Influence of cold ions on magnetotail Hall physics

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Reconnection as a two scale process

• Magnetic reconnection requires breaking of the frozen-in condition, $E + v \times B \neq 0$.

$$\vec{E} + \vec{v}_e \times \vec{B} = -\frac{1}{ne} \vec{\nabla} \cdot \vec{P}_e - \frac{me}{e} \left( \frac{\partial \vec{v}_e}{\partial t} + \vec{v}_e \cdot \vec{\nabla} \vec{v}_e \right)$$

• Generalized Ohm's law, ignoring inertial effects.

$$\vec{E} + \vec{v}_i \times \vec{B} = \frac{1}{ne} \vec{j} \times \vec{B} - \frac{1}{ne} \vec{\nabla} \cdot \vec{P}_e$$
Reconnection as a two scale process

- Two-scale reconnection.
  - Decoupling on scales smaller than gyro radius.
  - Extended ion diffusion region
  - Localized electron diffusion region.

Mozer et al. 2002
Reconnection as a two scale process

Birn et al. 2001
Reconnection as a multi-scale process

- Multi-scale reconnection
  - Multiple ion temperatures or masses.
  - Multiple ion diffusion regions.
  - Regions with reduced Hall current.

André et al. 2016
Reconnection as a multi-scale process

- PIC simulation with oxygen ions but same principles apply.
- Hall magnetic field has same peak magnitude with and without oxygen.
- Hall field is observed across a wider area.

Markidis et al. 2011
Cold ions

- Spacecrafts in a low density plasma can charge to several tens of volts, deflecting cold ions.
- Indirect measurements of cold ions through wake fields.

\[
\begin{align*}
(a) & \quad m v_i^2/2 > K T_i, \\
(b) & \quad K T_i < m v_i^2/2 <
\end{align*}
\]

Engwall et al. 2006
Cold ions

- Combining E-field measurements EFW and EDI.
- EFW will measure the wake electric field.
- EDI is insensitive to the wake field.

Engwall et al. 2009
The ionosphere is an important source of cold and heavy ions.

Cold (tens of eV) ions can account for a majority of the tail lobe plasma [e.g. Engwall et al. 2009, André et al. 2012].

High geomagnetic activity allows ionospheric ions to convect to the plasma sheet rather than escape downtail [Kistler et al. 2005, Li et al. 2013].
Recent results from MMS

- Study of cold ions at the dayside magnetopause
- The Hall electric field is mainly balanced by the jxB term.

André et al. 2016
Cold ions in the magnetotail

- Can MMS observe cold ions in the magnetotail?
  - 414 burst intervals containing cold ions has been identified between May and August 2017.
- Can we observe cold ions inside the plasma sheet.
- Will cold ions remain cold once inside the plasma sheet?
- Does the cold ions have a significant effect on the Hall fields.
Example of cold ions
Event overview
Event summary
Calculating particle moments
Calculating particle moments
Satellite motion

- Determined using Spatio-Temporal difference method [Shi et al. 2005, Denton et al. 2016]
- Determines the velocity of a magnetic structure by assuming that
  \[
  \frac{dB}{dt} = -V_{str} \cdot \nabla B
  \]
- Requires sufficiently strong gradients and is most reliable to determine motion in along the normal direction.
Satellite motion

• Solved using the magnetic field from each satellite rather than the barycentric average of the magnetic field. Gives a over-determined system of equations.

\[
\begin{align*}
\frac{dB_{MMS1}}{dt} &= -V_{str} \cdot \nabla B \\
\frac{dB_{MMS2}}{dt} &= -V_{str} \cdot \nabla B \\
\frac{dB_{MMS3}}{dt} &= -V_{str} \cdot \nabla B \\
\frac{dB_{MMS4}}{dt} &= -V_{str} \cdot \nabla B
\end{align*}
\]

• Reduces the issues with offsets and singularities.
Satellite motion

\[ B_x = B_{x,0} \tanh((dZ-Z_0)/h) \]

- \( B_{x,0} = 23.5 \text{ nT} \)
- \( Z_0 = -1840 \text{ km} \)
- \( h = 846 \text{ km} \)
Interpretation of the event

Ion Jet
Generalized Ohm's law

- Start with a generalized Ohm's law ignoring electron inertial effects.

\[
\vec{E} = \frac{1}{ne} \vec{j} \times \vec{B} - \frac{1}{ne} \nabla \cdot \vec{P}_e - \frac{n_c}{n} \vec{v}_c \times \vec{B} - \frac{n_h}{n} \vec{v}_h \times \vec{B}
\]

- Currents calculate using the curlometer method.
- Ion and electron moments from FPI.
- Divergence of the electron pressure calculated across the spacecraft tetrahedron.
Generalized Ohm's law

- Cold ions are fully covered by FPI.
- FPI can not cover the entire hot ion population.
  - Unreliable velocity.
  - Underestimates density.
- The electrons are fully covered FPI energy range.
  - \( n_e = n_i = n_c + n_h \).
- Ignore the \( (n_h/n)v_h x B \) term for now.
- Hot ions are accounted for indirectly in the \( j x B \) term.
Generalized Ohm's law
Generalized Ohm's law
Summary and Conclusions

- The Hall electric field is mainly balanced by the jxB term. In agreement with previous studies.
- There is a significant contribution from the electron pressure term. Not typically seen at the dayside magnetopause.
- This indicates that $E+v_e x B \neq 0$, non-ideal electron motion.
Summary and Conclusions

• The cold ions cancel parts of the Hall current and are required to explain the observed Hall electric field.
• Cold ions account for ~30% of the total ion density in the plasma sheet.
• The cold ions are heated as they enter the plasma sheet but even at the deepest part ~65% are cold enough to remain magnetized.