ELEMENTARY ENERGY RELEASE EVENTS IN SOLAR FLARES

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ABSTRACT

Most theoretical investigations of particle acceleration during solar flares cannot be applied to observations for detailed study of the time evolution. We propose a phenomenological model for turbulence evolution and stochastic particle acceleration that links observations to the energy release and particle acceleration through two coefficients characterizing particle interactions with turbulent electromagnetic fields. In the linear regime the particle distribution does not affect the turbulence energy cascade. It is shown that electron acceleration critically depends on the intensity of small-scale turbulence and an impulsive nonthermal component only appears near the peak of the gradually evolving turbulence intensity. The model naturally reproduces the soft–hard–soft pattern of hard X-ray pulses, and we attribute the observed change in flux and spectral index correlation from the rise to decay phase of some pulses to changes in the background plasma. Detailed modeling of well observed individual events will probe the energy release processes.

Key words: Sun: flares – turbulence

1. INTRODUCTION

Given the short particle acceleration timescales inferred from observations of solar flares, it has been assumed that the acceleration processes are decoupled from other processes in most theoretical models (Miller et al. 1997; Aschwanden 2002; Petrosian & Liu 2004; Fletcher & Hudson 2008). As a result, theoretical investigations of particle acceleration are aimed at meeting some basic observational requirements, such as timescales, energetics, and numbers. There are significant ambiguities in quantitative tests of specific models with observations due to free parameters introduced to characterize the related, not-well-understood processes. On the other hand, particle acceleration is just one important aspect of the energy release processes, which are essentially multiscale as evident from the rich time, space, and energy characteristics of flares. Direct modeling of the energy release, which can be related to magnetohydrodynamical simulations of large-scale processes, may better our understanding of flares. In the context of stochastic particle acceleration (SA) by turbulent electromagnetic fields, we introduce the concept of elementary energy release events characterized with an energy release rate and length scale and discuss its implications.

The relation between the gradually varying thermal and bursty nonthermal emission component is a critical aspect of flare studies (Veronig et al. 2005). Previous modeling focused on the correlation between the light curve of nonthermal emission and derivative of the thermal emission light curve (Dennis & Zarro 1993). This correlation has been attributed to chromospheric evaporation driven by a beam of nonthermal electrons that is injected at the top of flaring coronal loops, propagates to the chromosphere along magnetic field lines, and collisionally heats the background plasma (Brown 1973). In this “classical” electron beam model, most of the nonthermal energy is reprocessed to appear as thermal energy producing the dominant thermal signatures (Neupert 1968; Antonucci et al. 1984). However, this model does not address the origin of impulsive nonthermal electrons, and has difficulties in accounting for impulsive soft X-ray emission observed from some footpoints and slower than expected decay of thermal emission after the nonthermal emission already disappears (Dennis & Zarro 1993; Hudson et al. 1994; Li et al. 1997; Jiang et al. 2006). By assuming a low-energy cutoff for a power-law or broken-power-law nonthermal distribution, observations give a very poor constraint on the energetics since the beam power is dominated by low-energy electrons due to steep power-law slopes, and there are uncertainties in observationally constraining this low cutoff energy due to the dominance of low-energy X-rays by a thermal component (Holman et al. 2003; Saint-Hilaire & Benz 2005). Such a cutoff is also not expected in most theoretical models hampering further investigations even for some well-observed flares (Veronig et al. 2005). With the elementary energy release events, we propose a simple alternative to this electron beam model. The model is based on two facts that (1) while low-energy particles couple strongly with each other through Coulomb collisions forming a thermal distribution, (2) high-energy particles must decouple from the thermal background and obtain their energy through interactions with electromagnetic fields (Hamilton & Petrosian 1992). The key issues are then the dynamics of the fields and their interactions with charged particles.

A significant amount of energy can be released during flares, and the flux of nonthermal particles inferred from observations in combination with the source size measurement sometimes implies a nonthermal particle density possibly comparable to that of the coronal background plasma (Fletcher & Hudson 2008), suggesting very efficient acceleration. A large fraction of the solar corona must be involved if the bulk of the energy and accelerated particles are stored in the pre-flare coronal magnetic fields, as postulated in most theoretical models (Grigis & Benz 2006). On the other hand, the strong coronal magnetic field implies tiny gyro-radii for charged particles. An energy cascade from large to small scales appears to be inevitable.

