Prompt ionospheric/magnetospheric responses 29 October 2003
Halloween storm: Outflow and energization

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[1] 3D multifluid simulations of the 29 October 2003 Halloween storm show the event to be a good example of conditions which lead to prompt penetration of solar wind electric field into the magnetosphere and prompt acceleration of heavy ionospheric ions. Causal relationships are established that tie solar wind conditions to ionospheric/magnetospheric responses, and the results are correlated with features in both IMAGE/HENA data and AMIE cross-polar cap potential. The simulations are able to capture the AMIE potentials. Difference between model results and AMIE data can be attributed to the ability of the model to capture fast enhancements in the convective electric field that can be tied with the IMF variations. The total auroral currents show a smoother profile, with the magnetosphere acting like an inductor. A period of southward IMF with simultaneous rapid $B_y$ rotation leads to the largest currents and ionospheric outflows. These outflows produce an initial ionospheric mass loading of the magnetosphere and originate from the dayside cusp/cleft region. During this period the energization of $O^+$ lags that of $H^+$, consistent with that seen in the HENA data. Once the ionospheric outflows mass load the magnetosphere, prompt acceleration of $O^+$ is seen simultaneous with $H^+$ acceleration. This prompt response is due to the acceleration of $O^+$ ions that have previously flowed into the magnetosphere. The enhanced convective electric field, also leads to enhanced ionospheric outflows that resupply ionospheric ions into the magnetosphere. During this period of resupply, the nightside auroral zone becomes an important contributor to the outflows.


1. Introduction

[2] The Halloween 2003 storm was a three day long event, beginning on 29 October 2003 and ending on 31 October 2003, associated with two coronal mass ejections, the first on the 28th and the second occurring on the 29th. This occurred during a longer period of intense activity on the Sun. The Halloween storm was unusual in that extremely high speed flows were associated with the arrival of the shocks associated with the two CMEs. ACE measured solar wind speeds in excess of 2000 km/s with the arrival of the first shock on the 29th and greater than 1500 km/s with the arrival of the second shock on the 30th [Skoug et al., 2004]. Between 6 UT and 9 UT on 29 October 2003 (which is the focus of this paper), $Kp$ increased from 3–4 to 9 [Courtesy NOAA/SEC, Boulder, CO], indicating that this event was particularly effective in creating disturbed magnetospheric conditions.

[3] These Halloween Storms have been studied extensively over the last few years because of the large impact that the solar wind conditions generated within the magnetosphere and in the ionosphere. Strong compression of the magnetotail, as evidenced by enhanced tail field strengths and increased plasma density, was observed by Geotail [Miyashita et al., 2005]. Mannucci et al. [2005] have demonstrated extreme ionospheric response during the events with the total electron content increasing by 40% for the event on 29 October and up to 250% on 30 October. Studies of IMAGE/LENA data indicate that the $H^+$ energy density showed no difference between storm times and quiet intervals, while the $O^+$ energy density increased from 0.05–3 keV cm$^{-3}$ during quiet periods to $\sim$100 keV cm$^{-3}$ during the storm, and the $O^+$/H$^+$ energy density ratio increased to 10–20 for the ring current [Nose et al., 2005].

[4] The presence of high concentrations of $O^+$ is important as previous simulations of storm events have indicated that this $O^+$ can lead to significant mass loading of the magnetosphere which, in turn, can lead to saturation of the cross-polar cap potential [Winglee et al., 2005]. Such saturation of the polar cap potential was observed for this event. Using DMSP data, Hairston et al. [2005] indicated that cross-polar cap potential saturated – the cause of this saturation still remains unclear. Siscoe et al. [2004] compared four competing mechanisms for the saturation, but all involved a significant role for the Region 1 current. This
paper indicates the oxygen outflow is responsible for saturation during this event.

[5] The acceleration of O\(^+\) has been demonstrated to be a several step process [Winglee, 2003]. Ions moving out of the cusp/cleft region experience centrifugal acceleration due to the rapid motion of field lines over the polar cap. If these ions enter the tail current sheet they can experience additional energization from current sheet acceleration or interaction with the near-Earth neutral sheet. Ions moving out from the night side auroral region can also experience auroral acceleration and centrifugal acceleration but typically fall short of the current sheet so that they do not experience significant current sheet acceleration. All ions, if they are then convected into the inner magnetosphere into strong magnetic field, experience betatron acceleration.

[6] Acceleration processes during storms is modified by processes that do not necessarily occur in isolated substorms. For example, using the synchronous orbit particle analyzer on the Los Alamos National Laboratory geosynchronous spacecraft and images of ENAs from the comprehensive energetic particle pitch angle distribution/imaging proton spectrometer on the Polar satellite, Reeves and Henderson [2001] have shown that when comparing isolated substorms versus storm-time substorms, ion injection is very similar at the beginning of the injection. However, the subsequent injection can be very different, with isolated substorm injections decaying to pre-injection levels within about an hour while storm-time injection can last for several hours and on occasion expand eastward opposite their drift motion direction.

