QUICK STUDY

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Space weather on the Moon

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Apollo missions placed astronauts outside Earth's protective magnetosphere for days at a time. Future missions risk exposing them to solar and cosmic radiation for months.

No one has been to the Moon since 1972. Nearly half a century later, NASA is planning a return visit—the Artemis mission (see PHYSICS TODAY, July 2019, page 8)—to establish sustainable exploration. The effort would be a radical departure from our previous experience. During nine earlier missions, only six of them landing on the lunar surface, Apollo astronauts spent a cumulative time of less than three months in space over a four-year period. Altogether, the astronauts spent just 80 hours outside the lunar module.

Radiation dosimeters measured the crews' total skin exposure on those six missions to be between 160 and 1400 mGy, below levels that would trigger health concerns. Currently established skin-absorbed dose limits are 1500 mGy within a 30-day period. During future missions, astronauts are likely to spend far more time outside. (One gray, the energy absorbed from ionizing radiation per unit mass, is defined as 1 J/kg.)

An unfiltered sky

The surface of the Moon is itself a dangerous environment. Aside from its lack of a large magnetic field to deflect charged particles, the airless surface is covered with a finely granulated layer of dust, made up mainly of silicon dioxide crystals. The crystals, which have the consistency of flour, are abrasive, easily disturbed, and hazardous to both humans and equipment. In the weak gravitational field, kicked or otherwise disturbed dust particles are lofted above the surface for longer times than on Earth, and their angular surfaces adhere to lunar rovers, habitats, and space suits. Although the toxicity of lunar dust is unclear, Apollo astronauts commonly complained about eye, nose, and lung irritation.

Crews on the Moon also need protection from its extreme variations in temperature; a lunar day reaches as high as 127 °C (260 °F), and a lunar night dips as low as −173 °C (−280 °F). Space suits can insulate against those temperature swings. Astronauts and electronics are far more likely to be affected by exposure to space weather—the natural radiation environment in deep space.

Space weather includes the solar wind, solar flares, coronal mass ejections (CMEs)—the release of billions of tons of plasma from the Sun's corona, as figure 1 illustrates—galactic cosmic rays (GCRs), and micrometeoroid bombardments. Solar flares and the shock waves from CMEs can yield protons, electrons, and energetic ions—collectively known as solar energetic particles (SEPs). Earth's magnetic field and atmosphere shield us on the ground from most of that radiation, and our exposure—a combination of dose rate and duration—mainly comes from small particle fluxes of muons and neutrons. Above the atmosphere, charged particles can leak through Earth's magnetic field and damage the control systems and solar cells of satellites traversing the planet's van Allen belts (see the article by Daniel Baker and Mikhail Panasyuk, PHYSICS TODAY, December 2017, page 46).

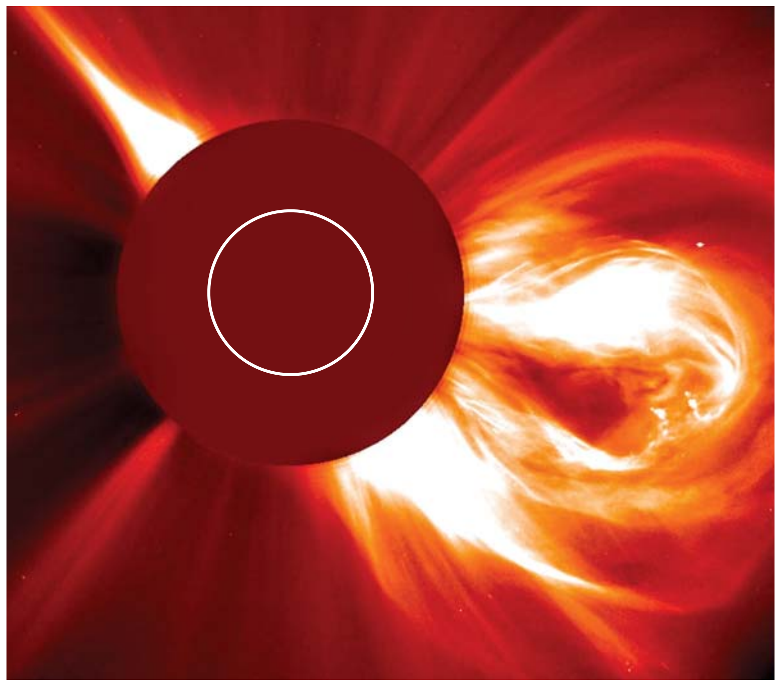

FIGURE 1. THIS IMAGE OF A CORONAL MASS EJECTION and solar flare was taken on 2 December 2003 by the *Solar and Heliospheric Observatory* (*SOHO*).The occulting disk blocks the brightness of the Sun (outlined in white) and its corona. (Courtesy of *SOHO*.)

The bursts of electromagnetic energy emitted in solar flares pose virtually no hazard to crews of missions beyond Earth; x rays are blocked by space suits and the intensities of gammas are too low to worry anyone. But SEPs are a different story. Protons, which make up about 95% of the SEP spectrum, are of most concern because they are charged and can ionize cellular components, damage DNA strands, and at high exposure levels kill cells and cause irreparable organ damage.

Solar-particle releases are random events, and the longer the time spent outside Earth's magnetosphere, the higher the exposure risk. Most SEP events pose little threat because their proton spectra have low fluence levels (flux integrated over time) and are mainly composed of low-kinetic-energy protons. Even thin spacecraft structures or modest surface habitats—including such natural enclosures as caves and underground lava tubes—can shield against them.

