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Extreme Solar Energetic Proton Events

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Solar energetic proton (SEP) events pose a key space weather threat for our technology-based society. Here I briefly review the research which has led to our current understanding of proton acceleration at the Sun and then focus on extreme SEP events, a topic that has received much attention in the last decade because of the inferred occurrence of huge historical SEP events from sharp increases in the concentration of cosmogenic nuclides in tree rings and ice cores.

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1. Introduction

The last two decades have witnessed a rapid growth of interest in space weather generally and extreme solar-terrestrial events in particular. Because extreme solar events are rare by definition, looking back in time and elsewhere in the universe for such events increases the sample size for statistical and physical studies. The study of the Carrington magnetic storm by Tsurutani et al. (2003) opened a window to extreme events in the past when they quantified the storm as one more intense than any seen in modern times. In 2012, Miyake et al. (2012) identified a huge increase in the concentration of ^{14}C in the growth rings of two Japanese cedar trees from 774 to 775 AD (hereafter 774 AD) that has been attributed to an extreme solar energetic proton (SEP) event (Usoskin et al., 2013; Miyake et al., 2019). In that same year, Maehara et al. (2012) reported the discovery of superflares (those with bolometric energy $\geq 10^{33}$ erg) on solar-type stars. Here we present a brief review of extreme SEP events, beginning in Section 2 with a recounting of how we arrived at our current understanding of SEP acceleration. In Section 3, we focus on the extreme SEP event in 774 AD inferred from cosmogenic nuclides that had a calculated spectrum ~70 times stronger than any directly observed event in the modern era.

2. Evolution of thinking on SEP acceleration: From flares to CME-driven shocks

2.1 The initial paradigm

Although the first two SEP events were recorded in 1942 as sharp short-lived increases in ionization chamber counting rates (Lange and Forbush, 1942a,b; Berry and Hess, 1942), they were not recognized as solar events until 1946 when a third such increase was detected. Even then, Forbush (1946) was hesitant to attribute them to the Sun, as indicated by the title of the discovery paper: “Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun.” The first SEP event to be studied in detail was that of 23 February 1956 (Meyer et al., 1956) for which Parker (1957) assumed that the protons were accelerated in a flare-resident process (“in the visible body of the flare”) by the Fermi mechanism, because, “It is difficult to imagine how one could fill the corona with a sufficient intensity of shock waves and other abrupt disturbances to produce the necessary particle acceleration without dissipating into purely thermal motions much more energy than goes into the relativistic particles.” Thus a flare-centric process became the initial paradigm for the acceleration of protons at the Sun. In this picture, the source of the SEPs observed at Earth could be viewed as a delta-function acceleration in space and time (Figure 1). As discussed below, support for aspects of the initial paradigm persist to this day. The intrinsic appeal of a flare origin for high-energy SEPs is captured by Grechnev et al. (2015), who write, “ ... it is difficult to expect that if a powerful flare occurs, then shock accelerated protons provide the main contribution to [GLEs], relative to the flare-related contribution dominating at high energies.”

2.2 Two particle accelerators at the Sun: Flares and shocks

The initial paradigm was challenged in a prescient paper by radio astronomers Wild, Smerd, and Weiss (1963) in Volume 1 of the Annual Reviews of Astronomy and Astrophysics. They wrote, “Studies of the radio emission [of flares] give the most detailed appreciation of the behaviour of the fast electrons. In particular they give striking evidence that two separate phases [of particle acceleration in a flare] are involved. The

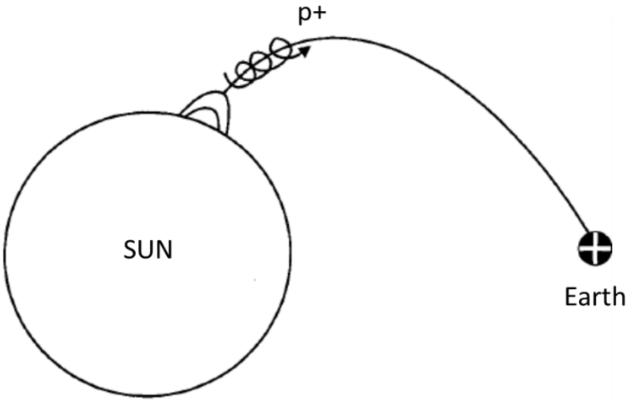
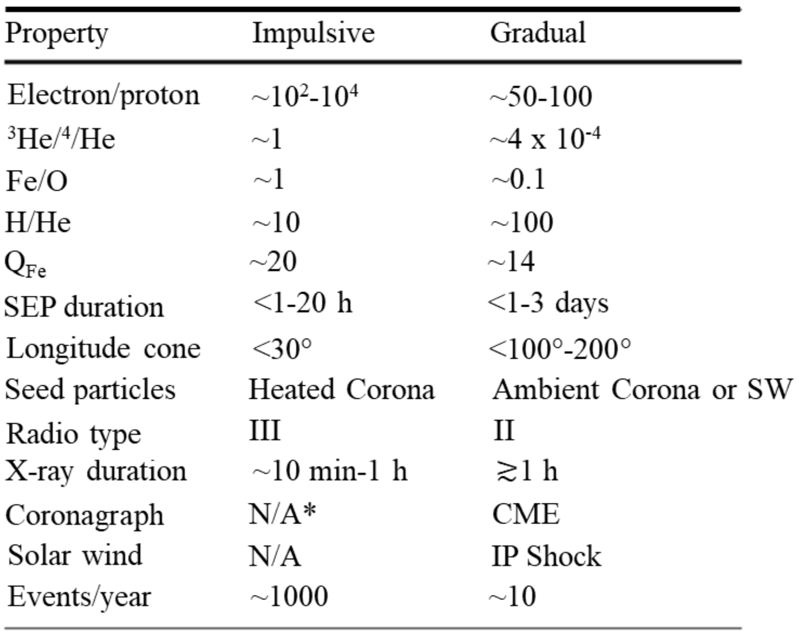


