Particle Heating and Thermalization in Collisionless Shocks in the MMS Era

2019 GEM Summer Workshop
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What is a Shock?

Supersonic flow + Obstacle = Shock wave

Shock wave: a discontinuous change in
- Pressure
- Temperature
- Density

Main Function:
Slow supersonic flow so it can move past obstacle

Kinetic Energy $\rightarrow$ Thermal Energy
Collisional vs Collisionless Shocks

**Collisional**

- Dominant Mechanism: Particle Collisions

**Collisionless**

- Dominant Mechanisms:
  - Turbulence
  - Particle Reflection
  - Nonlinear Processes

**Kinetic Energy -> Thermal Energy**
Shocks in Space Plasmas

Astrospheres (maybe)

Supernova

Galactic Jets

Planets!
**Earth’s Bow Shock**

- Solar wind slowed and heated by bow shock

- Becomes magnetosheath, diverted around magnetosphere

- Magnetosheath plasma interacts with magnetopause leading to
  - Reconnection
  - Kelvin-Helmholtz
  - Aurora

- **Bow Shock is a vital player in the solar wind-magnetosphere interaction!**
Earth’s Bow Shock – A Breathing “Barrier”

- Macrostructure of the bow shock is complex
- Quasi-perpendicular
  - $n \perp B$
  - “cleaner”
  - Compressive
- Quasi-parallel
  - $n \parallel B$
  - “messy”
  - Turbulent
  - Extended into foreshock regions
- Heavily dependent on upstream conditions
  - Constantly changing
- Kinetic -> Thermal Energy?
  - Complicated to answer
Observations Provided By…

ISEE (Launched 1977)

WIND ( Лаunched 1994)

Cluster (Launched 2000)

THEMIS (Launched 2007)
It’s Hard to Observe Shocks

**Rankine-Hugoniot Conditions:**
- Mass in = Mass out
- Momentum in = Momentum out
- Energy in = Energy out*

*We do not know exactly how energy is converted in the shock

Can estimate what happens inside shock

Very hard to observe

Upstream and Downstream conditions frequently observed
It’s Hard to Observe Shocks

McFadden et al., [2008]

Only a few data points of particle data during actual shock

Must rely on E and B field observations to observe within the shock

THEMIS
~80 minutes

~3 second
Particle time resolution
Quasi-Static Fields - Cross Shock Potential

- Ions are reflected by cross shock potential $\phi$
- $\phi$ accelerates electrons
- Waves fill in the gaps within $e\phi$
- Result: thermalized distribution
- Difficult to observe

Paschmann et al., 1982
Waves and Microinstabilities

- Bow Shock host to many wave modes
- Not clear how these waves are generated
- Can connect to different microinstabilities like:
  - Buneman
  - Electron Cyclotron Drift
  - Two-stream instability
  - Many others
- Wave influence on shock dynamics is not clear
- Can’t observe particle behavior with waves

L. Wilson et al., JGR, 2014
Magnetospheric MultiScale (MMS)

Objective: observe reconnection in magnetosphere

small separation (10 – 100 km)

high time resolution particle instruments

30 ms electrons
150 ms ions
Objective: observe reconnection in magnetosphere

small separation (10 – 100 km)

high time resolution particle instruments

30 ms electrons

150 ms ions

*coincidentally a great observer of bow shock microscale processes
Shock

~80 minutes

~3 second
Particle time resolution

Only a few data points of particle data during actual shock

Must rely on E and B field observations to observe within the shock
MMS

~9 min

30/150 ms
e/ion resolution

EM Whistler Waves

Large Amplitude E

Electrostatic wave modes
100 Hz to kHz

Magnetosonic-whistler Waves
< 100 Hz

Up to 700 mV/m!
*(that’s really high!)*
$E_\parallel$ waves begin to grow as transport of phase-space-density to anti-parallel starts

Buneman $\rightarrow$ ECDI $\rightarrow$ 3D IAWs in B?

Chen et al., [2018]
Unexpected Influence of Waves

Ion Acoustic Waves

Reflected ion beams
Unexpected Influence of Waves

Vasko et al., [2018]
Magnetic Reconnection

Wang et al., [2019]

Gingell et al., [2017]
Let’s Check In…

• Particle Heating and Thermalization is persistent question in shock physics
  • Answers limited due to observational capabilities

• MMS observed >100 bow shock crossings
  • Provides a few answers
  • Creates many more questions

• We need help from the GEM community to answer these questions
Goals for Bow Shock Focus Group

1) Address the structure of the quasi-static electric fields in collisionless shocks

2) Understand waves in collisionless shocks and their generation mechanisms

3) Quantify contributions of quasi-static and high-frequency electric fields to particle heating and thermalization and

4) Enable advances of MHD, hybrid, and PIC simulations to model the Earth’s bow shock and magnetosheath plasma.
Focus Group Chairs

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Schedule and Locations

Monday
• FG Splinter 10:00 – 12:00 – Santa Fe Room
• FG Splinter 13:30 – 15:00 – Lumpkins Ballroom South

Tuesday
• Poster Session 17:00 – 20:00

Wednesday
• Dayside Joint Session 13:30 – 15:00 – Lumpkins Ballroom South
• MMS Joint Session 15:30 – 17:00 – New Mexico Room