An Integrated Framework for the Radiation Environment in Space, on Mars and on the Moon and its Implications for Human Space Flight

Bruna Lima June 2025 - XXII Seminar on Software for Nuclear, Subnuclear and Applied Physics

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

TÉCNICO LISBOA

INFN Istituto Nazionale di Fisica Nucleare

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

CA 21128 PROBONO

Funded by the European Union

Photo Credit: ESA/Hubble & NASA

The Radiation Challenge in Space Exploration

- Space radiation is a **significant threat** to **astronauts** and **electronic equipment**.
- **Mars** has minimal protection compared to Earth.
- The **Moon** has no protection at all, compared to the Earth.
- **Cosmic rays** and **solar events** pose health risks.

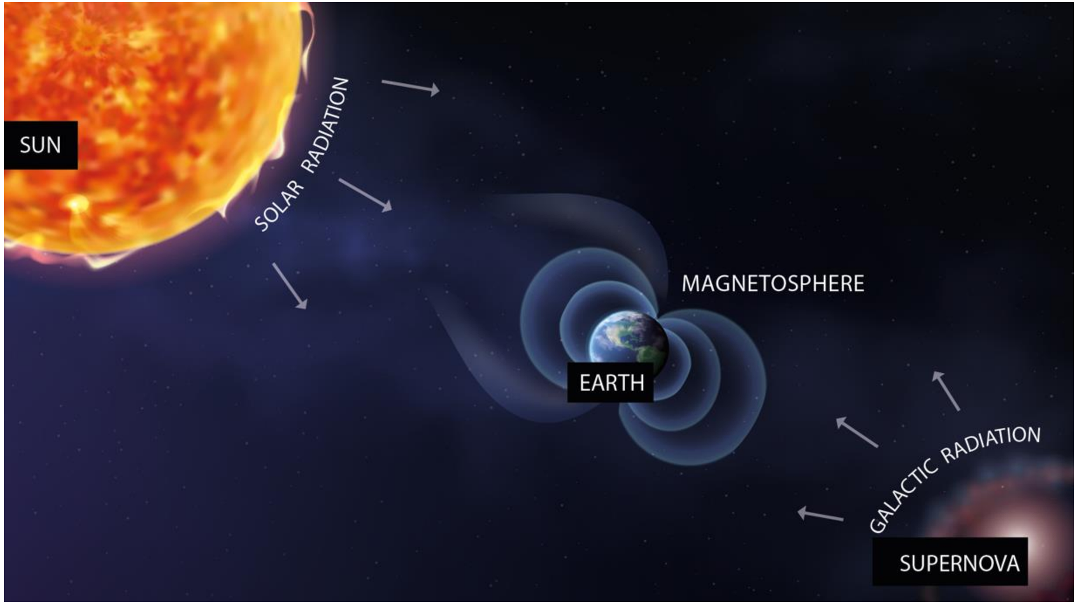


Figure 1: Cosmic radiation can be galactic and solar. The Earth's magnetosphere deflects cosmic rays and protects us from solar flares. (Image: L. Han/IAEA)

