MEASURING COLLISIONLESS DAMPING IN HELIOSPHERIC PLASMAS USING FIELD–PARTICLE CORRELATIONS

K. G. Klein\textsuperscript{1,2} and G. G. Howes\textsuperscript{3}

\textsuperscript{1}Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
\textsuperscript{2}Space Science Center, University of New Hampshire, Durham, NH 03824, USA
\textsuperscript{3}Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

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ABSTRACT

An innovative field–particle correlation technique is proposed that uses single-point measurements of the electromagnetic fields and particle velocity distribution functions to investigate the net transfer of energy from fields to particles associated with the collisionless damping of turbulent fluctuations in weakly collisional plasmas, such as the solar wind. In addition to providing a direct estimate of the local rate of energy transfer between fields and particles, it provides vital new information about the distribution of that energy transfer in velocity space. This velocity-space signature can potentially be used to identify the dominant collisionless mechanism responsible for the damping of turbulent fluctuations in the solar wind. The application of this novel field–particle correlation technique is illustrated using the simplified case of the Landau damping of Langmuir waves in an electrostatic 1D–1V Vlasov–Poisson plasma, showing that the procedure both estimates the local rate of energy transfer from the electrostatic field to the electrons and indicates the resonant nature of this interaction. Modifications of the technique to enable single-point spacecraft measurements of fields and particles to diagnose the collisionless damping of turbulent fluctuations in the solar wind are discussed, yielding a method with the potential to transform our ability to maximize the scientific return from current and upcoming spacecraft missions, such as the Magnetospheric Multiscale (MMS) and Solar Probe Plus missions.

Key words: plasmas – solar wind – turbulence – waves

1. INTRODUCTION

A grand challenge problem at the forefront of space physics and astrophysics is to understand how the energy of turbulent plasma flows and electromagnetic fields is converted into energy of the plasma particles, either as heat or some other form of particle energization. Under the typically low-density and high-temperature conditions of turbulent plasmas in the heliosphere, such as the solar wind, the turbulent dynamics is weakly collisional, requiring the application of six-dimensional (3D-3V) kinetic plasma theory to follow the evolution of the turbulence, where the damping of the turbulent fluctuations occurs due to collisionless interactions between the electromagnetic fields and the individual plasma particles. Although in situ spacecraft measurements in the solar wind provide detailed information about the electromagnetic and plasma fluctuations, these measurements are typically limited to one point (or, at most, a few points) in space. Of great benefit to plasma turbulence research would be a scheme to use single-point measurements of the electromagnetic fields and particle velocity distribution functions (VDFs) to diagnose the collisionless damping of the turbulent fluctuations and to characterize how the damped turbulent energy is distributed to particles with different velocities.

Here, we present an innovative technique to identify and characterize the collisionless mechanisms that govern the net transfer of energy from the electromagnetic fields to the plasma particles by correlating measurements of the electromagnetic fields and particle VDFs at a single point in space. These field–particle correlations yield a local estimate of the rate of particle heating and further provide a characteristic velocity-space signature of the collisionless damping mechanism that leads to the energization of the plasma particles.

Early attempts to explore wave–particle interactions using spacecraft measurements sought the spatial or temporal coincidence of wave fields with enhanced particle fluxes (Gough et al. 1981; Park et al. 1981; Kimura et al. 1983). Later, wave–particle correlators were flown on rockets and spacecraft to identify the phase-bunching of electrons by correlating the counts of electrons in a single energy and angle bin with the phase of the dominant wave (Ergun et al. 1991a, 1991b; Muschietti et al. 1994; Watkins et al. 1996; Ergun et al. 1998, 2001; Kletzing et al. 2005; Kletzing & Muschietti 2006). Motivated by modern particle instrumentation with improved temporal and phase-space resolution, the field–particle correlation technique described here takes a significant leap forward by recovering the correlation as a function of particle velocity, generating a much more detailed velocity-space signature of the collisionless interactions.

Although the novel field–particle correlation technique devised here is intended for use in diagnosing the damping of turbulent fluctuations in the weakly collisional solar wind, to illustrate the concept in a simplified framework, we present here its application to the 1D–1V Vlasov–Poisson system to explore the collisionless damping of electrostatic fluctuations in an unmagnetized plasma. After this demonstration of the fundamental concept of using field–particle correlations to investigate collisionless damping of fluctuations, we discuss the application of this technique to spacecraft observations of solar wind turbulence.

