Solar Wind Electron Energization by Plasma Turbulence

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Abstract. The solar wind electrons are made of the low-energy Maxwellian core, intermediate-energy halo, field-aligned strahl, and the highly-energetic super-halo electrons. The present paper discusses a model in which the halo electrons interact with the whistler fluctuation via cyclotron wave-particle resonance, and the super-halo electrons interact through Landau resonance with the Langmuir fluctuation, thus maintaining a local steady state.

1. INTRODUCTION
The solar wind electrons are comprised of the Maxwellian “core,” suprathermal “halo,” and a field-aligned component called the “strahl,” which is typically associated with the high-speed solar wind. The “super-halo” electrons are a highly energetic component. The Maxwellian core is characterized by tens of eV energy, the halo is defined up to \( \sim 10^2 - 10^3 \) eV or so, and the super-halo is characterized by \( 10^3 - 10^5 \) eV \[1\]. The strahl component overlaps the halo in energy range. Observations at 1 AU shows that the Maxwellian component makes up about \( \sim 95\% \) in terms of the number density, the halo is roughly estimated to possess \( \sim 4\% \) density, and the strahl component takes up the remaining \( \sim 1\% \). The super-halo component is very low in terms of the number density (almost negligible, on the order of \( 10^{-9} \) to \( 10^{-6} \)), yet owing to their high energy, their presence can be clearly identified in velocity distribution function (VDF).

To model the solar wind electrons in a comprehensive manner, one must first address the issue of what physical processes are responsible for energizing the source electrons \[2\]. Then, how the source electrons escape the corona must be considered. For low corona, collisions become important \[3\]. Above 10 solar radii (\( 10R_\odot \)) or so and beyond the Coulomb collision is no longer effective (for highly energetic electrons, the collision becomes insignificant even for lower altitudes), and thus it becomes necessary to include the effects of collective wave-particle acceleration and pitch-angle scattering \[4\]. The physics of these processes can be discussed on the basis of a formal all-embracing kinetic equation,

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \left[ \mathbf{g} - \frac{e}{m_e} \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right) \right] \cdot \frac{\partial f}{\partial \mathbf{v}} = \left( \frac{\delta f}{\delta t} \right)_{\text{coll.}} + \left( \frac{\delta f}{\delta t} \right)_{\text{wp}},
\]

where \( f \) represents the total electron velocity distribution function (VDF), \( \mathbf{g} \) is the solar gravitational acceleration, \( \mathbf{E} \) stands for the large-scale (ambipolar) electric field, \( \mathbf{B} \) designates the inhomogeneous solar magnetic field, \( \left( \delta f/\delta t \right)_{\text{coll.}} \) denotes the collision integral, and \( \left( \delta f/\delta t \right)_{\text{wp}} \).
refers to the time rate of change in VDF by wave-particle interaction. The wave-particle interaction may be owing to various self-generated plasma waves, or those that are intrinsic to the solar wind.

In the present paper, we pay attention to the role played by the local wave-particle resonant interaction,

$$\frac{\partial f}{\partial t} = \left( \frac{\delta f}{\delta t} \right)_{wp}. \quad (2)$$

We assume that the total electron VDF can be treated as being made of three-components, $f = f_0 + f_h + f_s$, where $f_0$, $f_h$, and $f_s$ stand for the isotropic Maxwellian core, halo, and the super-halo VDF. We do not consider the strahl, since we assume isotropy at the outset. We assume that the Maxwellian core electrons are generally nonresonant with any high-frequency waves, so that they maintain the Gaussian form,

$$f_0 = \frac{n_0}{\pi^{3/2} v_T^3} \exp \left( -\frac{v^2}{v_T^2} \right), \quad (3)$$

where $v_T = \sqrt{2T_0/m_e}$ is the thermal speed associated with the core electrons, $T_0$ being the core temperature, which is in the range of tens of eV. Note, however, that the core electrons may interact with low frequency turbulence such as the ion-acoustic fluctuations or kinetic Alfvén turbulence. For instance, Rudakov et al. [5] show that the interaction of low-energy electrons with kinetic Alfvén waves may lead to the flattening of the parallel electron distribution near $v \sim 0$ range. From the standpoint of the present discussion, which is concerned with the wave-particle interaction between intermediate to high energy electrons and high-frequency fluctuations, we may ignore such an effect. We assume that the halo electrons ($f_h$) are resonant with the whistler turbulence, while the super-halo electrons ($f_s$) are resonant with the Langmuir turbulence.

