White Paper: The Physics of Collisionless Dissipation in the Heliosphere

Primary Author:

Colby Haggerty, Institute for Astronomy, University of Hawaii, Manoa

Co-Authors:

Riddhi Bandyopadhyay, Department of Astrophysical Sciences, Princeton University
Jason TenBarge, Department of Astrophysical Sciences, Princeton University
Paul Cassak, Department of Physics and Astronomy, West Virginia University
Alexandros Chasapis, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder
Jimmy Juno, Princeton Plasma Physics Laboratory, Princeton University
Subash Adhikari, Department of Physics and Astronomy, University of Delaware
Narges Ahmadi, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder
Harry Arnold, Applied Physics Laboratory, Johns Hopkins University
Afshari Arya, Department of Physics and Astronomy, University of Iowa
Lev Arzamasskiy, Institute for Advanced Study
M. Hasan Barbhuiya, Department of Physics and Astronomy, West Virginia University
Damiano Caprioli, University of Chicago
Joel Dahlin, Department of Astronomy, University of Maryland at College Park
James Drake, University of Maryland, College Park
Imogen Gingell School of Physics & Astronomy, University of Southampton, UK
Fan Guo, Los Alamos National Laboratory
Gregory Howes, University of Iowa
Kristopher Klein, Lunar and Planetary Laboratory, University of Arizona
Matthew Kunz, Department of Astrophysical Sciences, Princeton University
Emily Lichko, University of Arizona
William H. Matthaeus, Department of Physics and Astronomy, University of Delaware
Sean Oughton, Department of Mathematics, University of Waikato, NZ
Tulasi Parashar, School of Chemical and Physical Sciences, Victoria University of Wellington
Oreste Pezzi, Institute for Plasma Science and Technology, National Research Council of Italy, IT
Sergio Servidio, Department of Physics, University of Calabria, Italy
Michael Shay, Department of Physics and Astronomy, University of Delaware
Jason Shuster Department of Astronomy, University of Maryland, College Park
Mikhail Sitnov, Applied Physics Laboratory, Johns Hopkins University
Luca Sorriso-Valvo, Institute of Space Physics, Sweden, Institute for Plasma Science & Technology, IT
Jonathan Squire, University of Otago, NZ
Marc Swisdak, Institute for Research in Electronics and Applied Physics, University of Maryland
Domenico Trotta, The Blackett Laboratory, Department of Physics, Imperial College London, UK
Jaye Verniero, NASA Goddard Space Flight Center
Minping Wan, Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, CN
Shan Wang, Department of Astronomy, University of Maryland at College Park
Lynn Wilson III, NASA Goddard Space Flight Center
Yan Yang, Department of Physics and Astronomy, University of Delaware

Synopsis:
The dynamics and evolution of the heliosphere are principally governed by the collective physical processes of the constituent plasma and the associated electric and magnetic fields. Many heliospheric systems, such as the outer corona, the solar wind, and planetary magnetospheres, are composed of hot, tenuous plasma where the relevant length and time scales are orders of magnitude smaller than the plasma mean free path and collision time, respectively, implying that the evolution of these systems is nearly collisionless. Despite the dearth of collisions, energy contained in fields and bulk flows is still exchanged/dissipated into thermal (or random) degrees of freedom through processes including turbulence, instabilities, magnetic reconnection, and shocks. While this collisionless dissipation occurs throughout the heliosphere, only in the last few years has the heliospheric community begun focused development of the theoretical tools and frameworks to study dissipation from a collisionless, kinetic, perspective in simulations, observations and experiments. ***The physics of collisionless dissipation is a crucial component of heliospheric plasma systems, and advancements in this fundamental study in the next decade will be necessary to develop a comprehensive understanding of the heliosphere, as well as other astrophysical systems where similar processes are in play.*** This white paper aims to showcase recent advances in our understanding of collisionless dissipation, identify key problems that can be solved in the next decade, and encourage support for related research projects in theory, modeling, observations, and laboratory experiments.

Introduction. The heliosphere is a large complex system, in which the dynamics of the sun controls the plasma environment of the solar system through the solar wind. In this system, energy is transferred from the largest length scales, set by the dynamics of the sun, to smaller scales, eventually reaching the kinetic scales (the gyroradius) of the constituent charged ions, protons, and electrons in the form of random kinetic (i.e., thermal) energy. This transfer of energy is referred to as dissipation and is a significant element for understanding, for example, the thermodynamics of the solar wind, solar eruptions and magnetospheric storm activity that occur as a result of reconnection, and the slowing of the solar wind at the bow shock. Detailing the ways in which energy is dissipated without collisions is crucial for working towards a more complete understanding of the heliosphere.