Figure 1. The original paradigm for SEP acceleration at the Sun: a flare-resident process localized in time and space. (Adapted from Cliver, 2000.)

first ... is a succession of bursts of electrons (~100 keV) [giving rise to fast-drift type III metric radio bursts], the accceleration of each burst being accomplished in a very short time (~1 sec); this requires a catastrophic event, probably involving the conversion of magnetic into kinetic energy ... The acceleration of protons to high energies need not be involved in this phase. The second phase, occurring only in large flares, is initiated directly by the first: the sudden release of energy sets up a magnetohydrodynamic shock wave [manifested by a slow-drift type II burst] which travels out through the coronal plasma and creates conditions suitable for Fermi acceleration of protons and electrons to very high energies ($\lesssim$ GeV)." Statistical evidence for a shock picture of SEP acceleration was provided by early satellite observations in which "pure" low-energy (~40 keV) electron events were identified with type III bursts while "mixed" proton and electron events were accompanied by type II emission (Lin, 1970).

The next key finding, by Kahler et al. (1978, 1984), was an association between SEP events and the then relatively newly-discovered coronal mass ejections (CMEs; see Gopalswamy, 2016, for a historical review). This result was followed by association studies linking interplanetary (2 MHz – 30 kHz) type II bursts with SEP events (Cane and Stone, 1984) and fast (>500 km s^{-1}) CMEs (Cane et al., 1987). From ~1985-2000, a unifying picture (Reames, 1995, 1999) emerged in which solar particle events were separated into small "impulsive" and large "gradual" classes on the basis of flare duration (Cane et al., 1986), ion composition (Reames et al., 1985; Mason et al., 1986), ion charge states (Luhn et al., 1987), and CME and radio burst associations, as shown in Table 1 from Desai and Giacalone (2016) that is based on an iconic table from Reames (1995; with input from Kallenrode, 2003). In this picture the principal SEP accelerator was identified as a CME-driven coronal/interplanetary shock (Figure 2), although ambiguity remained about the driver of the coronal (metric type II) shock, either flare (Gopalswamy et al., 1998) or CME (Cliver et al., 1999). This uncertainty was resolved in favor of CMEs (Veronig et al., 2008, 2010) based on high-cadence EUV observations from the STEREO spacecraft (Kaiser et al., 2008). Table 1 contains a persistent misconception — that impulsive ^{3}He-rich and Fe-rich events lack associated CMEs. Various studies (Yashiro et al., 2004; Nitta et al., 2006; Reames et al., 2014) give CME-association rates for such events ranging from 28% to 69% (for the largest sample of 111 events; Reames et al., 2014). The associated CMEs tend to be jet-like and narrow indicating particle

Table 1. Two-class Paradigm for SEP Events (Desai and Giacalone, 2016)



Property	Impulsive	Gradual
Electron/proton	~10^2-10^4	~50-100
^{3}He/^{4}/He	~1	~4 x 10^{-4}
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
SEP duration	<1-20 h	<1-3 days
Longitude cone	<30°	<100°-200°
Seed particles	Heated Corona	Ambient Corona or SW
Radio type	III	II
X-ray duration	~10 min-1 h	≳1 h
Coronagraph	N/A*	CME
Solar wind	N/A	IP Shock
Events/year	~1000	~10

acceleration and plasma injection involving open field lines (Shimojo and Shibata, 2000; Kahler et al., 2001). These CMEs are weakly associated with low-frequency type II bursts (11/111), reflecting the requirement for mass motion perpendicular to magnetic field lines for shock generation (Vršnak and Cliver, 2008).

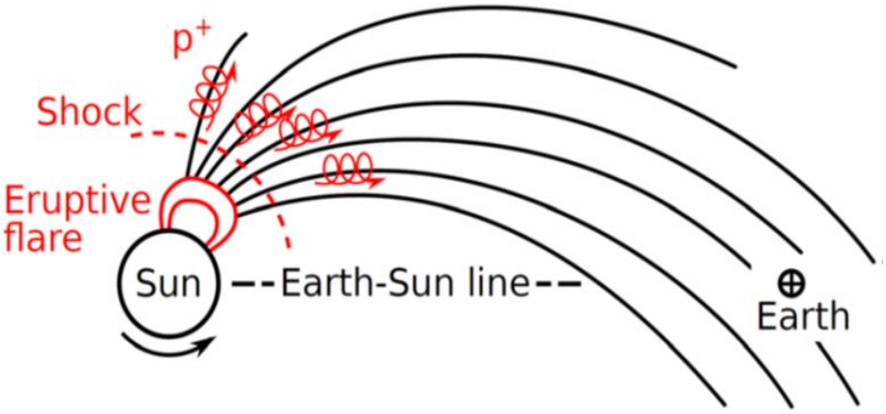


Figure 2. Schematic showing CME-driven bow-shock (dashed-red-line) acceleration of protons in the corona and interplanetary space on open Parker spiral field lines connecting to Earth. (From Cliver et al., 2022.)