Pierrard et al. [6] developed a kinetic exospheric model that contains the Coulomb-collision effects, $(\delta f/\delta t)_{coll}$, as well as the wave-particle resonant interaction term, $(\delta f/\delta t)_{wp}$, where the source of wave-particle resonance was assumed to arise from the pre-existing whistler fluctuations. While Ref. [6] is more general than the present limited approach of just considering the wave-particle interaction, our discussion treats the waves in a self-consistent manner, whereas Ref. [6] simply models the waves. Recently Lacombe et al. [7] identified quasi-parallel right-hand circularly polarized whistler waves for certain solar wind conditions. Even though the quasi-parallel whistler fluctuations of the type discussed by Lacombe et al. [7] may not always be easily identifiable due to the occultation by the Doppler-shifted permanent solar wind turbulence, we believe that a finite level of quasi-parallel whistler fluctuations are always present in the solar wind. Whistler waves are characterized by the frequency range $\sim 10^2$ Hz. Considering that the halo electrons have energy in the range $10^2$ to $10^3$ eV, one can show that the cyclotron resonance between the halo electrons and whistler waves can be satisfied.

For higher frequency range, the solar wind is permeated by the quasi-electrostatic Langmuir-wave type of fluctuations known as the quasi-thermal noise [8]. Reference [9] formulated a theory of electron kappa distribution that is in dynamical equilibrium with the quasi-thermal noise Langmuir spectrum. This theory applies to the super-halo electrons, since the Langmuir wave frequency of the range $10^5$ Hz is too high for the intermediate halo electrons to effectively resonate. The asymptotic theory of super-halo electrons in Ref. [9] assumes that these energetic electrons are already present. The purpose of the theory is to provide a self-consistent explanation of how the Langmuir fluctuations scatter the electrons in order to maintain the shape of the super-halo electron distribution. How these electrons are accelerated at the source region is not understood at present.
2. ASYMPTOTIC TURBULENT STATE
We are interested in the asymptotically steady-state solution of the particle kinetic equation \( (2) \). A recent paper by Gaelzer et al. [10] derives the specific form for the right-hand side of equation \( (2) \), based upon which Kim et al. [11] discuss the steady-state solution for the halo electrons subject to whistler fluctuations.

Inserting equation \( (6) \) to equation \( (5) \), and upon identifying

\[
\Gamma (k_s - 1/2) = \left( \frac{2\omega_{pe}^2}{\kappa_s - 3/2} \right)^{v_T^2_s},
\]

we obtain the steady-state solution for the super-halo electrons in resonance with Langmuir wave fluctuations,

\[
f_s = C \exp \left( -\frac{m_e\omega_e^2\Omega_e^2}{4\pi\epsilon_0 k_0^2 v_T^2} \int du \frac{1}{u} \int_{-1}^{1} d\mu \frac{1 - \mu^2}{|\mu|} \mathcal{E}_W \left( \frac{|\mu|}{v} \right) \right),
\]

where \( \mathcal{E}_W(k) \) is the whistler fluctuation spectrum, \( C \) represents a suitable normalization constant, and \( \mu = \cos \theta = v_\parallel/v \) is the cosine of the velocity pitch angle. Likewise Kim et al. [11] obtained the steady-state solution for the super-halo electrons in resonance with Langmuir wave fluctuations,

\[
f_s = C \exp \left( -\frac{m_e\Omega_e^2}{4\pi v_T^2} \int dv \frac{1}{v} \int_{-1}^{1} d\mu \frac{1 - \mu^2}{|\mu|} \mathcal{E}_L \left( \frac{\omega_{pe}}{v_T} \frac{\mu}{v} \right) \right),
\]

where \( \mathcal{E}_L(k) \) is the Langmuir wave fluctuation spectrum.

