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Variation of SEP event occurrence with heliospheric magnetic field magnitudes

S.W. Kahler

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

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Abstract

Recent work based on nitrate abundances in polar ice cores has shown that large fluence solar energetic ($E > 30$ MeV) particle (LSEP) events during the spacecraft era of observations (1960–present) are diminished in comparison with those of some preceding eras detected in the ice cores dating back to 1561. McCracken et al. [McCracken, K.G., Dreschhoff, G.A.M., Smart, D.F., Shea, M.A. A study of the frequency of occurrence of large-fluence solar proton events and the strength of the interplanetary magnetic field, Sol. Phys., 224, 359–372, 2004] have reported an inverse correlation between LSEP events and the magnitudes of the associated reconstructed heliospheric magnetic fields (HMF). A physical working model by McCracken [McCracken, K.G. Changes in the cosmic ray and heliomagnetic components of space climate, 1428–2005, including the variable occurrence of solar energetic particle events, Adv. Space Res., 40, 1070–1077, 2007a; McCracken, K.G. High frequency of occurrence of large solar energetic particle events prior to 1958 and a possible repetition in the near future, Space Weather, 5, S07004, 2007b] is that the lower HMF and coronal magnetic field B imply that fast coronal mass ejections (CMEs) produce shocks with enhanced Alfvenic Mach numbers M_A and higher compression ratios r, leading to shock production of more numerous and energetic LSEP events. From a possible decline of the HMF over the next several solar cycles he has urged a watch for a return to the environment of high-frequency, high-fluence LSEP events preceding the current spacecraft era. His LSEP event watch involves three independent questions about (1) the physical model, (2) the prediction of decreasing solar-cycle sunspot numbers and heliomagnetic fields, and (3) the inferred anti-correlation between LSEP events and HMFs. Here we discuss observational evidence bearing on the last question and find little support for the claimed LSEP-HMF anticorrelation.
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Keywords: Solar energetic particles; Interplanetary magnetic fields; Coronal mass ejections

1. Introduction

Observations of low energy ($E > 10$ MeV) solar protons at 1 AU are confined to the spacecraft era beginning about 1960. However, it has been determined that thin nitrate-rich layers in Arctic and Antartic ice cores dating back to 1561 correspond to large fluence $E \geqslant 30$ MeV SEP (LSEP) events (McCracken et al., 2001a). Several modern LSEP events were used to establish a scaling factor to convert the impulsive nitrate layers into LSEP fluences. A plot of the running means of the $> 2 \times 10^9$ cm^{-2} LSEP events per solar cycle with the smoothed maximum sunspot numbers (SSNs) extended back to 1561, shown in Fig. 1, indicated a clear 80–90 year modulation matching the well known Gleissberg cycle (McCracken et al., 2001b) of SSNs.

The low frequency of LSEP events during the current spacecraft era, was interpreted by McCracken et al. (2001b) as a recurrent minimum in the Gleissberg cycle. The LSEP events were up to 8 times more frequent in earlier solar cycles than in the space era. This raises the questions of why the LSEP events were more frequent in the past and whether or when those more active environments will recur. If we assume SEP acceleration at MHD shocks driven by coronal mass ejections (CMEs) (Reames, 2004), then some fundamental difference in the past condition of the corona and heliosphere may have favored enhanced SEP acceleration.