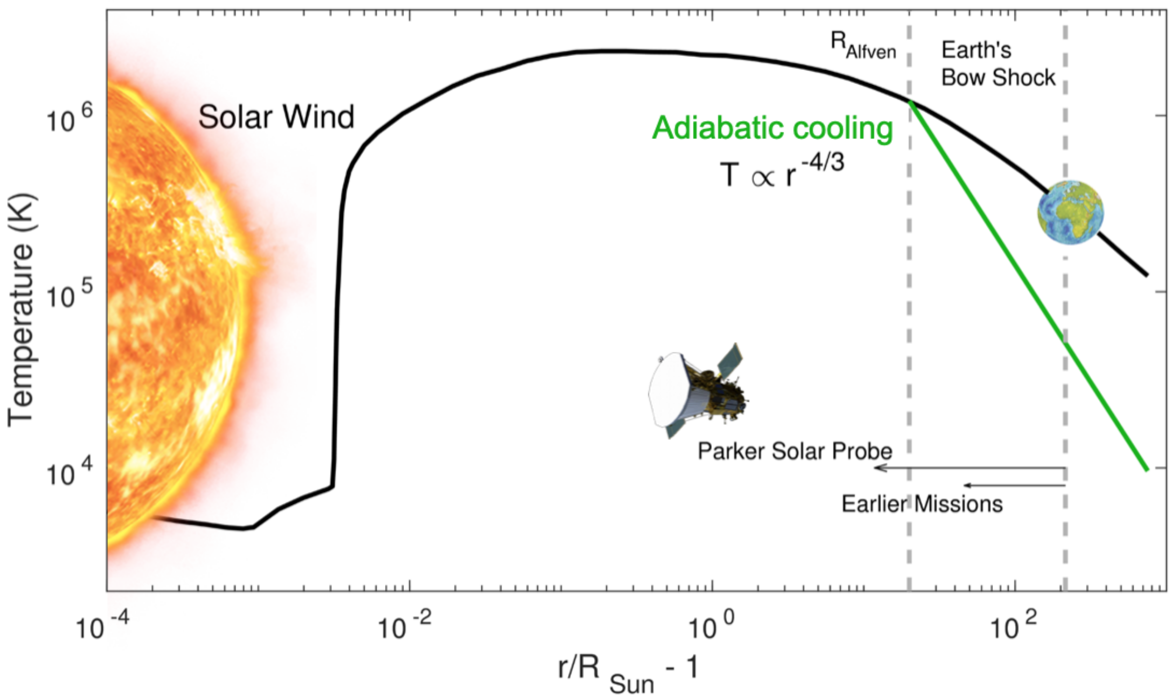

Figure 1. Plot of temperature as a function of distance from the surface of the Sun (black) adapted from Cranmer *et al.* 2007. The location of the Alfvén surface and Earth's bow shock are denoted with vertical dashed gray lines. The green line is an illustration of what the temperature of the solar wind would be if it only underwent cooling from adiabatic expansion starting at the Alfvén surface. Since the adiabatic expansion should start much closer to the Sun, the distance between the black and green lines can be thought of as a conservative estimate for the temperature gain from additional dissipation mechanisms.

Historically, the word "dissipation" has been used for collisional processes to imply that energy transfer is irreversible, i.e., entropy is generated and mediated by collisional processes. However, the solar wind is only weakly collisional, with particles traveling on the order of an AU before the effects of collisions become significant [Marsch 2006]. Yet, even without the necessary collisional processes, both thermal and nonthermal random particle energization beyond heating predicted by adiabatic compression, and thus dissipation, is consistently found in weakly collisional systems like the corona, the solar wind and planetary magnetospheres. This fact is evident in two major unresolved questions in heliospheric science: why does the corona have such a large temperature compared to the photosphere and chromosphere, and why does the solar wind not cool adiabatically as it expands from the sun. In each of these cases *collisionless dissipation* must be occurring, i.e., a process that transfers energy into random, thermal degrees of freedom through plasma interactions mediated by the self generated electric and magnetic fields.

