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The Gleissberg periodicity in large fluence solar proton events

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Abstract Using solar proton events (SPE) identified in ice cores, and from satellite and other data, it is shown that the frequency of occurrence of large SPEs has varied by a factor >10 in the interval 1561-1994. There is a well defined "Gleissberg" (80-85 year) periodicity in the data, with six well defined minima, two in close association with the Maunder and Dalton minima in sunspot numbers. The present "satellite" era is a recurrence of this series of minima. It is shown that the rate of occurrence of SPE during Schwabe cycle 1698-1711, at the end of the Maunder Minimum, was one of the highest in the period 1561-1994. This and auroral data indicate that the sun recommenced the acceleration of cosmic rays 15 years prior to the onset of significant geomagnetic activity. It is proposed that major changes in the solar corona at the end of the Maunder Minimum, and during the Gleissberg cycle, modulated the efficiency of the cosmic ray acceleration processes near the sun.

1 Introduction

Elsewhere in this conference, McCracken et al. (2001a) show that the impulsive nitrate events observed in polar ice cores (Dreschhoff and Zeller, 1990, Zeller and Dreschhoff, 1995) are the consequence of the occurrence of large fluence solar proton events (SPEs) at Earth. Using this technique, solar proton events can be usually dated to within ± 2 months for the period 1561-1950, and McCracken et al. (2001b) have detailed the computations that allow an estimate of the > 30 MeV fluences for the 125 impulsive nitrate events with fluences > 1.0 x 10^9/cm^2 identified in that interval.

2 The Occurrence of Large Solar Proton Events in the Interval 1561-1994

These 125 solar proton events (SPE) are displayed in Fig.1, together with SPE for the period after 1950 identified in satellite and other data (Shea and Smart, 1990; 1994). The SPE in Fig 1 prior to 1950 are from Greenland only, and as described by McCracken et al (2001b), this means that the fluence of SPEs occurring in the northern summer may be underestimated or even missing. This uncertainty is indicated by the detection efficiency bar in Fig.1. For comparison with the data after 1950, the earlier frequencies of occurrence are normalized to the present epoch by multiplication by 1.33.

Figure 2 displays the two-cycle running average of the number of large fluence events (> 30 MeV fluence of >2 x 10^9/cm^2) and the two-cycle running average of the

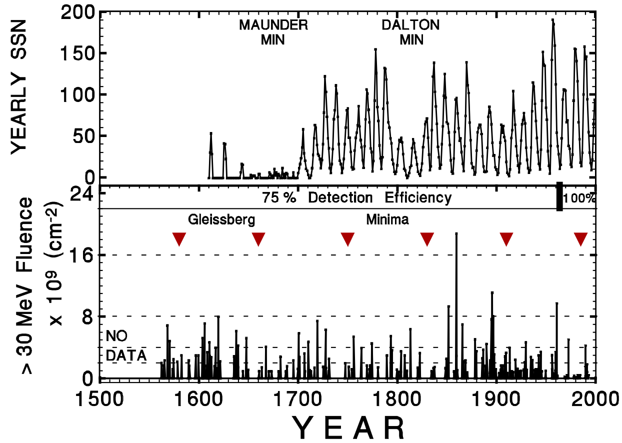

Fig. 1. The times of occurrence of >30 MeV solar proton events with fluence exceeding 1.0 x 10^9/cm^2, and the annual international sunspot numbers.

maximum value of the annual sunspot number for each Schwabe (11-year) sunspot cycle. Figure 2 shows that the normalized frequency of these large fluence SPE has varied strongly with time since 1561, from zero for two separate periods of 22 years (centered on 1744 and 1833), up to five and six per 22 year cycle (centered on 1889 and 1611, respectively). The detailed data show that some individual Schwabe cycles have higher normalized frequencies, ranging from zero to eight. For example, after normalization, we estimate that there were eight large SPE for the Schwabe cycle that peaked about 1605 and seven large events for cycle 13 which peaked about 1893. For the period 1650-1699 in the Maunder minimum, the normalized frequency is 0.6 events per Schwabe cycle. Thus, the event frequency for these large fluence SPEs averaged over periods of approximately 20 years, varied by a factor of 10 or more over the interval 1561-1994.