Turbulence is the most natural agent for energy cascade over a large dynamical range, and the corresponding SA models have been widely used for solar flare studies (Miller et al. 1997; Petrosian & Liu 2004). In these models a broad spectrum of particles is energized by interacting stochastically with a spectrum of electromagnetic fluctuations over a broad range of spatial and temporal scales. One of the key features of the SA is that wave–particle interactions determine not only the energy gain rate of particles but also their spatial diffusion along magnetic field
lines. Consequently, the particle acceleration is very sensitive to the turbulence intensity (Benz 1977; Petrosian & Liu 2004), which may explain the bursty behavior of nonthermal emissions. Detailed studies of nonthermal hard X-rays (HXRs) also reveal spectral soft–hard–soft (SHS) evolution of HXR pulses suggesting independent electron acceleration events (Grigis & Benz 2004; Battaglia & Benz 2006). We propose a phenomenological model for the evolution of turbulence associated with elementary energy release events and use two coefficients to characterize electron interactions with the turbulence (Section 2). The model can naturally fit HXR observations. With imaging spectroscopic observations of RHESSI, the model will allow us to extract the turbulence properties and its evolution for individual well observed flares, which constrain the wave–particle interactions and better our understanding of the relation between the thermal and nonthermal emission components (Section 3). Conclusions are drawn in Section 4. Notations for different quantities are listed in Table 1.

### Table 1

**Notations**

| Quantities | Symbol | Typical Value | Units |
|------------|--------|---------------|-------|
| Magnetic Field | $B$ | 100–500 | Gauss |
| Density | $n$ | $10^6$–$10^{10}$ | cm$^{-3}$ |
| Flaring Region Length | $l_0$ | $10^9$–$10^{10}$ | cm |
| Loop Cross Section | $A_0$ | $10^{15}$–$10^{16}$ | cm$^2$ |
| Temperature | $T$ | $10^6$–$10^7$ | K |
| Energy Release Scale | $l_e$ | $10^7$–$10^8$ | cm |
| Energy Release Level | $b_0$ | $< 1$ | 1 |

### Table 2

**Quantities Symbol Typical Value Units**

| $\Delta$ | $b$ | $\Delta$ |
|-----------|-----|---------|
| $b_0$ | $\langle \Delta \rangle$ | $b_0$ |

### Figure 1

Evolution of elementary energy release events. The time unit is $\tau_e/\Delta$ and $\tau_0/\Delta^2$ for the rise and decay phase, respectively. The upper: thick and thin lines are for $b_0 = \Delta$ and $\Delta/2^{1/2}$, respectively. The latter lines are shifted to the right by $\tau_0/\Delta^2$ so that the decay phase overlaps with the former. $N$ is for $E_0 = 10^4 \Delta T$ and normalized to the peak value for $b_0 = \Delta$. Lower: the dotted line is for $N \Sigma$. The solid line and normalizations of $N$ and $\Sigma$ are the same as the upper panel. The dashed lines are the same as the thick-dashed line in the upper panel except that from high to low the corresponding electron temperatures are $0.1$, $5$, and $10$ times lower, respectively.

The particle acceleration from the background plasma is determined by small-scale turbulence characterized by the amplitude of the corresponding magnetic field fluctuations $b B$. The growth of $b$ is driven by large-scale eddies with growth rate $\tau_e^{-1} = v_e/\ell_e = b_0/\tau_0$, where $\tau_0 = \ell_e/\nu_0$ is the transit time of Alfvén waves through $\ell_e$. The turbulence starts to decay once $b$ reaches $b_0$, and we adopt the Kraichnan phenomenology with the decay time given by $\tau_d = \tau_e/\nu_e = \tau_0/\nu_0$, where the eddy speed $v_e = b_0 \nu_0$ and the eddy turnover time $\tau_e = \ell_e/\nu_e$ (Kraichnan 1965). Then we have

$$
\frac{b}{b_0} = \begin{cases} 
\exp(t/\tau_r) & \text{for the turbulence rise phase}, \\
(1 + 2t b_0^2/\tau_0)^{-1/2} & \text{for the turbulence decay phase}.
\end{cases}
$$

This is the proposed basic equation for the turbulence evolution. Considering the variety of flare triggers (Aschwandt 2002), the turbulence evolution can be much more complicated. These equations can be modified wherever there are sufficient observational or theoretical Justifications.

