A prospectus on kinetic heliophysics

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Under the low density and high temperature conditions typical of heliospheric plasmas, the macroscopic evolution of the heliosphere is strongly affected by the kinetic plasma physics governing fundamental microphysical mechanisms. Kinetic turbulence, collisionless magnetic reconnection, particle acceleration, and kinetic instabilities are four poorly understood, grand-challenge problems that lie at the new frontier of kinetic heliophysics. The increasing availability of high cadence and high phase-space resolution measurements of particle velocity distributions by current and upcoming spacecraft missions and of massively parallel nonlinear kinetic simulations of weakly collisional heliospheric plasmas provides the opportunity to transform our understanding of these kinetic mechanisms through the full utilization of the information contained in the particle velocity distributions. Several major considerations for future investigations of kinetic heliophysics are examined. Turbulent dissipation followed by particle heating is highlighted as an inherently two-step process in weakly collisional plasmas, distinct from the more familiar case in fluid theory. Concerted efforts must be made to tackle the big-data challenge of visualizing the high-dimensional (3D-3V) phase space of kinetic plasma theory through physics-based reductions. Furthermore, the development of innovative analysis methods that utilize full velocity-space measurements, such as the field-particle correlation technique, will enable us to gain deeper insight into these four grand-challenge problems of kinetic heliophysics. A systems approach to tackle the multi-scale problem of heliophysics through a rigorous connection between the kinetic physics at microscales and the self-consistent evolution of the heliosphere at macroscales will propel the field of kinetic heliophysics into the future. *Published by AIP Publishing.*

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I. INTRODUCTION

Humanity continually strives to understand its environment, not only to ensure its continued survival, but also for the sake of knowledge itself. The heliosphere—the realm of influence of our Sun, within which the planets of our solar system orbit—is our home in the universe. Nuclear fusion within the core of the Sun is the source of energy that enables life to thrive on our planet. The majority of this energy emerges as light, but a small fraction of this energy also drives a supersonic flow of diffuse ionized gas, or plasma, that blows radially outward toward the outer reaches of the heliosphere. Carrying along with it an embedded magnetic field, this solar wind varies dramatically in response to conditions at the Sun, and is strongly disturbed during periods of violent activity on the Sun's surface. It is the dynamics of this magnetized plasma that governs the interaction of the Sun with the Earth and the other planets of our solar system. Humankind has spent billions of dollars to launch spacecraft to explore our heliosphere in the scientific endeavor to understand and predict the dynamics of the interplanetary plasma that affect the Earth and its environment, and here I highlight some issues at the frontier of that effort.

The inaugural Ronald C. Davidson Award for Plasma Physics recognized the development of a simple analytical model and supporting numerical simulations of the turbulent

cascade and its kinetic dissipation at small scales,¹ but to progress further requires kinetic theory. The low density and high temperature conditions of the plasma that fills the heliosphere—as well as many more remote astrophysical systems—lead to a mean free path for collisions that is often longer than the length scales relevant to many dynamical processes of interest. Under these weakly collisional conditions, the dynamics of the plasma require investigation using the equations of kinetic plasma physics.

For example, many space and astrophysical plasmas are found to be turbulent. One of the key impacts of this turbulence is the nonlinear transfer of the energy of large-scale electromagnetic fields and plasma flows down to small scales at which the turbulent energy is ultimately converted to plasma heat, or to some other energization of the plasma ions and electrons. At the largest scales of the astrophysical turbulent cascade in the interstellar medium,^{2,3} the length scales of the turbulent fluctuations may be much larger than the collisional mean free path, meaning that a fluid description of the turbulent dynamics at these scales is generally sufficient. But at all scales of the turbulence in the solar wind,^{4,5} and at the smallest scales of the turbulence in the interstellar medium,⁶ the length scales of the turbulent fluctuations are much smaller than the collisional mean free path. Under these conditions, the effect of collisions is negligible on the timescale of the turbulent fluctuations. Not only are collisions insufficient to maintain the Maxwellian particle velocity distributions that motivate the use of a fluid

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description, but collisionless interactions generally dominate the energy exchange between the fluctuating electromagnetic fields and the plasma particles.^{7,8} Therefore, the equations of kinetic plasma physics are essential to describe the mechanisms responsible for removing energy from the turbulent fluctuations and consequently energizing the plasma particles.

For the weakly collisional interplanetary plasma, such “microphysical” kinetic processes govern the heating of the plasma and the energization of particles, and thereby they exert a significant influence on the macroscopic evolution of the heliosphere. Plasma turbulence, magnetic reconnection, particle acceleration, and instabilities are four fundamental plasma processes operating under weakly collisional conditions that significantly impact the evolution of the heliosphere. These four grand-challenge topics lie at the frontier of heliophysics. The details of these kinetic plasma processes remain relatively poorly understood, motivating the heliophysics community to pursue a coordinated effort of spacecraft observations, numerical simulations, kinetic plasma theory, and even laboratory experiments to develop a thorough understanding, and ultimately a predictive capability, of these processes in kinetic heliophysics. This prospectus examines important issues in our exploration of the kinetic plasma physics of the heliosphere.

A. The transport of mass, momentum, and energy in the heliosphere

The key impact of these four fundamental kinetic plasma physics processes—kinetic turbulence, collisionless magnetic reconnection, particle acceleration, and instabilities—is their effect on the transport of particles, transfer of momentum, and flow of energy throughout the heliosphere.