2.3 A challenge to the two-class picture

In the same year of the influential Reames (1999) review, the two-class picture in Table 1 was challenged by a composition study (Cohen et al., 1999) of the first four large SEP events observed by the ACE mission (Stone et al., 1998) — at higher ion energies than those considered in Table 1. For one of these events, corresponding ion charge states were obtained by Mazur et al. (1999) from observations made by instrumentation on the

SAMPEX satellite (Baker et al., 1993) and the geomagnetic cut-off technique. In brief, these large (presumably gradual) SEP events exhibited ion composition and charge states characteristic of the small impulsive events in Table 1. The above papers initiated a controversy in which competing flare-centric (Cane et al., 2003, 2006) and shock-centric (Tylka et al., 2005; Tylka and Lee, 2006) pictures were proposed as the dominant accelerator of protons observed in space in large gradual events. The case for a flare source for the discordant ACE events was based on the fact that the highest event-averaged Fe/O ratios in such events are observed for western hemisphere (magnetically well-connected) flares, with the Fe intensity time profiles peaking shortly after the flare. Alternatively, Tylka et al. (2005) attributed this behavior to quasi-perpendicular shock acceleration, taking seed particles into account. Thus the "Gradual" column in Table 1 would be bifurcated, with one column for quasi-perpendicular shock acceleration and the other for quasi-parallel shock acceleration (Cliver, 2009a). With this shock geometry and seed particle framework, Tylka and Lee (2006) were able to provide the first theoretical explanation for the organization of SEP elemental abundances by charge/mass ratio that had been discovered 20 years earlier by Breneman and Stone (1985).

2.4 Current working hypothesis

The flare vs. shock debate continues to this day for high-energy SEP events, in particular the ground level events (GLEs; requiring >500 MeV protons for detection by neutron monitors). Arguments for a propagating shock vs. a flare-resident process as the dominant accelerator in such events include their association with strong shocks and high-speed CMEs (Gopalswamy et al., 2012; Gopalswamy, 2018); the fast propagation zone of SEP events (Reinhard and Wibberenz, 1974; Lario et al., 2016; Cliver et al., 2020a); and GLEs arising from weak solar flares during times of enhanced background (seed) populations (Cliver, 2006). In addition, Cliver (2020a) argued that the variation of GLE spectra with flare longitude (Figure 3) could be explained in terms of shock geometry, with the hardest spectra GLEs favoring, on average, not the zone of good magnetic connection from W40-W80 as might be expected, but rather locations >W100 for which quasi-perpendicular CME-driven shocks would cross the longitudes of nominal good magnetic connection to Earth in the low corona by eastward lateral motion. Shocks to the east of W40 will also have a quasi-perpendicular component for well-connected longitudes but this is more than offset in SEP spectra by the longer times that such shocks propagate parallel to the magnetic spiral to Earth and the effect of low-energy shock spikes at 1 AU. GLEs originating from W40-W80 have intermediate spectra reflecting the softer SEP spectra generated by quasi-parallel shocks relative to quasi-perpendicular shocks. This organization of SEP spectra in terms of the flare location at which the shock originated parallels that reported for SEP time profiles (Cane et al., 1988).

The most compelling arguments for the picture in which proton acceleration in a flare-resident process is the dominant contributor to large SEP events are: (1) the indirect observation of high-energy (>300 MeV) protons during the flare impulsive phase (Forrest et al., 1985, 1986; Ackermann et al., 2012) via pion-decay emission, and (2) the flare longitude organization of Fe/O in large SEP events (Cane et al., 2003, 2006). The escape of such flare-accelerated protons from closed flare and CME loops remains problematic (e.g., Share et al., 2018), however. The shock picture of SEP acceleration does not have this difficulty because acceleration occurs outside of the eruptive flare driver, on open field lines. High-energy (>1 GeV) protons from pion decay are also inferred from

