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Generation of Suprathermal Electrons by Collective Processes in Collisional Plasma

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Abstract

The ubiquity of high-energy tails in the charged particle velocity distribution functions (VDFs) observed in space plasmas suggests the existence of an underlying process responsible for taking a fraction of the charged particle population out of thermal equilibrium and redistributing it to suprathermal velocity and energy ranges. The present Letter focuses on a new and fundamental physical explanation for the origin of suprathermal electron velocity distribution function (EVDF) in a collisional plasma. This process involves a newly discovered electrostatic bremsstrahlung (EB) emission that is effective in a plasma in which binary collisions are present. The steady-state EVDF dictated by such a process corresponds to a Maxwellian core plus a quasi-inverse power-law tail, which is a feature commonly observed in many space plasma environments. In order to demonstrate this, the system of self-consistent particle- and wave-kinetic equations are numerically solved with an initially Maxwellian EVDF and Langmuir wave spectral intensity, which is a state that does not reflect the presence of EB process, and hence not in force balance. The EB term subsequently drives the system to a new force-balanced steady state. After a long integration period it is demonstrated that the initial Langmuir fluctuation spectrum is modified, which in turn distorts the initial Maxwellian EVDF into a VDF that resembles the said core-suprathermal VDF. Such a mechanism may thus be operative at the coronal source region, which is characterized by high collisionality.

Key words: solar wind – Sun: corona – Sun: particle emission

1. Introduction

Inverse power-law velocity or energy distributions of charged particles are either directly observed or inferred in various regions of the universe accessible to either direct or remote observations, which includes 4–5 MeV protons accelerated at the heliospheric termination shock and detected by the *Voyager 1* and *2* spacecraft (Stone et al. 2008), tens of MeV electrons energized at the magnetic-field loop-top X-ray sources during solar flares (Krucker & Battaglia 2014; Oka et al. 2015), energetic ions and electrons measured in the geomagnetic tail region during disturbed conditions (Christon et al. 1991), etc. The solar wind is also replete with background populations of protons and electrons featuring inverse power-law tail distributions even in extremely quiet conditions (Vasyliunas 1968; Feldman et al. 1975; Lin 1998; Gloeckler 2003; Fisk & Gloeckler 2012).

In particular, the solar wind electron velocity distribution function (EVDF) is composed of a Maxwellian core ($\gtrsim$95% of the total density), with energies around 10 eV, a tenuous ($4 \sim 5\%$) high-energy halo with energies up to $10^2 \sim 10^3$ eV, and a highly energetic "superhalo" population with the density ratio of $10^{-9} \sim 10^{-6}$ and with energies up to $\sim$100 keV (Lin 1998). For fast wind, sometimes a narrow beam-like structure called the *strahl*, which is aligned with the magnetic field and streaming in the anti-sunward direction, is also measured (Feldman et al. 1976, 1978; Pierrard et al. 1999).

Given the prevalence of non-thermal distributions in nature, the study of the charged particle acceleration mechanisms that produce such distributions is of obvious importance and has a wide-ranging applicability across different sub-disciplines in astrophysical and space plasma physics. One of the first kinetic models on how suprathermal electron populations are generated involves the assumption that a sub-population of suprathermal electrons in low coronal regions exists, which is "selected" by Coulomb collisions and interacts with the thermal core and the surrounding environment in order to form the power-law EVDF at 1 au (Scudder & Olbert 1979a, 1979b). Later improved models generally rely on Coulomb collisional dynamics at the coronal base and phase-space mapping along inhomogeneous solar magnetic field lines (Lie-Svendsen et al. 1997; Pierrard et al. 1999, 2001). Collisional effects, however, become rather insignificant for solar altitudes higher than, say, 10 solar radii. In order to explain the observed quasi-isotropic nature of EVDF near 1 au, wave-particle resonant interaction must be important. Thus, the collective effects on the EVDF have been considered with or without other global features (Vocks et al. 2005; Vocks 2012; Pavan et al. 2013; Seough et al. 2015; Kim et al. 2016).