The Space Radiation Environment

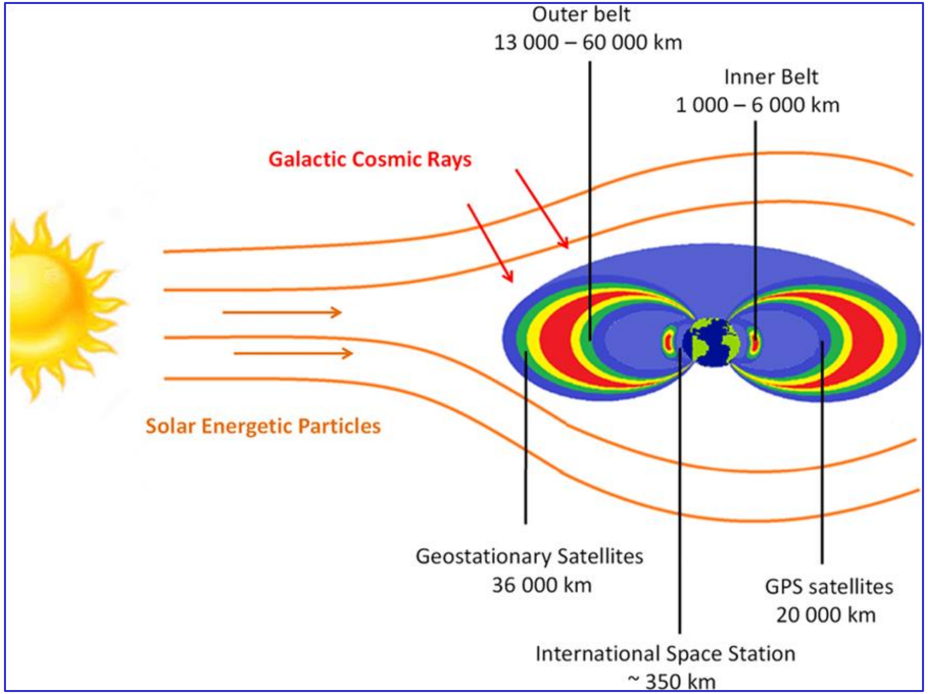


Figure 2: Earth's particle environment, dominated by galactic cosmic rays and solar particles, with the influence of the geomagnetic field. Adapted from ResearchGate, Space as a Tool for Astrobiology.

Galactic Cosmic Rays

High-energy particles from outside the Solar System.

Solar Energetic Particles

Bursts of particles from the Sun (solar flares, Coronal Mass Ejections)

Planetary Radiation Belts

Trapped charged particles around planets (Earth's Van Allen belts)

Why do we care?

- Future human missions to Mars and the Moon are being planned.
- Safe exploration requires accurate radiation risk assessment.
- Ensuring astronaut safety is critical for long-term space exploration.

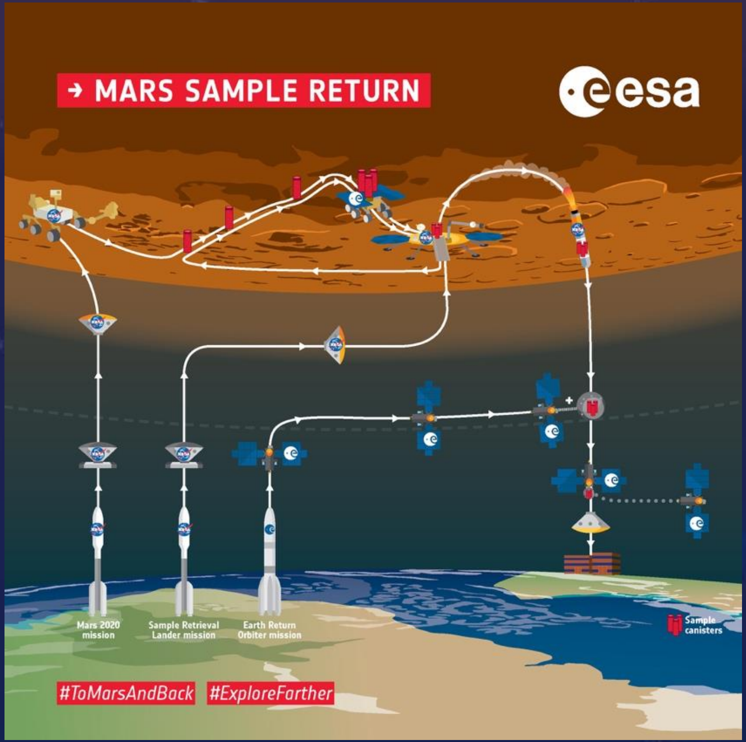
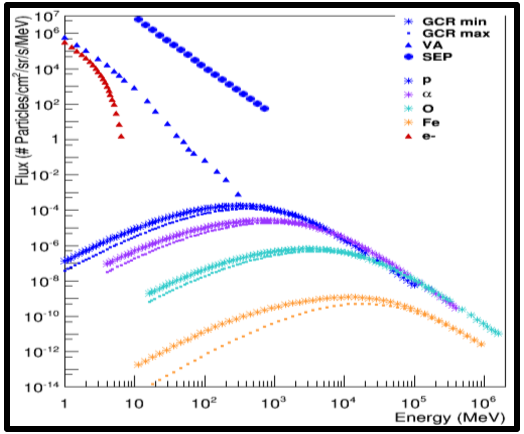