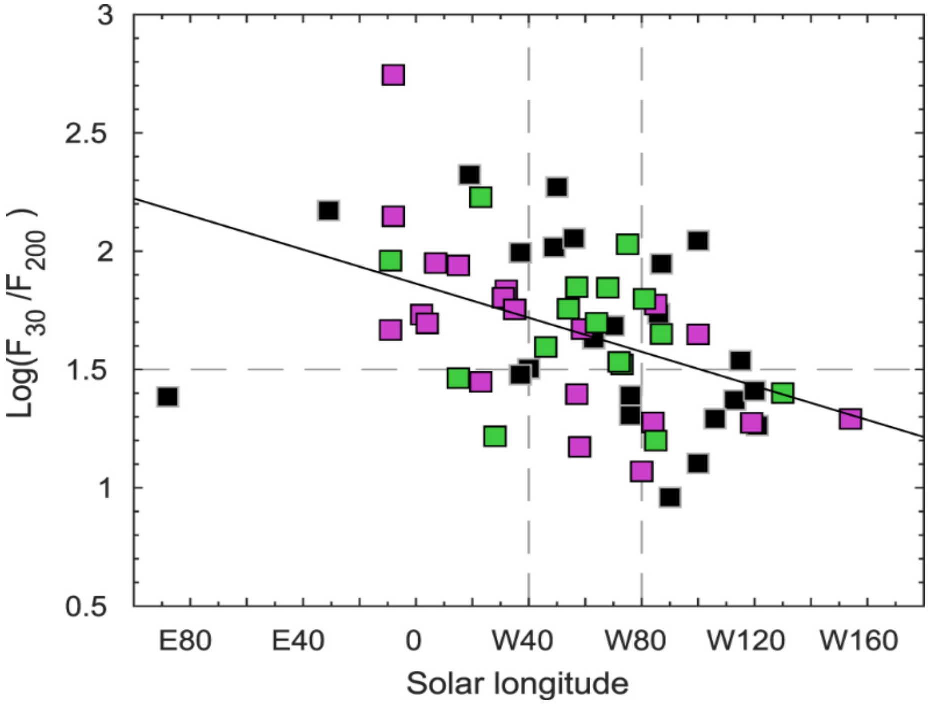


Figure 3. Plot of the log of the proton fluence spectral index (F_{30}/F_{200}) vs. solar longitude for 59 GLEs from 1956 to 2012. The events are color-coded according to the rank order of their >430 MeV (1 GV) fluence: top third (magenta), middle third (black), and bottom third (green). An ordinary least-squares fit (solid line) is shown. (From Cliver et al., 2020a.)

gamma-ray observations during delayed phases of large flares (Forrest et al., 1985, 1986; Akimov et al., 1996; Kanbach et al., 1993; Omodei et al., 2018). In the discovery paper of the delayed pion-rich phase, Forrest et al. (1985) speculated that this component might be associated with the protons observed in space. This idea was expanded on by Ramaty et al. (1987; see also Murphy et al., 1987) who linked the late phase pion emission in the 3 June 1982 flare to the second phase acceleration of Wild et al. (1963). Alternatively, Akimov et al. (1996) attributed delayed high-energy gamma-ray emission in the 15 June 1991 flare to a late phase flare pocess involving magnetic reconnection in a vertical current sheet in the wake of a CME. Following the launch of the high-sensitivity Fermi Large Area Telescope (Atwood et al., 2009) in 2008, the observation of numerous late phase >100 MeV gamma events triggered a vigorous flare vs. shock debate, similar to that for SEP events, in regard to the acceleration mechanism of the interacting protons responsible for delayed high-energy gamma-ray emission. Multiple studies have supported (either directly or by presenting arguments against the alternative) both viewpoints, viz., flare-accelerated protons trapped and/or reaccelerated on large-scale loops (e.g., Grechnev et al., 2018; de Nolfo et al., 2019; Hutchinson et al., 2022; also see Ryan, 2000) vs. precipitation of protons accelerated at a coronal/interplanetary shock to the solar surface (Plotnikov et al., 2017; Jin et al., 2018; Share et al., 2018; Gopalswamy et al., 2018). The combined scenario in which a CME-driven shock accelerates both the high-energy SEPs observed in space and those that interact at the Sun to produce delayed gamma-ray emission is depicted in Figure 4.

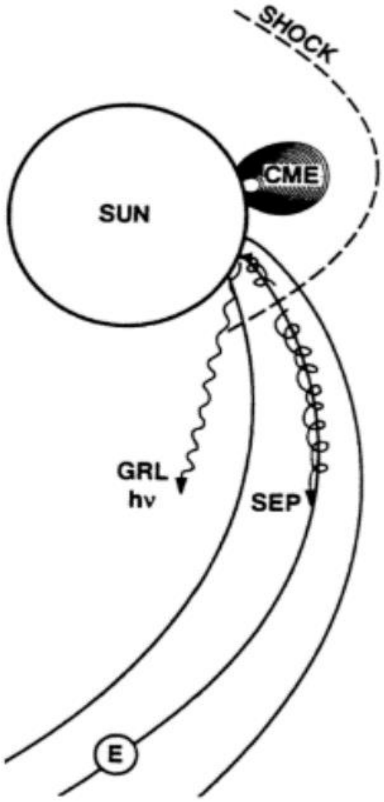


Figure 4. Schematic depicting spatially-extended gamma ray line (GRL) emission from a behind-the-limb flare. This shock accleration/precipitation/escape picture for high-energy protons is also applicable to late phase pion-decay gamma ray events. (From Cliver et al., 1993.)

Although multiple refinements to the picture painted by Wild et al. (1963) have occurred as observations of SEP events and their solar sources became increasingly detailed, the two mechanisms they suggested — a flare-resident process (without any well-accepted mechanism at present; Miller et al., 1997; Cargill et al., 2012) and a propagating shock — still form the basis for the on-going flare vs. shock debates. While the current working hypothesis for the accleration of protons at the Sun favors the CME-driven shock for both the SEPs observed at Earth and the protons that interact at the Sun to produce gamma-ray emission (e.g., Mewaldt et al., 2012; Desai and Giacalone, 2016; Share et al., 2018; Bruno et al., 2018; Reames, 2021), experience shows the susceptibility of working hypotheses to new observations and Solar Probe (Fox et al., 2016) and Solar Orbiter (Müller et al., 2020) will have their say. Early results from these two missions support the shock mecanism for both large gradual SEP events — with Bučík et al. (2023) reporting that ^{3}He enhancement for the first gradual SEP event observed by Solar Orbiter was most likely due to shock seed particles from a series of preceding impulsive flares rather than from the directly associated flare, and for the precipitating high-energy protons that give rise to delayed (>100 MeV) pion decay emission at the Sun — with Pesce-Rollins et al. (2022) finding that the injection of such protons for a behind-the-limb flare on 17 July 2021 coincided with the appearance of a coronal wave on the visible disk. In addition, Mason et al. (2023) showed that ^{3}He-rich flares can lack jets, contrary to current thinking — shedding light on the process(es) by which the impulsive low-energy elctron events in the left-hand column of Table 1 are generated.

