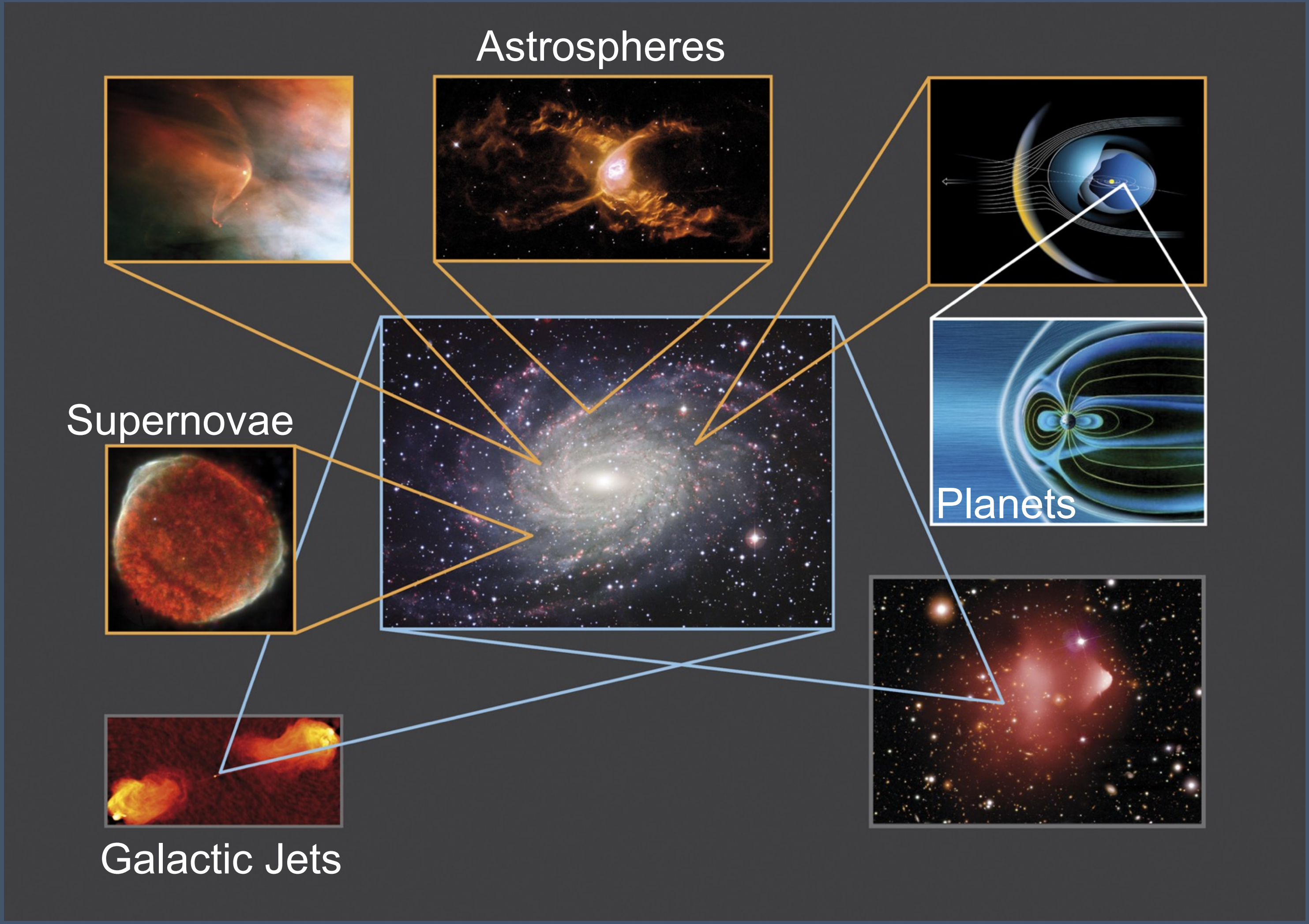
Future goals and ideas for collisionless shock research with MMS and beyond

Drew L. Turner |$_{\text{JHU/APL}}$
Katy Goodrich |$_{\text{WVU}}$
Lynn B. Wilson |$_{\text{GSFC}}$
Ian Cohen |$_{\text{JHU/APL}}$
Steve Schwartz |$_{\text{CU-LASP}}$

With many thanks, as ever, to the MMS team and our many additional collaborators!

drew.turner@jhuapl.edu

Shocks in Space Plasmas – A Universal Process



- Collisionless shocks are observed throughout our Universe
- **Shocks are a fundamental energy conversion mechanism in space plasmas**
  - heating and deflection of bulk flows to
  - acceleration of cosmic rays
- **Energy conversion and resulting energy partitioning at/across collisionless shocks are not well understood, parameterized, or constrained**
- Investigation of this fundamental plasma physics process is relevant and vital to the goals of Heliophysics Decadal Survey
  - **KSG3**: Determine the interaction of the Sun with the solar system and the interstellar medium.
  - **KSG4.** Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Collisionless Shocks

An intriguing and dynamic plasma regime

- ***Supercritical shocks:*** $M_{fast} \geq M_c$, (M_c ~ 1 to 2 for SW) resistivity alone cannot account for shock jump conditions; shock "foot", overshoot, and reflected particles (accounting for the additional dissipation required!) [e.g., see: Gosling and Robson, GeoMono 1985]
- ***Shock geometries:***
  - ***Quasi-parallel*** *(θ_{Bn} < ~45 deg)*
  - ***Quasi-perpendicular*** *(θ_{Bn} > ~45 deg)*
- ***Foreshock*** upstream of quasi-para shocks characterized by:
  - *Suprathermal, specularly reflected [e.g., Meziane et al., AnGeo 2004] ions and electrons back-streaming from the bow shock*
  - *Plasma instabilities [e.g., Le and Russell, PSS 1992a, b]*
  - *Wave activity (several different characteristic frequencies: e.g., ~1sec, ~3sec, ~30sec) [e.g., Russell and Hoppe, SSR 1983]*
- A foreshock region shifts locations based on upstream B-field orientation compared to shock normal
- A variety of transient kinetic phenomena are self-generated (i.e., autogenously) within the ion foreshock
- See foreshock review by Eastwood et al. [SSR, 2005]
- Key question: how is the bulk flow energy converted and how does the energy portioning/conversion change with shock geometry???

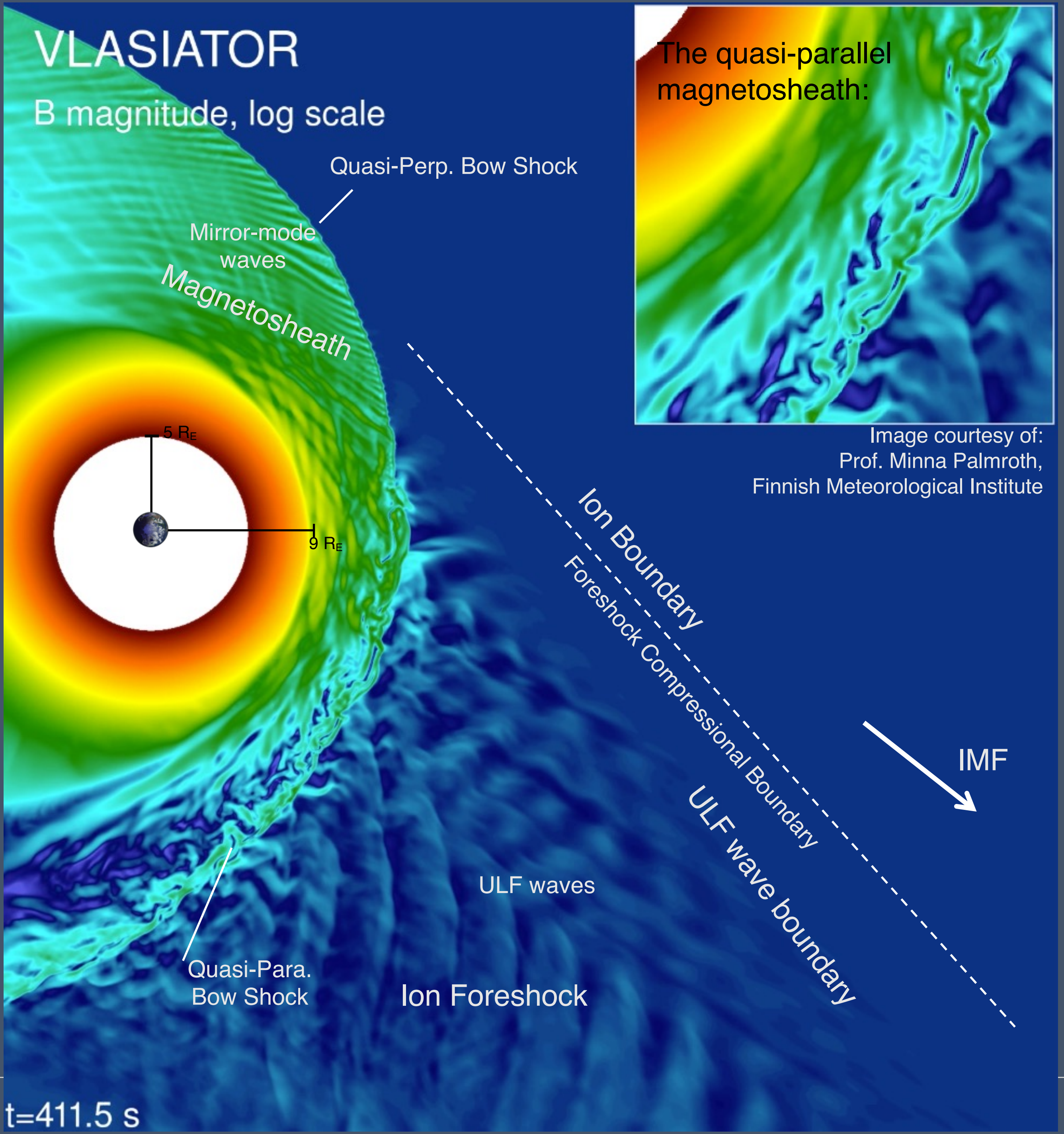
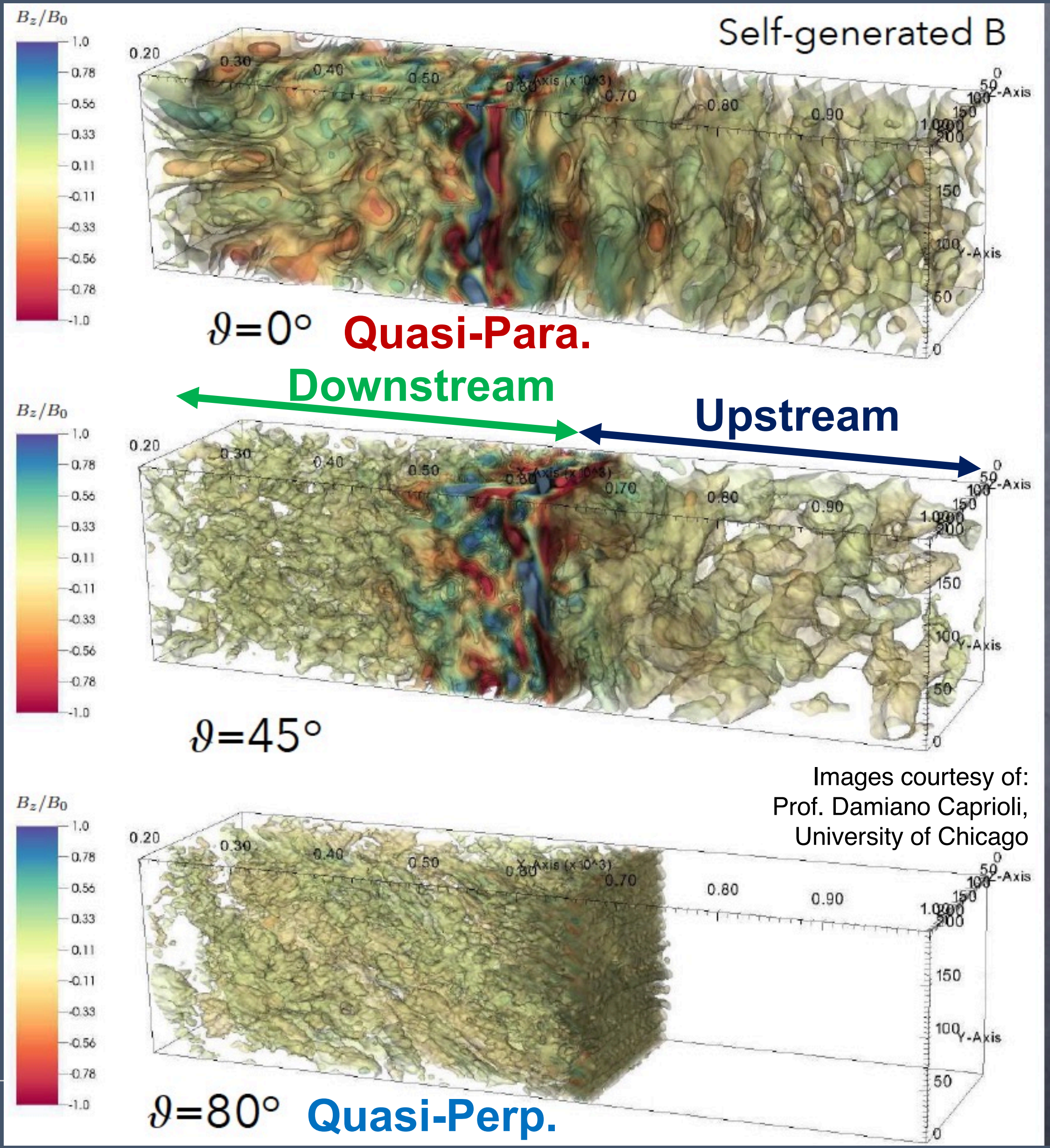


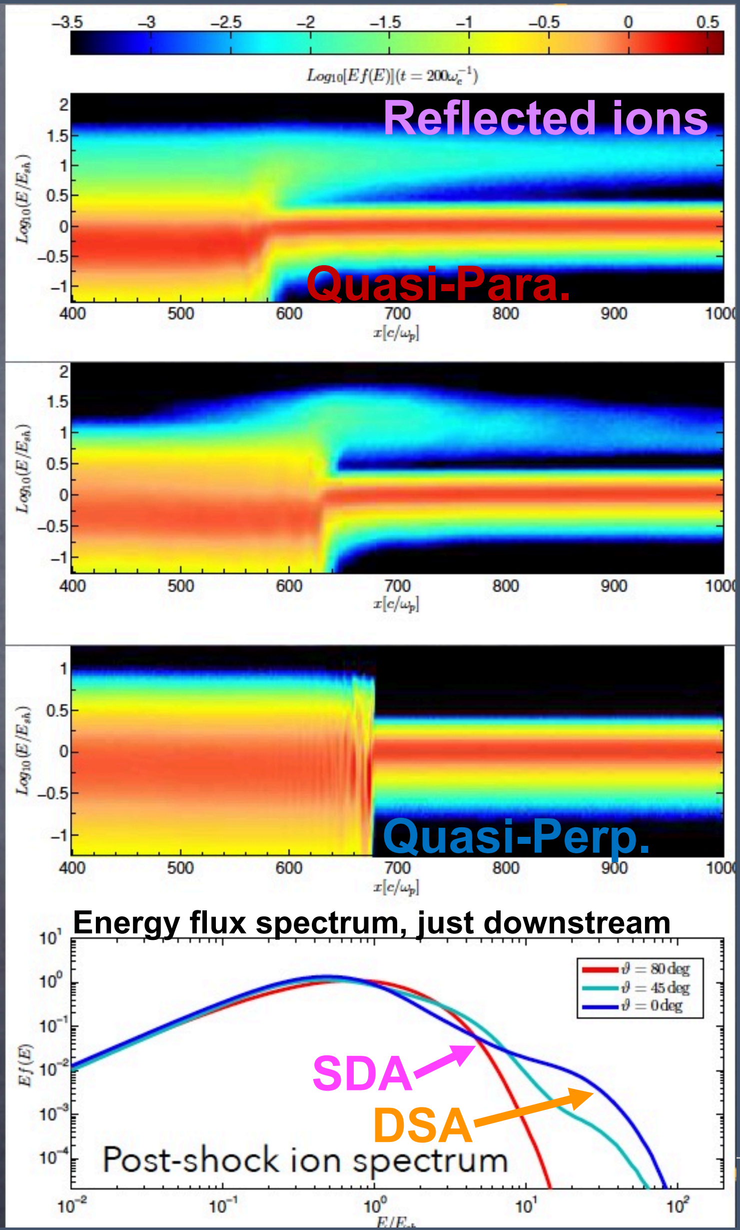
Image courtesy of:
Prof. Minna Palmroth,
Finnish Meteorological Institute