An outstanding issue is whether the suprathermal EVDFs are generated at the coronal source region in the first place. This issue may have important ramifications on the coronal heat flux and inverted temperature profile. If an enhanced number of high-energy particles is assumed to be present in the low transition region of the Sun, more particles are capable of escaping the gravitational potential, unleashing the so-called "velocity filtration effect," which is shown to produce the observed temperature inversion in the solar corona, a feature that may be relevant to the coronal heating (Scudder 1992a, 1992b; Teles et al. 2015). In this regard, Che & Goldstein (2014) proposed a scenario in which electron streams accelerated by nanoflares can lead to the two-stream instability, and ultimately produce a core-halo distribution in the inner corona. According to their model, the core-halo population is simply convected outward along open field lines while preserving the phase-space properties.

In this Letter we propose an alternative mechanism. This is not an acceleration in the traditional sense, but rather it is a mechanism that relies on a new fundamental plasma process involving the wave-particle interaction in a collisional plasma. Our theory is based on a recent paper by Yoon et al. (2016), where the kinetic theory of collective processes in collisional plasmas was formulated. The problem of combined collisional dissipation and collective processes had not been rigorously investigated from first principles in the literature. This is not to say that collisional dissipation processes or collective processes are not understood separately. On the contrary, each process is well understood. Indeed, if one is interested in the situation where the binary collisional relaxation is dominant, then transport processes can be legitimately discussed solely on the basis of the well-known collisional kinetic equation (Helander & Sigmar 2002; Zank 2014). Conversely, if one's concern is only on relaxation processes that involve collective oscillations, waves, and instabilities, there exists a vast amount of literature on linear and nonlinear theories of plasma waves, instabilities, and turbulence. It is the dichotomy that separates the purely collisional versus purely collective descriptions that had not been rigorously bridged until Yoon et al. (2016).

Among the findings of Yoon et al. (2016) is a hitherto-unknown effect that came out without any ad hoc assumption. The first principle equation of this new effect depicts the emission of electrostatic fluctuations, in the eigenmode frequency range, caused by particle scattering. This electrostatic form of "braking radiation" was appropriately named electrostatic bremsstrahlung (EB) by the authors of Yoon et al. (2016), which is not to be confused with a process sometimes known in the literature by the same terminology. In the literature, the process of relativistic electrons scattering Langmuir waves into transverse radiation is also called the "electrostatic bremsstrahlung" (Gailitis & Tsytovich 1964; Colgate 1967; Melrose 1971; Windsor & Kellogg 1974; Akopyan & Tsytovich 1977; Schlickeiser 2003), which is actually an induced scattering of transverse radiation off of relativistic electrons mediated by Langmuir waves. The "electrostatic bremsstrahlung" of Yoon et al. (2016) is the emission of electrostatic eigenmodes by collisional process, which is analogous to but distinct from the emission of transverse electromagnetic radiation by collisional process.

As will be demonstrated subsequently, the combined effects of Langmuir wave-electron resonant interaction in the presence of the new EB process leads to the self-consistent formation of the core-halo EVDF, which is a process that may be operative pervasively in the lower coronal environment. We thus suggest that the present mechanism may be the most widely operative process that is responsible for the formation of non-thermal EVDFs, not only in the solar environment, but also in other astrophysical environments. In the rest of this Letter, we detail the present finding.

2. Theoretical Formulation

The essential idea behind the new process responsible for taking a fraction of the electron population out of thermal equilibrium and redistributing it to suprathermal velocity and energy ranges is that the presence of the EB emission term (as well as the collisional damping term) in the wave-kinetic equation, combined with the particle kinetic equation, leads to a new steady-state electron distribution function, which corresponds to a Maxwellian core plus a quasi-inverse power-law tail. Conceptually, such a state is a new quasi-equilibrium that is distinct from thermodynamic equilibrium. In such a state, enhanced electrostatic fluctuations coexist with a population of charged particles while maintaining a dynamical steady state. In order to demonstrate this process, we numerically solve the system of particle- and wave-kinetic equations of the generalized weak turbulence theory (Yoon et al. 2016), starting with an initially Maxwellian electron velocity distribution and Langmuir wave spectral intensity that reflects the presence of only the customary spontaneous and induced emissions, but not the EB or the collisional damping. Of course, such an initial state is out of force balance. The EB and collisional damping terms subsequently drive the system to a new force-balanced steady state for the wave intensity. The initial Langmuir fluctuation spectrum is thus significantly modified as a result of the additional terms in the wave-kinetic equation. The modified Langmuir wave spectrum in turn distorts the initial Maxwellian electron distribution, and transforms it into a new quasi-steady-state velocity distribution function (VDF) that superficially resembles the core-suprathermal velocity distribution function. In what follows, we discuss the details of this numerical demonstration.