[7] The 29 October event is reexamined here using a comparison of HENA data, AMIE cross-polar cap potential and multifluid modeling. This event is distinguished by a strong southward component in the interplanetary magnetic field (IMF) as well as a rapid IMF rotation in \(B_z\). Statistical studies have shown that variations in \(B_z\) can trigger substorms [e.g., Troshichev et al., 1986; Bae et al., 2001; Hsu and McPherron, 2003] but not all changes in \(B_z\) will trigger a substorm. In the present case, the strong southward IMF is shown to produce initial mass loading of the magnetosphere with heavy ionospheric ions. The rotation in \(B_z\) component of the IMF leads to prompt energization of the magnetospheric O\(^+\) as well as enhanced ionospheric outflows. The prompt acceleration of the heavy ions coincides with the prompt penetration of solar wind electric fields into the magnetosphere during storms. Such prompt penetration of electric field has been previously documented in previous storm studies [e.g., Basu et al., 2001]. The prompt acceleration of ionospheric ions is generated by the initial loading period and then subsequent reloading during periods of enhanced convection and particle acceleration.

[8] In order to demonstrate the loading and reloading of the magnetosphere by heavy ionospheric ions, we use a 3D multifluid model (section 2). The multifluid model has previously demonstrated saturation of the cross-polar cap potential due to the presence of heavy ionospheric ions [Winglee et al., 2002, 2005] using various static ionospheric boundary conditions. The present model differs from model used to generate previous results in that it uses a dynamic ionospheric boundary conditions where the relative concentration of heavy ions is tied to the magnitude of the auroral field aligned-current system. The present work is able to account for many features seen in the cross-polar cap potential (section 3) as determined by the AMIE model [e.g., Lu et al., 2001], but we show that rapid changes in IMF can lead to spikes in the potential that are possibility not resolved by AMIE. The total auroral current does not show these spikes even though there is substantial movement of the current sheet in terms of invariant latitude (ILAT) and magnetic local time (MLT). As such, the system is behaving as a massive inductor, with fast transient showing up in the potential but not current.

[9] In sections 4 and 5, the model results are used to demonstrate the origin of the induced ionospheric outflows in terms of ILAT and MLT and determine the mass loading that these outflows produce on the magnetosphere. The timing of this mass loading is compared with IMAGE/HENA data for validation. We are then able to establish a link between the ionospheric outflows and the generation of energetic populations within the magnetosphere. It is shown that the \(B_y\) and \(B_z\) components of the IMF play important roles in the generation of the energetic components with the magnetosphere. It is demonstrated that these swings are associated with fast penetration of the solar wind electric field, which leads to a sling shot, or centrifugal acceleration, of heavy ions on the dawn and dusk flanks (and hence the appearance of the two sources noted by Yamauchi et al. [2006]). Once the ionospheric plasma loads the magnetosphere, small perturbations in IMF \(B_z\) can yield lead to prompt creation of energetic populations in H\(^+\) and O\(^+\) as seen in the HENA data, with energetic particles being observed well down the tail. The enhanced convective electric field that energize the plasma also leads to the resupply of the ionospheric plasma components within the magnetosphere, producing prompt responses in heavy ion acceleration over an extended period. A summary of results and conclusions regarding particle acceleration during storms and the influence of the inner magnetosphere on the presence of long duration of energetic particles are presented in section 6.

2. Numerical Algorithm

[10] The multifluid code was developed to move away from the single fluid treatment of MHD to incorporate a more complete and realistic treatment of the plasma dynamics within a magnetosphere. The first generation of the code incorporated Hall effects on the electrodynamics and used a simple perturbation expansion [Winglee, 1994] valid for \(|V \times B| \gg |J \times B|/en\) to provide a first glimpse of how the magnetic topology predicted by MHD would be modified by a small but non-zero Hall correction (where \(n\) is the total ion density and \(e\) the electron charge). The model was then improved to fully incorporate the Hall and \(\nabla P\) terms in the generalize Ohm’s law/electron dynamics and demonstrated that at even a coarse resolution of 0.25 R\(_{\text{e}}\), these corrections could produce a core magnetic field that is comparable to that observed in tail flux ropes [Winglee et al., 1998]. The model was then expanded to include the evolution of different sources of ions and this work lead to the first three dimensional identification of the geopause, as well as the relative roles of ionospheric and solar wind plasma in populating the magnetosphere [Winglee, 2000] and the importance of ionospheric mass outflows in mass loading of the magnetosphere, the generation of the Harang
discontinuity and the cross polar cap potential [Winglee et al., 2002, 2005; Winglee, 2004]. The present version of the code includes a full incorporation of ion skin depth effects in the Ohm’s law and ion cyclotron terms in the momentum equation [Winglee et al., 2005], and has been modified to include a dynamic ionospheric composition that is typical of storm conditions. The specifics of the code are as follows. [11] The specific equations for mass, momentum and pressure for each ion component $\alpha$ are:

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{V}_\alpha) = 0$$  \hspace{1cm} (1)$$

$$\frac{\partial \mathbf{V}_\alpha}{\partial t} = \frac{q_\alpha n_\alpha (\mathbf{E} + \mathbf{V}_\alpha \times \mathbf{B}(r)) - \nabla P_\alpha - \left(\frac{GM_\alpha}{R^2}\right) \rho_\alpha \mathbf{r}}{\rho_\alpha}$$  \hspace{1cm} (2)$$

$$\frac{\partial P_\alpha}{\partial t} = -\gamma \nabla \cdot (P_\alpha \mathbf{V}_\alpha) + (\gamma - 1) \mathbf{V}_\alpha \cdot \nabla P_\alpha$$  \hspace{1cm} (3)$$

