Evidence for Nonadiabatic Oxygen Energization in the Near-Earth Magnetotail From MMS

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Abstract We present Magnetospheric Multiscale (MMS) mission observations of substorm-related ion injections at magnetotail positions between ~7.5 RE and 8.5 RE. Energization of supra-thermal ions (50 keV–1,000 keV) is strongly species dependent, with oxygen reaching significantly higher peak energies than protons. Using a previously established correlation technique, we confirm that the highest energy (>400 keV) oxygen ions are multiply charged of solar wind origin, enabling them to reach high energies in rough proportion to their charge states. Significantly, we conclude that oxygen ions between 130 keV and 330 keV are singly charged, and that they sometimes achieve higher energizations relative to protons, that is, higher than expected based on their charge states. We conclude that nonadiabatic processes can boost the energies of the oxygen ions. The technique does not depend on “before injection” and “after injection” spectral comparisons, and therefore likely represents the most definitive test yet of nonadiabaticity.

Plain Language Summary Earth’s space environment, its magnetosphere, forms an invisible comet-like shape, with a “magnetotail” extending away from the Sun. Satellite observations there often show “injections”, sudden enhancements of ions from 10 to 100s of kilo-electron volts. The ions of hydrogen (H), helium (He), and oxygen (O) come from both the solar wind and from the Earth’s ionosphere. Oxygen from the solar wind is more strongly ionized (charge state often +6) than that from the ionosphere (charge state +1). In the magnetosphere, ions gyrate around in spirals in Earth’s magnetic field. Because singly charged oxygen (O+) gyrate more slowly and with larger gyrating orbits than other ions, we expect that such ions can be more strongly accelerated compared to lighter ions during injections. But, that expectation is difficult to prove from a single spacecraft. Here, we present a method that more definitively demonstrates that O+ is sometimes preferentially energized compared to H+ during injections.

1. Introduction

The primary ion species in the magnetosphere are protons, oxygen, and helium (e.g., Welling et al., 2015). Protons originate from both the ionosphere and the solar wind. Singly charged O+ originates from the ionosphere; however, multiply charged oxygen O>3+ originates from the solar wind and is also found throughout the magnetosphere (e.g., Kremser et al., 1987). Magnetospheric He++ originates from the solar wind, while He+ comes from both the charge exchange of He++ with neutrals or directly from the ionosphere (e.g., Gloeckler & Hamilton, 1987). During geomagnetic storms, the pressure enhancement of 10s to 100s of keV ions from the plasma sheet form the ring current, driving a depression of the global magnetic field (e.g., Cahill, 1966). Typically, during quiet times the pressure of the plasma sheet is dominated by protons. However, ionospheric O+ can have a significant, and sometimes dominant, pressure contribution during geomagnetically active times (e.g., Hamilton et al., 1988; Kistler et al., 1989).

Determining the nature and prevalence of the enhanced contribution of O+ has been a longstanding challenge in understanding the energy density of the magnetosphere during geomagnetically active periods (e.g., Keika et al., 2013). Sudden enhancements of ion flux, called ion injections, have been shown to substantially contribute to the energy density of the inner magnetosphere (Gkioulidou et al., 2014). These injections are associated with local- or large-scale dipolarizations of the magnetic field and enhanced transient electric fields, and can be associated with bursty bulk flows (e.g., Angelopoulos et al., 1992; Gabrielse et al., 2014; Liu et al., 2013, 2016).
During dynamical events, O\(^+\) is often expected to behave nonadiabatically compared to H\(^+\) because of its larger gyroradius and lower gyrofrequency. This behavior could lead to greater energization, associated with impulsive electric fields during dipolarizations (e.g., Delcourt et al., 1990; Delcourt & Sauvaud, 1994; Sánchez et al., 1993), with magnetic fluctuations during dipolarizations (e.g., Ono et al., 2009), or with other local processes (e.g., Ukhorskiy et al., 2018; Keika et al., 2013). Often, to determine cases of preferential oxygen energization, the spectral characteristics are compared before and after dynamical events (e.g., Keika et al., 2018; Mobius et al., 1987; Nosé et al., 2000). When using single satellite measurements for such an approach, there is intrinsic uncertainty arising from the fact that the observed “before” and “after” particles are not the same population; the “after” particles were at a position inaccessible to the spacecraft prior to the occurrence of the dynamical event.

