Regions of ion energization observed during the Galaxy-15 substorm with TWINS

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Abstract Ions in the plasma sheet are measured by the energetic neutral atom imagers on the Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) spacecraft. A line of sight (LOS) projection is used to determine the location of the ions that dominate the measured spectrum, assuming that the equatorial plane is the hottest region along the LOS. We verify reasonable agreement between ion spectral shapes measured using this remote measurement technique and in situ measurements from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft during two moderate geomagnetic storms. Conditions for reliable use of this technique to determine ion spectra and effective ion temperatures are identified. The technique is applied to the substorm interval associated with the loss of communication with the Galaxy-15 satellite. During this interval, localized and broad regions of ion energization are observed, demonstrating that magnetic reconnection and current disruption may have played a role during this very extreme event. These observations demonstrate the ability of this technique to cast local ion spectra measurements in a global context.

1. Introduction

Many important physical processes occur in the plasma sheet during quiet geomagnetic intervals, e.g., drifts leading to dusk-dawn asymmetries [Wing and Newell, 1998]; during geomagnetic storms, e.g., injection of plasma sheet plasma into the ring current [Wang et al., 2008]; and during substorms, e.g., transient strong plasma flows in the plasma sheet now known as bursty bulk flows [Baumjohann et al., 1990; Angelopoulos et al., 1992]. While low-altitude emissions and emissions from the ring current tend to dominate energetic neutral atom (ENA) images, emissions from the plasma sheet have been detected using the Medium Energy Neutral Atom (MENA) imager from the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission [McComas et al., 2002], the Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) ENA imagers [Keesee et al., 2011a], and the Interstellar Boundary Explorer (IBEX) [McComas et al., 2011]. ENA imaging can provide global characterization of the plasma sheet to study such phenomena.

Energetic neutral atoms (ENAs) are created through charge-exchange collisions of magnetospheric ions with geocoronal neutral atoms. ENAs are not tied to the magnetic field and can thus be observed by a detector located remotely from the parent ion population, unlike in situ particle detectors. The shape of the energy spectrum of the plasma sheet ions is obtained from analysis of the ENA energy spectrum. In contrast to the low-altitude emissions that require a “thick-target approximation” that accounts for multiple atomic collisions to extract the ion spectra [Bazell et al., 2010], the ring current and plasma sheet are “optically” thin to neutral fluxes. Thus, the ion spectra for these regions can be calculated directly from the ENA emissions. However, the ENA measurements are integrated along the line of sight (LOS) such that the location of the measured ions is not well determined. We have developed and validated with in situ instruments a mapping methodology based on the assumption that the ENA flux is dominated by the hottest region along the LOS [Scime et al., 2002] that assigns the ENA flux to the geocentric solar magnetospheric (GSM) equatorial plane (in the plasma sheet) using LOS projections [Keesee et al., 2011a]. The nature of the ENA energy distribution to decrease rapidly as a function of energy is the reason the hottest populations along the LOS dominate the high-energy (E > 7) portion of the measured ENA energy spectrum. Ion energy spectra have also been calculated from ENA data using more complex deconvolution [Perez et al., 2012] and forward modeling techniques [Brandt et al., 2001]. Those methods require accurate global models of the magnetic field and geocorona but provide more accurate determination of the trapped ion populations of the inner
magnetosphere. The deconvolution technique has recently been used to validate the ion energy spectral shape and pitch angle distribution calculated from TWINS data with those measured by Time History of Events and Macroscale Interactions during Substorms (THEMIS) [Grimes et al., 2013]. The Time History of Events and Macroscale Interactions during Substorms (THEMIS) [Angelopoulos, 2008] mission has provided a wealth of information about the plasma sheet. However, obtaining a global picture of the plasma sheet requires accumulation of data over many orbits of these spacecraft, reducing the ability to distinguish between spatial and temporal dependencies. To obtain a more complete picture of the spatial and temporal variation of the plasma sheet ions, THEMIS measurements can be placed in the context of global ENA images obtained remotely by the TWINS spacecraft.