Many of the works aimed at understanding energy transfer in heliospheric systems have employed fluid, typically magnetohydrodynamic, models. The key assumptions underlying these models require that collisions occur frequently, the particle probability distribution functions are drifting Maxwellians, and that any temperature change must come from adiabatic compression or expansion. While fluid models have had success in describing large scale structures, fundamentally they cannot accurately model dissipation and energy transfer in collisionless heliospheric systems; an accurate description requires information about the particle distribution, i.e., a kinetic plasma description. It is these facts that motivate this white paper: **an accurate understanding of the heliosphere includes collisionless dissipation, and future progress in coronal, solar wind and magnetospheric science will require the development and inclusion of this physics.**

Collisionless dissipation in heliospheric plasmas can occur through various processes in which energy is transferred by electric and magnetic fields. This fact implies that research progress on this topic is explicitly linked to understanding fundamental plasma processes such as turbulence, magnetic reconnection and shocks, each of which have been shown in simulations and observations to energize plasma [(e.g., Matthaeus et al. 2015, Howes 2015, Hesse and Cassak 2020 and Marcowith et al. 2016 and references therein). Furthermore, works on these processes have shown that collisionless dissipation does not occur at only the smallest length scales, and that through resonant interactions or the generation of energetic particles, energy can be dissipated without collisions over MHD length scales (e.g., Zweibel 2003, Bell 2004, Drake et al. 2006 and Arnold et al. 2021) . In the last decade, significant advances have been made through theory, simulations, observations, and laboratory experiments of these processes; however, the physics through which dissipation occurs in them is still an active research topic.

Recent Key Advances. Some of the most promising avenues for making progress in this area involve kinetic measurements of energy dissipation in collisionless plasma processes, most of which have only been developed in the last few years (e.g., Klein et al. 2017, Yang et al. 2017a, Sorriso-Valvo et al. 2018, Liang et al. 2019, Pezzi et al. 2022). These measurements consider aspects of plasmas that are unique to collisionless systems, such as off-diagonal components of the pressure tensor and the deformation of the distribution function in phase space. These represent important advancements beyond the standard dissipation measurement, $J \bullet E$, which describes the conversion of electromagnetic energy into and out of the plasma, but is a single, spatial quantity that suffers from ambiguities such as frame dependence and containing both reversible and irreversible dissipation.

Research on dissipation in turbulence and magnetic reconnection has been bolstered by examining the pressure-strain interaction [i.e., $(P\bullet\nabla)\bullet u$)] in generating internal energy. In both observations and simulations, these processes have been found to channel energy into heat through the traceless pressure-strain interaction "Pi-D", i.e., the full contraction of the deviatoric pressure tensor (Π_{ij} and the gradient of the flow $\nabla_i u_j$) (Yang et al. 2017a). This quantity can approximately represent the non-compressional thermal energization, i.e., non-adiabatic heating. While $J\bullet E$ measures the energy transfer between the fields and the plasma, in a closed system, "Pi-D" is one of only a few channels through which a plasma can be heated. Recent works have demonstrated that the pressure-strain interaction can serve as a direct estimate of the energy dissipation rate in simulations of turbulence, contributing to a long outstanding problem in collisionless turbulence (Yang et al. 2022). When taken in the guiding center limit, this quantity is connected to the magnetic curvature term which has been shown to be crucial for accelerating non-thermal particles in magnetic reconnection (Dahlin et al. 2014, Arnold et al. 2020). This diagnostic has been used to show that fundamental plasma processes such as turbulence, magnetic reconnection, and shocks heat plasma beyond compressional, adiabatic predictions (e.g., Yang et al. 2017b, Sitnov et al. 2018, Bandyopadhyay et al. 2018, Chasapis et al. 2018, Pezzi et al. 2019, Bandyopadhyay et al. 2020, Arzamasskiy et al. 2022), physics which cannot be captured with traditional fluid descriptions of plasma.

Another promising avenue for measuring and understanding the physics of collisionless dissipation comes from examining the full 3D velocity-space structure of the distribution function. Many plasma systems exhibit waves and instabilities that can energize and deform the distribution functions through complex interactions. Particle distribution functions can be driven away from Maxwellians by magnetic and electric fluctuations, resulting in phase space structure in the distribution function which may persist without frequent collisions to drive the distribution back to a Maxwellian. A recent triumph in the study of these processes is a measurement referred to as the Field Particle Correlation (FPC) diagnostic (Klein et al. 2017). By correlating various components of the electric field with (space and time) gradients in the distribution function, the FPC can measure the electromagnetic work done on the distribution function at any point in phase space. Although it is a relatively new diagnostic (Klein et al. 2017, Howes et al. 2017), in the last six years it has been used to identify different dissipative processes in both simulations and observations (such as Landau damping, transit time damping, cyclotron damping, stochastic heating, and shock drift acceleration, to name only a few; Howes et al. 2017, Arzamasskiy et al. 2019, Chen et al.2019, Howes et al. 2019, Klein et al. 2019, Horvath et al. 2020, Cerri, Arzamasskiy and Kunz 2021, Juno et al. 2021, Verniero et al 2021).