Figure 3: Mars Sample Return overview
Infographic Credit ESA–K. Oldenburg

Project Overview – The Solution to the Problem

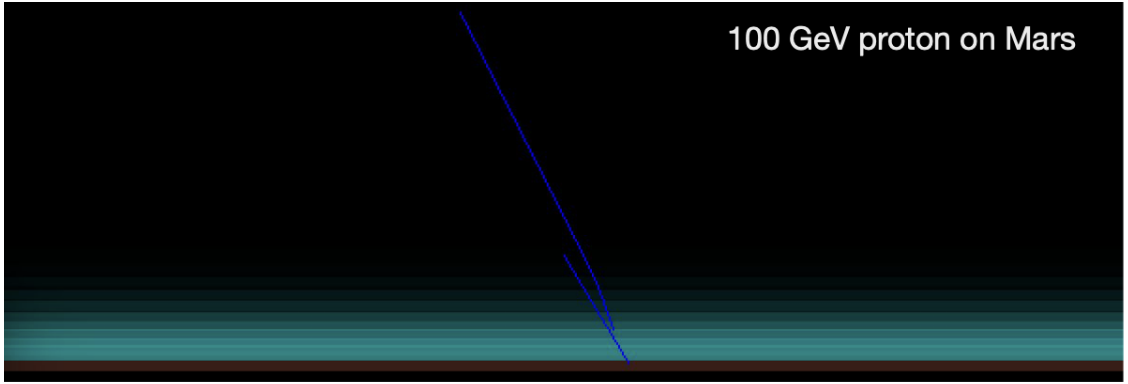


CRaTER Cosmic Ray Telescope for the Effects of Radiation
Experiment on NASA's Lunar Reconnaissance Orbiter

SEPEM

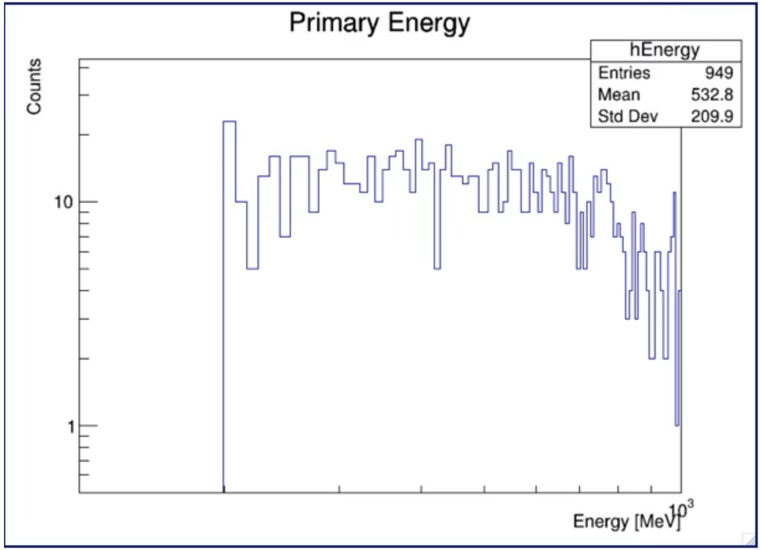
SPENVIS
The Space Environment Information System