E-mail address: stephen.kahler@hanscom.af.mil

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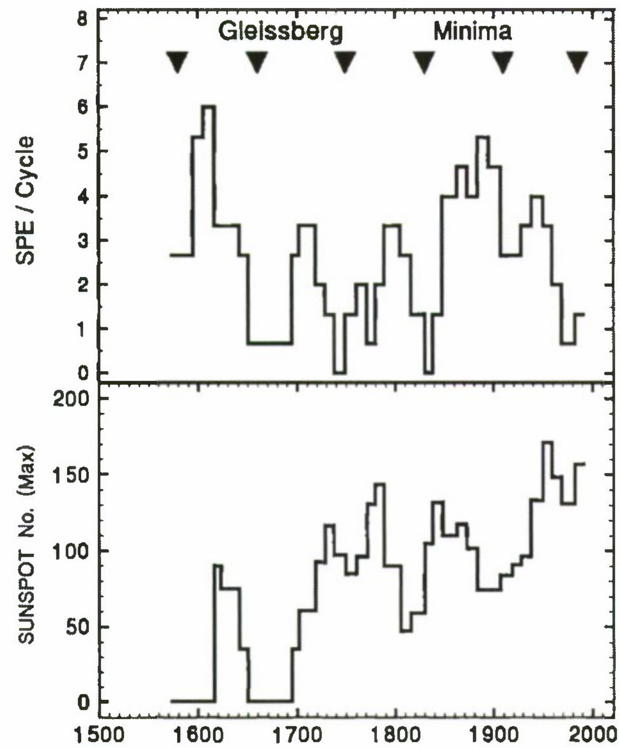

Fig. 1. The frequency of occurrence of $E > 30$ MeV LSEP (here SPE) events (top) and maximum annual SSNs (bottom), both averaged by two solar-cycle running means. Arrows indicate minima in the ~80–90 year Gleissberg cycle. From Fig. 2 of McCracken et al. (2001b), which gives further details.

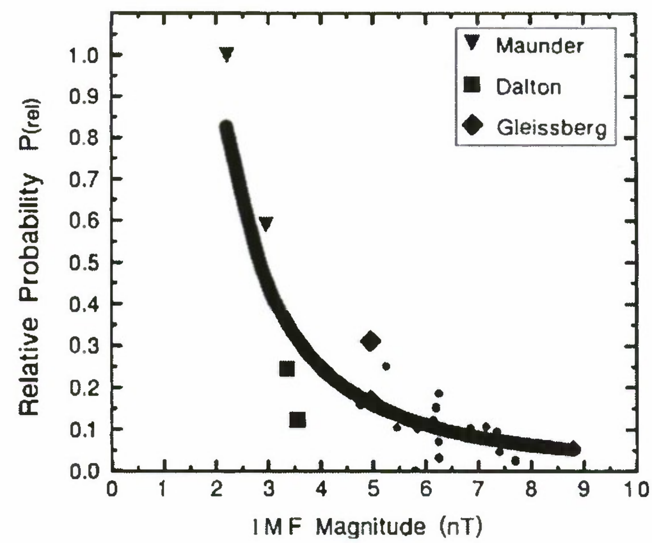

Fig. 2. The 22-year running means of P_{spe} (here $P_{(rel)}$) versus the concurrent average HMF (here IMF) inferred from SSNs for each solar cycle in the interval 1700–1985. The highest values of the P_{spe} occurred during the late Maunder (1700–1715), the Dalton (1800–1830) and the last Gleissberg (1879–1914) minima. Note that during periods of solar minima there are generally both fewer CMEs and fewer LSEP events, although P_{spe} can be enhanced. This is Fig. 2 of McCracken et al. (2004). (With kind permission of Springer Science and Business Media.)

The history of the heliospheric magnetic field intensity has been inferred by methods using geomagnetic indices (Lockwood et al., 1999), SSNs (Solanki et al., 2002), and cosmic-ray records (McCracken, 2007c). McCracken et al. (2004) compared the HMFs derived from SSNs (Solanki et al., 2002) with the LSEP events of the nitrate records and satellite data for 1700–1985. They assumed that the frequency of CMEs capable of driving shocks and producing LSEP events scales with the group SSN. This enabled a calculation of 22-year running means of relative LSEP event probabilities per CME, P_{spe}, by dividing the number of observed LSEP events by their averaged peak group SSNs (Hoyt and Schatten, 1998). A plot of P_{spe} versus the HMF B was empirically fitted by the relation $P_{spe} \sim B^{-2}$, showing more likely LSEP events with lower HMF (Fig. 2).