Another ongoing challenge in evaluating the adiabatic/nonadiabatic nature of oxygen energization is incompleteness of most measurements. Many supra-thermal ion instruments either do not resolve mass composition (e.g., missions like THEMIS, GOES, LANL) and/or cannot resolve charge state (e.g., missions like Magnetospheric Multiscale [MMS], Van Allen Probes, Cluster, Geotail). Heavy ions are often assumed to be singly charged. Recent observations at highly supra-thermal energies (>200 keV–300 keV) have shown that flux intensities are often dominated by heavy ions of likely solar wind origin (He\(^{++}\) and O\(^{6+}\)) over intensities of singly charged ions (Allen et al., 2017; Bingham et al., 2020; Cohen et al., 2017; Mitchell et al., 2018). Incorrect assumptions about ion charge states can lead to the misinterpretation of charge-state-dependent energization as mass-dependent energization.

Given these complexities, addressing the issue of adiabatic versus nonadiabatic energization is challenging. One must discriminate supra-thermal solar wind heavy ions from ionospheric heavy ions during energetic ion enhancements. Mitchell et al. (2018) developed a technique that goes a long way toward meeting these challenges. Using supra-thermal ion observations from the Van Allen Probes during injection events, they deduced the charge states of helium and oxygen ions using a correlation analysis of their time-varying intensities as a function of energy. Bingham et al. (2020) applied this technique to MMS mission observations in more distant regions downtail. This technique worked well for the events considered because the flux responses were generally well ordered by energy per charge (E/q). We anticipate E/q ordering with adiabatic behavior.

The present work presents a case study of supra-thermal energetic ion enhancements observed by the MMS mission during a substorm on August 9, 2016. We demonstrate the utility of the correlation analysis introduced by Mitchell et al. (2018) to distinguish O\(^+\) and to analyze a nonadiabatic boost in energy to O\(^+\) relative to H\(^+\). Section 2 introduces the instrumentation and measurements used. Section 3 describes the observations of the event studied. Sections 4 and 5 discuss and summarize the findings.

### 2. Instrumentation

The MMS mission comprises four identically instrumented spacecraft maintained in a tight tetrahedral spacing (~10 km–100 km) over elliptical, low-inclination orbits (Burch et al., 2016), with a geocentric apogee that has ranged from ~12 R\(_E\) to 29 R\(_E\).

The energetic ion spectrometer (EIS) is part of the Energetic Particle Detector (EPD) investigation (Mauk et al., 2016). EIS measures energetic ion distributions in energy, angle, and mass composition for protons (~20 keV–1 MeV), helium (~60 keV–1 MeV), and oxygen (~130 keV–1 MeV). EIS can discriminate ion-mass composition and energy but not charge state. Lower energy ion measurements come from the Hot Plasma Composition Analyzer (HPCA; Young et al., 2016). HPCA measures ion distributions in energy, angle, and composition for H\(^+\), He\(^+\), He\(^{++}\), O\(^+\), and O\(^{4+}\) between a few eV and ~40 keV/q. The local vector magnetic field is measured by the onboard fluxgate magnetometer (FGM) instrument (Russell et al., 2016), a part of the Fields Investigation (Torbert et al., 2016). Ion moments are provided from the fast plasma instrument (FPI; Pollock et al., 2016), which measures the total ion population from a few eV to 30 keV/q. Substorm auroral index data are obtained from the OMNI database (King & Papitashvili, 2005).
3. Observations

