KINETIC-SCALE PHYSICS OF MAGNETIC RECONNECTION IN THE MMS ERA: ACCOMPLISHMENTS AND FUTURE CHALLENGES FOR THEORETICAL RESEARCH

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Support:

CHARGE FOR THIS TALK


Image taken by speaker, March 11, 2015

- From Bill Daughton —
  "What did we learn from the MMS mission about the basic plasma physics of kinetic reconnection? What are the key theoretical challenges that remain for understanding magnetospheric reconnection – or other larger systems?"
  - Companion to Jim Burch's earlier talk on observations
- Much learned in the MMS era (~500 papers from MMS alone!); of course, much will be omitted
- Target audience — early-career researchers and reconnection experts not on the MMS team

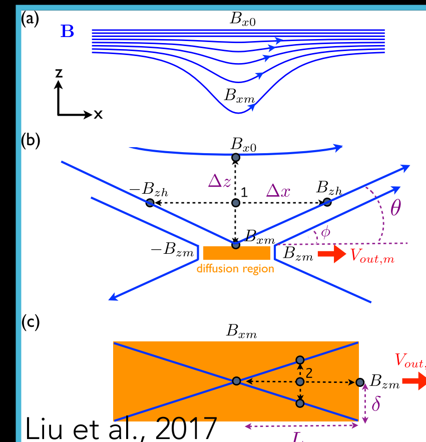
MOST IMPORTANT THEORY ACCOMPLISHMENTS OF THE MMS ERA

- Asked for input from the MMS community to identify their thought of the most important theory/simulation results of the MMS era — received 27 responses from 19 people
  - Have added to them in what follows; won't get to those listed below (names of those that recommended them)
- Secondary reconnection in turbulent reconnection outflow regions (M. Zhou, M. Goldman)
- Stagnation point shift in the outflow direction (R. Denton)
- New framework to understand electron dynamics using electron canonical vorticity (H. Hasegawa)
- Guide field influences crescent distributions and the location of energy conversion (J. Burch)
- KH vortex-induced reconnection at magnetopause transports solar wind more efficiently than high-latitude reconnection (T. Nakamura)
- Energetics - Poynting fluxes dominate at separatrices, ion-enthalpy fluxes dominate at neutral line (M. Goldman)
- Cold ions remain magnetized inside separatrix, reducing Hall currents and electric fields, affects energy conversion (S. Petrinec)
- Magnetic entanglement occurs when flux tubes/ropes collide (C. Russell)
- Using crescents to develop asymmetric equilibria (J. Shuster)
- Using machine learning to model dynamics of plasmasphere and global magnetosphere (M. Argall, D. Turner)
- Stochastic particle acceleration mechanisms at quasi-perpendicular shocks (R. Nakamura)

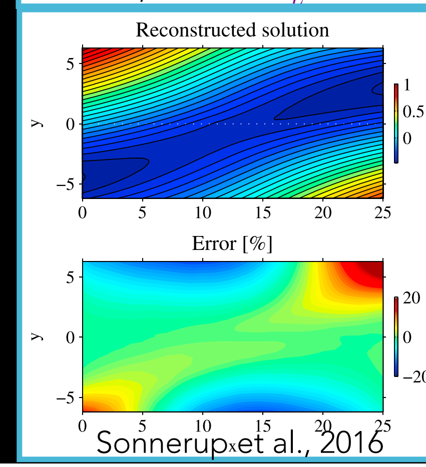
Special thanks to respondents: Matt Argall, Jim Burch, Brandon Burkholder, Richard Denton, John Dorelli, Bob Ergun, Stephen Fuselier, Marty Goldman, Hiroshi Hasegawa, Yi-Hsin Liu, Rumi Nakamura, Takuma Nakamura, Steve Petrinec, Chris Russell, Jason Shuster, Misha Sitnov, Marc Swisdak, Drew Turner, and Meng Zhou