Collisionless Shocks: Quasi-Perpendicular vs. Quasi-Parallel

Reflected Ions



Images courtesy of:
Prof. Damiano Caprioli,
University of Chicago

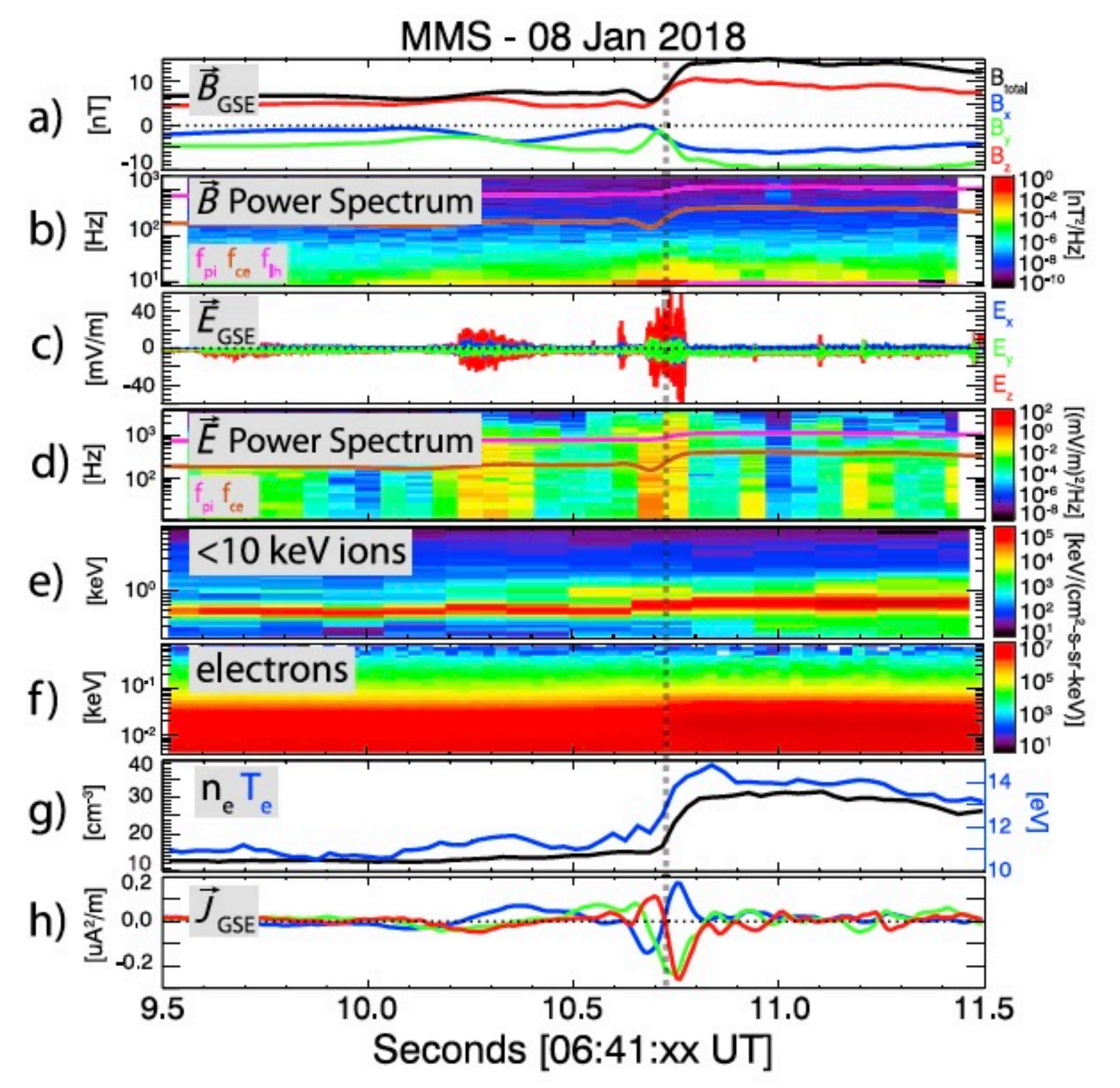


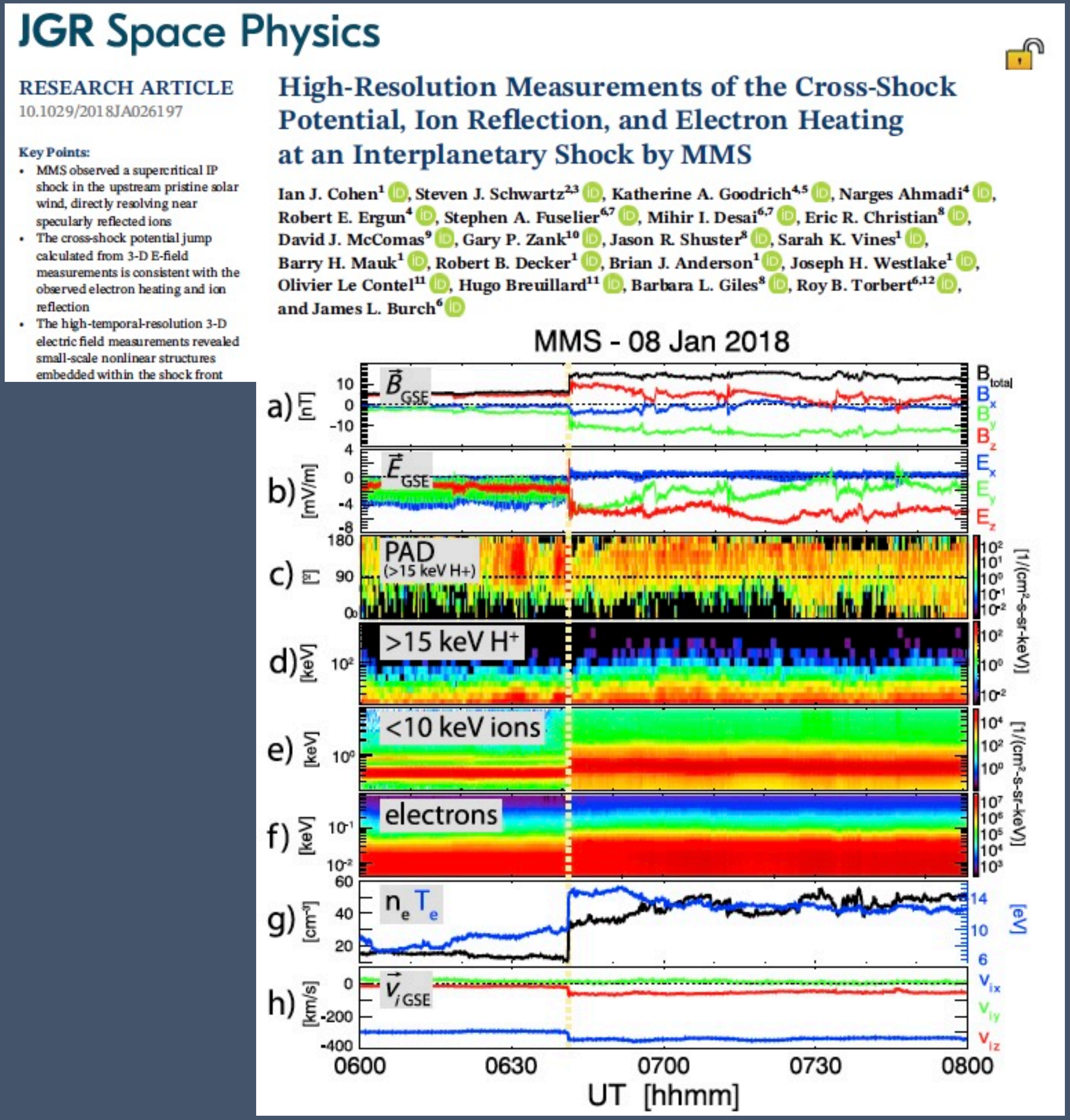
- Unlike collisional fluid shocks, collisionless shocks can and do provide information back into the upstream medium
- de Hoffman-Teller frame: only particles with $V_{||} \rightarrow \infty$ can "outrun" an ideal perpendicular shock, but particles with $V_{||} > V_{up}$ can outrun an ideal parallel shock; *any acceleration and reflection at a parallel shock enables particle backstreaming into incident flow!*
- Particles accelerated at a collisionless shock via a combination of diffusive shock acceleration (DSA; 2nd order Fermi-type) and shock-drift acceleration (SDA; gyro-kinetic effect)
- In simplest model: reflected particles are analogous to elastic collisions of infinitesimal balls bouncing off of an infinite moving wall (i.e., the shock is the wall moving at V_{sw}, so $\Delta V_{particle} = 2V_{sw}$ and $\Delta E_{particle} = 2m(V_{sw}^2 + v_i V_{sw})$
- Solar wind core proton ($v_i = V_{sw}$) gains a factor of 9 in energy with a perfectly elastic collision (e.g., mirroring off of ramp); that excludes any additional gain from SDA or DSA!

New Insights on Collisionless Shocks Observed by MMS

drew.turner@jhuapl.edu

Interplanetary Shocks





JGR Space Physics

RESEARCH ARTICLE
10.1029/2018JA026197

Key Points:

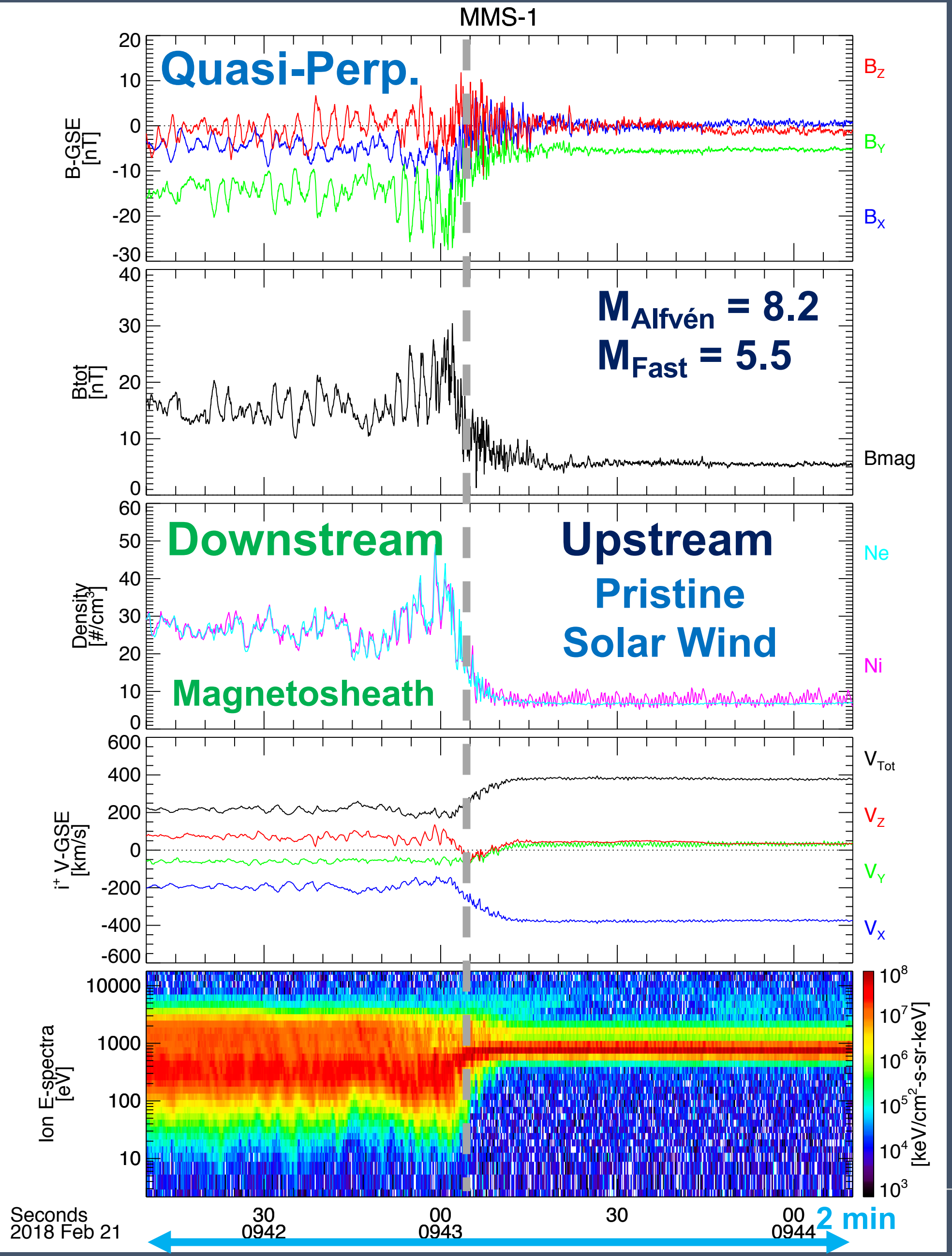
- MMS observed a supercritical IP shock in the upstream pristine solar wind, directly resolving near specularly reflected ions
- The cross-shock potential jump calculated from 3-D E-field measurements is consistent with the observed electron heating and ion reflection
- The high-temporal-resolution 3-D electric field measurements revealed small-scale nonlinear structures embedded within the shock front

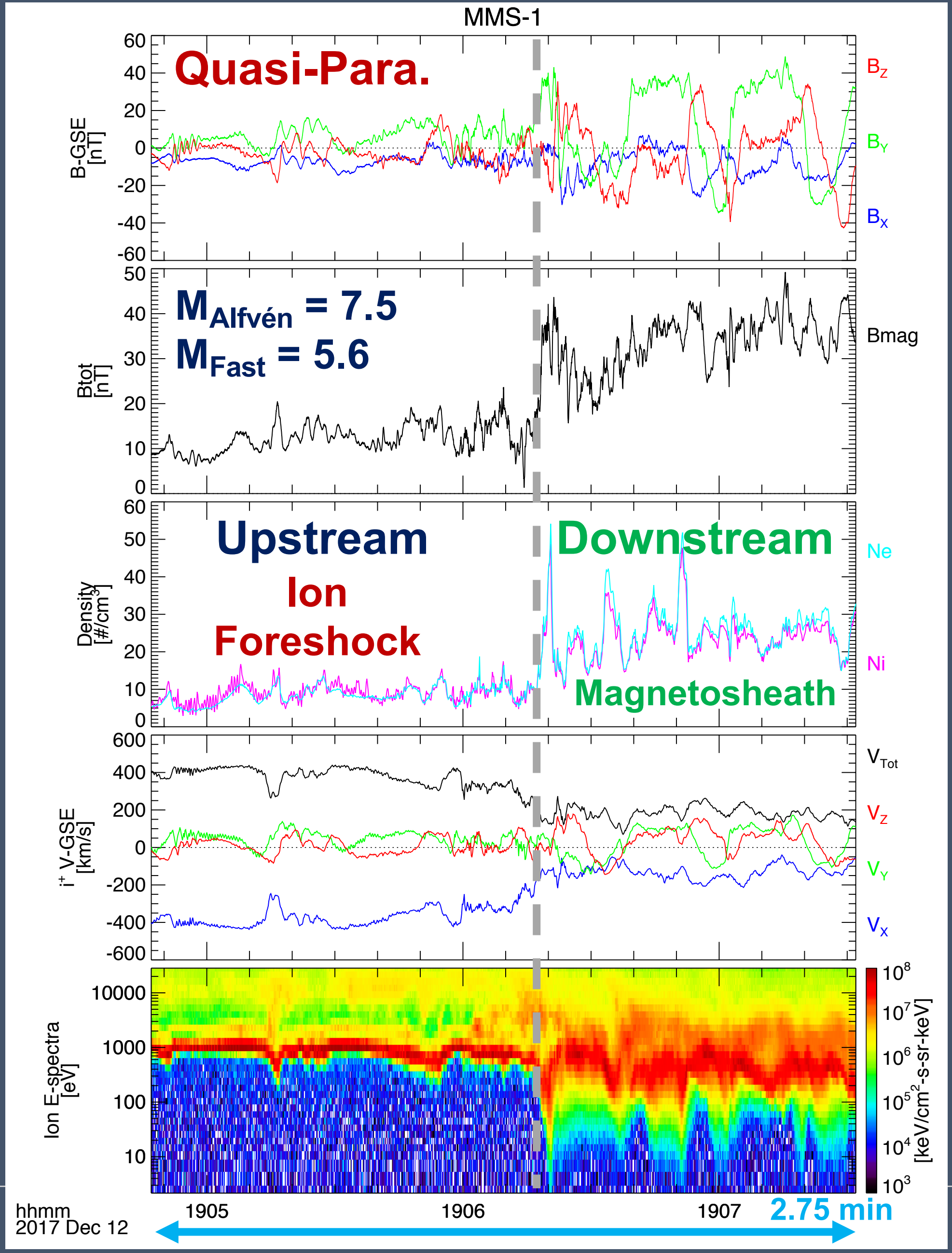
High-Resolution Measurements of the Cross-Shock Potential, Ion Reflection, and Electron Heating at an Interplanetary Shock by MMS

Ian J. Cohen[1], Steven J. Schwartz[2,3], Katherine A. Goodrich[4,5], Narges Ahmadi[4], Robert E. Ergun[4], Stephen A. Fuselier[6,7], Mihir I. Desai[6,7], Eric R. Christian[8], David J. McComas[9], Gary P. Zank[10], Jason R. Shuster[8], Sarah K. Vines[1], Barry H. Mauk[1], Robert B. Decker[1], Brian J. Anderson[1], Joseph H. Westlake[1], Olivier Le Contel[11], Hugo Breuillard[11], Barbara L. Giles[8], Roy B. Torbert[6,12], and James L. Burch[6]