2. PARTICLE ENERGIZATION IN A VLASOV–POISSON PLASMA

The dynamics of electrostatic fluctuations in a collisionless plasma is governed by the Vlasov–Poisson equations, where the Vlasov equation determines the collisionless evolution of
the distribution function for each species \( s, f_s(x, v, t) \), and the Poisson equation determines the self-consistent evolution of the electric field, \( E(x, t) = -\partial \phi(x, t)/\partial x \), dictated by the fluctuating charge density in the plasma.

To diagnose the collisionless transfer of energy between fields and particles, we define the phase-space energy density for a particle species \( s \) as \( w_s(x, v, t) = m_v v^2 f_s(x, v, t)/2 \), the energy density per unit length per unit velocity. Integrating \( w_s \) over velocity yields the standard spatial energy density, and integrating over volume produces the total microscopic kinetic energy of the species, \( W_s \). Splitting \( f_s \) into equilibrium and perturbed components, \( f_s(x, v, t) = f_{s0}(v) + \delta f_s(x, v, t) \) where the magnitude of \( \delta f_s \) is limited only by the physical constraint \( f_s \geq 0 \)—we can use the Vlasov equation to obtain an equation for the rate of change of \( w_s \).

\[
\frac{\partial w_s(x, v, t)}{\partial t} = -\frac{m_v v^3}{2} \frac{\partial \delta f_s(x, v, t)}{\partial x} - \frac{q_v v^2}{2} \frac{\partial f_{s0}(v)}{\partial v} E(x, t) - \frac{q_v v^2}{2} \frac{\partial f_{s0}(v)}{\partial v} E(x, t).
\]

The rate of change of \( w_s \) is governed by three terms: from left to right, the (linear) ballistic term, the linear wave–particle interaction term, and the nonlinear wave–particle interaction term. When integrated over space using either periodic or infinitely distant boundary conditions, the ballistic and linear wave–particle interaction terms yield zero net energy transfer. Only the nonlinear wave–particle interaction term produces a net change in particle energy. Therefore, the term \(-q_v v^2 (\partial f_{s0}/\partial v) E/2\) governs the net rate of energy transfer between the electromagnetic fields and plasma particles that is associated with collisionless damping (Howes et al. 2016).

Taking the average of Equation (1) over the entire spatial domain—the approach taken in quasilinear theory—provides a rigorous approach to determine the net transfer of energy between the fields and particles, but the spatial information necessary to perform this average is not observationally accessible using single-point measurements. At a single point \( x_0 \), all three terms of Equation (1) are nonzero. These terms describe both the oscillatory energy transfer associated with wave motion and the secular energy transfer associated with a net transfer of energy between fields and particles. Unless the collisionless damping rate is particularly strong, the magnitude of the oscillatory energy transfer described by these terms is generally much larger than that of the secular energy transfer, so the key challenge is to devise a procedure to isolate the small-amplitude rate of secular energy transfer governed by the nonlinear wave–particle interaction term.

Note that this local approach is valuable even in numerical simulations where full spatial information is accessible because there is significant evidence that energy dissipation is often highly localized in space (Wan et al. 2012; Karimabadi et al. 2013; TenBarge & Howes 2013; Wu et al. 2013; Zhdankin et al. 2013, 2015), so spatial averaging may obscure the details of the local dissipation mechanism, making it more difficult to identify the physical mechanism responsible.

3. FIELD–PARTICLE CORRELATION

The form of the nonlinear wave–particle interaction term in Equation (1) suggests that the rate of change of phase-space energy density can be estimated by correlating single-point measurements of the electric field and particle VDFs. Below, we specify the procedure to isolate the local secular transfer of energy associated with the collisionless damping of electrostatic fluctuations in a 1D–1V Vlasov–Poisson plasma.

Labeling discrete measurement times as \( t_j \equiv j\Delta t \) for \( j = 0, 1, 2, ... \), we define the single-point measurements at position \( x_0 \) and time \( t_j \) of the field as \( E_j = E(x_0, t_j) \) and the perturbed distribution function as \( \delta f_{j0}(v) \equiv \delta f_s(x_0, v, t_j) \). For a correlation interval of \( \tau = N\Delta t \), we define the field–particle correlation at time \( t_j \) at position \( x_0 \) by

\[
C_j(x_0, v, t_j, \tau) \equiv \frac{1}{N} \sum_{i=1}^{N} \frac{q_v^2 v^2}{2} \frac{\partial \delta f_{j0}(v)}{\partial v} E_i.
\]

Note that this correlation is not normalized since the product directly corresponds to the rate of energy transfer, so the amplitude variation of this product as a function of velocity yields valuable information about the nature of the collisionless field–particle interaction.