At the low range of $B \sim 2$ nT,P_{spe} is about an order of magnitude larger than when $B \sim 6$ nT. Fig. 2 shows that the periods of low HMF occurred during well known solar activity minima. Most LSEP events occurred near solar cycle maxima at high SSN and HMF values because the numbers of CMEs are greatest at those times, but the probabilities P_{spe} are lowest at those times.

The relationship between LSEP events and the HMF was recently extended to the $E > 4$ GeV energy range of ground-level events (GLEs) by McCracken (2007b). He noted that there were 5 large fluence (>10% of that of the 23 February 1956 GLE) GLEs (LGLEs) during the 22-year period from the first observations in 1936–1958 and only three during the 47-year period 1958–2005. The 5 LGLEs prior to 1958 occurred when the HMF was <6.5 nT. No LGLEs were observed after ~1954, when the HMF increased to a range of 7–9 nT. The three LGLEs occurring after 1958 were much smaller than the earlier 5 LGLEs and occurred during relatively low HMF values. McCracken (2007b) suggested that LGLEs occur preferentially when the HMF is ⩽6.5 nT, supporting the earlier LSEP event results (McCracken et al., 2004).

Based on their comparison of P_{spe} with the HMF (Fig. 2), McCracken et al. (2004) suggested a model, henceforth the McCracken Working Model (MWM), in which a decrease of the coronal/HMF B results in an increase of the Alfven Mach number $M_A = V/V_A = (V/B)(4\pi n_p m)^{0.5}$, where V_A is the Alfven speed, V is a fixed CME speed, and n_p and m are the density and the mass of the plasma particles. In turn, this increased M_A means an increase in the shock compression ratio r and a flatter SEP energy spectrum. McCracken (2007b) further asserted that the particle acceleration efficiency of the shock would be enhanced by the higher r.

After reviewing the evidence for an anticorrelation of both GLEs and LSEP events with the HMF, McCracken (2007b) suggested (we will call it a watch) that a future decrease in the HMF to <6.5 nT, characteristic of most of the cycle of 1944–1954 and all the previous cycles, could result in the lower values of coronal V_A associated with more frequent and higher fluence GLEs observed at those times compared to the GLEs of the current spacecraft

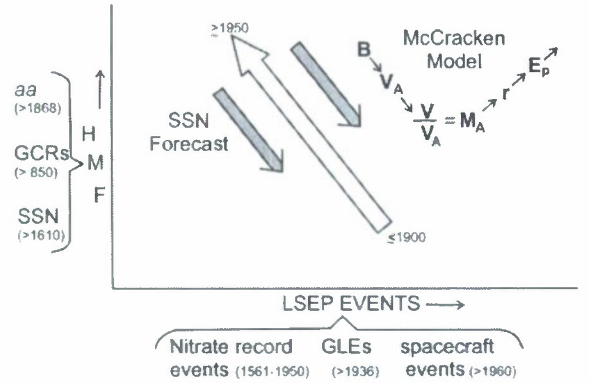

Fig. 3. Schematic showing the inferred inverse relationship between HMF and LSEP events. Scales are qualitative only and show in the brackets the methods and data sources used to derive each parameter. For the HMF the three techniques and periods of the data sets used are the geomagnetic *aa* indices, the galactic cosmic rays (GCR), and SSNs. For the LSEP events the techniques are the nitrate ice core records, the higher-energy LGLEs, and spacecraft LSEP events. Each of the three thick arrows represents a separate basic assumption of the McCracken watch, with the direction of the arrow showing the change in time. The left gray arrow shows that the forecast for SSNs in approaching solar cycles will decrease to levels of Gleissberg minima. The right grey arrow shows the MWM, with a decreasing B leading to a decreasing V_A and increasing M_A, r, and SEP energy E_P. The white center arrow shows the inferred trend of more intense HMF and diminished LSEP events from $\leqslant$1900 to $\geqslant$1950. The three assumptions are independent of each other, e.g., the model may or may not be valid, the HMF/LSEP correlation may or may not be valid, and the declining SSN forecast may or may not be valid. Here we examine only the question of the HMF/LSEP correlation.