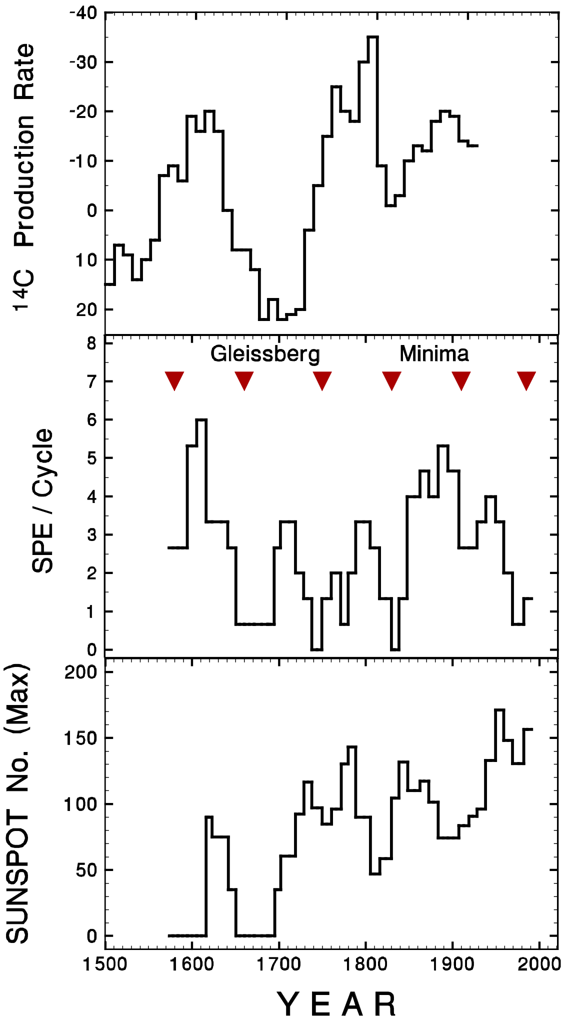

Fig. 2. The frequency of occurrence of solar proton events; the maximum annual sunspot number; and the variation in ^{14}C for the period 1561-1994.

Referring again to Fig. 2, note that the normalized frequency of large SPEs in the "satellite measurement era" (Schwabe cycles 20-22, 1964-1996) averaged about one event per Schwabe cycle. This is to be compared with normalized frequencies of 6-8 SPEs per Schwabe cycle in the vicinity of 1605 and 1893 as noted above.

3 The Gleissberg Periodicity in Solar Proton Event Frequency

It has long been recognized that the sunspot number exhibits a "long" period of 80-90 years that appears as an amplitude modulation of the Schwabe cycle (Gleissberg, 1958; Sonett et al., 1997), and this is commonly referred to as the Gleissberg cycle. Figure 2 (and later Fig. 4) shows that the frequency of occurrence of large SPE (>30 MeV fluence of >2 x $10^9/cm^2$) exhibits a very clear Gleissberg periodicity. There are five well-defined maxima in the vicinity of 1610, 1710, 1790, 1870, and 1950 with an average repetition period of about 85 years.

Referring to Fig. 1 and 2, note the clearly defined minima of the Gleissberg periodicity in the solar proton event data. Two of the minima are closely associated in time with the well-known Maunder (1645-1700) and Dalton (1810-1830) minima of the sunspot number. Four other minima near 1560-80, 1750, 1910, and the vicinity of 1980 appear to be members of the same approximately 80-85 year sequence. Thus, the "satellite era" of observations has coincided with a recurrence of this persistent series of minima in solar proton event frequency.

We have shown elsewhere (McCracken et al, 2001c) that the ratio between the total fluence for the SPE in a Schwabe cycle, and the sum of the fluences of the five largest SPE, is approximately constant. Using this relationship, we calculate that the total fluence has not varied by more than a factor of 2-2.6 from one Gleissberg cycle to another. Further, we find that our total experience of SPE since the 1940s, both with ground-based instruments and with satellites, has been for one of the least active Gleissberg cycles in the past 433 years. Furthermore, 80% of the events and fluence for the Gleissberg cycle starting in 1910 occurred prior to 1960.

Section 2 and 3 therefore demonstrate that the present "satellite era" is a period of abnormally low SPE frequency. Satellite engineering practice uses the SPE for solar cycles 20-22 to determine aspects of engineering and commercial risk , and operational lifetimes. Clearly, a return to the high SPE rates observed at the maxima of the Gleissberg periodicity in Fig. 2 would have substantial impact on space engineering, space travel, and on "space weather" in general

4 The End of the Maunder Minimum

In the following, we examine a feature of the SPE data that may provide insight into the varying conditions in the inner solar system during the Gleissberg cycle. Figure 3 displays the international sunspot number (National Geophysical Data Center, 2000) and the occurrence of aurorae [Eddy, 1976, 1977] between 1650 and 1750. The occurrence of SPE for the same period is also shown. The abrupt increase in aurorae circa 1715 led Eddy and others to conclude that the Maunder Minimum ended in 1715. Certainly, the auroral data make it clear that the major break with the past behavior of the geomagnetic field did not occur until 1715-1716.

