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Solar proton and GLE event frequency: 1955-2000

M. A. Shea[1,2] and D. F. Smart[1,2]

[1]CSPAR, University of Alabama, Huntsville, AL 35899 USA
[2]Air Force Research Laboratory (VSBS), 29 Randolph Road, Bedford, MA 01731, USA

Abstract. The number of > 10 MeV solar proton events with peak flux exceeding 10 (cm^2-sec-ster)$^{-1}$ during each solar cycle was remarkably constant for solar cycles 19-22 even though the total integrated fluence experienced at the earth per solar cycle varied by a factor of four. In addition the number of ground-level events each solar cycle has also remained relatively constant. Similarities between the first five years of this present solar cycle 23 and the first five years of solar cycle 20 are presented. If the proton event occurrence for these two cycles continues to be similar, we would expect the majority of solar proton events to occur during years 5-8 of the 23rd cycle (i.e. from 2000-2004) with perhaps a surge of activity during the waning years of the cycle.

1 Introduction

Solar proton events were first identified by Forbush (1946) who deduced that the unusual rapid increases in the background cosmic radiation intensity were from relativistic cosmic rays generated by solar activity. The measurements he used were from ionization chambers which record the cosmic ray intensity above energies of ~4 GeV. When neutron monitors became the principal detector to monitor the cosmic radiation at Earth a decade later, it became possible to identify solar proton events with energies above ~450 MeV, the atmospheric threshold energy of solar protons incident at geomagnetic latitudes higher than ~60 degrees. A decade later, in December 1965, routine satellite measurements extended the detection threshold down to levels below 10 MeV. These measurements have continued although the instrumental background levels have decreased allowing smaller and smaller events to be identified.

Correspondence to: sssrc@msn.com

Although only high-energy solar proton events were recorded during the 19th solar cycle (1954-1964), complementary polar ionospheric absorption records (Bailey, 1964) and subsequent studies have allowed crude extrapolations to lower energies (Shea and Smart, 1990). We now have a solar proton event database extending for more than four 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.

2 Database of Solar Proton Events

We have defined a significant solar proton event as one having 10 particles (cm^2-sec-ster)$^{-1}$ above 10 MeV, in agreement with the criteria established by the NOAA Space Environment Laboratory. Using these criteria our database now includes 330 events recorded near the earth between May 1954 (the start of cycle 19) and May 2001. 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.

Table 1 shows the number of discrete solar proton events for each of the four cycles from solar cycle 19 through 22. 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.

Table 1. Solar Proton Events for Solar Cycles 19-22

Cycle	Discrete Proton Events	No. GLEs	Percent GLE	Omnidirectional >10 MeV Fluence (cm^{-2})
19	65*	10	(15.4)	7.2×10^{10}
20	72	13	(18.0)	2.2×10^{10}
21	81	12	(14.8)	1.8×10^{10}
22	84	15	(17.8)	5.8×10^{10}

*Limited spacecraft data. Small events may have been missed.

3 Results

Inspection of Table 1 shows a similarity in the total number of events for each solar cycle although the cycles themselves differ in their magnitude as characterized by the sunspot number. The average number of events for these four cycles is 75. This is a lower limit because of the possible underestimation of events in cycle 19. There is also a surprising consistency in the percentage of solar proton events that are ground-level events.

Figure 1 presents the time distribution of solar proton events over each of the past four solar cycles. Each dot in these figures represents a discrete solar proton injection; the histograms represent the 12-month mean value of the actual sunspot number. The starting date 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 Figure 1 shows the following.

(1) The solar proton event distributions are different from one solar cycle to another. Of the four 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 (Bazilevskaya, et al., 1999; Storini, et al., 2001) in the frequency of solar proton events near solar sunspot maximum. 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.

