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Observations of downgoing velocity dispersed O^+ and He^+ in the cusp during magnetic storms

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[1] Downgoing, velocity-dispersed (<1 keV to 25 keV) O^+ and He^+ ions accelerated at the magnetopause have been observed by the FAST satellite in the polar cusp. These ions, together with H^+ ions, were observed during 24 magnetic storms. In comparison, only H^+ was observed during >300 cusp crossings during low activity periods. During the largest storm, the O^+ energy flux was an order of magnitude larger than the H^+ energy flux. Velocity dispersed H^+, with a signature of decreasing energy with increasing latitude during southward IMF, are normally observed in the low altitude cusp. These ions originate in the magnetosheath and, during dayside reconnection, are accelerated along the magnetopause with some ions funneled into the cusp. Poleward convection of the plasma leads to the latitude-velocity dispersion signature. Magnetospheric plasma can also be accelerated at the magnetopause, however the magnetosheath plasma density is much larger and magnetospheric composition is normally dominated by H^+, so that distinguishing magnetospheric and magnetosheath plasma becomes difficult. During magnetic storms, auroral ionospheric outflow of O^+ and He^+ can be large enough to produce a significant, non-hydrogen component in the plasma sheet. These ions are convected through the inner magnetosphere and ring current, eventually appearing at the dayside magnetopause where they are accelerated and form this atypical cusp signature. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2788 Magnetospheric Physics: Storms and substorms; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2455 Ionosphere: Particle precipitation; 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736). **Citation:** McFadden, J. P., C. W. Carlson, R. Strangeway, and E. Moebius, Observations of downgoing velocity dispersed O^+ and He^+ in the cusp during magnetic storms, *Geophys. Res. Lett.*, *30*(18), 1947, doi:10.1029/2003GL017783, 2003.

1. Introduction

[2] Magnetic storms represent one of the largest perturbations to the Earth's magnetosphere and, as such, are important to understanding the dynamics of the near Earth environment. Measurements by *Hamilton et al.* [1988] and later by *Daglis* [1997] have demonstrated that for large magnetic storms, the ring current is dominated by ionospheric plasma, with a large contribution from O^+ during the storm's maximum phase. How O^+ is energized and becomes a major constituent of the ring current is still under debate, however it seems likely that the ring current O^+ was part of the plasma sheet at an earlier time. Statistical studies show that during active times the plasma sheet composition changes and that O^+ becomes a significant component [*Lennartsson and Sharp*, 1982; *Lennartsson and Shelley*, 1986; *Daglis et al.*, 1994]. *McFadden et al.* [2001] showed that the auroral region can provide significant O^+ and He^+outflow to the plasma sheet during storms, and that these ions are cycled through the inner magnetosphere. Figures in *McFadden et al.* [2001] also show that these injections have a significant low energy component. These ionospheric ions should eventually convect to the dayside magnetopause where they are accelerated through reconnection, with some fraction reflected back into the magnetosphere [*Fuselier et al.*, 1991] and eventually appearing in the cusp.

[3] The enhanced O^+ in the magnetosphere should have other effects on the dynamics of the near Earth environment. One consequence is that dayside reconnection will be affected by a the presence of a heavy constituent. Spacecraft crossing the magnetopause often see accelerated jets of ions [*Paschmann et al.*, 1979]. (For reviews of magnetopause reconnection see *Cowley* [1995] or *Fuselier* [1995], and references therein.) Under normal conditions, the dayside magnetospheric composition is primarily H^+ and its density is much smaller than the magnetosheath, so the observed jets are dominated by magnetosheath plasma. The most field aligned and Earthward moving of these ions eventually travel down into the cusp producing a latitude-velocity dispersion signature at low altitudes.

[4] The dominant component of these ions is always H^+, although He^{++} can be detected when a sensitive mass spectrometer is present on the spacecraft. O^+ ions have been reported in the cusp [*Peterson*, 1985; *Seki et al.*, 2000], but do not show a dispersive ion signature. In this report we present observations of velocity dispersed, earthward travelling O^+, He^+ and H^+ in the cusp during magnetic storms. These rare events were observed because the magnetosphere was filled with a high concentration of