Additionally, as the FPC follows from a measurement of the entire distribution function, it can assess the energization process for different populations, including thermal, non-thermal and energetic particles. This allows for the identification and characterization of different, more nuanced processes which may occur at the same region of space and time, but act on different particles in phase space. This aspect is likely crucial for understanding dissipation occurring at multiple length scales, as energetic particles can transfer energy across non-adjacent scales. This non-local transfer is evident in shock waves such as ICMEs or Earth's bow shock in which energetic particles can drive waves and instabilities 100’s of Earth radii away from their source, and in the process, modify the MHD scale dynamics (e.g., Greenstadt, Le and Strangeway 1995, Gary et al. 2016, Haggerty et al. 2020). The FPC is a powerful tool for identifying and quantifying dissipation processes in the complex, collisionless, and often turbulent plasma that constitutes the solar wind and will likely be significant for understanding dissipation in the next decade.

Even more recently, research has begun to reevaluate the fundamental thermodynamics description for the collisionless plasmas found in many space and astrophysical systems, drawing from non-equilibrium thermodynamics and statistical mechanics. Only in the last year have researchers begun working to formalize a generalization of thermodynamics for collisionless systems (Cassak et al., submitted); the theory retains information about the distribution function’s phase space deformation, a feature that has been omitted from previous analyses in heliophysics yet constantly seen in *in-situ* observations (e.g., Valentini et al. 2017, Servidio et al. 2017, Wilson et al. 2019 or Shuster et. al 2021). Additionally, these works are showing that as the distribution functions become less Maxwellian in nature, high-order moments, such as the heat flux, must be included in the governing equations (e.g., Schekochihin et al. 2015, Servidio et al. 2017, Song et al. 2020, Du et al. 2020, Matthaeus et al. 2020, Zhdankin 2022).

All these works represent important initial steps forward in our understanding of collisionless dissipation in both space physics and plasmas more generally. The collection of recent works discussed above have demonstrated the importance of collisionless dissipation and begun to identify tools and procedures necessary for its identification and quantification. However, these successes, while clearly significant, are still relatively small compared to the magnitude of the larger problems: *how is energy dissipated throughout segments of the heliosphere, and how does this shape* *the evolution of heliospheric systems where collisions are infrequent*? Many of these works have demonstrated the importance of this question and begun to develop the tools to try to address this, but in the next decade strategic investments must be made to answer this fundamental question.

Highest priority science goals:
For the next decade, we suggest three key science goals that are of the highest priority for understanding collisionless dissipation.

1. The physics through which collisionless dissipation occurs must be determined, and the associated dissipation rates must be quantified for fundamental plasma processes, including turbulence, shocks, magnetic reconnection, waves, and instabilities.

Much work within the last decade has made efforts to this end for various processes in theory, observations, and modeling (limited examples including Phan et al. 2013, Shay et al. 2014, Yoo et al. 2014 and Yamada et al. 2016 for reconnection, Matthaeus et al. 1999, Cramer et al. 2006, Servidio et al. 2012, Wan et al. 2015, Shay et al. 2018, Parashar et al 2018 for turbulence, Burgess, Möbius, and Scholer 2012, Caprioli et al. 2014, Haggerty and Caprioli 2020, Juno et al. 2021 for shocks, and van der Holst et al. 2014, Kunz, Schekochihin and Stone 2014, Klein and Mihailo 2019 for waves and instabilities). However, these processes must be reevaluated to determine the rates at which energy is transferred into different degrees of freedom of each species through the dissipation. The dissipation rates of different plasma species are crucial for estimating the relative importance of different processes in the heating of the corona and solar wind.

2. Dissipation rates throughout the heliosphere must be measured and compared with the predictions derived from theory and modeling.

This scientific goal is necessary for evaluating the developed theory of collisionless dissipation and is crucial for incorporating collisionless dissipation into our working model of the heliosphere including phenomena such as flares, coronal heating, turbulent heating of the solar wind and magnetospheric-solar wind interactions through shocks and reconnection.