Extreme space weather illustrates concisely how the transport of mass, momentum, and energy by these kinetic plasma physics mechanisms governs conditions within the heliosphere, possibly leading to adverse impacts on the Earth and its near-space environment. Magnetic buoyancy instabilities cause the strong magnetic fields generated by the solar magnetic dynamo to rise out of the turbulently boiling solar convection zone, emerging through the photosphere and building up strong magnetic fields in lower solar atmosphere, or corona. Eventually, some type of explosive instability can initiate vigorous magnetic reconnection, hurling tons of magnetized plasma out into the heliosphere at thousands of kilometers per second, an event known as a coronal mass ejection. Magnetic energy released through the process of reconnection can also accelerate electrons back down towards the photosphere, often causing a powerful solar flare that enhances x-ray and UV fluxes radiating from the Sun. In addition, as the magnetized cloud of ejected plasma barrels at supersonic and super-Alfvénic speeds through the slower ambient solar wind, a collisionless shock forms on the leading edge, frequently accelerating protons, electrons, and minor ions to nearly the speed of light, showering the heliosphere in a solar energetic particle event.

These energetic particles stream through the heliosphere, being scattered by fluctuations in the turbulent interplanetary magnetic field. Because these energetic particles

pose a serious hazard to communication and navigation satellites as well as manned spacecraft missions, predicting their fluxes in the near-Earth environment is a critical element of space weather forecasting, requiring an understanding of the transport of these particles through the turbulent solar wind. In addition, the enhanced x-ray and UV fluxes from a strong solar flare can boost ionization in the ionosphere, interfering with or even totally disrupting radio communications with satellites and aircraft on polar flight paths.

If the coronal mass ejection is directed towards the Earth, its momentum can lead to a severe compression of the Earth’s magnetosphere, altering the system of currents that modify the Earth’s magnetic field, and triggering a geomagnetic storm. During a geomagnetic storm, the magnetic field embedded within the ejected coronal plasma can undergo reconnection with Earth’s protective magnetic field, greatly enhancing the penetration of interplanetary plasma into the magnetosphere, thereby boosting the density of the ring current caused by the azimuthal (longitudinal) drift of ions and electrons trapped in Earth’s dipolar magnetic field. During particular strong geomagnetic storms, this enhancement of the ring current can depress the magnitude of the magnetic field at the Earth’s surface by a few percent, causing intense geomagnetically induced currents that may damage critical components of the electrical power grid. As the geomagnetic storm rages, the aurorae at the poles light up, driven either by particles streaming down along open field lines toward the ionosphere or by the acceleration of electrons by Alfvén waves which transmit shifts in Earth’s distant magnetosphere along field lines down to the Earth.

This complicated interplay of the different phenomena that constitute space weather illustrates the fundamental importance of turbulence, magnetic reconnection, particle acceleration, and instabilities to the dynamics of the heliosphere and its impact on Earth and society. It is important to emphasize that most of the processes mentioned above remain poorly understood in detail. An overarching aim of heliophysics is to improve our understanding of these fundamental processes and their effect on the transport of particles, momentum, and energy, with the ultimate aim to develop a predictive capability for space weather and its impact on our lives. The path forward is through the application of kinetic plasma physics to the study of heliospheric processes, giving birth to the new frontier of *kinetic heliophysics*.

B. A coordinated approach

Although spacecraft missions enable *in situ* measurements of the fluctuating electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ and of the particle velocity distribution functions in the three-dimensions of velocity space $f_s(\mathbf{v})$, many of these fundamental kinetic processes in heliospheric plasmas remain poorly understood. One reason is that spacecraft measurements suffer the significant limitation that we measure information only at a single point, or at most a few points, in space. To circumvent this limitation of spacecraft observations, many of these kinetic processes can alternatively be explored in laboratory experiments under more controlled

conditions and with the ability to make measurements at many points in space, even if it is not possible to achieve the same plasma parameters or scale separations found in space. A further complication in exploring kinetic heliophysics is the inherent high dimensionality of kinetic plasma theory, with its fundamental variables being the particle distribution functions for each species s in six-dimensional phase space (3D-3V, three dimensions in physical space and three dimensions in velocity space), $f_s(\mathbf{r}, \mathbf{v}, t)$. Theoretical insights from kinetic plasma theory are vital to reduce this six-dimensional phase space to a more tractable, smaller number of essential dimensions, for either space-based or laboratory investigations. Finally, kinetic numerical simulations provide a critical bridge between the often idealized conditions susceptible to analytical theory and the more complex, nonlinear evolution of actual space or laboratory plasmas.

A closely coordinated approach of analytical theory, numerical simulations, spacecraft measurements, and laboratory experiments has the greatest potential for transforming our understanding of the kinetic plasma physics that influences the evolution of the heliosphere. Here, we discuss some important considerations for the next generation of investigations into kinetic heliophysics.

II. DAMPING, DISSIPATION, AND HEATING IN WEAKLY COLLISIONAL PLASMAS

A subtle but important issue arises in the investigation of the conversion of the electromagnetic energy of fields and the kinetic energy of bulk plasma flows into plasma heat by kinetic physical mechanisms in weakly collisional heliospheric plasmas. That bottom line is that, unlike in the more well-known case of fluid systems, in weakly collisional plasmas, the dissipation of turbulent energy into plasma heat is inherently a two-step process.

Fluid systems are derived from the strongly collisional, or small mean free path, limit of the Boltzmann equation in kinetic theory. In this limit, frequent microscopic collisions maintain the Maxwellian equilibrium velocity distributions of local thermodynamic equilibrium. A hierarchy of moment equations may be derived in the limit of small mean free path (relative to the characteristic length scales of gradients in the system) by the Chapman-Enskog procedure⁹ for neutral gases, or an analogous procedure for plasma systems.¹⁰ Microscopic collisions in the limit of finite mean free path give rise to the diffusion of velocity fluctuations by viscosity and of magnetic field fluctuations by resistivity. Because viscosity and resistivity are ultimately collisional, the diffusion of the velocity and magnetic field fluctuations by these mechanisms is irreversible, dissipating the kinetic and electromagnetic energy of these fluctuations, and consequently realizing thermodynamic plasma heating and the associated increase of the system entropy. This picture of plasma heating, based on the physical intuition derived from the fluid system, implies that energy removed from the velocity and electromagnetic field fluctuations through viscosity and resistivity is immediately converted into plasma heat.