age. Another SSN minimum in the Gleissberg cycle in the near future would mean that the LSEP events could also reach the enhanced levels inferred from the nitrate observations of the Gleissberg minimum of 1875–1910 (Fig. 1). A decrease in the HMF would also mean an accompanying increase in the galactic cosmic ray intensities, implying serious challenges for future manned and satellite activity in space.

A near-term return to more intense SEP activity merits closer scrutiny because of its implications for a harsher space-weather environment. The McCracken (2007b) watch was based on several observational and phenomenological associations that we show schematically in Fig. 3. The validity of the MWM and of the forecast for lower SSNs leading to the next Gleissberg minimum have been discussed in detail elsewhere (Kahler, 2008). We focus here on observations that bear on the question of whether larger or more frequent LSEP events are associated with weaker HMFs. In the following sections we consider six topics that bear on the LSEP/HMF inverse relationship claimed by McCracken et al. (2004) and McCracken (2007b).

2. Observations relevant to the LSEP/HMF relationship

2.1. LSEP events in earlier Gleissberg minima

Fig. 1 shows averaged frequencies of occurrence of $E > 30$ MeV LSEP events aligned in time with maximum annual SSNs, both variables averaged by two solar-cycle running means. The current era, extending to just beyond the end of the graphs, is characterized by a high SSN and a low rate of LSEP events. McCracken (2007b) suggested that a return to another Gleissberg minimum of solar activity (shown by arrows), such as that of 1875–1910, could result in the four to sixfold increase in LSEP events observed during that period. However, of the five past SSN Gleissberg minima shown in Fig. 1, that particular one had by far the highest rate of associated LSEP event occurrence. It would seem as or more likely that a return to another SSN minimum would be associated with a lower LSEP event occurrence rate similar to one of the first four Gleissberg minima of Fig. 1.

2.2. LSEPs and the HMF

The comparisons between LSEP events and SSNs (Fig. 1, McCracken (2001b)) and between P_{spe} and the HMF (Fig. 2, McCracken et al. (2004)) were based on running means over two solar cycles. However, a better test of an inverse correlation between LSEP events and the HMF is to compare the reported LSEP events with the deduced annual HMFs. The annual averages of the HMF reconstructed from cosmic-ray records have been reported by McCracken (2007c), and lists of 70 LSEP events prior to 1950 and 8 LSEP events after 1950 were published by McCracken et al. (2001a) and Shea et al. (2006), respectively. These data can be used directly to look for the proposed inverse correlations of LSEP fluences and of LSEP event frequencies versus HMF. A plot of the 78 LSEP event fluences versus the annual HMFs (Fig. 4) shows no correlation (c.c. = −0.037). The occurrence of LSEP events spans the full HMF range from ~0.5 to ~9 nT. The normalized LSEP frequencies versus

