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DOES A SCALING LAW EXIST BETWEEN SOLAR ENERGETIC PARTICLE EVENTS AND SOLAR FLARES?

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ABSTRACT

Among many other natural processes, the size distributions of solar X-ray flares and solar energetic particle (SEP) events are scale-invariant power laws. The measured distributions of SEP events prove to be distinctly flatter, i.e., have smaller power-law slopes, than those of the flares. This has led to speculation that the two distributions are related through a scaling law, first suggested by Hudson, which implies a direct nonlinear physical connection between the processes producing the flares and those producing the SEP events. We present four arguments against this interpretation. First, a true scaling must relate SEP events to all flare X-ray events, and not to a small subset of the X-ray event population. We also show that the assumed scaling law is not mathematically valid and that although the flare X-ray and SEP event data are correlated, they are highly scattered and not necessarily related through an assumed scaling of the two phenomena. An interpretation of SEP events within the context of a recent model of fractal-diffusive self-organized criticality by Aschwanden provides a physical basis for why the SEP distributions should be flatter than those of solar flares. These arguments provide evidence against a close physical connection of flares with SEP production.

Key words: acceleration of particles – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: particle emission

1. INTRODUCTION

Understanding the relationship of solar energetic ($E > 10\,\mathrm{MeV}$) particle (SEP) events to their associated solar phenomena, flares, and coronal mass ejections (CMEs) in particular, is a continuing challenge. The general consensus is that gradual SEP events are produced in large-scale shock waves driven by CMEs, while smaller, lower-energy ($E < 10\,\mathrm{MeV}$) impulsive SEP events are connected to the flare process (Reames 1999, 2013). One expects then that good correlations will be found between gradual SEP event parameters such as peak intensities p, and CME properties such as their speeds V or widths W, which are factors in driving the shocks that produce the SEPs.

An alternative view is that the flares are major contributors or factors in the production of the SEPs of gradual events (Bazilevskaya 2009; Cane et al. 2010; Firoz et al. 2011), in which case physical connections or correlations between properties of gradual SEP events and their associated flares should be found. Logs of SEP p have been correlated with logs of associated flare X-ray peaks x and with logs of associated CME V in attempts to distinguish between flares and CMEs as sources of gradual SEP events. For large SEP events, the correlation coefficients (CCs) are generally ∼0.6 for V and ∼0.4 for x (Gopalswamy et al. 2003; Park et al. 2010, 2012), but the comparable CCs for V and for x for western hemisphere SEP events with a broader range of p (CC = 0.6 and 0.6, Cane et al. 2010; CC = 0.63 and 0.59, Miteva et al. 2013; and CC = 0.53 and 0.52, our calculation of data in Cliver et al. 2012) fail to support the case of CME shock acceleration.

The attempt to distinguish between CME V and *GOES* X-ray x as indicators of SEP production is further complicated by significant CCs between log V and log x. Yashiro & Gopalswamy (2009) found CC = 0.50 for several thousand western hemisphere events, and we calculate CC = 0.37 for 56 similar SEP-associated events of Cliver et al. (2012). Bein et al. (2012) and Miteva et al. (2013) reported CC = 0.32 and 0.39, respectively, for samples of flare-CME populations at all longitudes.

The CME W is less often used in statistical comparisons with p, generally because of the large fraction of full halo ($W = 360°$) CMEs associated with SEP events. Miteva et al. (2013) found a lower CC ∼ 0.35 between log p and W than between log p and log V. Comparable to their V versus x comparison of western hemisphere CMEs, Yashiro & Gopalswamy (2009) reported for log W versus log x a CC = 0.41, indicating that both the CME V and W parameters correlate with the flare x parameter. Furthermore, the ∼100 SEP events of Miteva et al. (2013) and ∼4000 CME-flare events of Yashiro & Gopalswamy (2009), both over nearly all of solar cycle 23 and restricted to western hemisphere events, show that both the CME and flare populations greatly exceed that of the SEP events.