We consider the solution, where $b = b_0$ at $t = 0$:

$$
b(t) = \begin{cases} 
\exp(t/\tau_r) & \text{for } t \leq 0 \text{ the turbulence rise phase}, \\
(1 + 2t b_0^2/\tau_0)^{-1/2} & \text{for } t > 0 \text{ the turbulence decay phase}.
\end{cases}
$$

The solid lines in Figure 1 show the time evolution of $b/\Delta$ for $b_0 = \Delta$ (thick) and $\Delta/2^{1/2}$ (thin), where $\Delta \ll 1$ is an upper limit for $b_0$, below which the turbulence evolution is not significantly affected by nonthermal particles (see discussions near the end of this section). The corresponding total amount of energy per unit volume dissipated through small-scale turbulence is given by

$$
\Sigma(t) = 2 \rho b_0^2 \int_0^t \langle \Delta \rangle^2 v_e^{-1} dt'
$$

$$
= \rho v_0^2 b_0^2 \begin{cases} 
(b_0/2) \exp(4t/\tau_r) & \text{for } t \leq 0, \\
b_0^2/2 + 1 - (1 + 2t b_0^2/\tau_0)^{-1} & \text{for } t > 0.
\end{cases}
$$

2. ELEMENTARY ENERGY RELEASE EVENTS AND STOCHASTIC PARTICLE ACCELERATION

Most SA models treat turbulence as an input and do not consider its dynamical evolution (Benz 1977; Miller et al. 1997; Petrosian & Liu 2004; Grigis & Benz 2006). Although Bykov & Fleishman (2009) modeled the turbulence, their particle acceleration is sensitive to an injection process, which is treated as an input independent of the turbulence evolution. Observations of solar flares, on the other hand, indicate that the large-scale energy release and particle acceleration are intimately connected. We aim at realizing such a connection with a phenomenological SA model so that the model can be applied to individual events for detailed studies.

We consider elementary energy release events, where large-scale eddies are assumed to be generated instantaneously upon the event trigger, which can correspond to a simple flare, or one HXR pulse within a large complex flare. These eddies are characterized by a generation scale $\ell_e$, and speed $v_0 = b_0 \nu_0$. The particle acceleration from the background plasma is determined by small-scale turbulence characterized by the amplitude of the corresponding magnetic field fluctuations $b B$. The growth of $b$ is driven by large-scale eddies with growth rate $\tau_e^{-1} = v_e/\ell_e = b_0/\tau_0$, where $\tau_0 = \ell_e/\nu_0$ is the transit time of Alfvén waves through $\ell_e$. The turbulence starts to decay once $b$ reaches $b_0$, and we adopt the Kraichnan phenomenology with the decay time given by $\tau_d = \tau_e/\nu_e = \tau_0/\nu_0$, where the eddy speed $v_e = b_0 \nu_0$ and the eddy turnover time $\tau_e = \ell_e/\nu_e$ (Kraichnan 1965). Then we have

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\frac{b}{b_0} = \begin{cases} 
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(1 + 2t b_0^2/\tau_0)^{-1/2} & \text{for the turbulence decay phase}.
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$$

This is the proposed basic equation for the turbulence evolution. Considering the variety of flare triggers (Aschwendt 2002), the turbulence evolution can be much more complicated. These equations can be modified wherever there are sufficient observational or theoretical Justifications.

We consider the solution, where $b = b_0$ at $t = 0$:

$$
b(t) = \begin{cases} 
\exp(t/\tau_r) & \text{for } t \leq 0 \text{ the turbulence rise phase}, \\
(1 + 2t b_0^2/\tau_0)^{-1/2} & \text{for } t > 0 \text{ the turbulence decay phase}.
\end{cases}
$$

