THE EFFECT OF WAVE–PARTICLE INTERACTIONS ON LOW-ENERGY CUTOFFS IN SOLAR FLARE ELECTRON SPECTRA

I. G. HANNAH1, E. P. KONTAR1, AND O. K. SIRENKO2
1 Department of Physics and Astronomy, University of Glasgow, G12 8QQ, UK
2 Main Astronomical Observatory, Ukrainian Academy of Sciences, Ukraine

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ABSTRACT

Solar flare hard X-ray (HXR) spectra from Reuven Ramaty High Energy Solar Spectrometer (RHESSI) are normally interpreted in terms of purely collisional electron beam propagation, ignoring spatial evolution and collective effects. In this Letter, we present self-consistent numerical simulations of the spatial and temporal evolution of an electron beam subject to collisional transport and beam-driven Langmuir wave turbulence. These wave–particle interactions represent the background plasma’s response to the electron beam propagating from the corona to chromosphere and occur on a far faster timescale than Coulomb collisions. From these simulations, we derive the mean electron flux spectrum, comparable to such spectra recovered from high-resolution HXRs observations of solar flares with RHESSI. We find that a negative spectral index (i.e., a spectrum that increases with energy), or local minima when including the expected thermal spectral component at low energies, occurs in the standard thick-target model, when Coulomb collisions are only considered. The inclusion of wave–particle interactions does not produce a local minimum, maintaining a positive spectral index. These simulations are a step toward a more complete treatment of electron transport in solar flares and suggest that a flat spectrum (spectral index of 0–1) down to thermal energies maybe a better approximation instead of a sharp cutoff in the injected electron spectrum.

Key words: Sun: activity – Sun: flares – Sun: particle emission – Sun: X-rays, gamma rays

Online-only material: animation

1. INTRODUCTION

Hard X-ray (HXR) emission has long been used as the prime diagnostic tool to study particle acceleration and energy release in solar flares. From these X-ray observations, the mean electron flux spectrum (e.g., averaged over the X-ray emitting volume; see Brown et al. 2003 for details) can be determined either through forward fitting (Holman et al. 2003) or more advanced inversion techniques (Piana et al. 2003; Kontar et al. 2004; Brown et al. 2006). At higher energies, typically above 10–20 keV, the observed HXR spectrum is considered to be due to an accelerated population of electrons being stopped by the dense chromosphere via Coulomb collisions (Brown 1971). The spectrum below 10–20 keV normally originates from thermal coronal sources with temperatures of tens MK (e.g., Krucker & Lin 2008).

The Reuven Ramaty High Energy Solar Spectrometer (RHESSI) provides high-resolution HXR spectra of solar flares (Lin et al. 2002), greatly improving on previous measurements (Johns & Lin 1992). This high energy resolution spectra has allowed, for the first time, scrutinization of the X-ray and electron spectra in search of non-power-law features, revealing vital clues about electron acceleration and transport. In some RHESSI flares, the recovered mean electron flux spectrum demonstrates a local minima or dip between the non-thermal and the thermal components instead of a smooth transition (Piana et al. 2003; Holman et al. 2003; Kašparová et al. 2005; Sui et al. 2007; Kontar et al. 2008a). The presence of the dip, as a real physical feature of the electron spectra, has been questioned as in many cases it can be attributed to photospheric albedo, e.g., Compton backscattered X-rays (Kašparová et al. 2005; Kontar et al. 2008a). However, a few events have been found in which after isotropic albedo correction (Kontar et al. 2008a), the X-ray spectrum is still relatively flat, so they could be fitted with a thick-target model single power-law spectrum with a low-energy cutoff (Sui et al. 2007). In these flares, a dip was not directly observed in the mean electron spectrum, but instead inferred from forward fitting a model with low-energy cutoff to the X-ray spectrum. This model has a thermal component at low energies and at higher energies a purely collisional thick-target model of a single power law of accelerated electrons above a cutoff. In this thick-target scenario (Brown 1971; Holman 2003), the dip in the mean electron spectrum originates from a positive slope at low energies developing below the cutoff as the accelerated electrons propagate from a coronal acceleration site downward to the chromosphere, having Coulomb collisions with the background plasma. If the dip is real, it provides important insights into flare energetics since the energy in accelerated electrons is strongly dependent on the low-energy cutoff.