It is assumed that the electrons have sufficiently high mobility along the field lines that they are approximately in steady state or drift motion (i.e., $d/dt = 0$) so that the momentum equation for the electrons reduces to:

$$\mathbf{E} + \mathbf{V}_e \times \mathbf{B} + \frac{\nabla P_e}{e \mathbf{v}_e} = 0$$  \hspace{1cm} (4)$$

[12] Equation (4) is equivalent to the modified Ohm’s law with Hall and $\nabla P$ corrections included. Gravity is dropped in (4) since it has essentially no effect on the dynamics of the electrons. The rest of the electron dynamics are given by assuming quasi-neutrality, and applying the definitions for current, and electron pressure, i.e.:

$$n_e = \sum_i n_i, \hspace{0.5cm} \mathbf{V}_e = \sum_i \frac{n_i}{n_e} \mathbf{V}_i - \frac{\mathbf{J}}{e n_e}, \hspace{0.5cm} \mathbf{J} = \frac{1}{\rho_0} \nabla \times \mathbf{B}$$  \hspace{1cm} (5)$$

$$\frac{\partial P_e}{\partial t} = -\gamma \nabla \cdot (P_e \mathbf{V}_e) + (\gamma - 1) \mathbf{V}_e \cdot \nabla P_e$$  \hspace{1cm} (6)$$

and the evolution of the magnetic field by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$  \hspace{1cm} (7)$$

Substitution of (5) into (4) yields the modified Ohm’s law of

$$\mathbf{E} = -\sum_i \frac{n_i}{n_e} \mathbf{V}_i \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{e n_e} - \frac{1}{e n_e} \nabla P_e + \eta(x)\mathbf{J}$$  \hspace{1cm} (8)$$

[13] The first term in (8) is the ideal Ohm’s law and the last term $\eta(x)\mathbf{J}$ is added to allow for finite conductivity in the ionosphere. Collisions beyond this region are assumed to be negligible. No anomalous resistivity is included in the code, as the non-ideal terms included in (8) are sufficient to drive reconnection.

[14] The grid spacing in the inner magnetosphere is 0.25 $R_E$ and as such we are able to resolve heavy ion cyclotron dynamics in the magnetotail and magnetopause current sheets. In the mid- to distant tail, the grid spacing is increased steadily from 0.25 to about 3 $R_E$. The simulation region encompasses the distant tail at $x \sim -200$ $R_E$ (GSM) and at the flanks at $\pm 60$ $R_E$. The solar wind boundary is at $x = 35$ $R_E$. The inner radius of the simulations is set to 2.5 $R_E$. The region within the inner boundary is given a finite resistance equivalent to a Reynolds number of 10. At the actual inner boundary (representing the ionosphere), the Reynolds number is increased to 20 and at one grid point above it set is at 40. At all other points the resistivity is zero. These values yield an overall height integrated resistance similar to that of the Earth’s ionosphere.

[15] The parameter that has the most impact on the cross-polar cap potential and mass in the magnetosphere is the ionospheric density profile. Previous studies by Winglee et al. [2002, 2005] have detailed the magnitude of the outflows for various IMF conditions and how these outflows are related to the composition of observed outflows derived by Yau and André [1997]. In these studies a fixed light ion density at the inner boundary was assumed and then multiple simulations where run to show the dependence variations in the ionospheric/magnetospheric response for different $O^+$ densities. Outflows occur in the model when assuming constant ionospheric density profiles at the inner boundary, a variable ionospheric density merely allows for enhanced ionospheric outflows that can be present during active periods. For these simulations, we use a constant light ion density but instead of multiple runs with different profile $O^+$ densities we use a variable $O^+$ density at the inner boundary, where the density is tied to the magnitude of the auroral currents. By varying the densities in this fashion the model yields the outflow rates as a function of magnetospheric activity (Kp) in a quantitative fashion similar to Yau and André [1997]. Specifically, the heavy ion density is assumed to be 5% of the $H^+$ density when the total auroral current (integrated over the high latitude region) is less than 0.75 MA (low activity) and equal to the $H^+$ density at 20 MA (high activity), with a linear variation assumed between these two limits. As noted above, this form of heavy ion variations was developed from previous studies of ionospheric outflow correlated with the cross-polar cap potential where the total current is used as a proxy for electromagnetic flux and hot electron precipitation. The form was not fitted for the present storm study nor does it assume an empirical model such as the ones developed by Strangeway et al. [2005] and Zheng et al. [2005], but as shown in the following this variable ionospheric boundary condition is able to provide an excellent model for the observed cross-polar cap potential for this event. Simulations by Winglee et al. [2008] for quiescent solar wind conditions show an outflow rate that correlates well with observations when dynamic boundary conditions are included. The 18 March 1997 event was simulated and results were compared to observations from the Polar and Akebono satellites. Assuming a constant...
Ionospheric density profile led to an underestimation of the ionospheric outflow rate.


[16] Figure 1 shows the solar wind parameters as measured by the ACE spacecraft at L1. Arrival of the high speed flow starts at about 0545 UT at ACE. Over a period of about 2 h the solar wind speed increases from a typical speed of 525 km/s to nearly 2000 km/s. During this period, the density drops from about 13 cm$^{-3}$ to about 4 cm$^{-3}$, though the overall dynamic pressure of the solar wind increases.