The substorm of interest began around 09:20 UT on August 9, 2016, as indicated by the sudden increase in the AE auroral index in Figure 1. The MMS constellation was traveling inbound from ~8.5 Re to 7.5 Re within the premidnight magnetic local time (MLT) sector (~22.5 h). The figure shows spin-averaged differential intensities from EIS for protons, helium, and oxygen, respectively, represented with both spectrograms (Panels 1b-1d) and line plots (1e-1g). Since the spacings between the four spacecraft are much smaller than the ion gyroradii, ion measurements from MMS-2-4 have been combined (MMS1 EIS ion data are not available during this event). As each plot is generated, we combine the data from the different spacecraft in a strictly time-based fashion as we average the data over a selected time frame, while keeping careful track of angular information. Here, we use 20 s averaging, the approximate spin period of the spacecraft. Note that at the beginning and ending of each 20 s averaging period, the spin phases of the multiple spacecraft are offset with respect to each other, since the spin phases are not locked together. Panels (1h) and (1i) show MMS3 measurements of the local magnetic field (FGM) and ion flow speeds (FPI) in geocentric solar magnetic (GSM) coordinates. Minus $B_x$ ($-B_y$) is plotted in Figure 1h to provide a better visual comparison of the magnetic field components.

MMS begins the time period in the southern lobe. Near 09:20 UT magnetic field measurements suggest a dipolarization front (DF) embedded in a strong earthward flow (with a ~12 nT dip in $|B_x|$; a ~10 nT enhancement in $B_y$, and peak flow speeds of ~600 km/s). We provide in Figure S1 a higher time resolution plot for several of the parameters in Figure 1 for the 0915 to 0925 UT time frame. Until ~09:24 UT, MMS observes continued fast flows, which are primarily in the earthward and duskward directions. At this point, MMS is firmly in the plasma sheet, but still well south of the neutral sheet (note the large value of $-B_x$). EIS observed energetic ion enhancements for all species starting at ~09:20 UT. At ~09:30 UT, EIS observes a more sudden and nearly dispersionless ion injection. At ~09:36 UT, magnetic field measurements suggest MMS observes another DF. Throughout the next 40 min, energetic ion fluxes remain elevated for the 10s to 100s of keV energies, with several further injections observed. Of particular note is that the energy-time spectrograms (1b-1d) show oxygen and helium energetic enhancements that appear to reach higher energies than do the protons. For example, the peak energies registering flux enhancements for protons, helium, and oxygen are typically between 200 keV and 400 keV, and 800 keV and 1 MeV, respectively.

We employ the correlation analysis introduced by Mitchell et al. (2018) and employed by Bingham et al. (2020) to determine the heavy ion charge states. Figure 2 shows an example using hydrogen and helium channels for the 0940 UT to 1010 UT event times in Figure 1. Correlation coefficients within each box are created using the ion intensities versus time between each set of energy channels of the two different species, one of which (protons) has a known charge state. By subtracting off the mean value of each series (call these new series “A” and “B”), each box in the array corresponds to $\Sigma(A_i \cdot B_i)/\sqrt{\Sigma(A_i^2) \cdot \Sigma(B_i^2)}$, where summations are performed over the index “i,” and $\sqrt{[\ ]}$ is the square root of the quantities in square brackets. The sliding or off-set parameter for these cross correlations is not time in this case but is rather energy, as we move from box to box (representing different energies) in the array. Ridges of high correlation signify the likely dominant charge state of a mass-resolved ion species. For example, for H$^+$ and He$^{++}$, a high correlation often develops for energies where $E_{\text{He}} = 2 \times E_{\text{H}}$, as seen in Figure 2. Here, the high correlation blue color coincides mostly with the overlaying yellow boxes that correspond to a double charge on the helium (see also Figure 7 in Mitchell et al., 2018). Bingham et al. (2020) provide more information about the cross-correlation process as applied to the EIS data.

Figure 3a shows the cross correlation between oxygen and hydrogen channels, also taken between 09:24 UT and 10:10 UT. For both Figures 2 and 3a, we have deliberately avoided the region with high flows before 09:24, because flow effects might distort the ion energies through the Compton-Getting effect. In Figure 3a, overlaying yellow boxes outline energy channels that are closest to $E_0 = E_{\text{H}}, E_0 = 2 \times E_{\text{H}},$ and $E_0 = 6 \times E_{\text{H}}$, respectively. These boxes signify where peak correlations would be expected if transport and energization were ordered by $E/q$ for H$^+$ versus O$^+$, O$^{++}$, or O$^{+++}$, respectively.