For any reasonable X-ray producing flare, non-collisional beam–plasma interaction is much faster than that via Coulomb collisions (Zheleznyakov & Zaitsev 1970; Karlický 2009). Such processes are inferred to occur in downward propagating electron beams from radio observations of reverse slope drift burst in flares (e.g., Klein et al. 1997; Aschwanden & Benz 1997). Although generation and escape of electromagnetic radiation from Langmuir waves in a flaring plasma is not well understood. The role of wave–particle interactions in solar flares assuming stationary, time-independent injection of electrons has been considered analytically and numerically (Emslie & Smith 1984; Hamilton & Petrosian 1987; McClements 1987). Emslie & Smith (1984) have argued that the conditionally created distribution should be constantly being flattened by quasi-linear relaxation, while Hamilton & Petrosian (1987) and McClements (1987) suggest that although the wave–particle interactions have an important effect, the change of the electron spectra under stationary conditions should be minor. However, observations show that a more realistic injection (acceleration) of electrons...
in a flare is likely to be highly intermittent (Tsiklauri & Haruki 2008) with a number of short duration pulses (Kiplinger et al. 1984; Fleishman et al. 1994; Aschwanden et al. 1998), so the time-dependent solution of particle transport equations accounting for wave–particle interactions should be considered. Additionally, previous studies did not consider the spatial and temporal evolution of the beam from the coronal source down into the chromosphere—a crucial aspect when considering the propagation of an electron beam in comparison to X-ray observations.

The quasi-linear relaxation process of Langmuir waves has been considered in higher velocity dimensions (other than the parallel component considered here) (e.g., Churaev & Agapov 1980) but it has only been recently that the two-dimensional system has been fully numerically solved (Ziebell et al. 2008). Even then the evolution was considered in a spatially independent manner. In these studies, it was found that the parallel component (one-dimensional) is the fastest process and likely to dominate the electron transport.

In this Letter, we take a step toward a more complete treatment of electron transport in solar flares by including the spatial evolution of beam-driven Langmuir wave turbulence. We numerically study the system self-consistently, simulating the propagation of an electron beam from the coronal acceleration site down to the chromosphere, considering the truncated power-law spectrum frequently used for data interpretation (e.g., Holman 2003; Sui et al. 2007), to investigate the evolution of the mean electron flux spectrum below this cutoff. We demonstrate that the positive slope of the mean electron flux is not present, when the response of the background plasma via Langmuir waves to the propagating electron beam is taken into account. We also show that the injected electron spectrum flattens to a decreasing distribution due to collective interaction with plasma even for weak flares (e.g., Hannah et al. 2008a). Furthermore, we suggest that a flat spectrum (with spectral index 0–1) down to thermal energies maybe a better approximation as opposed to the sharp cutoff in the injected electron spectrum.

2. PARTICLE TRANSPORT AND WAVE–PARTICLE INTERACTION

Following the standard model approach for interpreting solar flare HXR spectra, we assume the electron flux spectrum of injected (flare accelerated) electrons is a power law, $F(E) \sim E^{-\delta}$, (electrons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) down to some energy $E_C$, typically 10–20 keV. The initial one-dimensional electron distribution function (accelerated electron population) subsequently is also a power law in velocity $f(v) = F(E)/m$, above a low-energy cutoff $v_C$ with spectral index $\alpha = 2\delta$. For our simulations, we consider such an initial electron distribution which is also spatially a Gaussian of characteristic size $d$

$$f(v, x, t = 0) = n_0 \left( \frac{v}{v_C} \right)^{-\alpha} \exp \left( -\frac{x^2}{d^2} \right) \quad (1)$$

normalized by the beam density $n_0$.

To self-consistently follow the temporal and spatial evolution of an electron beam from a coronal acceleration site, including the response of the thermal background plasma in the form of Langmuir waves, we use the one-dimensional equations of quasi-linear relaxation (Vedenov & Velikhov 1963; Drummond & Pines 1964; Ryutov 1969; Hamilton & Petsiassian 1987; Kontar 2001a)

$$\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial x} = 4\pi^2 e^2 \frac{\partial}{\partial v} \left( \frac{W f}{v^2} \right) + \gamma_C \frac{\partial}{\partial v} \left( \frac{f}{v^2} \right) \quad (2)$$

$$\frac{\partial W}{\partial t} + \frac{3v^2}{v} \frac{\partial W}{\partial x} = \left( \frac{\pi n_e}{\alpha} v^2 - \gamma_C \omega_p \right) W + S f \quad (3)$$