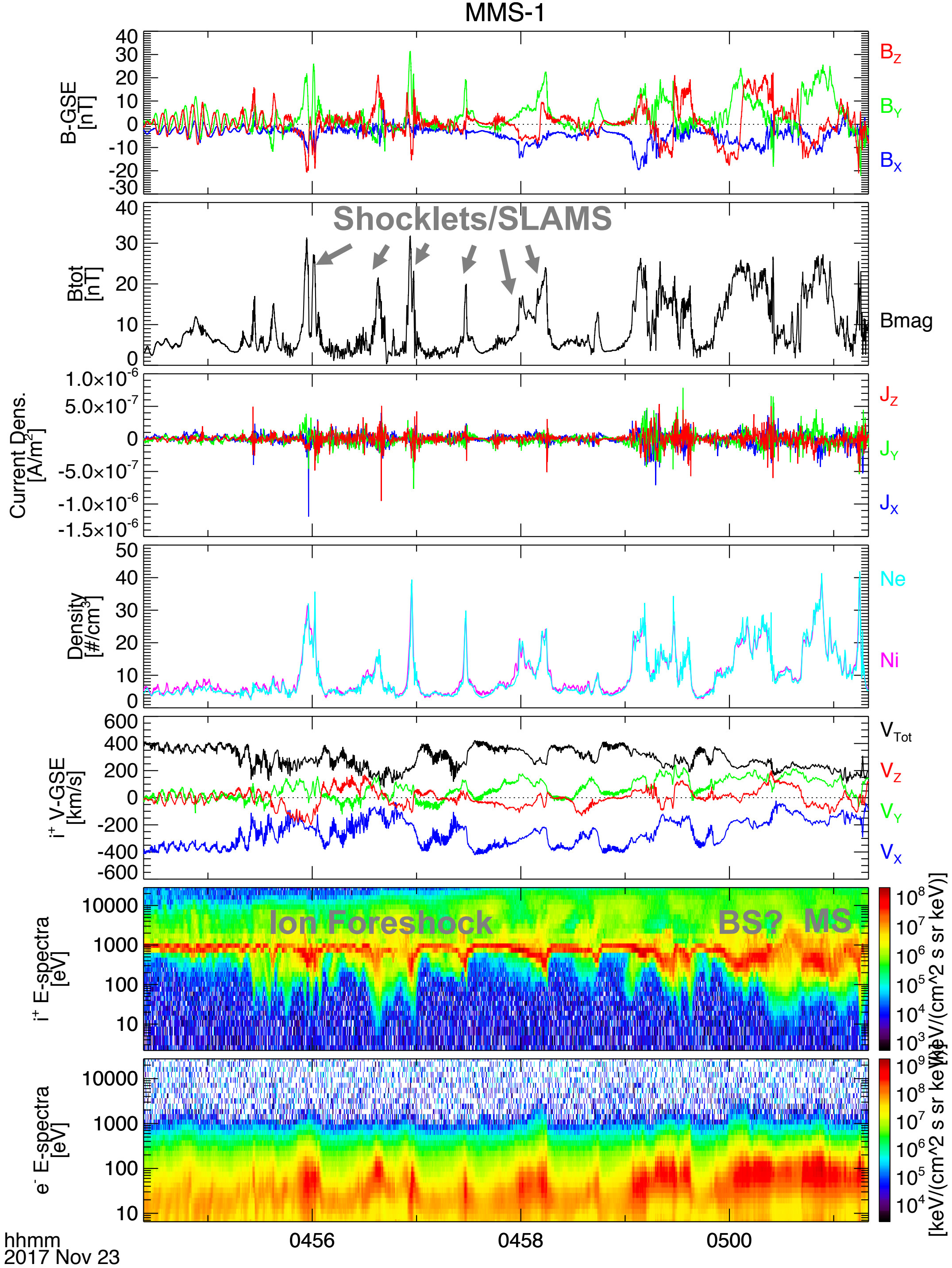
The Bow Shock: Quasi-Perpendicular vs. Quasi-Parallel

Overview and Examples





- Key point: MMS burst data and multipoint capabilities are a marvelous thing!
- Critical angle between IMF and BS normal
- Quasi-perp. shock is clean
  - *No upstream info beyond 1 r_{ci}*
  - *Incident plasma is pristine SW*
  - *Coherent mirror-mode waves in sheath*
- Quasi-para. shock is messy
  - *Lots of upstream information… ion foreshock!*
  - *Incident plasma is already highly modified*
  - *Shock can have multiple fronts/ structure*



Quasi-Parallel Shocks

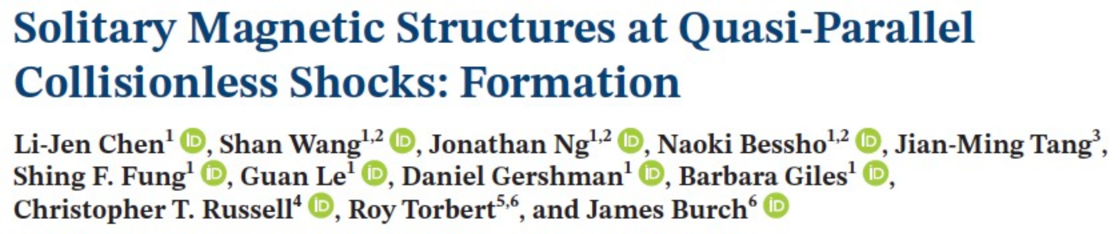
Reflected Ions and the Ion Foreshock

- Key point: Foreshock transients are large-scale (~1000 km to 10 RE) cross-scale, ion-kinetic into MHD, phenomena that form naturally out of the interaction between the incident solar wind plasma and the hot, diffuse ions counter-streaming in the ion foreshock

- Those magnetic structures are not stationary with respect to the shock, they are moving relative to it… (think about Fermi acceleration!)

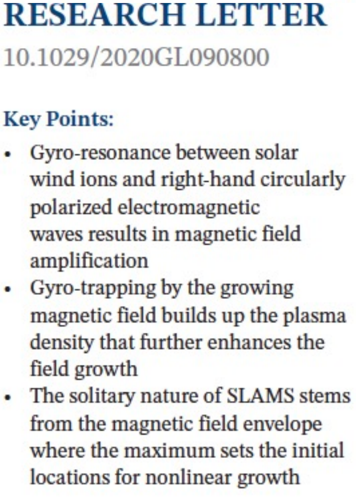
- They also provide feedback to the surrounding plasma; nonlinear interactions

SLAMS and Shocklets and ULF Waves



Solitary Magnetic Structures at Quasi-Parallel Collisionless Shocks: Formation

Li-Jen Chen[1], Shan Wang[1,2], Jonathan Ng[1,2], Naoki Bessho[1,2], Jian-Ming Tang[3], Shing F. Fung[1], Guan Le[1], Daniel Gershman[1], Barbara Giles[1], Christopher T. Russell[4], Roy Torbert[5,6], and James Burch[6]



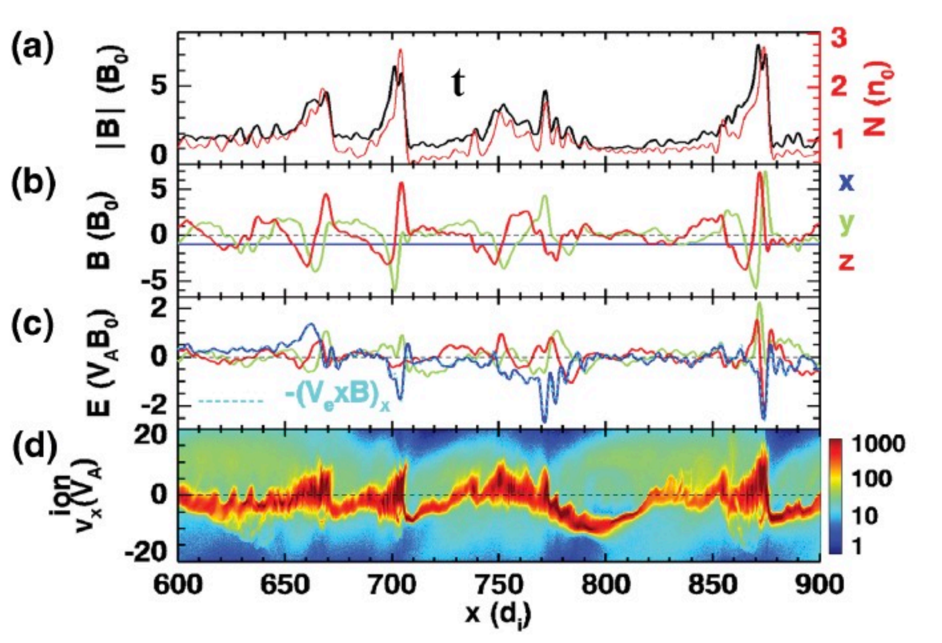
RESEARCH LETTER

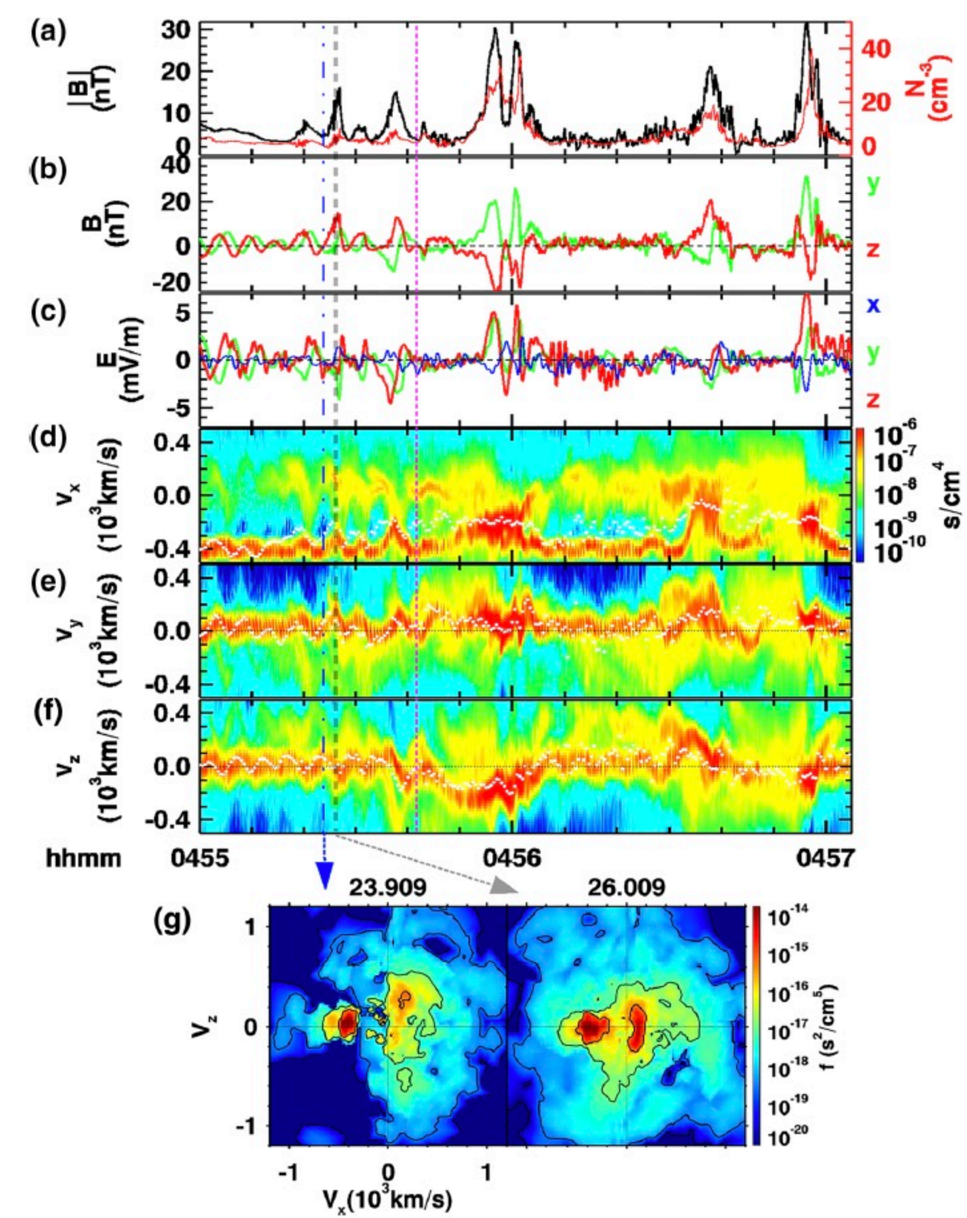
10.1029/2020GL090800

Key Points:

- Gyro-resonance between solar wind ions and right-hand circularly polarized electromagnetic waves results in magnetic field amplification
- Gyro-trapping by the growing magnetic field builds up the plasma density that further enhances the field growth
- The solitary nature of SLAMS stems from the magnetic field envelope where the maximum sets the initial locations for nonlinear growth

Content from L-J. Chen et al. [GRL 2021]





Foreshock Transients

THE ASTROPHYSICAL JOURNAL, 902:5 (15pp), 2020 October 10 https://doi.org/10.3847/1538-4357/abb249

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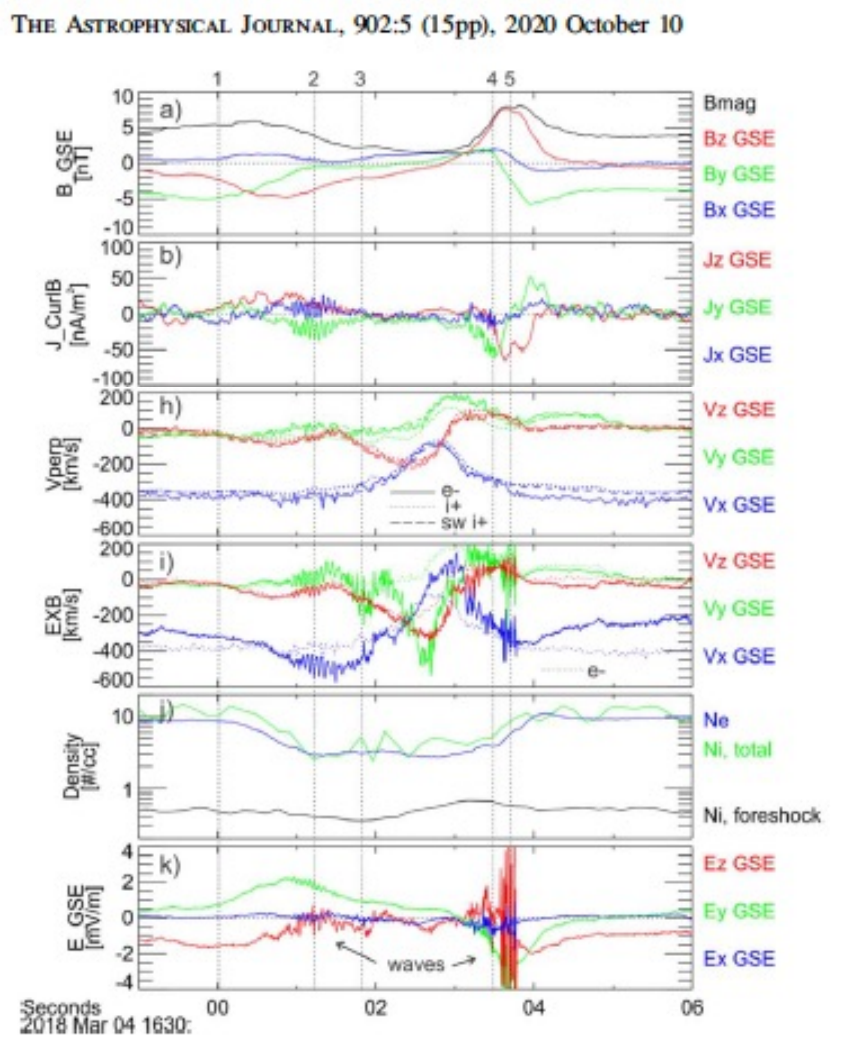
Magnetospheric Multiscale Observations of Foreshock Transients at Their Very Early Stage

Terry Z. Liu[1,2], Xin An[3], Hui Zhang[2], and Drew Turner[4]