3. The cosmogenic nuclide event of 774 AD and the inferred extreme SEP event

3.1 How big was the 774 AD ^{14}C event?

Miyake et al. (2012) presented the first evidence for a great ^{14}C event in 774 AD (transient 12‰ increase; global carbon production of 6 × 10^8 atoms/cm^2) based on analysis of two Japanese cedar trees. The reality of the event was confirmed by ^{14}C data from trees in both hemispheres as well as by ^{10}Be and ^{36}Cl data from ice cores in Greenland and Antarctica (e.g., Usoskin et al., 2013; Güttler et al., 2015; Mekhaldi et al., 2015; Büntgen et al. 2018). The initial estimate of 6 × 10^8 atoms/cm^2 for the global carbon production was too high because the carbon cycle model used by Miyake et al. (2012) neglected the deep ocean carbon reservoir, which contains 92−95% of all carbon (Usoskin et al., 2013). By including this reservoir in their carbon cycle model and correcting an assumption regarding SEP anisotropy in the Miyake et al. analysis, Usoskin et al. reduced the estimate for global carbon production in the 774 AD event to 1.1-1.5 × 10^8 atoms/cm^2. Subsequent models of increasing sophistication raised the annual global ^{14}C estimate for 774 AD to ~2 × 10^8 atoms/cm^2 (Table 2), with a maximum obtained value of 2.2 × 10^8 atoms/cm^2. The current standard based on a 22-box (reservoir) carbon cycle model is 1.88±0.1 × 10^8 atoms/cm^2 (Büntgen et al., 2018).

Table 2. Different estimates of the global radiocarbon production for the 774 AD event ($^{14}Q_{774}$), as published in different sources, using different carbon-cycle models

$^{14}Q_{774}$ (x 10^8 cm^{-2})	Carbon-cycle model	References
(1.1-1.5)	6-Box	Usoskin et al. (2013)
1.7	6-Box	Pavlov et al. (2013a,b)
2.2	11-Box	Güttler et al. (2015)
2.16	Box-diffusion	Mekhaldi et al. (2015)
2.18	11-Box	Uusitalo et al. (2018)
1.88 ± 0.1	22-Box	Büntgen et al. (2018)

3.2 What caused the 774 AD ^{14}C event?

The inference of an eruptive solar flare origin for the 774 AD event was arrived at by a process of elimination. The initial over-estimate of the ^{14}C event by Miyake et al. (2012) suggested a source more exotic than an eruptive solar flare, either gamma-ray emission from a nearby supernova (Miyake et al., 2012) or a short duration galactic gamma ray burst (Pavlov et al., 2013a,b; Hambaryan and Neuhäuser, 2013). The first of these was ruled out by the lack of a supernova remnant and the second became increasingly unlikely with the discovery of other such historical ^{14}C increases (e.g., 993-994 AD, Miyake et al., 2013; 660 BC, Park et al., 2017). Both are inconsistent with a measurable signal in ^{10}Be. Other more speculative causes of the 774 AD event, i.e., a comet striking the Sun and triggering a flare (Eichler and Mordecai, 2012) or a comet striking the Earth directly (Liu et al., 2014) were either not pursued further (for the first of these suggestions) or were dismissed (for the second) because of the lack of evidence in written history for an event that would have had disastrous geological/biospherical consequences (e.g., Usoskin and Kovaltsov, 2015). A suggestion by Neuhäuser and Neuhäuser (2015) of a sudden demodulation of galactic cosmic rays has the advantages of a solar origin, without the requirement for an extreme SEP event, but the amplitude of the 774 AD ^{14}C increase could not be met even if the full local interstellar spectrum of galactic comic rays was applied to the Earth, let alone on the observed rapid time scale of a year or less. The unfeasibility of these various alternatives enabled Usoskin and Kovaltsov (2013) to assign responsibility for the 774 AD ^{14}C event to a hard spectrum SEP event.

Usoskin et al. (2013) calculated that the proton spectrum of the 774 AD event was 25-50 times stronger than that of the 23 February 1956 SEP event (GLE No. 5), the largest hard-spectrum GLE in modern times, with the multiplier of 50 based on an estimated global carbon production of 2.5 × 10^6 atoms/cm^2 for GLE No.5 (Usoskin et al., 2006; Pavlov et al., 2014). Subsequently, Usoskin et al. (2020) obtained a value of 3.04 × 10^6 atoms/cm^2 for 1956. Taking the ratios of the (1.1-2.18 × 10^8 atoms/cm^2) range of production values from Table 2 for 774 AD to the corresponding range of published values (2.5-3.04 × 10^6 atoms/cm^2) for 1956 and adjusting the result upward by 15% for the derease of the geomagnetic field (Usoskin et al., 2016) since 774 AD yields a $^{14}Q_{774}$ / $^{14}Q_{1956}$ ratio of ~70±30, i.e., the proton spectrum of the 774 AD event was ~70 times stronger than that of the February 1956 event.

