Ion heating during geomagnetic storms measured using energetic neutral atom imaging

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Outline

• Motivation

• Overview of ENA measurements
  – Charge exchange
  – MENA and TWINS ENA instruments

• Calculating ion temperatures
  – LOS projection

• Overview of results

• Open questions
Why ion temperatures?

- Ion temperatures help us understand how ions move throughout the magnetosphere
- Ion temperatures increase during geomagnetic storms due to several processes
- Ion temperatures and densities are used to establish boundary conditions for inner magnetosphere models

Spence and Kivelson, JGR, 1993
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Baumjohann et al., JGR, 1989
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Tsyganenko and Mukai, JGR, 2003
Energetic Neutral Atoms (ENAs) created by charge-exchange

**Neutral source:**
the Earth’s geocorona that extends out many $R_E$.

**Ion source:**
the plasma trapped in the magnetosphere.
Medium Energy Neutral Atom (MENA) Imager uses time of flight.

IMAGE Mission 2000-2005
Two Wide-angle Imaging Neutral Atom Spectrometers (TWINS) features improvements on the MENA design

- Mission of Opportunity
- Two spacecraft in high inclination Molniya orbits
- 1-100 keV
- June 2008-present
Ion temperature calculated by a fit to the ENA energy spectrum

\[ j_{ENA}(E, \vec{u}) = \sigma_{cx}(E) \int_{0}^{R} \left( n_n(\vec{r}(s)) j_{ion}(\vec{r}(s), E, \vec{u}) \exp \left( -\int_{0}^{r(s)} \alpha(s') ds' \right) ds \right) \]

Spectrum dominated by hottest point along line of sight

\[ j_{ENA} \approx \sigma_{cx}(E) \xi n_n(z^*) j_{ion}(z^*, E) \]

- Maxwellian distribution
- “Optically” thin region
- All ENAs are hydrogen
Ion temperature calculated by a fit to the ENA energy spectrum

\[
\frac{j_{ENA}}{\sigma_{cx}(E)E} \approx \frac{\xi n_n(z^*) n_i(z^*)}{\sqrt{2m_i(\pi T_{i}(z^*))}^{3/2}} \exp\left(\frac{-E}{T_{i}(z^*)}\right)
\]

\[
\xi n_n(z^*) j_{ion}(z^*, E)
\]
MENA temperatures in agreement with *in situ* measurements

The MPA data has been averaged over twenty minute intervals to be consistent with the MENA ion temperature maps that are based on twenty-minute averages of the neutral atom flux. The temperature maps are centered at 12:00, 12:30, and 13:00 (UT).

*Scime et al.*, GRL 2002
Dawn-dusk asymmetry in ion temperatures observed in MENA measurements

Scime et al., GRL 2002
Ion temperature maps show that injection is cool plasma and ion heating is happening on dayside.

Averaged over 39 storms, lots of viewing directions.

Zaniewski et al., JGR 2006
Ion temperatures in the tail demonstrate various processes during a geomagnetic storm

- October 4-5, 2000 (DOY 278-279)
- 40 minute averages of MENA data
- 3 R_E bins along GSM x-axis

Keesee et al., JGR 2008
Ion temperatures agree with LANL MPA in situ measurements

MPA measurements within ±2 $R_E$ of $x$-axis

*Keesee et al.*, JGR 2008
Comparison to solar wind velocity correlation calculation demonstrates internal heating


\[ kT(t)[keV] = -3.65 + 0.019V_{sw}(t-3hr) \]

*Keesee et al., JGR 2008*
Dawn-dusk asymmetry observed for quiet magnetosphere

- January and February 2009
- Quiet magnetosphere: Dst > -30 nT
- Solar wind velocity: 400 < v_{sw} < 600 km/s
- 138.7 hours of data
- LAE and Sun contamination removed; disc of r = 3 R_E covers Earth

Keesee et al., GRL 2011
Asymmetry agrees with model prediction

• Spence and Kivelson, *J. Geophys. Res.* 1993 finite width model

• ExB drift earthward, gradient and curvature drift duskward

*Keesee et al.*, GRL 2011
Shielding at dawn controls convection of ions during a HSS-driven storm

• Ions arriving in the dusk-noon sector convect dawnward due to shielding

• Ions injected near midnight during substorm undergo adiabatic heating

*Keesee et al., JGR 2012*
Superposed epoch analysis demonstrates differences in ion heating depending on storm driver

- For intense CME storms, intense heating at SSC followed by decrease in temperature
- For HSS storms, heating occurs during recovery phase

Keesee et al., JASTP 2013
Regions of ion energization observed during extreme substorm, deflected dawnward

Keesee et al., JGR 2014
Ion temperatures used as boundary conditions for inner magnetosphere modeling

Elfritz et al., JGR 2014

Keesee et al., JGR 2014
Chen et al., JGR 2015
Database of ion temperatures available on CDAWeb

- 76 geomagnetic storms
- July 2008-December 2013

*Keesee and Scime, Earth and Space Science 2015*
Open questions:
An opposite dawn-dusk asymmetry?
Cold temperatures at minimum Dst?
Take Home Messages

• ENA imagers can be used to calculate ion temperatures with temporal and spatial resolution

• Ion temperatures can be used to study dynamics during geomagnetic storms

• Ion temperatures are needed for inner magnetosphere simulation boundary conditions-available on CDAWeb

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