[17] IMF $B_y$ on average is the dominant component. For the first 35 min between 0555 and 0630 UT it is strongly negative. At 0630 there is a rapid rotation where on average IMF $B_y$ stays positive for the next 75 min where it again flips sign. The $B_y$ component is much more variable, with sign or abrupt magnitude changes every 5–10 min. These swings in IMF $B_y$ are shown to be useful in providing insight into trigger mechanisms.

[18] The cross-polar cap potentials for the event as derived from AMIE and the multifluid model are shown in Figure 2. The AMIE potential shows slow rise in potential starting with the arrival of the fast solar wind and then reaches saturation at about 300 kV at about 0647 UT. It stays at this value until 0730 UT where there is a slow decline to more typical values of about 100 kV.

[19] The simulation potential has a much sharper rise than the AMIE results, indicating very fast penetration of the solar wind electric fields. The AMIE measurements are integrated over 10 min, and thus can not capture the short timescale changes seen by the model. The model can also sum over the entire polar cap while the AMIE results will be from measurements made from selected regions. This means that the absolute value of the cross polar cap potential determined from the model will be larger than that measured by AMIE. The faster penetration of the solar wind electric field is also seen in the very large swings in the cross-polar cap potential. If one were to time average through these swings, one would obtain smoothed profile that would resemble the AMIE results with a saturation potential of about 400 kV.

Figure 1. The solar wind conditions on 29 October 2003 as measured by ACE [Skoug et al., 2004]. The top panel is the solar wind density (dashed blue line) and speed (solid red line). The bottom panels are the components of the IMF. There is approximately a 20–10 min propagation time for the features seen in these plots to arrive at the Earth, when assuming a propagation speed of 1000 to 2000 km/s. The vertical dashed lines (A–F) show critical IMF features that drive key features in the cross-polar cap potential.
In order to determine the source of these large swings we examined the model results to determine the exact time when the features identified in Figure 1 arrive at the subsolar bow magnetopause. The derived timing is indicated by the vertical dashed lines in Figures 1 and 2. The peak at 0635 UT at 400+ kV is attributed to the penetration of the very negative southward IMF of Feature A into the polar cap, and this peak actually coincides with a small local maximum in the AMIE results. This maximum value is reached 10 min after the arrival of the strong southward IMF and also coincides with the end of this negative IMF Bz period. Though IMF Bz then becomes northward the cross-polar cap potential only drops by a small amount to about 300 kV.

The next big surge in the cross-polar cap potential is driven by the return of very negative Bz (seen at ACE at 0628 UT; dashed line B). Shortly after the arrival of this strong southward IMF, the largest potentials in the model of 600 kV occurs. Note that the rise of this very strong cross polar cap potential is cut short by IMF By flipping sign (as indicated by dashed line C). This is an important result in that is not just IMF Bz controlling the dynamics, but also rotations in IMF By are playing a significant role.

About 5–10 min later, the cross-polar cap potential recovers and starts to increase again under the influence of the strong negative IMF Bz. The potential reaches a saturation peak of about 500 kV at the end of this negative IMF Bz period as indicated by dashed line D. Though the IMF Bz then becomes northward it takes several minutes before the cross-polar potential finally responds and begins to decrease. The very short IMF By flip (dashed line E) shows as a very rapid decrease in the cross polar cap potential, and the potential stays relatively low despite the fact that the IMF Bz is on average slightly negative. At the dashed line F, the cross polar cap potential starts to increase again. This last increase appears to be driven by increase in the solar wind dynamic pressure, and overcomes the drop in potential that would be expected with a prevailing northward IMF Bz.

The total auroral field-aligned currents as shown in Figure 3 have a much smoother profile than the cross-polar cap potential. Such a smooth behavior would imply that the magnetosphere is behaving like an inductor, i.e., the energy is stored in magnetic field and the current can only vary slowly even though rapid changes in voltage are possible. Note also that there is an asymmetry in the upward and downward currents. This asymmetry arises in the presence of a dominant IMF Bz; predominantly dawnward IMF favors the upward (region 1) current/dusk convection cell while predominantly duskward IMF favors the downward (region 1) current/dawn convection cell.

After the initial rise in the auroral currents generated by the intense IMF negative Bz the total current is sustained at 15–25 MA until 0640 UT due to the presence of the very negative IMF Bz. At 0644UT (dashed line B) there is a major enhancement in the current, particularly the downward currents with the arrival of the very negative IMF Bz. This enhancement in the downward current field strength is cut short at 0650 UT (dashed line C) with the arrival in the flip in IMF Bz, which preferentially builds the downward currents. These downward currents continue to grow under the prevailing negative IMF Bz, though they reach their peak and start to decline about 5 min before IMF Bz becomes positive. There is a secondary enhancement starting at 0715 UT that coincides with a reduction in the cross-

![Figure 2.](image)
polar cap potential and then declines at 0736 UT associated with the northward turning of IMF Bz.