But in weakly collisional plasmas, the removal of energy from the electromagnetic field fluctuations and bulk

plasma flows is a separate process from the irreversible conversion of that energy into plasma heat. In fact, the energy removed by kinetic processes may not all be irreversibly converted into heat, but rather some energy may be channeled instead into nonthermal particle energization, such as the acceleration of small fraction of particles to high energy, in apparent defiance of the first law of thermodynamics. These subtleties require a significantly different approach to the study of the dissipation of plasma turbulence and the resulting energization of the plasma under the typically weakly collisional conditions of heliospheric plasmas.

To consider in more detail the dynamics and dissipation of turbulence in weakly collisional heliospheric plasmas, we turn to the Boltzmann equation which governs the evolution of the six-dimensional velocity distribution function $f_s(\mathbf{r}, \mathbf{v}, t)$ for a plasma species s

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right] \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t} \right)_{\text{coll}}. \quad (1)$$

Combining a Boltzmann equation for each species with Maxwell's equations forms the closed set of Maxwell-Boltzmann equations that govern the nonlinear kinetic evolution of a plasma. In the inner heliosphere (within 1 AU of the sun), the typical conditions of the interplanetary plasma lead to a collisional mean free path that is of order 1 AU, approximately 10^8 km.⁵ In comparison, the largest scale structures of the interplanetary turbulent cascade have a length scale of 10^6 km. The upshot is that the collisional term on the right-hand side of (1) is subdominant, not significantly affecting the turbulent dynamics on the timescale of the turbulent fluctuations.

Since the collisional term in (1) is insufficient to diminish the turbulent fluctuations in heliospheric plasmas, the removal of energy from the turbulent electromagnetic field and bulk plasma flow fluctuations occurs through interactions between the electromagnetic fields and the charged plasma particles,^{8,11} and these interactions are governed by the Lorentz force term, the third term on the left-hand side of (1). The linear collisionless wave-particle interactions—such as Landau damping,^{12,13} Barnes damping,¹⁴ and cyclotron damping¹⁵—provide familiar examples of such interactions. But it is important to note that a net transfer of energy from fields to particles, depleting the energy of electromagnetic fluctuations and boosting the microscopic kinetic energy of the particles, can occur under more general circumstances that do not require the persistent presence of waves. Fundamentally, when collisions are weak, the only avenue to remove energy from electromagnetic field and bulk plasma flow fluctuations is through collisionless interactions between the fields and the particles, where the electromagnetic forces do net work on the plasma particles.

One of the key fundamental distinctions, compared to the viscous and resistive dissipation in a fluid system, is that the net energy transfer between fields and particles by the work of electromagnetic forces is reversible, with no associated increase in the system entropy. In a kinetic system, Boltzmann's H Theorem shows that the increase of entropy, and therefore irreversible plasma heating, can only be

accomplished through collisions.^{16,17} So, how can one achieve irreversible heating in a plasma of arbitrarily weak collisionality? To accomplish irreversible heating requires a subsequent process that enhances the effectiveness of even arbitrarily weak collisions, as explained below.

When the collisionless interaction between fields and particles mediates the removal of energy of the electromagnetic field fluctuations, that energy is transferred to the particles, appearing as fluctuations in velocity space of the particle distribution functions. The general form of the collision operator involves second-derivatives in velocity, so the rate of change of the distribution function due to collisions takes the form¹⁷ $\partial f / \partial t \sim \nu v_t^2 \partial^2 f / \partial v^2 \sim \nu / (\Delta v / v_t)^2 f$. We must compare the rate of the collisional evolution to the typical frequency ω of the turbulent fluctuations, governed by the other terms of the Boltzmann equation. Even if the collisional frequency ν is arbitrarily small, $\nu \ll \omega$, the rate of change of the distribution function due to collisions can compete with the frequency of turbulent fluctuations if the scale of the velocity space fluctuations Δv is sufficiently small relative to the typical thermal velocity v_t , $\Delta v / v_t \sim (\nu / \omega)^{1/2}$. Note that these small fluctuations in velocity space typically contribute little to the first moment of the distribution functions (which yields the bulk plasma flows and current density), so the turbulent fluctuations are insignificantly affected by these small fluctuations in velocity space.⁷

How do the fluctuations generated by collisionless interactions reach sufficiently small scales in velocity space that collisions can effectively smooth them out? The answer depends on the associated spatial length scale of the fluctuations. One process is the linear phase mixing governed by the ballistic term of the Boltzmann equation [the second term on the left-hand side of (1)]. Note, however, it has been recently suggested that, for length scales large relative to the thermal Larmor radius of particle species s , $k_\perp \rho_s \ll 1$, an anti-phase mixing mechanism in the presence of turbulence may prevent these fluctuations in velocity space from reaching sufficiently small velocity scales, $\Delta v / v_{ts} \sim (\nu / \omega)^{1/2}$, to be thermalized by weak collisions.^{18,19} At length scales smaller than the Larmor radius, $k_\perp \rho_s \gtrsim 1$, a nonlinear phase-mixing mechanism, arising from differential drifts due to the particle-velocity-dependent Larmor averaging of the electromagnetic fields,²⁰ also known as the entropy cascade,^{17,21–24} may effectively drive velocity-space fluctuations to sufficiently small scales to achieve irreversible heating through collisions.

The primary message here is that the physical mechanisms governing the damping of turbulent fluctuations and the subsequent irreversible heating in weakly collisional heliospheric plasmas has an inherently different nature from dissipation in the strongly collisional, fluid systems with which most people are more familiar. Kinetic plasma physics plays a central role in the process of particle energization, defining a key frontier in kinetic heliophysics. Below, we will highlight how these key differences motivate powerful new approaches to the study of the flow of energy throughout the heliosphere, approaches that fully utilize the measurements routinely made by modern spacecraft missions.