3.3 How large was the SXR flare associated with the inferred 774 AD SEP event?

The GOES soft X-ray (SXR; 1-8Å) ABCMX flare classification system (defined as follows: SXR classes A1-9 through X1-9 correspond to flare peak 1–8 Å fluxes of 1–9 x 10^{-n} W m^{-2} where n = 8, 7, 6, 5, and 4, for classes A, B, C, M, and X, respectively) is the standard modern measure of solar flare intensity. The intensity of the SXR flare associated with the 774 AD event is based on that of the flare associated with the 23 February 1956 SEP event. Because routine SXR observations of solar flares began in the late 1960s, Cliver et al. (2020b) used various direct (white-light, Hα, and radio emission) and indirect (sudden ionospheric emissions, Sun-Earth transit time of the inferred CME (flare onset to geomagnetic storm sudden commencement), geomagnetic storm intensity) observations available at the time to infer a SXR class range of X10-X30 for the 23 February 1956 event. For context, only ~20 events were observed from 1976-present with SXR peak intensities > X10. Cliver et al. (2020b) constucted the scatter plot in Figure 5 of the log of the >200 MeV proton fluence vs. the log of the SXR intensity of associated flares for hard-spectrum GLEs from 1976 to 2012. The >200 MeV fluence is used because it is the near the center of the atmospheric response function for the creation of both the ^{10}Be and ^{14}C isotopes (Kovaltsov et al., 2014; Poluianov et al., 2016). As a result, the >200 MeV fluence can be assessed from the cosmogenic nuclide concentations, with little dependence on spectral slope.

In Figure 5, the light blue data points are based on the inferred limiting values of the peak SXR intensity for the 23 February 1956 flare and the modeled >200 MeV fluence from Usoskin et al. (2020) for this event based on neutron monitor observations. In the figure, the solid line is a reduced major axis fit to the data, with parallel lines (1) and (2) drawn through the points for the 1956 event to obtain a range of SXR classes corresponding to the inferred >200 MeV fluence for the 774 AD event. The resulting estimate of the SXR class for 774 AD is X285±140, with a nominal bolometric energy of ~1.9 x 10^{33} erg (Cliver et al., 2020b).

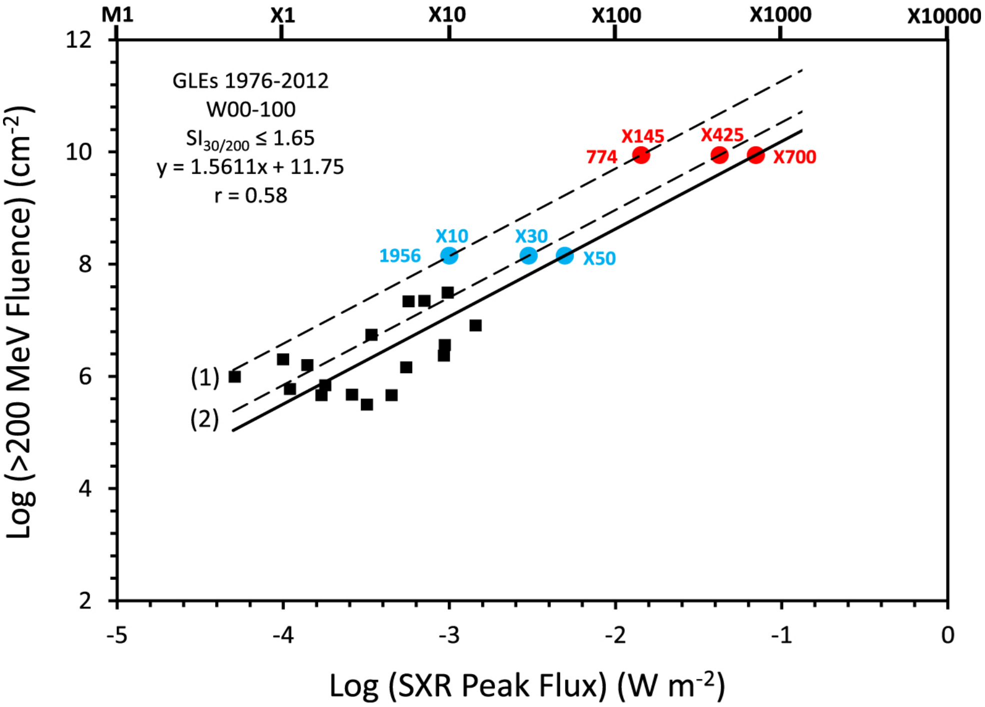


Figure 5. Scatter plot of the log of the >200 MeV proton fluence vs. the log of the SXR intensity of associated flares for hard-spectrum GLEs from 1976 to 2012. See text for explanation of symbols and lines. (From Cliver et al., 2020b.)

The underlying assumption of this SXR class determination is that the 774 flare was at least as effective at accelerating protons as the flare associated with the strongest GLE yet observed. Because of the low time-resolution of the cosmogenic nuclide measurements (a few months to a year), the 774 ^{14}C event may have been caused by multiple flares, e.g., if the 774 AD ^{14}C event was a composite of three SEP events with equal >200 MeV proton fluence, the SXR class (bolometric energy) estimates would decrease to X140±70 (~1.2 x 10^{33} erg; meeting the 10^{33} erg threshold for a superflare) (Cliver et al., 2022).

Finally, it is important to note that while the 774 AD SEP event is estimated to have been 70 times stronger than any event in modern times, this does not imply a commensurate increase in flare radiative energy. The ~2 x 10^{33} erg calculated for the 774 AD X285±140 flare is only ~5 times that of the directly observed bolometric energy of the largest flare observed in modern times (~4.3 x 10^{32} erg for the ~X30 flare on 4 November 2003; Emslie et al., 2012). If the 774 AD SEP event was an amalgamation of three equal fluence proton events, this ratio decreases to 3.