We perform the self-consistent numerical analysis on the EB emission in the Langmuir (L) electrostatic eigenmode frequency range by including the new mechanism in the wave-kinetic equation. Instead of making use of the complete set of nonlinear weak turbulence equations presented in Yoon et al. (2016), we restrict our analysis to the quasi-linear formalism, which includes single-particle spontaneous emission and wave-particle induced emission. We also take into account in the wave equations the effects of collisional damping. Such a simplified approach allows the study of the time evolution of the system, and puts in evidence the new mechanisms that have been introduced in Yoon et al. (2016). Besides, in the absence of free-energy sources, with which the present Letter is not concerned, the nonlinear mode-coupling terms are not expected to play any important dynamical roles. The equation describing the dynamics of L waves is therefore given by

$$\begin{aligned}\frac{\partial I_{\boldsymbol{k}}^{\sigma L}}{\partial t} &= \frac{\pi\omega_p^2}{k^2}\int d\boldsymbol{v}\,\delta(\sigma\omega_{\boldsymbol{k}}^L - \boldsymbol{k}\cdot\boldsymbol{v})\\ &\quad\times\left(\frac{n_0 e^2}{\pi}F_e(\boldsymbol{v}) + \sigma\omega_{\boldsymbol{k}}^L I_{\boldsymbol{k}}^{\sigma L}\,\boldsymbol{k}\cdot\frac{\partial F_e(\boldsymbol{v})}{\partial\boldsymbol{v}}\right)\\ &\quad + 2\gamma_{\boldsymbol{k}}^{\sigma L} I_{\boldsymbol{k}}^{\sigma L} + P_{\boldsymbol{k}}^{\sigma L},\end{aligned} \qquad (1)$$

where $I_{\boldsymbol{k}}^{\sigma L}$ is the wave intensity associated with the Langmuir wave defined via $E_{\boldsymbol{k},\omega}^2 = \sum_{\sigma=\pm 1} I_{\boldsymbol{k}}^{\sigma L}\delta(\omega - \sigma\omega_{\boldsymbol{k}}^L)$, $E_{\boldsymbol{k},\omega}$ is the spectral component of the wave electric field, and the dispersion relation is given by $\omega_{\boldsymbol{k}}^L = \omega_{pe}\left(1 + \frac{3}{2}k^2\lambda_D^2\right)$. Here, $\omega_{pe} = \sqrt{4\pi n_0 e^2/m_e}$ and $\lambda_D = \sqrt{T_e/(4\pi n_0 e^2)}$ stand for the plasma frequency and Debye length, respectively, and n_0, e, m_e, and T_e are the ambient density, unit electric charge, electron mass, and electron temperature, respectively.

The first term on the right-hand side of Equation (1) contains two contributions: the first term within the large parenthesis, proportional to the EVDF, $F_e(\boldsymbol{v})$, represents the discrete-particle effect of spontaneous emission; the second term, proportional to the derivative, $\partial F_e(\boldsymbol{v})/\partial\boldsymbol{v}$, represents the induced emission. The second line of Equation (1) on the right-hand side includes the collisional wave damping rate, $\gamma_{\boldsymbol{k}}^{\sigma L}$, obtained in the same context as the EB (Yoon et al. 2016), and numerically analyzed and discussed in Tigik et al. (2016a). The collisional damping is defined by

