Project Title: Reprocessing MMS Solar Wind Data for Reliable Plasma Moment Estimation

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Co- Investigator: Bennett Maruca
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Abstract

NASA's Magnetospheric Multiscale (MMS) mission has revolutionized the understanding of space plasmas through unprecedented high-resolution measurements of particle velocity distribution functions (VDFs). Although MMS was designed primarily to study Earth's magnetosphere, its orbit regularly carries it into the solar wind (the plasma flowing out of the Sun). These solar wind observations remain underutilized because the existing plasma data products were optimized for denser, hotter magnetospheric conditions and therefore are not ready for most scientific, quantitative analysis in the relatively low-density, low-temperature solar wind. Leveraging modern machine learning (ML) and statistical fitting techniques, this project will reprocess the MMS solar wind VDF data to recover accurate estimates of plasma moments: density, bulk velocity, and temperature. This project will enhance the University of Delaware's visibility in heliophysics and space data science by establishing a new framework for ML-based data reprocessing and generating preliminary results and algorithms suitable for open dissemination.

Narrative

Background and Motivation: The NASA Magnetospheric Multiscale (MMS) mission provides the fastest measurement of particle velocity distribution functions (VDFs). This has made it possible to probe very small-scale physics in space plasmas for the first time. The MMS mission has achieved groundbreaking science in the magnetosphere region (Burch & Phan 2016). However, MMS data in the solar wind represent an untapped resource for studying kinetic-scale turbulence, energy dissipation, and wave–particle interactions under pristine plasma conditions (Bandyopadhyay et al. 2018, 2020).

However, the current MMS plasma data products are not readily suitable for scientific analysis in the solar wind. An example of this can be seen in Fig. 1, where we compare the solar wind proton temperature by two NASA spacecraft in near-Earth space: MMS and Wind. While Wind measurements are more reliable, they are an order of magnitude slower than the MMS measurement cadence. Figure 1 shows that the MMS estimates of solar wind proton temperatures are systematically overestimated and noise dominated both of which are likely effects of the processing.

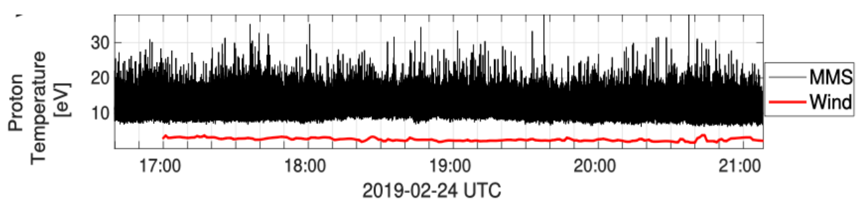

Figure 1: From Bandyopadhyay et al., (2020): the solar wind proton temperature measured by MMS and Wind spacecraft. The MMS instruments significantly overestimate the temperature values.

The onboard plasma instruments and associated moment calculation algorithms were optimized for the higher densities and higher temperatures typical of the magnetosheath. In the cold, tenuous solar wind, these algorithms often yield unreliable or incomplete plasma moments (density, bulk velocity, temperature). As a result, a rich trove of high-resolution solar wind data remains largely inaccessible to the heliophysics community.

The central goal of this project is to develop and validate a new data reprocessing framework to recover reliable plasma parameters from existing MMS VDFs in the interplanetary solar wind. The proposed work will establish the technical foundation required to pursue external NASA funding for large-scale MMS solar wind data reprocessing and public dissemination.

Approach: While space plasma instruments measure the statistical distribution of particle energies and directions, those measurements need to be processed to extract the plasma parameters– e.g., density, velocity, and temperature (see Sections 1 and 3 of Maruca (2012) for a detailed description). The MMS Team currently calculates these plasma parameters by simply integrating over the distribution function obtained from the particle counts measured by the Dual Electron Spectrometers (DES) and Dual Ion Spectrometers (DIS) in the Fast Plasma Investigation (FPI) suite (Pollock et al. 2016) onboard MMS.