Two distinct ridges of correlation develop, one for lower energy oxygen (<300 keV) and one for higher energy oxygen (>400 keV). For the higher energy oxygen population, the highest correlations are near energies where $E_0 = 6 \times E_{\text{H}}$, indicating high charge states in the vicinity of O$^{+++}$. Thus, we deduce that throughout
Figure 1. Auroral electrojet (AE) and corresponding upper (AU), and lower (AL) electrojet indices (a), and Magnetospheric Multiscale (MMS) observations (b)–(i) associated with energetic ion enhancements during substorm activity. Energy spectra of differential intensity from the energetic ion spectrometer (EIS) for: (b) H⁺, (c) He⁺, and (d) O⁺. Line spectra of differential intensity from EIS for: (e) H⁺, (f) He⁺, and (g) He++. Twenty second (spin period) averaging is used for the EIS plots. (h) Vector magnetic field from the fluxgate magnetometer (FGM) in geocentric solar magnetic (GSM) coordinates (note that since $B_x < 0$, $-B_x$ is plotted for better visual comparison). (i) Plasma flow speed from the fast plasma instrument (FPI) in GSM coordinates.
the time shown, oxygen with energy ≥400 keV is primarily of solar wind origin. The earlier Figure 1d shows this same separation crudely by revealing two distinct populations, most clear after 0940. For the lower energy oxygen in Figure 3a, the peak correlations fall between lines of $E_O = E_H$ and $E_O = 2 \times E_H$, suggesting $O^+$ or $O^{++}$, respectively. This correlation trend is different from those presented in Mitchell et al. (2018) or Bingham et al. (2020), which typically had clean peaks of correlation along energies where $E_H = E_O$ in cases where ionospheric oxygen was present. For comparison, Figure 3b depicts just such a case at a similar radial distance as that used for Figure 3a. Here, the responses are well ordered by constant $E/q$ versus $H^+$, similar to what Mitchell et al. (2018) found inside geosynchronous orbit.

To quantify the offset in peak correlation of the 130 keV–300 keV oxygen from $E_O = E_H$, we applied a fifth order polynomial fit to each column of the correlation coefficients table (i.e., fitting the correlations at different proton energies for fixed oxygen energies). Figure 4a lists the oxygen energy ($E_O$, the geometric means of the corresponding EIS oxygen energy channels), proton energy ($E_H$, the peaks in the polynomial fits to the correlation coefficients vs. proton energy), and the energy difference ($\Delta E$) between $E_O$ and $E_H$.

Excluding one outlier, the energy differences range between $\sim 29$ keV and 52 keV, with a mean difference of $\sim 39$ keV and standard deviation of $\sim 12$ keV.

Could it be that the 130 keV–300 keV oxygen is a mixed population of $O^+$ and $O^{++}$? If so, we believe that the response would not be so sharply peaked between the two species, but would rather show a flattened boxcar like response for each oxygen energy encompassing both $O^+$ and $O^{++}$ charge states. But also, the HPCA instrument has the ability to observe $O^{++}$ at energies below $\sim 40$ keV/q (or $\sim 80$ keV total energy). Figure 4b presents the time-of-flight spectrum from HPCA between 09:30 UT and 09:45 UT. There is very little $O^{++}$ observed for this time period and for adjacent time periods, whereas there is a large presence of $O^+$. This finding is consistent with typical conditions, where $O^{++}$ fluxes are generally around an order of magnitude lower than $O^+$ intensities, even during active times (e.g., Allen et al., 2016; Gloeckler & Hamilton, 1987; Kremser et al., 1987). Based on these observations and the results of previous studies, we conclude that the 130 keV–300 keV oxygen observed by EIS is most likely $O^+$. Its displacement from the position expected based on $E/q$ ordering is likely due to additional energy being added to the $O^+$ ions.
Adiabatic transport and energization of H⁺ and O⁺ should lead to enhancements that are highly correlated because for constant $E/q$, these two species come from the same position in the magnetotail and follow the same trajectory to the spacecraft from that position. Since that condition is not observed in the present case, the offset in peak correlation between H⁺ and O⁺ implies that they are not adiabatically energized and transported from the same initial point to MMS. We conclude that a nonadiabatic energization likely occurred that preferentially energized O⁺ relative to H⁺. Note that this conclusion does not depend on “before” and “after” spectral comparisons.
4. Discussion