However, tables in McCracken et al (2001b) show that there were four large solar proton events in the nitrate record during Schwabe cycle 1698-1711 (i.e. in 1700, 1701, 1706, and 1710). Examination of the data shows that this cycle was one of the four cycles yielding the highest number of SPE between 1561 and 1950. Hoyt and Schatten (1996) have located a reference that indicates that a white light flare was observed in late 1705; possibly associated with the SPE we associate with 1706. There were only 2 large SPE during the 50 year period prior to 1700; and then there were 4 in the next 10 years. This is a statistically significant increase in frequency of occurrence, and indicates that the physical conditions on and near the sun changed abruptly in the vicinity of 1700. Thus while the aurorae did not "switch on" until about 1715, the "switch-on" in the occurrence of large fluence SPE occurred 15 years earlier. That is, from the point of view of the sun, the Maunder Minimum appears to have ended in 1700.

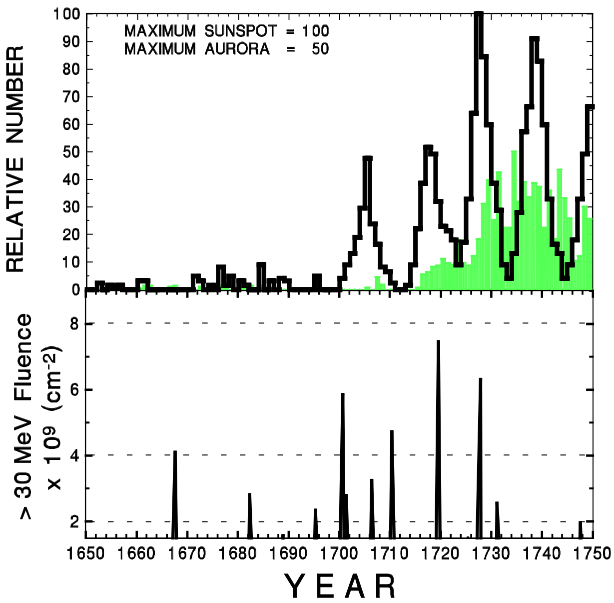

Fig. 3 Sunspot, aurorae, and SPE activity in the period 1650-1750. The sunspot numbers from the National Geophysical Data Center (2000) are normalized to 100 (solid dark line); the auroral data (gray shading) are normalized to 50.

5 The Role of the Corona

Eddy (1976; 1977) and Parker (1975) have discussed the fact that eclipse observations indicate that the solar corona was almost invisible at the end of the Maunder Minimum, and that the first observation of coronal streamers occurred in 1716. These authors suggest that the whole sun was essentially a "coronal hole" at the end of the Maunder Minimum. This would imply a considerably faster, less dense solar wind, and the paucity of sunspots suggests that the magnetic field entrained in the solar wind may have been considerably weaker than in the modern era. The low inferred K coronal intensities (Eddy, 1976) suggest that the matter density in the corona may have been one or more orders of magnitude less than in our present experience.

Table 1. A Phenomenological Model of Coronal Properties and their Consequences throughout the Gleissberg Cycle.

Solar and Interplanetary Features	Maunder Minimum	Gleissberg Minimum (e.g., 1910)	Gleissberg Maximum (e.g.,1947)
Matter density	very low	low	high
Magnetic field	low	higher	x2 higher
CME velocity	high	medium	low
Particle acceleration	very efficient	efficient	less efficient
Interplanetary shock	weak	strong	strong

Further, the corona is known to change greatly between the minimum and maximum of the Schwabe cycle and it is to be expected that there would be similar quantitative changes between the minima and maxima of the Gleissberg cycle. For example, Lockwood et al. (1999) have reported that the sun's coronal field has increased by a factor of 2.3 since 1901 (i.e., since the 1910 minimum of the Gleissberg cycle). Consider therefore a model summarized by Table 1. In this table both Gleissberg columns refer to the maxima of the Schwabe cycles at that phase of the Gleissberg cycle. The "coronal mass ejection (CME) acceleration model" of Reames and others (c.f., Reames, 1999) is used here to describe the particle acceleration process.