However, in the solar wind, a majority of the DIS and DES sensors do not measure any counts. In this situation, a straightforward integration of the VDF gives rise to high uncertainties. In this project, instead of integrating the VDFs to compute plasma moments, we propose to fit models to the measured VDFs which will give the density, velocity, and temperature as parameters in the fit. Figure 2 shows an example

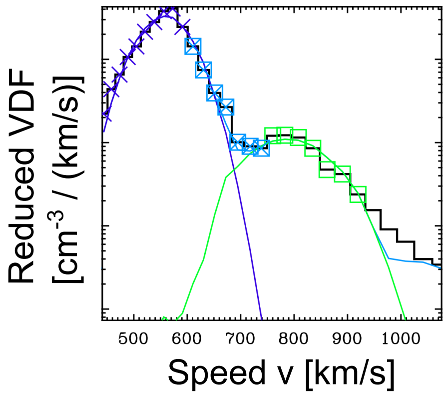

Figure 2: From *Maruca* (2012): a Wind ion VDF and associated fitting. The blue curve represents a Maxwellian fitting of the proton VDF and the green curve represents the alpha ion population.

of fitting Maxwellian to VDF measured by Wind spacecraft, using a code called **dvapbimax**, developed by Prof. Maruca. We will build on this code to extend similar analysis with MMS VDFs.

We will design and test an advanced data analysis pipeline that integrates physics-based fitting with machine learning (ML)–assisted correction and quality control. The project objectives are: 1.) Reprocess MMS solar wind VDFs to estimate plasma density, velocity, and temperature with improved accuracy and completeness. 2.) Validate results by comparing reprocessed plasma moments with independent measurements from other spacecraft other spacecraft in the near-Earth solar wind (e.g., Wind, ACE). While plasma measurements from Wind and ACE spacecraft are orders of magnitude slower than those from MMS, they will still be invaluable for calibration. 3.) Demonstrate proof-of-concept intervals across multiple mission phases to ensure the approach is robust to instrument configuration and operational mode changes.

The reprocessing pipeline will combine existing plasma calculation routines (e.g., moments from 3D VDFs) with ML-based fittings on simulated distributions and empirically validated datasets. Initial development will be carried out in Python, leveraging open-source tools for regression and anomaly detection. The pipeline will include uncertainty quantification to assess the confidence level of derived plasma moments.

The project includes a two-tiered mentoring structure. **Faculty Mentoring:** Associate Prof. Bennett Maruca will mentor Assistant Prof. Riddhi Bandyopadhyay on advanced VDF fitting, calibration, and validation strategies, drawing on his extensive experience with Wind data analysis. Prof. Maruca is already Prof. Bandyopadhyay's faculty mentor in the Department of Physics and Astronomy, and they have an established history of research collaboration (e.g., Bandyopadhyay et al. 2022; Maruca et al. 2018). **Student Mentoring:** Both Prof. Maruca and Prof. Bandyopadhyay (primary) will mentor Ph.D. student William Taranto, who will perform data processing, algorithm development, and testing. William will gain hands-on experience in heliophysics, statistical modeling, and ML tools, providing valuable training for a future research career in space plasma physics.

The proposed milestones are: 1.) Select representative MMS solar wind intervals which have already been used in previous solar wind studies. The selected intervals will span a wide range of plasma conditions (e.g., densities, speeds, temperatures, and plasma beta). **2.)** Develop baseline physics-based reprocessing routines for density, velocity, and temperature estimation. **3.)** Begin ML model training on synthetic and selected MMS intervals. **4.)** Integrate ML corrections into the reprocessing framework. **5.)** Validate results through cross-comparison with Wind and ACE plasma data. **6.)** Use outcomes to support a NASA Heliophysics proposal (e.g., Heliophysics Supporting Research, Heliophysics Guest Investigators – Open, Heliophysics Data Environment Enhancements). **7.)** Release code and documentation to the research community through GitHub and UD repositories. Present results at the AGU Meeting, 2027 and publish the results in peer-reviewed, open access journal.

References

Bandyopadhyay, R., Begley, L. J., Maruca, B. A., et al. 2022, Geophysical Research Letters, 49, e2022GL098053, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022GL098053

Bandyopadhyay, R., Chasapis, A., Chhiber, R., et al. 2018, The Astrophysical Journal, 866, 81, http://stacks.iop.org/0004-637X/866/i=2/a=81

Bandyopadhyay, R., Matthaeus, W. H., Chasapis, A., et al. 2020, The Astrophysical Journal, 899 (American Astronomical Society), 63, https://doi.org/10.3847%2F1538-4357%2Fab9ebe

Burch, J. L., & Phan, T. D. 2016, Geophysical Research Letters, 43, 8327, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL069787