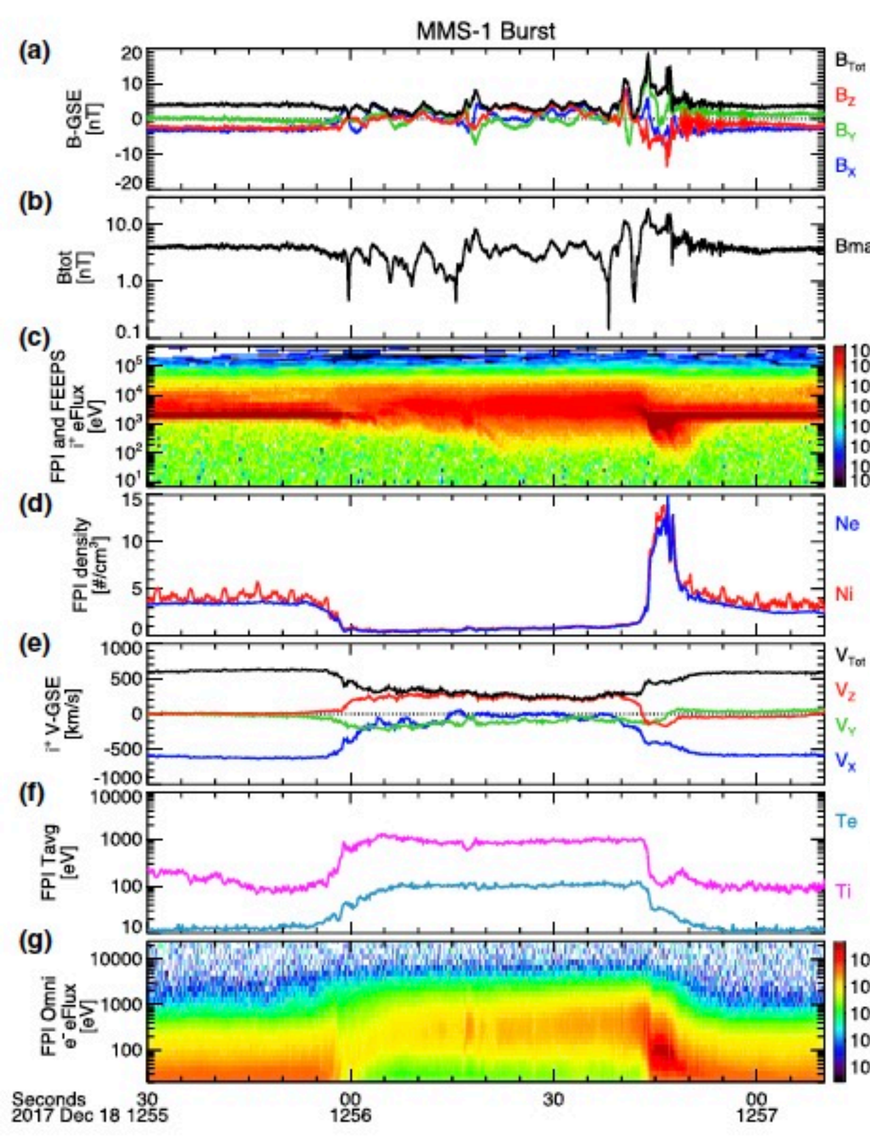
- Key point: Foreshock transients like FBs and HFAs form from ion kinetic physics but essentially become MHD-scale explosions expanding into the surrounding plasma; they also:
  - *impact the bow shock and magnetopause, resulting in globally observable magnetospheric activity*
  - *result in particle acceleration…*

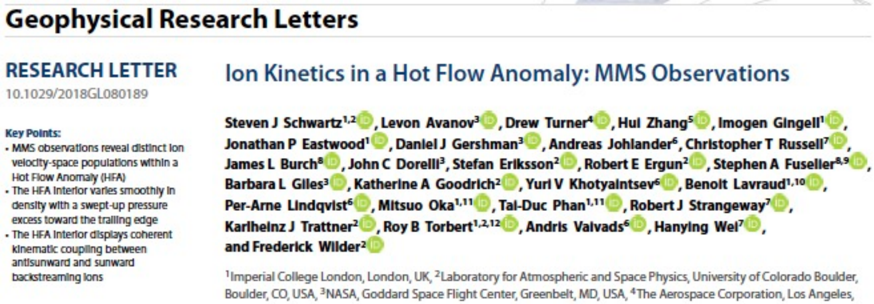


THE ASTROPHYSICAL JOURNAL, 902:5 (15pp), 2020 October 10

drew.turner@jhuapl.edu

Foreshock Transients





Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL080189

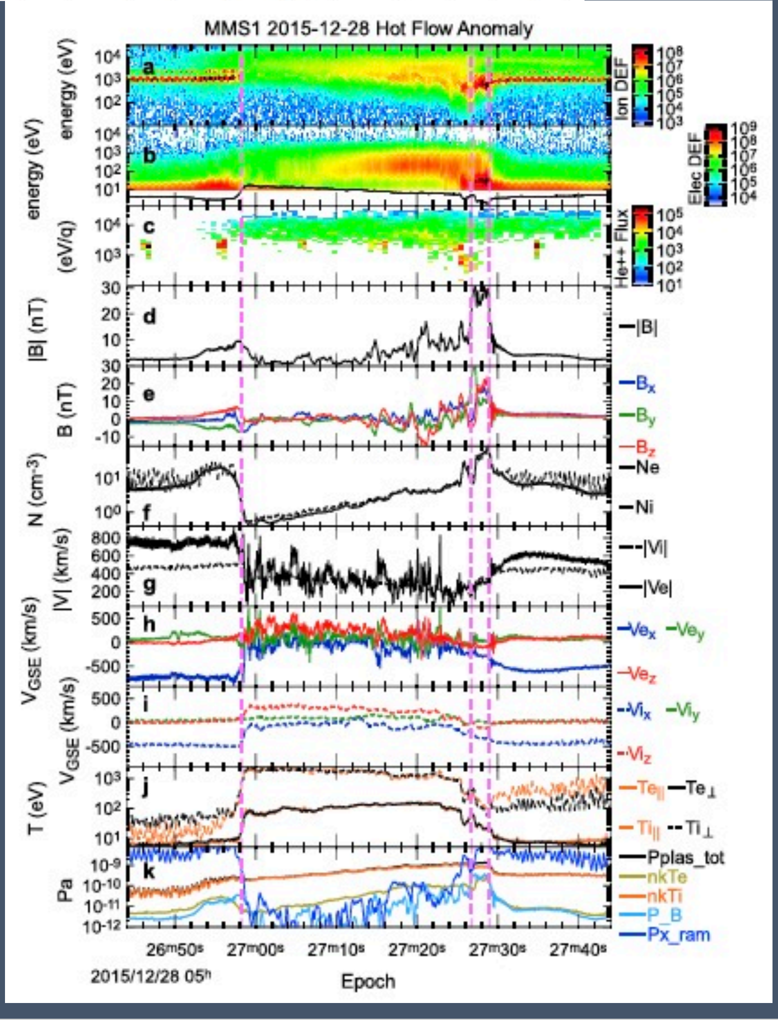
Key Points:

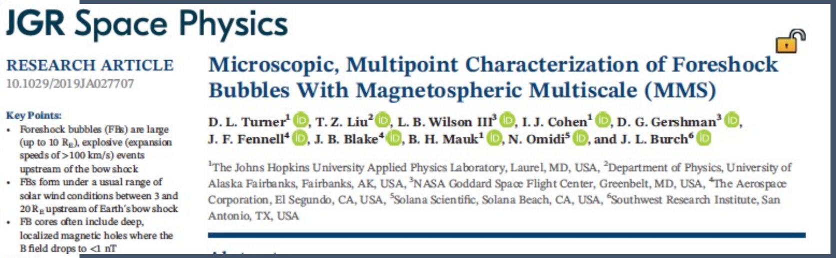
- MMS observations reveal distinct ion velocity-space populations within a Hot Flow Anomaly (HFA)
- The HFA interior varies smoothly in density with a swept-up pressure excess toward the trailing edge
- The HFA interior displays coherent kinematic coupling between antisunward and sunward backstreaming ions

Ion Kinetics in a Hot Flow Anomaly: MMS Observations

Steven J Schwartz[1,2], Levon Avanov[3], Drew Turner[4], Hui Zhang[5], Imogen Gingell[1], Jonathan P Eastwood[1], Daniel J Gershman[3], Andreas Johlander[6], Christopher T Russell[7], James L Burch[8], John C Dorelli[3], Stefan Eriksson[2], Robert E Ergun[2], Stephen A Fuselier[8,9], Barbara L Giles[3], Katherine A Goodrich[2], Yuri V Khotyaintsev[6], Benoit Lavraud[1,10], Per-Arne Lindqvist[6], Mitsuo Oka[1,11], Tai-Duc Phan[1,11], Robert J Strangeway[7], Karlheinz J Trattner[2], Roy B Torbert[1,2,12], Andris Vaivads[6], Hanying Wei[7], and Frederick Wilder[2]

[1]Imperial College London, London, UK, [2]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA, [3]NASA, Goddard Space Flight Center, Greenbelt, MD, USA, [4]The Aerospace Corporation, Los Angeles,





JGR Space Physics

RESEARCH ARTICLE

10.1029/2019JA027707

Key Points:

- Foreshock bubbles (FBs) are large (up to 10 R_E), explosive (expansion speeds of >100 km/s) events upstream of the bow shock
- FBs form under a usual range of solar wind conditions between 3 and 20 R_E upstream of Earth's bow shock
- FB cores often include deep, localized magnetic holes where the B field drops to <1 nT

Microscopic, Multipoint Characterization of Foreshock Bubbles With Magnetospheric Multiscale (MMS)

D. L. Turner[1], T. Z. Liu[2], L. B. Wilson III[3], I. J. Cohen[1], D. G. Gershman[3], J. F. Fennell[4], J. B. Blake[4], B. H. Mauk[1], N. Omidi[5], and J. L. Burch[6]

[1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [2]Department of Physics, University of Alaska Fairbanks, Fairbanks, AK, USA, [3]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [4]The Aerospace Corporation, El Segundo, CA, USA, [5]Solana Scientific, Solana Beach, CA, USA, [6]Southwest Research Institute, San Antonio, TX, USA

drew.turner@jhuapl.edu

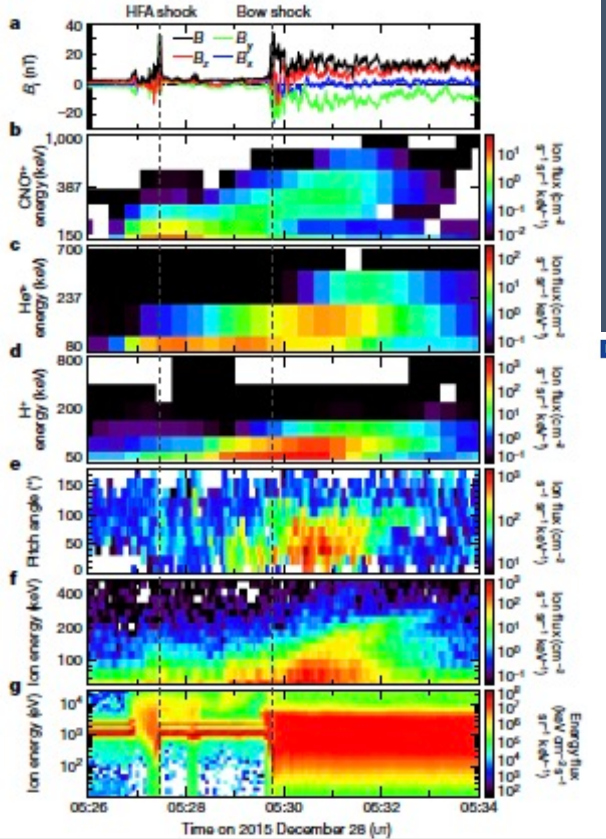
Particle Acceleration at Shocks

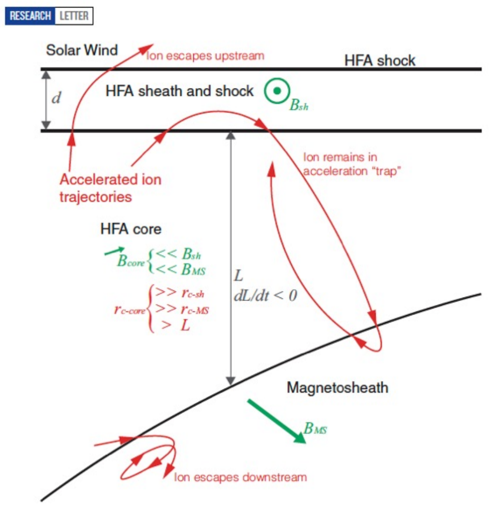
LETTER

https://doi.org/10.1038/s41586-018-0472-9

Autogenous and efficient acceleration of energetic ions upstream of Earth's bow shock

D. L. Turner[1*], L. B. Wilson III[2], T. Z. Liu[3], I. J. Cohen[4], S. J. Schwartz[5], A. Osmane[6,7], J. F. Fennell[1], J. H. Clemmons[1], J. B. Blake[1], J. Westlake[4], B. H. Mauk[4], A. N. Jaynes[8], T. Leonard[9], D. N. Baker[9], R. J. Strangeway[3], C. T. Russell[3], D. J. Gershman[2], L. Avanov[2], B. L. Giles[2], R. B. Torbert[10,11], J. Broll[11,12], R. G. Gomez[1,1], S. A. Fuselier[11,12] & J. L. Burch[11]





PHYSICAL REVIEW LETTERS **124,** 065101 (2020)

Observational Evidence for Stochastic Shock Drift Acceleration of Electrons at the Earth's Bow Shock

T. Amano,[1,*] T. Katou,[1] N. Kitamura,[1] M. Oka,[2] Y. Matsumoto,[3] M. Hoshino,[1] Y. Saito,[4] S. Yokota,[5]
B. L. Giles,[6] W. R. Paterson,[6] C. T. Russell,[7] O. Le Contel,[8] R. E. Ergun,[9] P.-A. Lindqvist,[10]
D. L. Turner,[11] J. F. Fenne

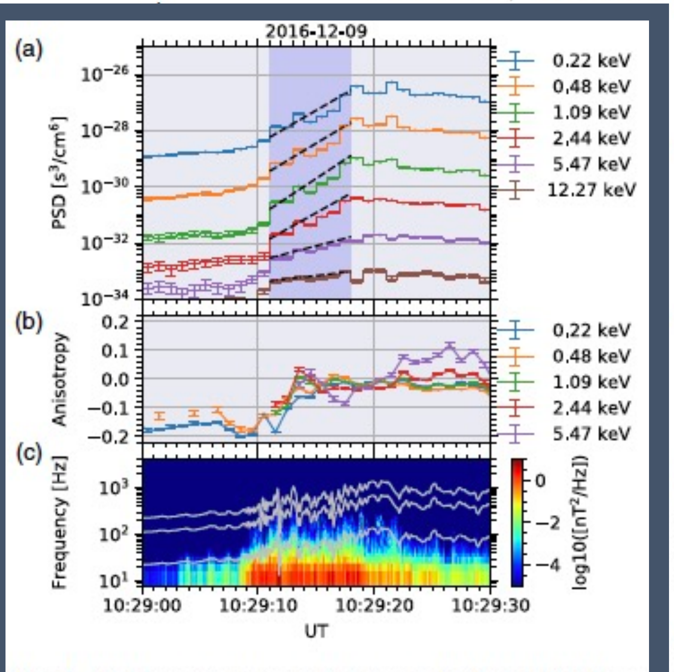
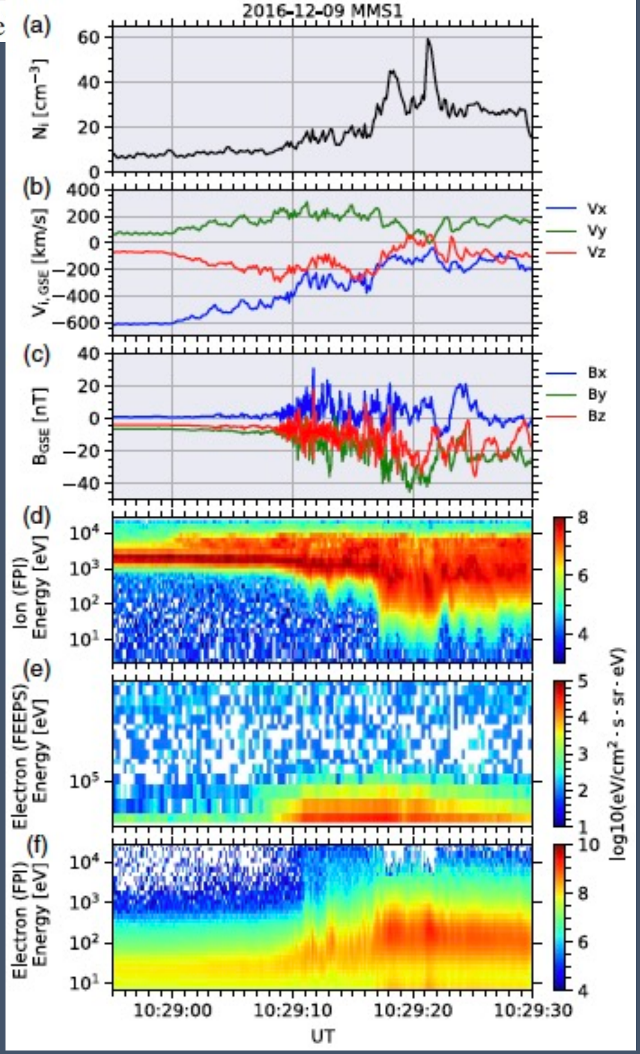
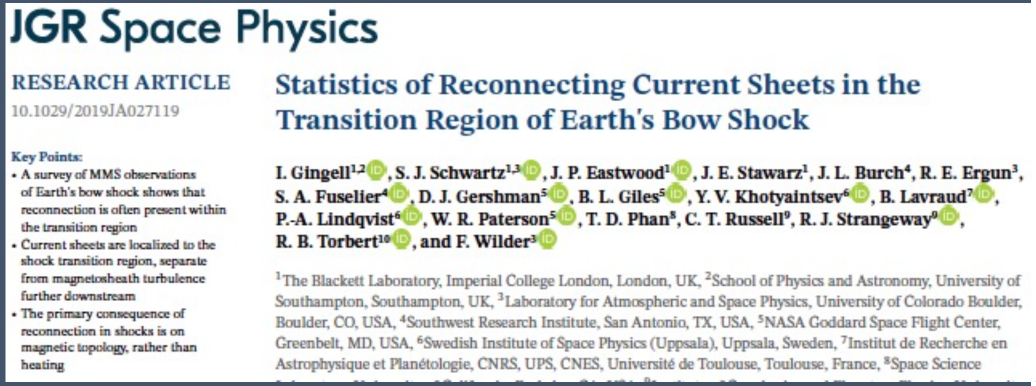


FIG. 2. Evidence for electron diffusion in shock transition layer.



