Inner magnetosphere convection and magnetotail structure of hot ions imaged by ENA during a HSS-driven storm

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1. Introduction

[2] Interplanetary Coronal mass ejections (ICMEs) are the dominant storm driver at solar maximum and are the drivers of the largest (as measured by the Kp index) storms throughout the solar cycle. High speed solar wind streams (HSSs) are the dominant driver during the declining solar phase due to the paucity of ICMEs and dominance of coronal holes [Richardson et al., 2001]. Denton et al. [2006] used magnetospheric plasma analyzer (MPA) data from geosynchronous (6.6 RE) spacecraft to perform a superposed epoch analysis of ICME- and HSS-driven storms ordered by the minimum value of the Dst index. They found that while electron and ion temperatures increase during both types of storms, the average temperature increase is much larger during HSS-driven storms. In a follow-up study, Denton and Borovsky [2008] performed another superposed epoch analysis of HSS-driven storms, but instead ordered the storms using convection onset as the zero epoch time. That analysis methodology revealed important characteristics of the HSS-driven storms. For example, they found that on average ion temperatures in the plasma sheet increase sharply at the time of convection onset and remain elevated for the duration of the HSS-driven event. These hot ions are convected from the magnetotail to the inner magnetosphere; first as part of a high-density “plug” then later as part of a continuous convection of plasma.

[3] The convection of ions from the magnetotail to the inner magnetosphere enhances the ring current. Jordanova [2006] simulated CME- and HSS-driven storms using the ring current-atmosphere interaction model (RAM) and found that additional injection of ions into the ring current was required to accurately simulate the Dst index during the HSS-driven storm. Liemohn et al. [2010] performed simulations of a set of CME- and HSS-driven storms using the hot electron and ion drift integrator (HEIDI) model. They found that currents within geosynchronous orbit dominate ring current dynamics for CME-driven storms and hypothesized that ring current dynamics are dominated by currents in the tail (beyond the boundary of the model) for HSS-driven storms. Simulations by Sitnov et al. [2010] using the high-resolution geomagnetic field model TSO7D combined with mapping of field-aligned currents from Iridium satellites demonstrated that tail-type currents do play an important role during a HSS-driven storm. These and other studies have all shown that the ion temperature and rate of ion heating in the plasma sheet and the dynamics of the ring current and inner magnetosphere play an important role in the dynamics of the magnetosphere during HSS-driven geomagnetic storms.

[4] Energetic neutral atoms (ENAs) are produced by charge exchange collisions between geocoronal neutral atoms and energetic ions in the magnetosphere. In contrast to typical satellite-based in situ instruments, ENA imagers provide a global view of the magnetospheric ions because they remotely measure the ion distributions via neutrals that are not tied to the magnetic field. Ions from the plasma sheet have been measured remotely from as far as tens of RE downtail by the Medium Energy Neutral Atom (MENA) imager from the IMAGE mission [McComas et al., 2002].
The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) mission [McComas et al., 2009] has the benefit of flying two ENA imagers on separate satellites that provide near-continuous temporal observations as well as two intervals of simultaneous observations each day.

[5] We established a technique to calculate ion temperatures from ENA measurements, yielding ion temperature “maps” of the magnetosphere, using data from MENA, and found the calculated values to agree well with temperatures measured in situ [Scime et al., 2002]. The ion temperature calculation technique has been applied to ENA flux measurements projected along the instrument line of sight to the equatorial plane, and has been shown to agree with in situ measurements at geosynchronous orbit and further downtail [Keesee et al., 2008]. A superposed epoch analysis of ENA flux data projected to the equatorial plane for 39 storms was performed by Zaniewski et al. [2006], from which they determined that ion density was enhanced across the nightside during storm main phase while the highest ion temperatures, calculated using this technique, occurred on the dayside. Long-time averages of ion temperatures in the magnetotail during quiet time have been analyzed, confirming a dusk-dawn asymmetry predicted by a finite width magnetotail model [Keesee et al., 2011].

[6] On 22 July 2009, a high speed stream yielded a moderate (minimum Dst of −79 nT) storm, one of the largest that occurred during the extended solar minimum between January 2007 and September 2010. The solar wind conditions including magnetic field magnitude, \( B \), magnetic field \( y \)- and \( z \)-components, \( B_y \) and \( B_z \), speed, \( v_{SW} \), and density, \( N \), as well as geomagnetic \( AE \) and \( SymH \) indices for this storm, obtained from OMNIWeb, are presented in Figure 1. Note that the solar wind parameters have been shifted in time to account for the travel time of the solar wind to the bow shock. Valek et al. [2010] presented TWINS ENA measurements from this storm and analyzed the temporal variations in low-altitude ENA emissions and ENA emissions from the ring current. TWINS ENA measurements were also used to validate simulations of this storm using the comprehensive ring current model (CRCM) [Fok et al., 2010], demonstrating that temporal variations in the magnetic field play a significant role in ring current ion dynamics. In this study, we present global ion temperature maps of the main phase of this storm. The images show that hot ions originating in the magnetotail are injected into the inner magnetosphere.

