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A study of the major solar proton events since 1955 has shown that the large fluence events are likely to be associated with a solar flare source near the central meridian of the sun while the events with large peak proton flux are likely to be associated with solar flares near the west limb of the sun. We compare the solar proton events to the measurements of nitrate concentrations in the Antarctic ice and find that the largest concentrations are associated with the major fluence events. From these results we are able to assign a probable solar proton event source to three of the major peaks in the nitrate record prior to 1955.

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The Flux and Fluence of Major Solar Proton Events and their Record in Antarctic Snow

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ABSTRACT

A study of the major solar proton events since 1955 has shown that the large fluence events are likely to be associated with a solar flare source near the central meridian of the sun while the events with large peak proton flux are likely to be associated with solar flares near the west limb of the sun. We compare the solar proton events to the measurements of nitrate concentrations in the Antarctic ice and find that the largest concentrations are associated with the major fluence events. From these results we are able to assign a probable solar proton event source to three of the major peaks in the nitrate record prior to 1955.

1. DATA BASE

The longest homogeneous record of solar proton events is that derived from cosmic ray measurements. Between 1933 and 1953 cosmic ray measurements were obtained by ionization chambers responding primarily to the muon component which for solar cosmic rays represents a threshold of 4-5 GV. Four GLEs were reported between 1942 and 1951 usir these detectors.

Since 1953 routine cosmic ray measurements have been obtained from neutron monitors. High latitude neutron monitors record the cosmic ray intensity above ~ 1 GV which is a considerably lower threshold than the threshold of a muon detector. There have been 50 ground-level enhancements recorded by neutron monitors since the start of routine measurements in 1953.

In reviewing the GLE data acquired since 1942, Smart and Shea (1991) ranked the events according to the maximum amplitude increase recorded at the cosmic ray station having an asymptotic cone of acceptance viewing into the probable interplanetary magnetic field direction. This ranking, together with the location of the solar flare associated with the proton acceleration is given in Table 1.

Table 1. Largest GLEs (1955-1992) Using the Peak Flux Criterion

Rank	Date	Flare Location	
1	23 Feb 1956	23 N	80 W
2	19 Nov 1949	2 S	70 W
3	29 Sep 1989	24 S	~105 W
4	25 Jul 1946	22 N	15 E
5	28 Feb 1942	7 N	4 E
6	7 Mar 1942	7 N	90 W
7	4 May 1960	13 N	90 W
8	7 May 1978	23 N	72 W

Although routine spacecraft measurements of solar proton intensities did not commence until late 1965, several attempts have been made to estimate the solar proton fluence for the major events of the 19th cycle. A summary of the largest fluence events from Shea and Smart (1990) and Shea et al. (1992) is given in Table 2. All events with a fluence > 5 x 10^9 above 10 MeV are listed. The events listed in Table 2 do not include any entries prior to the 19th solar cycle since fluence data have not been derived for those events.

2.

Table 2. Largest Solar Proton Fluence Events (E > 10 MeV) - 1955-1992

Rank	Date	Fluence	Solar Circumstances				
1	12-15 Nov 1960	3.4×10^{10}	Flares	4 W	-	35 W	Major GMS
2	19-30 Oct 1989	1.9×10^{10}	Flares	9 E	-	81 W	Major GMS
3	10-17 Jul 1959	1.5×10^{10}	Flares	60 E	-	31 W	Major GMS
4	2- 7 Aug 1972	1.1×10^{10}	Flares	35 E	-	37 W	Major GMS
5	22-26 Mar 1991	9.6×10^{9}	Flares	29 E	-	26 W	Major GMS
6	12-18 Aug 1989	7.6×10^{9}	Flares	36 W	-	88 W	Mod. GMS
7	10-12 May 1959	5.5×10^{9}	Flares	47 E	-	26 E	Mod. GMS

2. SOLAR LOCATION OF ASSOCIATED REGION

From an inspection of Table 1 we note that four of the events occurred prior to the 19th solar cycle. The other four events having a large peak proton flux are not listed in Table 2. From Table 1 we also note that the majority of events with a large peak proton flux are associated with solar flares on the western hemisphere of the sun (or slightly behind the western limb). These events are typified by a rapid increase to maximum intensity followed by a smooth decay; the earth is usually not in a good position to be severely impacted by any associated interplanetary shock.