The solid lines in Figure 1 show the time evolution of $b/\Delta$ for $b_0 = \Delta$ (thick) and $\Delta/2^{1/2}$ (thin), where $\Delta \ll 1$ is an upper limit for $b_0$, below which the turbulence evolution is not significantly affected by nonthermal particles (see discussions near the end of this section). The corresponding total amount of energy per unit volume dissipated through small-scale turbulence is given by

$$
\Sigma(t) = 2 \rho b_0^2 \int_0^t \langle \Delta \rangle^2 v_e^{-1} dt'
$$

$$
= \rho v_0^2 b_0^2 \begin{cases} 
(b_0/2) \exp(4t/\tau_r) & \text{for } t \leq 0, \\
b_0^2/2 + 1 - (1 + 2t b_0^2/\tau_0)^{-1} & \text{for } t > 0.
\end{cases}
$$
where $\rho$ is the mass density. It is indicated by the dot-dashed lines in the figure. The total energy dissipated through turbulence is $(b_0/2 + 1)\rho v^2 b_0^2$ with the first and second term resulted from the rise and decay phase, respectively. Less than $1/3$ of the total released energy is dissipated in the turbulence rise phase. Most of the energy is dissipated in the much longer decay phase. The rise of $\Sigma(t)$ approximately represents the rise of thermal emission.

We characterize the decoupling and acceleration of individual particles from the thermal background by small-scale turbulence with an acceleration timescale (Miller et al. 1997; Petrosian & Liu 2004)

$$\tau_{ac} = S_a \tau b^{-2},$$

where $S_a$ is a dimensionless coefficient describing the acceleration by waves. The energy loss time $\tau(E)$ of high-energy particles through Coulomb collisions with a low-temperature background is proportional to $E^{3/2}/n$, where $E \gg k_B T$ is the particle kinetic energy, $n$ and $T$ are the background particle density and temperature, and $k_B$ is the Boltzmann constant. The particle distribution is nonthermal at energies, where $\tau_{ac}(E) < \tau(E)$. The transition from the nonrelativistic thermal to nonthermal component occurs at

$$E_t = 2\pi ln\Delta \xi^2 \tau_{ac} / \pi^{1/2}/m^{1/2}/3,$$

where $n, m$ are the particle charge and mass, respectively, and $ln\Delta \xi \simeq 20$ for plasmas in the solar corona, i.e., $\tau_{ac}(E_t) = \tau(E_t)$ (Petrosian & Liu 2004).

The most natural way to produce a power-law high-energy particle distribution with an adjustable spectral index is in terms of a particle loss process, as proposed originally by Fermi (1949) for cosmic rays. For solar flares, this particle loss is due to escape from the energy release site through spatial diffusion. We use the scattering time

$$\tau_{sc} = l_s^2 / v^2 \tau_{sc}$$

where $l_s > l_c$ is the length of the energy release site. The electron acceleration timescale is much shorter than the flare duration. One may consider the steady-state solution. To have a power-law distribution as commonly adopted to model the observed nonthermal emissions, $\tau_{ac}$ and $\tau_{sc}$ need to have the same energy dependence, i.e., $\tau_{ac} \propto 1/v^2$, $\tau_{ac}$ and $\tau_{sc}$ may have different energy dependence (Petrosian & Liu 2004). For simplicity, we assume that their energy dependence is the same. For nonrelativistic particles, as considered in the paper, $1/v \propto E^{1/2}$, therefore $\tau_{ac} \propto E^{-1/2}$, and both $S_a$ and $S_s$ are independent of $v$.

In the high-energy range, where $\tau_{ac} \ll \tau_l$, the kinetic equation for nonthermal particle distribution $f(p)$ is given by

$$\frac{df}{dt} = \frac{1}{p^2} \frac{\partial}{\partial p} p^d \tau_{ac} \frac{\partial}{\partial p} f - \frac{f}{\tau_{ac}} + Q,$$

where $p$ is the particle momentum, and $Q$, a source term, exists at low energies. In the steady state,

$$f(p) \propto p^{-2-4}\tau_{ac}/\tau_{esc}^{1/2}. \tag{9}$$

The corresponding energy distribution $N(E) \propto E^{-1/2-1+\tau_{ac}/4\tau_{esc}^{1/2}}$, and the flux of escaping particles $F(E) \propto N(E)/\tau_{esc} \propto E^{-1+\tau_{ac}/4\tau_{esc}^{1/2}}$. For the convergence of energy flux carried away by nonthermal particles, the index of $F(E)$ must be greater than 2, i.e.,

$$\tau_{ac} > 12\tau_{esc}, \quad b^4 < S_a S_s (l_s/l_c)^2/12 \equiv \Delta^4. \tag{10}$$

For $b \geq \Delta$, one must consider the relativistic effect and/or the effect of nonthermal particles on the turbulence cascade and damping (Bykov & Fleishman 2009). We consider the linear regime, where nonthermal particles do not affect the turbulence cascade. $\Delta$ is an upper limit for the linear model to be valid.

