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Author(s):

Robert C. Reedy

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Solar Particle Events and Their Radiation Threats

Robert C. Reedy¹

¹ MS D436, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA

Abstract -- Energetic particles from the Sun have only been studied in detail during the last three decades. The modern record is good, although the number of the largest solar particle events are very few. The nuclides made by solar energetic particles in lunar rocks have been used to extend the record of these particles back $\sim 10^7$ years. The modern and ancient records are similar. By combining both sets of data, it has been inferred that solar particle events much larger than the largest events observed during the last four solar cycles are very rare.

I. INTRODUCTION

The main radiation threats from energetic particles in space are the galactic cosmic rays (GCRs), solar energetic particles (SEPs), and trapped radiation around planets. All are very serious sources of radiation, especially away from the Earth's strong magnetosphere [e.g., 1-3]. However, over a short period of time (a few days), the effects from a very large solar particle event (SPE) can be far greater than from any other natural source of radiation. Effects of large SPEs include high doses to humans [2], microelectronics [3], and solar panels [4].

The nature of GCRs is well characterized as is the variation in their flux over a typical 11-year solar-activity cycle. The models for the Earth's trapped radiation belts are often not very good, but a number of recent satellites are helping to map the spatial and temporal variations of the fluxes and spectral shapes of trapped energetic particles. The radiation threats from GCR or trapped particles can be very serious, but the data to plan for ways to manage them are in good shape.

The radiation threat that is least known is that from the very large solar particle events that occur, on average, about once a decade or from even larger and rarer events. This paper reviews SPEs, what is known about them (especially very large events), and what needs to be done to have better confidence in planning for missions to survive the largest SPEs.

II. SPEs IN GENERAL

Before direct measurements of solar energetic particles by spacecraft, a few observations were made using instruments on the Earth's surface that detected ionization, neutrons, or

radio disturbances produced by the high-energy particles in an SPE [5]. Several very large SPEs were observed in the 1940s and in 1956. Routine studies of SPEs started around the time of the International Geophysical Year in 1957-1958. It wasn't until 1965 that fairly continuous measurements of SEPs by spacecraft outside of the Earth's magnetosphere were made [5].

SEPs have energies from ~ 1 MeV to hundreds of MeV with the flux dropping rapidly with increasing energy [6]. Some events can have "relativistic" particles (>1 GeV), and only such very-high energy particles can produce effects observable at the Earth's surface, such as in neutron monitors [7]. The peak fluxes during a SPE last only a few hours, and a SPE lasts from only a few days to a week or two. The nuclei in a SPE are typically $\sim 98\%$ protons and a few heavier nuclei [6] with a proton/alpha-particle ratio of ~ 60 .

Solar particle events tend to occur when the Sun is not at its lowest levels of activity. Few large SPEs are observed in the ~ 4 years of lowest solar activity (fewest sunspots) [8,9]. During the remaining ~ 7 years of a typical 11-year solar cycle, large SPEs can occur any time. The largest SPEs tend to occur after the maximum in sunspot numbers (the "declining phase" of the solar cycle) [9], but some very large SPEs (such as 23 Feb. 1956) occurred before solar maximum. The exact causes of large SPEs are still being debated by some, but the earlier theory associating them with solar flares now is being replaced with one in which strong shocks in fast coronal mass ejections are the main cause of high fluxes of solar energetic particles [e.g., 10].

Most SEPs have enough energy to induce nuclear reactions in material into which they penetrate. Many nuclides have been observed as having been produced by SEPs in lunar samples [e.g., 11]. Solar-proton-produced radionuclides with half-lives of up to 3.7-Myr (^{53}Mn) have been observed in lunar samples, and some stable nuclides such as ^{21}Ne made by solar protons also have been studied [12]. When cross sections for the nuclear reactions making a SEP-produced nuclide are available, measurements of the concentrations of that nuclide as a function of depth in a lunar rock have been used to infer the average flux of solar protons over the mean-life of the radionuclide [11] or the surface exposure age of the lunar rock [12]. Such "fossil" records for several time periods enable us to study the long-term record of SEPs.

Figure 1. Smoothed monthly sunspot numbers (curve) and event-integrated solar-proton fluences above 10 MeV (dashed lines) and 30 MeV (solid lines) for recent solar particle events [from 15].

III. MODERN SOLAR PARTICLE EVENTS

The event-integrated fluences of SEPs have been compiled by several authors for SPEs since 1956 [e.g., 8,13,14]. Figure 1 [15] shows a plot of event-integrated solar-proton fluences since 1954 for protons with energies above 10 and 30 MeV. The fluences before 1965 are based on indirect measurements of relative fluences and activities of 2.6-year ^{22}Na and 2.7-year ^{55}Fe in lunar rocks [14]. Many events since 1989 are not in this plot as fluences for these events have not been reported in the literature.

