# Particle Radiation Environments and Their Effects at Planetary Surfaces:
## Lessons Learned at the Moon by LRO/CRaTER and Extension to Other Planetary Objects

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**Introduction:** Energetic charged particles fill interplanetary space and bathe the environments of planetary objects with a ceaseless source of sometimes powerful but always ever-present ionizing radiation. In turn, these charged particles interact with planetary bodies in various ways, depending upon the properties of the body as well as upon the nature of the charged particles themselves. The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) [1] on the Lunar Reconnaisance Orbiter (LRO) [2], launched in 2009, continues to provide new insights into the ways by which the lunar surface is influenced by these energetic particles. In this presentation, we briefly review some of these mechanisms and how they operate at the Erth and Moon, and then explore the importance of these same mechanisms at other planetary objects within our solar system based on the parameters that govern their physical behavior.

**Galactic Cosmic Ray (GCR) -** GCRs provide an incessant source of energetic particles, emanating from outside our solar system associated with supernova in our galaxy. GCRs wax and wane over a solar cycle, comparatively weakly (well less than a factor of 10) both in space and time throughout the solar system. GCR intensities are largest near the edge of the solar system; interplanetary magnetic fields and solar wind pose obstacles for GCR entry to the inner solar system thus creating a radial gradient. Near a planetary body, GCR intensity is moderated by any intrinsic planetary magnetic fields or atmosphere.

**Solar Energetic Particles (SEP):** Energetic particles are produced episodically by explosive solar events in association with shock waves near the Sun and also at coronal mass ejections propagating into interplanetary space. These bursts of particles stream outward, producing many order of magnitude flux increases, lasting hours to days. These particles race away from the Sun, encountering and interacting with any planetary objects in their path. Intensities are strongest closest to the Sun, diminishing with distance; particle trajectories diverge to fill the increasing volume of interplanetary space.

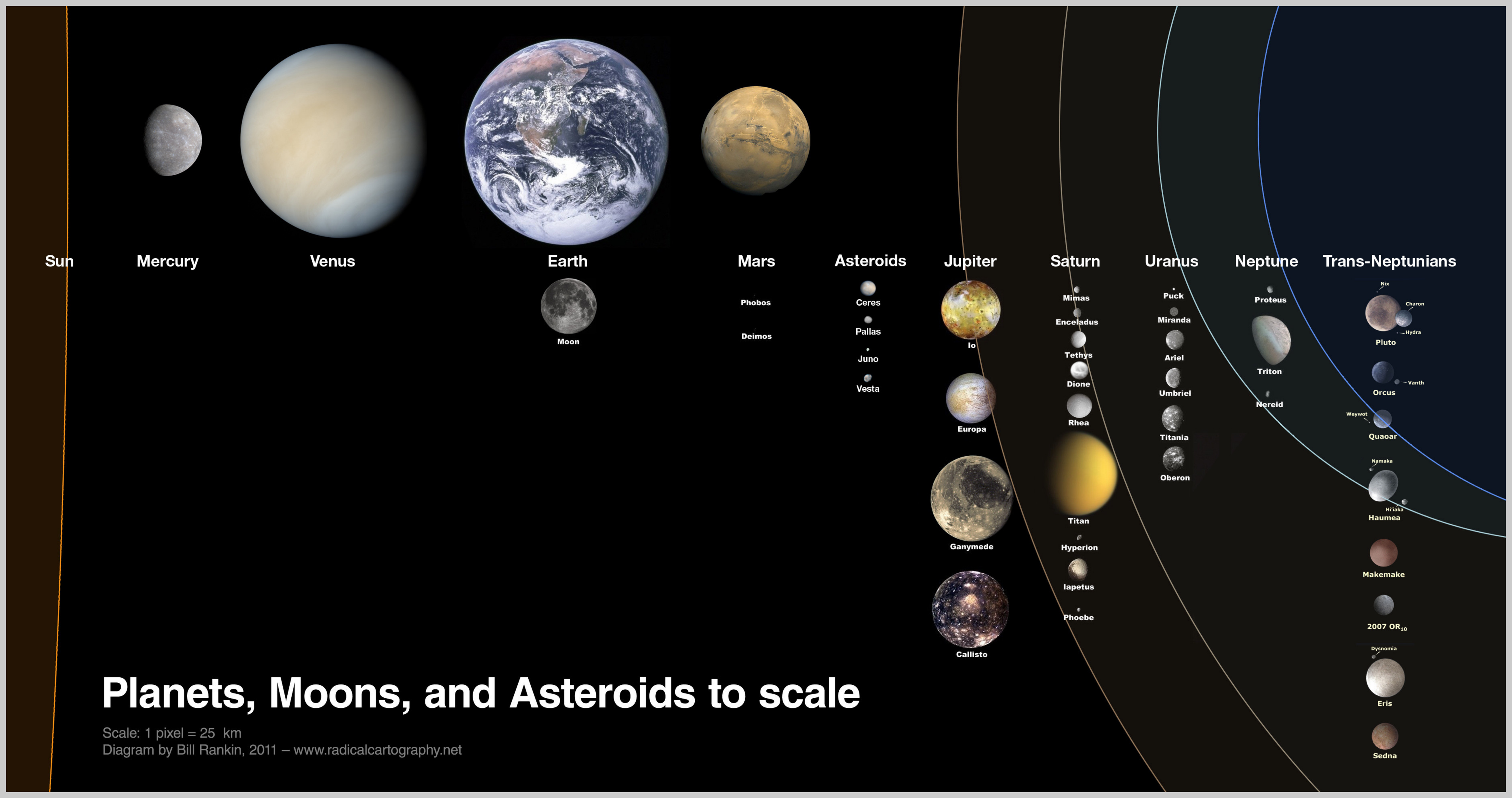
**Radiation Belt Particles (RBP):** Energetic charged particles can also become efficiently trapped by planetary magnetic fields. In the case of Earth, charged particles become trapped in Earth's strong dipole field. The component of trapped particles that also have extremely high energies is what we term the Van Allen radiation belts. Other planets with strong intrinsic magnetic fields (e.g., Jupiter) also have powerful radiation belts. These trapped particles vary dynamically, and pose a final source of ionizing radiation, both on the planet itself as well as on any moons embedded in particles trapped within the planet's magnetic field.

