HelioSwarm:
A Multipoint, Multiscale Mission to Characterize Turbulence

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HelioSwarm, a multispacecraft observatory designed to fly through the near-Earth solar wind in a swarm with inter-spacecraft separations spanning MHD and ion scales, has been selected by NASA as a Medium Class Explorer Mission. The measurements that HelioSwarm provides will reveal the structure and underlying dynamics of magnetized turbulence, a science priority identified in the 2013 Heliophysics Decadal Survey and deeply rooted in decades-earlier recommendations by the space science community in the 1980 report by the Plasma Turbulence Explorer Study Group. As of August 2022, HelioSwarm's planned launch readiness date is in 2028 and with a primary science phase extending into 2030; HelioSwarm thus promises to be a key mission needed to advance science priorities of the coming decade. This white paper provides an overview of turbulent systems that constitute an area of compelling heliophysics research, including why this mission is needed and how this mission will achieve the goal of revealing how energy is transferred across scales and boundaries in plasmas throughout the universe.

The Motivation for Studying Magnetized Turbulence Turbulence, the nonlinear scale-to-scale transfer of energy, plays a critical role in the transport of mass, momentum, and energy in plasma systems as varied as solar and stellar winds, black hole accretion disks, the interstellar media, and terrestrial laboratory environments. The motivation to understand turbulence is both diverse and fundamental. The general characterization of turbulence remains one of the outstanding tasks of classical physics, in particular understanding how energy is transported through a system, and how such transport changes the evolution of the system. Turbulence is fundamental to understanding solar wind plasma acceleration and heating, the nature of plasma fluctuations everywhere, and the scattering, acceleration, and transport of energetic particles.

While significant theoretical effort has been expended, there are still open questions about the mechanisms that transfer energy from scale-to-scale within the turbulent cascade as well as those that dissipate cascade energy and energize the particles. For example, there is still no universal agreement on basic issues such as the spectral or spatial distribution of turbulent power, with different theories predicting different distributions of power. Progress on characterizing turbulence in plasma systems will improve our understanding of some of the most important processes in astrophysics, including the formation of stars and planets, the heating of accretion flows, and turbulent dynamo generation. Characterizing these properties will enable the description of the thermodynamic fate of plasmas throughout the universe. **Answering these open questions about turbulence was identified as a science priority in the 2013 Heliophysics Decadal Survey[1] and deeply rooted in decades-earlier recommendations by the space science community in the 1980 report by the Plasma Turbulence Explorer Study Group[2]**.

What is Unknown about Plasma Turbulence? While there has been significant progress in understanding turbulence over the last eight decades, there are still a number of vital, unanswered questions about the nature of plasma turbulence. In particular, the nature of the turbulent fluctuations, the rate at which energy is transferred, the role of magnetic fields in organizing the transfer, how the plasma changes as it transitions from magnetofluid to kinetic scales, and the mechanisms that remove energy from the turbulent cascade are all topics of intense research. A review of some of the theories proposed to address these questions can be found in recently published review articles[3–5], as well as companion white papers submitted to the 2023 Decadal Survey for Solar and Space Physics (Heliophysics) [6, 7].

One of the key challenges to studying turbulence is the vast spatial and temporal scales covered by most turbulent systems. The length scales at which energy is injected into a turbulent system and those at which they are removed are typically separated by several orders of magnitude, with physical processes having characteristic timescales spanning similar separations. Any numerical simulation of such systems must choose between realistic scale separations, which are necessary to generate appropriate nonlinear structures, and kinetic plasma mechanisms, which are necessary to accurately damp and dissipate the energy from the cascade onto the ions and electrons. Similarly, laboratory experiments are of an insufficient size to generate a large enough inertial range to replicate solar and astrophysical cascades, and astrophysical systems are too remote to perform in situ diagnostics of turbulent phenomena.