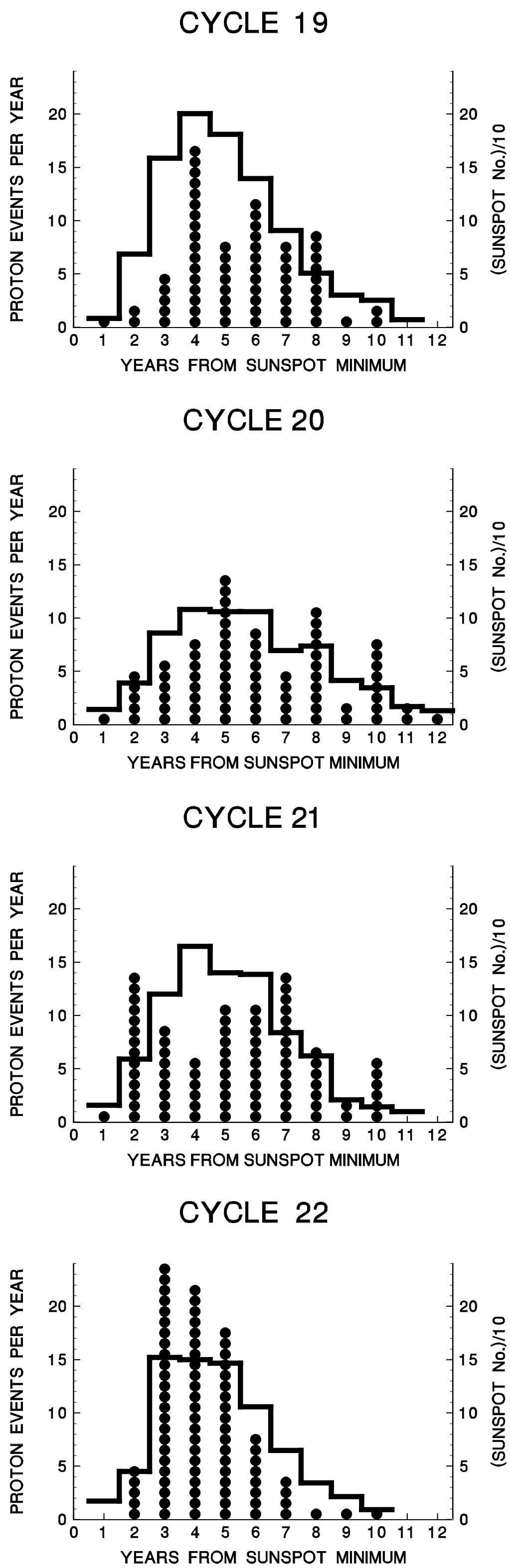

Fig. 1. The number of discrete solar proton events (dots) having a >10 MeV peak flux of more than 10 protons $(cm^2\text{-sec-ster})^{-1}$ for each 12-month period after solar minimum for each solar cycle. The histograms represent the actual sunspot number averaged over the same 12-month period.

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 make it difficult to identify the number of protons associated with each discrete event we have summed the total solar proton fluence over the entire solar cycle. Solar cycle 19 has the highest fluence above 10 MeV, cycle 21 has the lowest fluence. The factor of four difference between these two cycles can be partially explained by the fact that one extremely active region traversing the solar disk may completely dominate the total solar proton fluence for any one cycle. This was true for the events in August 1972, which had a fluence of 1.1 x 10^{10} protons cm^{-2} above 10 MeV (Shea and Smart, 1990). This was half of the total solar proton fluence recorded at Earth for the entire solar cycle.

4 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 identification 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 (Cliver et al., 1995) 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 ~60° E to ~120° W. This covers half the solar hemisphere.

However, major solar proton fluence events seem to be associated with solar activity that occurs within a narrow range of solar longitudes, primarily between 30° E and 30° W (Shea and Smart, 1993, 1996; Shea et al., 1999). 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).

Using the superposed epoch technique, we have summed the proton events each 12-month period for the four solar cycles. These results are shown by the histogram in Figure 2. This histogram exhibits a skewed Gaussian somewhat similar to the actual monthly sunspot number averaged in the same manner and shown in Figure 3. This result is somewhat surprising considering the extreme differences in the occurrence of these events during each individual solar cycle. There is an apparent "depletion" in the number of events during the 9th year of each cycle and an apparent "increase" in the number of events during the 10th year. We do not know the reason for this except that the apparent "increase" in proton events toward the end of the solar cycle (year 10) reflects those events in cycles 21 and 22. This effect may be the result of the statistics of small numbers.

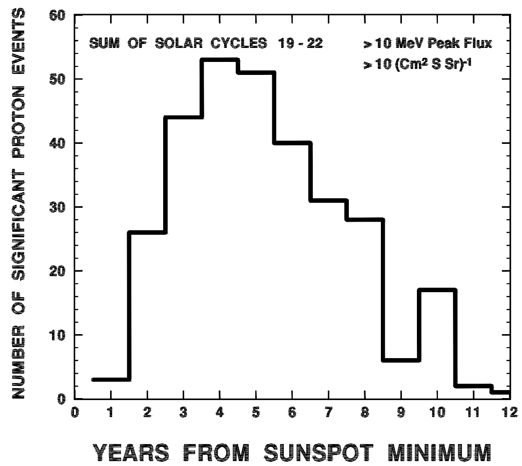

Fig. 2. The summation of significant discrete solar proton events for solar cycles 19-22.