In March 2011, a joint TWINS-THEMIS meeting was held, encouraging collaboration, comparison of data from the two missions, and, specifically, analysis of the substorm associated with the loss of communication of the Galaxy-15 communications satellite [Allen, 2010]. This paper is a report of a resulting collaboration in which we compare ion energy spectra calculated from TWINS ENA flux mapped to the GSM equatorial plane with ion energy spectra measured in situ by the THEMIS electrostatic analyzer (ESA) instrument [McFadden et al., 2008]. Preliminary results demonstrated good agreement during select intervals of the storm that included the Galaxy-15 event [Keesee et al., 2011b]. Using updated background-subtracted ESA data, we have performed a comparison of the ion energy spectra during two additional moderate geomagnetic storms. The first storm occurred 2 May 2010 with a minimum $Dst$ of $-67$ nT, driven by a high speed stream. The second storm occurred 29 May 2010 with a minimum $Dst$ of $-85$ nT, driven by a coronal mass ejection (CME). This comparison enables us to quantify the agreement between ion spectra obtained in situ and remotely. Finally, we present measurements during the geomagnetic storm that occurred on 5–6 April 2010, specifically during the substorm that disrupted the Galaxy-15 satellite. We compare ion spectra measured by TWINS and THEMIS as well as effective ion temperatures measured by TWINS and discuss the ion properties during the substorm. We demonstrate that the TWINS ENA measurements can be used to place studies using in situ instruments, such as those on THEMIS, in a global context, while also providing a wealth of measurements in regions where no in situ measurements are available.

2. TWINS Measurements

TWINS is a NASA Mission of Opportunity with two high-inclination, high-altitude, Earth-orbiting spacecraft [McComas et al., 2009]. The orbital paths of the spacecraft for 2–3 May 2010 are shown in Figure 1. Each spacecraft has a Lyman-$\alpha$ detector, an in situ particle detector, and an ENA imager that consists of two time-of-flight (TOF) resolving sensor heads offset by $\pm 15^\circ$ for a one-dimensional view of $\pm 140^\circ$. The imager is mounted on an actuator that rotates to provide the second spatial dimension for a full image obtained in 60 s. A detailed model of the instrument response is used to accurately sort the data into actuation angle, polar angle, and TOF bins. TOF bins are converted to energy bins with $\Delta E/E = 1$ (e.g., a bin with central energy of 12 keV includes energies from 6 keV to 18 keV) by assuming that all ENAs are hydrogen. For this work, we use $4^\circ \times 4^\circ$ imaging pixels, 11 bins with central energies ranging from 2 to 24 keV, and a statistics-based spatial smoothing algorithm [see McComas et al., 2011, Appendix]. ENAs are created by charge-exchange collision between an energetic ion and a cold neutral atom. The energy loss and path deflection in such a collision is minimal. The ENA flux measured is a convolution of the ion

![Figure 1. Orbital path of THEMIS-A (pink), THEMIS-D (light blue), THEMIS-E (dark blue), TWINS 1 (yellow), and TWINS 2 (red) for 2–3 May 2010 in GSM coordinates. Tick marks are at 2 $R_E$ intervals. Generated by SSC 4-D Orbit Viewer.](image)
distribution function and the energy-dependent charge-exchange cross section, yielding a flux rate that falls off rapidly with increasing energy. The measured ENA intensity, $j_{\text{ENA}}$ (with units of $(\text{cm}^2 \text{ sr} \times \text{s} \times \text{eV})^{-1}$), is related to the ion intensity, $j_{\text{ion}}$, by

$$j_{\text{ENA}}(E, \mathbf{u}) = \sigma(E) \int_0^\infty n_\text{i}(\mathbf{r}(s)) j_{\text{ion}}(\mathbf{r}(s), E, \mathbf{u}) \exp\left(-\int_0^s a(s') ds'\right) ds,$$  \hspace{1cm} (1)

where the integral is performed along the LOS from the location of ENA emission, $\mathbf{u}$, to the location of the satellite, $\mathbf{R}$, with $\mathbf{r}(s) = \mathbf{R} + \mathbf{u} s$ and $\mathbf{u}$ is a unit vector along the LOS, $\sigma(E)$ is the energy-dependent charge-exchange cross section [Freeman and Jones, 1974], and $n_\text{i}$ is the neutral density. The integral over $a(s')$ accounts for the attenuation of ENAs due to additional collisions or ionization along the path from the origin of the ENA to the instrument. This integral is approximately zero for optically thin regions, i.e., regions without recombination and significant scattering. Measurements from the optically thick region near the Earth (within $5^\circ$ of the limb) are removed from the images to ensure that this approximation is valid.

