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# The Cosmic Ray Radiation Dose in Interplanetary Space – Present Day and Worst-Case Evaluations

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A physics-based cosmic-ray transport model has been fit to solar-minimum and solar-maximum cosmic ray spectra and used for preliminary evaluations of the radiation dose and dose-equivalent of galactic cosmic rays (GCRs). We find a solar-minimum radiation dose-equivalent somewhat lower than previous estimates, with a smaller difference between solar minimum and solar maximum. Measurements of Be-10 in polar ice cores and other data show that the cosmic-ray intensity was significantly higher 50 to 100 years ago. The estimated radiation levels during these earlier periods were up to ~1.7 times greater than during recent solar minima.

## 1. Introduction

In interplanetary space the major contribution to the radiation dose received by astronauts is due to galactic cosmic rays (GCRs). Indeed the solar-minimum radiation level due to GCRs in interplanetary space is comparable to the present yearly limits for astronauts in low-Earth orbit. As a result, radiation exposure due to GCRs is a key concern for human missions to the Moon and Mars.

Spacecraft and balloon-borne data indicate that cosmic-ray intensities have reached much the same level during each of the last four solar minima (See Figure 1). However, it is important to ask whether we have as yet experienced the worst-case GCR radiation levels. Measurements of Be-10 in polar ice cores [1] show that the space era has been a period of anomalously-low GCR activity, as shown in Figure 2. The Be-10 record indicates that cosmic-ray intensities during the Maunder minimum and late 1800's were ~2x greater than during the 1976 solar minimum and ~50% greater during the first half of the 20$^{th}$ century. Balloon-borne experiments confirm the higher GCR levels from ~1932 to 1954 [2,3].

The CRIS experiment on ACE [4] has provided the first high-precision measurements of cosmic-ray spectra from Be to Ni over both solar-minimum and solar-maximum conditions. These data, along with HEAO-3 data at higher energy [5], and balloon and satellite measurements of H and He, have been fit with a GCR transport and solar modulation model and used to make preliminary evaluations of the radiation dose and dose equivalent.

## 2. Cosmic Ray Spectra and Radiation Doses

In radiation health physics the absorbed dose of radiation is measured in units of Gray or rads where 1 Gray = 1 Joule/kg = 100 rads = $10^4$ erg/g. However, not all sources of radiation have the same biological effectiveness, and the Dose Equivalent measured in units of Sieverts (or in rem) takes this into account. The Dose Equivalent (in Sv) is equal to the Dose (in Gray) times the quality factor (Q), where Q [6] is a function of the Linear Energy Transfer (LET) – the rate of energy loss of a particle measured in keV/micron of water.

Solar minimum measurements of GCR spectra for Be to Ni ($4 \leq Z \leq 28$) were made during the period from September 1997 though April 1998 (see Figure 1). Spectra have also been measured during the solar maximum period from May 2001 to September 2003 [8]. The ACE solar-minimum intensities are the highest reported, but by adjusting for the modulation level at the time of measurement (see, e.g., Figure 1) the ACE spectra are in agreement with earlier spectra at both low and high energies [8,9]. To evaluate the dose equivalent of each species (in Sv) we integrated the following:

$$\text{Dose Eq.} = (4\pi/\rho)Z^2\int_{10}^{10^5}(dJ/dE)\,(dE/dx)\,Q[LET]\,dE, \qquad (1)$$

where dJ/dE is the differential energy spectrum, $\rho$ is the density of water, dE/dx is the rate of energy loss of protons in water, and Q is the quality factor [6], which depends on the linear energy transfer ($LET = Z^2 dE/dx$ in keV/micron of water), with a maximum value of 30 at LET ≈ 100 keV/micron. The integration covered the energy range from 10 to $10^5$ MeV/nuc. The dose (in Gy) uses the same integral with Q = 1. The spectral shapes for $5 \leq Z \leq 28$ nuclei were taken from the cosmic-ray transport and solar modulation model of Davis et al. [9] with small adjustments to fit the measurements of George et al. [8]. The Li and Be spectra were also based on ACE data. For H and He we fit spectra measured by the BESS balloon experiment in 1997-1998 and 2000 [10] using a modified version of their interstellar spectra and the solar modulation model of Davis et al. [9]. Figure 3 shows the resulting solar-minimum dose equivalent for elements from H to Ni. The total dose and dose equivalent for the solar minimum periods are summarized in Table 1. Column 4 of Table 1 is for no shielding; in Column 5 we multiply all dose equivalent values by 0.56 at solar minimum and 0.69 at solar maximum to account for the approximate effect of 3 g/cm$^2$ of Al shielding and the self-shielding of the blood-forming organs (BFO) by the body (based on Wilson et al. [11]).