2. POWER LAWS AND SCALING LAWS FOR FLARES AND SEP EVENTS

When a sufficient number of SEP event peak proton intensities p were accumulated (van Hollebeke et al. 1975), it became clear that their size distribution fit a power law of the form

$$\frac{dN}{dp} \sim p^{-\alpha_p}\ \mathrm{events/unit}\ p, \qquad (1)$$

where the slope of the distribution $\alpha_p \sim 1.15$. Contemporary compilations of solar-flare parameters, such as soft and hard X-ray and microwave burst flux peaks, also yielded power-law distributions with steeper slopes of $\alpha_x \sim 1.8$ (Hudson 1978). Each SEP event was generally associated with a solar flare, but solar flares constituted a much larger population (e.g., ∼4000; Drake 1971) than that of the SEP events (163; van Hollebeke et al. 1975), as they have in subsequent studies.

Power-law distributions are a result of the phenomenon of self-organized criticality (SOC), which applies to a broad range of natural and social phenomena (reviewed by Aschwanden 2011a). The slope of each power law is understood to reflect the particular mechanism(s) giving rise to the events of the distribution. While both the solar flare and SEP distributions arise in the context of transient solar energetic events, their differing slopes imply different generation mechanisms for the two phenomena.

Hudson (1978) suggested three possibilities for the difference between $\alpha_p = 1.15$ and $\alpha_x = 1.8$: (1) flares with SEP events differ fundamentally from ordinary flares, (2) flares with SEP events are merely the large end of the flare distribution, and (3) flares with SEP events have a threshold behavior. Case (1) implies that although most SEP events are associated with flares, the two phenomena are not causally related and arise from differing physical mechanism(s). Case (2) implies that SEP events will be associated only with the largest flare events. The generating mechanisms of the two populations may or may not be related. In the last case (3), above some flare size threshold, SEP events are related one-to-one with flare events and the SEP production must scale more than proportionally with flare energy. Such a scaling implies a common or related mechanism for flare and SEP production. Case (3) may be consistent with case (2), but the big disparity between the larger flare and smaller SEP population sizes noted above poses a challenge to this possibility. In accordance with case (3), Hudson (1978) suggested a scaling law of the form $p \sim E^{\beta}$, where E is a measure of flare energy and that

$$\beta = \frac{\alpha_x - 1}{\alpha_p - 1}. \tag{2}$$

From his flare and SEP event statistical distributions $\beta \simeq 5.6$, implying a strongly nonlinear proton production with increasing E as measured by the peak X-ray flare intensity x. This result would rule out case (1) in favor of (3), that SEPs can be produced in a flare event if and only if the flare energy attains a sufficiently high level. A separate mechanism for producing SEPs, such as a fast CME, is not needed in this view.

3. COMPARISONS OF SEP EVENT DISTRIBUTIONS WITH ASSOCIATED FLARE DISTRIBUTIONS

With such a strong inferred nonlinear dependence of SEP p on flare energies E, and by implication, on flare x, one would expect that plots of SEP event peaks versus their associated flare X-ray (or microwave) peaks would show this dramatic trend. However, Hudson (1978) did not attempt to show such a direct correlation with a data set of common SEP and flare events. Subsequent studies correlating flare x with associated SEP p have shown correlations with considerable scatter (Balch 2008; Park et al. 2010), which seem inconsistent with the basic concept of a strong nonlinear dependence of SEP production on flare energy.

Since Hudson's (1978) work statistical compilations have been extended to more and larger data sets of flare burst events. Nita et al. (2002) examined 40 yr of radio bursts and found a power-law slope very close to ∼1.8. For six frequencies of the Nobeyama Radio Polarimeters, Song et al. (2012) recently found slopes of 1.74–1.87. Similarly, for six frequencies of type III bursts observed with the Nancay Radioheliograph, Saint-Hilaire et al. (2013) found a slope of 1.7 ± 0.05. Aschwanden (2011b) determined a slope of 1.73 ± 0.07 for hard X-ray flares using multiple instrument data sets. Similarly, the SEP event distributions have been brought up to date by Belov et al. (2007) for $E > 10$ MeV and > 100 MeV events from 1975 to 2006 for which they derived $\alpha_p = 1.34 \pm 0.02$ and 1.46 ± 0.04, respectively.

