Impacts of Space Weather for Human Exploration: Interplanetary and Lunar Radiation Environments

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We are preparing to return humans to the Moon and setting the stage for exploration to Mars and beyond. These ambitious goals create new urgency to develop predictive capabilities for radiation hazards that pose among the most significant risks to future human exploration:

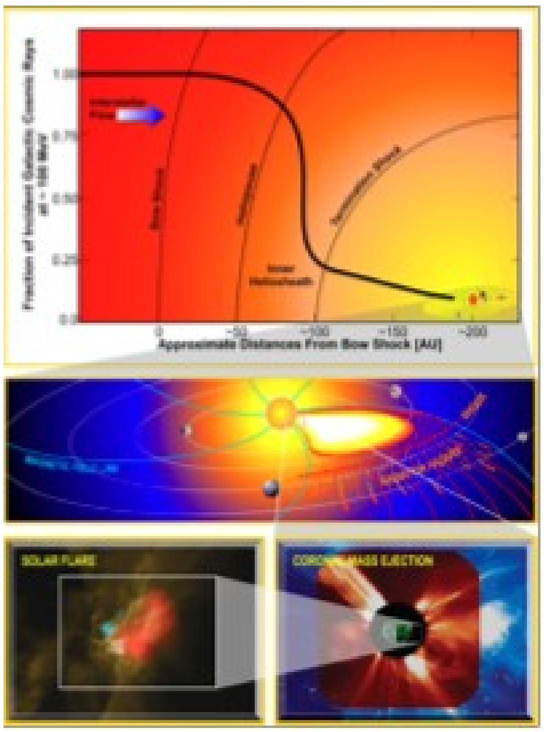

Figure 1: The hazards posed by space radiation: galactic cosmic rays from outside our solar system (top), from flares (bottom left) and shocks (middle) often driven by coronal mass ejections (bottom right).

- **Galactic Cosmic Rays (GCRs)** are an ever-present background radiation that originate from outside our solar system and produce chronic but not acute exposures. GCRs are extremely difficult to shield against outside the protection of Earth's atmosphere and magnetosphere. Astronauts under nominal shielding (*e.g.,* a few gm/cm2 of aluminum) could accumulate a career limit due to GCRs in roughly 3 years. We need to understand the current constraints imposed by GCRs as a function of mission transit time, shielding materials and thickness, and develop better techniques to shield them.
- Large **Solar Energetic Particle events (*SEP events*)** are also extremely dangerous to astronauts outside Earth's atmosphere and magnetosphere. To mitigate the hazard SEPs pose, we must develop the ability to predict when and where they will occur, and we must provide adequate shielding against them.
- There are **unique radiation environments** at each planet or satellite. At Earth, we have thoroughly characterized locations of the radiation belts, which allows us to mitigate the hazard they pose by transiting them rapidly. For future human and robotic exploration of other planets and satellites, we must characterize the planetary radiation environments so that appropriate mitigation strategies and adequate shielding are designed.

Shielding is often considered the answer to space radiation hazards. However, for very high-energy radiation (> 100 MeV), shielding may make matters worse by producing secondary, penetrating particles, such as neutrons and nuclear fragments, that, for some types of shields, increase the hazard.

The Heliophysics community is rapidly discovering the physical processes that control space weather, serving the basis to advance predictive capabilities of the space radiation environment. The challenge for heliophysics is twofold: advance predictive capabilities where needed, while also characterizing the radiation environment and understanding its impacts for human exploration.