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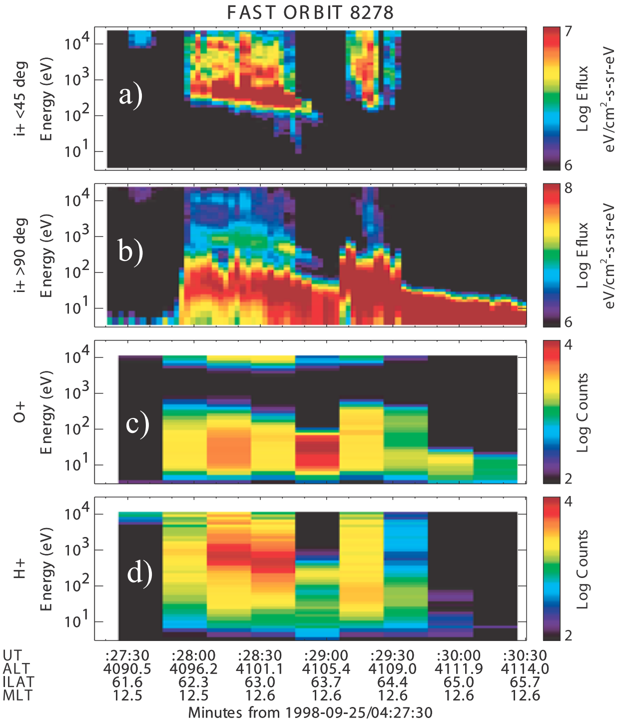

Figure 1. Ion energy-time spectrograms during the cusp crossing on orbit 8278 by the FAST satellite that shows latitude-velocity dispersion of H$^+$, He$^+$ and O$^+$. The top panel shows three velocity dispersed bursts of downgoing ions at 4:28 UT, with the higher and lower energy bursts identified as O$^+$ and H$^+$ from panels 3 and 4. The second panel shows upgoing ions which are predominantly low energy O$^+$ conics. Panels 3 and 4 show the unidirectional count rates for O$^+$ and H$^+$ ions as measured by the TEAMS mass spectrometer.

ionospheric plasma during the magnetic storm. This allowed the magnetospheric component, that was accelerated at the magnetopause, to be both observable and distinguishable from the magnetosheath component. We begin our description of cusp O$^+$ velocity dispersed ion signatures (VDIS) with the first event discovered. Since this event occurred during a magnetic storm that has received considerable attention, we provide additional details about this storm's activity.

2. Observations

[5] The magnetic storm on September 25, 1998 was initiated by a CME that reached the Earth 15 minutes before the start of the day. The Dst initially dropped to −85 at 3 UT, reached a minimum of −207 at 10 UT, and recovered to −50 by the end of the day. The initially large B_y and later large B_z in the solar wind led to enhanced reconnection on the dayside as reported by *Strangeway et al.* [2000] and to enhanced magnetospheric convection as indicated by AE > 500 for most of the first 2/3 of the day. Large outflows of O$^+$ from the cusp were reported by *Moore et al.* [1999] and *Strangeway et al.* [2000]. These outflows were energetic enough to provide escape for O$^+$ into the mantle, with magnetotail reconnection likely adding some of this plasma to the plasma sheet. Injection of ionospheric O$^+$ and He$^+$ from the nightside oval directly into the plasma sheet is also likely. An intense substorm initiated by the arrival of the CME brightened most of the nightside oval and shifted the polar cap boundary at midnight to ILAT∼82°. AE exceeded 1000 several times during the course of the storm indicating that additional substorms occurred. It has long been known that ionospheric outflow increases with geomagnetic activity.

[6] At about ∼2:50 UT, during a nightside auroral crossing, the FAST satellite measured plasma sheet ions (<10 keV) that were dominated by O$^+$ and contained significant amounts of He$^+$. On the following orbit, O$^+$ and He$^+$ became important constituents of the cusp precipitation at low altitudes. The FAST satellite had a noon-midnight orbit during this period, producing a latitudinal cut through the polar cusp at 12.6 MLT (4:28 UT). Velocity dispersed downgoing ions were observed, as is usual for this type of cusp crossing, with lower energy ions appearing poleward. This particular pass was unusual because three

