Lunar Radiation Environment and Space Weathering from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER).

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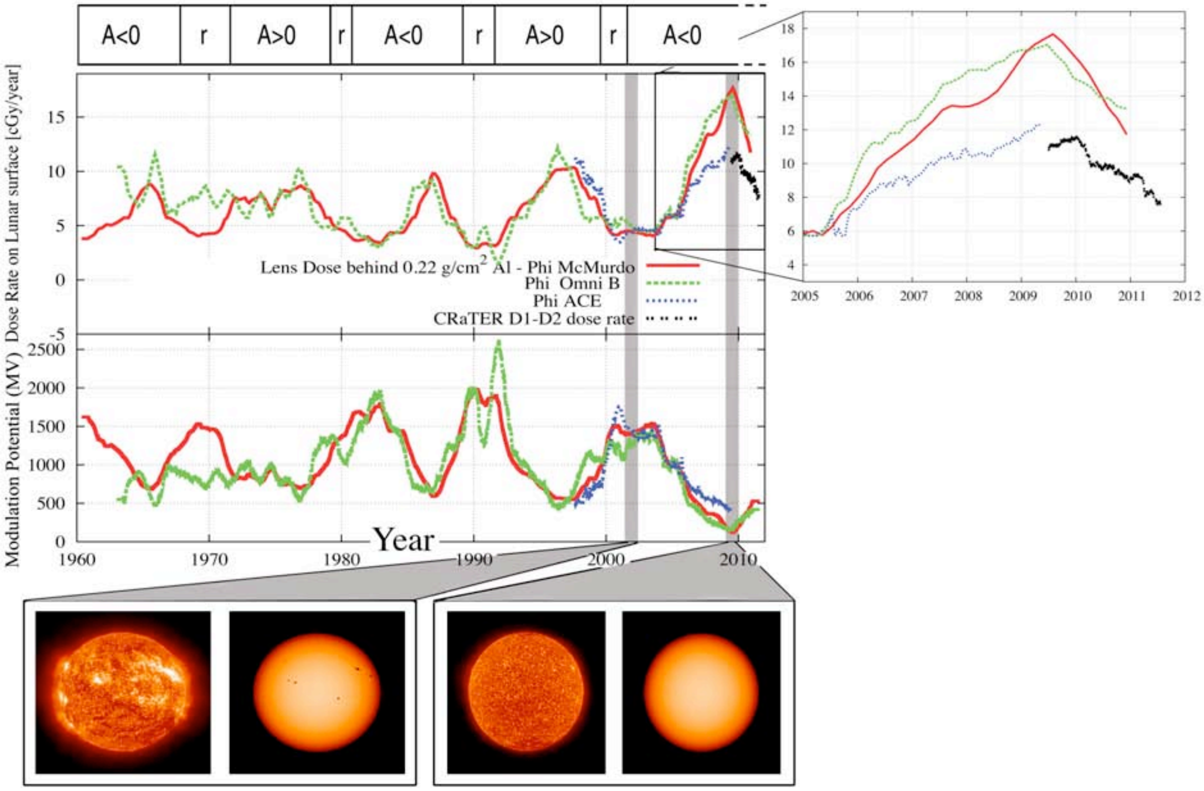

Figure 1. *The modulation parameter (lower panel) based on observations of neutrons using McMurdo data (red), interplanetary magnetic field (green) and based on the Advanced Composition Explorer (ACE) Cosmic Ray Isotope Spectrometer (CRIS) measurements [blue; see O'Neil, 2006]. The modulation potentials are used via EMMREM to infer GCR lens dose rates. Dose rates deduced from EMMREM are shown (upper panel) as well as measurements from CRaTER's D1-D2 detectors (black curve). The CRaTER D1-D2 dose rates were altitude adjusted to the lunar surface, have been adjusted for dose deposition in water (these dose rates), and represent two-week averages with SEP events removed. The polarity of the large-scale solar magnetic field is indicated by A: for A>0 the Sun's large-scale northern polarity is positive. The periods indicated by r show when field reversals occurred. Dose rates observed by CRaTER (black points in upper panel and upper right inset) near the highest dose levels during the space age. The solar images on the bottom panel show conditions of the corona (first and third images from left) and photosphere (second and fourth image from left) near solar maximum (left two images) and solar minimum (right two images).*