For single-point measurements, the general idea of diagnosing the energy transfer at each point in phase space reduces to determining the distribution of the energy transfer rate in velocity space, producing a velocity-space signature characteristic of the physical mechanism. Different collisionless mechanisms are likely to have distinct velocity-space signatures of the energy transfer. We illustrate this field–particle correlation analysis method for the case of the Landau damping of Langmuir waves in a 1D–1V Vlasov–Poisson plasma, but the concept of using field–particle correlations to diagnose collisionless energy transfer is extremely general. In principle, this method can use single-point spacecraft measurements to examine the energization of particles in any weakly collisional heliospheric plasma.

4. NUMERICAL RESULTS

Using the nonlinear Vlasov–Poisson simulation code VP (Howes et al. 2016), we apply field–particle correlations to examine collisionless damping in three cases: (I) a moderately damped standing Langmuir wave pattern with \( k\lambda_{de} = 0.5 \); (II) a weakly damped standing Langmuir wave pattern with \( k\lambda_{de} = 0.25 \); and (III) a moderately damped single propagating Langmuir wave mode with \( k\lambda_{de} = 0.5 \), where \( \lambda_{de} = \sqrt{k_B T_e/4\pi n_e q^2} \) is the electron Debye length. For cases I and II, \( \delta f_s(t = 0) \) is a sine wave with wavelength \( k\lambda_{de} \); for case III, \( \delta f_s(t = 0) \) satisfies the Langmuir wave linear dispersion relation.

The VP code evolves the nonlinear Vlasov–Poisson system of equations for ion and electron species using second-order centered finite differencing for spatial and velocity derivatives and a third-order Adams–Bashforth scheme in time. Spatial boundary conditions are periodic, and a Green’s function solution is used to determine \( \phi \). All cases have plasma parameters \( T_i/T_e = 1 \) and \( m_i/m_e = 100 \) and numerical resolutions \( n_x = 128 \) and \( n_v = 256 \) with a simulation domain of length \( L = 2\pi/k \). The cases with \( k\lambda_{de} = 0.5 \) have a resonant velocity of \( \omega/k = 2.86(4.4)\nu_{pe} \) and a linear damping rate of \( 1.59 \times 10^{-3}(2.05 \times 10^{-3})\nu_{pe} \).

In Figure 1, we plot the instantaneous rate of change of \( w_s \) due to the nonlinear wave–particle interaction term, \(-q_v^2 v^2 \partial \delta f E/2\), at \( x = 0 \) for the three cases (a)–(c). Without calculating the correlation \( C_j \) over an appropriate time interval \( \tau \), the largest rates of energy transfer do not necessarily
correspond to the resonant velocities, \( v = \omega/k \) (dotted-dashed black lines). The reason is that the larger-amplitude oscillating energy transfer of the Langmuir waves masks the smaller-amplitude secular energy transfer of the collisionless damping.

Also plotted in Figure 1 is the time evolution of the electrostatic field energy \( W_e = \int dx \, E^2/8\pi \) (long-dashed gray) and the perturbed electron energy \( dW_e = \int dx \, \int dv \, m_v^2 \delta f_e/2 \) (dashed red), showing that \( \partial W_e/\partial t \sim \delta W_e/\partial t \) because the Landau damping of Langmuir waves transfers little of the electrostatic field energy to the ions for \( m_i/m_e = 100 \). Thus, we focus here strictly on energy transferred to electrons. We also plot the nonlinear wave–particle interaction term integrated over all phase-space and time, 

\[
-\int_0^t dt' \int dx \int dv \, q_e v^2 (\delta f_e(x,v,t'))/2 \] (dotted blue), demonstrating that this term alone contains all of the net energy transfer to the electrons. Finally, at the single-point \( x = 0 \), we plot the time-integrated transfer rate, 

\[
-\int_0^t dt' \int dx \int dv \, q_e v^2 \delta f_e(0, v, t') E(0, t')/2 \] (solid black), showing that we obtain a significant net transfer of energy from the field to the electrons for both moderately damped cases with \( k\lambda_{pe} = 0.5 \).