The solar wind offers the most accessible environment for the in situ observation at all relevant scales of turbulent electromagnetic fields and particle distributions that are representative of magnetized turbulence throughout the universe[8]. At the largest scales, greater than $\sim 10^6$ km, solar wind varies as a result of velocity shear, compressions, and magnetic boundaries that are a direct result of solar structure and activity. This constitutes the *energy-containing* or *injection*

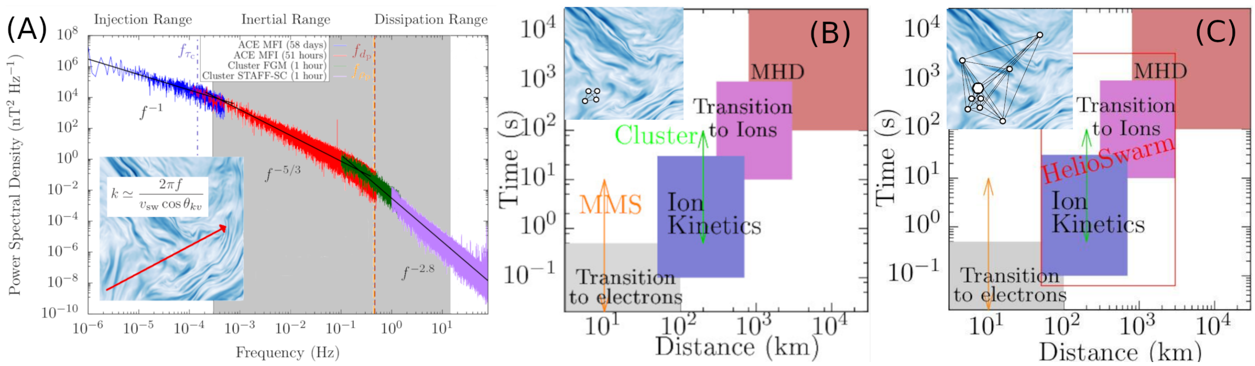

Figure 1: *Panel A* Single-spacecraft rely on simplifications to disentangle spatial and temporal dynamics and combine many different types of turbulence in order to have a statistically large enough data set. *Panel B* Multi-spacecraft missions (e.g. Cluster and MMS) revolutionized our understanding of the spatial structure of some plasma processes but are limited to measuring only a single scale size at a time. *Panel C* To transform our understanding of turbulence, we need simultaneous measurements at many points, with separations between the spacecraft spanning MHD and ion scales, and the transition region in between. Figures adapted from [3] and [9].

range that drives the turbulence at smaller scales. Between $\sim 10^6$ and $\sim 10^3$ km, the *inertial range* contains the nonlinear dynamics that transport energy from larger to smaller scales. This part of the spectrum often exhibits a universal form, typically a power-law spectrum, that is indicative of the nonlinear dynamics. At scales smaller than $\sim 10^3$ km, kinetic plasma processes begin to act on the cascade, leading to dissipation as the energy in the turbulent fluctuations is converted into thermal energy of the ions and electrons.

To date, all in situ observations of solar wind plasmas have been single point measurements (e.g., ACE, Wind)[10, 11], or have focused on a narrow range of scales through the use of carefully controlled formations of a few spacecraft (e.g., Cluster, MMS)[12, 13]. These missions have been exceedingly successful, with Wind alone providing data fpr ~ 6300 peer-reviewed publications from 1995 to 2021, but they are fundamentally limited in their application to studying turbulence. Single-point observations must map time series to spatial structure through Taylor's hypothesis[14], which assumes advected time scales are much faster than any temporal evolution in the plasma frame. Such assumptions allow the mapping of power spectral densities calculated as a function of frequency, e.g. Panel A of Fig. 1, to being a function of spatial scale. This hypothesis is frequently invoked, but may not be valid at the same scales where energy is removed from the turbulent cascade, depending on the frequency of the fluctuations and the angles between the fluctuations and local flow directions[15]. Even under conditions where Taylor's hypothesis is valid, one can only sample spatial structure parallel to the flow direction. A central problem in understanding turbulence is that key dynamics, both linear and nonlinear, depend upon the orientation of the wave vector relative to the mean magnetic field; no single spacecraft can measure this three-dimensional quantity. Assembling information on the three-dimensional structure of turbulence with a single point measurement requires averaging over long intervals with different flow directions, potentially mixing different kinds of turbulence together.