2. TWINS Instrumentation and Observations

[7] TWINS is a NASA Mission of Opportunity that began full science operation in June 2008 [McComas et al., 2009]. The instruments, which include ENA imagers and
Lyman-alpha detectors, are mounted on two spacecraft in ~12 h Molniya orbits at 63.4° inclination, each with apogee of 7.2 $R_E$ and perigee of 1000 km. The approximately nadir-pointingENA imagers consist of two time-of-flight (TOF) resolving sensor heads offset by ±15° for a one-dimensional view spanning ~140°. The instrument is mounted on an actuator that rotates to provide the second spatial dimension, and a complete image is produced over 60s and obtained each 72s. The instrument detects ENAs with energies ~1–100 keV/amu. The combination of detailed calibration results and a model of the instrument response is used to accurately sort the data into actuation angle (4 actuator sweeps) of ENA or $ION$.

where $l$ is along the LOS, $z$ is the location of the charge exchange collision, $a$ is the spacecraft location, $\sigma_{\text{cs}}$ is the energy-dependent charge exchange cross-section [Freeman and Jones, 1974], $n_i$ is the neutral density. The integral over $\alpha(l)$ accounts for the attenuation of ENAs due to additional collisions or ionization along the path from the origination of the ENA to the instrument. These collisions play an essential role in understanding LAE [Bazell et al., 2010], but the integral over $\alpha(l)$ is approximately zero for most of the magnetosphere because the magnetosphere is optically thin. The contribution to the high energy portion of the spectrum (energies much greater than the ion temperature) is dominated by emission from the hottest region along the line of sight (LOS) [Hutchinson, 1987]. Thus, we approximate the integral by the peak value at location $z^*$ of the integrand multiplied by a characteristic width, $\xi$ [Sciame and Hokin, 1992], to obtain

$$j_{\text{ENA}} = \sigma_{\text{cs}}(E) n_i(z^*) j_{\text{ion}}(z^*, E).$$

If we assume the ions are Maxwellian, then

$$\frac{j_{\text{ENA}}}{\sigma_{\text{cs}}(E) E} \simeq \frac{\xi n_i(z^*) n_i(z^*)}{\sqrt{2 m_i (\pi T_i(z^*))^{3/2}}} \exp \left( -\frac{E}{T_i(z^*)} \right).$$

and an exponential fit to the scaled flux versus energy measurements yields an effective ion temperature for the hottest region along the LOS. For ion distributions that are not Maxwellian, the effective temperature provides a measure of the average kinetic energy of the distribution. Because the values for a single location, $z^*$, are used, the neutral and ion densities, $n_i$ and $n_e$, are constants that scale the fit but do not affect the temperature determination.

Sample fits are shown in Figure 3. The error bars shown in Figures 3a and 3d were calculated based on statistical errors arising from the number of counts placed in a given pixel in instrument coordinates by the spatial smoothing algorithm.

By applying this technique to the ENA fluxes as a function of energy in each pixel in instrument coordinates,
we create fisheye projections of the ion temperatures shown in Figure 4 for each interval from Figure 2. Pixels within 8° of the Earth’s limb have been removed to suppress the LAE that violate our optically thin assumption as well as any signal caused by scattering of the LAE emissions as they pass through the carbon foils in the TWINS instruments. Regions with low ENA flux (values below the color bar minimum in Figure 2) have been removed because their statistical uncertainty produces large errors in the temperature calculation. The pixels selected for spectra plots in Figures 3a–3c are indicated by pluses in Figure 4e. Heated ions, around 11 keV, are observed initially in the dusk-midnight sector and move Earthward throughout the main phase of the storm. As the ions move toward the Earth, most are also convected dawnward on the night side, while a portion of the population ends up on the day side in the noon-dusk sector. A region of cooler ions on the day side, (∼3–4 keV) is centered at noon early in the main phase, but moves downward and heats to ∼5 keV as the storm progresses.