### 3. APPLICATION TO SOLAR FLARES

Electron acceleration during flares is better observationally constrained than that for ions. We next apply the model to electron acceleration in flaring loops with ions treated as a background of positive charges, which only changes through large-scale hydrodynamic processes. Then the length of the energy release site $l_0$ has a lower limit of the size of coronal looptop sources (Xu et al. 2008) and an upper limit of the length of flaring loops (Liu et al. 2006). Although high-energy electrons must escape from the acceleration site to produce a power-law distribution with the above SA model, the effect of nonthermal particles on the acceleration site requires that the total number of electrons remains the same as positive charges at $N_0 = l_0 e B_0$ (e.g., due to a return current), which gives the normalization for the electron distribution at the acceleration site $N(E)$. One of the key purposes of the paper is to introduce a simple phenomenological model to extract the energy release rate through turbulence from observations. Instead of solving the full kinetic equation for the electron distribution over the whole energy range, i.e., from the Coulomb collision dominated low energies to collisionless high energies (Petrosian & Liu 2004; Galloway et al. 2005), we assume that the electron distribution is thermal below $E_c$ a power law above it, and continuous at $E = E_c$. Then $N(E) = N_0 g(E)$, where $g(E)$ is the normalized distribution function, i.e., $\int g(E) dE = 1$ and

$$g(E) \equiv g_0 (E_i/k_B T, \delta) \begin{cases} E^{1/2} \exp(-E/k_B T) & \text{for } E < E_i, \\ E^{1/2} \exp(-E/k_B T)/(E/E_i)^{\delta} & \text{for } E \geq E_i, \end{cases}$$

where

$$\delta = 1/2 + (1 + \tau_{ac}/4\tau_{esc})^{1/2}, \tag{12}$$

and $\text{erf}$ is the error function. $E_i = (2\pi \ln \Delta \xi l_0 / n)^{1/2} e^{2b} / v_{\text{esc}}^2$, and $\delta = 1/2 + (1 + 3\Delta^4/b^4)^{1/2} r = E_i/k_B T \equiv R(\Delta/b)$ with $R = (2\pi \ln \Delta \xi l_0 / n)^{1/2} e^{2b} / k_B T \Delta$.}

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1. Other assumptions of the energy dependence of $\tau_{ac}$ and $\tau_{sc}$ will lead to different energy dependence of $\tau_{esc}$, which determines the flux of escaping particles and can be constrained by observations (Battaglia & Benz 2006). For example, with the standard quasi-linear theory, $\tau_{ac}/\tau_{sc} \propto (v/v_{\text{esc}})^2$. It can be shown that $\tau_{esc}$ is independent of $E$ and $S_s \propto 1/S_a \propto v$.

2. This is an assumption. Ion acceleration can be considered in appropriate theoretical and/or observational contexts.
The peak density of nonthermal electrons is smaller by more than one order of magnitude. The decrease of the peak density of nonthermal electrons is smaller by more than one order of magnitude. The decrease of the peak density of nonthermal electrons is smaller by more than one order of magnitude. The decrease of the peak density of nonthermal electrons is smaller by more than one order of magnitude.

\[ \delta = \frac{N}{\Sigma} \]

\[ N \] is described with four parameters: \( N_0, T, E_0 \), and \( \delta \). For a given energy release event discussed in Section 2 with \( b_0 \) given in units of \( \Delta \), the evolution of \( \delta \) is determined as indicated by the dotted lines in Figure 1. For \( b_0 = \Delta, \delta \) reaches 5/2 at the peak of \( b, N_0 \) and \( T \) can be measured observationally and vary gradually as \( \Sigma \) on a timescale much longer than \( \tau_{\text{arc}} \). We assume that they do not change during these events. For \( E_i = k_B T \) at \( b = \Delta \) (the fiducial model), the evolution of \( N \) at \( E_0 = 10k_B T \) (normalized to the peak value) is indicated by the dashed line. Because \( \delta \) has a strong dependence on \( b \), the nonthermal electron density at high energies is very sensitive to \( b \). A prominent peak of nonthermal electron numbers only appears near the peak of \( b \). The thin lines show another event with about two times lower released energy. As expected, the electron distribution becomes softer than the previous model with a minimum of \( \delta \) at 1/2 + 13^{1/2} \simeq 4.1.

