Tracing Energy Dissipation Rate from the Sun Through the Solar Wind to the Magnetosphere

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Abstract

Understanding how turbulent energy is transferred and dissipated in the Sun- heliosphere system remains a major scientific challenge. Accurately measuring the energy dissipation rate in space plasmas is notoriously complex, due to its inherent three-dimensional, scale-dependent nature, anisotropic plasma environments, and the need for multi-point measurements. This project addresses these challenges by applying three advanced analysis methods: DA, LPDE and special $60°$ polar angle, to observations from multiple space missions that span the Sun, the solar wind, and Earth's magnetosphere. This research directly addresses the NASA SMD Heliophysics objective "Explore and characterize the physical processes in the space environment ..." and aligns with the science goals of NASA space missions MMS and HelioSwarm. The results of this project will provide a foundation for future proposals to NASA Living With a Star and Heliophysics Foundational Research programs. The project will also strengthen research and education in Delaware by involving graduate students and expanding collaboration across institutions.

Narrative

Research question: What is energy dissipation rate across the Sun–heliosphere system, from the Sun, through the solar wind, to the magnetosphere? Answering this question is essential for understanding long-standing mysteries in space physics, such as how the solar corona and solar wind are heated and how energetic particles are accelerated. Although the question seems simple, it has remained difficult to answer because of complex theoretical and technical challenges, despite the significant efforts in the last several decades.

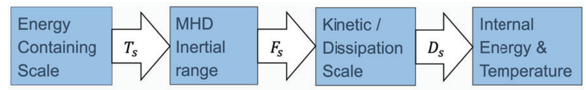

Figure 1: Three key steps (T, F, D) of energy transfer leading to dissipation.

Theoretical grounding & existing literature: The rate at which energy is dissipated (denoted as "ϵ") in a turbulent medium has been investigated from different perspectives, and the turbulence "cascade" [1–4] has been adapted to quantify energy dissipation rate ϵ. A turbulent (magnetized) fluid can be imagined as an ensemble of eddies of different sizes. The basic picture separates such structures into three regimes in Fig. 1: (i) the energy-containing scales include the large eddies that inject energy into the system (like the whirlpool that forms in a cup of coffee when it is stirred), (ii) the dissipation range comprises all the small-scale effects that dissipate the energy (e.g. into internal energy and increasing temperature), and (iii) the inertial range includes all intermediate scales across which energy "cascades" from the injection to dissipation regimes. Building on this picture, the three regimes are represented by terms T, D, F. The equation describing the energy transfer across time and scales for homogeneous incompressible magnetohydrodynamics (MHD) [2, 5] can be written as $T + F + D = \epsilon$. As shown in Fig. 1, the time-dependent term (T) is dominant at very large (injection) scales, the second term (F) grows in the inertial range, and the dissipative term (D) becomes relevant at small scales. This delicate balance suggests that if we were able to measure any one of T, D, F, we can obtain an estimate of the energy dissipation rate.

In the framework of spacecraft measurements, the T term cannot be evaluated, since spacecraft cannot follow parcels of plasmas. The D term requires the viscosity ν, which can only be roughly and empirically estimated [6, 7]. The only term that could be effectively evaluated is F. In the inertial range, with negligible contribution from time-dependent (T) and dissipative (D) terms, the equation can be expressed as

$$F = -\frac{1}{4}\nabla_\ell \cdot \boldsymbol{Y}^\pm = \epsilon^\pm, \tag{1}$$

which is called the Yaglom law. $\boldsymbol{Y}^\pm(\boldsymbol{\ell}) = \langle \delta \boldsymbol{z}^\mp |\delta \boldsymbol{z}^\pm|^2 \rangle$ is the Yaglom flux vector. $\boldsymbol{\ell}$ is the lag vector, ∇_ℓ derivatives with respect to the lag vector $\boldsymbol{\ell}$, the Elsässer variable ($\boldsymbol{z}^\pm = \boldsymbol{u} \pm \boldsymbol{b}$) with $\boldsymbol{u}$ velocity field and $\boldsymbol{b}$ magnetic field, its increment $\delta \boldsymbol{z}^\pm(\boldsymbol{x}, \boldsymbol{\ell}) = \boldsymbol{z}^\pm(\boldsymbol{x} + \boldsymbol{\ell}) - \boldsymbol{z}^\pm(\boldsymbol{x})$, and $\langle \cdot \rangle$ the ensemble average in the physical space, which is identical to the spatial average for homogeneous turbulence. $\epsilon^\pm$ represents the mean dissipation rates of Elsässer energies, and the total energy dissipation rate is $\epsilon = \frac{\epsilon^+ + \epsilon^-}{2}$.