3. The impact of collisionless dissipation must be included into larger scale dynamical models of the heliosphere to properly account for heating and other large scale features that collisionless dissipation may influence.

Ultimately, it is important to study collisionless dissipation because it is unclear to what extent it will affect the evolution of plasmas throughout the heliosphere. Research has hinted at the importance of dissipation and its effect on larger scale systems (e.g., Tóth et al. 2016, Drake et al. 2019); however, until collisionless dissipation is included into larger scale fluid models, predictive models will likely miss a crucial component. This represents the most significant goal and application of the study of collisionless dissipation.

Research Strategy and Recommendations:
To achieve these priority science goals in the next decade, several specific policies are recommended:

1. Funding opportunities should be made available for the continued study of collisionless dissipation in its various forms, including the research of the fundamental plasma physics in theory and modeling as well as direct, observational and experimental applications.
2. Training heliospheric graduate students in collisionless plasma physics, either through multi-institution collaborative courses or through dedicated workshops/summer schools.
3. Prioritizing satellite instrumentation design that can measure the non-Maxwellian particle distributions and associated field fluctuations tied to collisionless physics. Prioritize mission selection of spacecraft that will study collisionless dissipation processes like the selected HelioSwarm mission for turbulence and the proposed MAKOS mission for shocks.
4. Encourage interdisciplinary and multiscale approaches to models of heliospheric evolution. The physics of collisionless dissipation must be included in larger, heliospheric models.

References:

Arnold, H., et al. “Electron Acceleration during Macroscale Magnetic Reconnection.” Physical Review Letters, vol. 126, Apr. 2021, p. 135101, https://doi.org/10.1103/PhysRevLett.126.135101.

Arzamasskiy, L., et al. “Hybrid-Kinetic Simulations of Ion Heating in Alfvénic Turbulence.” The Astrophysical Journal, vol. 879, July 2019, p. 53, https://doi.org/10.3847/1538-4357/ab20cc.

Arzamasskiy, L., et al. Kinetic Turbulence in Collisionless High-Beta Plasmas. 1 July 2022, https://ui.adsabs.harvard.edu/abs/2022arXiv220705189A.

Bandyopadhyay, Riddhi, A. Chasapis, et al. “Incompressive Energy Transfer in the Earth’s Magnetosheath: Magnetospheric Multiscale Observations.” The Astrophysical Journal, vol. 866, Oct. 2018, p. 106, https://doi.org/10.3847/1538-4357/aade04.

Bandyopadhyay, Riddhi, William H. Matthaeus, et al. “Statistics of Kinetic Dissipation in the Earth’s Magnetosheath: MMS Observations.” Physical Review Letters, vol. 124, June 2020, p. 255101, https://doi.org/10.1103/PhysRevLett.124.255101.

Burgess, D., et al. “Ion Acceleration at the Earth’s Bow Shock.” Space Science Reviews, vol. 173, Nov. 2012, pp. 5–47, https://doi.org/10.1007/s11214-012-9901-5.

Cerri, S. S., Arzamasskiy, L., Kunz, M. W. “On stochastic heating and its phase-space signatures in low-beta kinetic turbulence.” Astrophysical Journal, vol. 916, Aug 2021, p. 120, https://doi.org/10.3847/1538-4357/abfbde.

Chasapis, Alexandros, et al. “Energy Conversion and Collisionless Plasma Dissipation Channels in the Turbulent Magnetosheath Observed by the Magnetospheric Multiscale Mission.” The Astrophysical Journal, vol. 862, July 2018, p. 32, https://doi.org/10.3847/1538-4357/aac775.

Chen, C. H. K., et al. “Evidence for Electron Landau Damping in Space Plasma Turbulence.” Nature Communications, vol. 10, no. 1, Feb. 2019, p. 740, https://doi.org/10.1038/s41467-019-08435-3.

Cranmer, Steven R., et al. “Self-consistent Coronal Heating and Solar Wind Acceleration from Anisotropic Magnetohydrodynamic Turbulence.” The Astrophys. J. Supp. Series, vol. 171, Aug. 2007, pp. 520-551, https://doi.org/10.1086/518001.

Cranmer, Steven R., et al. “Empirical Constraints on Proton and Electron Heating in the Fast Solar Wind.” The Astrophysical Journal, vol. 702, Sept. 2009, pp. 1604–14, https://doi.org/10.1088/0004-637X/702/2/1604.