Abstract: The Sun is now emerging from a deep protracted solar minimum when the power, pressure, flux, and magnetic flux of solar wind were their lowest levels [1,2,3]. Because of an anomalously weak heliospheric magnetic field and low solar wind flux, galactic cosmic rays (GCRs)—protons, electrons, and ionized nuclei of light elements accelerated to high energies—achieved the highest levels observed in the space age [4].

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) measures linear energy transfer by Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs) on the Lunar Reconnaissance Orbiter (LRO) Mission in a circular, polar lunar orbit. GCR fluxes remain at the highest levels ever observed during the space age. At the maximum CRaTER-observed GCR dose rate (~11.7 cGy/yr where Gy is a unit indicating energy deposition per unit mass, 1 Gy = 1 J/kg), GCRs deposit ~88 eV/molecule in water over 4 billion years, causing significant change in molecular composition and physical structure (e.g. density, color, crystallinity) of water ice, loss of molecular hydrogen, and production of more complex molecules linking carbon and other elements in the irradiated ice. This shows that space weathering by GCRs may be extremely important for chemical evolution of ice on the Moon. We show comprehensive observations from the CRaTER instrument on the Lunar Reconnaissance Orbiter that characterizes the radiation environment and space weathering on the Moon.

The radioisotope ^{10}Be, produced in Earth's upper atmosphere by collisions of carbon, nitrogen, and oxygen with GCRs, provides a recent proxy record of cosmic ray fluxes [5]. These isotopes are thought to precipitate out of the atmosphere; those that reach the poles are recorded in layers of ice. Antarctic ice ^{10}Be records show two prominent peaks, 35,000 and 60,000 years ago, when the radioisotope production rate was about twice the current value for about 1500 and 2000 years, respectively [6]. The fact that the ^{10}Be radioisotope changes significantly with time shows that significant changes in cosmic ray fluxes have occurred in the past. But the cause for these changes remains controversial. The most accepted explanation is that the peaks are caused by geomagnetic field disruptions and reversals, which is supported by the observed correlation between geomagnetic field strength and ^{10}Be levels in marine sediment records [7,8]. However, this explanation suggests that the ^{10}Be enhancements should be uniform over the globe, which contradicts the large variations observed at high latitudes where geomagnetic effects are small. Further, [9] found that the ^{10}Be level (and hence the amount in GCRs hitting Earth) actually starts to increase some 2000 years before drops in Earth's magnetic field strength, recorded by the magnetization measured in the same core sample. Thus, many of the long-term changes in the cosmic ray fluxes incident on Earth may be due to effects external to the Earth within the shielding of the heliosphere or changes in the incident fluxes of GCRs from outside the heliosphere.

The physical connection between climate and the changes in the Sun and space environment remain a critical question. Changes in GCRs and solar irradiance provide possible contributors to climate change, but the detailed physical links between these drivers and atmospheric responses remains unknown.

What will the Sun do next? Is it possible that we are headed into a cycle like a Maunder or Spoerer minimum? How will changing cosmic ray fluxes and solar conditions affect Earth's atmosphere and bodies throughout the solar system? The answers to these fundamental questions will require long-term observations of the space radiation environment. The observations of CRaTER have probed space environment conditions and the interactions of radiation with materials at the peak of a very deep solar minimum. It is critical that this record be extended so that we may test our understanding the changing conditions of the space environment, and learn to project these conditions into the distant past, and future and unravel the implications for planets and bodies throughout the solar system.

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