To isolate the small-amplitude secular energy transfer in the presence of a much larger-amplitude oscillating energy transfer, we must select an appropriate correlation interval \( \tau \). In Figure 2, we plot the correlation \( C_1(v_0, t, \tau) \) from Equation (2) for a range of correlation intervals \( 0 \leq \omega_{pe} \tau \leq 12 \) (color bar) for case I both for (a) an off-resonance velocity \( v_0 = 1.25 V_{te} \) and (b) an on-resonance velocity \( v_0 = 2.85 V_{te} \). The \( \tau = 0 \) curve (dark blue) corresponds to a vertical slice along Figure 1(a) at the selected velocity \( v_0 \). As the correlation interval \( \tau \) increases, the large-amplitude signal of the oscillating energy transfer is increasingly averaged out. For this case, the normalized wave period is \( T_{\omega_{pe}} = 4.39 \), and we find that for correlation intervals \( \tau > T \), the large-amplitude oscillating energy transfer rate is significantly reduced, revealing the smaller-amplitude secular energy transfer rate beneath. Integrating the correlation in time, 

\[
\int_0^\tau dt' C_1(v_0, t', \tau) \] (c) we find (c) little net energy at the non-resonant velocity, and (d) significant particle energization at the resonant velocity \( v_0 = 2.85 V_{te} \).

In Figure 3, we plot the key results of this Letter, the field–particle correlations \( C_1 \) for \( \tau_{\omega_{pe}} = 6.28 \) as a function of velocity and time for cases I–III (a)–(c). With a suitably long correlation interval \( \tau > T \), the large-amplitude signal of the oscillating energy transfer, dominating Figure 1, is diminished, revealing the secular transfer of energy. This velocity–space signature of the secular energy transfer rate is concentrated around the resonant velocity for the moderately damped cases, indicating a resonant process. Integrating \( C_1 \) over velocity yields the net energy transfer rate at that point in space (offset panels), equal to \( jE \). This velocity integration demonstrates a net transfer of energy to the particles, but loses all velocity–space information that can be used to identify the nature of the collisionless energy transfer mechanism. The weakly damped case has a relatively insignificant energy transfer rate. In panels (d)–(f), we plot the accumulated change in the electron phase-space energy density, \( \Delta W_e(x_0, v, t) = \int_0^\tau dt' C_1(v, t', \tau) \), showing a loss of energy at \( v > \omega/k \) and gain of energy at \( v < \omega/k \) for the moderately damped cases. This velocity–space signature corresponds physically to a flattening of the distribution function at the resonant velocity, consistent with the evolution of the spatially averaged electron VDF predicted by quasilinear theory (Howes et al. 2016). The nearly monotonic increase of \( \int dv d\tau C_1 \) for the moderately damped cases shows that \( C_1 \) serves as a measure of collisionless damping rate and not merely the presence of monochromatic waves.

5. APPLICATION TO SOLAR WIND TURBULENCE

Proposed collisionless damping mechanisms in the solar wind fall into three classes: (i) coherent collisionless wave–
Particle interactions, such as Landau damping, transit-time damping, or cyclotron damping (Landau 1946; Barnes 1966; Leamon et al. 1998, 1999, 2000; Quataert 1998; Quataert & Gruzinov 1999; Howes et al. 2008; Schekochihin et al. 2009; TenBarge & Howes 2013); (ii) incoherent collisionless wave–particle interactions, primarily leading to stochastic ion heating (Chen et al. 2001; White et al. 2002; Voitenko & Goossens 2004; Bourouaine et al. 2008; Chandran et al. 2010, 2011; Chandran 2010; Bourouaine et al. 2013); and (iii) dissipation in coherent structures, specifically current sheets, generally involving collisionless magnetic reconnection (Dmitruk et al. 2004; Markovskii & Vasquez 2011; Matthaeus & Velli 2011; Osman et al. 2011, 2012a, 2014b; Servidio et al. 2011; Wan et al. 2012; Karimabadi et al. 2013; Zhdankin et al. 2013, 2015). Under weakly collisional conditions, all of these mechanisms are mediated by interactions between the electromagnetic fields and the individual plasma particles, and therefore all will lead to a correlation between the fields and particle VDFs. Each mechanism is likely to generate a distinct velocity-space signature that can be diagnosed using the general approach of field–particle correlations.