4. RECENT SEP-FLARE SCALING-LAW COMPARISONS

Belov et al. (2007) also invoked Equation (2) to compare their SEP size distributions with their *GOES* soft X-ray size distribution, which had a slope of $\alpha_x = 2.19 \pm 0.04$ based on 62,000 flares from 1975 to 2006. Their slope was slightly larger than the recent value of Aschwanden & Freeland (2012) using over 300,000 flares from 1975 to 2011 to obtain a slope of $\alpha_x = 1.98 \pm 0.11$. With their fits for soft X-ray and SEP slopes Belov et al. (2007) found $\beta = 3.5$ and 2.6 for the $E > 10$ MeV and >100 MeV proton distributions of Hudson's (1978) preferred case (3) of a nonlinear dependence of p on x.

The fact that associated SEP events are a small subset of all flares, as discussed in Section 2, poses a fundamental problem for the comparison of the two size distributions. A comparison of all flare events with SEP events to seek scaling laws between the two, as done by Hudson (1978) and Belov et al. (2007), cannot be meaningful when most flares are excluded from the presumed scaling-law relationship. Recognizing this limitation, Belov et al. (2007) also compared the distributions of the SEP events within a source longitude range W20°–W75° with their associated flare X-ray flux distributions. For these subsets, they found power-law slopes of $\alpha_x = 1.29 \pm 0.12$ and $\alpha_p = 1.22 \pm 0.05$ and 1.26 ± 0.03 for the $E > 10$ and > 100 MeV protons. From Equation (2), these values then yield $\beta = 1.3$ and 1.1, respectively, now more consistent with a linear dependence between p and x.

A selection effect is introduced in distributions of subsets of flares with specific energetic restrictions. As one example, Yashiro et al. (2006) derived slopes of $\alpha_x = 1.98 \pm 0.05$ and 2.52 ± 0.03 for soft X-ray flares with and without associated CMEs. Earlier, Pearson et al. (1989) showed that flare hard X-ray peak intensities are statistically larger for flares with type II radio bursts than for those without. Flares with associated energetic phenomena, such as CMEs, type II bursts, γ-ray bursts, etc., tend to be larger events and are characterized by flatter distribution slopes. Distinguishing between two sets of flare events based on associated phenomena appears to be consistent with Hudson's (1978) case (1) above, which would invalidate his preferred case (3) of a general scaling law and a flare threshold for SEP events, which should apply to all flare events.

Invoking the current view of SEP production by CME-driven shocks, Cliver et al. (2012) have recently followed the second approach of Belov et al. (2007) to argue that only the subset of flares associated with SEP events and fast ($V > 1000$ km s^{-1}) CMEs should be compared with SEP events. They generated a data set of 58 well connected (W20°–W85°) $E > 10$ MeV SEP events with associated flares and CMEs for analysis. From the Yashiro et al. (2006) study they included all X-ray flares of sizes M1 or greater and restricted to the same W20°–W85° range and organized them into three groups. The groups and power-law slopes were: (1) all flares, $\alpha_x = 2.10$, (2) flares with associated SEP events, $\alpha_x = 1.31$, and (3) flares with fast ($V \geqslant 1000$ km s^{-1}) CMEs, $\alpha_x = 1.39$. The latter two slopes are close to that of their SEP events, $\alpha_p = 1.16$. Cliver et al. (2012) argue that the similarity of the power-law slopes of their SEP events, X-ray flares with SEP events (their group 2), and flares with fast CMEs (group 3) implies an energetic subset of all flares characterized by fast CMEs, which accounts for much of the discrepancy between the slopes of all X-ray flares and the SEP events.

Figure 1 shows their direct comparison of the logs of their SEP events with those of the associated X-ray flares. On the assumption that both flares and SEP events independently result