For a Maxwellian parent ion distribution, the contribution to the high-energy portion of the spectrum (energies greater than the ion temperature) is dominated by emission from the hottest region along the LOS [Hutchinson, 1987]. Thus, we approximate the integral by the peak value at location $z^*$ of the integrand multiplied by a characteristic length along $s$, $\zeta$ [Scime and Hokin, 1992], to obtain

$$j_{\text{ENA}} \approx \sigma(E) \zeta n_\text{i}(z^*) j_{\text{ion}}(z^*, E).$$  \hspace{1cm} (2)

Ion temperature calculation from ENA data using these assumptions was verified with comparison to in situ measurements [Scime et al., 2002]. We assume the hottest point along the LOS occurs in the central plasma sheet and, thus, near the equatorial plane for the plasma sheet in the magnetotail [Hughes, 1995]. An alternative LOS mapping technique that focuses on inner magnetosphere populations involves taking the position of closest approach of the LOS to the Earth and mapping it to the equator using a magnetic field model under the assumption that the position of closest approach will have the highest geocoronal density and, thus, dominate the measured ENA flux [Roelof, 1997]. However, for satellite locations on the dayside and LOSs that intersect the equatorial plane in the plasma sheet, this technique would map much farther downtail, where ion density is much lower [Tsyganenko and Mukai, 2003] and therefore would not yield significant ENA flux. Additionally, if the point of intersection of the LOS with the equatorial plane is mapped back to the Earth with a magnetic field model, that magnetic field line would intersect the LOS at a location close to the position of closest approach where the geocoronal density is only slightly smaller and therefore yields nearly the same ENA emission. Thus, our technique which focuses on plasma sheet populations gives a good approximation of the ion flux with the added advantage of being independent of a magnetic field model. The measured ENA fluxes are mapped along the LOS to the $xy$ plane (GSM coordinates) that is divided into a grid of $0.5 \times 0.5 R_E$ bins. 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 squared magnitude of the distance between the spacecraft and the intersection of the LOS with the $xy$ plane, is divided among the $xy$ plane bins in amounts proportional 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 an instrument FOV pixel overlapped a particular spatial bin. Projected ion temperatures from this method have been shown to be in good agreement with in situ measurements [Keesee et al., 2008]. For this study, TWINS ENA data were averaged over intervals of 25–30 sweeps (~34–41 min) for the two moderate storms and over intervals of five sweeps (~6 min) for the 5 April 2010 substorm interval.

3. THEMIS Measurements

The THEMIS mission is composed of five identical spacecraft placed in highly elliptical orbits [Angelopoulos, 2008]. All three storms analyzed occurred during a THEMIS tail science phase, when the THEMIS probes A, D, and E (THA, THD, and THE, respectively) spent most of their time in the nightside plasma sheet. At any given UT, the three spacecraft were close in magnetic local time. The top hat electrostatic analyzers (ESAs) measure energy per charge $(E/q)$ during 32 sweeps per spacecraft spin [McFadden et al., 2008]. The sensor
has a $180^\circ \times 6^\circ$ FOV, with the $6^\circ$ direction rotating with spacecraft spin for $4\pi$ steradian coverage. Measured energies range from $\sim 5$ eV to $\sim 25$ keV. The in situ ESA instrument directly measures the ion energy flux in units of $\text{eV/(cm}^2 \text{sr s eV)}$, related to ion intensity by $E \times j_{\text{ion}}$. The ESA background subtraction algorithm has been implemented for the data used in this study based on the THEMIS software TDAS provided by the mission data center. Data from the THEMIS Solid State Telescope (SST) [Angelopoulos, 2008] for $\sim 34$ to $66$ keV ions are also used to provide a more complete picture of the ion energy flux spectrum.

The $x$, $y$ position in GSM coordinates of each of the THEMIS probes is used to determine the time interval that it spends in a given spatial bin of the $0.5 \times 0.5$ RE grid. The average ion energy flux at each energy is calculated over the intersection of the time interval in a given spatial bin with the TWINS data time interval. During all intervals considered, the three THEMIS probes were in the $1.07 < z < 3.67$ RE range (see Figure 1).

### 4. Comparison of Spectra

The ion energy flux calculated from TWINS ENA measurements is given by

$$E \times j_{\text{ion}}(E) = E \times \frac{j_{\text{ENA}}(E)}{\sigma_{\text{ex}}(E) \xi n_n}.$$  \hspace{1cm} (3)

To obtain $j_{\text{ion}}$, the average ENA flux is divided by the product of the energy-dependent charge-exchange cross section, $\sigma_{\text{ex}}$, a neutral density, $n_n$, of $100$ cm$^{-3}$, and a characteristic width, $\xi$, approximated by the distance between the spacecraft and the intersection of the LOS with the GSM $xy$ plane (to address the increasing region of plasma sheet sampled by increasing LOS). The fixed neutral density value chosen is the average given by a model based on TWINS Lyman-$\alpha$ measurements for $3–10$ RE on the nightside [Zoennchen et al., 2011]. These simplified values for $n_n$ and $\xi$ have been selected because they are energy independent and, thus, do not affect the spectral shape and because our objective is only to obtain an order-of-magnitude calculation that will then be normalized to the THEMIS spectra for comparison.