The peak density of nonthermal electrons is smaller by more than one order of magnitude. The decrease of the peak density is more prominent at even higher energies due to the softer spectrum. Therefore strong and hard nonthermal emissions are expected only for strong events with \( b_0 \) close to \( \Delta \), and even with a relatively gradual evolution of the turbulence intensity, an impulsive nonthermal component appears at the peak of the energy dissipation. This may explain the bursty nature of the nonthermal component as compared with the thermal component. The dependence of \( N(E_0) \) on \( T \) is shown in the lower panel. There are fewer nonthermal electrons for longer \( T \). The evolution of \( T \) and \( N_0 \) will affect the quantitative details but not the impulsive nature of the nonthermal density, which is mostly determined by \( \delta(t) \).

One of the most important observations of nonthermal emission is the spectral SRS evolution of HXR pulses, which Grigis & Benz (2004, 2006) attributed to elementary electron acceleration events. The spectral index and nonthermal electron density evolution of our model naturally reproduces such a pattern. The thick solid line in Figure 2 shows the correlation between \( \delta \) and \( N(E_0) \) of the fiducial model. The correlation at a given energy is the same for the rise and decay phase in agreement with observations of some HXR pulses. For most pulses, this correlation changes from the rise to decay phase (Grigis & Benz 2004). This can be caused by chromospheric evaporation and/or plasma heating due to the energy release \( \Sigma \), which changes the density and temperature of the background plasma. The dashed lines show how the correlation changes with \( T \) and the dotted line shows the correlation between \( \delta \) and \( N \Sigma \). The chromospheric evaporation processes must be modeled properly to study this correlation.

4. CONCLUSIONS

Yohkoh and RHESSI observations of solar flares have revealed several phenomena challenging the classical electron beam model: impulsive soft X-ray emission from footpoint sources (Hudson et al. 1994; Hannah et al. 2008), continuous heating of the coronal source after the impulsive HXR phase (Li et al. 1997; Jiang et al. 2006), and more recently injection of electrons over a large coronal looptop region (Xu et al. 2008). All these point to the SA model, where electrons are accelerated by magnetized turbulence in flaring loops (Petrosian & Liu 2004). The acceleration site can be as compact as the observed coronal looptop sources and may also extend over the whole loops if the turbulence is transported along the loops quickly, e.g., in the form of plasma waves (Fletcher & Hudson 2008). The latter may explain impulsive soft X-ray emission from footpoints as electrons are injected at the footpoints directly. In this paper, we propose a simple phenomenological SA model and show that the nonthermal electron density in the acceleration site is very sensitive to the turbulence intensity. It therefore provides a mechanism to produce impulsive emissions even with a relatively gradual energy release process, which may account for the continuous heating inferred from thermal source evolution after the impulsive phase. With a simple model for the turbulence evolution, it also reproduces spectral SRS evolution of HXR pulses. Detailed modeling of the plasma heating and chromospheric evaporation is needed to quantify the flux and spectral index correlation.

Solar flares are multiscale phenomena in terms of not only the size and duration but also the amount of energy released by each flare. The physical processes involved in the large-scale energy release process can be scale dependent, which, in combination with the variety of initial and boundary conditions in the solar atmosphere, is expected to lead to very rich appearance (Aschwanden 2002). However, the microscopic scale processes of plasma heating and particle acceleration should be mostly determined by properties of the background plasma in terms of temperature, density, and large-scale magnetic field. Besides Coulomb collisions among these particles, particle interactions with the electromagnetic field fluctuations during the energy release process may be parameterized with an acceleration and scattering coefficient. We show that these two coefficients, in combination with the turbulence intensity and generation scale, should be used to determine the electron distribution in flaring loops and applied to individual flares. The model may not only overcome the observational challenges to the classical electron beam model but also address the intriguing problem of the low-energy cutoff. The two coefficients should not vary significantly. The turbulence intensity and release scale \( l_r \) are determined by the macroscopic processes of flare triggers. Detailed analyses of flare X-ray emissions will lead to quantitative constraints on the wave–particle interactions and turbulence evolution and may also help to understand the related large-scale processes.

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