Maruca, B. A. (2012). Instability-driven limits on ion temperature anisotropy in the solar wind: observations and linear Vlasov theory. Doctoral dissertation, Harvard University. http://nrs.harvard.edu/urn-3:HUL.InstRepos:9547903

Maruca, B. A., Chasapis, A., Gary, S. P., et al. 2018, The Astrophysical Journal, 866, 25, https://doi.org/10.3847/1538-4357/aaddfb

Pollock, C., Moore, T., Jacques, A., et al. 2016, Space Science Reviews, 199, 331, https://doi.org/10.1007/s11214-016-0245-4

Plan for Seeking External Funding

The expected outcome is a validated proof-of-concept demonstration showing that MMS solar wind VDFs can be reliably reprocessed to derive reliable plasma parameters using ML-aided techniques. These results will provide a foundation for a larger NASA proposal focused on full-mission data reprocessing and community release. The project directly aligns with NASA's Heliophysics System Observatory Data Environment and Heliophysics Guest Investigator program priorities, both of which seek improved accessibility and scientific use of existing mission datasets.

Beyond enabling external funding, the proposed work will position the UD as a leader in data-driven heliophysics research. It will create opportunities for interdisciplinary collaboration among plasma physicists, data scientists, and engineers, and it will contribute to the training of the next generation of researchers in computational space science.

Relevance of Proposed Activities to NASA EPSCoR RID mission, and relation to Existing Research

Strategic Objective 1.2 of the NASA 2022 Strategic Plan seeks to "[u]nderstand the Sun, solar system, and universe.'" The proposed project will directly support efforts "to understand the Sun and its interactions with Earth, the solar system and the interstellar medium." Though the vast majority of the universe consists of plasma, the solar wind is one of the very few space plasmas accessible to spacecraft. Thus, improved plasma moment evaluations from the MMS spacecraft will also help to "discover the fundamental physics governing how the universe works."

The project will greatly benefit the already ongoing MMS mission of NASA. MMS has already resulted in groundbreaking discoveries. The outcome of this project will open a new pathway for MMS investigations in the solar wind using plasma data.

The proposed research will help the PI, an early career faculty at the University of Delaware, to launch his group with a new direction of research. The activities of the proposed work will position the University of Delaware as a leader in data-driven heliophysics research. It will create opportunities for interdisciplinary collaboration among plasma physicists, data scientists, and engineers, and it will contribute to the training of the next generation of researchers in computational space science.

Budget

AGENCY: Bandyopadhyay and Maruca EPSCor budget
PROGRAM: **EPSCoR RID seed grant proposals**
PERIOD: 7/1/2026 – 6/30/202
TITLE:
PI: Bandyopadhyay
Co-I: Maruca
Due Date: 4/29/26

							YEAR 1 09/01/2026 09/02/2027	YEAR 2 09/01/2027 09/01/2028	YEAR 3 08/31/2028 09/02/2029	YEAR 4 09/01/2029 09/02/2030	YEAR 5 09/01/2030 09/03/2031	YEAR 6 09/01/2029 09/02/2030	TOTAL 01/00/1900 /1/2026 – 6/30/20
I.	**SALARIES & WAGES**												
	Personnel	**Role**	**Salary**	**Monthly Salary Rate**	**# Months**	**Type Months**							
	Bandyopadhyay	PI		-	0.5	summer months	-	-	-	-	-	-	-
		Co-I		-	0.5	calendar months	-	-	-	-	-	-	-
		Co-I				summer months	-	-	-	-	-	-	
		Post Doc Researcher		-		calendar months	-	-	-	-	-	-	
		Post Doc Researcher		-		calendar months	-	-	-	-	-	-	
		Undergrad Student		2,000		calendar months	-	-	-	-	-	-	-
	TBD	Grad Student		3,000	3	calendar months	9,000	-	-	-	-	-	9,000
						TOTAL SALARY & WAGES	**9,000**	**-**	**-**	**-**	**-**	**-**	**9,000**
II.	**BENEFITS**				**Rate**								
		1. Faculty and Professional			43.9%		-	-	-	-	-	-	-
		2. Other (Undergrad Student)			5.5%		-	-	-	-	-	-	-
		3. Graduate Student			7.4%		666	-	-	-	-	-	666
						TOTAL BENEFITS	**666**	**-**	**-**	**-**	**-**	**-**	**666**
III.	**SUPPLIES & EXPENSES**												
		1. Materials and Supplies					-	-	-	-	-	-	-
		2. Publications					955	-	-	-	-	-	955
						TOTAL SUPPLIES & EXPENSES	**955**	**-**	**-**	**-**	**-**	**-**	**955**
VI.	**TRAVEL**												
	A. Domestic Travel	2 meetings					7,700	-	-	-	-	-	7,700
	B. Foreign Travel	1 meeting						-	-	-	-	-	-
						TOTAL TRAVEL	**7,700**	**-**	**-**	**-**	**-**	**-**	**7,700**
VIII.	**TUITION**			**Per Year - FY26**	**Rate**								
		Tuition for each Graduate Student		20,088	40%	**TOTAL TUITION**	**2,679**	**-**	**-**	**-**	**-**	**-**	**2,679**
						TOTAL COSTS	**21,000**	**-**	**-**	**-**	**-**	**-**	**21,000**
					Rate								
IX.	**F&A RATE COSTS**				0%	**TOTAL F&A**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
						TOTAL PROJECT COSTS	**21,000**	**-**	**-**	**-**	**-**	**-**	**21,000**
						F&A BASE - 60%	18,321	-	-	-	-	-	18,321
						F&A - 60%	-	-	-	-	-	-	-
						Sub F&A - <25K	-	-	-	-	-	-	-