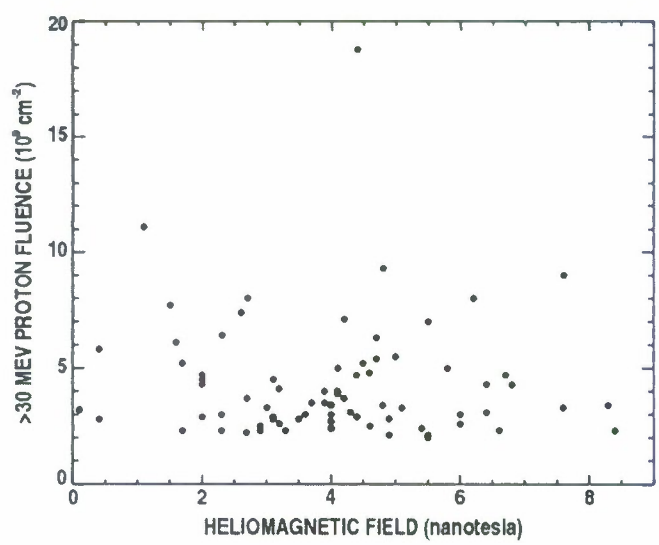

Fig. 4. Plot of 78 LSEP event fluences versus the HMF intensities reconstructed from cosmic ray records (Fig. 2 of McCracken (2007a)). The peak LSEP event is that of the Carrington event of 1859. The lack of correlation of LSEP event fluences with the HMF intensities is contrary to the basis of the McCracken LSEP event watch.

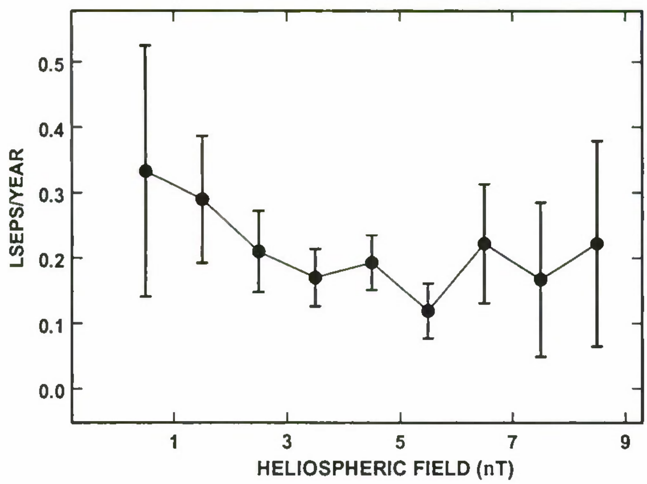

Fig. 5. Plot of LSEP event probabilities versus the average annual HMF intensities reconstructed from cosmic ray records (Fig. 2 of McCracken (2007a)). The probabilities are normalized by sorting the 78 LSEP events into 2-nT wide bins and dividing by the number of years from 1561 to 2005 in each HMF bin. The statistically significant inverse correlation of LSEP probability with HMF supports the McCracken LSEP event watch.

HMF are calculated by dividing the numbers of LSEP events in each HMF range by the numbers of annual HMF values from 1561 to 2005 (McCracken, 2007c) in the corresponding HMF range. The result (Fig. 5) is a statistically significant correlation of slightly declining LSEP event frequencies with increasing HMF, in support of McCracken's (2007a,b) thesis.

The LSEP data thus show no correlation of LSEP *fluences* with HMF but support a correlation of LSEP event *frequencies* with HMF. Note that both Figs. 4 and 5 are based on HMFs consistent with the consensus reconstructions discussed in the next Section, rather than on HMFs from the recent reconstruction from the geomagnetic interdiurnal variability (IDV) index (Svalgaard and Cliver, 2005). A comparison of the annual average HMFs of Fig. 4 of McCracken (2007c) with the solar-cycle average HMFs in Fig. 2 of Svalgaard and Cliver (2007b) shows significant differences between the two reconstructions. In particular, the McCracken (2007c) reconstruction has a series of solar minimum "floors" rising from ~0.5 nT before 1550 to ~5 nT after 1950. In contrast, Svalgaard and Cliver (2007b) established a long-term floor of ~ 4.6 nT, recently modified to a "no-CME" floor of ~4.0 nT by Owens et al. (2008). A comparison of the LSEP events with the IDV reconstruction of the HMF would be interesting, but that HMF reconstruction extends back only to 1856 and would include less than half the 78 LSEP events of Fig. 3.