[11] The ENA measurements are also projected to the equatorial plane to aid comparison with in situ measurements and simulations. We assume the hottest point along the LOS occurs near the equatorial plane; this is particularly likely to be true for the night side plasma sheet. Thus, the measured ENA fluxes are mapped along the LOS to the xy-plane (GSM coordinates) that is divided into a grid of 0.5 × 0.5 RE bins. Again, we ignore pixels with 8 keV flux below the color bar minimum in Figure 2. For each pixel in an ENA image, the intersection of the associated field-of-view (FOV) with the GSM xy-plane is calculated. The ENA flux multiplied by the square of the LOS magnitude for that pixel is divided among the xy-plane bins proportionally to the fractional area of the FOV that intersects each bin. This algorithm is used because the fixed angular resolution of the instrument yields a FOV that increases as a function of distance from the Earth. If the intersection location falls outside of a modeled magnetosphere boundary [Shue et al., 1997], the flux is ignored. An average flux for each bin is calculated by dividing the total flux by the number of times

![Figure 3](image-url). Scaled ENA flux (crosses) versus energy and the Maxwellian fit (solid line) used to calculate the ion temperature for the 03:49–04:47 UT interval. (a–c) Plots correspond to pixels in the fisheye plots (Figure 4e) and (d–f) to bins in the projected plots (Figure 5e) and are indicated by pluses in the corresponding figures. Figures 3a and 3d correspond to the midnight-dawn sector, Figures 3b and 3e correspond to the noon-dusk sector, and Figures 3c and 3f correspond to the dusk-midnight sector.

![Figure 4](image-url). Calculated ion temperatures for the six intervals shown in Figure 2 using the same fisheye projection. All images are plotted on the same temperature scale. The pixel locations for the spectra in Figures 3a–3c are indicated by pluses.
an instrument FOV pixel overlapped a particular spatial bin. The effective ion temperature is then calculated for each spatial bin using a fit of equation (3) as described above. The region within $3 R_E$ of the Earth is excluded to avoid mis-interpreting results for LOSs that pass through the optically thick region at low altitudes.

[12] The equatorial maps of ion temperature for each interval of Figure 2 are shown in Figure 5. The Sun is to the right and dusk is upward. Spatial bins with fluxes below the threshold within the modeled magnetosphere boundary are indicated by white. The changing spatial coverage of flux values above the threshold is a combination of the orbital motion of the spacecraft and a change in ENA flux rates, with the smallest coverage in Figure 5a when TWINS 1 is closest to the Earth and the ENA flux is lowest, as seen in Figure 2a. The white disc of radius $3 R_E$ is centered at Earth, indicating the excluded region described previously. The dashed black line indicates geosynchronous orbit ($6.6 R_E$).

The spatial bins selected for spectra plots in Figures 3d–3f are indicated by pluses in Figure 5e. The same general features as in Figure 4 can be seen, but more detail appears in the projected images of the magnetotail and plasma sheet. To quantify the error in the fits used to calculate the ion temperatures, the chi squared values for each bin are plotted in Figure 6 using the same format as Figure 5. We consider a chi squared value $\leq 10$ a good fit. For chi squared values $>10$, the distribution may be tending toward a kappa distribution. However, the kappa and Maxwellian distributions only differ toward higher ($>20–30$ keV) energies. The TWINS measurements do not provide enough measurements at higher energies to constrain an additional free parameter, $\kappa$. Thus we interpret the effective temperature as a measure of average kinetic energy for regions with chi squared $>10$.

4. Discussion

[13] According to the McPherron list of stream interfaces [McPherron and Weygand, 2006; R. L. McPherron, private communication, 2011], onset of the 22 July 2009 storm...
occurred a few hours before arrival of the stream interface in the solar wind; which was observed at 05:19 UT. Denton and Borovsky [2008] showed that the time of convection onset for HSS-driven storms is identifiable from the Air Force Research Laboratory Auroral Boundary Index, also known as the Midnight Boundary Index (MBI) [Gussenhoven et al., 1983]. For the 22 July 2009 storm, the first drop in MBI greater than 0.5° latitude indicates convection onset at 00:49 UT. This occurs early in the storm main phase, defined as the interval of decreasing Dst, as expected based on the superposed epoch analysis of 124 HSS-driven storms by Denton and Borovsky [2008]. In their analysis, these authors found an increase in ion temperatures at geosynchronous orbit occurred at the time of convection onset, except for a cooler region in the dawn-noon sector that is consistent throughout the storm evolution. The hottest region during the first 12 h after onset appeared in the noon-dusk sector. Upon further study of the same set, Denton and Borovsky [2009] noted that the “extra-hot” ion plasma sheet appears first on the night side toward dusk and is associated with the convection onset, then moves toward the day side over a few hours. They found that the ions flow sunward on both the dawn and dusk sides, but that the hot ions reached 1200 MLT via dusk more quickly.