**Mercury (~0.4 AU; modest dipole; no atmosphere):** Same as at Moon, but weaker GCR fluxes owing to radial gradient ; SEP intensity higher, but modest effects at surface (SEP energy generally too low for nuclear interactions); No significant RBP populations

**Venus (~0.7 AU; no field; dense atmosphere):** Direct GCR (slightly weaker) access to atmosphere but no trapping magnetic field for CRAND protons; More intense, direct, and global SEP access to atmosphere; No RBP

**Earth (1 AU; strong dipole; modest atmosphere):** Inner proton radiation belt through GCR access to and nuclear spallation off upper atmosphere (CRAND); High-latitude SEP access into middle atmosphere contributes to O3 and NOx chemistry; Precipitation of RBP influences middle atmosphere chemistry and ionization profile

**Moon (1 AU; weak, localized fields; no atmosphere) :** Direct access of GCR on surface produces energetic charged particle albedo [3,4,5] and chemical space weathering [6,7]; Deep dielectric discharges during SEP events, particularly in cold, permanently shadowed craters, can modify regolith properties [8,9]; Well outside Earth's RBP, so no effects




**Pluto/Trans-Neptunians (~>30 AU; weak or nil fields; transient, weak atmospheres):** GCR fluxes strongest toward edge of solar system with expected direct access to surface/atmosphere; Weaker still SEP fluxes, but coldest temperatures in outer solar system favor charging in shadowed regions; RBP populations not expected

**Neptune (~30.1 AU; very strong fields; deep, dense atmosphere):** GCR fluxes substantially stronger but powerful magnetic field moderates access to atmosphere except at highest magnetic latitudes; Weaker still SEP fluxes and limited access (stronger fields) into atmosphere, again at higher latitudes; Powerful RBP population impacts to atmosphere?

**Uranus (~19.2 AU; powerful fields; deep, dense atmosphere):** GCR fluxes substantially stronger but powerful magnetic field moderates access to atmosphere except at highest magnetic latitudes ("equator" given high tilt); Weaker still SEP fluxes and limited access (stronger fields) into atmosphere, again at higher latitudes; Powerful RBP population impacts to atmosphere?

**Uranian/Neptunian moons (weak or nil fields; atmosphere at Triton):** GCR fluxes substantially stronger but powerful magnetic field moderates access to surfaces (or atmosphere); Weaker still SEP fluxes and limited access (stronger fields) into atmosphere, again at higher latitudes, cold favors charging ; Powerful RBP population impacts to atmosphere for those embedded in fields and with atmosphere

**Mars (~1.4 AU; weak, localized fields; frail atmosphere):** GCR (slightly stronger) direct access to atmosphere (CRAND, but no trapping magnetic field) and to surface (albedo and chemical space weathering); Less intense but direct and global SEP access (no field) into atmosphere; No trapped RBP

**Phobos/Deimos (~1.4 AU; no fields; no atmosphere):** GCR (slightly stronger) direct access to surface (albedo and chemical space weathering); Less intense but direct and global SEP access (no field) to surface – possible charging effects?; No trapped RBP

**Asteroids (~2.2 to ~3.2 AU; weak or absent fields; no atmospheres):** GCR fluxes stronger with direct access to surfaces (albedo and chemical weathering effects); Weaker yet direct and global SEP access to surfaces – possible charging effects and regolith modification?; No trapped RBP

**Jupiter (~5.2 AU; monstrous fields; deep, dense atmosphere):** GCR fluxes much stronger but powerful magnetic field moderates access to atmosphere except at highest magnetic latitudes; Less intense SEP fluxes and limited access (stronger fields) into atmosphere, again at higher latitudes; Powerful RBP population impacts to atmosphere?

**Galilean Moons (~5.2 AU; embedded in Jovian fields plus induced or weak intrinsic fields in some cases; some with thin atmospheres):** GCR fluxes much stronger but magnetic shielding favors atmosphere/surface effects at more distant moons; Less intense SEP fluxes and limited access (strong fields) into those with atmospheres; Innermost moons embedded within RBP populations (atmosphere/ surface effects)

**Saturn (~9.6 AU; enormous fields; deep, dense atmosphere):** GCR fluxes substantially stronger but powerful magnetic field moderates access to atmosphere except at highest magnetic latitudes; Weaker still SEP fluxes and limited access (stronger fields) into atmosphere, again at higher latitudes; Powerful RBP population impacts to atmosphere?

**Saturnian Moons (~9.6 AU; some embedded in Jovian fields. induced fields; Titan atmosphere):** GCR fluxes substantially stronger (and SEP flux weaker still, cold improves charging environment)– those deep inside Jovian magnetosphere shielded, some orbit inside/outside magnetic shield; Innermost moons embedded within powerful RBP populations – impacts to atmospheres and surface likely; outermost moons affected minimally at most

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