeter
- **VETO** consisting of plastic scintillators + a crystal calorimeter with a preshower readout with SiPM technology and built with a modular approach.
- Detection of high energy cosmic rays with **radio antenna** exploiting the Askarian effect.

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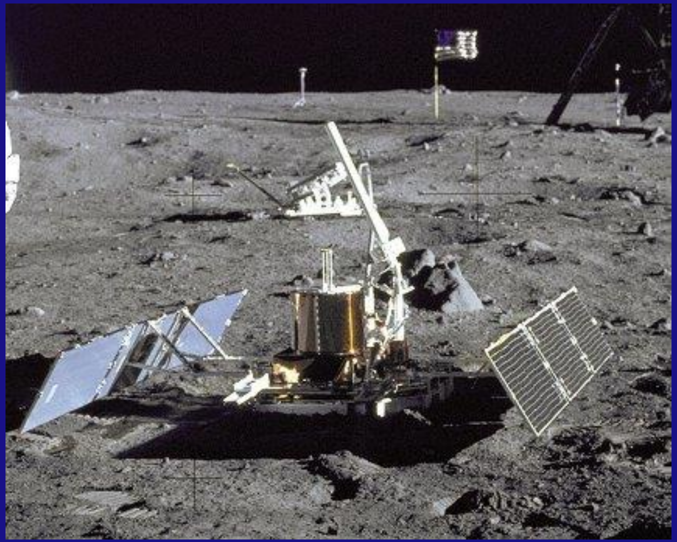
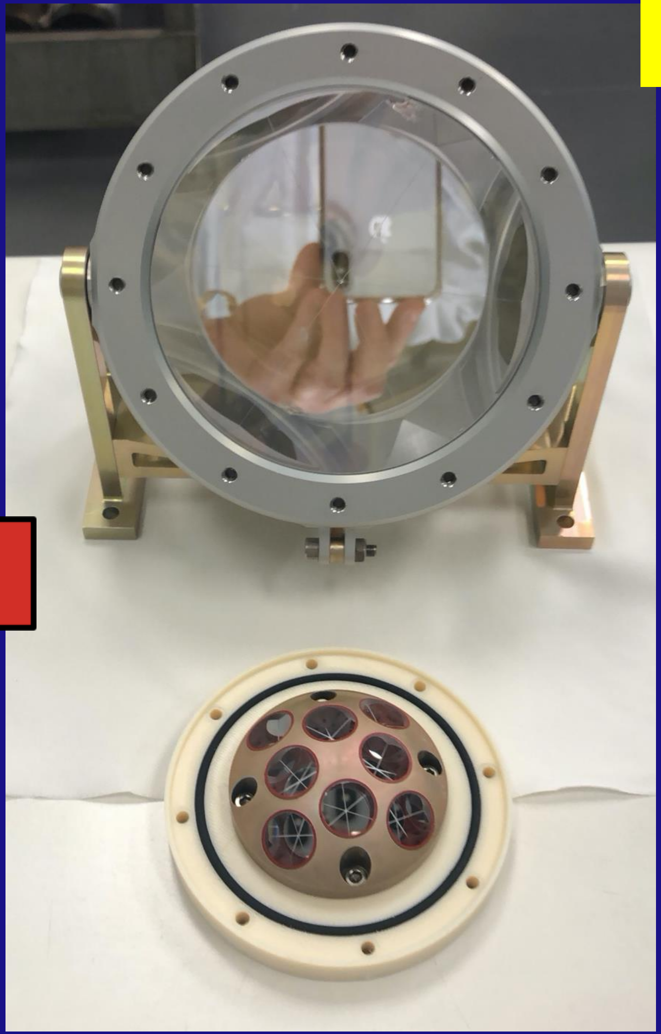
Science from the Moon – Fundamental physics

Seismometers for :

- Accelerometer / seismometer aimed to searching for strange quark matter by detecting the vibrations caused by a quark nugget hitting or crossing the Moon.
- Seismometer to be used for 1) gravitational-wave physics, 2) multi-messenger astronomy, 3) lunar internal structure characterization.



Dedicated experiments exploring gravitational effects on **CP Violation**



Full size and microreflectors network for:

- **Direct testing of the theory of general relativity** by accurately measuring the shape of the Moon's orbit through laser ranging between the Earth and Moon. Additional devices and with optimal spacing, ranging accuracy can improve by two orders of magnitude.
- **Georeferencing landing site & rovers** (near & far side);
- **Positioning & cartography** (global & local networks);
- Improve knowledge of **lunar interior**.

