SH 1.7.01

# PATTERNS OF SOLAR PROTON EVENTS OVER FOUR SOLAR CYCLES

**M.A. Shea and D.F. Smart**

*Air Force Research Laboratory, 29 Randolph Road, Hanscom AFB, Bedford, MA 01731, USA*

**Abstract**

A statistical study of solar proton events over four solar cycles indicates that the number of events as a function of time over the solar cycles exhibits a skewed Gaussian curve. There is a surprising consistency in the number of events per solar cycle recorded at Earth and in the percentage of events (~16%) containing measurable relativistic solar protons. The proton fluence differs by a factor of 4 between cycles; this difference is attributed to the location of the solar active regions with respect to Earth. The solar proton events during the first two years of the 23rd solar cycle will be discussed in context with the events of the previous four solar cycles.

## 1 Introduction:

The identification of solar proton events was first made by Forbush (1946). Using data from the Carnegie ionization chambers, he postulated that the unusual rapid increases in the background cosmic ray intensity recorded on 28 February 1942, 7 March 1942, and 25 July 1946 were associated with solar activity. The ionization chambers recorded particles having energies above ~4 GeV. When neutron monitors became the principal detector to record 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 changed allowing smaller and smaller events to be identified.

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. This study includes 302 events having more than 10 protons/($cm^2$-sec-ster) above 10 MeV as recorded near Earth. Although episodes of solar proton events may be associated with the same active solar region as it traverses the solar disk (e.g. July 1959, November 1960, August 1972, August 1989, October 1989, June 1991), we have identified each unique solar proton injection into the interplanetary medium as a discrete event for the purposes of this study.

## 3 Results and Discussion:

Figure 1 presents the distribution of solar proton events over each of the past four solar cycles. The dots represent discrete solar proton injections; 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.

An inspection of the distribution of solar proton events shown in Figure 1 shows: (1) the distributions are vastly different from one solar cycle to another; (2) more solar proton events occur during the maximum in solar activity than during the remaining portion of the solar cycle although solar cycle 21 may be an exception; and (3) significant solar proton events can occur at any time of the solar cycle. We also note the variance in the distributions does not seem to be "well behaved" and seems to exceed three sigma.

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.

Table 1 shows that the number of discrete solar proton events has been fairly consistent for each of the four solar cycles. Since routine spacecraft measurements were not available during the 19th solar cycle, the total number of discrete solar proton events for the 19th cycle may be underestimated. Also of interest is the percentage of events containing relativistic solar protons (i.e. GLE's). This percentage is relatively constant for each solar cycle.

Of special 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 the lowest fluence. The factor of 4 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 certainly true for the events in August 1972 and October 1989.

It is when we consider the relative consistency in the total number of events and the factor of 4 difference in the total proton fluence that we can 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 where the associated solar activity is between ~$60^o$ E to ~$120^o$ W. This covers half the solar hemisphere. However, major solar proton fluence events seem to be associated with solar activity that occurs within a much more narrow solar longitude, primarily between $30^o$ E and $30^o$ W. Thus a solar cycle where several active regions are associated with solar proton events in the $30^o$E-$30^o$W heliolongitude range would more likely have a higher proton fluence than a cycle where the phenomenon associated with solar proton acceleration is more randomly distributed around the sun.

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

| Cycle | Start | No. of Months in Cycle | Total No. Discrete Events | No. of GLE | Percent GLE | Omnidirectional Fluence ($cm^2$) |
|---|---|---|---|---|---|---|
| 19 | May 1954 | 126 | 65* | 10 | (15.4) | $7.2 \times 10^{10}$ |
| 20 | Nov 1964 | 140 | 72 | 13 | (18.0) | $2.2 \times 10^{10}$ |
| 21 | Jul 1976 | 123 | 81 | 12 | (14.8) | $1.8 \times 10^{10}$ |
| 22 | Oct 1986 | 120 | 84 | 15 | (17.8) | $5.8 \times 10^{10}$ |

