



Significant Solar Proton Events For Five Solar Cycles (1954-2007)

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Abstract: Using a solar proton database for the past five solar cycles (1954-2007) we have determined the total solar proton fluence above 10 MeV and the number of discrete events that occurred each cycle. We find: (1) The number of discrete events in cycles 19-22 were essentially the same; (2) Cycles 20 and 21, at the beginning of the space era, were relatively benign with respect to solar proton fluence; (3) Approximately 16% of the total number of discrete events each cycle are relativistic solar cosmic ray events (i.e. GLEs); (4) Cycle 23 has been the most active cycle since 1954. We also find that the number of GLEs can be associated with a relatively small number of solar active regions with each region producing several large events in a sequence of activity. Of the 70 GLEs between 1942 and 2006, 36 of these events were associated with only 15 active solar regions.

Introduction

We now have a solar proton event database extending for five solar cycles. We have examined this database in an effort to search for patterns in solar proton event occurrence as a function of solar cycle. We have defined a significant solar proton event as one having 10 particles (cm²-secster)⁻¹ above 10 MeV. This is in agreement with the criteria established by the NOAA Space Environment Laboratory definition. Using these criteria our database now includes 405 events recorded near the earth between May 1954 (the start of solar cycle 19) and May 2007. For the purposes of this study we have identified each unique solar proton injection into the interplanetary medium and detected at the earth as a discrete event. Thus each event in an episode of solar proton events that may be associated with the same active solar region as it traverses the solar disk is counted as a separate event. For example, while the solar proton flux remained very high from 19 through 24 October 1989, we have identified three unique injections of solar protons into the interplanetary medium during that time interval and thus count this as three events.

Table 1 shows the number of discrete solar proton events for each of the five cycles from solar cycle 19 through 23. Since routine spacecraft measurements were not available during the 19th solar cycle, the total number of discrete solar proton events for that cycle may be underestimated. Table 1 also lists the percentage of events with relativistic solar protons (i.e. protons with energies >450 MeV). These events were recorded by at least two neutron monitors and are called ground-level events (GLEs) since the incident particles have sufficient energy at the top of the atmosphere to generate a nuclear cascade within the atmosphere giving rise to an increase above the background cosmic radiation intensity measured on the surface of the earth. The total omnidirectional solar proton fluence for each solar cycle is also listed.

Results

Inspection of Table 1 shows a similarity in the total number of events for solar cycle 19-22 although the cycles themselves differ both in their duration and magnitude as characterized by the sunspot number. The average number of events for cycles 19-22 is 75. This is a lower limit

Table 1. Summary of Solar Proton Events for Solar Cycles 19-23

Cycle	Start	No. of Months in Cycle	Total No. Discrete Events	No. of GLEs	Percent of GLE	Omnidirectional Fluence (cm ⁻²)
19	May 1954	126	65*	10	(15.4)	7.2 x 10 ¹⁰
20	Nov 1964	140	72	13	(18.0)	2.2 x 10 ¹⁰
21	Jul 1976	123	81	12	(14.8)	1.8 x 10 ¹⁰
22	Oct 1986	120	84	15	(17.8)	5.8 x 10 ¹⁰
23	Oct 1996	132	103	16	(15.5)	7.5 x 10 ¹⁰

*Extremely limited spacecraft data. Small events may have been missed.