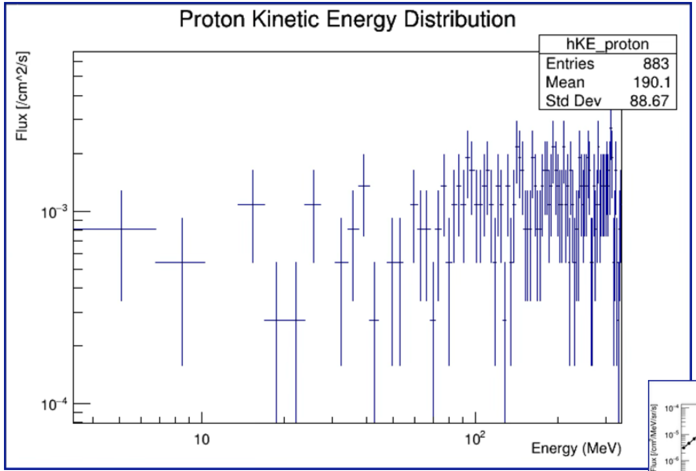
GEANT4
A SIMULATION TOOLKIT

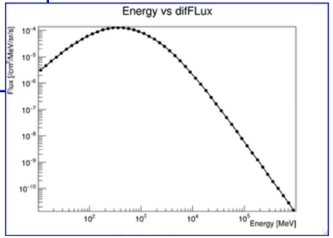


Input → Simulation → Results

Project Overview:
The Solution to our Problem

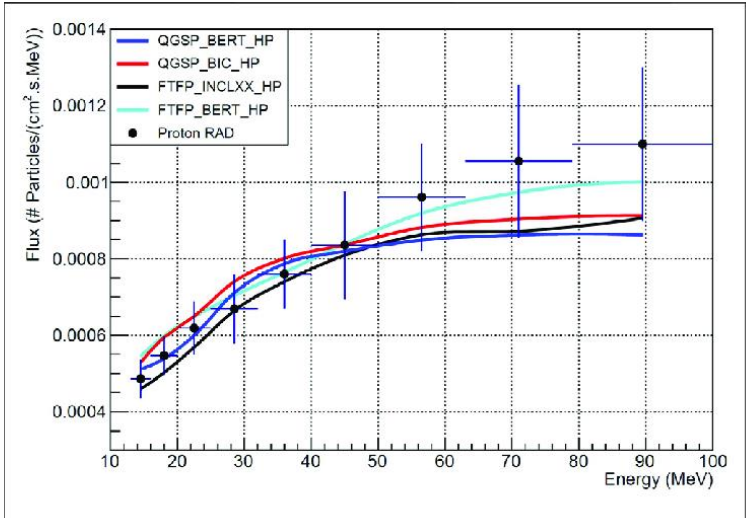






Input → Simulation → **Results**

Validation and Impact:
Building on dMEREM



- Validate models using mission data
- Assess radiation risks for spacecraft, EVAs, and different astronaut profiles.
- Provide mission planners with reliable data for safer crewed missions. (easy! 🥳)

Figure 4: Proton spectra reaching the Mars surface within the RAD field-of-view due to GCR-protons, helium, carbon and oxygen nuclei described with the GCR ISO-15 390 model, simulated with dMEREM using four different physics lists compared to RAD proton differential flux measurements of September 2017. (Credits:Validation of dMEREM, the Detailed Mars Energetic Radiation Environment Model, with RAD Data from the Surface of Mars)

Conclusion

Building a Safer Future for Space Exploration

- Unifying fragmented radiation data for better understanding and accessibility.
- Ensuring astronaut safety for long-duration missions.
- Supporting the next wave of human exploration on the Moon and Mars.

Figure 5: LUNA recreates the Moon's surface on Earth, located next to ESA’s Astronaut Centre (EAC) in Cologne, Germany.
CREDITS: ESA-L. Breggion