3.4 Mind the gap: The need for confirmation of the size of the 774 SEP event and the possibilty of a dragon-king

The composite occurrence frequency distribution function for annual >200 MeV SEP fluences in Figure 6 shows a ≳1 order of magnitude gap between directly observed SEP events since 1956 (open triangles) and the smallest confirmed historical cosmogenic-nuclide-based SEP events (open circles). Both Usoskin and Kovaltsov (2021) and Cliver et al. (2022) have drawn attention to this gap. Usoskin and Kovaltsov (2021) write,

”Extreme solar particle events of 775 CE, 994 CE, and 660 BCE are nearly two orders of magnitude stronger than those observed instrumentally. Because of the large observational gap between directly measured and historical events, it was unclear whether they can be produced by the Sun "normally" or from an unknown phenomenon.” Usoskin and Kovaltsov anticipate that additional smaller candidate historical events will be observed to close the gap that “if confirmed, would imply that the extreme solar events likely represent the high-energy/low-probability tail of the continuous distribution of solar eruptive events rather than a new unknown type of events.” Cliver et al. (2022) write, “the ultimate confirmation of the SEP hypothesis awaits direct observation of a significantly (≳3 times) stronger [in >200 MeV fluence] event than that of February 1956.” The possibility of “abnormal” SEP production or “new unknown types of events” alludes to “dragon-kings” — extreme events for which the physics differs from that in events which are merely large (Sornette, 2009; Sornette and Quillon, 2012), with “king” indicating the

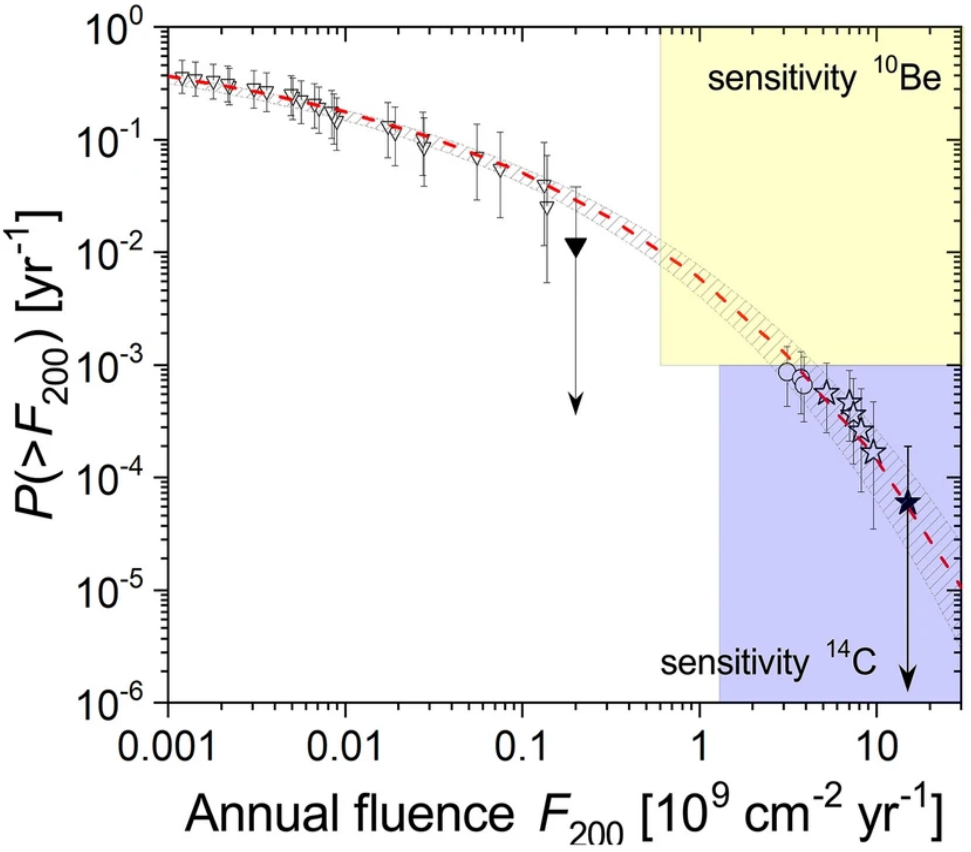


Figure 6. Downward cumulative frequency distribution of the occurrence of years with an annual >200 MeV fluence exceeding a given value (in units of 10^9 protons/cm^2/year). The triangles denote data for the space era (Koldobskiy et al., 2021) and the stars indicate extreme SEP events confirmed in terrestrial cosmogenic data. Open symbols correpond to the measured/estimated fluxes, filled symbols denote a conservative upper bound. Error bars bound the 90% confidence interval. The red-dashed line and gray-hatched area denote the best fit Weibull function and its 90% confidence interval. The range of sensitivity of ^{14}C and ^{10}Be-based reconstructions are shown by blue and yellow boxes, respectively. Image updated after Usoskin et al. (2020). (From Cliver et al., 2022.)

great size of such events and “dragon” their unusual nature. Sornette and Quillon (2012) defined dragon-kings as “as extreme events that do not belong to the same population as the other events…[they] appear as a result of amplifying mechanisms that are not necessary fully active for the rest of the population.” Candidate amplifying mechanisms or environmental factors identified by Cliver (2020b) that might foster a SEP event dragon-king include an enhanced pre-event SEP background (Cliver, 2006) and a favorable magnetic topology at the footpoint of the magnetic spiral fieldline connected to Earth (Kong et al., 2017, 2019).