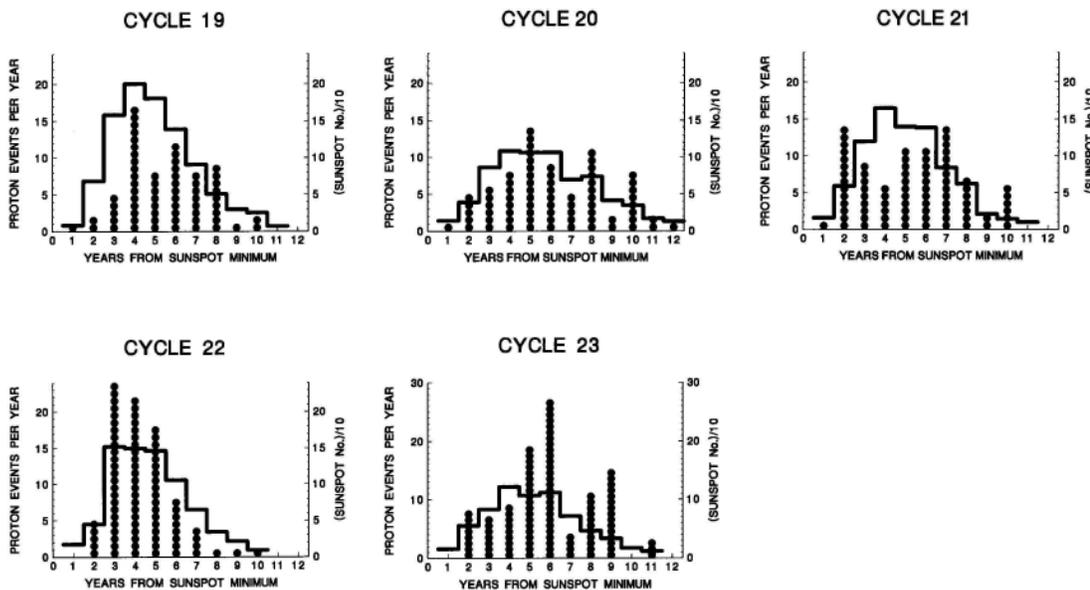


Figure 1: The number of discrete solar proton events (dots) having a >10 MeV peak flux of more than 10 protons (cm²-sec-ster)⁻¹ for each 12-month period after solar minimum for each solar cycle. The histograms represent the actual sunspot number averaged over the same 12-month period. The dates for each solar cycle are given in Table 1.

because of the possible underestimation of events in cycle 19. The number of events in cycle 23 is significantly above cycle 19-22 average.

Figure 1 presents the time distribution of solar proton events over each of the past five solar cycles. Each dot in these figures represents a discrete solar proton injection; the histograms represent the 12-month average sunspot number. The starting date (see Table 1) for each cycle is

the first month after statistical sunspot minimum as defined by the smoothed Zurich sunspot number. The 12-month intervals are each 12-month period starting with the onset of the cycle.

An inspection of the distribution of solar proton events in this figure shows the following:

- (1) The solar proton event distributions are different from one solar cycle to another [1]. Of the five solar cycles illustrated, the solar proton event

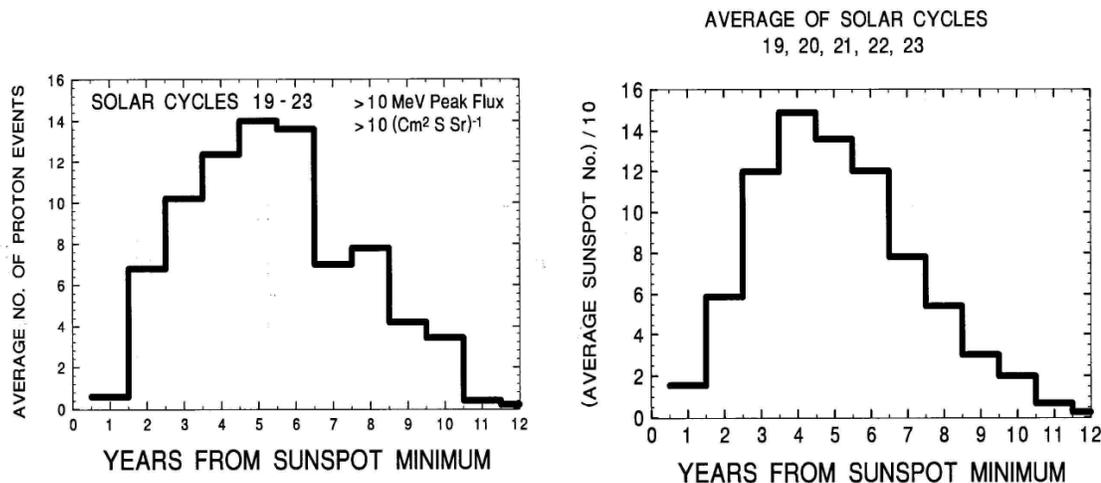


Figure 2: Left: Composite 12-month summation of solar proton events for 5 solar cycles. Right: Composite summation of 12-month sunspot numbers for 5 solar cycles.

five solar cycles illustrated, the solar proton event frequency pattern is not duplicated. We note that cycles 19 and 21 have a well defined Gnevyshev Gap [2-3] in the number of solar proton events. This effect is not so apparent in cycle 20, and is apparently missing in cycle 22.

(2) More solar proton events generally occur during the maximum of solar activity (years 3 through 8 of the solar sunspot cycle) than during the remaining portion of the solar cycle. (Solar cycle 21 may be an exception.)