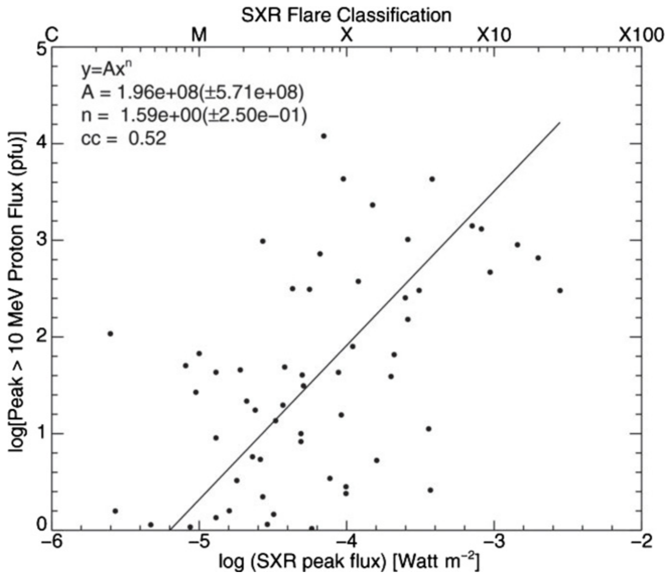

Figure 1. Scatter plot of peak $E > 10$ MeV SEP event flux vs. flare soft X-ray peak flux for proton events originating from W20° to W85° heliolongitude, with geometric mean regression slope of 1.59. We argue that p should be treated as the dependent variable and x as the independent variable, in which case the slope is 0.82. Reproduced from Cliver et al. (2012).

from an underlying common cause, the solar eruptive event, they took the slope of the geometric mean of the plot of 1.59 ± 0.25 as a direct measure of β in the context of Hudson's (1978) case (3). With their α_p and group (2) α_x in Equation (2) they found $\beta = 1.94$ (+11.9, −1.69), consistent with the plot slope and with the corresponding Belov et al. (2007) value of $\beta = 1.3$ (+1.1, −0.7), but obviously too unconstrained for them to draw any conclusion of agreement with either value. Their result therefore still allows for a possible scaling law between flares and SEP events, but now, contrary to the original idea of case (3) of Hudson (1978), it is based only on a subset of all flares and without an implied causal relationship between variables x and p.

Assuming, on the contrary, that p scales with some power of the independent variable x, we find that the least-squares slope of Figure 1 determined with p as the dependent variable is 0.82. This value is compatible with the Belov et al. (2007) slopes of 0.93 and 0.99 for $E > 10$ MeV and > 100 MeV for similar log p versus log x plots of much larger samples of SEP events in a similar well-connected longitude range. The data of Belov et al. (2007) and of Figure 1 are therefore consistent with only a linear relationship between p and x and therefore with case (1) of Hudson (1978). While a linear scaling ($\beta = 1$) is not explicitly excluded by his case (3), Hudson (1978) introduced it to account for the observed difference between α_x and α_p. The introduction by Cliver et al. (2012) of the CME- and SEP-associated X-ray flare distribution (group 2) renders the motivation for case (3) moot.

5. LIMITATION ON THE SCALING LAW BETWEEN TWO POWER LAWS

We now consider the validity of Equation (2) and the implication for determining the SEP-flare relationship from its use. Equation (2) has been widely cited (Hudson 1978; Crosby et al. 1993; Veronig et al. 2002; Belov et al. 2007) for scaling laws, but the only explicit derivation we find is that of Aschwanden (2011a). We show a full derivation here to point out an important restriction on the use of Equation (2). We take the distributions of p and x to be

$$\frac{dN}{dp} = Ap^{-\alpha_p} \tag{3}$$

and

$$\frac{dN}{dx} = Bx^{-\alpha_x} \tag{4}$$

and a scaling of the form $p = Cx^{\beta}$. Then since

$$dp = C\beta x^{\beta-1}dx, \tag{5}$$

we obtain

$$dN = A[Cx^{\beta}]^{-\alpha_p}dp \tag{6}$$

$$= AC^{-\alpha_p}x^{-\beta\alpha_p}C\beta x^{\beta-1}dx = Bx^{-\alpha_x}dx. \tag{7}$$

So

$$AC^{(1-\alpha_p)}\beta x^{\beta(1-\alpha_p)} = Bx^{(1-\alpha_x)}. \tag{8}$$

Equation (2) holds for all x of Equation (8) only if

$$\beta = BA^{-1}C^{(\alpha_p-1)}. \tag{9}$$

Even taking $C = 1$, β is still restricted to the value B/A, which we take as the normalizing coefficients in equating the matched number of p and x events

$$\int Ap^{-\alpha_p}dp = \int Bx^{-\alpha_x}dx \tag{10}$$

if one is doing a one-to-one comparison of sets of p and x events that a true scaling law requires. In general A/B will depend on the particular ranges of p and x of the related populations and hence will cause β in Equation (9) also to depend on that range. Our derivation differs from that of Aschwanden (2011a) in that he gives $dx/dp \propto p^{(1/\beta-1)}$ just before his Equation (7.1.41). The coefficient β cannot be neglected and invalidates the unfettered equality of the exponents of x in Equation (8). Therefore, the use of Equation (5) to claim an accordance with a scaling law is also invalid.