The location of the THEMIS probe during the TWINS data time interval is used to select the spatial bin(s) of the TWINS data with which to compare. The THEMIS data are averaged over the time interval that it is located in a given spatial bin. For many of the TWINS data intervals, the THEMIS probe traverses multiple spatial bins; thus, the THEMIS data are averaged over a smaller time interval than that of the TWINS data. The time interval over which the THEMIS data are averaged thus varies for each measurement, ranging from 1 to 24 min. The longest of these intervals occur when the THEMIS probes are near apoapce and moving at...
the slowest orbital rate. By limiting the THEMIS intervals to single spatial bins, these averages are less likely to incorporate fluxes from different regions in the magnetotail.

The TWINS ion energy flux in the selected spatial bin is normalized to the THEMIS ion energy flux at 12 keV to aid comparison of the spectral shapes. The normalization factor, \( N \), is given by the THEMIS ion energy flux divided by the TWINS ion energy flux at 12 keV such that \( E_{\text{flux(THEMIS)}} = N \times E_{\text{flux(TWINS)}} \). Two examples are shown in Figure 2 in which the diamonds correspond to the normalized TWINS ion energy flux. The TWINS error bars are based on the number of counts in each energy bin for a given pixel. The solid curve in Figure 2 is the average ion energy flux measured by THEMIS, with error bars based on the standard deviation of the data.

In Figure 2, the spectral shapes of the TWINS and ESA measurements are in excellent agreement. A Maxwellian distribution for a \( T = 10 \text{ keV} \) temperature, normalized to the THEMIS measurements at 12 keV, is also shown as a dashed curve in Figure 2 for comparison. In both intervals, the spectra deviate from the Maxwellian distribution shown at lower energies (<4 keV) and at energies greater than ~12 keV.

The TWINS measurements have greater uncertainty above 25 keV because the rapid decrease in the charge-exchange cross section reduces the conversion of ions to energetic neutrals at higher energies. Thus, we limit our comparison in this study to the ESA measurement range and do not compare to measurements from
Figure 4. TWINS 2 data for 3 May 2010 at 11:58–12:22 UT are compared to (a) THA data for 11:58–12:18 UT in the \((x, y) = (-9.0, -1.0)\) spatial bin, (b) THA data for 12:19–12:21 UT in the \((x, y) = (-8.5, -1.0)\) spatial bin, (c) THD data for 11:59–12:02 UT in the \((x, y) = (-9.5, -1.0)\) spatial bin, (d) THD data for 12:04–12:21 UT in the \((x, y) = (-9.0, -1.0)\) spatial bin, and (e) THE data for 12:00–12:21 UT in the \((x, y) = (-9.5, -1.0)\) spatial bin. Same format as Figure 2.
the THEMIS Solid State Telescope (SST). SST measurements are included in Figure 2 for a complete description of the ion spectra.

Because the TWINS measurements are dominated by populations near the neutral sheet/equatorial plane, we limit our comparison to intervals when THEMIS is near the neutral sheet, determined by times when $B_y < B_z$. Such intervals are considered from 12 h before minimum $Dst$ to 24 h after minimum $Dst$ for the two May storms. This yields 132 TWINS-THEMIS interval comparisons composed of 27 different TWINS time intervals. Three of the 132 comparison intervals (all during one TWINS time interval) have been discarded due to very large uncertainties (low counts) in the TWINS data. 32 of the remaining comparison intervals have TWINS 1 data and 47 have TWINS 2 data during the 2 May 2010 event, while 17 of the intervals have TWINS 1 data and 33 have TWINS 2 data during the 29 May 2010 event. Twenty-seven of the intervals have THA data, 26 have THD data, and 26 have THE data for the 2 May 2010 event; while 17 intervals have THA data, 15 have THD data, and 18 have THE data for the 29 May 2010 event.