The cartoon in Figure 7, based on the geometry of the 1956 GLE, depicts how a dragon-king SEP event might arise, with a quasi-perpendicular CME-driven shock arising from a west limb flare providing the hard spectrum and the streamer at ~W55 enhancing high-energy proton acceleration. The optimum scenario would include a series of eruptive flares beginning at disk center (not observed for the 1956 event) — to provide a strong low-energy proton seed population — culminating with a west limb event. Sequences of GLEs approximating this pattern were observed in November 1960 and October 1989. To produce the 774 AD SEP event, the flares would need to have radiative energies (which scale with CME kinetic energy; Emslie et al., 2012) three times greater than that for the X30 upper-limit estimate of the February 1956 GLE-parent flare. Could the above factors combine often enough to give rise to a qualitatively different, dragon-king, class of SEP events?

The possibility that the gap in Figure 6 is due to a SEP dragon-king, or an as yet unknown non-SEP source, or simply the relatively short time of observation, is a key question of extreme SEP physics.

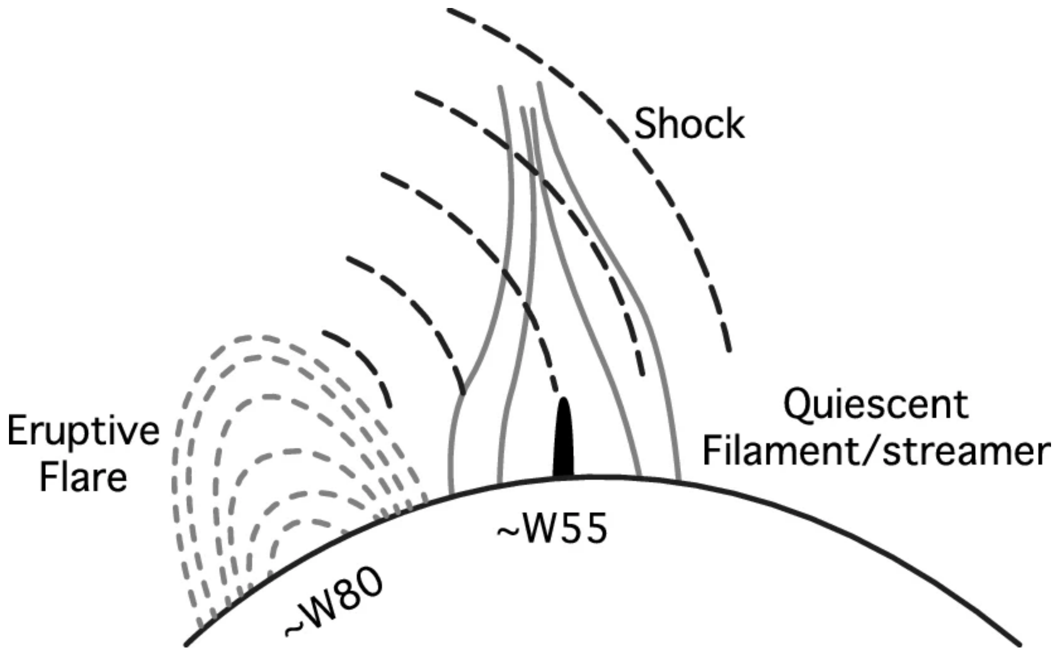


Figure 7. Cartoon showing a shock from an eruptive flare at ~ W80 impinging on a streamer at ~ W55, a favorable situation for acceleration of high-energy SEPs directed toward Earth that existed for the 23 February 1956 event. (Figure from Cliver et al., 2022, adapted from Wild, 1969).

4. Conclusion

In this brief review of extreme SEP events, we first gave an overview of how our understanding of the acceleration of the particles observed in space following solar flares has evolved over time. The current view retains the strong imprint of the proposal advanced by three radio astronomers 60 years ago of two basic processes: a flare-resident process characterized by electron-acceleration and type III metric radio bursts and acceleration at a propagating shock characterized by proton acceleration and metric type II bursts (Wild et al., 1960). The initial default view that protons, in particular, high-energy protons, are primarily accelerated in a flare-resident process retains its appeal but is not supported by the preponderance of evidence. With their near-Sun approaches, Parker Solar Probe and Solar Orbiter are certain to sharpen our current understanding of particle acceleration at the Sun.

A new window on extreme SEP events was opened by Miyake et al. (2012) with the report of a huge ^{14}C event in 774 AD. Such ^{14}C events are interpreted in terms of SEP events that are >10 times larger than any that have been observed in the modern era, leaving a gap in the SEP fluence distribution (Figure 6) to be filled either by identification of smaller historical cosmogenic-nuclide-based SEP events or by observation of future proton events larger than those directly recorded to date. Such observations are needed to ultimately confirm the current interpretation of the cosmogenic nuclide based SEP events as the normal extension of the high-fluence/low-probability tail of high-energy SEP events — rather than, e.g., a dragon-king phenomenon, involving different physics and implying a different SEP event population than the low fluence branch of the distribution. As Usoskin and Kovaltsov (2021) write in the title of their paper, it is necessary to “Mind the gap”.

It should also be kept in mind that while the 774 SEP event had a proton spectrum estimated to be ~70 times stronger than that of the 23 February 1956 GLE, the bolometric energy (~2 x 10^{33} erg) of the inferred 774 AD flare is only about five times that of the largest directly observed flare of the modern era, a factor that reduces to three if the 774 AD SEP event consisted of three equal fluence proton events closely spaced in time.

The talk given on this topic at the ECRS was more comprehensive in regard to extreme events, covering phenomena including solar flares, stellar flares, and geomagnetic storms, in addition to SEP events. It was based on a Living Reviews in Solar Physics paper (Cliver et al., 2022). A more detailed discussion of the evolution of thinking on proton acceleration at the Sun is given in Cliver (2009b).

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