III. VELOCITY SPACE: THE NEXT FRONTIER

Tackling the six-dimensional phase space of kinetic plasma physics presents the new challenge of interpreting not only the fluctuations in space and time, as necessary in fluid theory as well, but also the dynamics in velocity space. By utilizing the full information content of velocity-space measurements, however, we have the tremendous opportunity to realize a transformative leap in our understanding of kinetic heliophysics. Visualization of the high-dimensional datasets of modern spacecraft instrumentation and cutting-edge kinetic numerical simulations represents a new, big-data challenge. Physics-driven reduction of the data is essential for interpreting the results of complicated nonlinear kinetic dynamics, and innovative new analysis methods promise to shed new light on how particles in different regions of velocity space contribute to the dynamics. Here, I present some thoughts on exploiting velocity space, the next frontier in kinetic heliophysics.

A. New insights lurking in velocity space

Spacecraft suffer the inherent limitation that measurements are made at only a single point in space (or in the case of multi-spacecraft missions, a few points in space). But, at that single point in space, ion and electron instruments can measure the full three-dimensional distribution of particle velocities. Velocity space is a messy place, especially in the turbulent state typical of heliospheric plasmas, and although the fluctuations in the particle velocity distribution functions are hard to interpret, they contain a vast store of information that has been largely underutilized.

Often spacecraft measurements of the velocity distributions are used to compute moments of the distributions, yielding the density, bulk flow velocity, and (possibly anisotropic) temperature of the plasma, while more sophisticated approaches may compute other dynamic quantities, such as the heat flux. For example, over the last fifteen years, several breakthrough observational investigations have illuminated the role of kinetic temperature anisotropy instabilities in regulating the temperature anisotropy of the solar wind plasma.^{25–28} Kinetic plasma theory²⁹ provided critical guidance in this case, suggesting that the action of these kinetic temperature anisotropy instabilities is most clearly illustrated on a plot of the $(\beta_\parallel, T_\perp / T_\parallel)$ plane, often called a Brazil plot because the distribution of measurements of the near-Earth solar wind plasma on this plane resembles the geographic outline of Brazil.

Velocity space, however, contains far more information about the kinetic dynamics of heliospheric plasmas than just these low-order moments. In particular, velocity space retains an imprint of the collisionless interactions between the electromagnetic fields and the plasma particles, so the investigation of the morphology of the velocity distribution functions can be used to gain insight into the processes which govern the plasma evolution.

Early measurements from the *Helios* spacecraft within 1 AU showed proton velocity distributions with a strongly anisotropic core (having a characteristic temperature perpendicular to the local magnetic field that is greater than the

temperature parallel to the field) and a significant field-aligned beam.³⁰ Subsequent detailed examinations of the equilibrium proton velocity distribution functions measured in the solar wind have sought evidence for the quasilinear diffusion of proton distribution functions through pitch angle scattering by ion cyclotron waves^{31–35} and for the development of a plateau (quasilinear flattening) in the distribution function along the field-aligned direction through Landau damping.³⁵ Currently, proton and electron velocity distribution functions measured at unprecedented phase-space resolution and cadence by the *Magnetospheric Multiscale* (MMS) mission³⁶ are providing a detailed view of the kinetic plasma dynamics associated with collisionless magnetic reconnection in the Earth's magnetosphere.³⁷

Indeed, searching for evidence of the quasilinear evolution of the mean velocity distribution functions by examining structures in velocity space can provide important clues about the kinetic evolution of the plasma, but there is actually much more information contained within the *fluctuations* in velocity space.

For example, the Morrison G transform³⁸ is an integral transform of the perturbations in the velocity distribution function for an electrostatic system. This transform enables the perturbation to the distribution function to be written as a weighted sum of Case-Van Kampen modes, a continuous spectrum of solutions to the Vlasov equation.^{39,40} With reasonable assumptions, the Morrison G transform can be exploited to reconstruct the spatial dependence of the electric field from measurements of the perturbed distribution function made at just a single location in space.⁴¹ This example illustrates the potential for fully exploiting the information contained in the fluctuations in velocity space to gain much deeper insight into the kinetic plasma dynamics, an approach that requires detailed guidance from kinetic plasma theory.

Transformative progress can be made in kinetic heliophysics by capitalizing on the power of kinetic plasma theory to devise insightful new analysis techniques that can be applied to the high cadence and high phase-space resolution measurements of particle velocity distributions enabled by modern spacecraft instrumentation. One such promising new method is the field-particle correlation technique,^{8,11} described in Sec. III D. Cutting-edge nonlinear kinetic simulations of the plasma dynamics provide a valuable tool both to test these new techniques under realistic plasma conditions and to interpret the results of their application to spacecraft measurements. Finally, the development of powerful new diagnostics for measuring the velocity distribution functions in the laboratory will enable complementary experiments that test critical aspects of kinetic physical processes in space plasmas.

B. Visualizing velocity space

A key challenge for fully utilizing velocity distribution measurements is the visualization and analysis of the high-dimensional data arising from the six-dimensional (3D-3V) phase space of kinetic plasma theory. In particular, nonlinear kinetic numerical simulations are able to compute the full six-dimensional velocity distribution functions for each

species, $f_s(\mathbf{r}, \mathbf{v}, t)$, at each point in time, resulting in a big-data challenge for the analysis of kinetic heliophysics problems. Six-dimensions is more than can easily be visualized, so a physics-driven reduction of this high-dimensional data is essential for the interpretation of the complicated nonlinear kinetic dynamics.