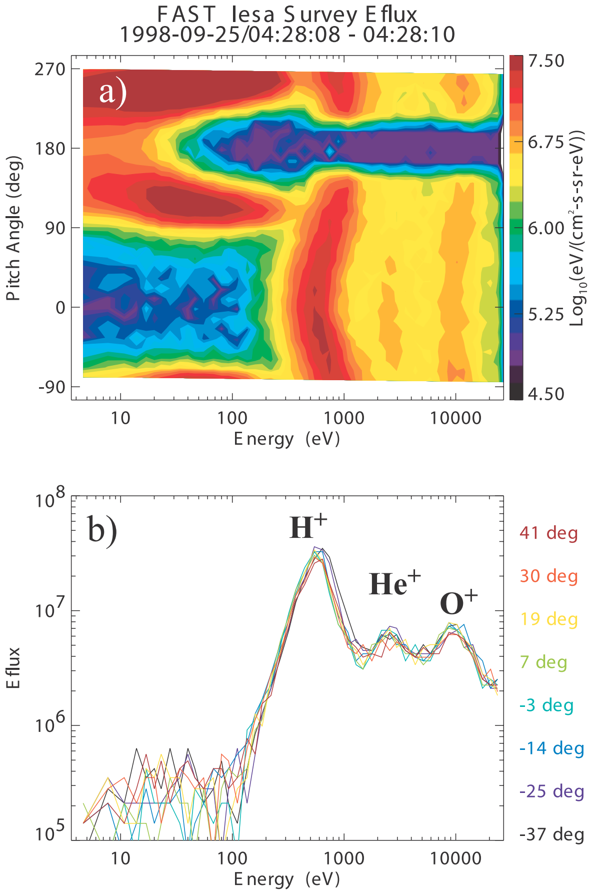

Figure 2. Figure 2a is a contour plot of the ion differential energy flux (proportional to count rate) during the velocity dispersed ion event in Figure 1. Three separate peaks at about 0.6 keV, 2.5 keV and 10 keV are identified as H$^+$, He$^+$ and O$^+$. Figure 2b shows energy flux spectra over downgoing pitch angles <45° which clearly show the peaks. Note that the protons have a high energy tail, and that approximately 1/3 (1/2) of the counts in the O$^+$ (He$^+$) peak is due to protons.

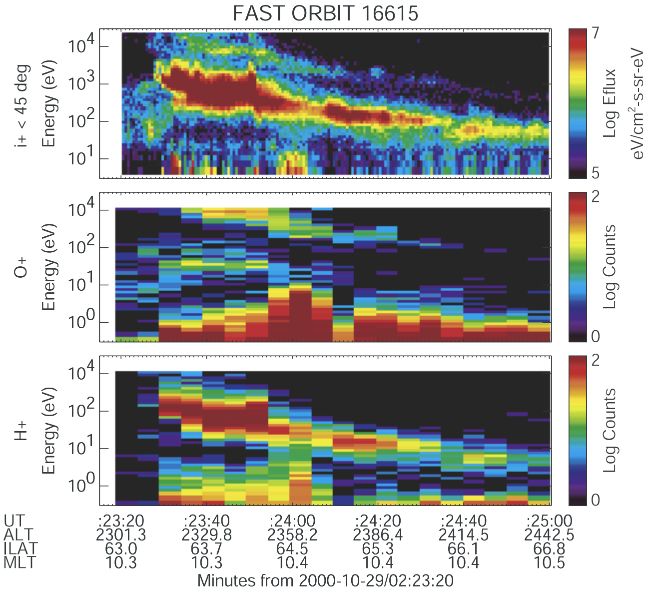

Figure 3. Ion energy-time spectrograms showing an O$^+$ VDIS signature in the cusp. Similar signatures were observed on 7 additional orbits during this storm encompassing the first 18 hours of the day.

separate peaks of velocity dispersed ions were observed separated by factors of four in energy. Mass spectrometer data clearly identify the higher and lower peaks as O$^+$ and H$^+$, with the intermediate He$^+$ peak not resolved by the sensor due to slow sampling.

[7] Figure 1 shows energy-time spectrograms of ions measured by the FAST satellite as it crossed the northern polar cusp at ~4:30 UT on September 25, 1998. The top panel shows the downgoing ions measured by the ion plasma sensor. Three dispersive peaks can be seen between 4:27:55 and 4:28:45 UT and at energies of about 0.2–0.6 keV, 1–2.5 keV and 5–10 keV. A second set of dispersive bursts of ions between 4:29:05 and 4:29:35 indicates that pulsed reconnection [*Lockwood et al.*, 1998] was taking place at the magnetopause. The second panel shows the upgoing ions which were primarily conics. The bottom panels show the count rates from the O$^+$ and H$^+$ channels of the TEAMS mass spectrometer which allow identification of the downgoing higher and lower energy dispersive peaks as O$^+$ and H$^+$, and the conics as primarily O$^+$. The intermediate energy dispersive burst in panel 1 was unresolved by the mass spectrometer due to slower sampling. This burst is consistent with He$^+$ since factors of four in the energy per charge ratio between the dispersive peaks should be the mass ratios for ions with the same velocity and charge.