THE RECONNECTION RATE AND MAGNETIC FIELD RECONSTRUCTION

- Simulations show the collisionless reconnection rate is ~0.1 (e.g., Birn et al., JGR, 2001); this is the necessary rate to explain observations (Parker, ApJ, 1973; Shay et al., GRL, 1999)
  - Liu et al., PRL, 2017: New model of why the reconnection rate is ~0.1
- Techniques to "reconstruct" the 2D/3D magnetic geometry from (1D) spacecraft trajectory
  - Denton et al., GRL, 2016; Sonnerup et al., JGR, 2016; Hasegawa et al., GRL, 2017; Shuster et al., GRL, 2017; Genestreti et al., JGR, 2018; Egedal et al., PRL, 2019; Torbert et al., GRL, 2020; Denton et al., JGR, 2020: Reconstruction methods honed / developed
    - Observations (Chen et al., JGR, 2017; Nakamura et al., JGR, 2018; Pritchard et al., GRL, 2019; Burch et al., GRL, 2020): Direct measurements agree with ~0.1
  - Sitnov et al., JGR, 2019: Reconstruction of magnetotail geometry using machine learning

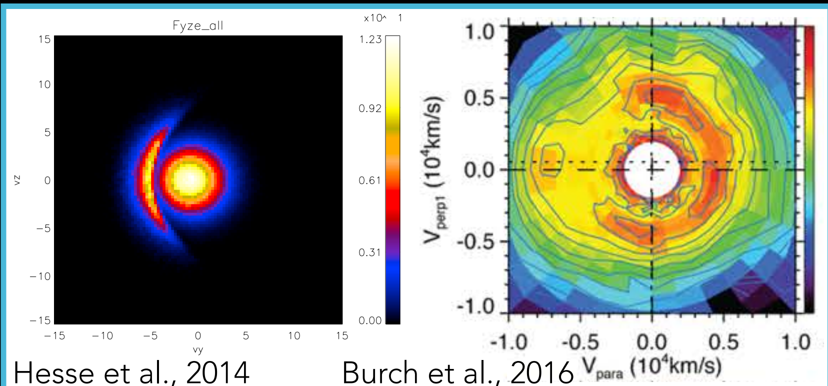


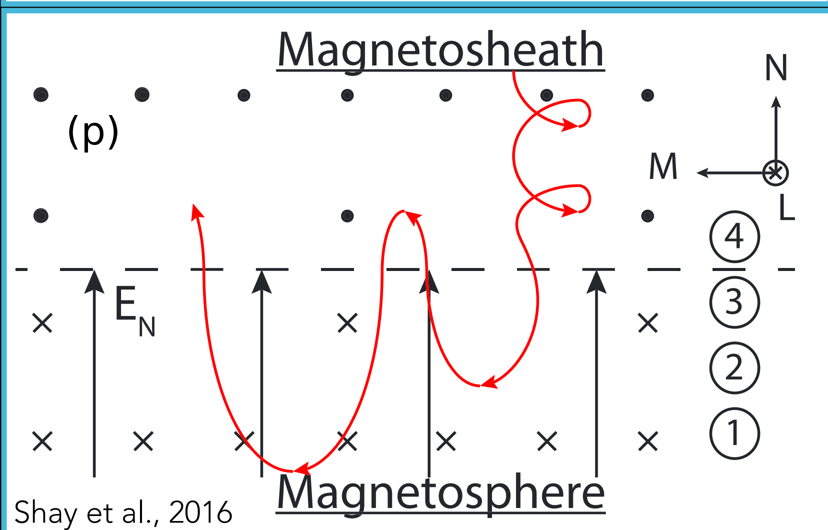
Liu et al., 2017



Sonnerup et al., 2016

UNDERSTANDING VELOCITY DISTRIBUTION FUNCTIONS (VDFS) IN RECONNECTION

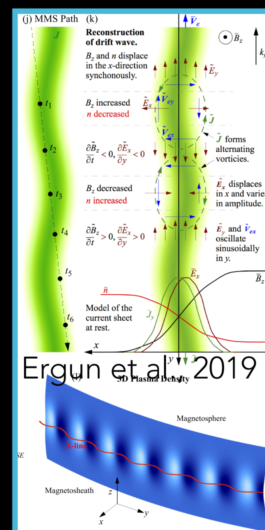




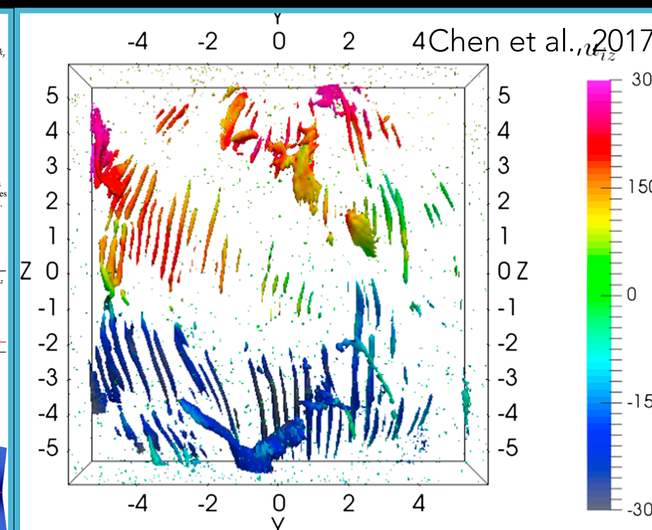
- Hesse et al., GRL, 2014: Crescent-shaped distributions occur at/near the electron diffusion region (EDR) in asymmetric reconnection
  - Observations (e.g., Burch et al., Science, 2016; Rager et al., JGR, 2018): crescents measured; rotation relative to B is evidence of reconnection; carries current, dominates energy conversion; diamagnetism important