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Science from the Moon – High energy experiments

Absence of a substantial atmosphere favors high-energy observations in the keV-GeV energy range.

With respect to satellites, the lunar surface offers a large platform, allowing for large collecting area instruments, much bigger than any conceivable instrument to be put in orbit, and lunar surface materials that can be used for construction, like regolith used as an absorbing medium in gamma-ray trackers or as a shielding of detectors.

- Low (10 keV – 10 MeV) and high energy **X/gamma-ray detector**. Charged particle detector for space weather and radiation dosimetry purposes.

- **X/Gamma-ray telescope** (tracker and the calorimeter assembly) to be installed on the surface of the Moon. AGILE and Fermi heritage, but with larger collecting area → improved sensitivity up to 1 order of mag.

- Innovative **refractive telescope in X-ray** band reaching the milli-arcsec resolution imaging for the first time. Decoupled architecture alternative to a formation flight layout: optical module on a lander, detector module hosted by a rover and kept at the desired position.

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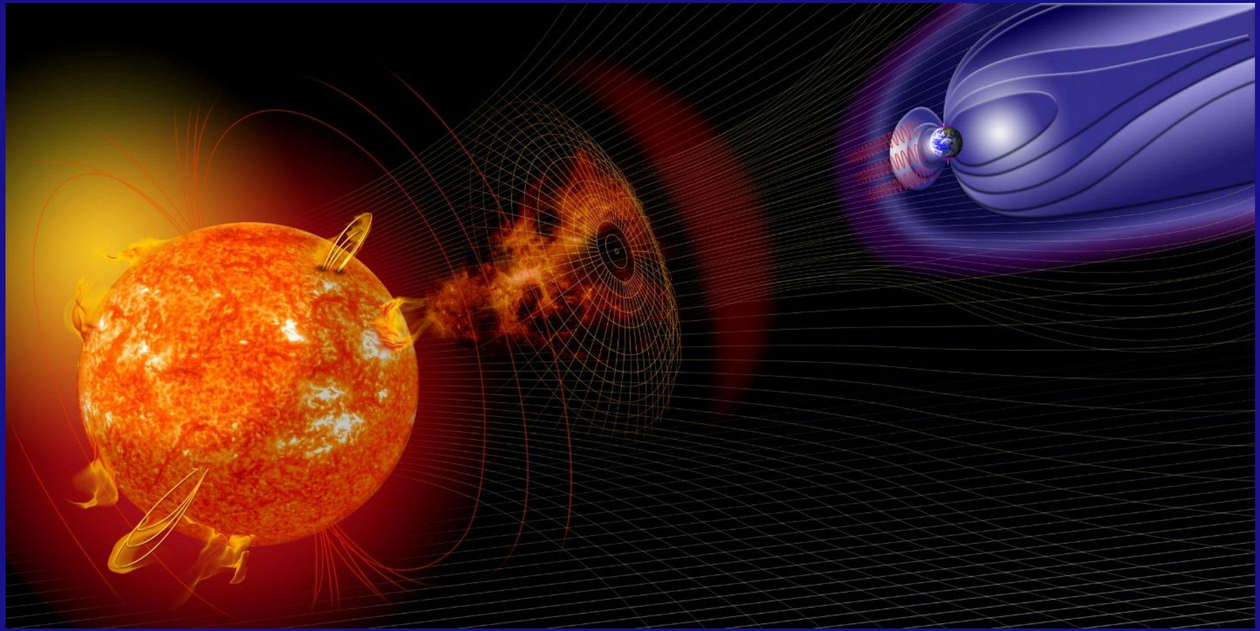
Science from the Moon - Heliophysics

Imaging and spectroscopy of the solar corona, coupled with polarimetry, are the only tools available at present to capture signatures of physical processes responsible for coronal heating and solar wind acceleration within the first few solar radii above the solar limb.



Coronagraph and Solar Wind Monitor to be accommodated on nanosat.

It is a solar VIS-NIR spectroscopic telescope onboard a lunar orbiting spacecraft that periodically (hourly to daily) images the inner to outer corona above the dark lunar limb from the night-side of the Moon.
Such observations would provide unprecedented angular resolution of the inner corona and brightness resolution of the outer corona.