For this case study, we find that the peak correlation of lower energy oxygen between 130 keV and 300 keV occurred at energies of roughly $\sim 39$ keV above proton energies. HPCA observations and previous studies show that O$^{++}$ likely did not play a role in this finding and that the low energy component was O$^+$. Previously, Mitchell et al. (2018) and Bingham et al. (2020) showed night-side cases both inside and outside of the geosynchronous orbit where the flux responses of ion injections for all species were well-ordered by $E/q$, suggesting adiabatic behavior. The $\sim 39$ keV offset between the energy channels with peak correlation in the present case for 130 keV–300 keV O$^+$ and H$^+$ indicates that O$^+$ and H$^+$ are not fully adiabatically energized and transported from the same point to MMS. We interpret these results as O$^+$ being nonadiabatically and preferentially energized compared to H$^+$.

A similar feature may have been observed by Motoba et al. (2018) with observations from Van Allen Probes during dipolarization events inside of geosynchronous orbit. The authors primarily found an adiabatic enhancement for all ion species. However, they did find a modest correlation between energy channels where oxygen was one-to-two times the proton energy. The authors interpreted this finding as a contribution of O$^{++}$. While that hypothesis remains possible, it is also possible that the O$^+$ had been preferentially energized compared to H$^+$.

| $E_O$ (keV) | 133 | 146 | 160 | 175 | 192 | 210 | 230 | 251 | 274 | 299 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E_H$ (keV) | 84  | 99  | 112 | 123 | 155 | 181 | 198 | 222 | 260 | 269 |
| $\Delta E$ (keV) | 49  | 47  | 48  | 52  | 37  | 29  | 32  | 29  | 14  | 30  |

Figure 4. (a) Offset (bottom row) in peak correlation between lower energy oxygen (top row) and protons (middle row) from Figure 3a. The oxygen energy ($E_O$, top row) is just the geometric mean of the corresponding energetic ion spectrometer (EIS) oxygen energy channel. The hydrogen energy ($E_H$, middle row) is the peak in the polynomial fit to the vertical row of correlation coefficients versus hydrogen energy in Figure 3a, for each of the corresponding oxygen energy values. $\Delta E$ is the difference between the top row and the middle row. (b) Average flux Time-of-flight spectrum from the hot plasma composition analyzer (HPCA) between 09:30 and 09:45 on August 9, 2016. Color depicts the average flux observed by HPCA for a given bin. Sets of solid and dashed lines mark bins where the flux within the lines denote composition of H$^+$, He$^{++}$, He$^+$, O$^{++}$, and O$^+$, respectively.
Test particle modeling by Delcourt et al. (1990, 1997), Delcourt and Sauvaud (1994), and Sánchez et al. (1993) showed that the closer the ion gyroperiod \(T_g\) was to the dipolarization timescale \(T_d\), the greater the non-adiabatic acceleration would be.

Delcourt et al. (1997) presented a simple mathematical description of the range of post dipolarization energy. As described by (Nosé et al., 2000), one can think of the limiting case of this nonadiabatic energization as being analogous to "pick-up" energization, like that classically observed in the solar wind (Möbius et al., 1985). In this scenario, the electric field is a step function which changes the energy in a fashion dependent on initial gyro-phase, but with an average thermal energy that changes from \(m(V^2)/2\) to \(m(V^2 + V_o^2)/2\), representing a simple constant addition (pick-up energy \(mV_o^2/2\)) to all initial energies \((mV^2/2)\). For the case presented here, FPI observed ion flow speeds of \(\sim 600\) km/s near 09:20 UT. If that flow were applied suddenly, it would lead to an average \(\sim 28\) keV of extra thermal energization of O\(^+\) compared to H\(^+\). The energization likely occurred away from the spacecraft location, and it is possible that the flow speed was slightly higher nearby than what was observed by MMS. A \(\sim 700\) km/s flow could provide the \(\sim 40\) keV difference in energization observed between H\(^+\) and O\(^+\).