These limitations of single-point measurements are widely recognized and served as the impetus for the Cluster and MMS missions. Flying four spacecraft in a tetrahedral formation, as was done with these missions, provides a limited set of separations between the spacecraft that can be used to sample the multi-directional structure of the plasma, illustrated in Panel B of Fig. 1. In the case of MMS, these separations allow the study of the multi-dimensional dynamics of magnetic reconnection at electron scales. As the primary science objectives for the Cluster and MMS missions are phenomena in Earth's magnetosphere, they infrequently measure the unperturbed solar wind, and instrumentation is not specifically optimized for solar wind measurements [16]. Even when those missions enter the solar wind, magnetic connection back to the magnetosphere frequently spoils measurements of turbulence, significantly limiting the number of useful intervals for studying turbulence. At a given time, the inter-spacecraft separations typically have very similar lengths, and therefore are inadequate to simultaneously resolve the cross-scale nonlinear couplings needed to understand the dynamics of plasma turbulence. Even with the most advanced analysis techniques, the scales sampled only cover a factor of approximately ten [17], nowhere near the orders of magnitude necessary for simultaneously measuring turbulent fluctuations through the inertial and dissipation ranges.

As turbulence is fundamentally a multi-scale, three-dimensional, time-evolving phenomenon, neither single-point measurements nor even a cluster of four spacecraft can provide the measurements necessary to reach closure on fundamental outstanding questions in plasma turbulence. HelioSwarm will reveal the temporal and spatial structure of turbulence by making measurements with spatial separations between the constituent spacecraft spanning MHD, transition, and ion-kinetic scales. The measurements will be made sufficiently rapidly to resolve advected ion-scale structures, and the overall configuration of the observatory evolves sufficiently slowly to provide stable configurations over intervals longer than typical correlation time scales, illustrated in Panel C of Fig. 1. **Making progress on fundamental questions about the multi-scale and three-dimensional nature of turbulence requires simultaneous measurements from a large number of spacecraft at a variety of separation distances, as will be provided by HelioSwarm.**

The goals of the HelioSwarm mission are focused on revealing how energy is transferred across scales and boundaries in turbulent plasmas throughout the universe. This will be accomplished by flying a swarm of small spacecraft with a wide range of spatial separations to simultaneously sample key physical quantities in turbulent solar wind, namely the interplanetary magnetic fields and proton densities, velocities, and temperatures. This observatory will reveal and quantify key, currently unmeasured aspects of turbulence, allowing us to describe the cascade of energy across scales and into different physical regions, including the pristine solar wind, intervals associated with large-scale structures such as interplanetary Coronal Mass Ejections (CMES) and Corotating Interaction Regions (CIRs), and strongly driven turbulence associated with Earth's magnetosheath and the magnetically connected foreshock. By studying the distributions of current sheets and other intermittent structures, HelioSwarm will resolve what role these structures play in heating protons in turbulent systems. This mission will provide a means of directly testing current conflicting models for the spectral and spatial distributions of turbulent power, which in turn affects our understanding of dissipation and scattering. There are two overarching goals, with six specific objectives that HelioSwarm will resolve, listed in Table 1.

Achieving these objectives will require measuring both typical solar wind plasma and more uncommon conditions, associated with extreme plasma parameters or strongly driven turbulence from CMEs, CIRs, and various magnetospheric processes. Estimates for the number of hours HelioSwarm will encounter in these distinct near-Earth regions and for different conditions given a launch in 2028 are given in Table 2.

G1: Reveal the three-dimensional spatial structure and dynamics distribution of turbulence in a weakly collisional plasma.	O1: Reveal how turbulent energy transfers in the typical solar wind plasma as a function of scale and time.
	O2: Reveal how the turbulent cascade of energy varies with background parameters in different solar wind environment.
	O3: Quantify transfer of turbulent energy between fields, flows, and proton heat.
	O4: Identify thermodynamic impacts of intermittent structures on protons.
G2: Ascertain the mutual impact between boundaries and large-scale structure and turbulence.	O1: Determine how Solar Wind turbulence affects and is affected by large-scale structures such as CMEs and CIRs.
	O2: Determine how driven turbulence differs from that in undisturbed solar wind.

Table 1: HelioSwarm's Scientific Goals and Objectives are designed to disentangle spatial and temporal variations in the solar wind and transform our understanding of the physics of plasma turbulence.