where $f(v, x, t)$ is the electron distribution function (electrons cm$^{-3}$s$^{-1}$), $W(v, x, t)$ is the spectral energy density (erg cm$^{-2}$), $k$ is the wavenumber of a Langmuir wave, $n$ is the background plasma density, and $\omega_p^2 = 4\pi n_e e^2/m$ is the local plasma frequency. The first components on the right-hand sides of Equations (2) and (3) are the quasi-linear terms that describe the resonant interaction between the electrons and Langmuir waves, $\omega_p = kv$. Also included are the Coulomb collision damping rate for both the electrons $\gamma_C = 4\pi e^4 n \Lambda/m^2 e^2$ (Emslie 1978) and waves $\gamma_{\omega_p} = \pi e^3 n \ln \Lambda/(m^2 v^2)$ (Melrose 1980). Where $\ln \Lambda = \ln (8 \times 10^n n^{-1/2} T)$ is the Coulomb logarithm, $T$ is the temperature of the background plasma, and $v_T = \sqrt{k_B T}/m$ is the velocity of a thermal electron, $k_B$ is the Boltzmann constant. Also included in Equation (3) is the Landau damping rate $\gamma_L = \sqrt{\pi/8} \omega_p (v/v_T)^3 \exp(-v^2/2v_T^2)$ (Lifshitz & Pitaevskii 1981) and the spontaneous emission $S = \omega_p^3 n v^2 \ln(v/v_T)/(4\pi n)$ (Melrose 1980; Tsytovich & Terhaar 1995; Hamilton & Petsiassian 1987).

In the simulations, we take $\alpha = 7$, or $\delta = 3.5$ from a cutoff of $v_C = 7.26 \times 10^6$ cm s$^{-1}$, or $E_C = 15$ keV, up to maximum of $v_0 = 2.4 \times 10^{10}$ cm s$^{-1}$. Our simulation extends in velocity space from $v = 7v_T = 2.73 \times 10^9$ cm s$^{-1}$ (taking $T = 1$ MK) to $v = 2.5 \times 10^{10}$ cm s$^{-1}$. The initial spatial scale of the beam is $d = 2 \times 10^8$ cm with density of $n_0 = 10^6$ cm$^{-3}$. The initial number of electrons in this simulation is $N \approx 23n_0 d^3 = 10^{32}$ electrons, which is an approximation as we only have one spatial dimension to estimate the volume from, taking this as the FWHM = $2\sqrt{2}\ln 2d$, which is typically measured as X-ray imaging observations (e.g., Hurford et al. 2002; Kontar et al. 2008b). Here, we have used a modest number of electrons, similar to that found in a small flare, or microflare (Hannah et al. 2008a, 2008b), a typical A- or B-class GOES flare. Since the rate of wave–particle interactions is proportional to electron beam density, the effects of wave–particle interaction will be present to a far greater extent in larger flares.

We approximate the background plasma density $n$ assuming a constant of $10^{10}$ cm$^{-3}$ at coronal heights, with a sharp density increase at the chromosphere level, with further steady hydrostatic increase toward the photosphere (Aschwanden et al. 2002), see Figure 1. The initial electron beam is spatially centered at $h_0 = 4 \times 10^6$ cm (see Figures 2 and 4 for details).

Equations (2) and (3) are solved numerically using a finite difference method as described by Kontar (2001b). This is over a grid of 60 points in velocity space and 160 in position space. The fastest process here is the quasi-linear relaxation, occurring on a timescale of $\tau_Q \approx n_0 / \omega_p \approx 2 \times 10^{-3} \sqrt{n_0}$ s. Therefore, we numerically solve Equations (2) and (3) using a time step at least an order of magnitude smaller. The initial spectral energy density is taken to be the thermal background which has reached a steady state through Coulomb collisions and wave–particle emission/absorption. These simulations are run for 1 s in simulation time, enough time for all of the electrons to reach the highest density region, lose energy and then leave the simulation grid, joining the thermal electrons.
These densities.

Also shown is the corresponding plasma frequency for each of the beam subject to Coulomb collisions, i.e., the standard thick-target model (Brown 1971). (An animation of this figure is available in the online journal.)

Figure 2. Evolution of the electron distribution

2.1. Beam Coulomb Collisions

We start by simulating the propagation of the electron beam in the absence of waves, with only Coulomb collisions acting on the electrons, following the standard thick-target model (Brown 1971). So we are only solving Equation (2) and ignoring the wave–particle interactions, the first term on the right-hand side. The resulting electron distribution $f(v, x)$ for various times during the simulation is shown in Figure 2. The electrons with the highest velocities move quickly to lower heights where they encounter the sharply increasing background plasma density (chromosphere) below about 3 Mm. Here, the Coulomb collisions quickly cause the electrons to lose energy and eventually have velocities outside of the simulation grid. At lower energies, the sharp initial low-energy cutoff is smoothed out through Coulomb collisions reducing the electrons velocity. The time-averaged mean electron flux spectrum of purely collisional transport is shown in Figure 3. This spatially integrated mean electron flux spectrum $⟨nV F⟩$ or $πVF$ is related to the simulated electron distribution $f(v, x, t)$ as $πVF(E, t) = A ∫ [n(x)f(v, x, t)]dx$ where $A$ is the cross-sectional area of the beam. We take this to be FWHM$^2 = 5.5d^2$ given our one-dimensional simulation. The positive slope at low energies is clearly visible with the expected decreasing power law above roughly the original low-energy cutoff (Figure 3, left). Overplotted is an example model thermal X-ray spectrum.