Budget Justification

SENIOR PERSONNEL
Dr. Bandyopadhyay, PI, will serve as Project Director and will oversee the entire project. Additionally, he acts as the doctoral supervisor for graduate student, William Taranto, for the project and will directly work with William Taranto on interval selection, downloading the data, and data analysis. He will devote 0.5 summer month for the project.

Dr. Maruca, Co-I will help with writing the new fitting routines for observational distribution functions and will devote 0.5 summer month for the project.

Both Dr. Bandyopadhyay's and Dr. Maruca's 9 month salary is supported by UD, and they will devote appropriate additional effort on the project as they arise.

OTHER PERSONNEL
Funding is requested to support one Graduate Student in the College of Arts and Sciences, Physics department for three months. The Graduate Student will work on downloading the MMS data and applying new fitting routines to evaluate improved moments. The annual salary amount for a Graduate Student in the Department of Physics & Astronomy is $36,000 for 12 months effort.

FRINGE BENEFITS
According to University policy, fringe benefits are calculated as 43.9% for faculty and professional Employees, 7.4% for graduate students, 71% for Salaried Staff, and 5.5% for undergraduate students and miscellaneous wage employees.

DOMESTIC TRAVEL
Domestic travel is requested for the PI, Co-I and grad student to attend conferences such as American Geophysical Union (AGU) Fall meeting. Costs include registration ($566), airfare ($500) ground transportation ($250), lodging ($800), and meals $450 per person. Attendance at this conference will benefit the project by engaging with the community and disseminate results to the broader community.

OTHER DIRECT COSTS
Publication Costs- $955 for the Astrophysical Journal.

INDIRECT COSTS
The University of Delaware's provisional indirect cost rate of 60%, effective 7/1/2025, was used. The University of Delaware's Facilities and Administrative (F&A) rates are approved by the Department of Health and Human Services. The distribution base for the F&A rate is MTDC. Equipment, capital expenditures, charges for patient care, tuition remission, rental costs of offsite facilities, scholarships, fellowships, vessel (ship) charges, participant support costs and the portion of each subcontract in excess of $25,000 shall be excluded from the modified total direct costs.

The University of Delaware will consider the costs and requests in the justification approved if an award is made and no contrary guidance from the agency is included in the award notice.

Riddhi Bandyopadhyay
Curriculum Vitae

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Office: 104 The Green,
Newark, DE, 19716, USA

EDUCATION

2016- 2020 **Ph.D. in Physics**, University of Delaware, Newark DE, USA
Thesis supervisor: Prof. William H. Matthaeus

2014- 2016 **M.Sc. in Physics**, Indian Institute of Technology (IIT) Kanpur, India

2011- 2014 **B.Sc. with Physics Honours**, University of Calcutta, India

PROFESSIONAL EMPLOYMENT

2025- present Assistant Professor
Department of Physics and Astronomy, **University of Delaware**, Newark DE, USA

2021- present Associate Research Scholar
Department of Astrophysical Sciences, **Princeton University**, Princeton NJ, USA

2020- 2021 Postdoctoral Research Associate
Department of Astrophysical Sciences, **Princeton University**, Princeton NJ, USA
Group of Prof. David J. McComas.