6. AN ALTERNATIVE EXPLANATION FOR FLATTER SEP POWER-LAW DISTRIBUTIONS

A comprehensive new model (Aschwanden 2012; Aschwanden & Freeland 2012), called the fractal-diffusive SOC model, offers explanations for the differences among solar-flare frequency distributions. It treats flares (and other phenomena) as avalanches in nonlinear dissipative systems and begins with four basic assumptions: (1) the avalanche grows spatially in a diffusive process, (2) the spatial volume of the dissipation process is fractal, (3) the fractal dimension is a function of the maximum dimension of Euclidean space, and (4) the probability of an avalanche size L scales as L^{-3}. These assumptions are discussed in detail in Aschwanden (2012) and Aschwanden & Freeland (2012). A critical parameter of the model is the spatial dimension S, i.e., one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D), in which the avalanches occur. Table 1 reproduces the parameters of interest from Table 1 of Aschwanden (2012).

Aschwanden (2012) applied his model to the solar-flare X-ray peak size distributions. In particular, he distinguished

Table 1
Predicted Fractal Dimension and Frequency Power-law Slopes α Predicted for SOC Cellular Automatons with Euclidean Space Dimensions $S = 1, 2, 3$

Parameter	Theory	$S = 1$	$S = 2$	$S = 3$
Fractal dimension	$D_S = (1 + S)/2$	1	3/2	2
Instantaneous energy dissipation rate slope	$\alpha_F = 1 + (S - 1)/D_S$	1	5/3	2
Peak energy dissipation rate slope	$\alpha_P = 2 - 1/S$	1	3/2	5/3

Note. Excerpted from Table 1 of Aschwanden (2012).

between the hard X-ray distributions for which $\alpha_{hx} = 1.71$–1.73 (Aschwanden 2011b) and the soft X-ray distributions for which $\alpha_{sx} = 1.98$ (± 0.11) (Aschwanden & Freeland 2012). His $S = 3$ (Table 1) model predictions of slopes of 1.67 and 2.00 agree closely with α_{hx} and α_{sx}, respectively. The primary difference is that the hard X-ray burst peak is due to the maximum fluctuation of the energy dissipation rate α_P during an erratically fluctuating time profile, while the soft X-ray flux peak is the maximum value of the dissipation rate slope α_F, smoothed by a convolution of the spiky energy dissipation rate with a cooling time (Table 1; Aschwanden & Freeland 2012).

How do we interpret the $\alpha_p = 1.2$–1.4 for SEP events (Belov et al. 2007)? In contrast to the 3D source regions of flares, SEPs are produced at 2D shock wave surfaces, requiring that $S = 2$ in the menu of slopes of Table 1. If we further consider an observer in a magnetic flux tube along which the shock is propagating and injecting particles, and that the particles remain confined to the flux tube, then perhaps the more appropriate description is the 1D or $S = 1$ spatial configuration of Table 1. The next question is whether the instantaneous energy dissipation rate, appropriate for the soft X-ray peak fluxes, or the peak energy dissipation rate, applied to hard X-ray peak fluxes, is appropriate for peak SEP intensities. We suggest that the continued acceleration of SEPs through multiple crossings of the shock front and interactions with the Alfvén wave field preceding the shock (Ng et al. 2012) are best described as an accumulation of bursts of energy and should be described with the instantaneous energy dissipation rate slope α_F, as Aschwanden (2012) treated the soft X-ray peak flux distribution. Table 1 then gives $\alpha_p = 5/3$ for $S = 2$ or 1.0 for $S = 1$.

We have to consider that in contrast to the X-ray observations that sample the entire solar flare volume, the SEP observations are made in situ and sample SEPs from only a small region of the spatial extent of the shock. This may explain why the slopes of well-connected SEP events are slightly but significantly flatter than those of all SEP events (Belov et al. 2007). A more careful comparison may be required, but the typical values of $\alpha_p = 1.2$–1.4 lie between these two extremes of α_F for $S = 1$ and $S = 2$, and they are less than the $S = 3$ value of 2 for the soft X-ray flare peaks. Thus, we believe that the basic reason for the flatter peak SEP slopes may well lie in the spatial dimensionality at the core of Aschwanden's (2012) fractal-diffusive SOC model.