(3) Significant solar proton events can occur at any time of the solar cycle.

Also of interest is the total solar proton fluence recorded at Earth during each solar cycle as listed in Table 1. Since sequences of activity often make it difficult to identify the fluence associated with each discrete event we have summed the total solar proton fluence over the entire solar cycle. Solar cycle 23 has the highest fluence above 10 MeV; cycle 21 the lowest fluence.

Discussion

The relative consistency in the total number of events and the factor of four difference in the total proton fluence allows us to postulate some physical factors that play a role in these statistics. With the concept of solar proton event occurrence shifting from the "flare scenario" to the "fast CME shock scenario" we note that the identifica-

tion of a discrete solar proton event at Earth will be dominated by particles accelerated via the widely expanding CME shock as it propagates from the sun through the interplanetary medium. Previous studies [4-5] have shown that solar activity over a large range of solar longitudes can produce a discrete solar proton event at Earth. Earth is most likely to be impacted by CME shock accelerated protons when the associated solar activity is between $\sim 60^\circ$ E to $\sim 120^\circ$ W. This covers half the solar hemisphere.

However, major solar proton fluence events seem to be associated with solar activity that occurs within a relatively narrow range of solar longitudes, primarily between 30° E and 30° W [4-7]. This represents only 17 percent of the solar hemisphere. Thus a solar cycle where several active regions are associated with solar proton events in the 30° E- 30° W heliolongitude range would more likely have a higher proton fluence than a cycle without major solar activity near the central meridian of the sun (as viewed from Earth). The events in August 1972 were near the central meridian of the sun. With a fluence of 1.1×10^{10} protons cm^{-2} above 10 MeV this represented half of the total solar proton fluence recorded at Earth for the entire 20th solar cycle.

Using the superposed epoch technique, we have summed the number of proton events each 12-month period for the five solar cycles. These

results are shown by the histogram in the left of Figure 2. This histogram exhibits a skewed Gaussian somewhat similar to the actual monthly sunspot number averaged in the same manner and shown in the right of Figure 2. This result is somewhat surprising considering the extreme differences in the occurrence of these events during each individual solar cycle.

There is also a surprising consistency in the percentage of solar proton events that are ground-level events. Approximately 16% of all proton events are GLEs. While the majority of GLEs occur during years 2-8 of the solar cycle, GLEs have occurred during solar minimum (e.g. 1976 and 2006). The distribution of GLEs over the five solar cycles, shown in Figure 3, does not exhibit the same overall pattern as the pattern for all proton events shown in Figure 2.

In assigning a solar active region to each GLE, we have found that of the 70 GLEs between 1942 and 2006, 15 active regions were associated with 36 individual relativistic solar proton events. Thus once an active region is associated with one GLE, there is a good chance that additional activity might result in another GLE. Two particularly active regions have been associated with four GLEs each. While we have not yet extended this study to all 405 proton events in the five solar cycles, we believe that both the number of discrete events and the total fluence can be associated with a smaller number of solar active regions with each region producing several significant proton events in a sequence of activity.

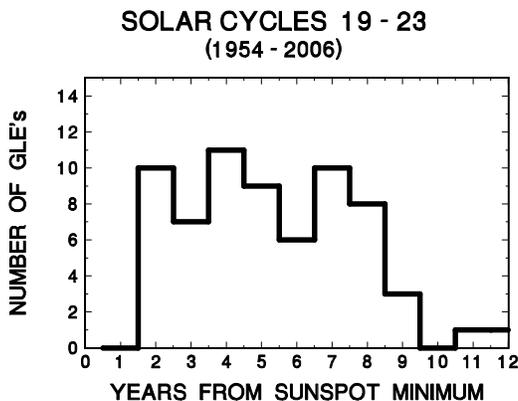


Figure 3: Distribution of GLEs for 5 solar cycles.

Conclusions

A statistical study of the significant solar proton events over five solar cycles shows that while the distribution of these events differs from cycle to cycle, the total number of events summed over all five cycles exhibits a skewed Gaussian curve similar to the actual sunspot number. Approximately 16% of the events each solar cycle contain relativistic solar protons.

While there is consistency in the number of discrete solar proton events per solar cycle recorded at Earth, the total solar proton fluence differs by a factor of 4 between cycles. These results are related to the physical phenomena of solar particle acceleration and propagation in the interplanetary medium as measured at the position of the Earth.

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