The modern record is fairly good since 1965, although several reports of event-integrated fluences differ for some events by up to ~50%. More data sets that can be used to get SPE fluences need to be studied to improve this recent record. The record from 1956 to 1962 is less certain, and reported SEP fluxes and SPE fluences occasionally differ by up to about an order of magnitude. Earth-based measurements need to be examined to give good fluences, especially relative ones. These data sets can then be used with lunar short-lived radioactivity measurements, as in [14], to determine the absolute fluxes for this period.

Statistics on SPEs since 1956 have been studied [8] and used to develop a model for fluences of solar protons [16]. This model is better than some older ones in that it includes events from almost four full solar cycles and properly includes the rare but important very large events, such as those in 2/56 (with its many relativistic protons), 7/59, 11/60, 8/72, 8/89, 9/89, 10/89, and 3/91.

One problem in modeling SPEs has been that huge events, which have event-integrated 4π (omnidirectional) fluences above 10 MeV of $>3 \times 10^{10}$ protons/cm², have not been observed. Thus the statistics for such events are very uncertain. A few decades ago, some authors proposed that

events many orders of magnitude larger than any SPEs observed recently could occur. Now that there are more measurements, it is generally accepted that events an order of magnitude larger than those very large ones recently observed do not occur or are very rare.

IV. ANCIENT FLUXES OF SOLAR PARTICLES

The production of nuclides in lunar samples by SPEs has been known since the first samples returned by Apollo 11 in 1969 [11,14]. However, even a decade ago, nuclear-reaction cross sections did not exist for interpreting the records of several of the SEP-produced radionuclides [11]. Several groups have recently measured or are now measuring the needed cross sections. Thus the results mentioned below are not final.

Other uncertainties in interpreting the fossil record of SEPs, besides cross sections, are the corrections for nuclide production by GCR particles and the effects of the erosion of the rocks' surfaces by micrometeoroids (~1 mm/Myr) [11,12]. Because of these uncertainties, it has been difficult to get good fluences and spectral shapes from the lunar fossil record. However, the results for solar-proton fluxes over various time periods are known now to much better than a factor of two.

The fossil record is improving. Besides new cross sections for the reactions making SEP-produced nuclides having been measured, new measurements are being made of SEP-produced nuclides in lunar rocks. Better models to use in making corrections for production by GCR particles are also being developed. Recently, several radionuclides, especially 1.5-Myr ^{10}Be , have been shown to be sensitive to the spectral shape of solar protons [17]. Within a few years, many new or better average fluxes should be available from the lunar fossil record for SEPs.

Lunar SEP-produced nuclides only give an average flux of solar protons over the mean-life of the radionuclide or the surface-exposure age of the sample. The average 4π flux of solar protons above 10 MeV over the last few million years is ~100 protons/cm²/s with most nuclides giving fluxes within about 50% of this value [11,12]. This flux is similar to that from modern SPEs averaged over the last four decades.

V. THE COMPLETE SPE RECORD

While the similarity of modern and ancient SEP fluxes has been known for almost three decades, few have combined both data sets. Many have plotted events per year above a given fluence versus event fluence, but few have added the ancient record. Figure 2 [from 15] shows a plot of events per year above a given fluence F versus the event fluence F for the modern record. The point for $3 \cdot 10^{10}$ protons/cm² is an upper limit of one event during the last four decades as no event of this fluence or greater has been observed.

Figure 2. Probabilities of solar particle events with fluences above a value occurring per year versus the fluences for modern events and for limits from various fossil records [from 15].

A plot similar to Fig. 2 was given by [18], who also determined a limit on large SPEs using measurements for ^{14}C in tree rings over the last 7000 years. Their point based on tree-ring ^{14}C is in Fig. 2. Also shown are several points using the lunar record discussed above. The limits using the lunar data assume that all of the activity of the various radionuclides was made by a single, huge event a half-life of that radionuclide ago, an extreme assumption but clearly a limiting case [15].

Figure 2 shows that there has to be a sharp break in the probability plot of SPE fluences at about 3×10^{10} protons/cm². Thus models that use the complete modern record over the last four decades, like that in [16], and include the limits from the fossil record should be good for long time periods. While an event of this fluence is a serious radiation hazard [e.g., 1-4], it is good to know that events even only an order of magnitude greater than any seen since 1956 are very unlikely.

VI. SUMMARY

Both the modern and ancient records for solar energetic particles have been quickly reviewed above. High fluxes of solar energetic particles are serious radiation hazards in space. The main conclusion is that huge solar particle events should be extremely rare and that recent models for SPE fluences such as [16] should be good guides in planning future deep space missions. However, the record for SEPs is not complete. More work is needed on both the modern and ancient records.

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