2020- 2020 Postdoctoral Researcher
Department of Physics and Astronomy, **University of Delaware**, Newark DE, USA
Group of Prof. William H. Matthaeus.

RESEARCH GRANT SELECTION

NASA ROSES-2020 Heliophysics Guest Investigator (H-GI) "Open" Program: "Investigation of the Nature of Turbulent Dissipation in near-Earth Space Plasma" (**PI**, 2021 – 2025).

NASA ROSES-2021 Parker Solar Probe Guest Investigator (PSP-GI) Program: "Geometry of Magnetic Fluctuations near the Sun" (**PI**, 2021 – 2025).

NASA MMS Early-Career Grant: "Ion and Electron Heating within Current Sheets in the Magnetosheath" (**PI**, 2021 – 2025).

INVITED TALKS

Pathways to Dissipation in Weakly-Collisional Plasmas, Geophysical Fluid Dynamics Session, AGU 2020.

Dissipation in Electron-only Reconnection Events: Insights from Pressure-Strain Interaction, Electron-only Reconnection Splinter Session, MMS Spring 2021 SWT Meeting.

Characterization of the sub-Alfvénic Solar Wind Observed by Parker Solar Probe, Asia Oceania Geosciences Society (AOGS) 2022 Virtual Meeting.

Energy transfer and proton-electron heating in turbulent plasmas, TESS 2022.

Energy transfer and proton-electron heating in turbulent plasmas, AAPPS-DPP 2022.

Energy Dissipation in Electron-only Reconnection, MR2023 Workshop on Magnetic Reconnection.

Turbulent Cascade and Proton–Electron Heating in Collisionless Plasmas, AGU 2023.

SELECTED PUBLICATIONS (from 78 total, 26 first author, Google-Scholar citations=1973, h-index=26)

Bailey, Z., Bandyopadhyay, R., *et al. Measurement of Turbulence Injection Scale Down to the Chromosphere*, 2025, The Astrophysical Journal Letters.

Bandyopadhyay, R., *et al. Collisional-like Dissipation in Collisionless Plasmas*, 2023, Physics of Plasmas (**Featured**; Companion science highlight published in Scilight).

Bandyopadhyay, R., *et al. Sub-Alfvénic Solar Wind Observed by the Parker Solar Probe: Characterization of Turbulence, Anisotropy, Intermittency, and Switchback*, 2022, The Astrophysical Journal Letters.

Bandyopadhyay, R., *et al. Statistics of Kinetic Dissipation in the Earth's Magnetosheath: MMS Observations*, 2020, Physical Review Letters.

Bandyopadhyay, R., *et al. Finite Dissipation in Anisotropic Magnetohydrodynamic Turbulence*, 2018, Phyical Review X.

SYNERGISTIC ACTIVITIES

Reviewer for The Astrophysical Journal (ApJ), The Astrophysical Journal Letters (ApJL), Geophysical Research Letters (GRL), Monthly Notices of the Royal Astronomical Society (MNRAS), Physics of Plasmas (PoP), Physical Review Letters (PRL), Earth and Space Science (ESS), Physical Review E (PRE), Scientific Reports, Astronomy & Astrophysics (A & A), Nature Communications, , Journal of Plasma Physics (JPP), Space Science Reviews (SSR) (~ 10 per year).

NASA Review Panels: Review Panelist, External Reviewer, Executive Secretary on several NASA review panels (~ 1 per year).

Conference Panel Organization

Magnetospheric Multiscale (MMS) Mission Science Working Team meeting	Spring 2020, Fall 2020, Fall 2024
Interstellar Boundary Explorer (IBEX) Mission Science Team meeting	2021, 2022
Solar Heliospheric and INterplanetary Environment (SHINE) workshop	2022, 2023, 2024

Graduate Student & Dissertation Advising

William Taranto (Ph.D. expected 2030, University of Delaware).

Sohom Roy (Ph.D. conferred on December 2024, University of Delaware).

Camryn Phillips (Fall 2021 and Spring 2022 semester projects, Princeton University).

Undergraduate Student Advising

Yanwen Wang '22 (2019 Sophomore Project), University of Delaware.