Unlike coronagraph telescopes that need external and internal occultation systems, in each orbit, the Moon will create a natural eclipse. For this reason, the optical system can be greatly simplified with respect a classical coronagraph, and it can fit a small satellite (e.g., nanosat).

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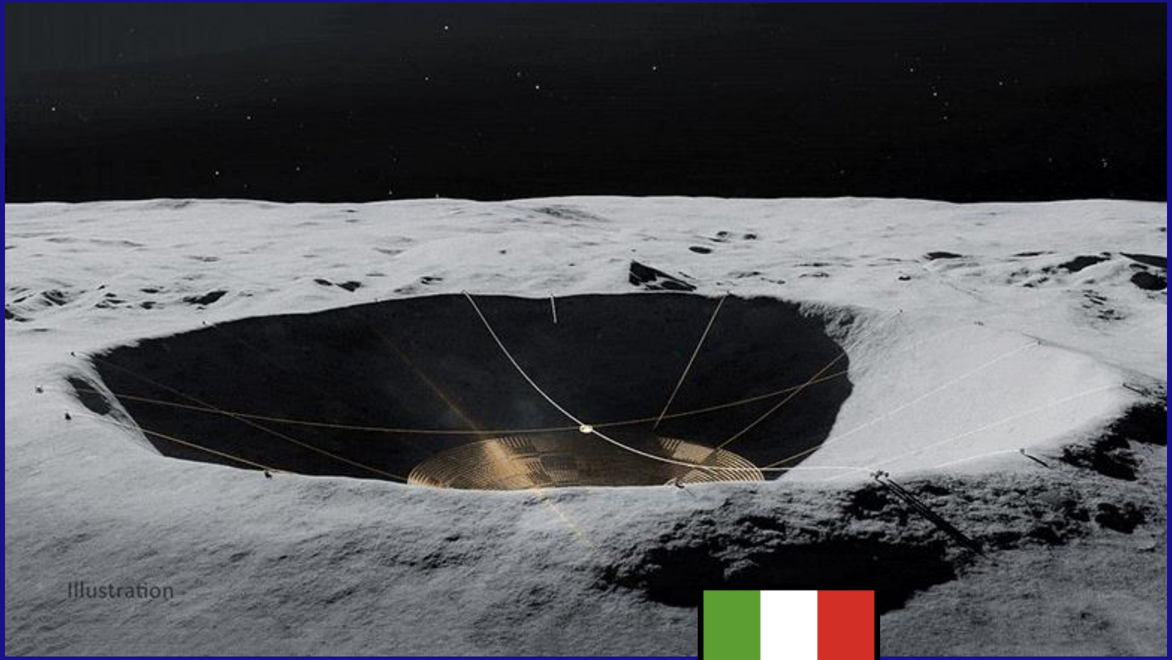
Science from the Moon – Radio astronomy

The Moon provides an excellent platform for radio observations below 10 MHz. This window is completely reflected by the Earth Ionosphere and impossible to observe from ground.

The far side of the lunar surface is shielded from terrestrial radio interference.

1) **Moving interferometer made of antennas mounted on rovers**, capable to increase the relative distance and therefore the final angular resolution of the data.
The aim is to produce an all sky image with a resolution of 2 – 10 arcmin in the frequency range 10 – 2 MHz. This is a completely new approach, given the much better angular resolution (at least 100X) that can be achieved through the proposed infrastructure.



2) **K/Ka-band transceiver, microwave radiometer, radio spectrometer** aimed at studying the Moon surface (brightness temperature measured at higher temperature sensitivity and spatial resolution) and at carrying out occultation, Doppler shift, etc experiments.
Conceived for Cubesat platforms but it can be also accommodated on both landers and rovers

Summary

Scientific heritage and expertise of the Italian scientific community

For each reported scientific objective, the community identified instrumentation and technologies, available in Italy at different level of TRL:

1. **Upgrade or copy of payload** developed in Italy for a different mission. Some of them have spare parts to be used. Most are < 1.5 - 2 kg.

2. **New instruments with important heritage** from other missions, allowing a relative fast development (4-6 years).

3. **Novel instrumentation** (some potentially breakthrough) with low space heritage, but high heritage in terrestrial contexts.

The outcome of the survey will be published very soon.

Step forward

Interaction with NASA to find common interests in lunar exploration.

Workshop @ ASI 1 - 3 February 2022

Workshop: "Una Roadmap per la Luna: Scienza e tecnologia"
Agenzia Spaziale Italiana