[25] The total flux of H\(^+\) and O\(^+\) coming out of the ionosphere at radial distance of 5 RE is shown in Figure 4. The average flux for both species averaged over the event is a few 10\(^{26}\) ions/s, is of order of that report Yau and André [1997] for disturbed conditions. However, the appearance of the very negative IMF Bz (dashed line B) produces a large spike in the ionospheric outflows, which is substantially modified by the IMF By flip (dashed line C). The outflow is eventually restored producing a secondary peak in the outflow that coincides with the peak in the downward auroral currents (Figure 3). Note that the H\(^+\) density at the inner boundary is kept constant through the simulations, so that the enhanced H\(^+\) outflows are purely convectively driven.

[26] The O\(^+\) density at the inner boundary is variable, and this allows the heavy ion outflows to essentially match the magnitude of the H\(^+\) outflow at the peak of the outflow. Note though that at early times, the O\(^+\) outflow is much smaller than the H\(^+\) outflow, whereas Yau and André [1997] would indicate that for moderately disturbed conditions the two outflows should be comparable and for very disturbed conditions the O\(^+\) outflow rate should exceed the H\(^+\) outflow rate. In other words the model boundary conditions could be underestimating the magnitude of the O\(^+\) outflows. A key point though is that the largest outflows from the model occur prior to 0703 UT, but we will demonstrate in the next sections that substantial energetic ions signatures are seen during both the injection period as well as several tens of minutes later. This indicates that prompt energetic particle signatures can be generated by acceleration of existing populations within the magnetosphere as opposed to having to wait for new populations to be pulled from the ionosphere for each event, except for the very first event.

4. HENA/Magnetospheric Mass Loading and Energization Comparisons: 0620–0710 UT

[27] In order to obtain an estimate of whether the model is yielding ionospheric outflows at the right time and in the right region, we compared the model predictions for mass loading of the magnetosphere with the IMAGE/HENA data to first validate the timing of the outflows. An example of this comparison is shown in Figure 5. Note that HENA gives a line of sight integration of energetic H\(^+\) and O\(^+\) convolved with neutral density profiles. It is beyond the model capabilities to provide such a line-of-sight integration since the neutral profile is unknown. Instead, we created a proxy by plotting a constant density surface of the different ion species within the magnetosphere, and then mapping onto the isosurface the energy of the particles in the region. This can be compared with HENA data because the energetic ions flowing out from the ionosphere will charge exchange with the background neutrals, creating the energetic neutrals measured by HENA. The two types of data are not identical, but instead are directly related. The ions outflow from the ionosphere, as indicated by the simulation results, will lead to neutrals originating near the Earth as measured by HENA. Additionally, the mean temperature of the outflowing ions in the simulation results (\(\sim 5–30\) keV) is high enough that the high-energy tail of the populations would create neutrals energetic enough to be measured by HENA. However, the actual values of neutral flux from the HENA should not be compared to the temperature of the surfaces shown for the simulation data. A similar method has been used previous by Winglee et al. [2005], yielding good correlation.

[28] The HENA observations are used in this analysis only to validate of the timing of ionospheric outflows seen
Figure 5. HENA observations and constant density surfaces from the simulations. The first column is HENA oxygen data and the third column is HENA low energy hydrogen data. The HENA images are for a ten minute interval listed on the left hand side. The second and fourth columns show surfaces of constant density equal to 1.3 cm$^{-3}$ for ionospheric oxygen and hydrogen, respectively, from the simulations at a time around those listed for the row. The color of the surface indicates the temperature of the bulk plasma. Also shown in the simulation data are magnetic fieldlines. The area shown for the simulation data is between ±21 RE along the y axis, and ±13 RE along the z axis. Along the x axis the area shown is between 17 RE on the dayside and 47 RE to 58 RE in the tail. The x, y and z axes in the simulation results are indicated both by the straight white lines in the images and the labels in the lower right corners in selected images. The axes follow the GSM convention.
in the simulation results. This is for two reasons, the first one being the inability of the model to determine neutral flux, as discussed above. The second reason is that during this time period, a background SEP haze is present in the images [P. Brandt, private communication]. This can be seen at the edge of the HENA images and it leads to increased uncertainty in value of the neutral flux. However, qualitative comparison between images for timing purposes is still possible.

The HENA O⁺ and H⁺ low energy data are shown in columns 1 and 3 of Figure 5, respectively, and the model results in columns 2 and 4. The energy range for the O⁺ HENA data shown is 52 keV to 180 keV, while the energy range for the H⁺ HENA data is 27 keV to 60 keV. The simulation results show the Earth from a static look angle that is approximately the same as the average look direction of the HENA detector, which changes in time but is focused on the southern polar cap. This simplifies comparison between plots. The simulation results show a more extended region around the Earth than the HENA data, encompassing both the inner and middle magnetosphere. This enables correlation between outflows seen in both the HENA data and the simulation results, while simultaneously indicating where the outflowing material travels to in the middle magnetosphere, which is not visible in the HENA images. It also facilitates establishing timing of the response of the magnetosphere to changes in the IMF.

Key features of the HENA data are that at the first time shown 0630–0639, there is already some brightening in the H⁺ observations but O⁺ is close to background levels. This timing is important because it is after the arrival of the first period of negative IMF Bz, and where the cross-polar cap potential, as determined by both AMIE and the global model, is substantially enhanced. In other words, it appears that O⁺ has a delayed response at the beginning of the event and the model reproduces this delayed response, both in terms of the total outflow rate (Figure 4) and the sphere of influence of O⁺ is very much smaller than that of H⁺ as seen in the top row of Figure 5.