Dahlin, J. T., et al. “The Mechanisms of Electron Heating and Acceleration during Magnetic Reconnection.” Physics of Plasmas, vol. 21, Sept. 2014, p. 092304, https://doi.org/10.1063/1.4894484.

Drake, J. F., et al. “Electron Acceleration from Contracting Magnetic Islands during Reconnection.” Nature, vol. 443, Oct. 2006, pp. 553–56, https://doi.org/10.1038/nature05116.

Drake, J. F., et al. “A Computational Model for Exploring Particle Acceleration during Reconnection in Macroscale Systems.” Physics of Plasmas, vol. 26, no. 1, Jan. 2019, p. 012901, https://doi.org/10.1063/1.5058140.

Du, Senbei, et al. “Energy Dissipation and Entropy in Collisionless Plasma.” Physical Review E, vol. 101, Mar. 2020, p. 033208, https://doi.org/10.1103/PhysRevE.101.033208.

Gary, S. Peter, et al. “Ion-Driven Instabilities in the Solar Wind: Wind Observations of 19 March 2005.” Journal of Geophysical Research (Space Physics), vol. 121, Jan. 2016, pp. 30–41, https://doi.org/10.1002/2015JA021935.

Greenstadt, E. W., et al. “ULF Waves in the Foreshock.” Advances in Space Research, vol. 15, Jan. 1995, pp. 71–84, https://doi.org/10.1016/0273-1177(94)00087-H.

Haggerty, C. C., et al. “Exploring the Statistics of Magnetic Reconnection X-Points in Kinetic Particle-in-Cell Turbulence.” Physics of Plasmas, vol. 24, Oct. 2017, p. 102308, https://doi.org/10.1063/1.5001722.

Haggerty, Colby C., and Damiano Caprioli. “Kinetic Simulations of Cosmic-Ray-Modified Shocks. I. Hydrodynamics.” The Astrophysical Journal, vol. 905, Dec. 2020, p. 1, https://doi.org/10.3847/1538-4357/abbe06.

Hesse, M., and P. A. Cassak. “Magnetic Reconnection in the Space Sciences: Past, Present, and Future.” Journal of Geophysical Research (Space Physics), vol. 125, Feb. 2020, p. e25935, https://doi.org/10.1029/2018JA025935.

Horvath, Sarah A., et al. “Electron Landau Damping of Kinetic Alfvén Waves in Simulated Magnetosheath Turbulence.” Physics of Plasmas, vol. 27, Oct. 2020, p. 102901, https://doi.org/10.1063/5.0021727.

Howes, G. G. “A Dynamical Model of Plasma Turbulence in the Solar Wind.” Philosophical Transactions of the Royal Society of London Series A, vol. 373, Apr. 2015, pp. 20140145–20140145, https://doi.org/10.1098/rsta.2014.0145.

Howes, Gregory G. “A Prospectus on Kinetic Heliophysics.” Physics of Plasmas, vol. 24, May 2017, p. 055907, https://doi.org/10.1063/1.4983993.

---. “Spatially Localized Particle Energization by Landau Damping in Current Sheets Produced by Strong Alfvén Wave Collisions.” Journal of Plasma Physics, vol. 84, Feb. 2018, p. 905840105, https://doi.org/10.1017/S0022377818000053.

Juno, James, et al. “A Field-Particle Correlation Analysis of a Perpendicular Magnetized Collisionless Shock.” Journal of Plasma Physics, vol. 87, June 2021, p. 905870316, https://doi.org/10.1017/S0022377821000623.

Klein, K. G., et al. “Inferred Linear Stability of Parker Solar Probe Observations Using One- and Two-Component Proton Distributions.” The Astrophysical Journal, vol. 909, Mar. 2021, p. 7, https://doi.org/10.3847/1538-4357/abd7a0.

Klein, Kristopher G., Gregory G. Howes, et al. “Diagnosing Collisionless Energy Transfer Using Field–Particle Correlations: Gyrokinetic Turbulence.” Journal of Plasma Physics, vol. 83, no. 4, Aug. 2017, https://doi.org/10.1017/S0022377817000563.

Klein, Kristopher G., Mihailo Martinović, et al. “Linear Stability in the Inner Heliosphere: Helios Re-Evaluated.” The Astrophysical Journal, vol. 887, Dec. 2019, p. 234, https://doi.org/10.3847/1538-4357/ab5802.