Other processes may ultimately be responsible for the oxygen energization (e.g., Section 3 of Keika et al., 2013). Note, for example, that the "pick-up" process would strongly favor perpendicular (near 90°) pitch angles. When we sort Figure 2a by pitch angle (not shown) we find very reduced correlation for parallel directions, but still a ridge of modest correlation between O\(^+\) and O\(^{++}\). It may be that scattering occurs close to the current sheet at the magnetic equator; or, are other processes responsible? Reflection or fermi-type acceleration can also add energy in the parallel direction. In general, it is commonly predicted by particle trace modeling that the energy of the plasma flow and associated electric field can more effectively transfer 10s to 100s of keV of energy to O\(^+\) than to H\(^+\). Examples of such predictions can be found in Artemyev et al. (2015), Birn et al. (2004), Delcourt et al. (1997), Delcourt and Sauvaud (1994), Greco et al. (2015), Nakayama et al. (2016), and Sánchez et al. (1993). In Figure 2 for H versus He correlation, there is a low energy deviation of the correlation from the \(E_{He} = 2 \times E_{H^+}\) line and so there could be some kind of nonadiabatic behavior going on for those He\(^{++}\) ions as well.

Considering just the pickup energization process, the average gyroperiods are \(\sim 12.3\) s for O\(^+\), \(\sim 0.8\) s for H\(^+\), \(\sim 1.5\) s for He\(^{++}\), and \(\sim 2.0\) s for O\(^{++}\) (using \(|B| = 85\) nT). While the two most distinct DFs observed by MMS evolve over \(\sim 30\) s –40 s, there are many smaller enhancements in \(B_z\) that develop on timescales near the O\(^+\) gyroperiod. These enhancements have \(> 4\) nT in \(< 24\) s, whereas there is only one which occurs over \(< 4\) s. Thus, during this event with suspected nonadiabatic O\(^+\) acceleration, more local enhancements of \(B_z\) associated with the transient dipolarization are found to be close to the O\(^+\) gyrofrequency compared to gyrofrequencies of the lower \(m/q\) ions.

5. Conclusions
This study presents observations of substorm-related energetic ion enhancements in the near-Earth magnetotail from MMS on August 9, 2016. Observations show a strong species dependent energization in the supra-thermal ion populations (H: 50 keV–1,000 keV; He: 60 keV–1,000 keV; O: 130 keV–1,000 keV), where oxygen and helium reach significantly higher energies than protons. Using a correlation technique introduced by Mitchell et al. (2018), it is inferred that the helium and the higher energy oxygen (\(\geq 2400\) keV) are multiply charged (He\(^{++}\) and O\(^{+++}\)) and of solar wind origin. The solar wind heavy ion energizations are well ordered by \(E/q\) with respect to H\(^+\), pointing to charge state dependent energization with little mass-dependence. However, for the events studied here, oxygen between 130 keV and 300 keV is inferred to be O\(^+\), which is not well-ordered by equal \(E/q\) with respect to H\(^+\), but rather has energy offsets of \(\sim 39\) keV (\(\sim 29\) keV–52 keV range) above H\(^+\). Since, as described in Mitchell et al. (2018), adiabatic transport and energization of H\(^+\) and O\(^+\) should lead to organization by \(E/q\), this result is interpreted as nonadiabatic preferential energization of O\(^+\) relative to H\(^+\). The technique does not depend on "before injection" and "after injection" spectral comparisons, and therefore may represent the most definitive test yet of nonadiabaticity.
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Data Availability Statement

The MMS data used are publicly available at the MMS Science Data Center at https://lasp.colorado.edu/mms/sdc/. Data from the Wind spacecraft and geomagnetic indices are from https://omniweb.gsfc.nasa.gov/.

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