We note that our SEP size distributions are confined to those of $E > 10$ MeV ions. An obvious next comparison to make would be that of the slopes of solar electron events, both relativistic and nonrelativistic. Cliver et al. (1991) found a slope of $\alpha_e = 1.30 \pm 0.07$ for $E > 3$ MeV electron events, steeper than their $\alpha_p = 1.13 \pm 0.04$ for 24–43 MeV proton events, but definitely flatter than that of solar flare X-ray peak slopes. The energetic electron events may arise from both flare processes and shocks (Kahler 2007) so a detailed treatment may be required to determine their sources based on the size distributions.

7. CONCLUSION AND DISCUSSION

We have reviewed the most recent observations of soft X-ray flare and SEP peak intensity size distributions and the question of whether the SEP events result from a scaling of the flare energy producing the soft X-ray flares. If the answer is yes (Hudson's 1978 case (3)), then the interplanetary SEP events can be considered as part of a system in which they are physically coupled with the X-ray flare, the energetic flare particles producing the X-ray and γ-ray event, and the CME (Lin 2011). If the answer is no (Hudson's 1978 case (1)), then we can regard the flare process producing coronal energetic particles and soft X-ray bursts as essentially separate, if not independent, of the process(es) producing the CME-driven shock and SEP event.

We have to be mindful of studies that show close spatial, temporal, and energetic relationships between CME properties and their associated impulsive (Berkebile-Stoiser et al. 2012) and thermal (Bein et al. 2012) flare characteristics. However, for the 61 events of the Figure 10 plot of Bein et al. (2012) there is considerable scatter between logs of CME V and logs of the *GOES* x, and the CC is only 0.32, comparable to the CCs found in other recent studies (Cliver et al. 2012, Miteva et al. 2013). Those CME-flare studies do not clarify the basic physics and energy partitions between the flares and the subset of those fast ($V > 900\,\mathrm{km\,s^{-1}}$) and wide ($W > 60°$) CMEs (Kahler & Reames 2003) required for SEP production. Factors other than the CME speeds or widths obviously play roles in the SEP production (Kahler et al. 2000).

We give four arguments against the SEP/flare scaling concept. The first is that a true scaling relationship between two parameters must involve a one-to-one correspondence between the two. It is not valid to consider that SEP events scale with only a small subset of solar X-ray flare events. Cliver et al. (2012) have redefined the original scaling question posed by Hudson (1978) to include only those X-ray flares associated with SEP events. Their view invokes the current paradigm of CMEs rather than flares as the sources of SEP events to explain why distribution slopes of SEP events and flares differ, but their analysis does not preclude a nonlinear causal relationship between those flares and the associated SEP events. However, as the Belov et al. (2007) study showed, the data of Figure 1 are also consistent with only a linear correlation between logs of SEPs and logs of flares, hence with case (1) of Hudson (1978).

Our second argument, a consequence of the first, is that the scaling exponent β of Equation (2) has an additional constraint due to the requirement that the numbers of x and p events of a compared sample must be equal. This precludes the idea that β directly follows from the values of α_p and α_x. The third is that direct comparisons of log p versus log x plots (e.g., Figure 1) yield a high degree of scatter. We offer no criteria to confirm or refute a scaling relationship, but the scattering of orders of magnitude in the plots seems inconsistent with a clear scaling. Further, the slopes of the log p versus log x plots are consistent with unity (Belov et al. 2007), again inconsistent with a scaling law. The fourth is that within the framework of a comprehensive fractal-diffusive SOC model (Aschwanden 2012) the flatter slope of the SEP events may be understood in terms of their inherent 1D or 2D shock-wave source geometry, which contrasts with that of the 3D geometry intrinsic to the flare process.

The similar size distributions of the SEP events and of the subset of X-ray flares associated with SEP events (group 2 of Cliver et al. 2012) renders Hudson's (1978) original comparison of α_p and α_x invalid because α_x was based on all observed flares. The explanation leads us away from the idea of a close physical connection of flares and SEP events. Our explanation of the SEP size distribution expected from the dimensional consideration of the SOC model also distinguishes the physics of SEP acceleration from that of flares.

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