2.3. LGLEs and the HMF

Based on the 11-year running means of reconstructed HMFs, McCracken (2007b) found that the 5 LGLEs before 1958 occurred when the HMF was <6.5 nT, and the 3 later LGLEs occurred when the HMF $\geqslant$6.5 nT. When compared with the 11-year running averages of HMFs reconstructed from the geomagnetic IDV index (Svalgaard and Cliver, 2005), the first 5 LGLEs now appear to have occurred during a relative peak in the HMF of ~7 nT. The HMF reconstruction from the IDV index is very similar to a recent independent reconstruction from another geomagnetic index by Rouillard et al. (2007). The only marginally weaker HMFs of the earlier 5 LGLEs discussed by McCracken (2007b) now appear as enhanced HMFs.

If we accept monthly SSNs as proxies for the HMF, we can match the appropriate SSNs with the dates of the 8 LGLEs. For the 5 LGLEs before 1958 the monthly SSNs range from 53 to 143 and for the 3 LGLEs after 1958 the range is 31–177. The 29 September 1989 LGLE had the largest fluence of the latter 3 LGLEs (A. Tylka, private comm.), and its associated monthly SSN was 177, a relatively high number. We conclude that there is no good evidence that the LGLEs before 1958, or LGLEs of any era, were associated with weaker HMFs.

2.4. SEP production in fast and slow solar wind

Similar to the McCracken (2007a,b) argument that lower V_A and higher M_A should be more conducive to LSEP production by fast CMEs, Kahler and Reames (2003) argued that CME shock acceleration in coronal sources of slow solar wind should be more effective than in sources of fast solar wind because both the solar wind flow speed v_{flow} and V_A are lower in the slow solar wind regions. A CME of a given frontal speed would therefore be more likely to drive a shock in the slow solar wind regions. However, Kahler (2004) found both the presence of SEP events in fast solar wind regions and no requirement for those associated CMEs to have enhanced speeds. These results contradict the McCracken (2007a,b) argument that SEP production should be enhanced in regions of lower V_A. A mitigating factor here is that Kahler and Reames (2003) assumed that SEPs accelerated in fast or slow solar wind regions near the corona remain in those solar wind source regions as they propagate to 1 AU. Ragot (2006) has established a lower limit of ~20° to the angular deviation of cross-field displacements in the slow solar wind by supradiffusive field-line wandering. This suggests that SEPs observed in fast solar wind regions may have originated near the Sun in adjacent slow solar wind regions with lower characteristic V_A.

2.5. Variance in flares and SEP events with SSN

Hudson (2007) has pointed out the striking difference in X-class flare occurrence during the three-year declining periods of the last three solar cycles. There were 15 X-class X-ray flares in 1983–1985 of cycle 21, but none in 1993–1995, and 34 such flares in 2004–2006, despite comparable SSNs and inferred and measured HMFs of ~6–7 nT (Svalgaard and Cliver, 2007a,b) during the three epochs.

This stark difference extends to LSEP events (Fig. 2 of Reedy, 2006 and reproduced as Fig. 2 of Hudson, 2007). Although much smaller, the numbers of GLEs showed a similar variation: 1, 0, and 3 during the three consecutive declining periods, with the 2004–2006 period accentuated by the large "maverick" GLE of 13 December 2006 (Bieber et al., 2007). While this selected comparison may be atypical for many cycles or different cycle phases, it strongly suggests a poorly defined relationship between solar magnetic fields and LSEP events.

