Temporal evolution of the transpolar potential after a sharp enhancement in solar wind dynamic pressure

A. Boudouridis,[1] E. Zesta,[1] L. R. Lyons,[1] P. C. Anderson,[2] and A. J. Ridley[3]

Received 27 August 2007; revised 13 November 2007; accepted 29 November 2007; published 17 January 2008.

[1] Recent studies of ionospheric convection have shown that sudden enhancements in solar wind dynamic pressure have significant effect on the transpolar potential and the coupling efficiency between the solar wind and the terrestrial magnetosphere. Super Dual Auroral Radar Network observations of the dayside convection have demonstrated that the strength of convection correlates well with solar wind dynamic pressure variations, implying an enhancement of dayside reconnection induced by changes in solar wind pressure. At the same time, dynamic pressure increases have been shown to lead to closing of the polar cap, particularly on the nightside, and thus directly drive enhanced tail reconnection. The enhanced dayside and nightside reconnection potentials can both lead to changes in the transpolar potential, but their individual contributions and the balance between the two is not known. We present a case study of the transpolar potential evolution after a long-lasting solar wind pressure step increase. We show that the potential first rises in response to the increase in pressure, then gradually subsides a few hours later despite the solar wind pressure remaining high. We interpret this behavior in terms of pressure-driven changes in dayside and nightside reconnection. **Citation:** Boudouridis, A., E. Zesta, L. R. Lyons, P. C. Anderson, and A. J. Ridley (2008), Temporal evolution of the transpolar potential after a sharp enhancement in solar wind dynamic pressure, *Geophys. Res. Lett.*, *35*, L02101, doi:10.1029/2007GL031766.

1. Introduction

[2] The significant effect of sudden enhancements in solar wind dynamic pressure to many aspects of magnetospheric dynamics has been amply demonstrated in the past few years [*Boudouridis et al.*, 2003, 2007; *Liou*, 2006, and references therein]. One of the results of a sudden increase in dynamic pressure is the enhancement of ionospheric convection as seen by several low-altitude Defense Meteorological Satellite Program (DMSP) spacecraft [*Boudouridis et al.*, 2004a, 2004b, 2005] and Super Dual Auroral Radar Network (SuperDARN) observations [*Boudouridis et al.*, 2007].

[3] For cases of southward interplanetary magnetic field (IMF) before and after the increase in pressure, *Boudouridis et al.* [2005] has shown that the solar wind/magnetosphere coupling efficiency increases after the pressure enhancement. They defined the coupling efficiency as the ratio of the transpolar potential (measured by DMSP spacecraft) to the potential in the undisturbed solar wind across the width of the magnetosphere (calculated from solar wind parameters). Their result suggests that the abrupt increase in dynamic pressure contributes to the ionospheric convection enhancement independently from any concurrent changes in the IMF. A recent statistical study by *Palmroth et al.* [2007] shows that the coupling efficiency, as defined by *Boudouridis et al.* [2005], increases on the average after pressure-front events with a concurrent decrease in the total IMF magnitude (slow type discontinuities), while it decreases after pressure-front events with a simultaneous increase in the total IMF magnitude (fast type discontinuities). The three cases studied by *Boudouridis et al.* [2005] exhibit either steady or decreasing total field magnitude and therefore are consistent with the results of *Palmroth et al.* [2007].

[4] One of the most striking effects of solar wind dynamic pressure fronts is the poleward expansion of the auroral oval and the closing of the polar cap observed over a wide range of Magnetic Local Times (MLTs), often with the exception of the near-noon region [*Boudouridis et al.*, 2003, 2004a, 2005]. This can range from a few degrees magnetic latitude (MLAT) up to 10° in some cases over certain MLT ranges. The dramatic shrinking of the polar cap suggests an enhancement of magnetotail reconnection induced by the pressure front [*Boudouridis et al.*, 2003, 2004a; *Milan et al.*, 2004; *Hubert et al.*, 2006]. *Hubert et al.* [2006] estimated the tail reconnection potential for two consecutive pressure front impacts. They found it to increase from initial values of ~30 kV and ~20 kV to 132 kV and 114 kV, respectively. *Milan et al.* [2004], studying a similar case, observed a reduction of the open magnetic flux in the Northern Hemisphere from 0.5 GWb to 0.2 GWb, down to 2.5% of the total hemispheric flux from a nominal value of 7–8%. They report a corresponding tail reconnection potential of 150 kV.