$$\gamma_{\boldsymbol{k}}^{\sigma L} = \omega_{\boldsymbol{k}}^{L} \frac{4 n_e e^4 \omega_{pe}^2}{T_e^2} \int d\boldsymbol{k}' \frac{(\boldsymbol{k} \cdot \boldsymbol{k}')^2 \lambda_D^4}{k^2 k'^4 |\epsilon(\boldsymbol{k}', \omega_{\boldsymbol{k}}^{L})|^2} \times \left(1 + \frac{T_e}{T_i} + (\boldsymbol{k} - \boldsymbol{k}')^2 \lambda_D^2\right)^{-2} \times \int d\boldsymbol{v}\, \boldsymbol{k}' \cdot \frac{\partial F_e(\boldsymbol{v})}{\partial \boldsymbol{v}} \delta(\omega_{\boldsymbol{k}}^{L} - \boldsymbol{k}' \cdot \boldsymbol{v}), \quad (2)$$

where T_i is the proton temperature, and $\epsilon(\boldsymbol{k}, \omega)$ is the linear dielectric-response function. In the literature, the collisional damping rate of plasma waves are often computed by heuristic means. That is, the collisional operator is simply added to the exact Vlasov (or Klimontovich) equation by hand, as it were, and the small-amplitude wave analysis is carried out, leading to the so-called Spitzer formula for the collisional damping rate (Lifshitz & Pitaevskii 1981). A similar heuristic and ad hoc recipe is also applied even for a turbulent plasma (Makhankov & Tsytovich 1968). Such approaches are at best heuristic and, strictly speaking, incorrect, as the collisionality represents dissipation and irreversibility, whereas the Vlasov or Klimontovich equation exactly preserves the phase-space information, and thus is reversible. In the non-equilibrium statistical mechanics it is well known that the irreversibility enters the problem only as a result of statistical averages and the subsequent loss of information. The authors of Yoon et al. (2016) carried out the rigorous analysis of introducing the collisionality starting from the exact Klimontovich equation and taking ensemble averages. The collisional damping rate that emerged, namely Equation (2), is the correct expression that replaces the heuristic Spitzer formula, and it was found in Tigik et al. (2016a) that the heuristic Spitzer collisional damping rate grossly overestimates the actual rate.

The term $P_{\boldsymbol{k}}^{\sigma L}$ in Equation (1) describes the EB emission process, which is new and is the subject of this Letter. In Yoon et al. (2016) a specific approximate form of $P_{\boldsymbol{k}}^{\sigma L}$ was derived. In this Letter we have revisited the approximation procedure, and find that a more appropriate form is given by

$$P_{\boldsymbol{k}}^{\sigma L} = \frac{3e^2}{4\pi^3} \frac{1}{(\omega_{\boldsymbol{k}}^{L})^2} \left(1 - \frac{m_e}{m_i} \frac{T_e}{T_i}\right)^2 \frac{v_e^4}{k^2} \int d\boldsymbol{k}' k'^2 |\boldsymbol{k} - \boldsymbol{k}'|^2 \times \left(1 + \frac{T_e}{T_i} + k'^2 \lambda_D^2\right)^{-2} \left(1 + \frac{T_e}{T_i} + (\boldsymbol{k} - \boldsymbol{k}')^2 \lambda_D^2\right)^{-2} \times \int d\boldsymbol{v} \int d\boldsymbol{v}' \sum_{a,b} F_a(\boldsymbol{v}) F_b(\boldsymbol{v}') \times \delta[\sigma\omega_{\boldsymbol{k}}^{L} - \boldsymbol{k} \cdot \boldsymbol{v} + \boldsymbol{k}' \cdot (\boldsymbol{v} - \boldsymbol{v}')], \quad (3)$$

where m_i is the proton mass and $v_e = \sqrt{2T_e/m_e}$ stands for electron thermal speed. The detailed derivation of the above-improved formula is reserved for another full-length article, as it is too lengthy for the present Letter.

The dynamical equation for EVDF $F_e(\boldsymbol{v})$ is given by the particle kinetic equation, which includes the Coulomb collision operator written in the form of the velocity-space Fokker-Planck equation,

$$\frac{\partial F_a(\boldsymbol{v})}{\partial t} = \frac{\partial}{\partial v_i}\left(A_i(\boldsymbol{v}) F_a(\boldsymbol{v}) + D_{ij}(\boldsymbol{v}) \frac{\partial F_a(\boldsymbol{v})}{\partial v_j}\right) + \sum_b \theta_{ab}(F_a, F_b),$$