To make a quantitative comparison between the spectra, the Pearson correlation coefficient between each interval of THEMIS and TWINS spectra is calculated, defined as

$$
\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})
\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}.
$$

where $X$ and $Y$ represent the TWINS and THEMIS spectra, respectively, and $\bar{X}$ is the mean. More specifically, the THEMIS ion energy flux values measured at $E = 1.79, 2.36, 3.11, 4.09, 5.39, 7.09, 9.34, 12.29, 16.18$, and $21.30$ keV are linearly interpolated to obtain approximate ion energy flux values at $E = 2, 4, 6, 8, 10, 12, 14, 16, 18, 20$, and $24$ keV to match the energy spacing used for the TWINS data. The correlation coefficient between the linearly interpolated THEMIS ion energy flux and the TWINS ion energy flux is then calculated. The lowest correlation coefficient of all the compared intervals is 0.804, the highest is 0.999, the mean is 0.967, the standard deviation is 0.041, and the median is 0.983.

The two intervals shown in Figure 2 are those with the highest correlation coefficient, $c = 0.999$. Figure 2a compares TWINS 1 data for 2 May 2010 at 21:39–22:03 UT to THE data for 21:42–21:49 UT in the $(x, y) = (-4.5 R_E, 5.0 R_E)$ spatial bin. Figure 2b compares TWINS 2 data for 2 May 2010 at 11:14–11:38 UT to THA data for 11:15–11:34 UT in the $(x, y) = (-9.5 R_E, 0.5 R_E)$ spatial bin.

The interval with the lowest correlation coefficient, $c = 0.804$, is for a comparison between TWINS 1 data for 30 May 2010 at 02:24–02:48 UT and THA data for 02:25–02:47 UT in the $(x, y) = (-8.0 R_E, 7.5 R_E)$ spatial bin. To determine why there is poor agreement between the spectra, all four comparisons for that same TWINS interval are shown in Figure 3. Figures 3a, 3b, and 3d involve the same spatial bin (same TWINS data), each a comparison to a different THEMIS probe, and demonstrate significant error (low counts) in the TWINS data. The large normalization factors ($N > 3$) are indicative of the low count rate in the TWINS data. The low counts are due to only one instrument pixel contributing to this spatial bin and low flux measured by that pixel. For Figure 3c, the adjacent $(x, y) = (-7.5 R_E, 7.5 R_E)$ spatial bin is compared to THE data toward the beginning of the interval. The TWINS data for this spatial bin have smaller error, due to contributions from more than one instrument pixel, but still has low counts as seen by the high normalization factor, $N = 2.56$. In this case the agreement is slightly better, though still low, with a correlation coefficient of $c = 0.920$. An energization event was observed by the THEMIS probes between 02:05 and 02:10 UT, with elevated fluxes at energies of 1–25 keV persisting through the interval measured in Figure 3. The fields of view of the TWINS pixels contributing to this spatial bin have an area of $0.9 R_E^2$, so they are averaged over a larger area than the $0.25 R_E^2$ spatial bins. It is possible that the energization event is spatially localized such that the low spatial resolution limits the ability for this event to be observed in the TWINS data. Additionally, the low counts limit our confidence with the TWINS measurements for this interval. Thus, our LOS projection technique should not generally be used for TWINS intervals with low counts.

An interval with correlation coefficient of $c = 0.966$, which is close to the mean value, along with all THEMIS comparisons for that same TWINS time interval, with correlation coefficients ranging from 0.958 to 0.980, are shown in Figure 4. Figures 4a and 4d show the TWINS data in the $(x, y) = (-9.0 R_E, -1.0 R_E)$ spatial bin compared to THA and THD, respectively. The normalization factors are very similar, $N = 0.39$ and 0.37, respectively, indicating that the THA and THD measurements are similar in magnitude. In contrast,
Figures 4c and 4e show the TWINS data in the \((x, y) = (−9.5 \text{ RE}, −1.0 \text{ RE})\) compared to THD and THE, respectively, but have somewhat less agreement between the data from the THEMIS probes, with normalization factors of \(N = 0.75\) and 0.91, respectively. This is likely due to temporal variations because the THEMIS data in Figures 4a and 4d overlap with the TWINS interval by 15 min, while in Figures 4c and 4e there are only 3 min of overlap. The THD data in Figure 4c are also averaged over only 4 min, compared to 22 min of THE data in Figure 4e. Thus, Figure 4e has a higher correlation coefficient between the THE and TWINS data which is also averaged over a longer time interval.

Grimes et al. [2013] used a deconvolution method to also compare ion spectra calculated from TWINS to those measured by ESA for two intervals during the 2 May 2010 event. In Figure 5 we show the ion differential flux spectra using our LOS projection method with their comparison of the flux spectra calculated using the deconvolution method for TWINS ENA data and from THEMIS ESA and SST instruments. (Note that the differential flux, \(j_{\text{ion}}\), is the ion energy flux divided by energy. See equation (3).) The spectra obtained from TWINS using both the deconvolution method and our technique are normalized to the ESA data. The spectra using our technique have peaks at slightly lower energies than those obtained using the deconvolution method but agree with the peak location of the ESA measurements.