- Chen et al., GRL, 2016; Bessho et al., GRL, 2016; Shay et al., GRL, 2016; Bessho et al., GRL, 2018: Crescents caused by electrons E x B drifting in Hall electric field; can deduce reconnection rate from shape of crescents
- Egedal et al., PRL, 2016: Crescents occur along whole boundary, crescent shape set by electrons needing sufficient energy to overcome Hall E field
- Bessho et al., GRL, 2014; Shuster et al., GRL, 2015; Lapenta et al., JGR, 2017: Crescents due to meandering, should be in magnetotail
  - Observations (Torbert et al., Science, 2018) in tail reveal crescents

CAUSES OF LOCALIZED STRONG ELECTRIC FIELDS AND TURBULENCE

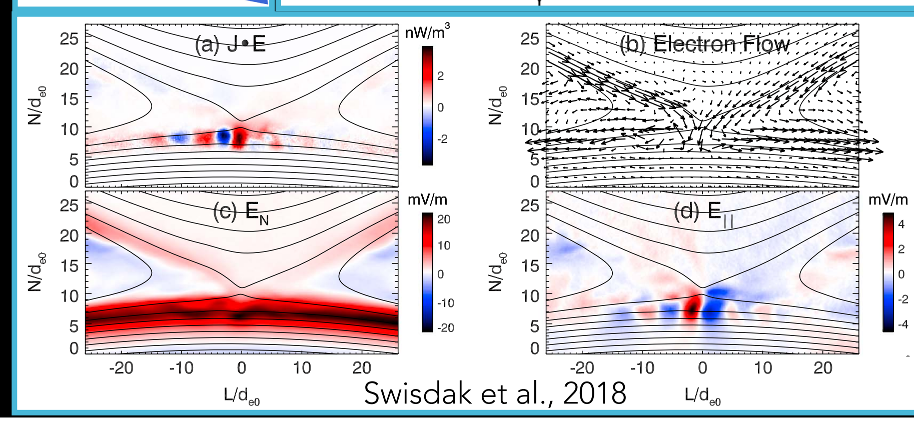
- Observations (Burch et al., Science, 2016; Ergun et al., PRL, 2016; GRL, 2016; GRL, 2018; Eriksson et al., PRL, 2016): Local parallel E fields <u>far</u> exceed rates
  - Cassak et al., JGR, 2017: Cannot be global reconnection rate because it would exceed observed global measures
  - Ergun et al., PRL, 2016; GRL, 2018; JGR, 2019; Price et al., GRL, 2016; JGR, 2017: Huge E fields and energy conversion associated with tangled B fields, waves (including drift waves), and turbulence
  - Chen et al., JGR, 2017: Drift waves captured in global-MHD w/embedded-PIC, strong electric fields as in observations
- Observations (Burch et al., GRL, 2018): localized oscillatory energy conversion with strong electric fields
  - Swisdak et al., GRL, 2018; Egedal et al., PRL, 2018: 2D PIC simulations reproduce structure, studied flow patterns and fields