$$A_i(\boldsymbol{v}) = \frac{e^2}{4\pi m_e} \int d\boldsymbol{k}\, \frac{k_i}{k^2} \sum_{\sigma=\pm1} \sigma\omega_{\boldsymbol{k}}^{L}\, \delta(\sigma\omega_{\boldsymbol{k}}^{L} - \boldsymbol{k} \cdot \boldsymbol{v}),$$

$$D_{ij}(\boldsymbol{v}) = \frac{\pi e^2}{m_e^2} \int d\boldsymbol{k}\, \frac{k_i k_j}{k^2} \sum_{\sigma=\pm1} \delta(\sigma\omega_{\boldsymbol{k}}^{L} - \boldsymbol{k} \cdot \boldsymbol{v}) I_{\boldsymbol{k}}^{\sigma L}, \quad (4)$$

where the coefficient $A_i(\boldsymbol{v})$ represents the velocity-space friction, and the coefficient $D_{ij}(\boldsymbol{v})$ describes the velocity diffusion. The distribution functions, $F_a(\boldsymbol{v})$ and $F_b(\boldsymbol{v})$, are both normalized to unity, $\int d\boldsymbol{v} F_{a,b}(\boldsymbol{v}) = 1$, where $a = e, i$ and $b = e, i$ represent the interacting particles. The term $\theta_{ab}(F_a, F_b)$ depicts the effects of Coulomb collisions between particles of species a and b.

For the present analysis, we adopt a linearized form of the Landau collision integral for $\theta_{ab}(F_a, F_b)$, in which it is assumed that the evolving EVDF collides with a Maxwellian background distribution. This assumption relies on the fact that the growing tail population of the EVDF has a much lower density than the core electrons, so that the effects of collisions between the tail electrons with the background EVDF are more significant than the effects of collisions among electrons of the tail population. The lengthy linearization procedure can be found in detail in Tigik et al. (2016b) and will not be repeated here for the sake of space economy. In short, the linearized collision operator is given by

$$\theta_{ab}\quad (f_a, f_b) = \Gamma_{ab}\Bigg[\frac{\partial}{\partial \boldsymbol{v}_a} \cdot \left(2\frac{m_a}{m_b} \Psi(x_{ab}) \frac{\boldsymbol{v}_a}{v_a^3} f_a\right) + \frac{\partial}{\partial \boldsymbol{v}_a} \cdot \left\{\left[\left(\Phi(x_{ab}) - \frac{1}{2x_{ab}^2}\Psi(x_{ab})\right) \frac{\partial^2 v_a}{\partial \boldsymbol{v}_a \partial \boldsymbol{v}_a}\right] \cdot \frac{\partial f_a}{\partial \boldsymbol{v}_a}\right\} + \frac{\partial}{\partial \boldsymbol{v}_a} \cdot \left[\left(\frac{1}{x_{ab}^2}\Psi(x_{ab}) \frac{\boldsymbol{v}_a \boldsymbol{v}_a}{v_a^3}\right) \cdot \frac{\partial f_a}{\partial \boldsymbol{v}_a}\right]\Bigg], \quad (5)$$

where $x_{ab} \equiv v_a/v_{tb}$, v_{tb} is the thermal velocity of the particles of species b, $\Gamma = 4\pi n e^4 \ln\Lambda / m_e^2$, and $\Psi(x) \equiv \Phi(x) - x\Phi'(x)$ is an auxiliary function (Gaffey 1976), in which $\Phi(x_{ab}) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$ is the error function and $\Phi'(x_{ab}) = \frac{2}{\sqrt{\pi}} e^{-x^2}$ is its derivative.

3. Numerical Analysis

The set of integro-differential equations for waves and particles, (1) and (4), was numerically solved in 2D wave-number space and 2D velocity space, respectively. The purpose of the numerical analysis is to demonstrate that the coupled system of equations leads to an asymptotically steady-state EVDF that resembles the core-halo distribution, regardless of how the solution is initiated. As a concrete example, we assumed an initial state of isotropic Maxwellian VDF for both ions and electrons, given by

$$F_a(\boldsymbol{v}) = \frac{1}{\pi^{3/2} v_a^3} \exp\left(-\frac{v^2}{v_a^2}\right), \tag{6}$$