Reconnection at Shocks



JGR Space Physics

RESEARCH ARTICLE

10.1029/2019JA027119

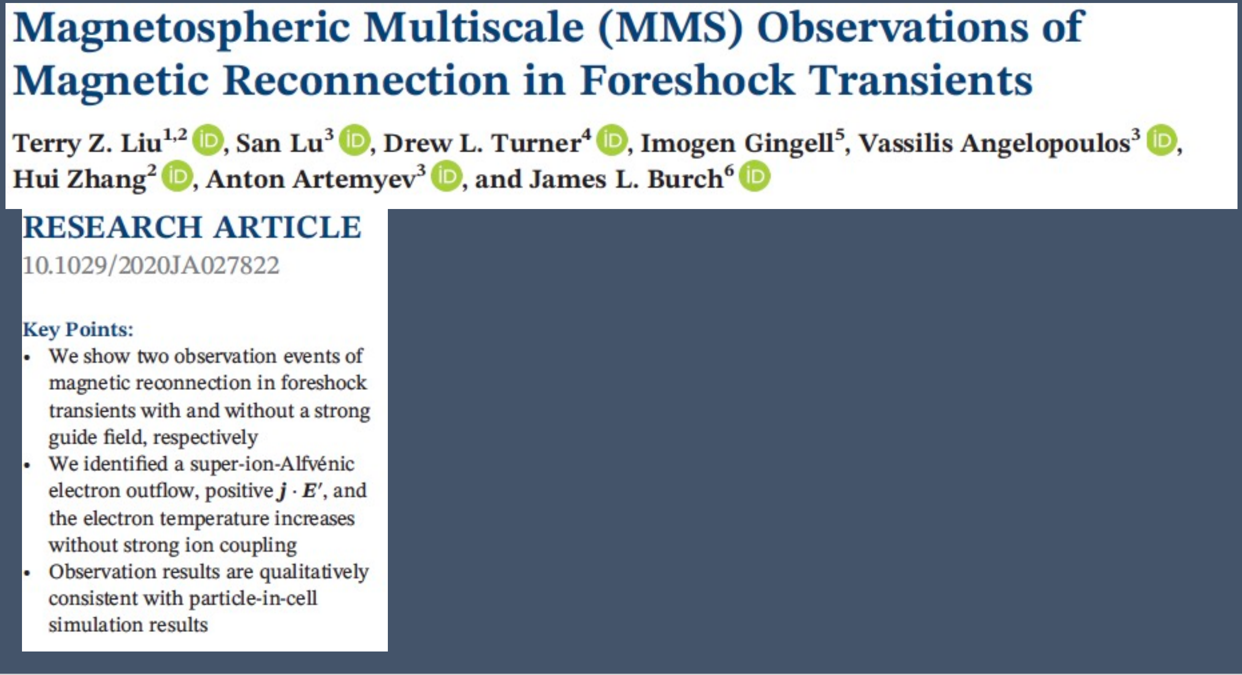
Key Points:

- A survey of MMS observations of Earth's bow shock shows that reconnection is often present within the transition region
- Current sheets are localized to the shock transition region, separate from magnetosheath turbulence further downstream
- The primary consequence of reconnection in shocks is on magnetic topology, rather than heating

Statistics of Reconnecting Current Sheets in the Transition Region of Earth's Bow Shock

I. Gingell[1,2], S. J. Schwartz[1,3], J. P. Eastwood[1], J. E. Stawarz[1], J. L. Burch[4], R. E. Ergun[3], S. A. Fuselier[4], D. J. Gershman[5], B. L. Giles[5], Y. V. Khotyaintsev[6], B. Lavraud[7], P.-A. Lindqvist[6], W. R. Paterson[5], T. D. Phan[8], C. T. Russell[9], R. J. Strangeway[9], R. B. Torbert[10], and F. Wilder[3]

[1]The Blackett Laboratory, Imperial College London, London, UK, [2]School of Physics and Astronomy, University of Southampton, Southampton, UK, [3]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA, [4]Southwest Research Institute, San Antonio, TX, USA, [5]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [6]Swedish Institute of Space Physics (Uppsala), Uppsala, Sweden, [7]Institut de Recherche en Astrophysique et Planétologie, CNRS, UPS, CNES, Université de Toulouse, Toulouse, France, [8]Space Science



Magnetospheric Multiscale (MMS) Observations of Magnetic Reconnection in Foreshock Transients

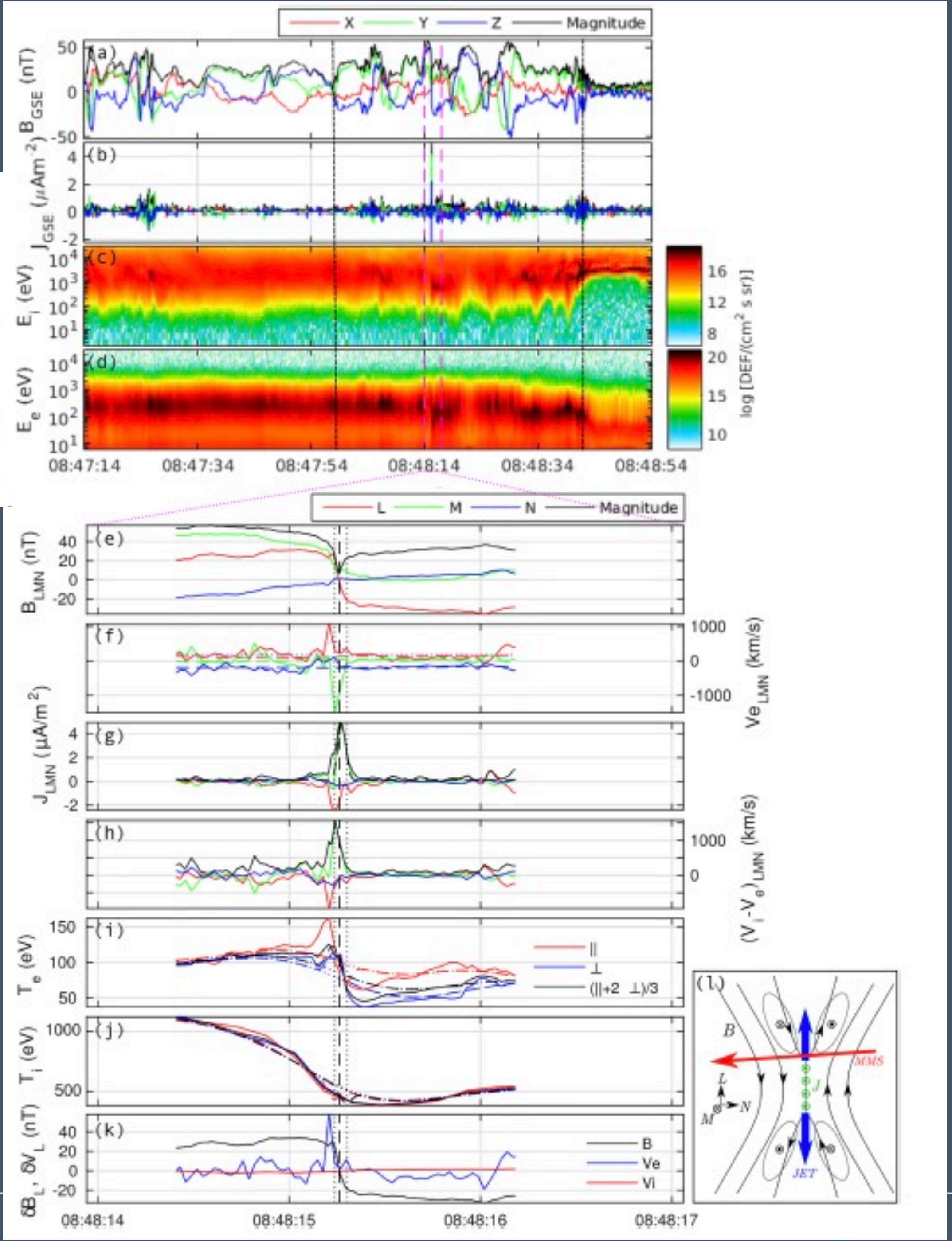
Terry Z. Liu[1,2], San Lu[3], Drew L. Turner[4], Imogen Gingell[5], Vassilis Angelopoulos[3], Hui Zhang[2], Anton Artemyev[3], and James L. Burch[6]

RESEARCH ARTICLE

10.1029/2020JA027822

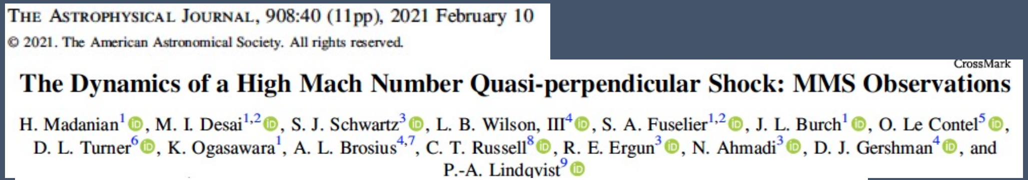
Key Points:

- We show two observation events of magnetic reconnection in foreshock transients with and without a strong guide field, respectively
- We identified a super-ion-Alfvénic electron outflow, positive $\boldsymbol{j} \cdot \boldsymbol{E}'$, and the electron temperature increases without strong ion coupling
- Observation results are qualitatively consistent with particle-in-cell simulation results



Quasi-Perpendicular Shocks

Reflected Ions and cross-shock potential

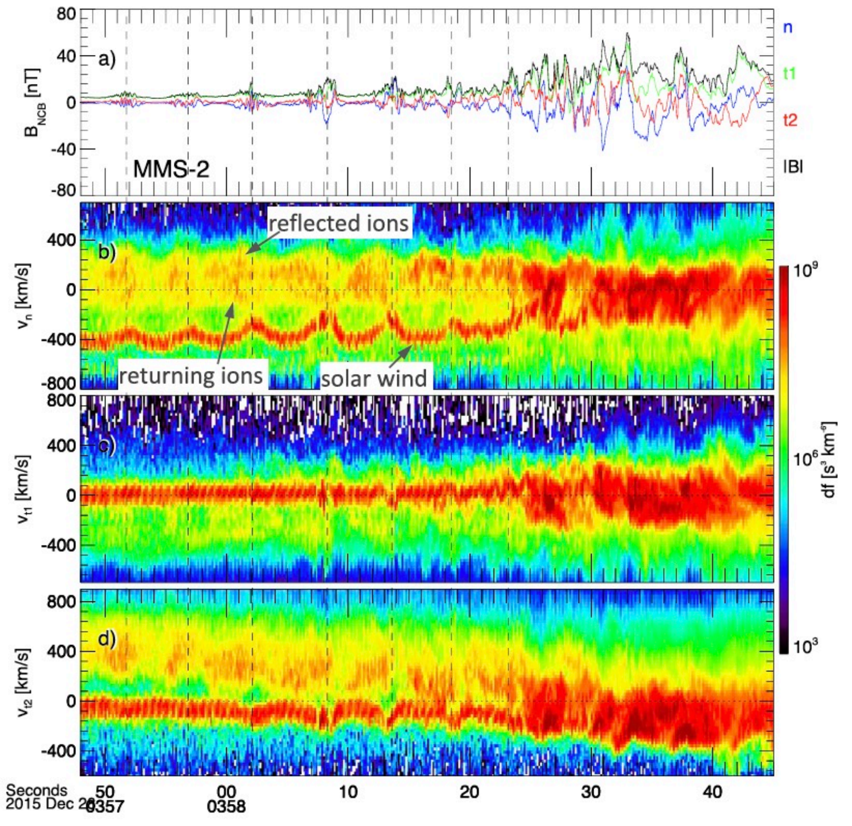


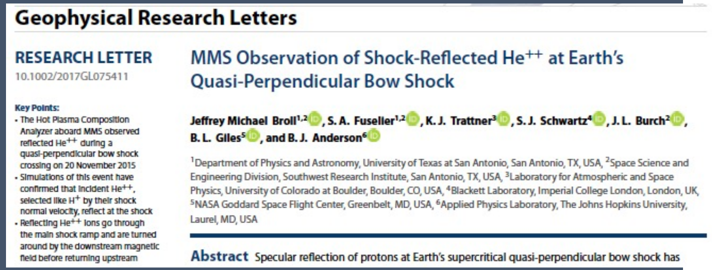
The Astrophysical Journal, 908:40 (11pp), 2021 February 10

CrossMark

The Dynamics of a High Mach Number Quasi-perpendicular Shock: MMS Observations

H. Madanian[1], M. I. Desai[1,2], S. J. Schwartz[3], L. B. Wilson, III[4], S. A. Fuselier[1,2], J. L. Burch[1], O. Le Contel[5], D. L. Turner[6], K. Ogasawara[1], A. L. Brosius[4,7], C. T. Russell[8], R. E. Ergun[3], N. Ahmadi[3], D. J. Gershman[4], and P.-A. Lindqvist[9]





Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL075411

MMS Observation of Shock-Reflected He^{++} at Earth's Quasi-Perpendicular Bow Shock

Jeffrey Michael Broll[1,2], S. A. Fuselier[1,2], K. J. Trattner[3], S. J. Schwartz[4], J. L. Burch[2], B. L. Giles[5], and B. J. Anderson[6]

[1]Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, [2]Space Science and Engineering Division, Southwest Research Institute, San Antonio, TX, USA, [3]Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, CO, USA, [4]Blackett Laboratory, Imperial College London, London, UK, [5]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [6]Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, USA

Key Points:

- The Hot Plasma Composition Analyzer aboard MMS observed reflected He^{++} during a quasi-perpendicular bow shock crossing on 20 November 2015
- Simulations of this event have confirmed that incident He^{++}, selected like H^+ by their shock normal velocity, reflect at the shock
- Reflecting He^{++} ions go through the main shock ramp and are turned around by the downstream magnetic field before returning upstream

Abstract Specular reflection of protons at Earth's supercritical quasi-perpendicular bow shock has

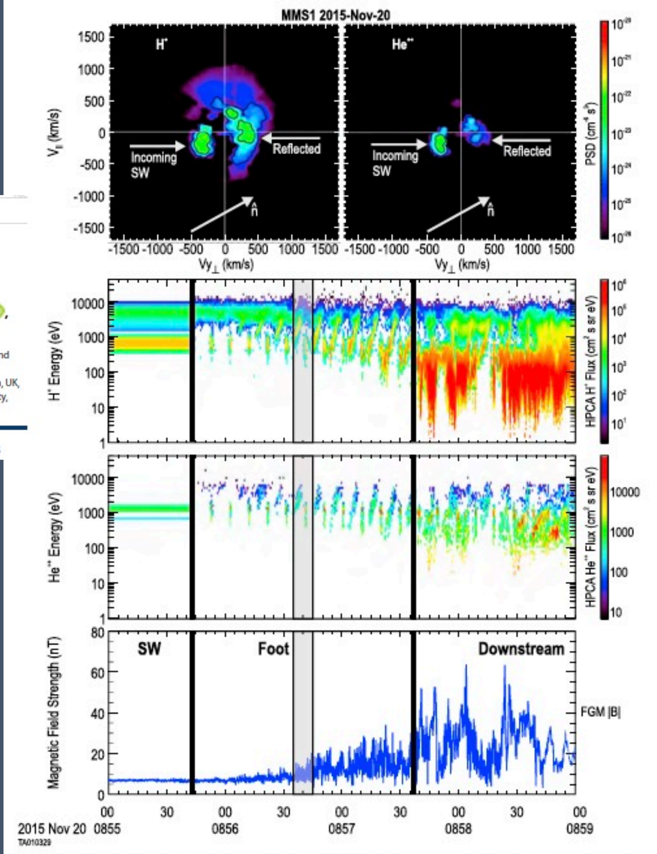
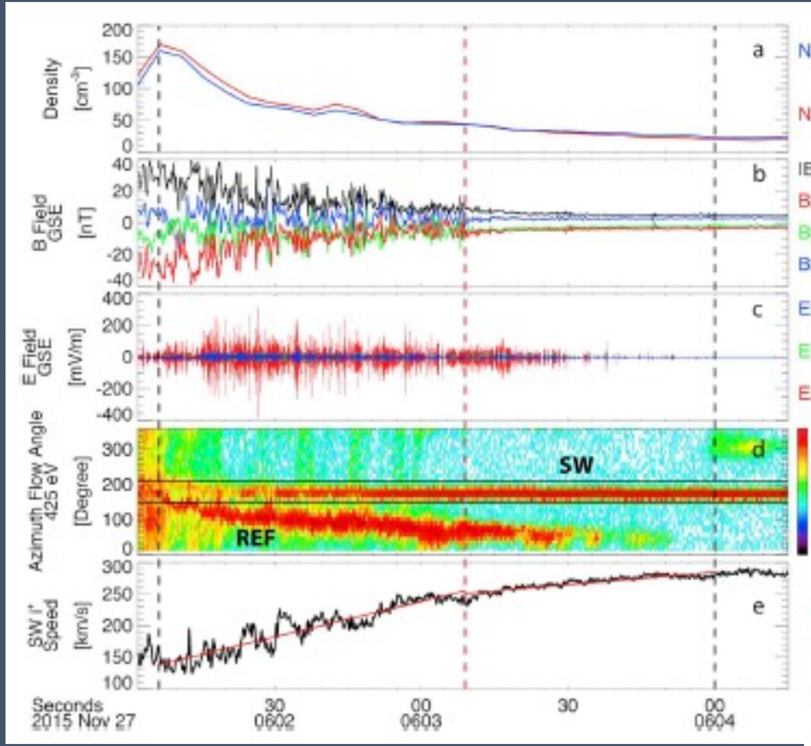
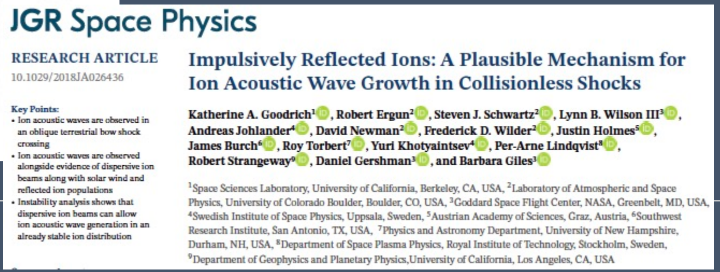


Figure 2. Inbound MMS bow shock crossing around 20 November 2015 08:58. From top: H^+ and He^{++} PSDs in $V_\perp - V_\parallel$ coordinates, with incoming and reflected populations labeled; HPCA omnidirectional H^+ and He^{++} flux; FGM *B*. The PSDs were taken in the shock foot, during the interval shaded in the four lower plots. The calculated shock normal direction in these coordinates is shown at the bottom.