Ergun et al., 2019

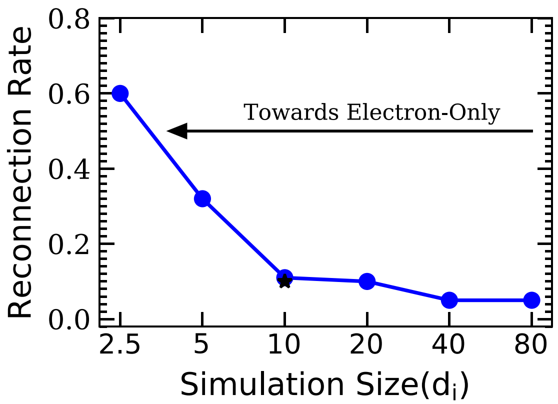


Chen et al., 2017

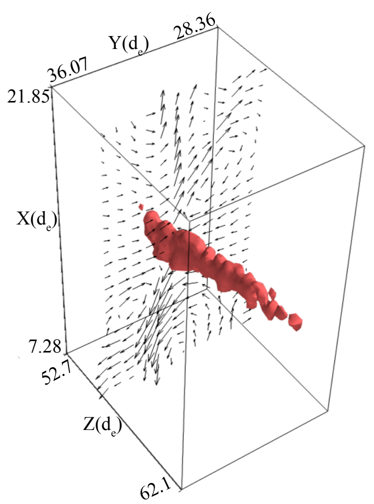


Swisdak et al., 2018

"ELECTRON ONLY" RECONNECTION



Sharma Pyakurel et al., 2019

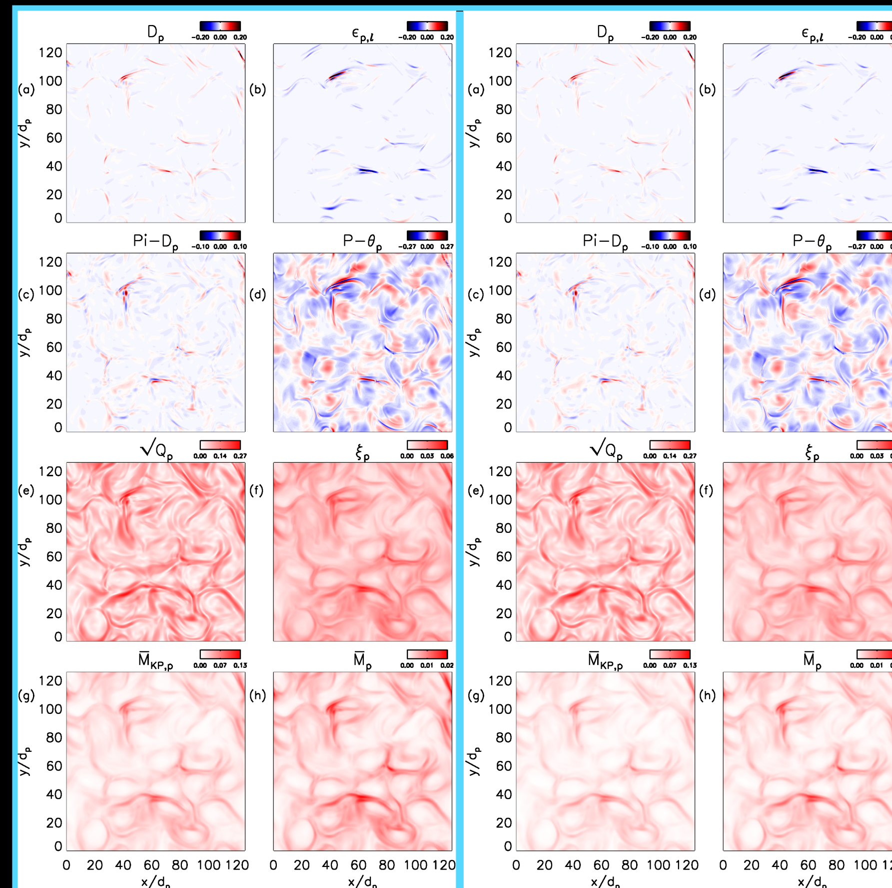


Sharma Pyakurel et al., in prep

- Observations (Phan et al., Nature, 2018; Stawarz et al., ApJ, 2019; Gingell et al., GRL, 2019; Gingell et al., JGR, 2020): magnetosheath reconnection downstream of quasi-parallel shock not coupled to ions; near shock too
  - Sharma Pyakurel et al., PoP, 2019; PRL, in prep; Mallet, JPP, 2020: 2D electron only reconnection faster than fully coupled reconnection and is well-described by a model based on kinetic theory wave speeds, 3D localized electron only can be faster than 2D; study of onset
  - Califano et al., Front. Phys., 2020; Vega et al., ApJ, 2020; Arrò et al., A&A, 2020; Boldyrev and Loureiro, PRL, 2019; Loureiro and Boldyrev, ApJ, 2020; Bessho et al., GRL, 2019: Electron only may be important to turbulence in volume-limited regions (and in general?), downstream of bow shocks