Let us first discuss the super-halo electrons. In the paper by Yoon [9] it was shown that the Langmuir wave intensity given by the form

\[
\mathcal{E}_L(k) = \mathcal{E}_0 \left( 1 + \frac{k_0^2}{k^2} \right),
\]

satisfies the steady-state nonlinear wave kinetic equation for the Langmuir turbulence. Upon inserting equation \( (6) \) to equation \( (5) \), and upon identifying

\[
\frac{m_e\omega_e^2\Omega_e^2}{4\pi\epsilon_0 k_0^2 v_T^2} = \kappa_s + 1,
\]

\[
\frac{k_0^2}{2\omega_{pe}^2} = \frac{1}{(\kappa_s - 3/2)v_T^2},
\]

where \( v_T^2 = \sqrt{2T_s/m_e} \) is the thermal speed for the super-halo electrons, we obtain the desired asymptotic super-halo electron velocity distribution function, as well as the self-consistent steady-state Langmuir fluctuation spectrum,
Wang et al. [1] made detailed statistical survey of \( \sim 2 - 20 \) keV super-halo electrons during quiet times in the interplanetary space over the year 2007 - 2008 time period, and based upon data from Supra Thermal Electron (STE) instrument onboard STEREO A and B spacecraft, they determined that the observed quiet-time super-halo VDF behaves as an inverse power-law,

\[
f_s(v) \sim v^{-b},
\]

with \( b \) ranging from 5 to 8.7, with an average of 6.69 \( \pm \) 0.90, and about half the measured cases in a peak at

\[6.5 < b < 7.5.\]

Given the observational uncertainties and inherent approximate nature of the theory, the convergence between the theoretical value of \( b = 6.5 \) and the observed values \( 6.5 < b < 7.5 \) is quite remarkable. We thus believe that our theory of super-halo electrons maintaining locally isotropic asymptotic power-law VDF via steady-state interaction with Langmuir-type fluctuations (i.e., quasi-thermal noise) is substantially correct. This conclusion is irrespective of how the original super-halo population is generated at the solar source. The theory of Langmuir fluctuation-mediated super-halo VDF already assumes that the seed population is available at the source and travelled to the local region.

Next we consider the asymptotic theory for the halo electrons in dynamical equilibrium with whistler turbulence. In a submitted paper, Yoon et al. [12] show that the whistler turbulence characterized by the frequency range \( \Omega_p \ll \omega \ll |\Omega_e| \), where \( \Omega_p \) is the proton cyclotron frequency, the electric and magnetic field fluctuation spectra of the form,

\[
\mathcal{E}_W(k) = \mathcal{E}_0 \left( \frac{\omega^2}{\omega_{pe}^2} \right)^{2-\gamma}, \quad \mathcal{B}_W(k) = \mathcal{E}_0 \left( \frac{\omega^2}{\omega_{pe}^2} \right)^{1-\gamma},
\]

where \( \mathcal{B}_W(k) = \mathcal{E}_W(k)(ck/\omega_k^W)^2 \), satisfies the steady-state nonlinear wave kinetic equation for whistler waves propagating parallel to the ambient magnetic field. The solution, however, does not take into account the pre-existing level of whistler turbulence, which might be the product of quasi-parallel cascade of intrinsic solar wind turbulence. To account for the influence of the intrinsic level of whistler fluctuation, we generalize (10) by

\[
\mathcal{E}_W(k) = \mathcal{E}_0 \left( \frac{\omega^2}{\omega_{pe}^2} \right)^{2-\gamma}, \quad \mathcal{B}_W(k) = \mathcal{E}_0 \left( \frac{\omega^2}{\omega_{pe}^2} \right)^{1-\gamma},
\]

where \( \gamma \) is a free parameter, but it represents the typical power-law index associated with the intrinsic solar wind turbulence in the kinetic whistler frequency range. Making use of this solution, and substituting to equation (4), we may construct the desired halo electron VDF,

\[
f_h(v) = \frac{n_h(2 - \gamma)}{2\pi v_{Th}^4 \Gamma \left( \frac{3}{4} - 2\gamma \right)} \exp \left[ -\left( \frac{v^2}{v_{Th}^2} \right)^{2-\gamma} \right],
\]

\[
\mathcal{E}_W(k) = \frac{m_e e^2 \Omega_e^2}{4\pi v_T^0} \left( \frac{\Omega_e}{\omega_{pe}} \right)^4 \left( \frac{k v_{Th}}{\Omega_e} \right)^{4-2\gamma},
\]

\[
\mathcal{B}_W^{(1)}(k) = \frac{T_h}{\pi} \frac{\Omega_e^2}{2 \omega_{pe}^2} \left( \frac{k v_{Th}}{\Omega_e} \right)^{2-2\gamma},
\]

where \( n_h \) is the halo density. Here, we have defined the halo electron "temperature," \( T_h \equiv m_e v_{Th}^2/2 \), and the associated with the "halo thermal speed" \( v_{Th} \),

\[
\frac{1}{v_{Th}^{4-2\gamma}} = \frac{1}{4-2\gamma} \frac{m_e e^2 \Omega_e^2}{\pi^2 v_T^0 \mathcal{E}_0 \omega_{pe}^{2\gamma}},
\]
and identified
\[ \mathcal{E}_0 = \frac{\Omega_e^2 m_e c^4 v_{T0}^{-2\gamma} \left( \frac{\Omega_e^2}{\omega_{pe}^2} \right)^{\gamma}}{2\pi(2-\gamma)v_{T0}^2}. \]  
(14)