Observatory Spacecraft and Instrumentation HelioSwarm will fly eight node spacecraft in a loose formation around a central hub with slowly varying inter-spacecraft separations, thereby forming and reforming desirable configurations on multiple scales. The hub and nodes are high heritage, 3-axis stabilized spacecraft. The hub is a powered Evolved Expendable Launch Vehicle Secondary Payload Adaptor (ESPA) ring provided by Northrop Grumman SPace Systems (NGSP). It carries and deploys the eight nodes to the science orbit. The nodes are Venus Bus micro-satellites provided by Blue Canyon Technologies (BCT). Each node possesses identical instrument suites consisting of three high-heritage, high-TRL sensors optimized for HelioSwarm: a Faraday Cup (FC), a Fluxgate Magnetometer (FGM), and a Search Coil Magnetometer (SCM).

The FGM[18] is a dual core fluxgate magnetometer designed and built by Imperial College London selected to measure the interplanetary magnetic fields's lower frequencies. Previous versions of the FGM have flown on SolO[18] and the instrument has JUpiter ICy moons Explorer (JUICE) design heritage. The SCM[19] is a heritage set of magnetic sensors designed and built by Laboratoire de Physique des Plasmas selected to measure the IMF's higher frequencies. The SCM has JUICE design heritage. The FC is a heritage-based design developed at the Smithsonian Astrophysical Observatory, in conjunction with University of California, Berkeley (UCB), and Draper Laboratories. The sensor makes measurements of the radial velocity distribution function (VDF) of solar wind ions along with the flow angle of the incoming beam. Previous versions of the FC have been employed on WIND[20], DSCOVR, and PSP[21].

The hub has the same instrument suite as the nodes, as well as an additional electrostatic analyzer (iESA) to measure the ion distribution functions in more detail. The iESA, a particle sensor designed and built using heritage designs (e.g., SolO[22]) by Research Institute in Astrophysics and Planetology (IRAP), will measure 3D ion VDFs, providing detailed measurements of the proton and alpha plasma parameters. UCB will lead the development of an optional (not required for primary mission objectives) student electron experiment (SEE), an electron Electrostatic Analyzer (eESA) that will be included on the hub to provide contextual measurements for the state of the electrons and the kind of plasma turbulence the observatory is sampling. The hub will also be responsible for collecting and downlinking data from the observatory.