The characteristic features of HSS-driven storms identified by Denton and Borovsky [2009] are evident in the ENA-derived single storm ion temperature maps of Figure 5. Note that in Figure 5, geosynchronous orbit is indicated by the dashed line. In the ENA-derived temperature images, hot ions first appear in the duskward region of the nightside soon after the time of convection onset (Figure 5b). The hot ions then move toward the day side across the midnight meridian (Figures 5d–5f). The local time location of the initial hot ions and their subsequent motion is entirely consistent with the Denton and Borovsky [2009] study.

A region of cooler temperatures on the dayside inside of geosynchronous orbit is evident throughout the main phase. For most of the dayside magnetosphere, the 8 keV ENA flux at geosynchronous orbit is below the threshold set for this study, as seen in Figure 2. The absence of 8 keV ENA fluxes is consistent with dayside ion temperatures below a few keV. In Figures 5e and 5f, the hottest region at geosynchronous orbit is in the noon-dusk sector; again, completely consistent with the Denton and Borovsky [2009] superposed epoch study. The absolute magnitude of the ion temperatures in Figure 5.

Figure 6. Chi squared values from the Maxwellian fits used to calculate the ion temperatures in Figure 5.
temperatures is also in agreement with Denton and Borovsky [2008, 2009] with nightside temperatures at geosynchronous orbit increasing from ~7 keV to ~10 keV and dayside temperatures increasing from ~4 keV to ~7 keV.

[16] While the ion temperature maps calculated from TWINS measurements agree well with the averaged in situ geosynchronous measurements for HSS-driven storms, they also provide a more global picture of the ion temperature evolution. On the night side, ions that arrive in the dusk-midnight sector are convected dawnward as they move toward the Earth. This is consistent with the pre-dawn enhancement of tens of keV ions calculated for this storm using the comprehensive ring current model (CRCM) that demonstrates the effect of the shielding field resulting from the ring current [Fok et al., 2010]. A portion of ions in the dusk region gradient-curvature drift toward the day side, resulting in an increase in ion temperature up to ~12 keV in the post-noon sector in MLT (Figures 5e and 5f).

[17] It is important to note that the expansion phase of a substorm also occurred during the main phase of this storm, from approximately 00:00 to 04:00 UT, as seen in the AE index (Figure 1e), which may have been an important driver of this convection. A study of dispersionless substorm injections found that the enhanced dawn to dusk electric field, $E_z$, associated with substorm dipolarization yields an influx of ions above ~20 keV from the magnetotail to geosynchronous orbit, leading to higher ion temperatures [Birn et al., 1997]. Thus, the substorm activity may play a role in the ion heating observed during this storm.

[18] A completely new result for HSS-driven storms is the evolution of ion temperature in the magnetotail shown in Figures 5d–5f. A region of ~11 keV ions extends tailward from geosynchronous orbit near midnight throughout those intervals. In the final two intervals (Figures 5e and 5f), these >10 keV ions are at the center of the hotter of two distinct regions that are apparent in the magnetotail. The massive region of ≥6 keV ions is primarily on the dawnward side of the magnetotail near geosynchronous orbit and widens toward the duskward flank further downtail; exhibiting a distinct boundary shaped like a gramophone horn. The horn-shaped region and an Earth-concentric ring of ≥6 keV ions that extends just past geosynchronous orbit create a boundary for a second region of cooler <5 keV ions on the duskward half of the magnetotail. Terasawa et al. [1997] and Wing and Newell [2002] demonstrated that the plasma sheet flanks tend to be populated with cold ions crossing the flank magnetopause during northward IMF conditions. During these two intervals, the IMF $B_z$ (Figure 1b) magnitude is decreasing and turns northward just after 05:00 UT (during the final interval).

[19] The shapes of these regions are influenced by the projection of the TWINS ENA instrument pixels to a 2-D plane. Shown in Figure 7 are the number of times each spatial bin is filled with projected ENA flux at 8 keV for the final two intervals. In the magnetotail region, the “contours” of 4-count bins outline the polar angles of the instrument, while the scan in actuation angle can be seen between the outermost “contours” where two pixels overlap to create 2-count bins. Figure 7 demonstrates the decrease in spatial resolution with increasing distance from Earth inherent in the TWINS ENA instrument. In addition, the distinct regions are viewed by different instrument sensor heads. The ion temperatures calculated from the fluxes in each sensor head independently are shown in Figure 8. The top row corresponds to the 03:49–04:47 UT interval and the bottom row corresponds to the 04:46–05:45 UT interval. The magnetotail region of <5 keV ions seen in Figures 5e–5f originates from the edge of the sensor head in the dusk-midnight sector seen in Figures 8a and 8c. There is some overlap in the spatial location viewed by the sensor heads at this edge, but decreased detector sensitivity also occurs at the sensor head edges. In the region of overlap in the dusk-midnight sector, the second head yields ion temperatures as much as 5 keV greater than those from the first head. However, an MLT-dependent increase in temperatures from the dusk-midnight sector toward the noon-dusk sector is consistent for both sensor heads. The distinct regions seen in the ion temperature calculations are each measured by many instrument pixels and over two long-time averaged intervals. Analysis