The Yaglom law in Eq. 1 requires accurate determination of derivatives in three-dimensional (3D) *lag space* $\boldsymbol{\ell}$, i.e. ∇_ℓ. Most space missions involve a single spacecraft, and single spacecraft observation provides lags in only one direction. In these circumstances, the divergence operator $\nabla_\ell \cdot$ cannot be computed and observational analyses [8–11] typically employ one-dimensional (1D) form of Eq. 1, $Y_\ell^\pm = -\frac{4}{3}\epsilon^\pm \ell$, where $Y_\ell^\pm$ is the radial component of the Yaglom flux vector $\boldsymbol{Y}^\pm$. It has been shown that this 1D form gives inaccurate results when the system is anisotropic [12–14] as most of space plasmas are [15]. To resolve this issue, three novel techniques have been investigated in our group, including Direction-Averaging (DA) [12, 14, 16], Lag Polyhedral Derivative Ensemble (LPDE) [17], and the special 60° polar angle [18] methods, which properly account for the effect of anisotropy in the inertial range. (I) **Direction-Averaging (DA)**: Eq. 1 can be reformulated in spherical coordinates as: $\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} Y_\ell^\pm \sin\theta d\theta d\phi = -\frac{4}{3}\epsilon^\pm \ell$, where θ represents the polar angle (from the mean magnetic field B_0 axis) and ϕ the azimuthal angle. As shown in Fig. 2, the DA value achieves the actual dissipation rate to a remarkable degree. (II) **Lag Polyhedral Derivative Ensemble (LPDE)**: evaluate the full divergence in Eq. 1 for the first time in space plasmas using multipoint measurements. The technique is based on the numerous permutations in which the spacecraft can be arranged in lag space and employs well-tested techniques for the computation of derivatives [19]. Several hundred up to a million estimates of the cascade rate can be obtained with LPDE, see Fig. 2. (III) **Special** 60° **Polar Angle**: our recent results [18] show that the energy dissipation rate estimated around a polar angle of $\theta \simeq 60^\circ$ agrees reasonably with the exact dissipation rate in anisotropic cases, see Fig. 2.

Ultimately, this research proposal seeks to achieve **two primary objectives**: (i) to make a systematic comparison among the DA, LPDE and 60° polar angle estimators to clarify their respective strengths, limitations, and regimes of validity in anisotropic MHD turbulence. (ii) to establish, for the first time, an accurate measurement of the global energy dissipation rate in different regimes of the Sun-heliosphere system. The present research proposal is considered particularly timely due to the unprecedented volumes of data from observations, from Parker Solar Probe (PSP) [20] at the Sun observing the very start of the solar wind, to satellites around Earth like MMS [21].

(a) DA (b) LPDE (c) 60° Polar Angle

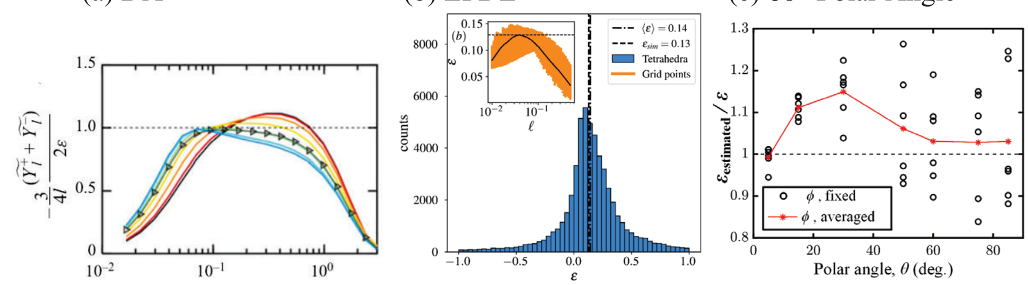

Figure 2: (a) The solid line with triangles represents the direction-averaging (DA) profile [14]. (b) Histograms of over $50,000$ estimations of dissipation rate using LPDE [17]. (c) The solid red curve with stars represents the azimuthally averaged profiles at different θ [18].