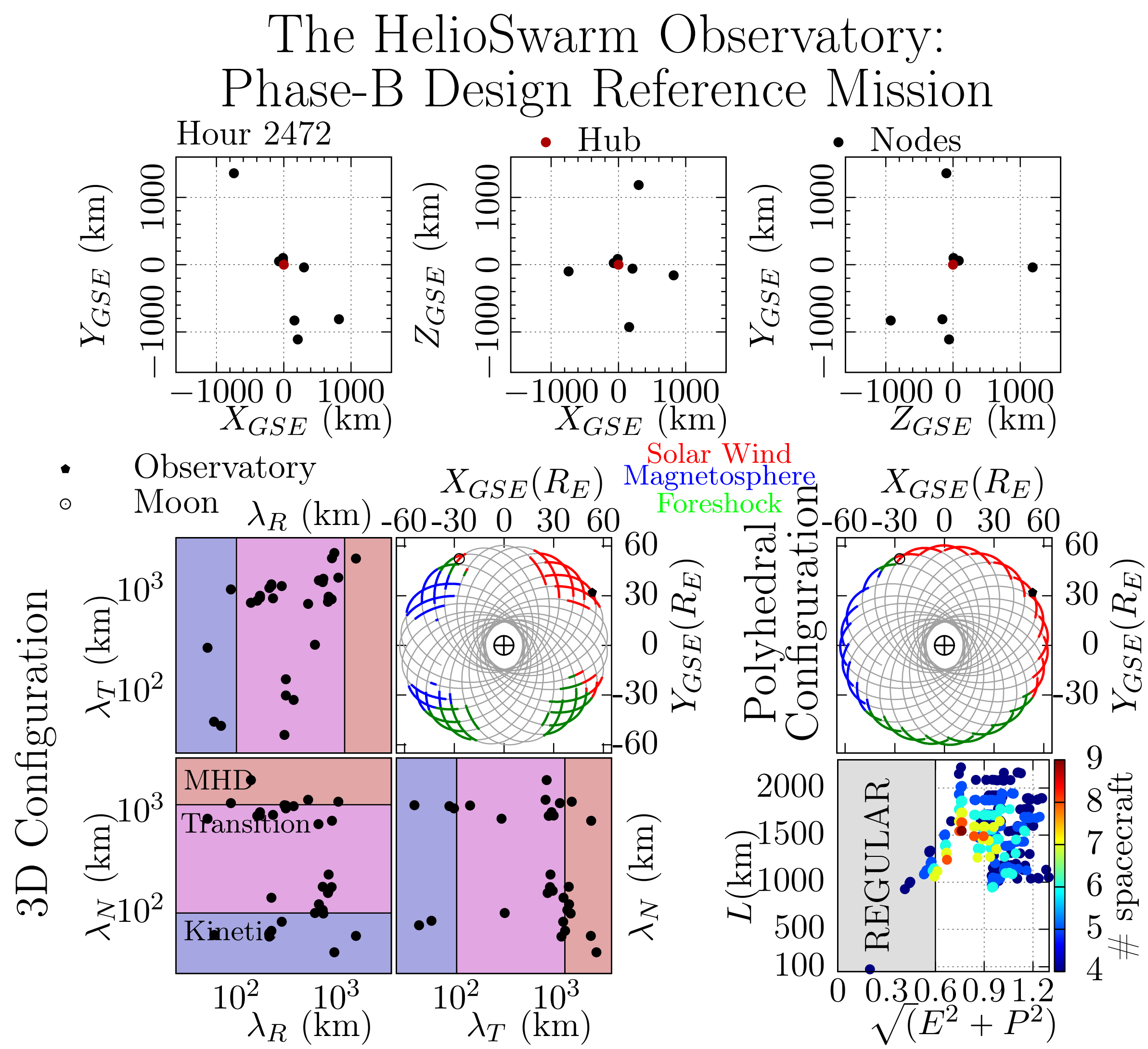

Figure 2: Summary plot of HelioSwarm Observatory Phase-B Design Reference Mission (DRM) positions and separations. *Top Row* Relative positions between the hub (red) and eight nodes (black) projected into the GSE coördinate system at 2472 hours into the DRM. *Bottom Left* Projected vector components of the 36 inter-spacecraft baseline separations (black dots) demonstrate coverage of MHD and ion-kinetic scales, as well as the transition region in-between. The lunar resonant orbit of the observatory (black dot) in the GSE coördinate system is shown as grey lines in the upper-right inset, with the moon's location (open circle) included to illustrate scale. Times with orthogonal coverage over all three scales, highlighted in color, arise in the pristine solar wind (red lines), the magnetically connected solar wind (green) and the magnetosphere/magnetosheath (blue). *Bottom Right* The size and geometric configurations of the polyhedra constructed by spacecraft subsets of the HelioSwarm observatory. The number of vertices is indicated by color, while the size of the polyhedra L and its regularity (the RMS of the elongation E and planarity P) are indicated on the ordinate and abscissa respectively. The times when there are at least two regular polyhedra with characteristic sizes more than a factor of three different are indicted in the upper inset, using the same color scheme as the 3D Configuration inset. As quantified in Table 2, due to the high eccentricity of the orbit, the Observatory samples these regions near apogee for a substantial fraction of the orbit period.

A summary plot of the Phase-B Design Reference Mission (DRM) for HelioSwarm for a launch readiness date in 2028 is shown in Fig. 2. The swarm will travel in a two-week lunar-resonant orbit optimized to minimize station-keeping, sampling the pristine solar wind as well as strongly driven turbulence in the magnetosphere and magnetically connected solar wind[23, 24]. A typical distribution of the nodes with respect to the hub at hour 2472 of the DRM is shown in the top row of Fig. 2, projected into the X-Y, X-Z, and Y-Z GSE planes; the position of the swarm relative to the Earth at this time is indicated by a black dot in the inset figures in the bottom sets of panels, with the orbital trajectory shown in grey lines. The moon is shown as an open circle for reference.

The 36 baseline vectors separating the nine spacecraft will simultaneously span scales in the MHD and ion-kinetic ranges, and the transition range in-between. As ion kinetic scales, e.g. proton inertial lengths and gyroradii, are on the order of 100 km in the pristine solar wind, the minimum baselines will be as small as 50 km. Since the break scale between MHD scales and the dissipation range is typically found to be on the order of 1000km, it will be necessary to simultaneously measure baselines as large as 3000 km. Because of the natural anisotropies in the system due to the solar wind flow direction and the local magnetic field, it is essential that the measurement points not be aligned in a single line or plane, but rather cover baselines along and across the local flows and fields so that the three-dimensional structure of solar wind turbulence can be reconstructed.