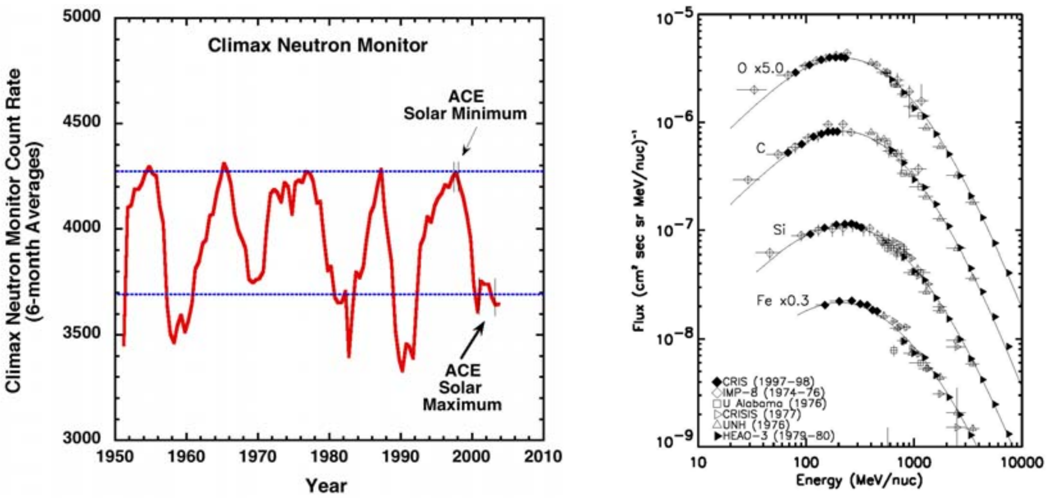


**Figure 1.** (Left) Climax neutron monitor rates showing the ACE solar minimum and maximum periods. (Right) Fits of the GCR model to solar minimum spectra. Data from other time periods were scaled in intensity to the ACE period using the Climax neutron monitor, as described in Davis et al. [9] and George et al. [8].

During the 1954 and ~1894 solar minima the $^{10}Be$ data indicate that the GCR intensity was substantially greater than for recent minima (see Figure 2). McCracken et al. [1] have estimated the 1954 and 1894 proton spectra based in part on the balloon data of Neher [2] and Forbush [3]. To evaluate the radiation levels we decreased the modulation level ($\phi$) to reproduce these estimated proton spectra, and then evaluated all species at these levels ($\phi$ = 250 and 100 MV). Table 1 and Figure 3 summarize the radiation levels.

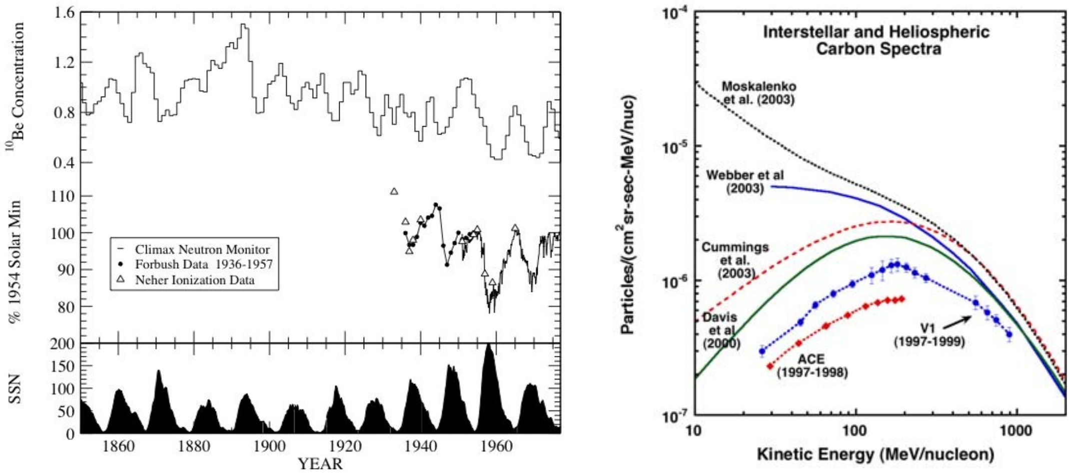


**Figure 2.** (Left) Be-10 concentrations in polar ice cores [1] and balloon data [2,3] show that the space era has been a period of anomalously-low cosmic-ray activity, probably because solar activity was greater (figure from [1]). (Right) A comparison of GCR spectra at Voyager and Earth with models of GCR spectra in interstellar space illustrate that modulation beyond the termination shock is 2 to 4 times greater than between 1-AU and the termination shock (from Mewaldt et al. 2004 [7]).