Research plan & collaborators: A combination of multiple missions will be used. As PSP approaches closer to the Sun, we can measure the dissipation rate in the near-sun solar wind. PSP data does not support the computation of the 3D form in Eq. 1, so the 60° polar angle method is employed. The DA and LPDE methods require multi-spacecraft observations, so the MMS data will also be used to measure the dissipation rate in near-Earth solar wind. Data will be stored within Virgilio, the DSpOC computational and storage facility (PI Prof. B. Maruca, UD). The project will involve the development of numerical algorithms to analyze the acquired data, extract global turbulence information, implement DA, LPDE and 60° methods, and measure the energy dissipation rate. The graduate student in my group, Zhuoran Gao, has been mentored in implementing these techniques and the most recent results have been submitted to the Journal of Geophysical Research: Space Physics. We also established collaboration with F. Pecora (UD), K. Klein (University of Arizona), A. Chasapis (University of Colorado Boulder), and J. Stawarz (Northumbria University).

Significance of the larger project: The application of DA, LPDE and special 60° to space plasmas to obtain accurate information on energy transfer is of great relevance to future multispacecraft missions such as HelioSwarm [22, 23] and Plasma Observatory (PO) [24], meanwhile refine the existing studies using PSP [20] and MMS [21]. Regarding HelioSwarm and PO, we already collaborated with Dr. Klein from the HelioSwarm team and Dr. Chasapis and Dr. Stawarz from the PO team. Regarding PSP and MMS, we already collaborated with Dr. Pecora who developed the LPDE technique. This project will provide unique information on the evolution of turbulence from the interplanetary medium to our magnetosphere. Accurate estimates of the energy transfer rate will also improve Space Weather models where this fundamental quantity is often neglected.

References

[1] G. I. Taylor. The spectrum of turbulence. *Proc. Roy. Soc. Lond. A*, 164:476–490, 1938.

[2] T. de Kármán and L. Howarth. On the statistical theory of isotropic turbulence. *Proc. Roy. Soc. London Ser. A*, 164:192–215, 1938.

[3] A. N. Kolmogorov. 1941aLocal structure of turbulence in an incompressible viscous fluid at very high Reynolds numbers. *Dokl. Akad. Nauk SSSR*, 30:301–305, 1941. [Reprinted in Proc. R. Soc. London, Ser. A **434**, 9–13 (1991)].

[4] A. N. Kolmogorov. 1941bOn degeneration of isotropic turbulence in an incompressible viscous liquid. *C.R. Acad. Sci. U.R.S.S.*, 31:538–540, 1941.

[5] H. Politano and A. Pouquet. Dynamical length scales for turbulent magnetized flows. *Geophys. Res. Lett.*, 25:273–276, 1998.

[6] Yan Yang, William H. Matthaeus, Sean Oughton, Riddhi Bandyopadhyay, Francesco Pecora, Tulasi N. Parashar, Vadim Roytershteyn, Alexandros Chasapis, and Michael A. Shay. Effective viscosity, resistivity, and Reynolds number in weakly collisional plasma turbulence. , 528(4):6119–6128, March 2024.

[7] Riddhi Bandyopadhyay, Yan Yang, William H. Matthaeus, Tulasi N. Parashar, Yan Yang, Vadim Roytershteyn, Alexandros Chasapis, Daniel J. Gershman, Barbara L. Giles, and James L. Burch. Collisional-like dissipation in collisionless plasmas. *Phys. Plasmas*, in press, 2023.

[8] L. Sorriso-Valvo, R. Marino, V. Carbone, A. Noullez, F. Lepreti, P. Veltri, R. Bruno, B. Bavassano, and E. Pietropaolo. Observation of inertial energy cascade in interplanetary space plasma. *Phys. Rev. Lett.*, 99, 2007.

[9] Benjamin T. MacBride and Charles W. Smith. The turbulent cascade at 1 AU: energy transfer and the third-order scaling for MHD. *Astrophys. J.*, 679:1644–1660, 2008.