In the next two time periods (0640–0649 and 0650–0659) there are intensification in H⁺ and O⁺ in the HENA data as well as the model results with the latter showing energetic ions not only in the tail but also on the dawn and dusk flanks. Within the next period 0700–0709 there is a reduction in the intensity of the HENA emissions, as well as a reduction in the size and intensity of the energetic populations in the model for both H⁺ and O⁺. This drop out occurs within a few minutes of IMF Bz turning positive and where the model shows a major reduction in the outflow of ionospheric H⁺ and O⁺.

The HENA data can not distinguish between hydrogen of ionospheric origin and hydrogen of solar wind origin, but the model can. Figure 6 shows the balance between plasma of solar wind origin and plasma of ionospheric origin. The left hand column (Figures 6a–6c) shows the ratio of the ionospheric hydrogen density to the solar wind density in the equatorial plane and at two locations downtail. The right hand column shows the log of the ratio of total ionospheric plasma pressure (both hydrogen and oxygen) to solar wind pressure at the same locations. The white contour line indicates a value of zero, or where the two quantities in the ratios are equal. The equatorial plane shows an area from 17.0 Re to −62.8 Re along x and ±21.2 Re along y. The cross-tail cuts show an area between ±21.2 Re along y and ±12.8 Re along z.

Figure 6. The left hand column shows the log of the ratio of the ionospheric hydrogen density to the solar wind density in the equatorial plane and at two locations downtail. The right hand column shows the log of the ratio of total ionospheric plasma pressure (both hydrogen and oxygen) to solar wind pressure at the same locations. The white contour line indicates a value of zero, or where the two quantities in the ratios are equal. The equatorial plane shows an area from 17.0 Re to −62.8 Re along x and ±21.2 Re along y. The cross-tail cuts show an area between ±21.2 Re along y and ±12.8 Re along z.
the ratio of total ionospheric plasma pressure (both hydrogen and oxygen) to solar wind pressure. The values are shown at a time just before Event 1 (Figures 6a and 6d), at the end of Event 1 (Figures 6b and 6e), and the end of Event 2 (Figures 6c and 6f). The figures show that prior to Event 1, ionospheric plasma dominates out past $5 \, \text{R}_E$ on the flanks and dayside and to about $13 \, \text{R}_E$ downtail. At the end of Event 1, the region dominated by ionospheric plasma compresses on the dayside but expands out to $8 \, \text{R}_E$ on the flanks and past $60 \, \text{R}_E$ downtail.

**Figure 7.** Constant density surfaces for oxygen (columns 1 and 2) and hydrogen (columns 3 and 4) as viewed from the dusk side (columns 1 and 3) and above the north pole (columns 2 and 4). The constant density isosurfaces are at the same value of $1.3 \, \text{cm}^{-3}$ as in Figure 5, but show a sequence with higher time resolution. The area shown is between $\pm 10 \, \text{R}_E$ over the poles, $\pm 16 \, \text{R}_E$ on the dawn and dusk flanks, $+10 \, \text{R}_E$ on the dayside and either $-26 \, \text{R}_E$ or $-35 \, \text{R}_E$ in the tail.
The agreement between the model proxy and the HENA data suggests that the outflows from the model are providing a reasonable estimate for magnetospheric conditions. We can therefore use the model results, at higher time resolution to obtain a better understanding of the influence of IMF perturbations on the magnetospheric dynamics. Plots of the evolution of the energetic O\(^+\) and H\(^+\) population at a 3 minute cadence are shown in Figure 7. As before, O\(^+\) is shown on the left hand side and H\(^+\) on the right hand side. For each species a side view as well as a top view is given. Sample field lines are shown in red. The isosurface extends out to the magnetopause so that field lines to the left of the isosurface are primarily magnetosheath field lines. The direction of the IMF at the magnetopause can then be inferred with predominantly north/south IMF field lines being clearly seen in the side view but not the top view, and similarly predominantly dawn/dusk IMF

**Figure 8.** Auroral currents in the northern polar cap (column 1) and ionospheric outflow of hydrogen (column 2) and oxygen (column 3) from the north pole. In all figures, red implies flux out of the polar cap and blue indicates flux into the polar cap. Figures employ the standard polar projection convention with noon at the top of the image and midnight at the bottom of the image. Latitudinal contours are in increments of 10°. The time for each row is indicated on the left hand side.
field would be most clearly visible in the top views but not the side views.

[34] Thus at 0650 UT (top panels of Figure 7) the IMF is predominantly in the southward direction at the magnetopause. The energetic populations in H\(^+\) are predominantly in the nightside, with some energetic components extending around beyond the terminator. The O\(^+\) as already noted appears smaller/delayed relative to the H\(^+\) response. At 0653 UT one sees the arrival of the flip in IMF \(B_y\) in the field line mapping. Because the magnetosphere is not in a configuration that matches the new IMF \(B_y\), there is excess plasma on the dusk side which is seen to be ejected tailward in both H\(^+\) and O\(^+\) profiles. Thus the IMF \(B_y\) rotation produces a prompt response on the existing plasma within the magnetosphere, and increases the area occupied by energetic ionospheric ions. By 0655, the IMF is entirely southward, and drives large outflows from the polar cap. At 0704 the flip from southward to northward IMF reaches the magnetopause and the polar outflow shuts off.