- Caution — identifying "electron only" is non-trivial! An absence of ion flow is not sufficient to imply electron only reconnection!

PHYSICS OF KINETIC-SCALE ENERGY CONVERSION AND "DISSIPATION"

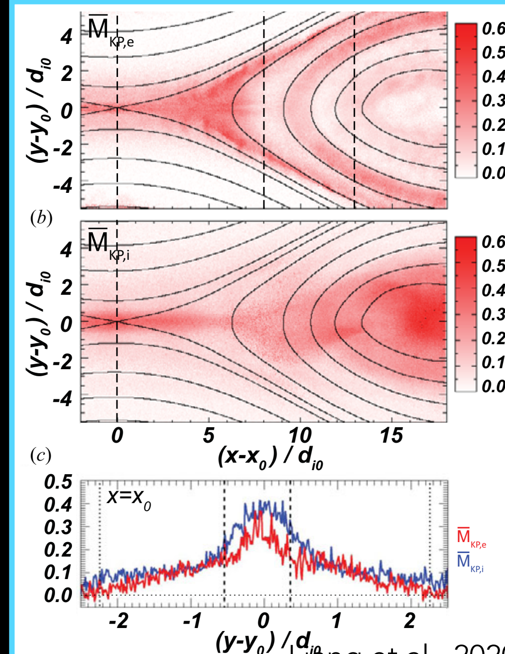
- Numerous proxies of energy conversion and dissipation; challenging to even define "dissipation" in collisionless plasmas!
  - Work done on/by electric field D (Zenitani et al., PRL, 2011)
  - Pressure-strain interaction Pi-D and P-θ (Yang et al., PoP, 2017)
  - Local Energy Transfer rate (LET) ε (Sorriso-Valvo et al., Solar Phys., 2018)
  - Pressure agyrotropy Q (Scudder and Daughton, JGR, 2008; Aunai et al., PoP, 2013; Swisdak, GRL, 2016)
  - Quadratic non-Maxwellianity ξ (Greco et al., PRE, 2012)
  - Entropy-based non-Maxwellianity M (Kaufmann and Paterson, JGR, 2009; Liang et al., JPP, 2020)
  - Field particle correlation (Klein and Howes, ApJL, 2016)
- Comparisons of proxies in kinetic models during reconnection and turbulence is underway (e.g., Pezzi et al., JPP, in prep)



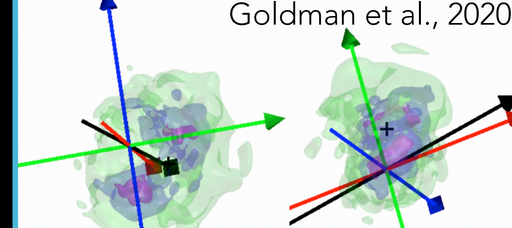
Left — collisionless; right — collisional (Pezzi et al., in prep)