Table 1 – Radiation Levels (Preliminary)

| Period | Modulation Level (MV) | Unshielded Dose (cGy/yr) | Unshielded Dose Equivalent (cSv/yr). | Shielded Dose Equivalent (cSv/yr) |
|---|---|---|---|---|
| Solar Maximum | 925 | 6 | 39 | 27 |
| Solar Minimum | 325 | 16 | 88 | 50 |
| Est 1954 | 250 | 19 | 109 | 62 |
| Est 1890 | 100 | 30 | 147 | 83 |

## 3. Discussion and Summary

Although there are not as yet any dose limits established for astronauts on deep-space missions, the yearly limit in low-Earth-orbit is 50 cSV, with career limits ranging from 1 to 4 Sv, depending on age and gender [6]. For a mission to Mars one might expect a 6-month trip, 18 months at Mars with some shielding by the atmosphere and planet, followed by a 6-month return. Wilson and Cucinotta [12] estimate a radiation dose equivalent of 114 cSv due to GCRs for a Mars mission at solar minimum, including 73 cSv enroute and 41 cSv on the Martian surface. Our shielded 1-year value of 50 cSv in Table 1 is considerably lower. Although this difference is not understood, it is most likely due to details of the calculation rather than to the cosmic-ray data. For a solar maximum trip Wilson et al. get 46 cSv, including 28 enroute and 18 on the surface. Our solar maximum value for the trip is 29 cSv. Figure 1 shows that there were only a few of the last 50 years when a 2.5-yr mission could be launched at lower average modulation levels than for the ACE period.

Although the absolute level of the radiation levels that we derive must be considered preliminary until we reconcile the differences with Wilson and Cicinotta [12], the recognition that the cosmic-ray intensity was greater in 1954 and even more so before 1900 will not change. This result is particularly important because it shows that cosmic-ray studies during the space era have not experienced the worst-case cosmic-ray intensity at 1 AU. Based on the proton spectra deduced by McCracken et al. [1] the radiation levels during earlier solar minima were ~20% to ~70% greater. These conditions could return at any time, as indicated by studies of long-term solar activity [13].

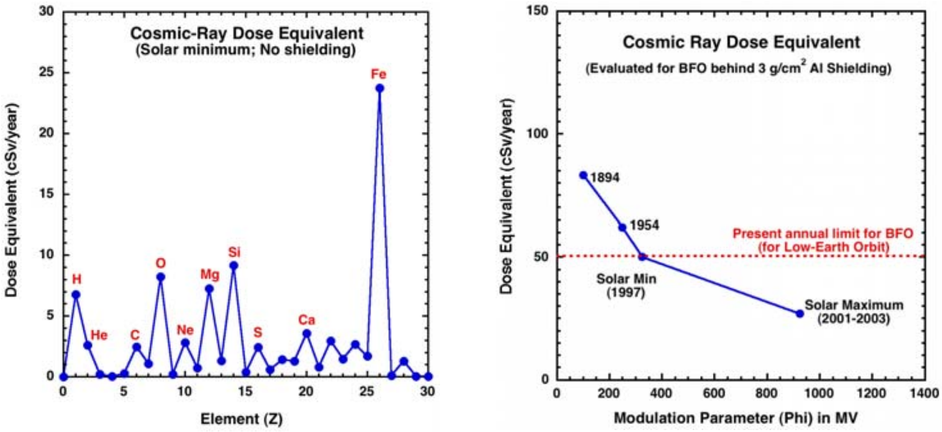


**Figure 3.** (Left) Calculated contribution to the yearly dose equivalent (in cSv/yr) due to elements from H to Ni (assuming no shielding). Note that heavy elements make the largest contributions. (Right) Calculated dose equivalent (in cSv/yr) during the ACE solar-minimum and solar-maximum periods and during the 1954 and 1894 solar minima.

The absolute level of our worst-case estimates are uncertain for other reasons. Although the proton spectra deduced by McCracken et al. can account for earlier $^{10}$Be readings [1], it must be realized that $^{10}$Be production in the atmosphere is due mostly to protons, while the dose-equivalent (which determines the cancer risk) is due mainly to heavy nuclei like Fe (see Figure 3). It is possible that atmospheric $^{10}$Be is a poor proxy for Fe. Another concern is the uncertain shape of interstellar (IS) cosmic-ray spectra. Our estimates use the lowest of the IS spectra in the right of Figure 2. As a result, there is only a limited degree to which the radiation level can increase even if solar modulation disappeared completely. If any of the other IS spectra are closer to the truth, the worst-case cosmic-ray intensity will be greater, possibly by as much as a factor of ~2. It is therefore imperative that Voyager-1&2 continue to explore the heliosheath to learn the true nature of interstellar cosmic-ray spectra and measure directly the worst-case radiation environment, and that high-precision instruments like CRIS continue to measure cosmic-ray spectra at 1 AU.

## 5. Acknowledgements

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