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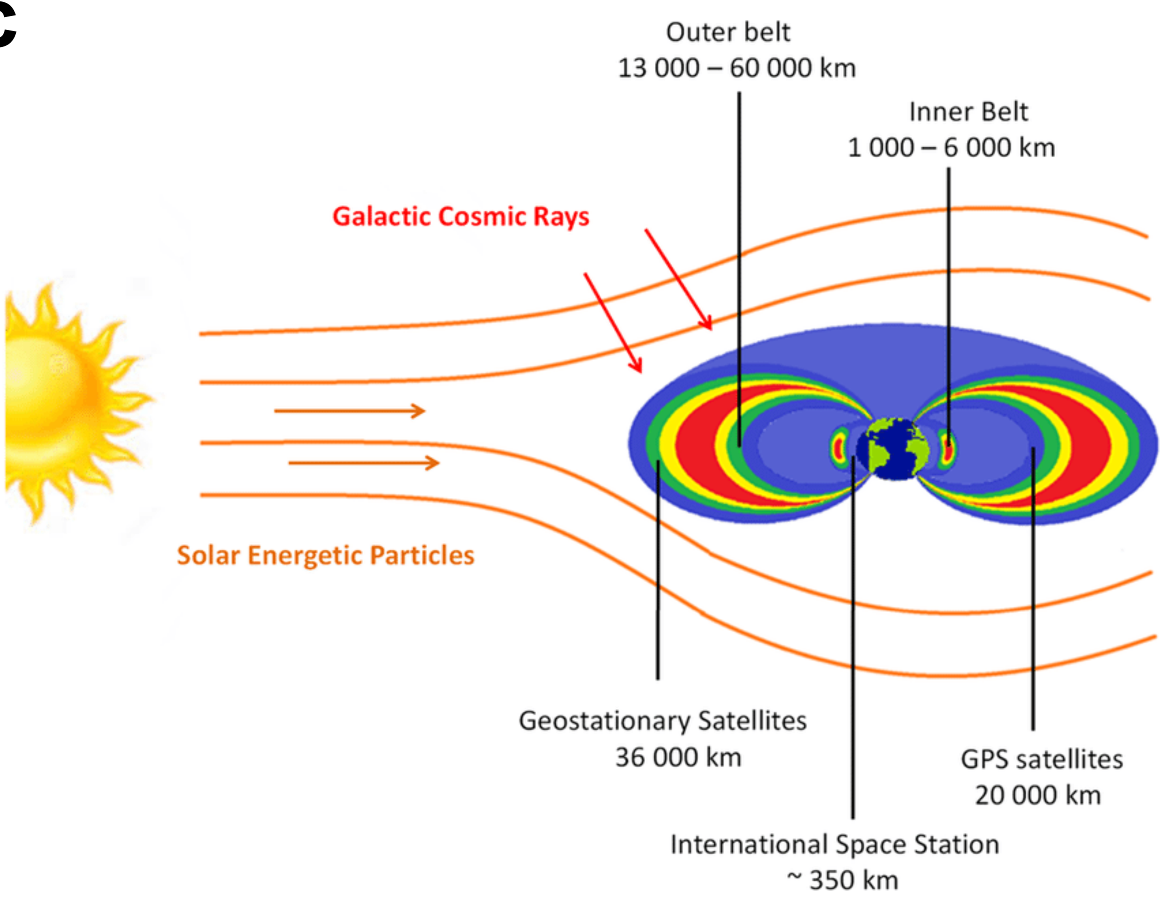
Extra Slides

Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP)

Credits: Space as a Tool for Astrobiology: Review and Recommendations for Experimentations in Earth Orbit and Beyond - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Earths-particle-environment-dominated-by-galactic-cosmic-rays-and-solar-particles-and_fig3_318029811



Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP)

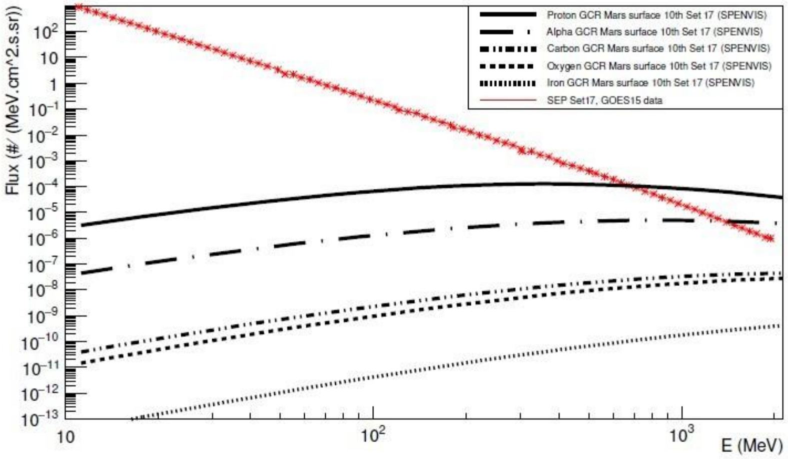
Galactic Cosmic Rays (GCR):

- High-energy particles from outside the solar system
- Originate from supernovae and distant stars
- Composed of protons, heavy ions, and electrons
- Can penetrate deep into planetary atmospheres and affect radiation environments