ADVANCES TO FUNDAMENTAL KINETIC THEORY

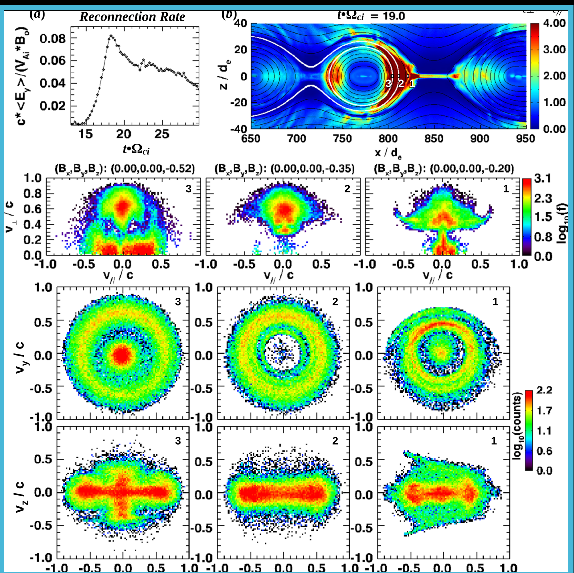
- Liang et al., PoP, 2019; JPP, 2020: Kinetic entropy (Boltzmann, Wiener Berichte, 1877) can be useful for studying dissipation; can decompose kinetic entropy into position space and velocity space kinetic entropy, velocity space kinetic entropy more natural to study local dissipation; new non-Maxwellianity measure; calculated kinetic entropy for model distributions
  - Observations (Matt Argall, unpublished): calculated entropy using MMS data
- Goldman et al., JGR, 2020: New multi-moment approach to kinetic theory treats beams separately; relative bulk flow energy counts as bulk flow energy (it’s thermal in standard theory)
- Observations (Shuster et al., JGR, 2019): can measure terms in Vlasov equation
  - Shuster et al., Nature, submitted: New understanding of how spatial gradients of VDFs determine contributions to the electron pressure divergence
- Drake et al., PoP, 2019; Arnold et al., PoP, 2019; Wetherton et al., GRL, 2019; JGR, 2020: Kinetic-based closures for global fluid modeling; capturing electron Fermi acceleration in large-scale fluid simulations; “Egedal equations of state” (Lê et al., PRL, 2009) works from EDR scales to ~100 ion inertial scales