For the model in Table 1, the matter and magnetic densities are lowest in the Maunder Minimum, somewhat higher in the other minima of the Gleissberg cycles, and highest near the maxima of a Gleissberg cycle. As a consequence, even a small CME at the end of the Maunder Minimum would meet little resistance from the surrounding coronal medium, and the ejection velocity would be high. It has been shown that the efficiency of solar proton acceleration varies as the fourth power of the CME velocity (Reames, 2000); as a consequence acceleration would be particularly effective during and immediately after the Maunder minimum. Furthermore, the low particle and magnetic density in interplanetary space would mean that the shock wave generated by a small CME would have a considerably smaller momentum density than in the present era, and there would be minor geomagnetic activity when it reached Earth. These predictions are consistent with the paucity of aurorae in Fig. 3 prior to ~1715.

On the basis of this model, efficient propagation of shock waves to the orbit of Earth would not occur until there had been enough solar activity to increase the coronal and interplanetary matter and magnetic density, through the development of coronal streamers, and an extended corona. As noted above, clear evidence of the development of the corona was not reported until 1716, at which time the upsurge in aurorae indicates that geomagnetic storms had commenced fifteen years after the commencement of large fluence SPE. The model implies that CME's near the maximum of the Gleissberg cycle would encounter the greatest resistance from the matter and magnetic densities. As a consequence, the average ejection velocities would be lower, and in view of the fourth power law of velocity, particle acceleration would be less efficient. The kinetic energy of the CMEs would increase as the maximum of the Gleissberg cycle is approached, and this would compensate to some degree for the increased coronal matter densities.

Through the declining phase of the Gleissberg cycle, the model indicates that the matter and magnetic densities of the corona would slowly decline. As a result the CME ejection velocities could be higher and the particle acceleration increasingly efficient. Approaching the minimum of the Gleissberg cycle, CME's would achieve higher ejection velocities, and particle acceleration would become more efficient.

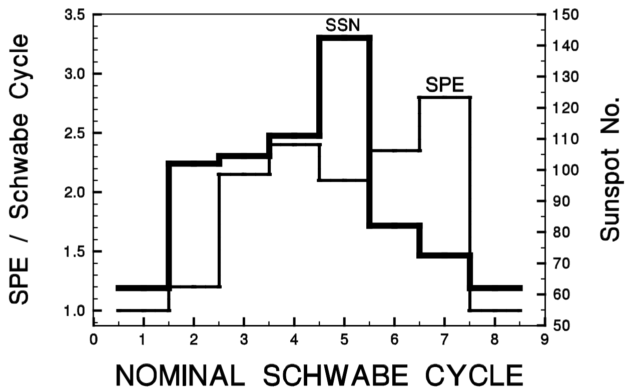

Fig 4. The variation in SPE frequency and peak sunspot number throughout the Gleissberg cycle. A linear detrend has been used.

Figure 4 displays the frequency of occurrence of large fluence SPE and the peak sunspot number as a function of time within the Gleissberg cycle (data from the two cycles 1750-1830 and 1830-1910). While the sunspot number is broadly symmetric about the mid point of the Gleissberg cycle, the SPE frequency rises in a monotonic manner until late in the cycle. This is consistent with the predictions of the model outlined above. In particular, the model predicts that - provided that there was sufficient magnetic activity on the sun to generate CMEs - the frequency of occurrence of SPE could be at a maximum during the Schwabe cycles immediately prior to the sunspot Gleissberg minima. Reference to Figure 1 shows that this was the case for the Gleissberg minima circa 1820 and 1910. On the basis of this model, the relative absence of SPEs during the Maunder Minimum would be due to the virtual absence of CMEs during this period.

In summary, our phenomenological model accounts for the early "turn on" of large fluence SPE after the Maunder minimum and the delayed onset of geomagnetic activity. It is also in accord with the higher frequency of large SPE during the declining phase of several Gleissberg cycles. Examination of eclipse and magnetic records, in conjunction with the SPE data for the period 1880-1920, may allow validation of this model, and further extend our understanding of the extent to which coronal changes are associated with the time variability of SPE.

6 Conclusions

It has been shown that the frequency of occurrence of large SPEs varied by a factor of >10 throughout the period 1561-1994, and that the frequency was relatively low during the satellite era (1960-date). It has been further shown that the production of cosmic rays by the sun shows a strong Gleissberg periodicity. The sun resumed the production of large SPE in 1700, 15 years prior to the resurgence of geomagnetic activity. It is postulated that this was due to the coronal medium being relatively tenuous during the Maunder Minimum; thereby allowing relatively small CME to be efficient in the acceleration of cosmic rays. This model based on a corona that varies throughout the Gleissberg cycle is in broad accord with the SPE variability throughout the cycle.

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