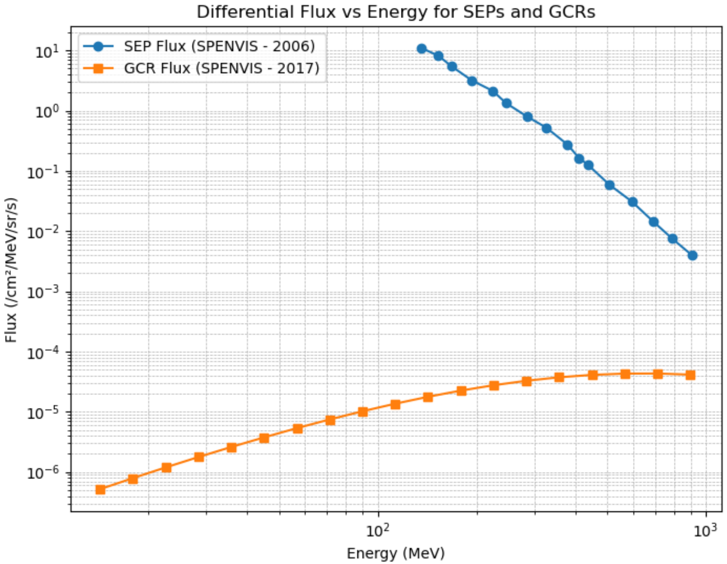
Solar Energetic Particles (SEP):

- Emitted during solar flares and coronal mass ejections
- Consist mainly of protons, with some heavier ions and electrons
- More intense but localized compared to GCR
- Pose radiation risks to spacecraft, astronauts, and satellites in space

Radiation Spectra Simulation

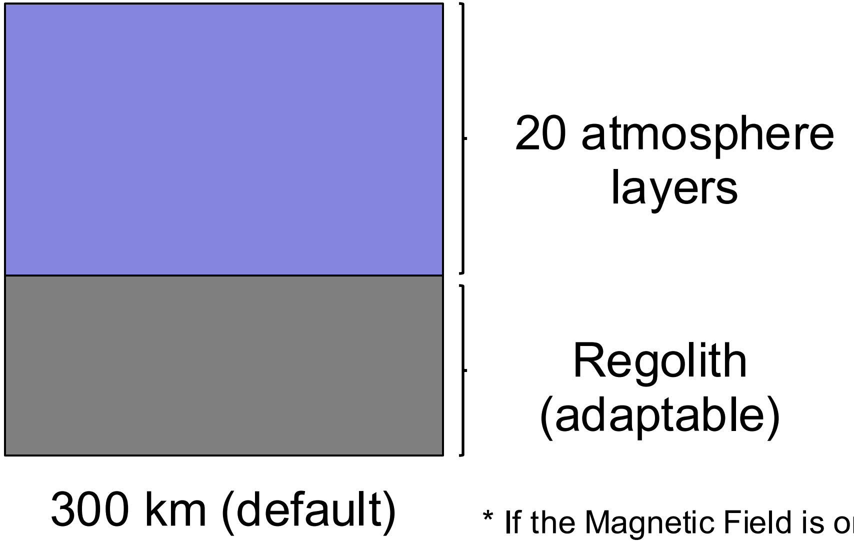


Differential flux as a function of kinetic energy (GCR)



Comparative flux spectra of GCRs and SEPs extracted from SPENVIS

dMEREM



* If the Magnetic Field is on, the values and configuration are different

- ❑ Geometry Definition and Materials;
- ❑ Primary Particle Generation;
- ❑ Event Generation & Simulation;
- ❑ Physics Processes & Interactions;
- ❑ Sensitive Detectors & Scoring Mechanisms;
- ❑ Tracking & Data Collection;
- ❑ Output & Visualization.

Lunar Radiation Environment

Particle	Energy (eV)
GCRs	10^8 to 10^{20}
SEPs	10^8 to 10^9
Albedo Particles	Up to 10^8
Other sources	

SEPs fluxes can exceed background GCRs fluxes by factors of 10^3 or more!