[10] Riddhi Bandyopadhyay, M. L. Goldstein, B. A. Maruca, W. H. Matthaeus, T. N. Parashar, D. Ruffolo, R. Chhiber, A. Usmanov, A. Chasapis, R. Qudsi, Stuart D. Bale, J. W. Bonnell, Thierry Dudok de Wit, Keith Goetz, Peter R. Harvey, Robert J. MacDowall, David M. Malaspina, Marc Pulupa, J. C. Kasper, K. E. Korreck, A. W. Case, M. Stevens, P. Whittlesey, D. Larson, R. Livi, K. G. Klein, M. Velli, and N. Raouafi. Enhanced Energy Transfer Rate in Solar Wind Turbulence Observed near the Sun from Parker Solar Probe. *Astrophys. J. Suppl.*, 246(2):48, February 2020.

[11] Honghong Wu, Chuanyi Tu, Jiansen He, Xin Wang, and Liping Yang. The yaglom scaling of the third-order structure functions in the inner heliosphere observed by helios 1 and 2. *The Astrophysical Journal*, 927(1):113, 2022.

[12] Yanwen Wang, Rohit Chhiber, Subash Adhikari, Yan Yang, Riddhi Bandyopadhyay, Michael A. Shay, Sean Oughton, William H. Matthaeus, and Manuel E. Cuesta. Strategies for Determining the Cascade Rate in MHD Turbulence: Isotropy, Anisotropy, and Spacecraft Sampling. *Astrophys. J.*, 937(2):76, October 2022.

[13] Andrea Verdini, Roland Grappin, Petr Hellinger, Simone Landi, and Wolf Christian Müller. Anisotropy of Third-order Structure Functions in MHD Turbulence. *Astrophys. J.*, 804(2):119, May 2015.

[14] Bin Jiang, Cheng Li, Yan Yang, Kangcheng Zhou, William H Matthaeus, and Minping Wan. Energy transfer and third-order law in forced anisotropic magneto-hydrodynamic turbulence with hyperviscosity. *Journal of Fluid Mechanics*, 974:A20, 2023.

[15] S. Oughton, W. H. Matthaeus, M. Wan, and K. T. Osman. Anisotropy in solar wind plasma turbulence. *Phil. Trans. R. Soc. A*, submitted, 2015.

[16] M. A. Taylor, S. Kurien, and G. L. Eyink. Recovering isotropic statistics in turbulence simulations: The Kolmogorov 4/5th law. *Phys. Rev. E*, 68:026310, 2003.

[17] Francesco Pecora, Sergio Servidio, Leonardo Primavera, Antonella Greco, Yan Yang, and William H. Matthaeus. Multipoint turbulence analysis with helioswarm. *The Astrophysical Journal Letters*, 945(2):L20, mar 2023.

[18] Bin Jiang, Zhuoran Gao, Yan Yang, Francesco Pecora, Kai Gao, Cheng Li, Sean Oughton, William H Matthaeus, and Minping Wan. Angular dependence of third-order law in anisotropic mhd turbulence. *The Astrophysical Journal*, 1000(1):71, 2026.

[19] Francesco Pecora, Yan Yang, William H Matthaeus, Alexandros Chasapis, Kristopher G Klein, Michael Stevens, Sergio Servidio, Antonella Greco, Daniel J Gershman, Barbara L Giles, et al. Three-dimensional energy transfer in space plasma turbulence from multipoint measurement. *Physical Review Letters*, 131(22):225201, 2023.

[20] N. J. Fox, M. C. Velli, S. D. Bale, R. Decker, A. Driesman, R. A. Howard, J. C. Kasper, J. Kinnison, M. Kusterer, D. Lario, M. K. Lockwood, D. J. McComas, N. E. Raouafi, and A. Szabo. The Solar Probe Plus Mission: Humanity's First Visit to Our Star. *Space Sci. Rev.*, 204:7–48, December 2016.

[21] J. L. Burch, T. E. Moore, R. B. Torbert, and B. L. Giles. Magnetospheric Multiscale Overview and Science Objectives. *Space Sci. Rev.*, 199:5–21, March 2016.

[22] H. E. Spence. HelioSwarm: Unlocking the Multiscale Mysteries of Weakly-Collisional Magnetized Plasma Turbulence and Ion Heating. In *AGU Fall Meeting Abstracts*, volume 2019, pages SH11B–04, December 2019.