Luke Begley '22 (2020 Junior Project), Princeton University.

Siegfried Gawenda, '23 (2022 Spring Junior Project), Princeton University.

Ryan LoRusso, '24 (2022 Fall Junior Project), Princeton University.

Cole Meyer, '24 (2022 Fall Junior Project), Princeton University.

Jian Arnold, '24 (2023 Spring Junior Project), Princeton University.

Josiah Taylor, '24 (2023 Spring Junior Project), Princeton University.

Juston Ward, '24 (Princeton University Undergraduate Summer Research Program via National Radio Astronomy Observatory/National Astronomy Consortium; 2023&2024 Summer), Sam Houston State University.

Public Outreach

Lecture and Interaction at the "Science Under the Stars" series organized by the New Jersey State Museum.

Biographical Sketch

Bennett A. Maruca

Education

Harvard University	Astronomy and Astrophysics	PhD	2012
	Astronomy	AM	2008
Carnegie Mellon University	Physics	BS	2006
	Mathematical Sciences	BS	2006

Research Experience

2022 –	Associate Professor, Department of Physics & Astronomy, University of Delaware
2018 –	Member, Bartol Research Institute
2016 – 2022	Assistant Professor, Department of Physics & Astronomy, University of Delaware
2015 – 2016	Assistant Researcher, Space Sciences Laboratory, University of California, Berkeley
2012 – 2015	Charles Hard Townes Postdoc. Fellow, Space Sciences Lab., Univ. of California, Berkeley
2006 – 2012	Graduate Research Fellow, Department of Astronomy, Harvard University

Relevant Experience

2016 –	Collaborator for the *Cubesat Radio Interferometry Experiment* (*CURIE*)
2018 – 2021	Member of steering committee for NSF/SHINE program
2014 – 2019	PI of Janus project (analysis software for *Wind* ion measurements)
2014 – 2017	Co-PI of Turbulence and Intermittency Long-Duration Atmospheric Experiment (TILDAE)
2016	Antarctica Service Medal (US Armed Forces; NSF)
2013 – 2016	Lead developer of flight-software for the *Gamma-Ray Imager/Polarimeter for Solar flares* (*GRIPS*); member of launch team (2015 – 2016; McMurdo Station, Antarctica)

Selected Publications

B. A. Maruca, A. Chasapis, et al., "MMS Observations of Beta-Dependent Constraints on Ion TemperatureAnisotropy in Earth's Magnetosheath," *Astrophys. J.*, **866**, 25, 2018

B. A. Maruca, R. Marino, et al., "Overview of and first observations from the TILDAE High-Altitude Balloon Mission," *Atmos. Meas. Tech.*, **10**, 1595, 2017

B. A. Maruca, S. D. Bale, L. Sorriso-Valvo, J. C. Kasper & M. L. Stevens, "Collisional Thermalization of Hydrogen and Helium in Solar-Wind Plasma," *Phys. Rev. Lett.*, **111**, 241101, 2013

P. A. Isenberg, B. A. Maruca & J. C. Kasper, "Self-Consistent Ion Cyclotron Anisotropy-Beta Relation for Solar Wind Protons," *Astrophys. J.*, **773**, 164, 2013

D. Verscharen, S. Bourouaine, B. D. G. Chandran & B. A. Maruca, "A Parallel-Propagating Alfv´enic IonBeam Instability in the High-Beta Solar Wind," *Astrophys. J.*, **773**, 8, 2013

B. A. Maruca & J. C. Kasper, "Improved interpretation of solar wind ion measurements via high-resolution magnetic field data," *Adv. Space Res.*, **52**, 723, 2013

J. C. Kasper, B. A. Maruca, M. L. Stevens & A. Zaslavsky, "Sensitive Test for Ion-Cyclotron Resonant Heating in the Solar Wind," *Phys. Rev. Lett.*, **110**, 091102, 2013

B. A. Maruca, J. C. Kasper & S. P. Gary, "Instability-Driven Limits on Helium Temperature Anisotropy in the Solar Wind: Observations and Linear Vlasov Analysis," *Astrophys. J.*, **748**, 137, 2012

B. A. Maruca, J. C. Kasper & S. D. Bale, "What are the relative roles of heating and cooling in generating solar wind temperature anisotropies?" *Phys. Rev. Lett.*, **107**, 201101, 2011