Kunz, Matthew W., et al. “Firehose and Mirror Instabilities in a Collisionless Shearing Plasma.” Physical Review Letters, vol. 112, May 2014, p. 205003, https://doi.org/10.1103/PhysRevLett.112.205003.

Liang, Haoming, et al. “Decomposition of Plasma Kinetic Entropy into Position and Velocity Space and the Use of Kinetic Entropy in Particle-in-Cell Simulations.” Physics of Plasmas, vol. 26, Aug. 2019, p. 082903, https://doi.org/10.1063/1.5098888.

Marcowith, A., et al. “The Microphysics of Collisionless Shock Waves.” Reports on Progress in Physics, vol. 79, Apr. 2016, p. 046901, https://doi.org/10.1088/0034-4885/79/4/046901.

Marsch, Eckart. “Kinetic Physics of the Solar Corona and Solar Wind.” Living Reviews in Solar Physics, vol. 3, no. 1, July 2006, p. 1, https://doi.org/10.12942/lrsp-2006-1.

Martinovic, Mihailo, et al. Ion-Driven Instabilities in the Inner Heliosphere as Observed by Helios. Dec. 2021, pp. SH35C-2063, https://ui.adsabs.harvard.edu/abs/2021AGUFMSH35C2063M.

Martinović, Mihailo M., et al. “Ion-Driven Instabilities in the Inner Heliosphere. I. Statistical Trends.” The Astrophysical Journal, vol. 923, Dec. 2021, p. 116, https://doi.org/10.3847/1538-4357/ac3081.

Matthaeus, W. H., G. P. Zank, et al. “Coronal Heating by Magnetohydrodynamic Turbulence Driven by Reflected Low-Frequency Waves.” The Astrophysical Journal, vol. 523, Sept. 1999, pp. L93–96, https://doi.org/10.1086/312259.

Matthaeus, W. H., M. Wan, et al. “Intermittency, Nonlinear Dynamics and Dissipation in the Solar Wind and Astrophysical Plasmas.” Philosophical Transactions of the Royal Society of London Series A, vol. 373, Apr. 2015, pp. 20140154–20140154, https://doi.org/10.1098/rsta.2014.0154.

Matthaeus, William H., et al. “Pathways to Dissipation in Weakly Collisional Plasmas.” The Astrophysical Journal, vol. 891, Mar. 2020, p. 101, https://doi.org/10.3847/1538-4357/ab6d6a.

Parashar, Tulasi N., et al. “Dependence of Kinetic Plasma Turbulence on Plasma β.” The Astrophysical Journal, vol. 864, Sept. 2018, p. L21, https://doi.org/10.3847/2041-8213/aadb8b.

Pezzi, O., H. Liang, et al. “Dissipation Measures in Weakly Collisional Plasmas.” Monthly Notices of the Royal Astronomical Society, vol. 505, Aug. 2021, pp. 4857–73, https://doi.org/10.1093/mnras/stab1516.

Pezzi, O., Y. Yang, et al. “Energy Conversion in Turbulent Weakly Collisional Plasmas: Eulerian Hybrid Vlasov-Maxwell Simulations.” Physics of Plasmas, vol. 26, July 2019, p. 072301, https://doi.org/10.1063/1.5100125.

Phan, T. D., et al. “Electron Bulk Heating in Magnetic Reconnection at Earth’s Magnetopause: Dependence on the Inflow Alfvén Speed and Magnetic Shear.” Geophysical Research Letters, vol. 40, Sept. 2013, pp. 4475–80, https://doi.org/10.1002/grl.50917.

Schekochihin, A., et al. Phase Mixing vs. Nonlinear Advection in Drift-Kinetic Plasma Turbulence. Nov. 2015, p. PP12.019, https://ui.adsabs.harvard.edu/abs/2015APS..DPPPP2019S.

Servidio, S., F. Valentini, et al. “Local Kinetic Effects in Two-Dimensional Plasma Turbulence.” Physical Review Letters, vol. 108, no. 4, Jan. 2012, p. 045001, https://doi.org/10.1103/PhysRevLett.108.045001.

Servidio, S., A. Chasapis, et al. “Magnetospheric Multiscale Observation of Plasma Velocity-Space Cascade: Hermite Representation and Theory.” Physical Review Letters, vol. 119, no. 20, Nov. 2017, p. 205101, https://doi.org/10.1103/PhysRevLett.119.205101.