[23] Kristopher G Klein, Harlan Spence, Olga Alexandrova, Matthew Argall, Lev Arzamasskiy, Jay Bookbinder, Theodore Broeren, Damiano Caprioli, Anthony Case, Benjamin Chandran, et al. Helioswarm: a multipoint, multiscale mission to characterize turbulence. *Space Science Reviews*, 219(8):74, 2023.

[24] Alessandro Retinò, Yuri Khotyaintsev, Olivier Le Contel, Maria Federica Marcucci, Ferdinand Plaschke, Andris Vaivads, Vassilis Angelopoulos, Pasquale Blasi, Jim Burch, Johan De Keyser, et al. Particle energization in space plasmas: towards a multi-point, multi-scale plasma observatory. *Experimental Astronomy*, 54(2):427–471, 2022.

Plan for Seeking External Funding

The analysis from this project represents a critical step towards accurate measurements of energy dissipation in the Sun-heliosphere system, which will refine existing studies, prepare for future missions, maximize the scientific return of operating and future missions, and build a broad picture of energy dissipation from the Sun through the solar wind and to the Magnetosphere. We have already initiated collaborative efforts with F. Pecora (University of Delaware), K. Klein (University of Arizona), A. Chasapis (University of Colorado Boulder), and J. Stawarz (Northumbria University). The most recent results are promising and have been submitted to the Journal of Geophysical Research: Space Physics. We also contributed to the Plasma Observatory's Yellow Book, which includes the energy dissipation as one of its science objectives. These serve as a strong foundation for proposals to NASA's Heliophysics Research Program such as NASA Living With a Star and Heliophysics Foundational Research programs in Space and Earth Sciences (ROSES)-2025 solicitation. Among the relevant ROSES calls, B.2 Heliophysics Foundational Research presents suitable avenues for this research, which includes "The Cross-Regime Coupling (CRC) SST addresses the foundational problem of how physical processes initiated in one regime of the Sun-Heliosphere-Planetary system are transported, transformed, and manifested in another". These proposals are typically submitted during the spring-summer timeframe, making an application feasible within the coming months.

Relevance of Proposed Activities to NASA EPSCoR RID Mission and Relation to Existing Researchs

Our group has a well-established history in the energy dissipation measurement, which dates back to 2019 and we already have at least 8 papers published on this path, including high-impact journals such as Physical Review Letters. The research proposed stems from the recent development of the new DA, LPDE and 60° polar angle techniques that provide unprecedented accuracy in evaluating the energy dissipation rate – a long-sought parameter within the field of space plasmas, as evidenced by the vast existing literature. The broad interest calls for immediate broadening of the results. This research directly addresses the NASA SMD Heliophysics objectives "Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe". This research also supports the goals set forth in Section 2.5.1 of NASA Strategic Plan, which promotes scientific studies of the Sun and solar system using space as a natural laboratory. The research aligns with NASA's Strategic Objective 1.3 by ensuring data accessibility through the DSpOC facility, led by Professor B. Maruca, at the University of Delaware. This not only fulfills a key NASA goal but also leverages Delaware's state-of-the-art research infrastructure. The development of higher education in the state of Delaware will be achieved by training grad students in high-performance computational languages for handling vast amounts of data and teaching the basic universal physics of turbulent energy transfer. This project will offer the PI, a great opportunity to mentor a graduate at UD. In addition, the PI will incorporate the state-of-art observational results into her classroom. This project is tightly aligned with the research interest in NASA SMD and STMD, and we plan to use the data from multiple NASA missions. We would directly collaborate with NASA-related institutions. We will apply for NASA-provided High-End Computing (HEC) resources as needed.