Even for spacecraft observations, where particle velocities are measured at only a single point in space as a function of time, visualizing the three-dimensional velocity distributions can be awkward, but theoretical considerations can point to helpful simplifications. The recent study by He *et al.*,³⁵ for example, presents cross-sections through the three-dimensional proton velocity distribution functions measured by the *WIND* spacecraft. Physical considerations led them to orient these cross-sections relative to the directions of the solar wind flow velocity and the local magnetic field, enabling the characteristic structures in the mean velocity distribution functions to be more easily seen.

But rather than taking cross-sections through a three-dimensional velocity space, which effectively discards the bulk of the 3-V information that lies outside of that cross-section, integrating the data over an ignorable coordinate incorporates the full data set, yielding an improved signal-to-noise ratio. Under the strongly magnetized conditions typical of heliospheric plasmas—specifically meaning that the typical radius of a particle's Larmor motion about the magnetic field is much smaller than the length scale of spatial gradients in the plasma equilibrium, a condition that is almost always well satisfied in space plasmas¹⁶—the local magnetic field establishes a preferred direction in the plasma. In this case, the helical motion of a charged particle about the magnetic field, caused by the Lorentz force, is most efficiently expressed using cylindrical coordinates for velocity space, $(v_\perp, \theta, v_\parallel)$. Here, $v_\perp$ is the velocity perpendicular to the local magnetic field, θ is the angle of the particle's gyromotion about the magnetic field, and $v_\parallel$ is the particle velocity parallel to the local magnetic field.

If the characteristic frequencies for the evolution of both the equilibrium and the fluctuations are smaller than the cyclotron frequency, $\omega \ll \Omega$, then the distribution function turns out to be *gyrotropic*,⁴² meaning that it is independent of the gyrophase angle θ about the magnetic field, $f(v_\perp, v_\parallel)$. Therefore, integrating over the gyrophase angle incorporates all of the data in three-dimensional velocity space to yield an optimal representation in *gyrotropic velocity space*, $(v_\perp, v_\parallel)$. Note that, in the case of spacecraft measurements, the origin of the velocity-space coordinate system should be centered at the plasma bulk flow velocity.

It is worthwhile noting that, even in cases where the frequencies of the fluctuations violate the low frequency approximation, $\omega \gtrsim \Omega$, and thereby the physics cannot be described using a gyrotropic model, gyrotropic velocity space $(v_\perp, v_\parallel)$ may still be a useful reduction of the three-dimensional velocity space for visualization. For example, in the case of cyclotron damping, the dynamics are inherently not gyrotropic, but the effect on the distribution function is a broadening of the distribution in the plane perpendicular to the local magnetic field,^{43,44} an impact that can be usefully visualized in gyrotropic velocity space $(v_\perp, v_\parallel)$.

In summary, determining the optimal, physics-based reductions of the six-dimensional (3D-3V) phase space of kinetic plasma theory for important heliophysics problems will enable better utilization of the full information content of velocity space. Tackling this challenge to visualize efficiently the high-dimensional data will enable the heliophysics community not only to maximize the scientific return from the high phase-space resolution plasma measurements of current and upcoming spacecraft missions, but also to gain deeper insight into the underlying kinetic physical mechanisms governing the evolution of massively parallel, nonlinear kinetic numerical simulations.

C. Spectral decomposition of velocity space

In a weakly collisional plasma, valuable insight into the flux of free energy in velocity space can be gained by using an appropriate spectral decomposition of the structure of the perturbations to the velocity distribution function. The kinetic equation for the evolution of fluctuations in velocity space parallel to the magnetic field is simplified by recasting the perturbed distribution functions in terms of Hermite polynomials, an approach exploited in early investigations of kinetic plasma physics.^{45–50} Specifically, the linear parallel phase mixing due to the ballistic term in the kinetic equation reduces to a coupling between adjacent Hermite moments, and the Lenard-Bernstein collision operator⁵¹ takes on a particularly simple form since its eigenfunctions are the Hermite polynomials. Recent studies of the dissipation of weakly collisional plasma turbulence have exploited this Hermite representation of parallel velocity fluctuations to diagnose the flow of energy through velocity space.^{18,19,52–57} Likewise, the perpendicular velocity-space structure arising from nonlinear phase mixing^{17,20–22} can be conveniently represented using a Hankel transform,^{21–23,58,59} enabling the flow of energy to smaller scales in perpendicular velocity to be diagnosed clearly. Further use of these optimal spectral decompositions of the structure of fluctuations in velocity space will facilitate greater insights into the nature of particle energization in weakly collisional heliospheric plasmas.

D. Field-particle correlations

To make the most of the velocity-space information provided by modern spacecraft instrumentation and high-performance kinetic numerical simulations, it is essential to develop innovative analysis methods that enable us to gain deeper insight into the grand-challenge problems of kinetic heliophysics: turbulence, collisionless magnetic reconnection, particle acceleration, and instabilities. The recently developed *field-particle correlation technique*^{8,11} employs the electromagnetic field fluctuations along with fluctuations in the particle velocity distribution functions to determine the energy transfer between the fields and particles.

The idea of using correlated field and particle measurements to explore the kinetic physics of space plasmas has found limited application in the aurora^{60–66} and the Earth's magnetosphere^{67,68} using wave-particle correlator instruments flown on sounding rockets and spacecraft. A detailed review of these previous efforts is found in Howes, Klein

and Li.⁸ These early instrumental efforts largely focused on seeking electron phase-space bunching in finite amplitude Langmuir waves, in a regime where the electron count rate was generally significantly lower than the frequency of the Langmuir waves.