[8] Figure 2a shows the energy-angle distribution of the ion energy flux during the dispersed ion event. To avoid mixing measurements, the 360° field-of-view measurements are plotted as ±180° pitch angle, where the pitch angle sign just distinguishes the two halves of the sensor. Three different mass peaks can be seen in the downgoing distribution. The increased energy at larger pitch angles is due to velocity dispersion. Ions that arrive at the same time from an impulsive injection must have the same average parallel velocity, so larger pitch angle particles must have a higher energy. (Upgoing ions have mirrored below the spacecraft, and thus have traveled a larger distance requiring even higher energy.) Figure 2b shows slices through the downgoing energy flux distribution at several pitch angles which clearly shows the peaks. There is also a high energy tail for H$^+$ contributing about 1/3 (1/2) the counts to the O$^+$ (He$^+$) peak. The three flux peaks represent phase space densities of about 6×10^{-11}, 6×10^{-12} and 9×10^{-12} s^3/m^6 for the H$^+$, He$^+$ and O$^+$ peaks, respectively.

[9] The unusual cusp dispersion signature in Figures 1 and 2 led to a search of the FAST data set for similar events. Greater than 300 cusp crossings with clearly defined H$^+$ VDIS signatures were examined during low activity periods (Dst < 30) that were not associated with magnetic storms. None of these crossings had O$^+$ or He$^+$ VDIS signatures. We identify valid O$^+$ (He$^+$) signatures from the differential energy flux spectrograms by looking for a separate peak at 16 (4) times the energy of the H$^+$ VDIS peak, containing counts significantly above background for >20 seconds. During 24 magnetic storms (Dst > 70) where FAST passed on north-south trajectories through the cusp, FAST measured downgoing VDIS O$^+$ and/or He$^+$ signatures in all 24 instances. Dst for these storms ranged from 73 to 292 nT, with an average of 136. Ten periods with intermediate activity (30 < Dst < 70) were examined and some showed evidence of downgoing O$^+$ or He$^+$ in the cusp.

[10] Most signatures were observed during the main phase or near the peak of the storm. This is expected since these times correspond to the peak in magnetospheric plasma pressure with significant O$^+$ [*Daglis et al.*, 1994], and to the period when VDIS signatures are most likely observed in the cusp. During the recovery phase of storms, B_z is often northward so that VDIS signatures are not observed. However, many storms had O$^+$ VDIS signatures during the recovery phase. Figure 3 shows an O$^+$ VDIS from a magnetic

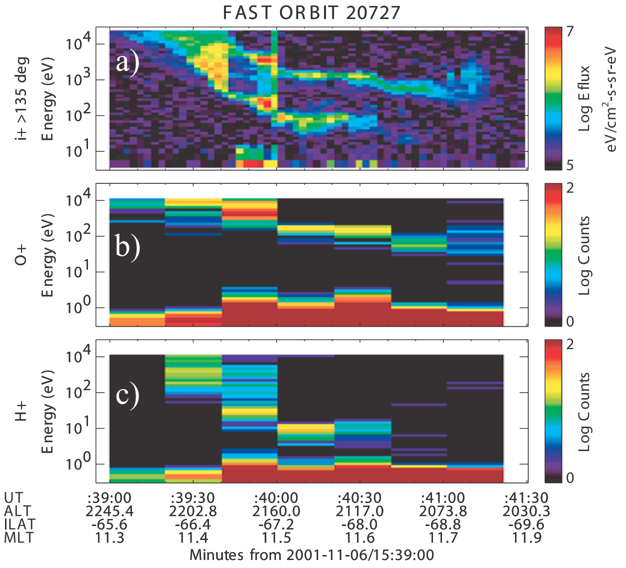

Figure 4. Ion energy-time spectrograms during a large magnetic storm (Dst = 292) showing an O$^+$ VDIS signature that is as intense as the H$^+$ signature. The O$^+$ energy flux was an order of magnitude larger than the H$^+$ energy flux.