where $v_a = (2T_a/m_a)^{1/2}$, with $a = i, e$. The ion VDF is assumed to be constant along the time evolution, which is a reasonable assumption as we are working in the much-faster timescale of electron interactions. The electron-ion temperature ratio of $T_e/T_i = 7.0$ is adopted, and the plasma parameter of $(n_0 \lambda_D^3)^{-1} = 5 \times 10^{-3}$ is used. This choice represents a relatively high collisionality. For the coronal-base source region, at the point where the plasma becomes fully ionized, the electron density is of the order 10^9–10^{11} cm^{-3} and the electron temperature may reach $\sim 10^4$–10^6 K (Aschwanden 2005) [or equivalently, $\sim 10^0 - 10^2$ eV]. If we assume a central value for the density and the temperature, 10^{10} cm^{-3} and 10^5 K, for instance, the corresponding plasma parameter would be $(n_0 \lambda_D^3)^{-1} \approx 10^{-5}$, more than two orders of magnitude below the value, which we have used for the numerical analysis. Such a higher value was purposely utilized in order to reduce the computational time necessary to obtain the results. The final outcome of the time evolution, however, is not affected by the inflated plasma parameter.

The initial Langmuir wave intensity was chosen by balancing only the spontaneous- and induced-emission processes in the equations for the wave amplitudes, namely,

$$I_{\boldsymbol{k}}^{\sigma L}(0) = \frac{T_e}{4\pi^2}(1 + 3k^2\lambda_D^2). \tag{7}$$

Because the VDF and the Langmuir spectrum have azimuthal symmetry, we plot the results of numerical solution by using a 1D projection on the parallel direction of the velocity and wave number.

It is important to note that the initial electron distribution and Langmuir wave spectral intensity, (6) and (7), *do not* satisfy the steady-state condition $\partial/\partial t = 0$ in the particle- and wave-kinetic Equations (4) and (1), respectively. This is purposeful, since our aim is to demonstrate that the set of Equations (4) and (1) do not permit the electron distribution and Langmuir wave spectral intensity, (6) and (7), respectively, as the legitimate steady-state solution, and so the equations will force the initial state to make a transition to a new steady state or, equivalently, a new quasi-equilibrium state.

For the numerical analysis, we take into account the new effects of collisional damping and EB, starting from the above initial condition. With the addition of these new terms, the initial wave spectrum is no longer in equilibrium with the particle distribution, triggering an interesting evolution. Let us define normalized Langmuir wave intensity

$$\mathscr{E}_{\boldsymbol{q}}^{\sigma L} = \frac{(2\pi)^2 g}{m_e v_e^2} I_{\boldsymbol{k}}^{\sigma\alpha},$$

where $g = [2^{3/2}(4\pi)^2 \, n_e \lambda_D^3]^{-1}$. We also define the normalized temporal variable, $\tau = \omega_{pe} t$, and the normalized wave number $k v_e/\omega_{pe}$. Figure 1 shows the time evolution of $\mathscr{E}_{\boldsymbol{q}}^{\sigma L}$. It is seen that the bremsstrahlung radiation emitted in the frequency range corresponding to L waves alters the spectrum, creating a modification that starts at $q \approx 0.4$ and ends in a peak around $q = 0$. The wave growth appears early in the time evolution and evolves rapidly, as can be seen in Figure 1. After $\tau = 5000$, the shape of the curve starts to change and the wave growth becomes slower. At $\tau = 50{,}000$, the Langmuir spectrum appears to be very close to an asymptotic state.