With the modern instrumentation on current (*MMS*³⁷), upcoming (*Solar Probe Plus*^{69,70} and *Solar Orbiter*⁷¹), and proposed (*Turbulence Heating ObserveR*, *THOR*⁷²) spacecraft missions, particle velocity distribution function measurements can now be made with unprecedented phase-space resolution and at cadences sufficient to resolve the frequencies of the electromagnetic turbulent fluctuations involved in the damping of the turbulence and resulting energization of the particles. With access now to such high quality velocity-space data from spacecraft observations, and with cutting-edge numerical simulations now capable of simulating the full high-dimensional phase-space of kinetic plasma physics, advanced analysis methods based on kinetic plasma theory have the potential to break new ground in our understanding of kinetic heliophysics.

The field-particle correlation technique was developed to exploit these new instrumental and computational capabilities to provide a new window on the kinetic mechanisms at play in heliospheric plasmas. The novel aspect of this method is that it determines the energy transfer between fields and particles as a function of the particle velocity, yielding a velocity-space signature that characterizes the kinetic mechanism responsible for the energy transfer.

This technique was primarily developed to diagnose the particle energization in plasma turbulence as energy is removed from the turbulent magnetic field and plasma flow fluctuations through collisionless interactions between the fields and particles. The method, however, is simply based on the equations of nonlinear kinetic plasma theory.⁸ At the most basic level, collisionless magnetic reconnection, particle acceleration, and kinetic instabilities are simply nonlinear kinetic plasma physics phenomena, mediated by interactions between the electromagnetic fields and particles. Therefore, the field-particle correlation approach is a fundamental way to explore the evolution of these other processes and their impact on the plasma environment (often significantly influencing the large-scale, macroscopic evolution of the system).

As emphasized earlier in Sec. II, under the weakly collisional conditions relevant to most heliospheric plasmas, the collisional term in the Boltzmann Equation (1) cannot be responsible for the damping of the turbulent fluctuations. Instead, the Lorentz force term, the third term on the left-hand side of (1), governs the collisionless interactions that lead to the net transfer of energy from the electromagnetic fields to the microscopic kinetic energy of individual plasma particles. Therefore, we may drop the collisional term on the right-hand side of (1) to obtain the Vlasov equation for the following analysis.

As an example of the application of the field-particle correlation technique, we briefly derive here the appropriate field-particle correlation for Landau damping in a 3D, electromagnetic plasma. We begin by multiplying the Vlasov

equation by $m_s v^2/2$ to obtain an expression for the rate of change of the phase-space energy density

$$\frac{\partial w_s(\mathbf{r}, \mathbf{v}, t)}{\partial t} = -\mathbf{v} \cdot \nabla w_s - q_s \frac{v^2}{2} \mathbf{E} \cdot \frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s v^2}{c} (\mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}}, \quad (2)$$

where the energy density in six-dimensional phase space for a particle species s is given by $w_s(\mathbf{r}, \mathbf{v}, t) = m_s v^2 f_s(\mathbf{r}, \mathbf{v}, t)/2$.

Under appropriate boundary conditions, such as periodic or infinite spatial boundaries, the first and third terms on the right-hand side of (2) yield zero net energy transfer upon integration over all phase-space, including both spatial volume and velocity space. Therefore, this fundamental application of nonlinear kinetic plasma theory shows that it is the second term that is responsible for the net energy transfer between fields and particles in a collisionless plasma. Since Landau damping is mediated by the component of the electric field parallel to the local magnetic field, $E_{\parallel}$, the term that is responsible for the energy transfer from fields to particles through Landau damping has the form⁷³

$$-q_s \frac{v_{\parallel}^2}{2} \frac{\partial f_s}{\partial v_{\parallel}} E_{\parallel}. \quad (3)$$

Note that the $v^2 = v_{\parallel}^2 + v_{\perp}^2$ factor is reduced to $v_{\parallel}^2$ here because the net energy change is zero for the $v_{\perp}^2$ contribution when integrated over velocity.

But the term in (3) not only governs the physics of the net transfer of energy to the particles through the collisionless Landau damping of the electromagnetic fluctuations, but also contains a significant contribution from the undamped oscillatory motion in the plasma that yields no net energization of particles.⁸ To eliminate this contribution of the oscillatory energy transfer, which often has a larger amplitude than the secular transfer of energy that does yield a net energization of particles, we perform a correlation of the two factors in (3) over a suitably chosen correlation interval τ

$$C_{E_{\parallel}}(\mathbf{v}, t, \tau) = C \left(-q_s \frac{v_{\parallel}^2}{2} \frac{\partial f_s(\mathbf{r}_0, \mathbf{v}, t)}{\partial v_{\parallel}}, E_{\parallel}(\mathbf{r}_0, t) \right). \quad (4)$$

This unnormalized correlation gives the phase-space energy transfer rate between species s and the parallel electric field, and retains its functional dependence on velocity space.

We emphasize here that this method requires measurements of $f_s(\mathbf{v}, t)$ and $E_{\parallel}(t)$ at only a single-point in space $\mathbf{r}_0$. In order to achieve the cancellation of the oscillatory energy transfer, the measurements simply need to span at least 2π in the phase of the fluctuations.⁸ Essentially, this method is complementary to the approach used in quasilinear theory, where a spatial integration over all volume is used to eliminate any oscillatory contribution; here, we integrate over time, rather than space, to sample the full 2π phase of the fluctuations. Note however, that in the presence of fluctuations with different characteristic frequencies (for example, with dispersive waves that are common in plasma physics, such as kinetic Alfvén waves, or in a plasma exhibiting broadband turbulent fluctuations), the integration over time

achieves only an approximate cancellation of the oscillatory component, rather than the exact cancellation that is achieved in quasilinear theory using integration over all space.