JGR Space Physics

RESEARCH ARTICLE

10.1029/2018JA026436

Impulsively Reflected Ions: A Plausible Mechanism for Ion Acoustic Wave Growth in Collisionless Shocks

Katherine A. Goodrich[1], Robert Ergun[2], Steven J. Schwartz[2], Lynn B. Wilson III[3], Andreas Johlander[4], David Newman[2], Frederick D. Wilder[2], Justin Holmes[5], James Burch[6], Roy Torbert[7], Yuri Khotyaintsev[4], Per-Arne Lindqvist[8], Robert Strangeway[9], Daniel Gershman[3], and Barbara Giles[3]

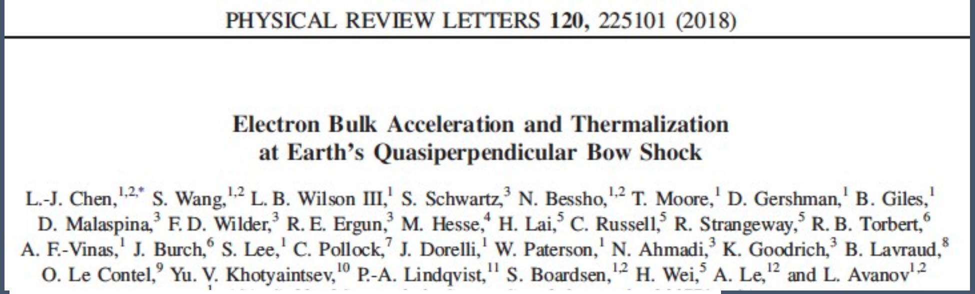
[1]Space Sciences Laboratory, University of California, Berkeley, CA, USA, [2]Laboratory of Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA, [3]Goddard Space Flight Center, NASA, Greenbelt, MD, USA, [4]Swedish Institute of Space Physics, Uppsala, Sweden, [5]Austrian Academy of Sciences, Graz, Austria, [6]Southwest Research Institute, San Antonio, TX, USA, [7]Physics and Astronomy Department, University of New Hampshire, Durham, NH, USA, [8]Department of Space Plasma Physics, Royal Institute of Technology, Stockholm, Sweden, [9]Department of Geophysics and Planetary Physics,University of California, Los Angeles, CA, USA

Key Points:

- Ion acoustic waves are observed in an oblique terrestrial bow shock crossing
- Ion acoustic waves are observed alongside evidence of dispersive ion beams along with solar wind and reflected ion populations
- Instability analysis shows that dispersive ion beams can allow ion acoustic wave generation in an already stable ion distribution

Quasi-Perpendicular Shocks

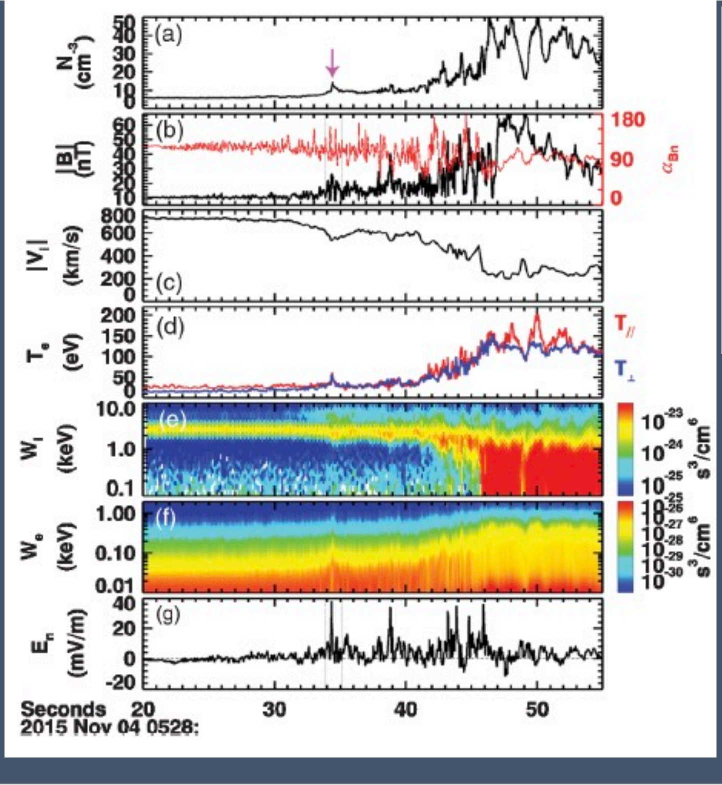
Reflected Ions and cross-shock potential

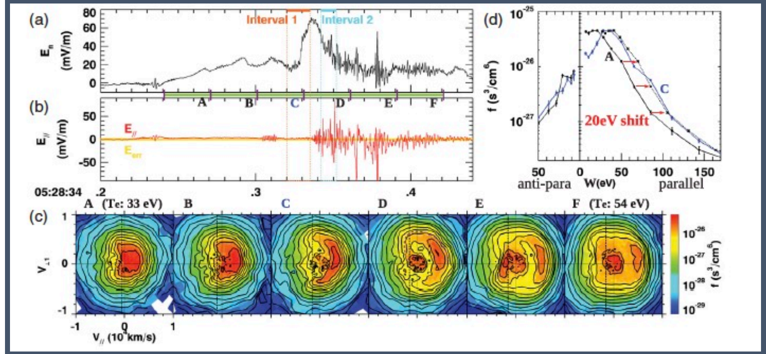


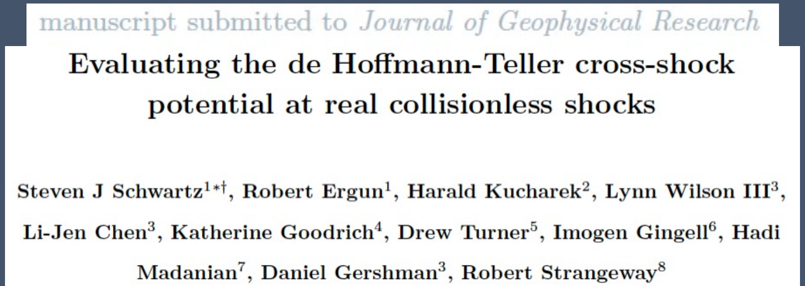
PHYSICAL REVIEW LETTERS 120, 225101 (2018)

Electron Bulk Acceleration and Thermalization at Earth's Quasiperpendicular Bow Shock

L.-J. Chen,[1,2,*] S. Wang,[1,2] L. B. Wilson III,[1] S. Schwartz,[3] N. Bessho,[1,2] T. Moore,[1] D. Gershman,[1] B. Giles,[1] D. Malaspina,[3] F. D. Wilder,[3] R. E. Ergun,[3] M. Hesse,[4] H. Lai,[5] C. Russell,[5] R. Strangeway,[5] R. B. Torbert,[6] A. F.-Vinas,[1] J. Burch,[6] S. Lee,[1] C. Pollock,[7] J. Dorelli,[1] W. Paterson,[1] N. Ahmadi,[3] K. Goodrich,[3] B. Lavraud,[8] O. Le Contel,[9] Yu. V. Khotyaintsev,[10] P.-A. Lindqvist,[11] S. Boardsen,[1,2] H. Wei,[5] A. Le,[12] and L. Avanov[1,2]



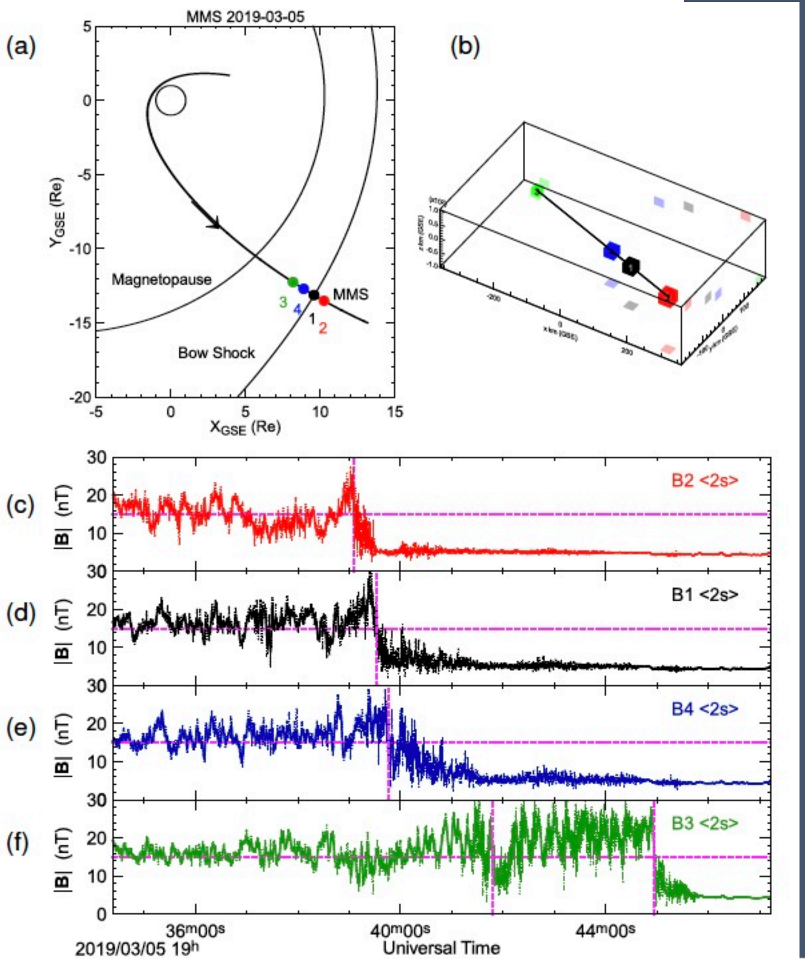




manuscript submitted to *Journal of Geophysical Research*

Evaluating the de Hoffmann-Teller cross-shock potential at real collisionless shocks

Steven J Schwartz[1*†], Robert Ergun[1], Harald Kucharek[2], Lynn Wilson III[3], Li-Jen Chen[3], Katherine Goodrich[4], Drew Turner[5], Imogen Gingell[6], Hadi Madanian[7], Daniel Gershman[3], Robert Strangeway[8]



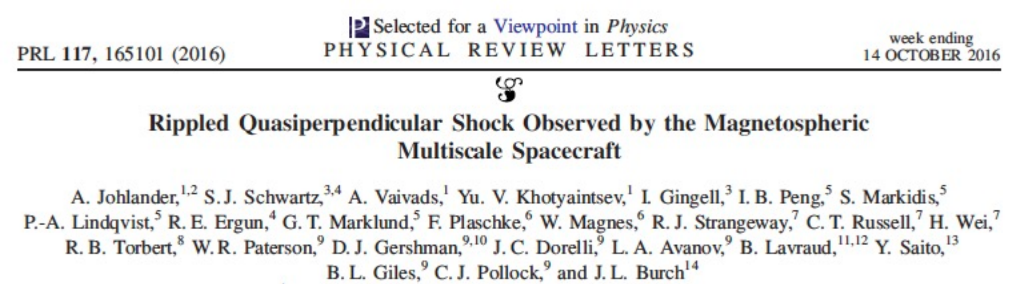
Schwartz et al.:

Elec. Liouville mapping and ambipolar fields agree well, but it may be impossible to accurately estimate the HT cross-shock potential

"Future work will need to assemble all parts of this puzzle, which lies at the heart of the dynamics and energy partition at collisionless shocks."

drew.turner@jhuapl.edu

Shock Surface Ripples

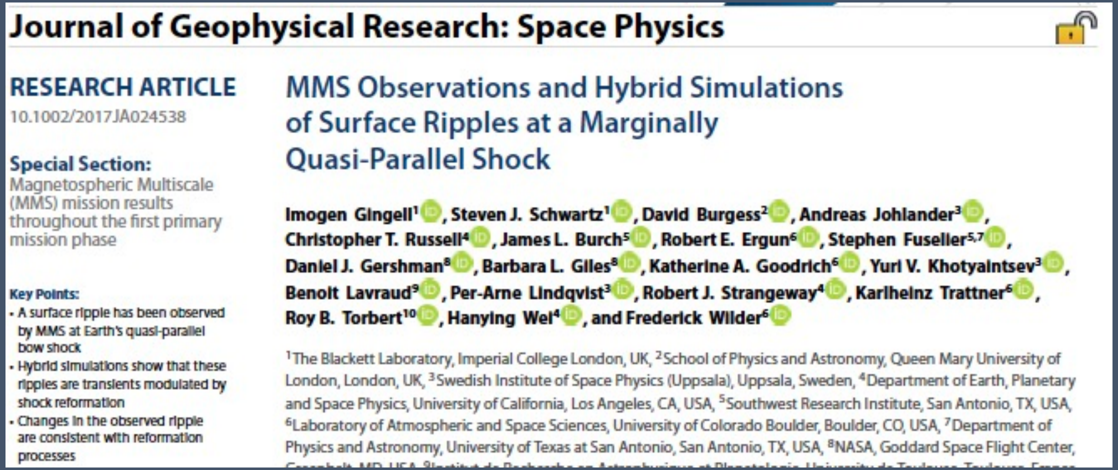


Selected for a Viewpoint in *Physics*

PRL 117, 165101 (2016) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2016

Rippled Quasiperpendicular Shock Observed by the Magnetospheric Multiscale Spacecraft

A. Johlander,[1,2] S. J. Schwartz,[3,4] A. Vaivads,[1] Yu. V. Khotyaintsev,[1] I. Gingell,[3] I. B. Peng,[5] S. Markidis,[5] P.-A. Lindqvist,[5] R. E. Ergun,[4] G. T. Marklund,[5] F. Plaschke,[6] W. Magnes,[6] R. J. Strangeway,[7] C. T. Russell,[7] H. Wei,[7] R. B. Torbert,[8] W. R. Paterson,[9] D. J. Gershman,[9,10] J. C. Dorelli,[9] L. A. Avanov,[9] B. Lavraud,[11,12] Y. Saito,[13] B. L. Giles,[9] C. J. Pollock,[9] and J. L. Burch[14]



Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2017JA024538

Special Section:

Magnetospheric Multiscale (MMS) mission results throughout the first primary mission phase

Key Points:

- A surface ripple has been observed by MMS at Earth's quasi-parallel bow shock
- Hybrid simulations show that these ripples are transients modulated by shock reformation
- Changes in the observed ripple are consistent with reformation processes

MMS Observations and Hybrid Simulations of Surface Ripples at a Marginally Quasi-Parallel Shock

Imogen Gingell[1], Steven J. Schwartz[1], David Burgess[2], Andreas Johlander[3], Christopher T. Russell[4], James L. Burch[5], Robert E. Ergun[6], Stephen Fuselier[5,7], Daniel J. Gershman[8], Barbara L. Giles[8], Katherine A. Goodrich[6], Yuri V. Khotyaintsev[3], Benoit Lavraud[9], Per-Arne Lindqvist[3], Robert J. Strangeway[4], Karlheinz Trattner[6], Roy B. Torbert[10], Hanying Wei[4], and Frederick Wilder[6]

[1]The Blackett Laboratory, Imperial College London, UK, [2]School of Physics and Astronomy, Queen Mary University of London, London, UK, [3]Swedish Institute of Space Physics (Uppsala), Uppsala, Sweden, [4]Department of Earth, Planetary and Space Physics, University of California, Los Angeles, CA, USA, [5]Southwest Research Institute, San Antonio, TX, USA, [6]Laboratory of Atmospheric and Space Sciences, University of Colorado Boulder, Boulder, CO, USA, [7]Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, [8]NASA, Goddard Space Flight Center,