3D Configurations The components of the baseline separations projected into an orthogonal RTN frame are shown in the bottom left panels of Fig. 2, showing that HelioSwarm will cover both MHD and ion scales simultaneously. We identify qualifying intervals as those with baseline components covering MHD, transition, and kinetic scales in all three orthogonal directions. The intervals that satisfy this restriction are shown in the top-right inset. The number of hours for the DRM that satisfy this configuration requirement over the 12-month nominal science phase are given in Table 2, both in total and sub-divided into regions of pristine solar wind, magnetically connected foreshock, and the magnetosphere/magnetosheath. *All science measurements will be telemetered to the ground without an in-flight selection process, regardless of the observatory configuration.* These spatially separated measurements will enable the first ever multi-scale calculation of two-point correlations with time and space as independent inputs, as well as multi-scale studies of cascade rates, structure functions, and intermittancy.

Polyhedral Configurations From an observatory of nine spacecraft, 382 distinct polyhedra with at least four vertices can be constructed. These shapes will allow for the study of the three-dimensional structure of the solar wind turbulence. The distribution of polyhedra have an enormous range of average interspacecraft spacings, as well as varying elongations and planarities, plotted in the bottom right panels of Fig. 2, allowing it to take advantage of the numerous multi-spacecraft analysis techniques developed for four-spacecraft missions [25], including direct calculation of spatial derivatives as well as those capable of measuring the distribution of power in frequency-wavevector space as a function of size scale and orientation. The number of hours that satisfy the polyhedral configurations are also shown in Table 2. Combined with multipoint correlation studies, these techniques enable detailed studies of the distribution, transport, and removal of energy in solar wind turbulence in a way not accessible to any current or previous mission.

With the advent of low-resource sensors and small satellites, configurations of many spacecraft simultaneously sampling many scales are possible for the first time and promise to transform our knowledge of turbulence. **The HelioSwarm mission will bring closure to some of the most pressing open questions in the study of solar wind, and advance our understanding of plasma turbulence throughout the universe.**

Phase B DRM; LRD 2028	Fig. 2	Total	3D	Polyhedral
Solar Wind	Red	2881	777	1068
Foreshock	Green	2470	977	852
Magnetosphere/Magnetosheath	Blue	3149	650	639
Science Phase		8850	2404	2559
	Objective	Total	3D	Polyhedral
Pristine SW	G1O1	2015	544	747
Extreme SW	G1O2	58	16	21
SW w/ Large Scale Structure	G2O1	866	233	321
Strongly Driven Turbulence	G2O2	5619	1627	1491

Table 2: HelioSwarm measures thousands of hours in targeted near-Earth regions of space, with hundreds of hours in optimal polyhedral and 3D configurations for the application of a variety of analysis approaches, providing measurements to advance understanding of turbulence in typical (G1O1,G2O2) uncommon (G2O1) and extreme (G1O2) plasma conditions.

[1] N. Council et al. *Solar and Space Physics: A Science for a Technological Society*. National Academies Press, 2013. ISBN 9780309262774. URL `https://books.google.com/books?id=FnaqDwAAQBAJ`.

[2] D. Montgomery et al. Report of the nasa plasma turbulence explorer study group. Technical Report 715-78, Jet Propulsion Laboratory, Pasadena, CA, 1980.

[3] D. Verscharen, K. G. Klein, and B. A. Maruca. The multi-scale nature of the solar wind. *Living Rev. Solar Phys.*, 16(1):5, December 2019. doi:10.1007/s41116-019-0021-0.

[4] A. A. Schekochihin. MHD Turbulence: A Biased Review. *arXiv e-prints*, art. arXiv:2010.00699, October 2020. doi:10.48550/arXiv.2010.00699.

[5] W. H. Matthaeus. Turbulence in space plasmas: Who needs it? *Physics of Plasmas*, 28(3): 032306, March 2021. doi:10.1063/5.0041540.

[6] J. M. TenBarge et al. [Heliophysics 2022 Decadal] Disentangling the Spatiotemporal Structure of Turbulence Using Multi-Spacecraft Data. September 2022.