Budget and Budget Justification

PROGRAM:	NASA EPSCoR RID Seed proposal						
PERIOD:	7/1/26 6/30/27						
TITLE:	Tracing energy dissipation rate from the Sun Through the Solar Wind to the Magnetosphere						
PI:	Yan Yang						
							YEAR 1 07/01/2026 06/30/2027
I.	**SALARIES & WAGES**						
	Personnel	**Role**	**Salary**	**Monthly Salary Rate**	**# Months**	**Type Months**	
	Yan Yang	PI				summer months	-
	TBD	Grad Student		3,000	4	calendar months	12,000
						TOTAL SALARY & WAGES	**12,000**
II.	**BENEFITS**				**Rate**		
		1. Faculty and Professional			41.9%		-
		2. Graduate Student			12.3%		1,476
						TOTAL BENEFITS	**1,476**
III.	**SUPPLIES & EXPENSES**						
		1. Materials and Supplies					800
		2. Publications					1,800
						TOTAL SUPPLIES & EXPENSES	**2,600**
VI.	**TRAVEL**						
	A. Domestic Travel	Dom Conference	1	5 days each			2,350
						TOTAL TRAVEL	**2,350**
VIII.	**TUITION**			**Per Year**	**Rate**		
		Tuition for each Graduate Student		19,240	40%	**TOTAL TUITION**	**2,565**
						TOTAL COSTS	**20,991**
					Rate		
IX.	**F&A RATE COSTS**				60%	**TOTAL F&A**	**-**
						TOTAL PROJECT COSTS	**20,991**

Dr. Yan Yang, PI, will oversee the entire project and conduct the main and significant part of the research in this project. Specifically, she will develop the theory for inertial range turbulence, design the techniques and mentor the graduate student. She will devote 2 months effort per year. No funding is requested for PI.

Funding is requested to support one Graduate Student Researcher in the Department of Physics and Astronomy. The student will devote 4 months effort per year. The student will learn advanced turbulence theory and space physics, develop associated computational and observational data analysis skills, and work on the project. The annual salary amount for a Graduate Student in the Department of Physics and Astronomy is $36,000 for 12 months effort. A 4-month effort for a graduate student adds up to $12,000. According to University policy, fringe benefits are 12.3% for graduate students. The 12.3% fringe benefit for the graduate student is $1,476.

Domestic travel funds of $2,350 is requested for the PI or Graduate Student working on the project to attend 1 conference (including registration fees, average cost based on recent experiences). Attendance at these conferences will benefit the project by presenting results to an audience of experts, enabling discussion with other leaders in the field and supporting the professional development and advancement of the team members.

Materials and Supplies - $800 is requested annually for Materials and Supplies, such as hard drives, memory media, monitors and presentation supplies (i.e. posters).

Publication Costs - $1,800 is requested for supporting the publication of the results in peer-reviewed scientific journals.

Tuition – Funds in the amount of $2,565 are requested for tuition of the graduate student working on this project.

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Education

Ph.D., Fluid Mechanics, Peking University — Sept 2012–July 2018
Supervisors: Yipeng Shi, Shiyi Chen and William H. Matthaeus

Visiting Student, Plasma Physics, University of Delaware — Aug 2015 –Aug 2017
Supervisor: William H. Matthaeus

B.S., Theoretical and Applied Mechanics, Peking University — Sept 2008 –July 2012

Professional Employment

Assistant Professor, University of Delaware — Aug 2023–present
Postdoctoral Researcher, University of Delaware — Sept 2021–July 2023
Supervisor: William H. Matthaeus

Research Assistant Professor, — Oct 2020–Aug 2021
Southern University of Science and Technology

Presidential Postdoctoral Fellow, — Aug 2018 –Sept 2020
Southern University of Science and Technology

Academic Activities

Reviewer:
Physical Review Letters, The Astrophysical Journal, Nature Astronomy, Physics of Plasmas, New Journal of Physics, Frontiers in Astronomy and Space Sciences, AGU Dewan Scholarship Reviewer, NASA Proposal Review Panelist, NSF Proposal Review Panelist.

Conference Session Chair and Organizer:
AGU Fall Meeting, Triennial Earth-Sun Summit (TESS), Solar Heliospheric & Interplanetary Environment (SHINE) Workshop, EGU General Assembly.

Co-leader and Team Member:
The International Space Science Institute (ISSI) international team in Space and Earth Sciences: *Cross-scale energy transfer in space plasmas*, 2022-2024
The International Space Science Institute (ISSI) international team in Space and Earth Sciences: *Unveiling energy conversion and dissipation in non-equilibrium space plasmas*, 2024-2026

Associate Investigator:
Science Team member of the NASA PUNCH mission in the Science Working Group: *Where and how do microstructures and turbulence form in the solar wind*?

Executive Committee Members:
Member-at-Large in APS Topical Group in Plasma Astrophysics.