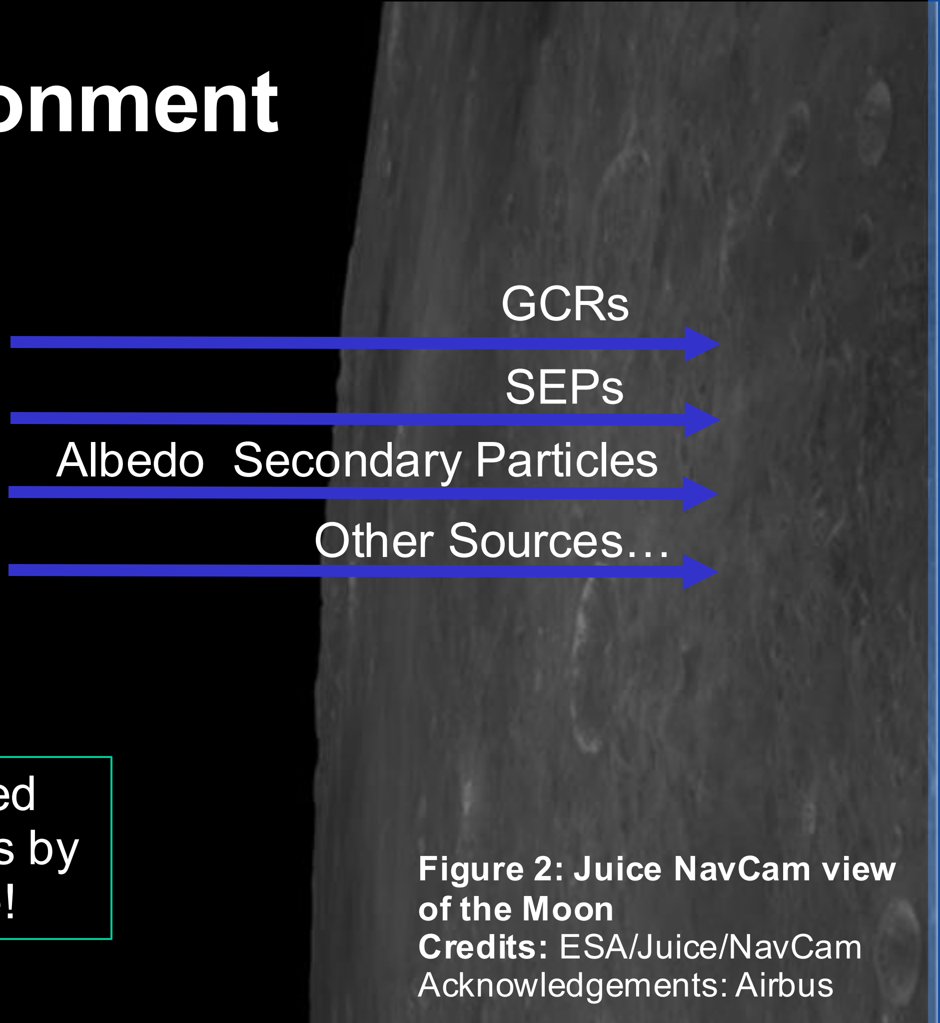


Figure 2: Juice NavCam view of the Moon
Credits: ESA/Juice/NavCam
Acknowledgements: Airbus

From Mars to the Moon

dMEREM

dMEREM
(Mars Model)

Adapting to the Moon:

- Replace Mars' atmospheric/soil models with lunar-specific data.
- Include lunar-specific radiation sources.
- Validate with existing mission data.

Developed by LIP's **SpaceRad** group using **Geant4**.

Simulates radiation environment at different Mars locations.