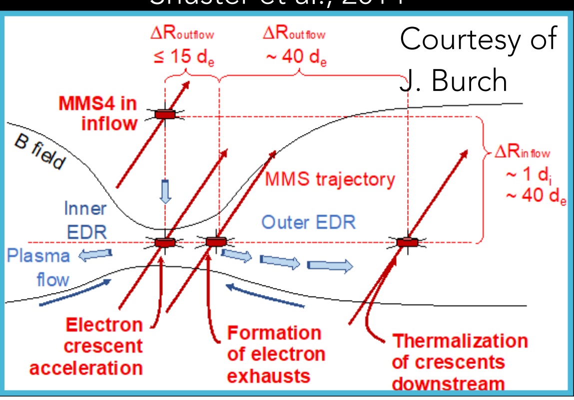
Liang et al., 2020

Goldman et al., 2020


FUTURE OPPORTUNITIES: MICRO- TO MESO-



Shuster et al., 2014

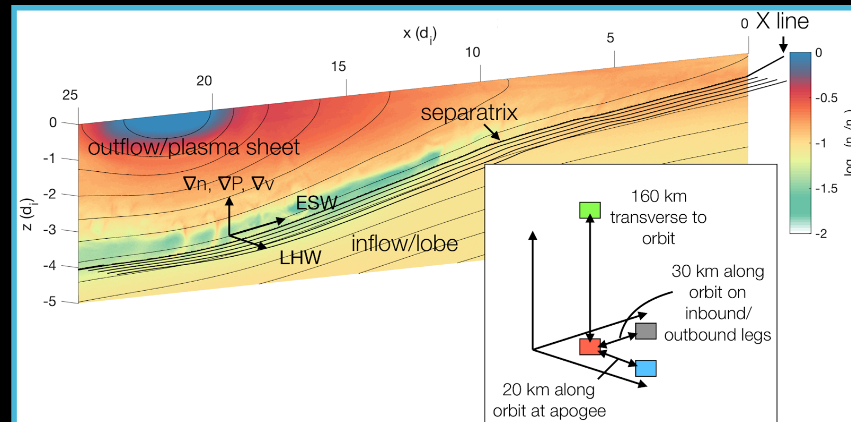


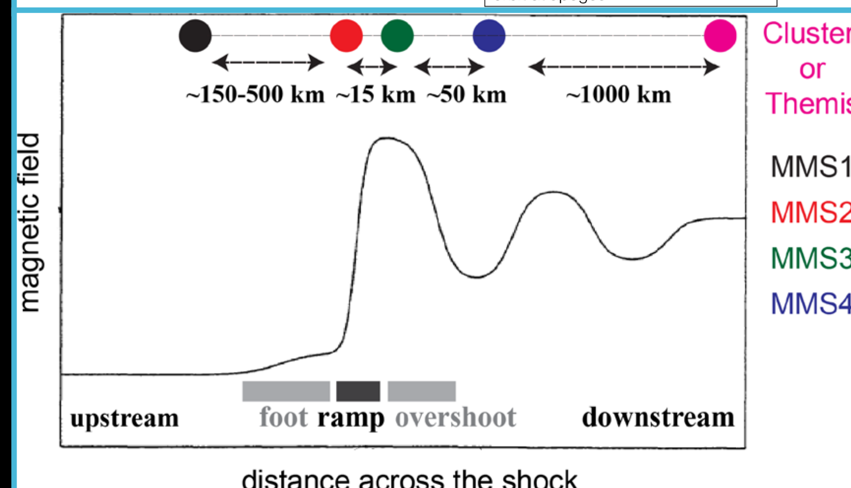
Courtesy of J. Burch

- Coupling of electron- and ion-scale, ion- and meso-scale
  - Physics of thermalization of non-gyrotropic electron/ion distributions in reconnection exhausts
  - Effect of small-scale waves on reconnection and vice versa
  - Effect of cold and/or heavy ions on reconnection
  - Effect of flow shear across the reconnection site
  - "Laminar" vs. "bursty" reconnection causes
    - Need to reconfigure MMS spacecraft from tetrahedron to pictured; planned for extended mission

FUTURE OPPORTUNITIES: MICRO- TO MACRO-

- Energy conversion, particle acceleration in reconnection
  - Role of kinetic-scale physics at separatrices in generating waves and nonlinear structures and energy conversion
    - Need to reconfigure MMS spacecraft from tetrahedron to pictured; planned for extended mission
- Reconnection as an element of other physical phenomena
  - Turbulence, bow shocks, interplanetary shocks, corotating interaction regions (CIRs), Kelvin-Helmholtz instability on magnetopause flanks, wave-particle interactions at dipolarization fronts and in radiation belts, cusp physics
    - Need to reconfigure MMS spacecraft;
      may be a part of the extended mission





Images courtesy of J. Burch

FUTURE OPPORTUNITIES: LABORATORY STUDIES

Images courtesy of E. Scime

- Reconnection research has benefited from close collaborations with experiments (MRX, FLARE, VTF, MST, TREX, SSX, RSX, LAPD, CalTech, DIII-D, …)
  - However, there are **no experiments in the world measuring VDFs** in heliophysics-relevant systems
- New experiment at West Virginia University: PHAse Space MApping (PHASMA, PI: Earl Scime)
  - Will measure ion VDFs (laser-induced fluourescence) and electron VDFs (Thomson scattering) <u>non-perturbatively</u> in a double flux rope (RSX-type) configuration, with in-house modeling capabilities

FUTURE CHALLENGES: THEORY

- Cross-scale coupling (ion-scale to meso-scale, meso-scale to macro-scale) is challenging observationally, experimentally, and numerically
  - Global-kinetic simulations still out of reach; need code coupling (SWMF), global hybrid (Vlasov-hybrid, PIC-hybrid), fluid closures
  - Satellite conjunctions (e.g., Cluster, THEMIS/ARTEMIS, Geotail, Arase, TRACERS) and/or new cross-scale missions
- Applying knowledge from MMS to reconnecting systems beyond Earth's magnetosphere is challenging — solar corona, planetary magnetospheres, astrophysical plasmas, fusion
  - See also Hesse and Cassak, JGR, 2020