We would like to emphasize the importance of these results. The TWINS instruments are, on average, \(\sim 12−15 \text{ RE}\) from the THEMIS probes but measure spectral shapes nearly identical to the THEMIS measurements. In addition, the technique used in this study to obtain plasma sheet spectra does not require accurate models of the neutral geocorona and magnetic field or a complex deconvolution algorithm. The count rates of the TWINS data provide an objective measure of the confidence level of the TWINS derived spectral shapes using this technique. Thus, TWINS is a powerful tool for remotely measuring high-time resolution (on a global scale) ion energy spectra throughout the entire magnetosphere.

5. Limitations of the TWINS Projection Method

The accurate measurement of ion spectra using projected TWINS data is limited by averaging along the LOS, the fact that the spatial resolution of each imaging pixel decreases as distance from Earth increases, and the fact that a temporal resolution based on accumulation of counts improves with geomagnetic activity. The remote nature of the ENA measurement is a benefit in that it enables global imaging from a remote location but yields limited accuracy in determining the source location. Each instrument pixel measures ENAs produced anywhere along that pixel’s LOS. We have assumed that the spectrum is dominated by ENAs from the hottest region along the LOS, and we have to make assumptions about where that hottest region is located. It is possible with the two TWINS spacecraft to improve the accuracy of spatial determination, particularly in the inner magnetosphere [Goldstein et al., 2012]. However, the dual view only occurs twice per day and typically when the spacecraft are low in their orbit, making simultaneous
views of the plasma sheet difficult. There are limited cases for which the satellites are at a reasonably high altitude which could be used to further verify this technique.

The projection of the TWINS imaging pixels to the equatorial plane yields varying spatial resolution as a function of location. While spatial bins near the Earth are filled with ENA flux from multiple imaging pixels, the spatial bins farther from the Earth contain ENA flux from pixels with FOVs that overlap multiple spatial bins. Thus, the spatial resolution decreases with distance from the Earth. The exact resolution of a given spatial bin also changes with time as the spacecraft moves in its orbital path. The spatial resolution for one time interval can be seen in Figure 6 which shows the number of times flux is populated in each spatial bin, i.e., the number of instrument pixels contributing to each spatial bin. Figure 6 demonstrates the high spatial resolution in the inner magnetosphere where each spatial bin includes data from multiple instrument pixels. However, farther from the Earth, spatial bins generally contain contributions from one pixel, except where the corners of the pixels overlap within spatial bins. There those bins contain contributions from four pixels. A group of spatial bins in this region will, thus, contain the same data from one instrument pixel, yielding poorer spatial resolution. In Figure 6, the outline of the projection of one instrument pixel is shown in white, corresponding to the spatial bins used in Figure 4.

As we saw in Figure 4, low counts affect the accuracy of the measured spectra. We must utilize temporal averages that are long enough to obtain count levels that enable reasonable statistics. Increased geomagnetic activity yields increased count rates through enhancement of the geocorona and increased plasma densities [McComas et al., 2002]. Therefore, the time resolution improves during intense geomagnetic storms. The two storms discussed above are of moderate intensity and we find ~40 min averages are required to obtain adequate counts. Such averaging limits the ability for this technique to completely characterize phenomena that occur on short timescales, such as substorms. However, periods of intense activity, such as the one described in the following section, allow averaging over shorter time intervals.

6. Substorm Interval on 5 April 2010

A halo coronal mass ejection (CME) released from the Sun on 3 April 2010 caused a geomagnetic storm that lasted 5–7 April 2010 with a minimum Dst of −73 nT [National Oceanic and Atmospheric Administration, 2010]. Soon after the sudden impulse at 0826 UT on 5 April 2010, a substorm occurred with AE peak of 2291 nT at 0920 UT. This substorm has been associated with the loss of control of the Galaxy-15 communications satellite at 0948 UT [Allen, 2010]. Connors et al. [2011] reported significant earthward flux transfer observed by THEMIS and overdipolarization observed by GOES 11 during this substorm. Clilverd et al. [2012] analyzed electron precipitation characteristics during the substorm, finding primarily dayside precipitation that was not at unprecedented levels. ENA emission measured by TWINS and IBEX during this period have been analyzed, showing that high-energy (>50 keV) ion precipitation from the ring current precedes that of low-energy ions (<10 keV) [McComas et al., 2012]. Our LOS projection method enables us to examine a global view of the ion dynamics during this interval of extreme activity. During such activity levels, the ion density in the plasma sheet is enhanced, which leads to an increase in the ENA
flux [McComas et al., 2002], enabling us to average over shorter time intervals. TWINS 1 data are divided into ~6 min averages over the period from 0807 to 0942 UT.