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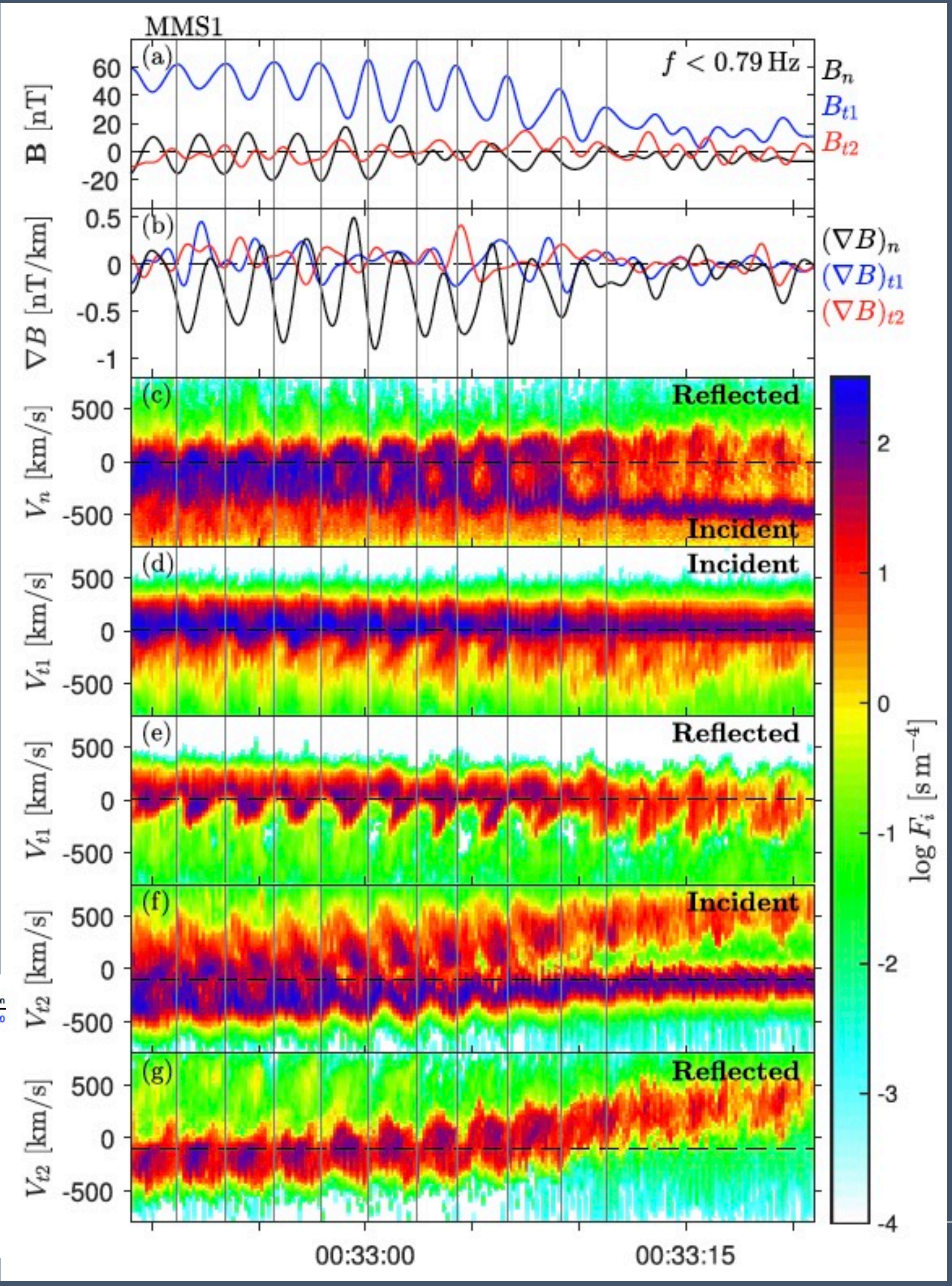
Plasma Phys. Control. Fusion **60** (2018) 125006 (11pp) https://doi.org/10.1088/1361-6587/aae920

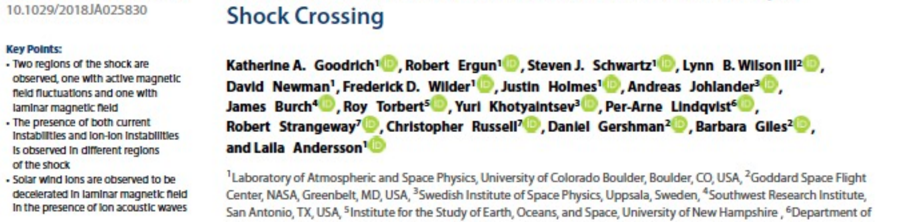
Shock ripples observed by the MMS spacecraft: ion reflection and dispersive properties

Andreas Johlander[1,2], Andris Vaivads[1], Yuri V Khotyaintsev[1], Imogen Gingell[3], Steven J Schwartz[3,4], Barbara L Giles[5], Roy B Torbert[6] and Christopher T Russell[7]



Waves at Shocks

- Evidence of magnetosonic-whistlers affecting incident and reflected ions
- Note: better resolution is necessary to actually resolve the net effect on the ions!



Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1029/2018JA025830

MMS Observations of Electrostatic Waves in an Oblique Shock Crossing

Key Points:

- Two regions of the shock are observed, one with active magnetic field fluctuations and one with laminar magnetic field
- The presence of both current instabilities and ion-ion instabilities is observed in different regions of the shock
- Solar wind ions are observed to be decelerated in laminar magnetic field in the presence of ion acoustic waves

Katherine A. Goodrich[1], Robert Ergun[1], Steven J. Schwartz[1], Lynn B. Wilson III[2], David Newman[1], Frederick D. Wilder[1], Justin Holmes[1], Andreas Johlander[3], James Burch[4], Roy Torbert[5], Yuri Khotyaintsev[3], Per-Arne Lindqvist[6], Robert Strangeway[7], Christopher Russell[7], Daniel Gershman[2], Barbara Giles[2], and Laila Andersson[1]

[1]Laboratory of Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA, [2]Goddard Space Flight Center, NASA, Greenbelt, MD, USA, [3]Swedish Institute of Space Physics, Uppsala, Sweden, [4]Southwest Research Institute, San Antonio, TX, USA, [5]Institute for the Study of Earth, Oceans, and Space, University of New Hampshire , [6]Department of

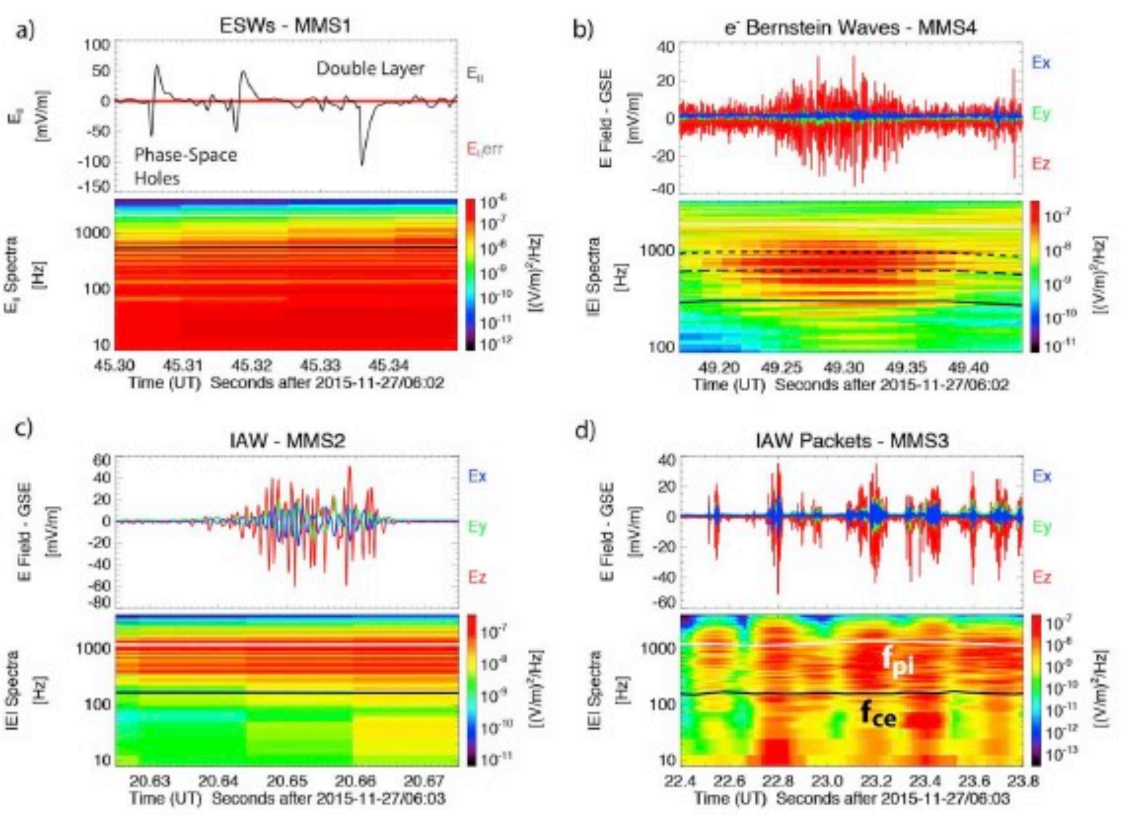
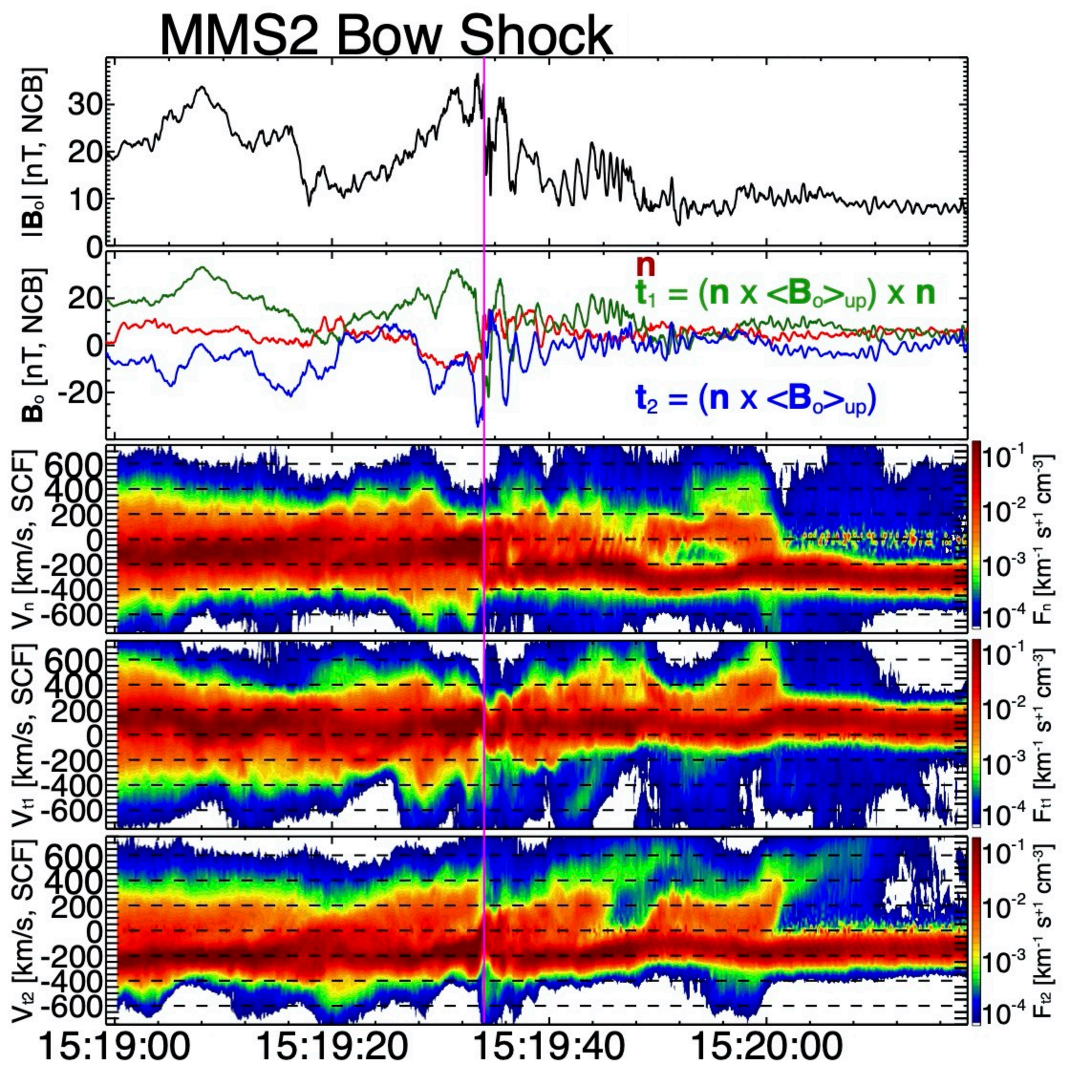
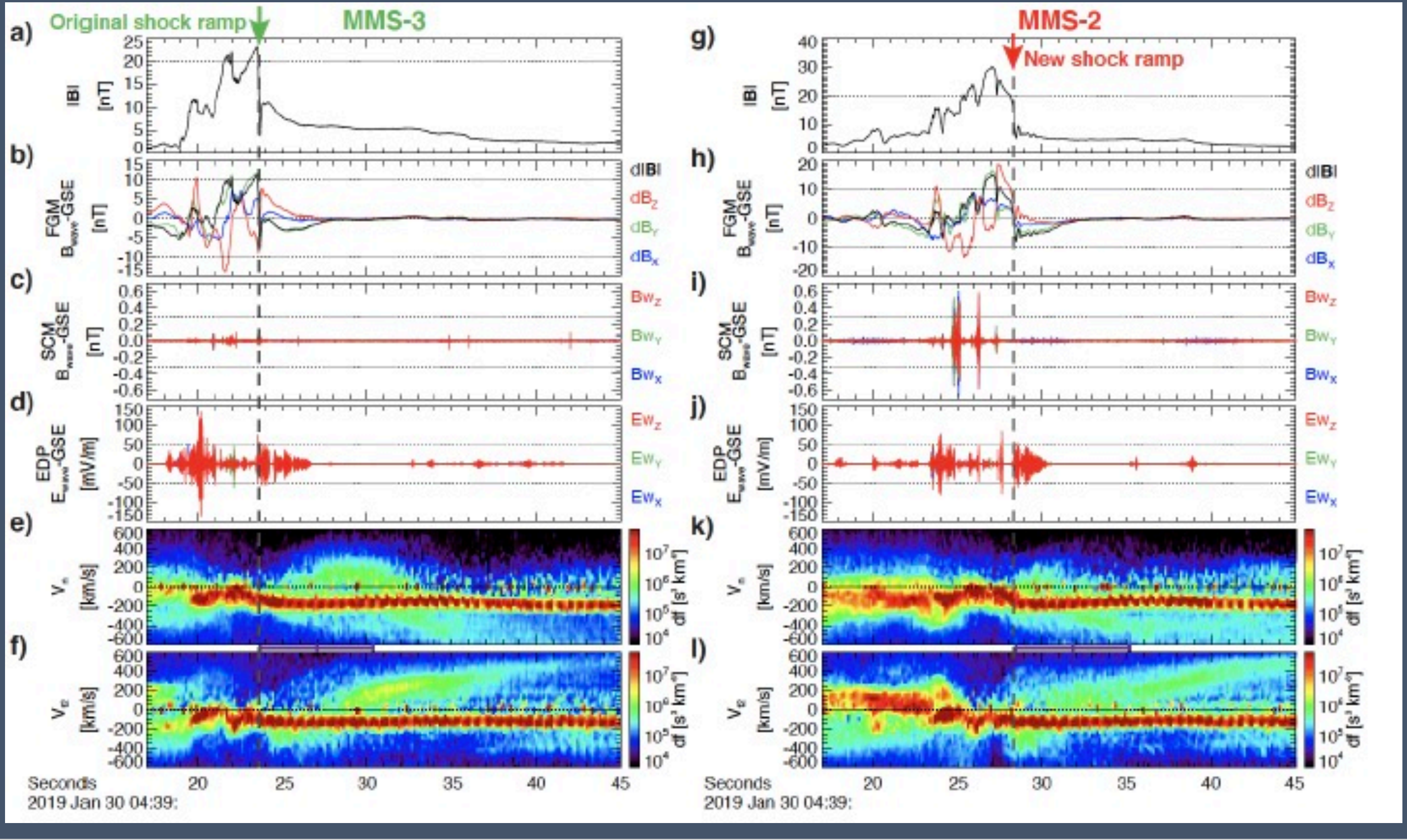