[5] Most recently *Boudouridis et al.* [2007] have investigated changes in dayside reconnection after impacts of solar wind dynamic pressure fronts by looking at dayside ionospheric convection changes using SuperDARN observations. They observed a significant increase in ionospheric velocities coinciding with the time of the pressure front impact. The flow enhancements were concentrated mostly near the expected location of the cusp in accordance with the prevailing direction of the IMF B_y component. Furthermore, for the two cases with southward IMF conditions throughout the pressure jump, the variations in the average flow magnitude follow the respective variations in solar wind pressure very closely, pointing to a definite association of the dayside convection with solar wind pressure. Con-

[1] Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA.
[2] Center for Space Sciences, University of Texas at Dallas, Richardson, Texas, USA.
[3] University of Michigan, Ann Arbor, Michigan, USA.

0094-8276/08/2007GL031766

sidering that the dayside poleward boundary of plasma sheet precipitation near the location of the observed convection enhancement did not move significantly during these two events [*Boudouridis et al.*, 2005], these results suggest a close connection between the dayside reconnection rate and the solar wind pressure.

[6] Observations therefore suggest that solar wind pressure fronts have a considerable effect on the global electrodynamics of the magnetosphere. Enhanced dayside and nightside reconnection compete in determining the size and shape of the polar cap, and may both contribute to changes in ionospheric convection and the transpolar potential. In this article we report on DMSP observations and Assimilative Mapping of Ionospheric Electrodynamics (AMIE) runs of the transpolar (or cross-polar-cap) potential for a long-lasting steplike increase in solar wind pressure on 30 April 1998. We seek to evaluate the temporal evolution of the transpolar potential for several hours after the increase in pressure and while the pressure remains high, and examine any possible connection to changes in dayside and nightside reconnection rates.

2. DMSP Potentials for 30 April 1998

[7] *Boudouridis et al.* [2004a] presented DMSP precipitating particle observations for the 30 April 1998 pressure-front event to demonstrate the nightside closing of the polar cap by about 5° MLAT. *Boudouridis et al.* [2004a] also showed solar wind pressure and IMF B_z measurements taken by three solar wind monitors, ACE, IMP8, and WIND. In the left plot of Figure 1 we show solar wind data from IMP8 taken at $X_{GSE} \sim 27\ R_E$. From top to bottom we plot IMF magnitude B, components B_y, B_z, solar wind velocity V_x, density N, and dynamic pressure P_{sw} in GSE coordinates. The pressure front reached IMP8 at ~0920 UT (~0925 UT for the magnetopause) marked with the black vertical line on the plot. At this moment the solar wind pressure increased from ~3 nPa to more than 12 nPa, and remained above 10 nPa until ~1345 UT. IMF B_z was weakly northward (~1 nT) before the increase in pressure and exhibited small-scale oscillations (~2–3 nT) around 0 nT during the entire high-pressure period after.

[8] Also marked in the same plot are four shaded intervals corresponding to four passes of DMSP F13 over the Southern Hemisphere oval and polar cap (the Northern Hemisphere DMSP flow data were of poor quality), before (B/blue) and after (A1/red, A2/green, and A3/orange) the pressure-front impact. DMSP F13 has a dawn-to-dusk orbit that crosses the southern polar region in ~15 min. During the 'before' pass (B), the spacecraft measures a low transpolar potential of 31 kV as expected for near-zero positive IMF B_z. Approximately 55 min after the increase in pressure, the first 'after' pass (A1) exhibits a more than doubling of the transpolar potential to 70 kV. However, despite the fact that the solar wind conditions do not vary substantially for the full 4 hours of high pressure, the second 'after' pass (A2), almost 2.5 hours after the front impact, shows a significant decline (~31% compared to the peak value measured) in the transpolar potential to 48 kV. This is still higher than the potential measured before the pressure enhancement, but significantly smaller than the initial response. On the last 'after' pass (A3), the spacecraft observes a further drop to ~40 kV even though the solar wind pressure is still high and IMF B_z begins to turn southward. This value includes ~10 kV of voltage resulting from interpolating over 1 min of missing data during this orbit. It should be mentioned that the DMSP potentials are a lower limit to the true transpolar potential since the satellite orbit might not pass through the peaks of the potential distribution. However, for orbits that reach above 75° MLAT, like the ones in our example, the DMSP-measured potential comes to within 80% or more of the true potential drop [*Hairston et al.*, 1999]. The DMSP measurements are summarized in Table 1.