First, we compare the ion energy spectra measured in situ by THEMIS at ~11 Re downtail with those measured remotely by TWINS 1 at that location using spectrograms shown in Figure 7. Figures 7a–7c are spectrograms of ESA data from THA, THD, and THE probes for which the data are averaged over time intervals selected, as described previously, where the probe orbit overlaps the TWINS spatial bins. The time on the axis is the middle of the interval for each spectrum. Figures 7d–7f are spectrograms of the TWINS 1 data for the corresponding spatial bins to the THEMIS data directly above it. The TWINS spectrograms are created by rebinning the TWINS ion energy spectra (normalized to the THEMIS spectra at 12 keV) into energy bins that most closely correspond with the THEMIS energy values, as shown in Table 1. The “skip” entries indicate energy bins that are calculated for TWINS measurements but are not used in the spectrograms because they do not have a closely matching THEMIS energy bin. The “empty” entries indicate energy bins for which there are not close TWINS energy values. These intervals have normalization factors $N < 2$, and the majority has $N < 1$, indicating significant count rates. These spectrograms show excellent qualitative agreement in spatial and temporal variations.

To get a global view of the ion spectra during these three intervals, Maxwellian fits of the ion spectra measured by TWINS are calculated, yielding an effective ion temperature value for each spatial bin using a technique originally developed using data from the Medium Energy Neutral Atom (MENA) instrument on the IMAGE mission [Scime et al., 2002]. While a kappa distribution might yield a more accurate representation of the spectra, such fits add an additional unknown parameter that adds to the uncertainty of the calculated temperature. We note that the calculated effective ion temperature is expected to be lower than the temperature of the full ion distribution because (a) the measurements are limited to ~1–30 keV and (b) a Maxwellian

![Figure 7. Spectrograms for intervals on 5 April 2010 using ion energy flux calculated from ESA data on the (a) THA probe, (b) THD probe, (c) THE probe, and (d–f) TWINS 1 data. The times shown indicate the center time of the interval over which the ESA data are averaged. The TWINS data are normalized to the ESA data at 12 keV for each time interval.](image)
distribution is assumed. However, an increase in the effective ion temperature indicates an energization of the bulk population. Assuming a Maxwellian ion distribution yields

$$\frac{J_{\text{ENA}}}{\sigma_{\text{cx}}(E)E} \approx \frac{\zeta n_i(z^*) n_i(z^*)}{\sqrt{2m_i(\pi T_i(z^*)}^{3/2} \exp \left( \frac{-E}{T_i(z^*)} \right).$$

(5)

Note that a DC offset was included in the fits to subtract off the noise floor. The global ion temperature “maps” obtained from fitting all spatial bins for eight of the time intervals are shown in Figure 8. The locations of the THEMIS probes are indicated by diamonds (THA), triangles (THD), and squares (THE) in Figure 8.

Ion energization is observed in the TWINS data starting at least 10 min following arrival of the CME shock near midnight at radial distances beyond 10 $R_E$ (see Figure 8b). The energized regions reach geosynchronous orbit at the time GOES observed dipolarization (see Figure 8c). The region of energization is approximately 3–4 $R_E$ wide in the azimuthal direction, consistent with the width of fast flow channels observed in situ [e.g., Angelopoulos et al., 1997; Nakamura et al., 2004]. The THEMIS probes appear just outside this region and did not observe dipolarization at this time because they were located in the plasma sheet boundary layer due to plasma sheet thinning. Within 10 $R_E$ the region appears to be deflected dawnward, consistent with previous observations [Nakamura et al., 2002; Runov et al., 2009; Zhang et al., 2011]. While higher energy ions typically are deflected duskward by the gradient-curvature drift, ions that are injected dawnward of the Harang reversal tend to be deflected dawnward (V. Angelopoulos, personal communication, 2014).

Another narrow region of energization is observed in Figures 8e and 8f, again with downward deflection within 10 $R_E$ in the second interval (0900–0906 UT). It is during this second interval that THA observes dipolarization (at 0903 UT) [Connors et al., 2011]. Connors et al. [2011] describe a second dipolarization at 0908 UT observed by THA and an “overdipolarization” at 0913 UT observed by GOES 11. These two events occur during the intervals shown in Figures 8g and 8h, respectively. A large region of energized ions is observed in the TWINS data during the interval including the overdipolarization.