It can be shown, through the integration of term (3) over velocity-space, that the net energy transfer rate to a species s is equivalent to $j_{\parallel s} E_{\parallel}$, the rate of net work done on the particles by the parallel electric field,⁸ an approach previously used with spacecraft observations as a direct measure of the plasma heating.^{37,74,75} However, by not integrating over velocity space, the field-particle correlation technique provides much more information than just the net rate of energy transfer to the particles—it provides the distribution of that energy transfer in velocity-space, denoted here the *velocity-space signature*, potentially enabling different mechanisms of energy transfer to be distinguished.

E. Example: Velocity-space signature of the Landau damping of a kinetic Alfvén wave

Here, I present the application of the field-particle correlation technique to determine the velocity-space signature of the particle energization due to the Landau damping of a kinetic Alfvén wave.

A useful reduction of the six-dimensional phase-space of kinetic plasma theory for the modeling of the Landau damping of kinetic Alfvén waves is the gyrokinetic approximation. The derivation of gyrokinetics, a rigorous low-frequency anisotropic limit of kinetic plasma theory,^{16,17,76–82} systematically averages out the particle cyclotron motion, leading to a reduction of the three-dimensional velocity space $(v_{\perp}, \theta, v_{\parallel})$ to the two-dimensional gyrotropic velocity space $(v_{\perp}, v_{\parallel})$. This procedure orders out the fast magnetosonic and whistler waves as well as the cyclotron resonances, but retains finite Larmor radius effects and the collisionless Landau resonance. We employ here the Astrophysical Gyrokinetics code `AstroGK`⁸³ to perform a nonlinear gyrokinetic simulation of the Landau damping of a single kinetic Alfvén wave.

`AstroGK` evolves the perturbed gyroaveraged distribution function $h_s(x, y, z, \lambda, \varepsilon)$ for each species s , the scalar potential φ , the parallel vector potential $A_{\parallel}$, and the parallel magnetic field perturbation $\delta B_{\parallel}$ according to the gyrokinetic equation and the gyroaveraged Maxwell's equations.^{16,80} Velocity space coordinates are $\lambda = v_{\perp}^2/v^2$ and $\varepsilon = v^2/2$. The domain is a periodic box of size $L_{\perp}^2 \times L_{\parallel}$, elongated along the straight, uniform mean magnetic field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$, where all quantities may be rescaled to any parallel dimension satisfying $L_{\parallel}/L_{\perp} \gg 1$. Uniform Maxwellian equilibria for ions (protons) and electrons are chosen, with the correct mass ratio $m_i/m_e = 1836$. Spatial dimensions (x, y) perpendicular to the mean field are treated pseudospectrally; an upwind finite-difference scheme is used in the parallel direction, z . Collisions employ a fully conservative, linearized collision operator with energy diffusion and pitch-angle scattering.^{84,85}

We initialize a single kinetic Alfvén wave with $k_{\perp} \rho_i = 1.3$ for plasma parameters $\beta_i = 1$ and $T_i/T_e = 1$ in a simulation domain of size $L_{\perp} = 2\pi \rho_i/1.3$ and $L_{\parallel} = L_{\perp}/\epsilon$, where $\epsilon \ll 1$ is the gyrokinetic expansion parameter. The simulation resolution is $(n_x, n_y, n_z, n_{\lambda}, n_{\varepsilon}, n_s) = (10, 10, 32, 64, 64, 2)$. The initialization procedure⁸⁶ specifies the initial

perturbed distribution functions and electromagnetic fields according to the eigenfunction from the linear collisionless gyrokinetic dispersion relation¹⁶ for the kinetic Alfvén wave. The solution for this kinetic Alfvén wave has a linear frequency $\omega/\omega_A = 1.237$ and collisionless damping rate $\gamma/\omega_A = -0.0445$, yielding a normalized period $T\omega_A = 5.079$, where $\omega_A = k_{\parallel}v_A = 2\pi v_A/L_{\parallel}$ is the characteristic angular frequency associated with crossing the parallel domain length $L_{\parallel}$ at the Alfvén speed v_A . The initialization procedure includes a short linear evolution of five wave periods with enhanced collisionality $\nu_i = \nu_e = 0.02\omega_A$ to eliminate any transients in the initial conditions that do not satisfy the properties of the desired kinetic Alfvén wave. After the linear transient elimination, the nonlinear evolution of the simulation begins with $\nu_i = \nu_e = 0.002\omega_A$, leading to weakly collisional conditions with $\nu_s/\omega \sim 10^{-3}$.

As the nonlinear simulation evolves, the distribution functions for each species and the electromagnetic fields are sampled at one spatial point in the simulation domain. We choose a correlation interval $\tau\omega_A = 10.0$, which is approximately equal to two periods of the kinetic Alfvén wave. In Figure 1(a), we present the gyrotropic $(v_{\parallel}, v_{\perp})$ velocity-space signature $C_{E_{\parallel}}(-(q_i v_{\parallel}^2/2)\partial f_i(\mathbf{v})/\partial v_{\parallel}, E_{\parallel})$ for the ions, showing the localization in velocity space of the energy transfer between the parallel electric field and the ions around the phase velocity of the kinetic Alfvén wave, $v_{\parallel}/v_{ti} = \omega/(k_{\parallel}v_{ti}) = 1.237$ (vertical black line). Similar to the case of the Landau damping of electrostatic fluctuations (Langmuir waves) in a 1D-1 V Vlasov-Poisson plasma,^{8,11} the energy gain (red) by ions with $v > \omega/k_{\parallel}$ and energy loss (blue) by ions with $v < \omega/k_{\parallel}$ is a signature of the familiar quasilinear flattening of the distribution function in the parallel direction as a result of Landau damping.