Students Supervised:
Zihang Cheng (Graduate, University of Delaware, 2024–), Zhuoran Gao (Graduate, University of Delaware, 2025–), Yuchen Ye (Graduate, Peking University, 2023–), Manuel Cuesta (Graduate, University of Delaware, 2022-2023), Bin Jiang (Postdoc, Southern University of Science and Technology, 2021-2023), Cheng Li (Postdoc, Southern University of Science and Technology, 2022-2023), Sohom Roy (Graduate, University of Delaware, 2022), Yanwen Wang (Undergraduate, University of Delaware, 2021-2022), Haomin Sun (Graduate, University of

Science and Technology of China, 2021), Chunhua Ying (Undergraduate, Southern University of Science and Technology, 2019).

Selected Publications

Books

Y. Yang, "Energy Transfer and Dissipation in Plasma Turbulence: From Compressible MHD to Collisionless Plasma", *Springer*, 2019.

Selected Publications (from 60 total; Google Scholar h-index 20, citations 1691)

[1] B. Jiang, Z. Gao, **Y. Yang**, F. Pecora, K. Gao, C. Li, S. Oughton, W. H. Matthaeus, and M. Wan, "Angular dependence of third-order law in anisotropic mhd turbulence", The Astrophysical Journal **1000**, 71 (2026).

[2] C. Li, Y. Yang, W. Matthaeus, B. Jiang, S. Oughton, M. Wan, and S. Chen, "Separate exact laws of kinetic and magnetic energy cascade in magnetohydrodynamic turbulence", Physical Review Letters **136**, 064001 (2026).

[3] F. Pecora, W. H. Matthaeus, A. Greco, P. Dmitruk, **Y. Yang**, V. Carbone, and S. Servidio, "Turbulence in the terrestrial magnetosheath: space–time correlation using the magnetospheric multiscale mission", Proceedings of the National Academy of Sciences **122**, e2519635122 (2025).

[4] B. Jiang, C. Li, **Y. Yang**, K. Zhou, W. H. Matthaeus, and M. Wan, "Energy transfer and third-order law in forced anisotropic magneto-hydrodynamic turbulence with hyper-viscosity", Journal of Fluid Mechanics **974**, A20 (2023).

[5] F. Pecora, S. Servidio, L. Primavera, A. Greco, **Y. Yang**, and W. H. Matthaeus, "Multipoint turbulence analysis with HelioSwarm", The Astrophysical Journal Letters **945**, L20 (2023).

[6] F. Pecora, **Y. Yang**, W. H. Matthaeus, A. Chasapis, K. G. Klein, M. Stevens, S. Servidio, A. Greco, D. J. Gershman, B. L. Giles, and J. L. Burch, "Three-dimensional energy transfer in space plasma turbulence from multipoint measurement", Phys. Rev. Lett. **131**, 225201 (2023).

[7] Y. Wang, R. Chhiber, S. Adhikari, **Y. Yang**, R. Bandyopadhyay, M. A. Shay, S. Oughton, W. H. Matthaeus, and M. E. Cuesta, "Strategies for determining the cascade rate in MHD turbulence: isotropy, anisotropy, and spacecraft sampling", The Astrophysical Journal **937**, 76 (2022).

[8] **Y. Yang**, W. H. Matthaeus, S. Roy, V. Roytershteyn, T. N. Parashar, R. Bandyopadhyay, and M. Wan, "Pressure–strain interaction as the energy dissipation estimate in collisionless plasma", The Astrophysical Journal **929**, 142 (2022).

[9] **Y. Yang**, M. Wan, W. H. Matthaeus, L. Sorriso-Valvo, T. N. Parashar, Q. Lu, Y. Shi, and S. Chen, "Scale dependence of energy transfer in turbulent plasma", Monthly Notices of the Royal Astronomical Society **482**, 4933–4940 (2019).

[10] **Y. Yang**, W. Matthaeus, T. Parashar, P. Wu, M. Wan, Y. Shi, S. Chen, V. Roytershteyn, and W. Daughton, "Energy transfer channels and turbulence cascade in vlasov-maxwell turbulence", Physical Review E **95**, 061201 (2017).

[11] **Y. Yang**, W. H. Matthaeus, T. N. Parashar, C. C. Haggerty, V. Roytershteyn, W. Daughton, M. Wan, Y. Shi, and S. Chen, "Energy transfer, pressure tensor, and heating of kinetic plasma", Physics of Plasmas **24**, 072306 (2017).