Figure 3: "Mars true-color generated image using OSIRIS"
CREDIT: ESA & MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA

From Mars to the Moon

dLEREM

Task 1: Characterize lunar radiation environment

Task 2: Develop a computational model (Geant4-based)

Task 3: Validate model against real mission data

Task 4: Assess astronaut radiation risks

Figure 4: “Full Moon as photographed from on board the International Space Station
CREDIT: NASA/Astronaut Jeff Williams

From Mars to the Moon

dLEREM

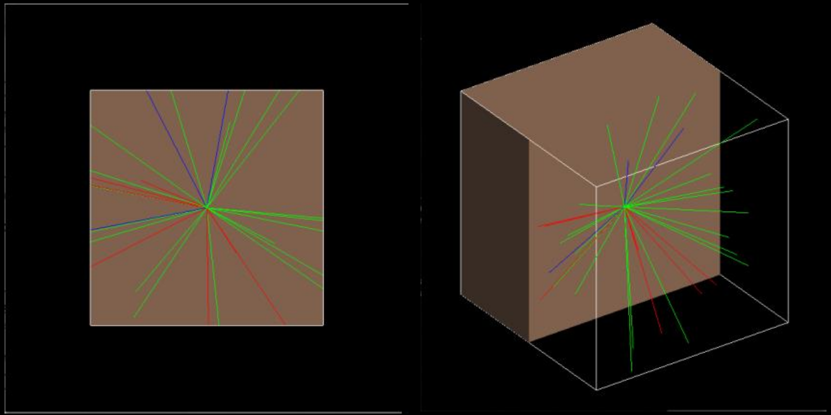


Figure: Geant4 Simulation Example with Moon Regolith and Proton Flux of 100 GeV

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      Position - y (mm)   : 1.083960349821405e-111.083963049215006e-11
      Position - z (mm)   : 1.479007345873014e-111.479011029067858e-11
      Global Time (ns)    :  0.01143614791999963 0.01143614791999963
      Local Time (ns)     : -7.001454533324725e-14-7.001471969092333e-14
      Proper Time (ns)    : -1.534098534712316e-14-1.534102355087841e-14
      Momentum Direct - x :   0.4453226691461333  0.4453226691461333
      Momentum Direct - y :  -0.5292833130974934 -0.5292833130974934
      Momentum Direct - z :  -0.7221820371769878 -0.7221820371769878
      Momentum - x (MeV/c):    1.013318641254679   1.013318641254679
      Momentum - y (MeV/c):   -1.204368618141755  -1.204368618141755
      Momentum - z (MeV/c):   -1.643303993605095  -1.643303993605095
      Total Energy (MeV)  :    2.332142006503581   2.332142006503581
      Kinetic Energy (MeV):    1.821143096503581   1.821143096503581
      Velocity (mm/ns)    :    292.5074555687947   292.5074555687947
      Volume Name         :             Regolith            Regolith
      Safety (mm)         :                5e-10               5e-10
      Polarization - x    :                    0                   0
      Polarization - y    :                    0                   0
      Polarization - Z    :                    0                   0
      Weight              :                    1                   1
      Step Status         :      AlongStep Proc.     AlongStep Proc.
      Process defined Step:                eIoni               eIoni
    ----------------------------------------------------------------------

   ++List of secondaries generated (x,y,z,kE,t,PID):  No. of secondaries = 0

**PostStepDoIt (after all invocations):
   ++List of invoked processes
     1) Transportation

   ++G4Step Information
     Address of G4Track    : 0x139f1d3f0
     Step Length (mm)      : -5.10009201886219e-17
     Energy Deposit (MeV)  : 0
    ----------------------------------------------------------------------
      StepPoint Information               PreStep             PostStep
    ----------------------------------------------------------------------
      Position - x (mm)   : -9.120109676571092e-12-9.120132388436999e-12
      Position - y (mm)   : 1.083960349821405e-111.083963049215006e-11
      Position - z (mm)   : 1.479007345873014e-111.479011029067858e-11
      Global Time (ns)    :  0.01143614791999963 0.01143614791999963
      Local Time (ns)     : -7.001454533324725e-14-7.001471969092333e-14
      Proper Time (ns)    : -1.534098534712316e-14-1.534102355087841e-14
      Momentum Direct - x :   0.4453226691461333  0.4453226691461333
      Momentum Direct - y :  -0.5292833130974934 -0.5292833130974934
      Momentum Direct - z :  -0.7221820371769878 -0.7221820371769878
      Momentum - x (MeV/c):    1.013318641254679   1.013318641254679
      Momentum - y (MeV/c):   -1.204368618141755  -1.204368618141755
      Momentum - z (MeV/c):   -1.643303993605095  -1.643303993605095
```