The events listed in Table 2 are primarily from what we call episodes of activity - a period when one active solar region crosses the solar disk during which several powerful solar flares generate a sequence of solar proton events, interplanetary shocks, and subsequent geomagnetic disturbances. Quite often the succession of interplanetary shock structures re-accelerates the already enhanced solar proton flux to higher energies than were originally present. The August 1972 series of events is an excellent example of a solar proton flux at the earth being enhanced with the arrival of the interplanetary shock wave (Levy et al., 1976; Smart et al., 1990). Ground-level events occurred for all the events in Table 2 except for the March 1991 and May 1959 sequences of activity; however, the peak relativistic solar proton flux for each of those events did not meet the peak flux amplitude necessary to be included in Table 1.

Major geomagnetic activity occurred in association with all of the solar flares and proton events listed in Table 2. We have used the Ap* index to evaluate the magnitude of the geomagnetic disturbances (Allen, 1982). The ap index is a linearization of the pseudo-logarithmic Kp index and is derived for each three-hour interval. The Ap* index is derived using a running mean to establish the most disturbed 24-hour period (instead of a standard UT day). This index is available from 1932 to the present time. Any 24-hour period with an Ap* index > 40 is considered to be a magnetically disturbed period.

Using the Ap* index, we find that the first six sequences of activity in Table 2 have Ap* values > 150 indicating an extremely disturbed period. These events rank in the top 45 events on this list for the 20 year period. The 24-hour period commencing 2100 UT on 12 November 1960 has an Ap* value of 293 and is No. 2 on the list. The remaining two events (No. 6 and 7 in Table 2) are associated with moderate geomagnetic disturbances with Ap* values of 77 and 113 respectively.

From this we conclude that solar proton events with major fluences tend to be associated with solar activity near the central meridian of the sun; those events with large peak proton fluxes tend to be associated with solar activity near the western limb of the disk.

3. EVENTS PRIOR TO 1955

It is difficult to determine solar proton fluence for events prior to 1955. Two of the events in Table 1 are associated with solar activity near the central meridian of the sun; therefore it appears reasonable to assume that these flares were part of activity sequences. The 25 July 1946 flare was the progenitor of the geomagnetic storm on 26-27 July with an Ap* value of 212 (No. 19 on the Ap* list). The 28 February 1942 event appears to be associated with an Ap* value of 132 on 1-2 March. The GLEs on 28 February 1942 and 24 July 1946 have been the only GLEs attributed to solar flares near the central meridian of the sun that produced an increase on the ionization chambers or the muon telescopes. Consequently we conclude that these were, indeed, major solar proton events.

4. RESULTS FROM THE ANTARCTIC SNOWS

Figure 1 shows the peaks in nitrate concentrations in ice core samples taken in Antarctica (Dreschhoff et al., 1993). Throughout several core samples, there are persistent peaks at 1928, 1946, 1959 and 1972; the peak at 1909 is present in the only sample analyzed that includes snow back to 1905. The peaks in 1959 and 1972 coincide with large solar proton fluence events. The 1946 peak coincides with a major high energy solar cosmic ray event attributed to a white light flare at the central meridian of the sun and subsequently associated with a major geomagnetic storm.