For the case of the damping of solar wind turbulence, the appropriate form of the correlation will depend on the specific mechanism. For example, ion transit-time damping (Barnes 1966; Quataert & Gruzinov 1999)—the magnetic analog of Landau damping—will involve a correlation of the parallel perturbed magnetic field $\delta B_k$ and the ion parallel VDF $\delta f_i(v_i)$. In addition, the appropriate component of the field may be difficult to measure in space, such as the parallel component of the electric field, $E_{||}$, that leads to Landau damping. In this case, since the electromagnetic components are related by Maxwell’s equations, another field component may be used as a proxy (since, at least in some instances, the fields have been shown to satisfy linear eigenfunction relationships; Howes et al. 2012; Klein et al. 2012; Salem et al. 2012; Chen et al. 2013). Although the proxy correlation no longer corresponds directly to the transfer rate of phase-space energy density, it may nonetheless indicate the order of magnitude of the net energy transfer and its velocity-space signature may reveal the resonant nature of the interaction.

The super-Alfvénic flow of the solar wind is often exploited to interpret the temporal fluctuations measured by the spacecraft as the result of spatial fluctuations being swept past the spacecraft by the solar wind flow, an approximation known as the Taylor hypothesis (Taylor 1938). How does this solar wind flow impact the field–particle correlation technique? The key step is to perform the correlation over a suitably long correlation interval $\tau$ in order to average out the generally larger-amplitude oscillating energy transfer. Fundamentally, to average out the oscillatory component, all that is necessary is that the measurements span more than $2\pi$ of the wave phase $\alpha$, a function of time and position, $\alpha(x, t) = kx - \omega t$. If the point of measurement is moving in space, $x_0(t)$, then the method simply requires that the phase $\alpha(t) = kx_0(t) - \omega t$ span more than $2\pi$ over the correlation interval $\tau$, so the technique is essentially insensitive to the solar wind flow. The confirmation of this assertion in a fully turbulent system is the focus of ongoing work.

The broadband nature of turbulent fluctuations could potentially smear out the velocity-space signature associated with damping at a particular wavelength. Preliminary studies (Howes et al. 2016) indicate that the narrow range of length scales over which certain damping mechanisms operate may alleviate this potential problem.

Finally, it may be impractical to compute the velocity derivative of the perturbed distribution function due to the noise and limited resolution of spacecraft measurements, so we may use an alternative correlation

$$C_2(x_0, v, t, \tau) = \frac{1}{N} \sum_{j=1}^{N} \frac{1}{N} \sum_{j=1}^{N} q_i \delta f_{j}(v) E_{j}. \quad (3)$$

![Figure 3. Velocity-space structure of the field–particle correlation $C_1$ (top row) and $\int_0^t dt' C_1$ (bottom) as well as the velocity integration of these quantities (offsets) for case I (a) and (d), II (b) and (e), and III (c) and (f). The correlation interval $\tau_{|||}$ is set to 6.28.](image-url)
Figure 4. Velocity-space structure of $C_2$ (top panel) and $\int_0^t dt' C_2$ (bottom panel) for case I, which may serve as an alternative observable to $C_1$. Integration over velocity of $C_1$ (black line in offset) and $C_2$ (red line) are in agreement.

Note that this correlation is related to $C_1$ by an integration by parts in velocity, so the velocity-integrated energy transfer rate is identical to that of $C_1$ (see offset panels in Figure 4). Both $C_2(v, t, \tau)$ and time-integrated correlation $\int_0^t C_2(v, t', \tau) dt'$ with $\tau \omega_{pe} = 6.28$ for case I are plotted in Figure 4, yielding a velocity-space signature that indeed indicates a resonant process.

6. CONCLUSION

Here, we present a novel field–particle correlation technique that requires only single-point measurements of the electromagnetic fields and particle VDFs to return an estimate of the net rate of energy transfer between fields and particles. Furthermore, this innovative method yields valuable information about the distribution of this energy transfer in velocity space, providing a vital new means to identify the dominant collisionless mechanisms governing the damping of the turbulent fluctuations beyond that provided by measurements of velocity-integrated quantities such as $j \cdot E$.

This field–particle correlation technique fully exploits the vast treasure of information contained in the fluctuations of the particle VDFs, potentially enabling new discoveries using single-point spacecraft measurements. We believe this very general technique of field–particle correlations will transform our ability to maximize the scientific return from current, upcoming, and proposed spacecraft missions, including the Magnetospheric Multiscale (MMS; Burch et al. 2016), Solar Probe Plus (Fox et al. 2015), Turbulent Heating ObserveR (THOR), and ElectroDynamics and Dissipation Interplanetary Explorer (EDDIE) missions. Further testing and refinement of this technique will characterize its sensitivity to the noise, limited velocity-space resolution, and limited cadence of spacecraft measurements, as well as its ability to extract a meaningful velocity-space signature of the collisionless damping mechanism in the presence of the broadband spectrum of fluctuations that is characteristic of a turbulent plasma.

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