3. AMIE Potentials for 30 April 1998

[9] The AMIE technique [*Richmond and Kamide*, 1988] utilizes a large number of observations from various sources (ground magnetometers, DMSP satellites, and radars) to determine the high-latitude convection pattern by means of a weighted, least squares fit of coefficients. It yields a number of desired ionospheric electrodynamics quantities including transpolar potential, hemispheric power (HP, a measure of auroral precipitation power), Joule heating (JH), AE and D_{st} indices [e.g., *Ridley et al.*, 1998; *Kihn et al.*, 2006].

[10] For our case study, AMIE was run with 1-min resolution using only ground magnetometers (with the number of stations varying from 116 to 119). In the right plot of Figure 1, AMIE results are shown for the same interval as in the left panel. From top to bottom the AMIE derived D_{st}, AE, JH, HP, and transpolar potential $\Delta\Phi_{PC}$ are plotted. The shaded areas correspond again to the DMSP F13 passes over the Southern Hemisphere polar region discussed above. All quantities computed by AMIE respond to the increase in solar wind pressure immediately or shortly after ~0925 UT, indicating increased energy input to the high-latitude ionosphere. In this study we concentrate on the behavior of the transpolar potential (bottom plot).

[11] The AMIE transpolar potential $\Delta\Phi_{PC}$ shows a remarkable qualitative agreement with the DMSP-measured potentials (shown as black diamonds in the same plot). The potential first exhibits a sharp spike that lasts ~15 min. This could be the result of a transient solar wind feature such as the increase of the IMF B_y component to ~−4 nT immediately after the increase in pressure. However, the long-term evolution of the transpolar potential is of more interest

Figure 1. (left) Solar wind data for 07–15 UT on 30 April 1998 taken by IMP8 located ~27 R_E upstream of the Earth. The black vertical line marks the pressure front which reached IMP8 at ~0920 UT (~0925 UT for the magnetopause). The four shaded intervals correspond to DMSP F13 polar passes over the Southern Hemisphere, before (B/blue) and after (A1/red, A2/green, and A3/orange) the increase in pressure. (right) AMIE output for the same period. Shown, from top to bottom, are computed D_{st}, AE, Joule heating (JH), hemispheric power (HP), and transpolar potential $\Delta\Phi_{PC}$. The DMSP potential measurements are also shown in the bottom panel as black diamonds for comparison.

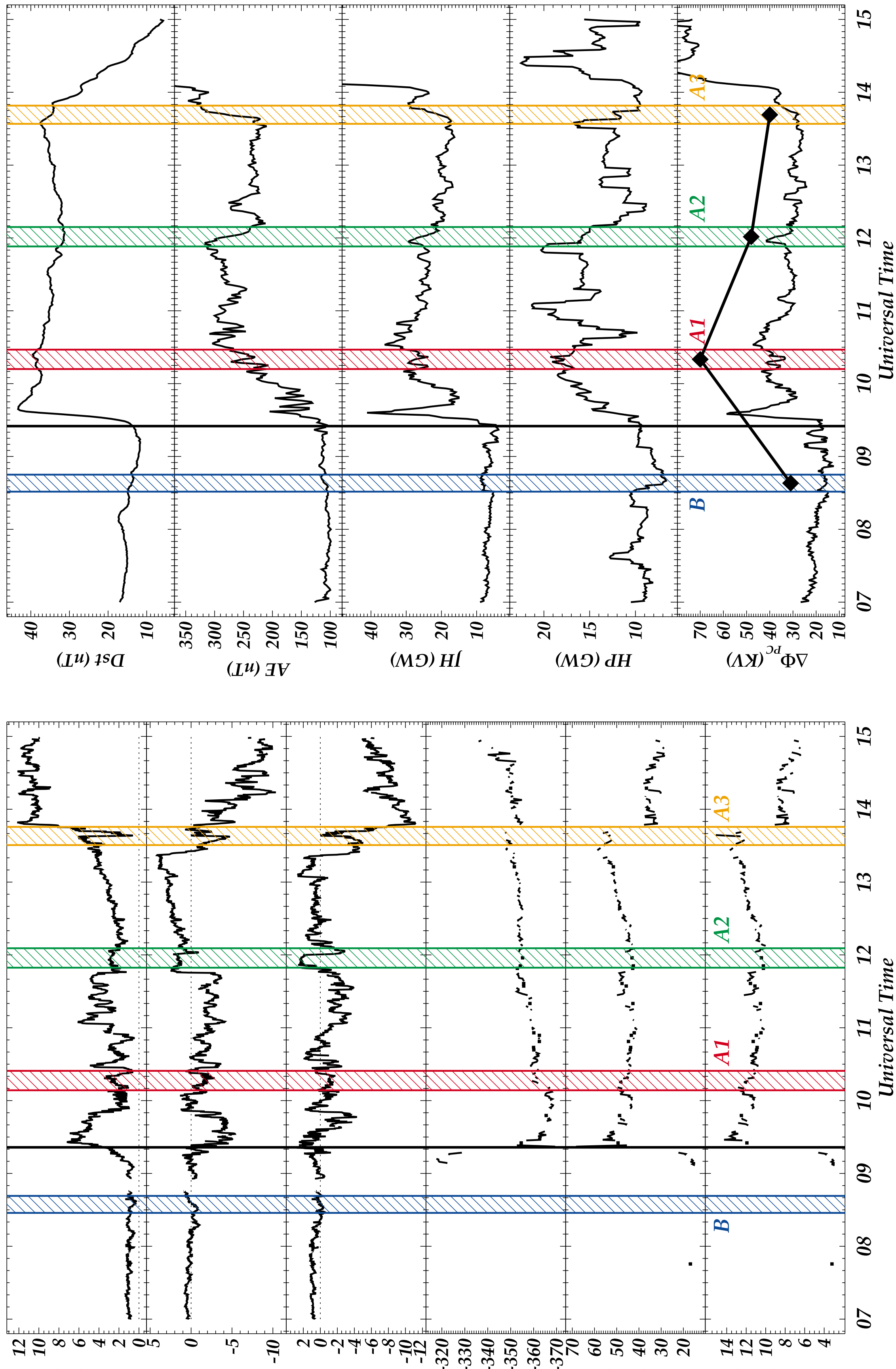
B (nT)
By (nT)
Bz (nT)
Vx (km/s)
N (cm⁻³)
Psw (nPa)
Dst (nT)
AE (nT)
JH (GW)
HP (GW)
ΔΦ_PC (KV)
B
A1
A2
A3
Universal Time
Universal Time