Shay, M. A., C. C. Haggerty, T. D. Phan, et al. “Electron Heating during Magnetic Reconnection: A Simulation Scaling Study.” Physics of Plasmas, vol. 21, Dec. 2014, p. 122902, https://doi.org/10.1063/1.4904203.

Shay, M. A., C. C. Haggerty, W. H. Matthaeus, et al. “Turbulent Heating Due to Magnetic Reconnection.” Physics of Plasmas, vol. 25, Jan. 2018, p. 012304, https://doi.org/10.1063/1.4993423.

Shuster, J. R., et al. “Structures in the Terms of the Vlasov Equation Observed at Earth’s Magnetopause.” Nature Physics, vol. 17, July 2021, pp. 1056–65, https://doi.org/10.1038/s41567-021-01280-6.

Sitnov, M. I., et al. “Kinetic Dissipation Around a Dipolarization Front.” Geophysical Research Letters, vol. 45, May 2018, pp. 4639–47, https://doi.org/10.1029/2018GL077874.

Song, Liangjin, et al. “Force and Energy Balance of the Dipolarization Front.” Journal of Geophysical Research (Space Physics), vol. 125, Sept. 2020, p. e28278, https://doi.org/10.1029/2020JA028278.

Töth, Gábor, et al. “Extended Magnetohydrodynamics with Embedded Particle‐in‐cell Simulation of Ganymede’s Magnetosphere.” Journal of Geophysical Research: Space Physics, vol. 121, no. 2, 2016, pp. 1273–93, https://doi.org/10.1002/2015JA021997.

Trotta, Domenico, et al. “Phase Space Transport in the Interaction between Shocks and Plasma Turbulence.” Proceedings of the National Academy of Sciences, vol. 118, no. 21, May 2021, p. e2026764118, https://doi.org/10.1073/pnas.2026764118.

Valentini, F., et al. A Study on the Non Maxwellian Nature of Ion Velocity Distribution Functions Using Magnetospheric Multiscale (MMS) Data. Dec. 2017, pp. SH11A-2415, https://ui.adsabs.harvard.edu/abs/2017AGUFMSH11A2415V.

Verniero, J. L., et al. “Determining Threshold Instrumental Resolutions for Resolving the Velocity Space Signature of Ion Landau Damping.” Journal of Geophysical Research (Space Physics), vol. 126, May 2021, p. e28361, https://doi.org/10.1029/2020JA028361.

Wan, M., et al. “Intermittent Dissipation and Heating in 3D Kinetic Plasma Turbulence.” Physical Review Letters, vol. 114, May 2015, p. 175002, https://doi.org/10.1103/PhysRevLett.114.175002.

Wilson, Lynn B., III, et al. “Electron Energy Partition across Interplanetary Shocks. II. Statistics.” The Astrophysical Journal Supplement Series, vol. 245, Dec. 2019, p. 24, https://doi.org/10.3847/1538-4365/ab5445.

Yamada, T., et al. “Localized Electron Heating during Magnetic Reconnection in MAST.” Nuclear Fusion, vol. 56, Oct. 2016, p. 106019, https://doi.org/10.1088/0029-5515/56/10/106019.

Yang, Yan, William H. Matthaeus, Tulasi N. Parashar, et al. “Energy Transfer, Pressure Tensor, and Heating of Kinetic Plasma.” Physics of Plasmas, vol. 24, no. 7, July 2017, p. 072306, https://doi.org/10.1063/1.4990421.

Yang, Yan, William H. Matthaeus, Sohom Roy, et al. “Pressure-Strain Interaction as the Energy Dissipation Estimate in Collisionless Plasma.” The Astrophysical Journal, vol. 929, Apr. 2022, p. 142, https://doi.org/10.3847/1538-4357/ac5d3e.

Yang, Yan, Minping Wan, et al. “Scale Dependence of Energy Transfer in Turbulent Plasma.” Monthly Notices of the Royal Astronomical Society, vol. 482, Feb. 2019, pp. 4933–40, https://doi.org/10.1093/mnras/sty2977.

Yoo, Jongsoo, et al. “Bulk Ion Acceleration and Particle Heating during Magnetic Reconnection in a Laboratory Plasma.” Physics of Plasmas, vol. 21, no. 5, May 2014, p. 055706, https://doi.org/10.1063/1.4874331.

Zhdankin, Vladimir. “Generalized Entropy Production in Collisionless Plasma Flows and Turbulence.” Physical Review X, vol. 12, July 2022, p. 031011, https://doi.org/10.1103/PhysRevX.12.031011.