Figure 4 as a function of $v$ and $x$ for various times during the simulation. The electron distribution function $f(v, x, t)$ quickly flattens to form a plateau-like distribution expected for beam–plasma interaction via plasma waves (e.g., Zheleznyakov & Zaitsev 1970). The electrons together with the waves move down and eventually end up in the dense regions of the atmosphere, where the transport becomes dominated by collisions.

The motion of the plasma turbulence (Figure 4) is not due to the group motion of waves, which is negligibly small $∂ω/∂k = 3v^2_e/v ≪ v$, but appears because the Langmuir waves are locally generated and efficiently reabsorbed by the beam itself or collisionally by the surrounding plasma. The wave–particle interactions clearly change the overall shape of spatially integrated electron flux spectrum, as shown in the right panel of Figure 3. Crucially, no positive slope is created in the non-thermal spectrum below the initial low-energy cutoff, resulting in no dip in the overall model spectrum. This can be further seen when we consider the spectral index $δ$ of the mean electron flux spectrum as a function of energy in Figure 5. Where as the beam only simulation produces a brief energy range where $δ < 0$, it is always positive in the beam and wave case. The slightly reduced level of the mean electron flux

2.2. Beam-driven Langmuir Waves

We now follow the beam propagating with Langmuir waves generated by the background plasma in response to the beam, numerically solving both Equations (2) and (3). The resulting electron and spectral wave density distributions are shown in Figure 4 as a function of $v$ and $x$ for various times during the simulation. The electron distribution function $f(v, x, t)$ quickly flattens to form a plateau-like distribution expected for beam–plasma interaction via plasma waves (e.g., Zheleznyakov & Zaitsev 1970). The electrons together with the waves move down and eventually end up in the dense regions of the atmosphere, where the transport becomes dominated by collisions.

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Figure 2. Evolution of the electron distribution $f(v, x, t)$ (with time increasing from left to right) for the simulation only following the progression of an electron beam subject to Coulomb collisions, i.e., the standard thick-target model (Brown 1971).

(An animation of this figure is available in the online journal.)
3. DISCUSSION AND CONCLUSIONS

Considering both the temporal and spatial evolution, the mean electron flux spectrum is very sensitive to the generation of Langmuir waves. The spectrum also suggests that the generation of Langmuir waves leads to additional energy losses by the beam (into heating the background plasma) and higher number of energetic electrons will be required to explain the same X-ray spectra.
waves. The influence of wave–particle interactions is seen to flatten the spectral index of the electron spectrum \( \delta(E) \approx 0 \). Our simulations show that the spectral index, \( \delta(E) \) is more than zero, which is the result of collisions. Similarly, Kontar & Reid (2009) show that the spatially integrated spectrum of particles will not deviate from an initial power law, but only when processes leading to absorption of waves or removal of waves out of resonance are included.

The simulations in this Letter are for typical microflare parameters (Hannah et al. 2008a) and given that the wave emission scales with the electron number density we would expect wave–particle interactions to have a more significant effect in large flares. Large flares could constitute multiple intermittent bursts of accelerated electrons directed along possibly different magnetic field lines. The fast time variations in XHR light curves (Kiplinger et al. 1984) indirectly support this idea. Numerical simulations of reconnection suggest “bursty” electron acceleration (Tsiklauri & Haruki 2008) and spatially fragmented electron acceleration (Bian & Browning 2008) which could result in electron propagation along different lines. The footpoint motion often seen in solar flares (Kruker et al. 2003) also suggests that the electrons are consecutively injected onto field lines. In this scenario, an ensemble of our simulations, multiple micro-beam injections, would lead to beam densities comparable to a large flare.

The convergence of the magnetic field at chromospheric heights (e.g., Kontar et al. 2008c) has been ignored in this work, however, in our simulations the overall evolution of the energetic particles in the top part of a relatively dense loop, \( 10^{16} \text{ cm}^{-3} \), is dominated by wave–particle interactions where the field is not converging. It is only in the denser chromosphere, where the field is likely to converge, that the collisions become dominant. The very fast flattening of the power-law distribution’s low-energy cutoff by the wave–particle interactions suggests that it is unlikely that such a cutoff could develop and is therefore an unwise initial distribution for any model of coronally accelerated electrons. The non-thermal distribution flattening at low energies as it transitions into the thermal distribution seems to be a realistic model. Given how strongly the total energy in the accelerated electrons depends on a cutoff, or its behavior at low energies approaching the thermal distribution (Emslie 2003; Galloway et al. 2005), this transition needs further study.

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