Figure 1

Table 1. DMSP and AMIE Potencials on 30 April 1998

Orbit	UT Range	P_{sw}, nPa	DMSP Potential	AMIE Potential
B	0831–0845	2.4 (WIND)	31 kV	17 kV
A1	1012–1028	11.8 (IMP8)	70 kV	40 kV
A2	1153–1209	10.5 (IMP8)	48 kV	34 kV
A3	1334–1349	12.9 (IMP8)	40 kV	30 kV

to the present study. The AMIE potential is first seen rising, reaching ~40 kV at around 1020 UT, approximately the same time that DMSP F13 measured a potential of 70 kV. This is a 135% increase from a pre-front value of ~17 kV as compared to a 126% increase observed by the DMSP. The potential then starts to decrease slowly measuring ~34 kV and ~30 kV during the DMSP A2 and A3 orbits, respectively, compared to 48 kV and 40 kV measured by F13. The AMIE potentials are shown in the last column of Table 1.

[12] The temporal evolution of the AMIE potentials is similar to that of the DMSP-measured potentials, first rising to a maximum in about an hour after the increase in pressure, then dropping slowly to a lower value over a period of 2–3 hours. Notice also that the AMIE potentials do not return to their prefront values, exhibiting a residual effect, as is also observed in the DMSP potentials. The absolute values of the AMIE potentials, however, are lower than those measured by the DMSP. This seems to be a consistent feature of the AMIE potentials as has been shown recently by *Kihn et al.* [2006] who found them to be about 30–50% lower than the DMSP potentials in a large statistical study. The maximum transpolar potential measured by AMIE for our case was 40 kV, 43% lower than the equivalent DMSP-measured potential of 70 kV, well within the statistical bias found by *Kihn et al.* [2006].

4. Summary and Discussion

[13] We presented observations associated with a sudden step increase in solar wind dynamic pressure. This case is unusual in that the dynamic pressure remained elevated and nearly constant under relatively steady IMF conditions for ~4 hours, allowing us to evaluate the internal long-term response of the magnetosphere-ionosphere system following the pressure enhancement. We examined the temporal evolution of the transpolar potential measured with two different methods, low-altitude DMSP spacecraft measurements and the AMIE technique. Both methods show the potential more than doubling, reaching a maximum about an hour after the pressure enhancement. Despite the solar wind and IMF conditions then remaining relatively steady, in the next 2.5 hours the potential slowly decreased from its peak value but still ended up at a value higher than its prefront level.