[7] W. H. Matthaeus et al. [Heliophysics 2022 Decadal] The essential role of multi-point measurements in investigations of turbulence, three-dimensional structure, and dynamics: the solar wind beyond the Taylor hypothesis and single-scale measurements. September 2022.

[8] R. Bruno and V. Carbone. The Solar Wind as a Turbulence Laboratory. *Living Rev. Solar Phys.*, 2:4, September 2005.

[9] L. Arzamasskiy et al. Kinetic Turbulence in Collisionless High-Beta Plasmas. *arXiv e-prints*, art. arXiv:2207.05189, July 2022.

[10] E. C. Stone et al. The Advanced Composition Explorer. *Space Sci. Rev.*, 86:1–22, July 1998. doi:10.1023/A:1005082526237.

[11] L. B. Wilson III et al. A Quarter Century of Wind Spacecraft Discoveries. *Reviews of Geophysics*, 59(2):e2020RG000714, May 2021. doi:10.1029/2020RG000714.

[12] C. P. Escoubet, M. Fehringer, and M. Goldstein. Introduction: The Cluster mission. *Annales Geophysicae*, 19:1197–1200, October 2001. doi:10.5194/angeo-19-1197-2001.

[13] J. L. Burch, T. E. Moore, R. B. Torbert, and B. L. Giles. Magnetospheric multiscale overview and science objectives. *Space Science Reviews*, 199(1):5–21, 2016. ISSN 1572-9672. doi:10.1007/s11214-015-0164-9. URL `http://dx.doi.org/10.1007/s11214-015-0164-9`.

[14] G. I. Taylor. The Spectrum of Turbulence. *Royal Society of London Proceedings Series A*, 164:476–490, February 1938. doi:10.1098/rspa.1938.0032.

[15] G. G. Howes, K. G. Klein, and J. M. TenBarge. Validity of the Taylor Hypothesis for Linear Kinetic Waves in the Weakly Collisional Solar Wind. *Astrophys. J.*, 789:106, July 2014. doi:10.1088/0004-637X/789/2/106.

[16] O. W. Roberts et al. A Study of the Solar Wind Ion and Electron Measurements From the Magnetospheric Multiscale Mission's Fast Plasma Investigation. *Journal of Geophysical Research (Space Physics)*, 126(10):e29784, October 2021. doi:10.1029/2021JA029784.

[17] F. Sahraoui et al. Three Dimensional Anisotropic k Spectra of Turbulence at Sub-proton Scales in the Solar Wind. *Phys. Rev. Lett.*, 105(13):131101, September 2010. doi:10.1103/PhysRevLett.105.131101.

[18] T. S. Horbury et al. Sharp Alfvénic Impulses in the Near-Sun Solar Wind. *Astrophys. J. Supp.*, 246(2):45, February 2020. doi:10.3847/1538-4365/ab5b15.

[19] A. Retinò. The Search-Coil Magnetometer onboard the ESA JUICE mission. In *EGU General Assembly Conference Abstracts*, EGU General Assembly Conference Abstracts, page 21172, May 2020. doi:10.5194/egusphere-egu2020-21172.

[20] K. W. Ogilvie et al. SWE, A Comprehensive Plasma Instrument for the Wind Spacecraft. *Space Sci. Rev.*, 71:55–77, February 1995. doi:10.1007/BF00751326.

[21] A. W. Case et al. The Solar Probe Cup on the Parker Solar Probe. *Astrophys. J. Supp.*, 246 (2):43, February 2020. doi:10.3847/1538-4365/ab5a7b.

[22] C. J. Owen et al. The Solar Orbiter Solar Wind Analyser (SWA) suite. 642:A16, October 2020. doi:10.1051/0004-6361/201937259.

[23] L. Plice, A. D. Perez, and S. G. West. Helioswarm: Swarm mission design in high altitude orbit for heliophysics. AAS/AIAA Astrodynamics Specialist Conference, 2019.

[24] P. Levinson-Muth, S. West, and L. Plice. Helioswarm: Swarm design methods in eccentric p/2 lunar resonant orbit. AAS/AIAA Astrodynamics Specialist Conference, 2022.

[25] G. Paschmann and P. W. Daly. *Multi-Spacecraft Analysis Methods Revisited*. 2008.