Figure from L. B. Wilson III

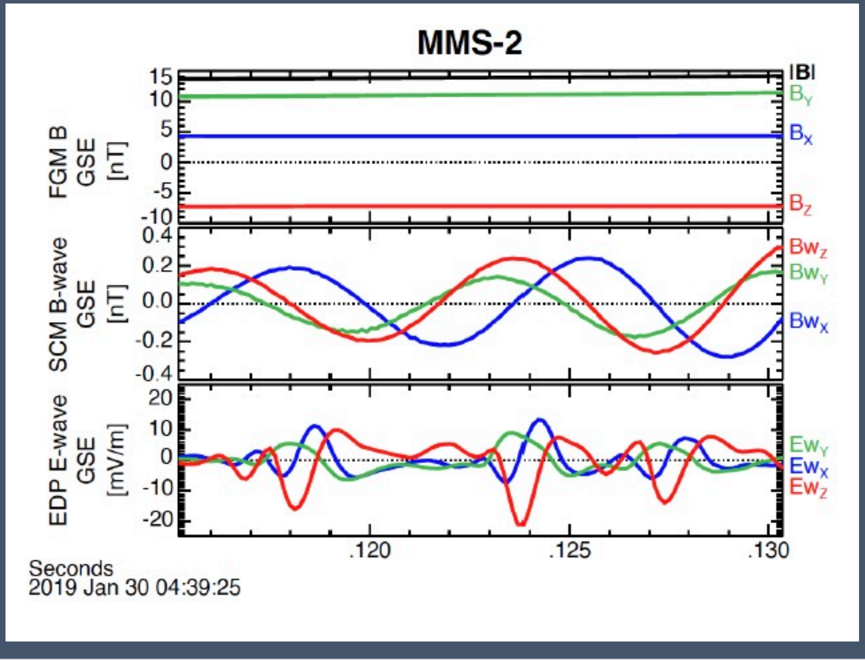


Waves at Shocks

Large amplitude electrostatic fluctuations:
- Vasko et al. [Frontiers 2020]
- Wang et al. [ApJL 2020]



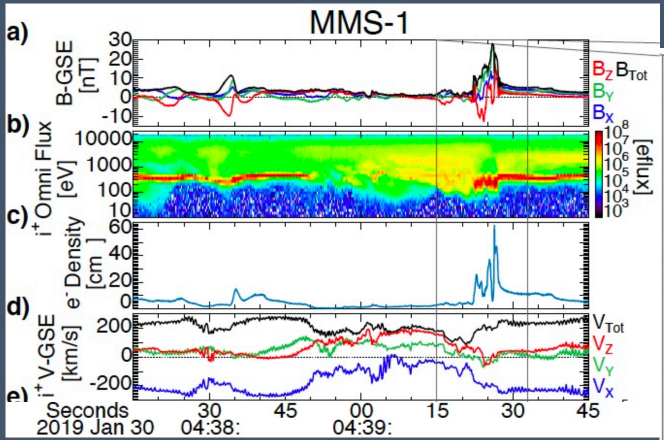
Figures from Turner+ [ApJL 2021]



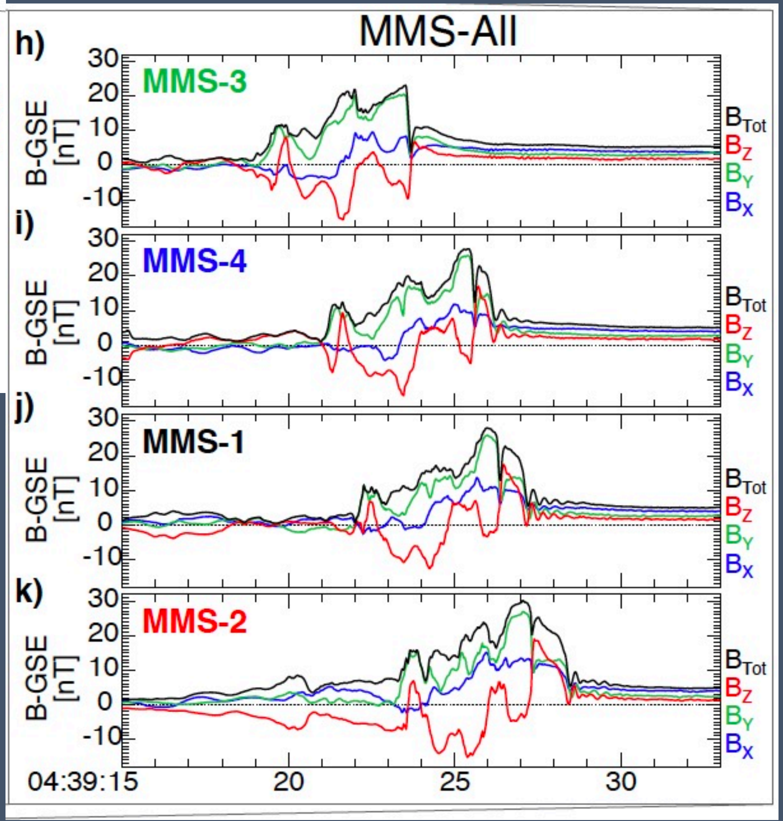
drew.turner@jhuapl.edu

Collisionless Shock Reformation

- **MMS in string-of-pearls configuration, offering unique perspective of spatiotemporal evolution at ion kinetic scales!!!**
- Time history indicates new structure developing along the shock ramp
- Turner+ [ApJL 2021] →
- T. Z. Liu+ [GRL 2020]



Figures from Turner et al. [ApJL 2021]



Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL091184

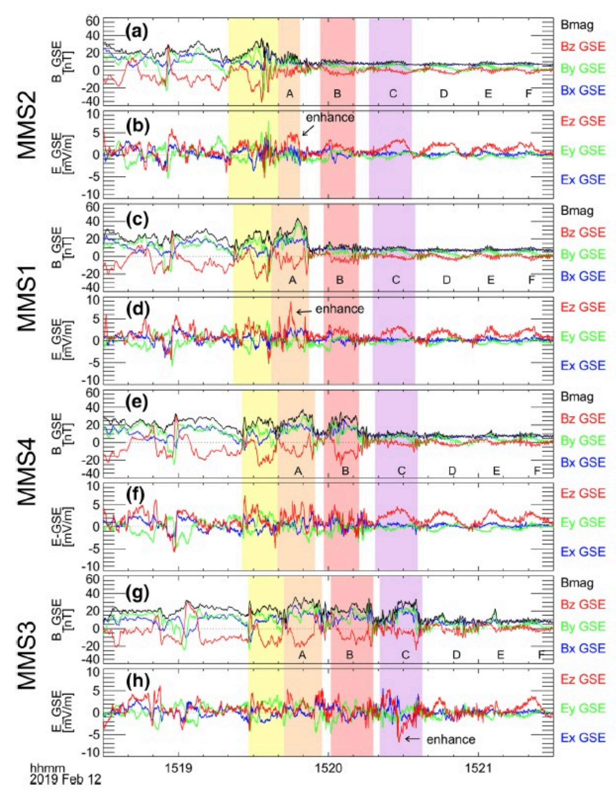
Key Points:
- MMS in a string-of-pearls formation observed oblique bow shock reformation induced by foreshock ULF waves
- We propose the reformation mechanism is the periodic modification of the bow shock upstream conditions by the ULF waves
- The bow shock reformation generated ULF perturbations in the magnetosheath and modulated reflected ions

Magnetospheric Multiscale Observations of Earth's Oblique Bow Shock Reformation by Foreshock Ultralow-Frequency Waves

Terry Z. Liu[1,2], Yufei Hao[3], Lynn B. Wilson III[4], Drew L. Turner[5], and Hui Zhang[2]

[1]Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, Boulder, CO, USA, [2]Geophysical Institute, University of Alaska, Fairbanks, AK, USA, [3]Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, China, [4]Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [5]Johns Hopkins University Applied Physic Laboratory, Johns Hopkins University, Laurel, MD, USA

Abstract Collisionless shocks can be nonstationary with periodic reformation shown in many simulation results, but direct observations are still tenuous and difficult to conclusively interpret. In this



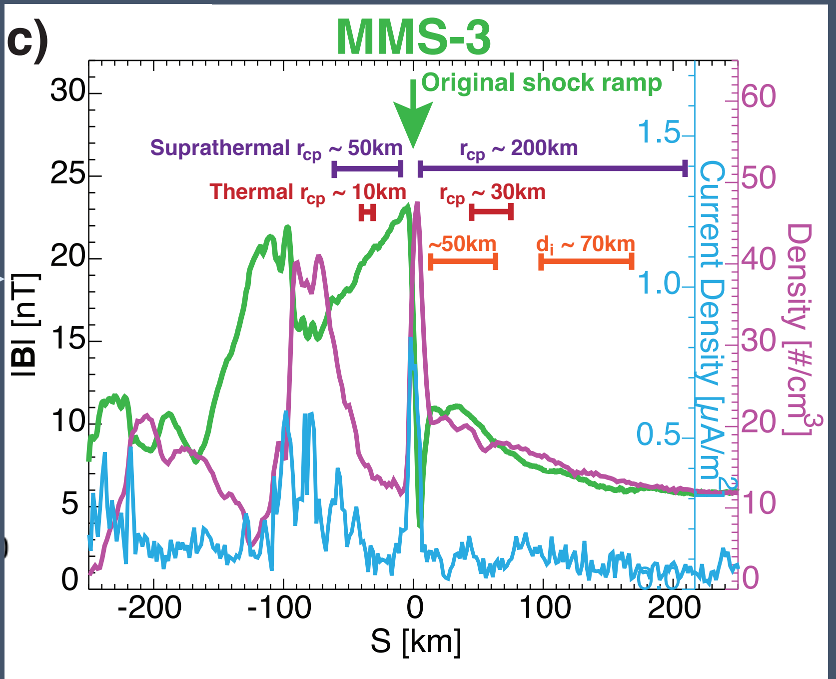
Looking to the Future

- Multipoint analysis at ion-kinetic scale separations allows for mapping time series into physical space and examining key spatiotemporal features of shock

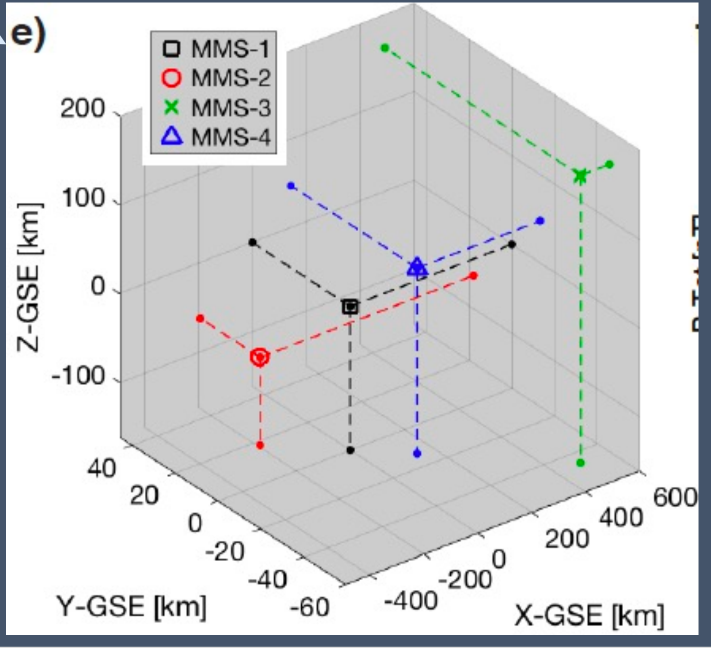
- Ideally, we could have cross-scale configuration from ion-kinetic to MHD scales on either side of the shock simultaneously *with* optimized instrumentation explicitly designed for shock energy budget and partitioning physics

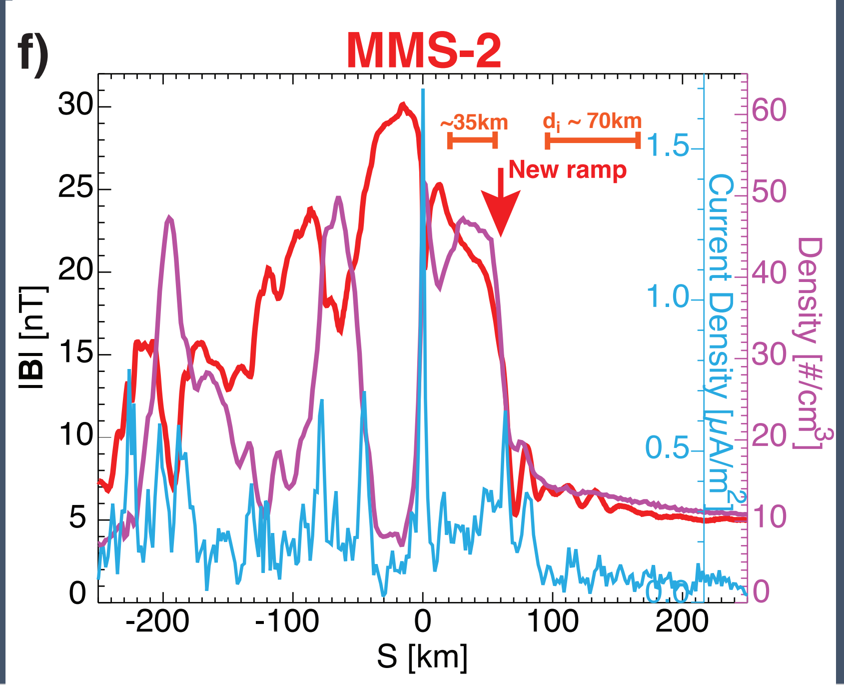
- MMS in the string-of-pearls configuration for the 2019 turbulence campaign gave us a wonderful glimpse into what was possible with such configurations…

- ***Alongside MMS, we should also ideally instrument and design a mission with the exclusive science objective of determining the nature of energy conversion and partitioning at collisionless shocks***



Figures from Turner et al. [ApJL 2021]





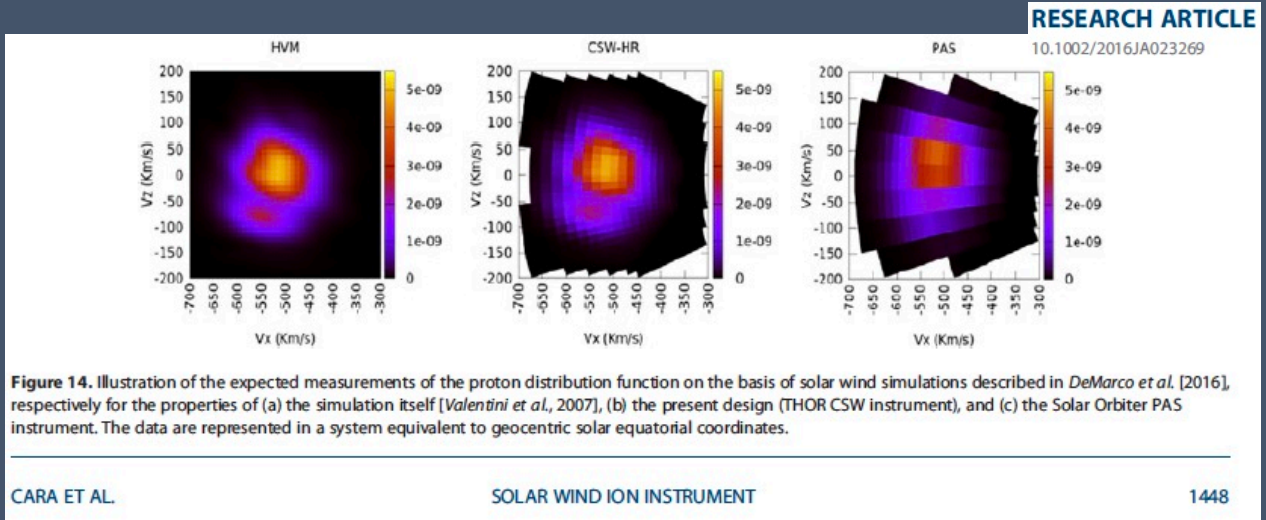
Looking to the Future

- MMS has *and will continue* to give us tremendous, new insights on the nature of collisionless shocks, despite the instrument designs being optimized for Rx at the magnetopause and in the magnetotail (!!!)

- MMS has provided a diamond mine of burst mode shock crossings to keep us busy for some time… and hopefully many more to come (especially more interplanetary shocks!!!)

- The ion-kinetic scale separations during the 2019 turbulence campaign were immensely fruitful for shock physics; another turbulence campaign like that or the “kite” 2x electron-kinetic and 3x ion-kinetic configuration would be highly valuable in the future

- MMS cannot do it all though, in particular, a future dedicated shock mission should carry particle instruments specifically designed to resolve (angular and energy) the solar wind core ions (incl. composition and suprathermals) and electron distributions and improved E-fields for very short wavelength (electron scale) wave modes



RESEARCH ARTICLE
10.1002/2016JA023269

Figure 14. Illustration of the expected measurements of the proton distribution function on the basis of solar wind simulations described in *DeMarco et al.* [2016], respectively for the properties of (a) the simulation itself [*Valentini et al.*, 2007], (b) the present design (THOR CSW instrument), and (c) the Solar Orbiter PAS instrument. The data are represented in a system equivalent to geocentric solar equatorial coordinates.

CARA ET AL. SOLAR WIND ION INSTRUMENT 1448

Looking to the Future

Slide courtesy of Katy Goodrich

MAKOS – Multipoint Assessment of the Kinematics Of Shocks

MAKOS will bridge the wide gap between the macroscale and microscale observations. It will measure energy conversion mechanisms within the shock and provide context to the energy partition process over the entire shock layer.

Science Questions:

1. *What is the energy budget on either side of a collisionless shock?*
   - *Measure all dominant forms of energy upstream and downstream of the bow shock*
   - *Upstream and downstream measurements taken simultaneously from ≥ two spacecraft*
2. *What are the processes governing energy conversion at & within collisionless shocks?*
   - *Observe electromagnetic and electrostatic waves within the shock layer*
   - *Observe other signatures of various instabilities*
3. *How & why do these processes vary with shock orientation and driving conditions?*
   - *Measure multiple crossings over a two year mission period*
   - *Collect a statistically relevant number of crossings*

drew.turner@jhuapl.edu