[14] *Boudouridis et al.* [2007] studied the response of dayside ionospheric convection after an abrupt step increase in solar wind dynamic pressure on 19 February 1999 using SuperDARN convection data. They showed that an enhancement of dayside reconnection is initiated by the pressure increase, and that the enhanced dayside reconnection rate remains high while the solar wind pressure is high. Such an increase of dayside reconnection leads to an increased transpolar potential. Since the enhanced reconnection correlates well with the pressure variation in the case presented by *Boudouridis et al.* [2007], we expected that if the transpolar potential increase was due solely to the enhancement of dayside reconnection, then the potential would remain high while the solar wind pressure stays high for the 30 April 1998 pressure front too. This is not the case for this event. *Ober et al.* [2006] suggested a transient inductive response of the dayside reconnection rate to an increase in pressure. In their scenario the transpolar potential behavior is well characterized by an L-R circuit equation derived from integrating Faraday's law around the Region 1 current loop. The potential first rises quickly after the increase in pressure, and then returns slowly to previous levels in the course of ~15 min. This response was verified for the 30 April 1998 event also using the AMIE technique [*Ober et al.*, 2007]. The 15 min response time is much shorter than the 3–4 hours found here, though it could account for the 15 min sharp spike observed by AMIE at ~0930 UT. It is therefore clear that enhanced dayside reconnection alone cannot fully account for the transpolar potential evolution seen after the step increase in solar wind dynamic pressure for this event.

[15] *Boudouridis et al.* [2004a], based on DMSP observations of the closing of the polar cap after a pressure enhancement, suggested that a solar wind pressure front can also induce enhanced magnetotail reconnection. The enhanced tail reconnection might have a limited lifetime, as evidenced by the fact that the nightside closing of the polar cap does not continue indefinitely after a pressure increase. The initial fast poleward motion of the polar cap boundary on the nightside, and the subsequent decrease of its poleward speed have been observed by DMSP spacecraft for the 30 April 1998 event. *Boudouridis et al.* [2004a] have shown that the nightside polar cap boundary moved poleward by ~5° to ~77° MLAT, as observed by DMSP F11 at 0946–1000 UT. DMSP F13, passing over the same region at 1012–1028 UT observed the same boundary above 80° MLAT. Subsequent F11 and F13 orbits from 1126 UT to 1349 UT showed the polar cap boundary located at the vicinity of 80° MLAT with no further poleward motion. Thus after the magnetosphere adjusts to a new compressed state, the increased reconnection rate in the tail might slowly fade away.

[16] In addition to reducing the size of the polar cap, it has been suggested [e.g., *Cowley and Lockwood*, 1992; *Boudouridis et al.*, 2005] that magnetotail reconnection may contribute to ionospheric convection and the transpolar potential. If true then magnetotail reconnection might contribute to the enhanced ionospheric convection observed immediately after an increase in solar wind dynamic pressure [*Boudouridis et al.*, 2004a, 2005; *Hubert et al.*, 2006]. If the observed convection enhancement after a solar wind pressure increase is related in part to the enhanced tail reconnection, it would also exhibit a transient behavior, despite the fact that solar wind and IMF conditions remain relatively steady. If instead it were related solely to external forcing, i.e., high solar wind pressure through an enhancement of dayside reconnection, it should remain steadily high throughout the high-pressure environment as observed by *Boudouridis et al.* [2007] locally near the dayside cusp.

[17] Our case study supports the transient nature interpretation and thus suggests a combined contribution to the transpolar potential from both dayside and nightside reconnection after a sharp enhancement in solar wind dynamic pressure. The enhanced dayside reconnection provides a steady contribution varying proportionally to the enhanced pressure. The nightside reconnection on the other hand provides a transient component that manifests as an initial increase of the transpolar potential which then fades away in a few hours when the tail reconnection rate returns to lower values. They both might be modulated by other factors, such as the background IMF conditions or the pressure-front characteristics, and hence their timescales and/or magnitudes may vary from case to case. There is also evidence that there remains a residual effect on the transpolar potential during the high-pressure regime that can possibly be associated with dayside reconnection, nightside reconnection, or both. Our observations also suggest that models which parameterize the state of the magnetosphere as a function of instantaneous solar wind and IMF conditions may lack an important aspect of magnetospheric dynamics, as they do not take into account long term effects (a few hours in duration) like the one discussed here.