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

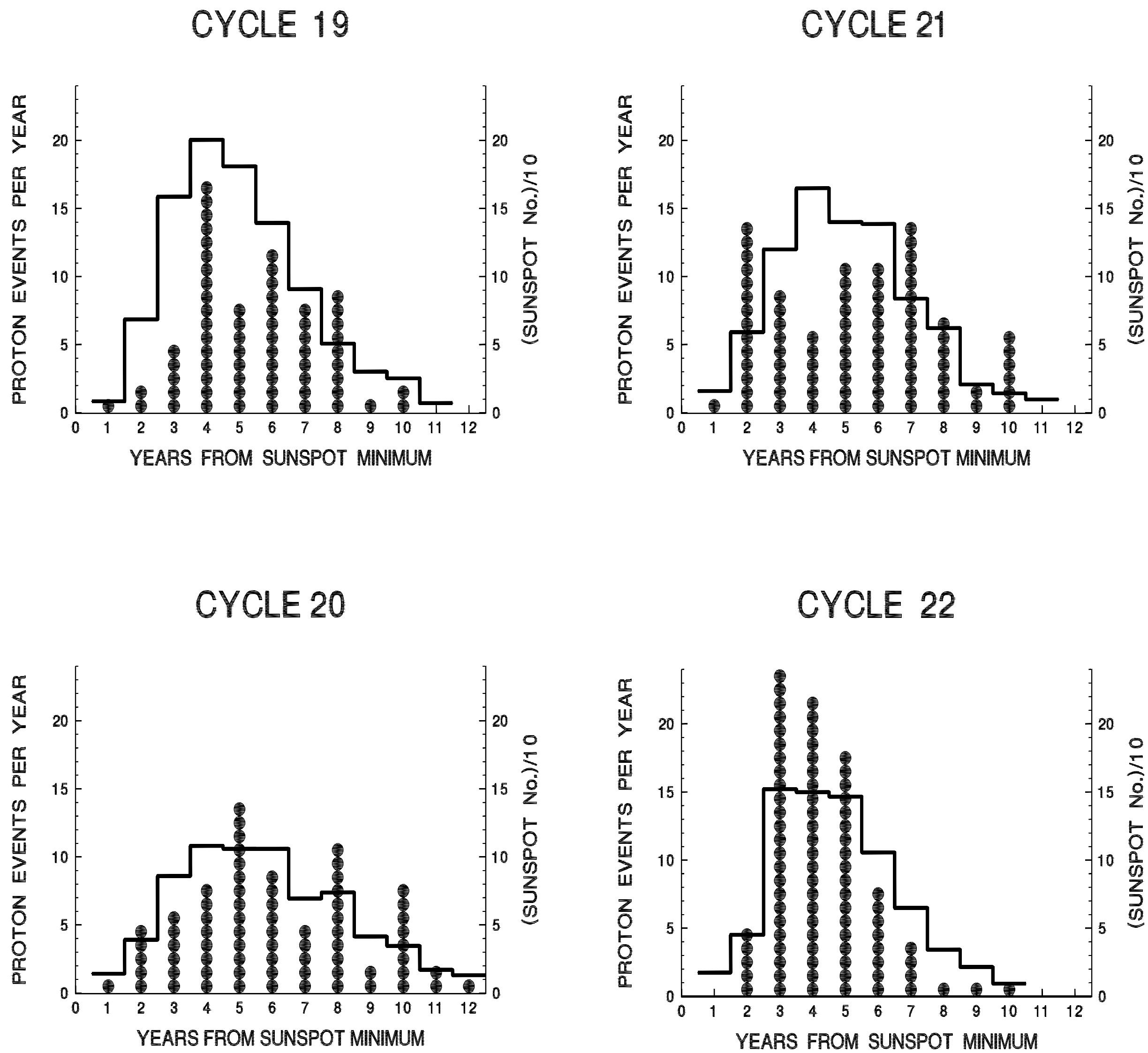


Figure 1. The number of discrete solar proton events (dots) having a >10 MeV peak flux of more than 10 protons/($cm^2$-sec-ster) for each 12-month period after solar minimum for the past four solar cycles. The histograms represent the actual sunspot number averaged over the same 12-month period. The dates where each cycle starts is given in Table 1.

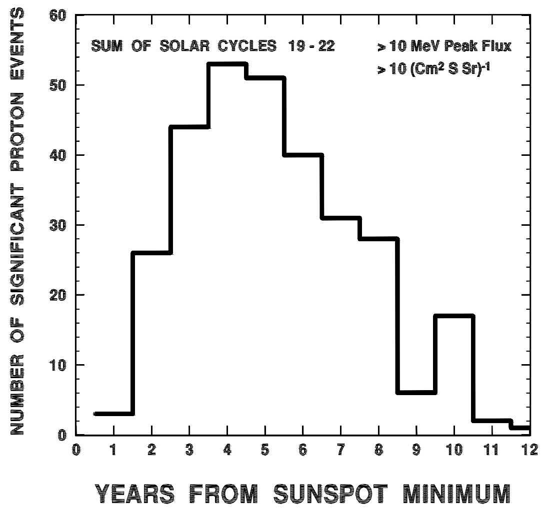


Figure 2. The summation of significant discrete solar proton events for solar cycles 19-22.

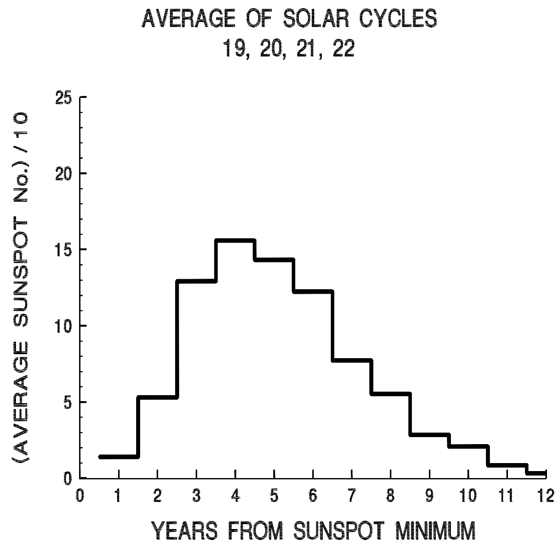


Figure 3. The summation of the 12-month sunspot numbers for solar cycles 19-22.

**3 Solar Cycle 23:**

There have been 12 discrete solar proton events during the first 31 months of solar cycle 23 (October 1996-April 1999). Not enough time has passed to see if there will be a unique distribution of proton events throughout this cycle or if the distribution will resemble any of the previous distributions.

**4 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 summed over all four 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, there is a factor of 4 difference in the total solar proton fluence between cycles. These results are related to the physical phenomena of solar particle acceleration and propagation in the interplanetary medium.

## REFERENCES

Bailey, D.K., 1964, *Planet. Space Sci.*, **12**, 495.
Cliver, E.W., Kahler, S.W. & Wibberenz, 1995, *Proc 24th ICRC*, **4**, 257.
Forbush, S.E., 1946, *Phys. Rev.*, **70**, 771.
Shea, M.A., and Smart, D.F., 1990, *Solar Phys.*, **127**, 297.