In Figure 1(b), we plot the corresponding field-particle correlation $C_{E_{\parallel}}(-(q_e v_{\parallel}^2/2)\partial f_e(\mathbf{v})/\partial v_{\parallel}, E_{\parallel})$ for the electrons using the same correlation interval $\tau\omega_A = 10.0$. One can see a similar localization in velocity space of the energy transfer near the resonant electron velocity $v_{\parallel}/v_{te} = \omega/(k_{\parallel}v_{te}) = 0.029$ (vertical black line), shown in more detail in Figure 1(c) where we have zoomed into the $v_{\parallel}$ range containing the resonant energy transfer. Also apparent in Figure 1(b) are two broader regions of energy transfer at $0.5 \leq |v_{\parallel}/v_{te}| \leq 2.0$. This component of the energy transfer is odd in $v_{\parallel}$, and therefore cancels upon integration over $v_{\parallel}$, leading to no net transfer of energy between fields and particles. This component arises from the incomplete cancellation of the larger-amplitude oscillating energy transfer, both because the correlation interval τ is not exactly an integral multiple of the wave period and because the damping of the wave amplitude leads to incomplete cancellation in the second-half of a wave period. Note that performing the field-particle correlation analysis at other spatial points in the simulation gives qualitatively the same result.

A key point to emphasize about the field-particle correlation technique is that the distribution of the energy transfer in velocity space is expected to depend on the kinetic mechanism of energy transfer. Other physical mechanisms—such as transit-time damping,¹⁴ ion cyclotron damping,^{43,44} stochastic ion heating,^{87–93} or collisionless magnetic reconnection^{54,94–105}—are expected to yield velocity-space signatures

FIG. 1. The gyrotropic $(v_{\parallel}, v_{\perp})$ velocity-space signature of Landau damping of a kinetic Alfvén wave with $k_{\perp}\rho_i = 1.3$, $\beta_i = 1$, and $T_i/T_e = 1$ using a correlation interval $\tau k_{\parallel} v_A = 10$. (a) The correlation $C_{E_{\parallel}}(-(q_i v_{\parallel}^2/2)\partial f_i(\mathbf{v})/\partial v_{\parallel}, E_{\parallel})$ for ions shows a clear signature at the resonant velocity, $v_{\parallel}/v_{ti} = \omega/(k_{\parallel}v_{ti}) = 1.237$ (vertical black line). (b) The correlation $C_{E_{\parallel}}(-(q_e v_{\parallel}^2/2)\partial f_e(\mathbf{v})/\partial v_{\parallel}, E_{\parallel})$ for electrons shows a signature at the resonant velocity $v_{\parallel}/v_{te} = \omega/(k_{\parallel}v_{te}) = 0.029$ (vertical black line). (c) Zooming into the region $-0.5 \leq v_{\parallel}/v_{te} \leq 0.5$ for $C_{E_{\parallel}}$ for the electrons, detailing the distribution of the energy transfer near the resonant velocity $v_{\parallel}/v_{te} = \omega/(k_{\parallel}v_{te}) = 0.029$.

that are qualitatively distinct from that of Landau damping. Ongoing work shows that this field-particle correlation technique, when an appropriate correlation interval is chosen, still works in the presence of strong, broadband kinetic plasma turbulence.⁷³ In addition, the same technique can be used to explore the transfer of free energy in kinetic instabilities from unstable particle velocity distributions to electromagnetic fluctuations.¹⁰⁶

IV. THE ROAD AHEAD

The increasing availability of high cadence and high phase-space resolution measurements of particle velocity distributions by spacecraft and of gyrokinetic 3D-2 V or fully kinetic 3D-3 V nonlinear simulations of weakly collisional heliospheric plasmas motivates a concerted effort to develop new methods to maximize the scientific return from these high-dimensional datasets. Plasma turbulence, magnetic reconnection, particle acceleration, and instabilities are four fundamental kinetic plasma processes operating under weakly collisional conditions that significantly impact the evolution of the heliosphere. The application of kinetic plasma physics to the study of these heliospheric processes is primary driver of the new frontier of *kinetic heliophysics*.

Unlike in a traditional (strongly collisional) fluid, the removal of energy from turbulent fluctuations and conversion of that energy to plasma heat is a two-step process under the weakly collisional plasma conditions relevant to many heliospheric environments. Learning to handle the high-dimensional phase-space of kinetic plasma theory and to exploit the information contained in velocity space holds the potential for transformational progress in our understanding of kinetic heliophysical processes. The development of innovative methods based on kinetic plasma physics, such as the field-particle correlation technique highlighted here, will enable us to gain much deeper insight into the dynamics and energetics of the heliosphere, our home in the universe. And, beyond laying the foundation of fundamental knowledge needed to construct a predictive capability for heliophysics phenomena, such as extreme space weather, advances in our understanding of fundamental physics through *in situ* measurements of heliospheric plasmas may be applied to better comprehend the dynamics of more remote or extreme astrophysical systems that lie out of reach of direct measurements.

Can we go further than some of the new directions discussed here to exploit the information contained in velocity space of kinetic theory? New capabilities enable fundamental aspects of the kinetic physics of space plasmas to be explored in the laboratory under controlled or reproducible conditions. The development of improved experimental diagnostics to measure the particle velocity distribution functions will enable some of the novel kinetic plasma physics methods endorsed here to be applied in a laboratory setting. Can machine learning, coupled with sufficient physics insight from kinetic plasma theory, be used to discover patterns in the high-dimensional phase space of kinetic plasma theory? And, of course, our urgent need to understand these essentially microphysical processes—turbulence, reconnection, particle acceleration, and instabilities—is motivated by their effect on the macroscopic evolution of the heliosphere, in particular, their impact on Earth and society. Using our refined knowledge of these kinetic physical mechanisms, we may attempt to build next-generation models that couple their impact to the global evolution of the heliosphere, enabling us to treat near-Earth space, and other heliospheric environments, as complex systems. Efforts to tackle the multi-scale problem of heliophysics through a rigorous

connection between the kinetic physics at microscales and the self-consistent evolution of the heliosphere at macroscales will propel the field of kinetic heliophysics into the future.

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