[35] The evolution of the auroral currents and ionospheric outflows from the northern hemisphere in a polar perspective are shown in Figures 8 and 9. During the interval shown in Figure 9, IMF \(B_y\) is very strongly negative, and this leads to the appearance of an asymmetric current system with the upward (red) region 1 currents on the dusk side being very much more intense than the downward

Figure 9. The same format as Figure 8, showing an additional portion of the time interval studied.
(blue) region 1 currents on the dawnside. When IMF $B_z$ becomes very negative the dayside currents intensify and move to the low latitudes (0640–0645 UT). For the protons, the source region of the ionospheric outflows is poleward of the region 1 currents, near the dayside cleft. The peak outflow rate of $H^+$ in each panel is approximately the same, and it is the area of the outflow that changes. For the $O^+$ the outflow position in MLT and ILAT are similar to that of the $H^+$ ions but at a substantially reduced level, at least initially. The outflow of $O^+$ has a rapid increase at 0645 that coincides with expansion and intensification of the auroral currents.

This change in flux can be understood as follows. The flux of $H^+$ is limited by the boundary conditions, i.e., the peak flux in any locale is determined by the inner boundary density and thermal velocity. The magnetosphere cannot draw more flux than this so that only a change in area can produce a net increase in total outflow rate. The magnetosphere though in storm time is capable of drawing as much flux as available. By allowing varying $O^+$ density at the inner boundary, that tracks current, the magnetosphere is able to pull this plasma out as soon as it becomes available in storm-time conditions. This outflow occurs near the cusp/cleft field lines where fast convecting field lines drive strong centrifugal acceleration.

The effect of the IMF $B_y$ rotation and northward turning of the IMF $B_z$ is shown in the follow-on sequence in Figure 9. The IMF $B_y$ rotation leads to an expansion of the dawn region 1 currents (0650 UT) and a reduction of the low altitude components of the dusk region 1 currents. Simultaneous with this alteration of the dayside region 1 currents, there is an expansion of the outflow region in both $H^+$ and $O^+$ to very low latitudes. An important consequence of this transient is that closed field lines are now loaded with substantial amounts of ionospheric plasma that aids in the preloading of the magnetosphere that can respond to future transients in the solar wind.

Within 5 min (0655 UT) the region 1 currents have a more typical configuration associated with a predominantly positive IMF $B_y$, the outflows return to just poleward of the region 1 currents, as well as being preferentially on the

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**Figure 10.** The same format as Figure 5, but now showing the time interval for the second outflow event.
The northward turning of IMF $B_z$, starting at 0700 UT, drives the reduction in the field aligned currents and outflows. The magnetic fields at this time (lower panels in Figure 7) appear very much more closed, aiding the confinement of the plasma to the inner magnetosphere. Also note the large ionospheric outflows near local noon, particularly at 0650 UT (Figure 9). Chi et al. [2005] calculated density enhancements in both the plasmasphere and the ionosphere during the entire Halloween superstorm interval and found enhanced densities at low latitudes during several of the events, including during the time period analyzed in this paper. Between 6UT and 8UT on 29 October, Chi et al. [2005] observed an enhancement in the equatorial density, although it was small compared to enhancements that occurred later in the superstorm. Similarly the model shows enhancements in the equatorial

Figure 11. The same format as Figure 7, but showing the beginning of the time interval shown in Figure 10.
density during this two hour period, in addition to outflows below 60° latitude.

5. HENA/Magnetospheric Mass Loading and Energization Comparisons: 0710–0800 UT

[40] On looking at the H+ and O+ profiles in Figure 4, a first guess might be that only during the period before 0703 UT should there be an intense signature in the energization of at least O+, since that is the time of the most intense ionospheric outflow, and if there is a signature in the protons, one could always argue that the protons are of solar wind origin and not ionospheric origin. However, this is not the case as demonstrated in Figures 6 and 10, with Figure 10 a continuation of Figure 5.

[41] In the last set of frames in Figure 5, the HENA observed fluxes are at a local minimum. In the top frames of Figure 10 (0710–0719 UT) the HENA fluxes in both O+ and H+ have again intensified. They then start to decrease (0720–0729) reaching a minimum at 0730–0739. There is then another intensification at 0740–0749 UT after which the HENA fluxes approach quiet conditions similar to levels just before the start of the event. The model results track the HENA intensifications including increases size in the nightside seen at both 0710–0719 and 0740–0749 UT.

[42] Note that during these intensifications the O+ from both the model and HENA data, track the H+ ions. In other words while there is a delay in the O+ response at the beginning of the event, O+ then tracks H+ indicating a prompt heavy ion response. The model results indicate that

Figure 12. The same format as Figure 11, but showing the remainder of the time interval shown in Figure 10.
this prompt response can occur because the magnetosphere is processing O+ that has already been convected into the magnetosphere. The ionospheric outflow rate, though much smaller than the peak rate, appears to make up for whatever losses of O+ occurs during the different intensifications. The sphere of influence of the ionospheric ions decreases to its pre-event size only near the very end of the period shown, with much of the ionospheric material from previous outflows traveling downtail.