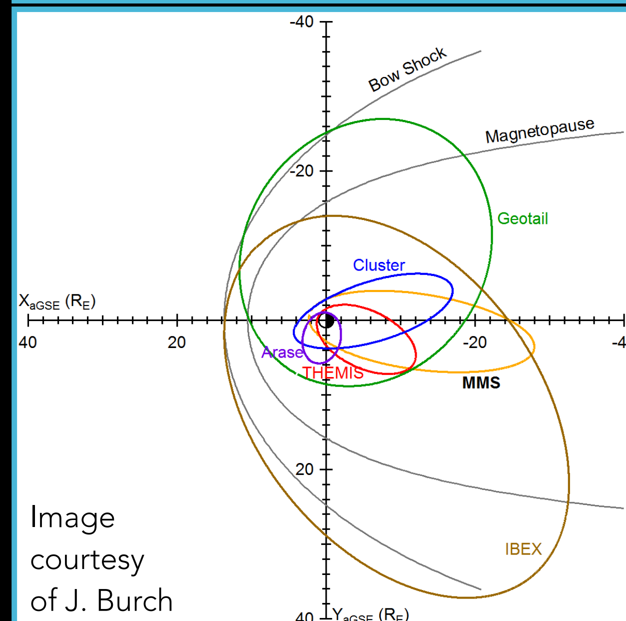


Image courtesy of J. Burch

FUTURE CHALLENGES: DEI

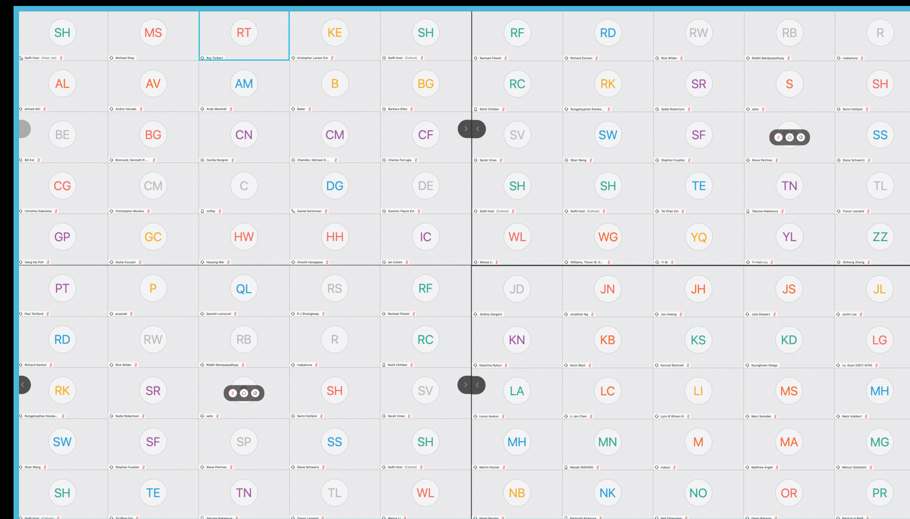

Image courtesy of L. Garrison

Image courtesy of J. Bryan

- DEI = Diversity, Equity, and Inclusity
  - Physics/science in America is not currently diverse, equitable, or inclusive; science community is not achieving what it is capable of
  - Accomplishments from MMS (courtesy of Leslie Garrison):
    323 outreach events reaching 98,500 people in the last three years, including 23 events reaching 1,062 people to build minority engagement and diversity
- Future challenges
  - Increase opportunities for a diverse population to be successful in physics, and make physics a welcome place for all to thrive
  - Think of what MMS has accomplished in 20 years; imagine what physics would be like in 20 years if we put in the effort to improve DEI
    - APS is leading the charge, e.g., its IDEAs Network
      https://www.aps.org/programs/innovation/fund/idea.cfm

CONCLUSIONS

- The first five years of the MMS era have been extremely fertile for answering old questions and addressing scores of new ones
  - The symbiosis between satellite observations and 2D/3D simulations has been surprisingly fruitful
  - New developments in kinetic theory will impact plasma physics far beyond the microphysics of reconnection
- Future research avenues include both new aspects of micro-scale physics and connections to meso- and macro-scale
  - Exciting era ahead allowing distribution function-level comparisons with laboratory experiments
- Numerous challenges still remain — sparseness of observational data, limitations of computer power, DEI issues in the sciences
- Acknowledgements — The entire MMS team, Jim Burch
  - *Dedicated to the memory of MMS team members Craig Tooley and Sam Bingham*



Group picture of MMS team from MMS SWT, October, 2020; Courtesy of K. Genestreti

Image courtesy of NASA