Not all regions of ion energization observed in the TWINS ion temperatures maps appear as narrow channels but are broad regions that spread across ~5 $R_E$ with some “holes” where local sites are not affected by the substorm activity. This behavior is consistent with the current disruption model that predicts localized activity leading to an avalanche of regions of activity [Lui et al., 2008].
7. Conclusions

In conclusion, there is good agreement between the ion spectral shapes calculated using remote data from the TWINS ENA instrument and those measured in situ by THEMIS for many intervals throughout the duration of two storms and during the time of the 5 April 2010 substorm. We have identified conditions for reliable use of our technique to project ENA data to the plasma sheet to calculate parameters measured by in situ instruments. Intervals of data that do not show good agreement tend to have low counts in the TWINS measurements or spatially localized enhancements measured by THEMIS.

The global view of the TWINS instruments enables measurements of the average spectral shape of ion distributions of ~1–30 keV in the plasma sheet with both spatial and temporal resolution, though this can be limited by the storm intensity and at distances farther from the Earth. The spatial resolution of the TWINS measurements in the outer magnetosphere does not provide detailed measurements of the phenomena that are spatially localized or occur on short timescales during active intervals but does provide an overall average of regions of the magnetosphere. Thus, this technique is useful for placing limits on the spatial and temporal extent of characteristics measured by in situ instruments to better understand such phenomena. The observations during the 5 April 2010 substorm interval demonstrate that an ENA imager can cast local measurements in a global context and provide information about the dynamic ion environment associated with storms and substorms. The two TWINS spacecraft also provide almost continuous coverage, enabling detailed study of many dynamic phenomena that occur in the plasma sheet.

An example of such a study is to characterize the time-dependent ion source distributions in the plasma sheet using the LOS technique of TWINS data and in situ THEMIS data for boundary conditions in ring current simulations. In an ongoing study being conducted by the authors, the ion spectra are used to calculate ion temperatures. Ion temperatures are calculated from the THEMIS data by fitting a kappa distribution to the spectrum. For the TWINS data, a Maxwellian distribution is fitted to the spectrum in each spatial bin. (Note that these fits were performed on a preliminary analysis of the TWINS data that did not include statistical smoothing and used six energy bins ranging from 4 to 33 keV.) A comparison of these calculated ion temperatures along with those calculated using the Tsyganenko and Mukai [2003] empirical model, based on statistical averaging of low-energy (≤ 40 keV) ion measurements from Geotail, are shown in Figure 9. The red and green crosses correspond to TWINS 1 and TWINS 2 ion temperatures, respectively, the black squares to THEMIS THA ion temperatures over the energies of 40 eV to 33 keV for geocentric radial distances r greater than 7 $R_E$, and the cyan curve to the ion temperatures for r greater than 10 $R_E$ from the Tsyganenko and Mukai [2003] model. The ion temperatures calculated from TWINS and THA measurements over similar energy ranges show reasonably good agreement. Overall the TWINS temperatures match the THA temperatures better than those from the Tsyganenko and Mukai model. This is not surprising as the Tsyganenko and Mukai model is based on long-term averages of data for different interplanetary magnetic field and solar wind conditions. Although not shown in Figure 9, the ion temperatures from the THEMIS THA over the
energy range of 40 eV to 660 keV are typically larger than the THA temperatures over the energy range of 40 eV to 40 keV by roughly a factor of 2. Despite the fact that the TWINS temperatures are calculated over the lower energy portion of the ion spectrum, the TWINS temperatures provide excellent spatial and temporal information about the variation of the ion temperatures. The TWINS and THEMIS ion temperatures are being used to guide boundary conditions in ring current simulation studies using the Rice Convection Model-Equilibrium [Lemon et al., 2004; Chen et al., 2012] and have been used as boundary conditions in the Comprehensive Ring Current Model [Elfritz et al., 2014]. The continuous, global coverage of the TWINS spacecraft enables more realistic plasma sheet boundary conditions for simulation studies of events even when THEMIS probes are not located in the regions needed for calculating model boundary conditions.

Observations during the 5 April 2010 substorm interval indicate several localized regions of ion energization. These include narrow channels consistent with localized flow channels, and they are diverted in the dawnward direction within 10 R_E of the Earth. Other regions are broader with some areas not affected by substorm activity. It is possible that both magnetic reconnection and current disruption played a role in the substorm activity that occurred during this very extreme event.

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