Note that the quantity \( v_{Th} \), which we conveniently termed the “halo thermal speed” and the related quantity \( T_h \), which we called the “halo temperature,” do not strictly follow from the correct thermodynamic definition for temperature. The rigorous definition for “effective” halo electron temperature is given by
\[ \frac{3}{2} n_h T_{h}^{\text{eff}} \equiv \int d\mathbf{v} \frac{m_e v^2}{2} f_h(v). \]  
(15)

Inserting \( f_h(v) \) from equation (12) to the above we obtain
\[ T_{h}^{\text{eff}} = \frac{3\Gamma \left( \frac{3}{2-2\gamma} \right)}{\Gamma \left( \frac{5}{2-2\gamma} \right)} T_h. \]  
(16)

We now bring together all the results we have discussed thus far and construct the total solar wind electron VDF near 1 AU. We compare our theoretical result with the left-hand panel of Figure 5 of Ref. [1], where the statistical survey of \( \sim 2 - 20 \) keV super-halo electron observations during quiet times in the interplanetary medium in 2007 - 2008, from the Supra Thermal Electron (STE) instrument onboard the STEREO A & B spacecraft are shown.

![Solar Wind Electron VDF](image)

**Figure 1.** Theoretical construction of the solar wind electron VDF \( f_e = f_0 + f_h + f_s \) and comparison against observation [1]. The red dots are the observed VDF values.

Shown in Figure 1 is the theoretical solar wind electron VDF superposed with the observed VDF with red dots. In order to facilitate direct comparison with observed VDF we have multiplied an arbitrary constant \( 10^7 \) to the theoretical VDF. We assume \( n_0/n_e = 0.96 \), \( v_{T0}/c = 0.006 \), \( n_h/n_e = 0.039999 \), \( v_{T0}/v_{Th} = 0.7 \), \( n_s/n_e = 1 - n_0/n_e - n_h/n_e = 10^{-6} \), and take \( v_{T0}/v_{Ts} = 0.16 \). Here, the total electron number density is \( n_e = n_0 + n_h + n_s \). In the numerical construction of the halo distribution, we chose \( \gamma = 1.35 \), which is close to the observed solar wind turbulence magnetic field spectrum in the nominal whistler frequency range. Note how the theoretical model closely fits the observed electron VDF.
3. CONCLUSIONS
In the present paper we presented a theory for asymptotically steady-state solar wind electron VDF. By treating the local solar wind electron VDF as a superposition of the low-energy Maxwellian core electrons with tens of eV energy range, which is considered to be non-resonant with any high-frequency waves, the intermediate $\sim 10^2$ to $10^3$ eV energy-range halo electrons that are treated as being in steady-state wave-particle resonance with the whistler turbulence, and the high $\sim 10^3$ to $10^5$ eV-range super-halo electrons, which is assumed to maintain dynamical steady-state equilibrium with the Langmuir fluctuations, we have provided a theoretical model for the quiet-time solar wind electrons.

Our model of the steady-state solar wind electrons relies on the presence of spontaneously generated whistler/Langmuir fluctuations, which might coexist with the intrinsic turbulence. The spontaneously emitted Langmuir turbulence is also known as the quasi-thermal noise [8]. However, the presence of spontaneously generated whistler noise has not been thoroughly investigated thus far. The present paper invokes the recent observation by Lacombe et al. [7] as perhaps the evidence for such an example, but obviously more systematic observational research program is called for.

The present model of the solar wind electrons leaves out the important strahl component, since it is our belief that the strahl is the consequence of inhomogeneity and magnetic mirror effect balancing the wave-induced pitch-angle scattering. The present theory lacks the inhomogeneity. We have also assumed isotropy at the outset. Including inhomogeneity and other effects will make the theory more complete but such a task is beyond the scope of the present paper.

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