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

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APS DPP MEETING
NOVEMBER 10, 2020

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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)

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.
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 far 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
“ELECTRON ONLY” RECONNECTION


- 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


- Caution — identifying “electron only” is non-trivial! An absence of ion flow is not sufficient to imply electron only reconnection!
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 $P_i-D$ and $P-\theta$ (Yang et al., PoP, 2017)
- Local Energy Transfer rate (LET) $\varepsilon$ (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 $\xi$ (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)
**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” (Lè et al., PRL, 2009) works from EDR scales to ~100 ion inertial scales
FUTURE OPPORTUNITIES: MICRO- TO MESO-

- 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
FUTURE OPPORTUNITIES: LABORATORY STUDIES

• 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) non-perturbatively 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.
FUTURE CHALLENGES: DEI

- DEI = Diversity, Equity, and Inclusivity

- 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

Image courtesy of L. Garrison

Image courtesy of J. Bryan
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.

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