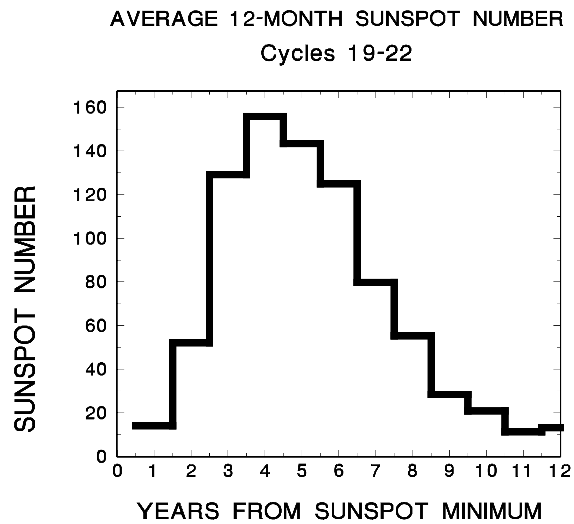

Fig. 3. The average of the 12-month sunspot numbers for solar cycles 19-22.

5 Solar Cycle 23

As shown in Figure 4 there have been 24 discrete solar proton events during the first four years of solar cycle 23 and a total of 37 events during the first 56 months of the cycle (1 October 1996-31 May 2001). In comparing the distribution of events in solar cycle 23 (Figure 4) with the distribution of events for the four previous solar cycles (Figure 1) it appears that the distribution of solar proton events and the sunspot numbers in solar cycle 23 may be following a pattern similar to solar cycle 20. If this is the case, we would expect the majority of solar proton events during the present 23rd solar cycle to occur during years 5-8 (i.e. from October 2000 – September 2004).

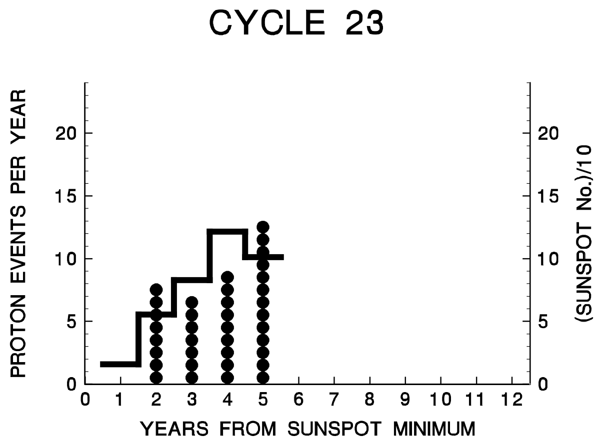

Fig. 4. The number of solar proton events during the rising portion of solar cycle 23.

Table 2. Date of Sequence Number of the Relativistic Solar Proton Events During the first 56 months of Solar Cycle23

Sequence Number	Date of GLE
55	6 November 1997
56	2 May 1998
57	6 May 1998
58	24 August 1998
59	14 July 2000
60	15 April 2001
61	18 April 2001

Seven of the proton events during solar cycle 23 have resulted in increases on the cosmic radiation background recorded by neutron monitors (i.e. GLEs). The magnitude of the increases for most of these GLEs has been relatively small, with increases less than ~20% as recorded by high latitude neutron monitors. However, the increases on 14 July 2000 (i.e. known as the Bastille Day event) and on 15 April 2001 (i.e. known as the Easter Sunday event) were considerably larger. Increases >100% were recorded at high latitude polar stations during the 15 April 2001 event (Duldig, 2001; Pyle, 2001). Table 2 lists the dates of the seven GLEs recorded during the first 56 months of solar cycle 23. The number listed for each event continues the numbering system used by Shea and Smart (1993) and maintained in the GLE computerized database.

5 Conclusions

A statistical study of the significant solar proton events over four solar cycles shows that while the distribution of these events differs from cycle to cycle, the total number of events summed over all four cycles exhibits a skewed Gaussian curve similar to the actual sunspot number. Approximately 16% of the events for each of these four solar cycles contain relativistic solar protons as recorded by ground-based neutron monitors. In comparing the first four years of solar cycle 23 with the first four years of the previous four cycles, it appears that cycle 23 more closely resembles cycle 20 than any other cycle in this time period.

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.

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