But a single 11-year solar cycle may see several SEP events large enough to threaten crews on the lunar surface. One such event, whose energy spectrum is shown in figure 2, occurred in August 1972 between the flights of *Apollo 16* and *Apollo 17*. It would have exposed a crew on the lunar surface to far higher radiation levels than are allowable. Astronauts protected only by a space suit would have received more than 10 Gy to the skin and 2 Gy to the bone marrow, resulting in severe skin blistering, ulceration, and tissue necrosis, often accompanied by nausea, vomiting, and diarrhea. Doses to the spleen and other blood-forming organs would likely also have damaged bone marrow and begun destroying stem cells.

Even a 2-cm-thick skin of aluminum on a spacecraft would have significantly reduced the organ doses, though not below an astronaut's allowable limit. (NASA's effective dose limit is not a fixed number; rather, it's based on a mission-specific 3% risk of exposure-induced death.) A protective storm shelter with a thickness of about 7.4 cm of Al would provide adequate protection for almost all SEP events. However, recent studies found historical evidence of an SEP event in AD 775 whose proton fluence was far larger than any event from the current era of space travel.

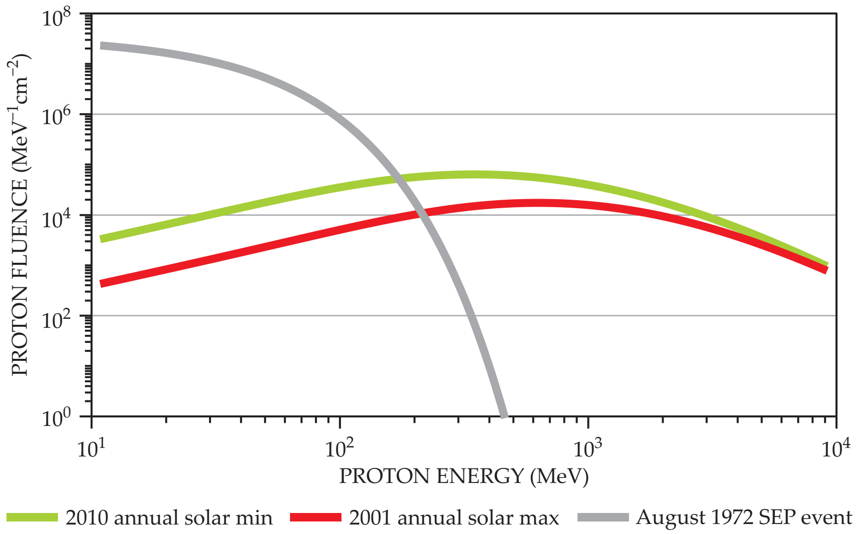

FIGURE 2. ANNUAL PROTON FLUENCES measured during the 2001 solar maximum (red) and the 2010 solar minimum (green) as a function of energy. Also displayed is the three-day proton fluence (gray) of a 1972 solar energetic particle event. The SEP event is four orders of magnitude higher in proton fluence at lower energies than galactic cosmic-ray protons, and the dose it delivered would have far exceeded NASA's allowable limit. At higher energies the GCR spectra clearly dominate. (Image by Lawrence Townsend.)

Galactic cosmic rays

The most dangerous radiation environment is the GCR background, composed of all naturally occurring elements and arising from supernovae explosions. Only elemental nickel and lighter species are abundant enough to deliver worryingly high exposures, but they are unavoidable. The GCR particles have kinetic energies up to tens of GeV/nucleon and beyond—they are much more energetic than typical SEP protons.

Galactic cosmic-ray particle fluxes are anticorrelated with solar activity. During times of high solar activity, the high magnetic fields associated with CMEs deflect the lower-energy GCR particles from the inner solar system, and fewer reach the Moon. The deflection reduces the GCR fluxes at kinetic energies below about 2 GeV/nucleon. Conversely, during solar minimum periods, the solar wind is less disturbed, which allows more lower-energy GCR particles to flood the inner solar system.

Because of their relatively low fluxes, GCR particles pose little risk of acute radiation sickness for crews on the lunar surface. In 2009 NASA's *Lunar Reconnaissance Orbiter* spacecraft was launched into lunar orbit carrying the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument. Shielded by less than 2 cm of aluminum, the dosimeter inside CRaTER indicated that the doses are about 130 mGy per year—almost entirely due to GCR ion exposures. That level is well below the blood-forming-organ limit of 250 mGy within 30 days.

However, GCRs do pose an increased risk of longer-term effects, including cancer mortality and cell damage to the heart, brain, and lenses of the eyes. GCR ions travel at close to the speed of light. Because they are charged, they release copious numbers of electrons and densely ionized tracks as the ions penetrate deep into human tissue. The ions frequently collide with spacecraft and the lunar surface, which generate many secondary ions and neutrons that penetrate further still.

Single ions can kill or damage multiple cells. In 2009 estimates of the effective dose measured by the Mars Science Lab on the *Curiosity* rover during its deep-space trip to Mars averaged about 0.66 Sv over the instrument's one-year travel time. (A measure of equivalent dose, one sievert equals 1 Gy multiplied by a biological factor that accounts for an organ or body part's radiation sensitivity.) Halving that estimate to account for shielding by the Moon's bulk suggests an annual effective dose of GCRs on the lunar surface of 330 mSv. That's about 140 times the average annual exposure on Earth.

Additional resources

▶ J. Guo et al., "MSL–RAD radiation environment measurements," *Radiat. Prot. Dosim.* **166**, 290 (2015).

▶ J. E. Mazur et al., "Update on radiation dose from galactic and solar protons at the Moon using the LRO/CRaTER microdosimeter," *Space Weather* **13**, 363 (2015).

▶ D. V. Reames, *Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration and Propagation*, Springer (2017).

▶ I. G. Usoskin et al., "The AD775 cosmic event revisited: The Sun is to blame," *Astron. Astrophys.* **552**, L3 (2013). PT