[43] The timing for these two intensifications are correlated with the IMF Bz becoming moderately negative at −5 to −10 nT at event E and just before event F in Figures 1 and 2. At these intermediate values of southward IMF, the energization of the ionospheric ions occurs over a much more extended region than earlier, as illustrated in Figures 11 and 12. Figures 11 and 12 show the evolution of the model isosurface, again with a 3 minute cadence, showing more fully the mass loading and acceleration occurring within the magnetosphere. Expansion of the area of influence of the ionospheric ions is seen to start at around 0718 UT, reaches a maximum at 0724 UT, when it extends to 20 RE down the tail, and then shrinks at <8 RE by 0730 UT.

[44] The expansion of the source region is attributed to two effects. First the outflows during the period before

Figure 13. The same format as Figure 8, but showing a portion of the time interval in Figure 10.
0703 UT lead to ionospheric plasma over an extended volume within the magnetosphere, as can be seen in Figure 6. Second, IMF B\textsubscript{z}, while negative, is not extreme so that the current sheet is not heavily truncated by a very near-earth neutral line, which would lead to the rapid loss of plasma down the tail.

[45] The source region of the ions at this stage are shown in the polar plots in Figure 13. Because of the reduced outflows, the scale has been decreases by a factor of about 10 so that salient features can be seen more clearly. A key difference in the outflows is that the dawn and midnight sectors are relatively more important in producing the ionospheric outflows, particularly for H\textsuperscript{+}. Since the flows from these sectors enter the magnetosphere closer in than the cusp/cleft region, the outflows during this time go more toward refilling losses, as opposed to the massive outflows at the beginning of the event which would produce initial mass loading the of the magnetosphere. Indeed the strength of the outflows from the nightside maximize at the same time that the extended regions of energetic ions are seen in Figures 6, 11 and 12 in the tail, which would suggest refilling is occurring. This refilling would explain how prompt responses in energization of the ionospheric ions can occur during storm events.

6. Summary and Conclusions

[46] This paper continues the investigation of heavy ion interactions in the magnetosphere, utilizing a comparison between IMAGE/HENA data, AMIE cross-polar cap potential estimates and global multifluid modeling. The HENA data shows the timing of outflow of hot heavy ion populations, while the AMIE data gives an indication of the overall global response of the magnetosphere. The global multifluid modeling provides a full 3-D representation of the magnetosphere, which, when tied to the above data, can relate magnetospheric features to specific solar wind and IMF changes. This study focuses on the 29 October 2003 Halloween event, and allows us to address one of the outstanding issues of how are prompt responses to changes in solar wind conditions results from \textit{Yau and André} [1997]. However, the peak rate driven by the above IMF fluctuations can lead to an order on magnitude increase in the total ionospheric outflow. At these high outflow rates the magnetosphere experiences strong mass loading from ionospheric ions, particularly O\textsuperscript{+}. As a result, the model predicts that there are substantial ionospheric ions within the magnetosphere and solar wind/IMF changes then produce a prompt response in the energization of the ionospheric ions. This prompt response within the model is shown to be well correlated with the rise and fall of the HENA emissions. In other words, once the initial loading of the magnetosphere occurs, energization of O\textsuperscript{+} does not have to wait for it to flow out into the magnetosphere. Rather prompt responses occur by the energization of O\textsuperscript{+} already convected into the magnetosphere. The same conclusion was reached by \textit{Fok et al.} [2006] using particle tracking and time varying fields from an MHD simulation for substorm conditions on 28 October 2001.

[52] The ion losses that occur during each intensification appear to be replaced by the enhancement of the ionospheric outflows that occur simultaneously with the magnetospheric energization. For example in the present case study, for an hour period after the peak outflow, southward turning of IMF B\textsubscript{z} was shown to produce increased energetic H\textsuperscript{+} and O\textsuperscript{+} intensification simultaneous with increases in the HENA observed fluxes along with enhanced the ionospheric outflows from the auroral region. One significant difference in the outflows is that in this latter period the dawn and evening sectors are important components to the outflow whereas in the beginning of the event the cusp/cleft region was the dominant source. This difference enables the
reloading of the magnetosphere since the dawn and midnight sectors typically feed the magnetosphere at smaller radial distances than the cusp/cleft region (due to the mapping of field lines from these regions). This reloading would then explain the presence of extended ENA emissions not only for this event but would explain the extended ENA emissions noted by Reeves and Henderson [2001] for storm-time substorms, as opposed to isolated substorm ENA emissions.

[51] In summary we have demonstrated that while O+ outflows may lag H+ outflows at the start of an event, mass loading of the magnetosphere can lead to ionospheric populations within the magnetosphere that can experience prompt acceleration. The enhanced convective electric field that is driving this acceleration also leads to enhanced ionospheric outflows, which provide replacement of any accelerated plasma so that sustained prompt acceleration of heavy ions can occur over an extended period. The initial mass loading is supported by cusp/cleft outflows, while maintenance of the ionospheric ions within the magnetosphere is support by outflows from the nightside auroral regions as well as the dayside source. These results are not only important in understanding the source of the prompt response within storms, but also show that ionospheric ions, and in particular O+, are probably important factors controlling magnetospheric dynamics during active periods.

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References

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References