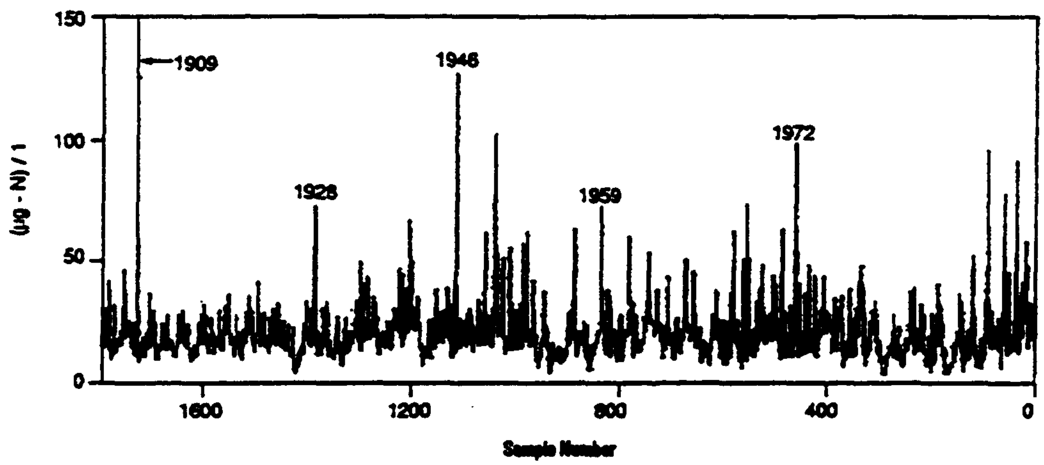

Figure 1. Nitrate concentrations in ice core samples taken in Antarctica.

Solar proton events that occur when the Antarctic polar vortex is present are more likely to be identified by the nitrate method than events that occur when the polar vortex circulation pattern is absent. The polar vortex is present primarily from June through August; however, the duration of the Antarctic polar vortex is highly variable year to year and has been known to start as early as May and extend into November. The major solar proton events in 1946, 1959 and 1972 occurred during the austral winter months when we expect the Antarctic polar vortex to exist. Since the event in 1946 was associated with a major geomagnetic storm, and since the ionization chambers recorded increases of the order of 15-20% from this central meridian flare (something that has not been equalled from any other central meridian flare in recent times), we conclude that the event in July 1946 was not only a major solar proton fluence event but probably contained more particles than the November 1960 activity sequence. Thus we rate July 1946 as the largest solar proton fluence event since 1942.

Routine solar flare observations started in 1932 with the development of the spectrohelioscope and the organization of the IAU solar flare patrol by Hale (1931). Prior to that time only an occasional solar flare was observed either in white light or by using a spectroheliograph. Therefore we must turn to these non-homogeneous solar records and proxy sources such as the geomagnetic parameters to determine if the nitrate peaks in 1928 and 1909 can be related to solar activity.

As mentioned previously the Ap index started in 1932. However, the geomagnetic aa index, which quantifies geomagnetic activity based on two antipodal stations has existed since 1868. As with the Ap* index, an AA* value can be derived from running means to determine the most disturbed 24-hour period.

Using the AA* list we find a major geomagnetic disturbance on July 7-8, 1928; this event ranks as the tenth largest for the 122-year record. Sunspot drawings on July 6 and 7 by H.H. Clayton of Canton, Massachusetts and the Greenwich records show a massive sunspot region just east of central meridian. We assume this was the region associated with the geomagnetic storm, and we further assume it was the source of a major solar proton event. For 1909 we likewise find a major geomagnetic storm on September 25-26; this storm ranks No. 8 on the AA* list with a value of 333. However, for this event there is a record of a solar flare on 24 September at 8 W (Newton, 1943). It is possible that this solar activity may have also produced a major proton event. Additional Antarctic snow core samples are necessary to verify the reality of the 1909 peak.

At the present time the events of the 22nd solar cycle are too recent to be verified by multiple detection in compacted snow sequences. However, preliminary measurements indicate a peak in 1989.

5. SUMMARY

We have found that the solar proton events with large peak fluxes as measured by ground-based cosmic ray detectors are primarily associated with solar activity at or near the western disk of the sun. Solar proton events with large fluences are primarily associated with solar activity near the solar central meridian which is subsequently related to a major geomagnetic storm a day or two later. The ice core measurements in the Antarctic have led us to select the proton event on 25 July 1946 as the probable largest solar proton fluence event since 1942. The use of historic solar observations and geomagnetic records coupled with the nitrate measurements in the ice core samples have aided in the identification of major events in 1909 and 1928. It is anticipated that even earlier events might be identified in this manner.

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