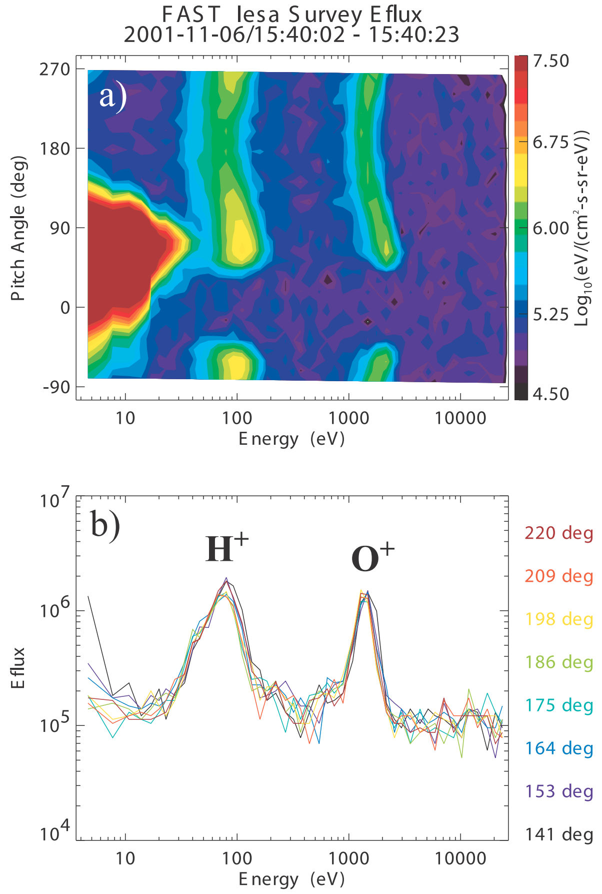

Figure 5. Contour and spectra plots, taken from the cusp crossing in Figure 4, illustrating the well separated H^+ (80 eV) and O^+ (1300 eV) peaks.

storm (Dst = 127) that had O^+ signatures on 8 consecutive orbits showing that significant oxygen was present at the magnetopause for ∼18 hours.

[11] Figure 4 shows the cusp event with the largest ratio of O^+/H^+ observed. This signature was recorded during the largest magnetic storm (Dst = 292) containing a FAST cusp crossing. The O^+ peak differential energy flux (or count rate) is nearly as intense as the H^+ peak. Figure 5a shows a contour plot of the differential energy flux illustrating both the mass dispersion and pitch angle dispersion. Figure 5b shows the downgoing ion spectra. For this distribution, the integrated precipitating proton flux is about a factor of 2 larger than the O^+ flux, however the O^+ has about an order of magnitude larger precipitating energy flux. This shows that during large magnetic storms, the bulk of particle energization at the dayside magnetopause may go into O^+.

3. Summary

[12] Measurements of velocity dispersed ions in the polar cusp are almost always dominated by H^+. When field lines reconnect, the magnetosheath and magnetospheric plasmas mix and are accelerated at the magnetopause. The accelerated plasma is observed in the low altitude cusp as velocity dispersed ions, exhibiting decreasing energy with increasing latitude. The dominance of H^+ in these events is primarily due to the much higher density of the magnetosheath plasma over magnetospheric plasma. When a constituent other than H^+ is observed, it is often He^{++} from the magnetosheath. In addition, the dominant dayside magnetospheric constituent is also normally H^+ which can't be distinguished from the magnetosheath H^+. However, during magnetic storms the magnetosphere has a substantial density of ionospheric O^+ and He^+. These ions likely originate in the auroral regions where they are injected directly (nightside oval) or indirectly (from the cusp through the lobes and across the plasma sheet boundary layer) to the plasma sheet. During storms, these ions are convected through the inner magnetosphere to the dayside magnetopause. They are then accelerated at the magnetopause and appear as a downgoing dispersive flux in the low altitude polar cusp. Due to their higher mass, these ions are clearly separated from the proton peak. We report the first observations of downgoing velocity dispersed O^+ and He^+ ions in the cusp in association with magnetic storms. These ions were observed because the storm associated ionospheric outflows filled the magnetosphere with enough ionospheric plasma to provide a substantial inflow to the dayside magnetopause. During the largest storm, the energy flux of O^+ was an order of magnitude larger than the H^+ flux indicating reconnection was primarily energizing magnetospheric plasma. The presence of significant heavy ions at the magnetopause may also have implications on reconnection rates and energy flow.

[13] **Acknowledgments.** The analysis of FAST data was supported by NASA grant NAG-3596.

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