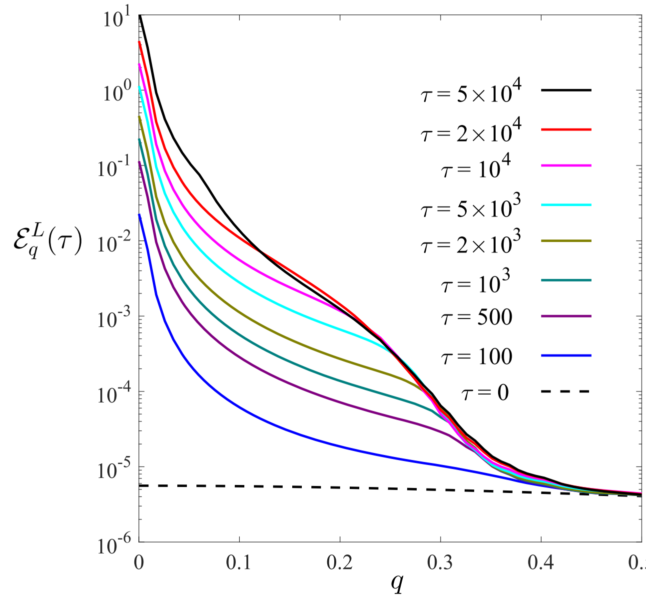

Figure 1. Time evolution of the Langmuir spectrum, taking into account the influence of the bremsstrahlung emission.

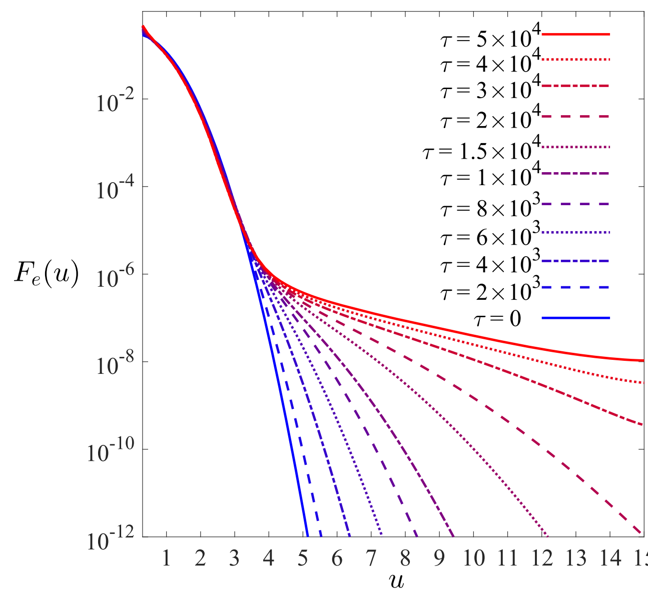

Figure 2. Time evolution of the electron velocity distribution function.

The early stages of the time evolution of the EVDF are quite gradual, but the first signs of modification start to appear around $\tau = 2000$ and are almost imperceptible. In Figure 2, the earliest indication of change is shown at $\tau = 4000$. At this time an energized tail becomes apparent. The demarcation between the core and tail occurs around $u = v/v_e \approx 4.6$. The velocity spectrum associated with the energetic tail population continues to harden as time progresses, while the core defined for $u \lesssim 4.6$ remains essentially unchanged. In short, we have demonstrated that the initial Maxwellian electron distribution

(6) has made a transition to a new quasi-equilibrium state in which the electron distribution function bears a superficial resemblance to the Maxwellian core plus a quasi-inverse power-law tail population.

4. Final Remarks

The results obtained suggest that, in the presence of EB emission, the wave-particle system attains a state of asymptotic equilibrium, in which the EVDF possesses a feature of core-halo distribution that is highly reminiscent of the solar wind EVDF. We thus conclude that the present mechanism of the collective wave-particle interaction process that takes place in a collisional environment, such as the coronal source region, may be a highly efficient and common process in many astrophysical environments. Before we close, we note that we have also analyzed the particle kinetic equation in which the collisional operator is not present on the right-hand side of (4). The result (not shown) is not very different from the present result, which indicates that the mechanism of generating the suprathermal electrons mainly comes from the wave dynamics that operate in a collisional environment.

We have also checked the overall energy budget of the system. Since the initial state, comprised of Maxwellian distribution and Langmuir spectral intensity that does not reflect the bremsstrahlung emission, is not in force balance, there is a transfer of energy between the particles and waves early on, but over a longer time period the system enters a state where the net exchange between the particles and waves gradually settles down to a minimal level. Note that in terms of the total energy content, the tail portion of the EVDF contains a relatively low proportion of the net energy, as the number density is several orders of magnitude lower than the core distribution. Although it is not so easy to verify by visual means, there is a slight cooling associated with the core part of the EVDF. This shows that the present process is not an acceleration mechanism, but rather involves the redistribution of particle population in velocity or energy space in order to form a new quasi-equilibrium.

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