Figure 7. Count of the number of times a spatial bin in the equatorial plane is filled with projected ENA flux at 8 keV for the final two intervals (a) 03:49–04:47 UT and (b) 04:46–05:45 UT with the same format as Figure 5.

Figure 8. Ion temperatures calculated separately for each instrument sensor head for the (a–b) 03:49–04:47 UT (corresponding to Figure 4e) and (c–d) 04:46–05:45 UT (corresponding to Figure 4f) intervals. The fisheye projections include the Earth’s limb and dipole field lines at L = 4 and 8, with sunward lines in red and duskward lines in purple.
of additional HSS-driven storms is needed to determine whether this structure is a fundamental characteristic of HSS-driven storms. Some of this structure may be more three-dimensional than can be determined from the view of one instrument. Thus, it will also be important to look for a similar event when both TWINS instruments are viewing the magnetosphere.

[20] Bursty bulk flows (BBFs) have been associated with substorms and tend to occur near midnight in the magnetotail [Baumjohann et al., 1990]. Ion temperatures have been observed to increase with the occurrence of a BBF. While the BBFs tend to occur on short time scales, the ion temperatures remain elevated over a longer time interval [Angelopoulos et al., 1994]. Thus, the hot ions observed near midnight in the magnetotail in Figures 5d–5f may be due to BBFs associated with the substorm. Elkington et al. [2005] performed MHD/particle simulations that agreed well with ENA measurements from IMAGE and found that particles from a region of minimum magnetic field in the magnetotail achieved the highest energies through adiabatic heating when injected into the near-midnight region during a storm-time substorm. Their calculated magnetic moments indicated nightside to dayside drift paths across dusk for high energy ions. Thus, the hot ions observed in the inner magnetosphere in Figure 5 may have originated in the magnetotail and undergone adiabatic heating as they were transported sunward.

5. Conclusion

[21] Ion temperatures have been calculated from ENA measurements for six intervals during the main phase of the HSS-driven storm that occurred on 22 July 2009. An injection of hot ions in the inner magnetosphere is observed near midnight in MLT. These hot ions convect toward the dayside in a manner consistent with the CRCM simulation results for this storm [Fok et al., 2010] and with a superposed epoch study of HSS-driven storms [Denton and Borovsky, 2008, 2009]. Two distinct regions of ion temperatures were observed in the magnetotail, the hotter of which may be associated with substorm-related bursty bulk flows.

[22] It is difficult to compare these results with those from ICME-driven storms anywhere but at geosynchronous orbit because the lack of continuous spatial coverage of in situ measurements does not allow for the study of the temporal evolution of ion temperatures during storms. Many studies [e.g., Wing and Newell, 2002; Tygansen and Mukai, 2003; Wang et al., 2006; Guild et al., 2008] involve long-time averages of ion temperatures sorted by solar wind condition, but not by storm phase or shorter time scales. Our technique of ion temperature calculation from ENA measurements provides a unique method for such studies. Of the events included in the Zaniewski et al. [2006] superposed epoch analysis of the ion temperatures in the magnetosphere, over 70% can be identified as driven by ICMEs using the list in Cane and Richardson [2003]. In that study, the most significant ion heating was observed on the dayside during the main phase of the storm in contrast to this study which found the most ion heating on the nightside. We studied the temporal evolution of ion temperatures in the magnetotail during an ICME-driven storm in Keesee et al. [2008], but limited our calculations to one spatial dimension to improve statistics. Ion heating was observed on the dayside and nightside at the beginning of the main phase, and ion temperatures decreased on the nightside during the second half of the main phase. Significant ion heating on the nightside near the Earth was seen at the time of a substorm. The substorm may have been the primary driver for the injection of hot ions into the nightside observed in both the ICME-driven storm of the Keesee et al. [2008] study and the HSS-driven storm in this study. Analysis of additional ICME- and HSS-driven storms with this technique is needed to understand this and other ion heating phenomena observed in this study.

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References