2.6. The Maunder Minimum LSEP events

The LSEP events at the end of the Maunder Minimum (McCracken et al., 2001b) play a key role in the derived relationship between P_{spc} and the HMF shown in Fig. 2. Four events occurred in the solar cycle of 1700–1711 and one (1719) in the maximum year of the subsequent cycle (McCracken et al., 2001a), which account for the two high Maunder Minimum data points. McCracken et al. (2004) initially compared the number of LSEP events in a cycle with the peak annual group sunspot numbers R_g (Hoyt and Schatten, 1998) of each 11-year cycle and found a poor correlation. To calculate the P_{spc} of Fig. 2 they used 22-year running averages of R_g to calculate the number of expected CMEs over each period. The peak R_g of the important 1700–1711 cycle is 5.5 (in 1705), but because it is so much lower than the Zurich number $R_z = 58$ for that year, McCracken et al. (2004) used the geometric mean of 18 to characterize that solar cycle. They do not make clear what R_g numbers were used for their 22-year running means to calculate P_{spc}, but including the smaller values of $R_g = 0$ for the preceding years of 1694–1699 (except for the value of 0.1 for 1695) in the running mean would substantially increase the calculated value of the highest P_{spc} data point in Fig. 2. The corresponding 22-year averages of HMF of Fig. 2 were taken from the calculations by Solanki et al. (2002), which apparently use R_z. Their HMF calculations assumed an initial open flux of 0 in 1700 (Solanki et al., 2000), but their ~2 nT value of B appears to be quantitatively consistent with similar calculations of the radial HMF ~0.3–0.7 nT at 1 AU based on different assumptions by Wang and Sheeley (2003).

There are several reasons to suspect a significant solar magnetic field strength during the 1700–1711 solar cycle. Foukal and Eddy (2007) have pointed out that reports of a red flash at the 1706 and 1715 solar eclipses imply a widespread photospheric magnetic field during the end of the Maunder Minimum, covering times of the 1706 and 1710 LSEP events. Hoyt and Schatten (1996) reported an English record of a possible white light flare on December 27, 1705, which implies the presence of a strong active region. The radiative outputs of stellar Maunder Minimum candidates were found to be similar to the solar spectra near sunspot minima (Judge and Saar, 2007), which are characterized by baseline HMF values of ~4.6 nT (Svalgaard and Cliver, 2007b). These several results suggest the solar presence of significant surface magnetic fields during the late Maunder Minimum. The yearly mean R_z, which peaks at 58 in 1705 might better reflect the solar field than the lower value of 18 used for the highest data point of Fig. 2 (McCracken et al., 2004).

3. Summary

We have considered six different lines of evidence that bear on the question, shown as the white arrow in Fig. 3, whether there is good evidence for an inverse correlation between numbers and/or fluences of LSEP events and the associated magnitudes of the HMF. The arguments in favor of such an association were based on (1) the enhanced LSEP events during the last Gleissberg Minimum of ~1875–1910 shown in Fig. 1; (2) the 5 LSEP events detected during the end of the Maunder Minimum, which contributed to the high P_{spc} values of Fig. 2; and (3) the weaker HMFs associated with the 5 LGLEs before 1958 compared with those of the 3 smaller LGLEs after 1958. We have discussed the observations that undermine each of those three arguments. In addition, we have presented four other factors that indicate no simple relationship between LSEP events and HMFs. These are (1) a plot of the 78 LSEP fluences versus the annual HMFs reconstructed from cosmic ray records (Fig. 4); (2) a plot of the LSEP event frequencies versus the same HMFs (Fig. 5); (3) the frequent presence of SEP events in fast solar wind regions, where V_A is higher than in the slow solar wind regions; and (4) the considerable variation of large solar flares and SEP events during the 3-year declining periods of the last three solar cycles even when the SSNs and HMFs were very similar. Our conclusion is that there is no firm evidence to link enhanced LSEP or GLE activity with less intense HMFs. Arguments concerning the other two questions shown in Fig. 3 have been presented elsewhere (Kahler, 2008).

We emphasize that the McCracken (2007b) watch for a possible return to the earlier 1875–1910 significantly enhanced LSEP activity shown in Fig. 1 should not be dismissed. The nitrate records reveal the presence of that and other more intense eras of LSEPs, which McCracken (2007a,b,c) has attempted to place in the context of diminished coronal and heliomagnetic fields, which allow easier or more frequent shock acceleration of SEPs. Although we argue that such a context is not justified, we also have no reason to expect the current benign LSEP environment to continue into the indefinite future. Thus, we must allow for the possibility that the future space climate will be dominated by an era of enhanced LSEP events.

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