[18] Another important issue is how dayside and nightside reconnection combine to produce the observed transpolar potential after a sharp increase in solar wind pressure. Does one dominate at any single time or both contribute at all times? In other words, is the transpolar potential controlled by the maximum of the two reconnection rates or is it always a function of both processes? A possible way to test the relative importance of dayside/nightside reconnection would be to use SuperDARN convection data during events with simultaneous dayside/nightside coverage, and concurrent polar cap boundary determinations from auroral images. Additional events are needed to establish the consistency of our results and the connection between solar wind dynamic pressure fronts, enhanced dayside/nightside reconnection, and the temporal evolution of the transpolar potential.

[19] **Acknowledgments.** We acknowledge A. Szabo and R. P. Lepping at NASA GSFC, A. Lazarus at MIT, and CDAWeb for the use of IMF and plasma data from the IMP8 spacecraft. This work was supported by NASA grants NAG5-12007, NNG05GF29G, and NNX06AB89G, and NSF grants ARC-0611717 and ATM-0646233.

References

Boudouridis, A., E. Zesta, L. R. Lyons, P. C. Anderson, and D. Lummerzheim (2003), Effect of solar wind pressure pulses on the size and strength of the auroral oval, *J. Geophys. Res.*, *108*(A4), 8012, doi:10.1029/2002JA009373.

Boudouridis, A., E. Zesta, L. R. Lyons, P. C. Anderson, and D. Lummerzheim (2004a), Magnetospheric reconnection driven by solar wind pressure fronts, *Ann. Geophys.*, *22*, 1367–1378.

Boudouridis, A., E. Zesta, L. R. Lyons, and P. C. Anderson (2004b), Evaluation of the Hill-Siscoe transpolar potential saturation model during a solar wind dynamic pressure pulse, *Geophys. Res. Lett.*, *31*, L23802, doi:10.1029/2004GL021252.

Boudouridis, A., E. Zesta, L. R. Lyons, P. C. Anderson, and D. Lummerzheim (2005), Enhanced solar wind geoeffectiveness after a sudden increase in dynamic pressure during southward IMF orientation, *J. Geophys. Res.*, *110*, A05214, doi:10.1029/2004JA010704.

Boudouridis, A., L. R. Lyons, E. Zesta, and J. M. Ruohoniemi (2007), Dayside reconnection enhancement resulting from a solar wind dynamic pressure increase, *J. Geophys. Res.*, *112*, A06201, doi:10.1029/2006JA012141.

Cowley, S. W. H., and M. Lockwood (1992), Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system, *Ann. Geophys.*, *10*, 103–115.

Hairston, M. R., D. R. Weimer, R. A. Heelis, and F. Rich (1999), Analysis of the ionospheric cross polar cap potential drop and electrostatic potential distribution patterns during the January 1997 CME event using DMSP data, *J. Atmos. Sol. Terr. Phys.*, *61*, 195–206.

Hubert, B., M. Palmroth, T. V. Laitinen, P. Janhunen, S. E. Milan, A. Grocott, S. W. H. Cowley, T. Pulkkinen, and J.-C. Gérard (2006), Compression of the Earth's magnetotail by interplanetary shocks directly drives transient magnetic flux closure, *Geophys. Res. Lett.*, *33*, L10105, doi:10.1029/2006GL026008.

Kihn, E. A., R. Redmon, A. J. Ridley, and M. R. Hairston (2006), A statistical comparison of the AMIE derived and DMSP-SSIES observed high-latitude ionospheric electric field, *J. Geophys. Res.*, *111*, A08303, doi:10.1029/2005JA011310.

Liou, K. (2006), Global auroral response to interplanetary media with emphasis on solar wind dynamic pressure enhancements, in *Recurrent Magnetic Storms: Corotating Solar Wind Streams*, *Geophys. Monogr. Ser.*, vol. 167, edited by B. Tsurutani et al., pp. 197–212, AGU, Washington, D. C.

Milan, S. E., S. W. H. Cowley, M. Lester, D. M. Wright, J. A. Slavin, M. Fillingim, C. W. Carlson, and H. J. Singer (2004), Response of the magnetotail to changes in the open flux content of the magnetosphere, *J. Geophys. Res.*, *109*, A04220, doi:10.1029/2003JA010350.

Ober, D. M., G. R. Wilson, N. C. Maynard, W. J. Burke, and K. D. Siebert (2006), MHD simulation of the transpolar potential after a solar-wind density pulse, *Geophys. Res. Lett.*, *33*, L04106, doi:10.1029/2005GL024655.

Ober, D. M., G. R. Wilson, W. J. Burke, N. C. Maynard, and K. D. Siebert (2007), Magnetohydrodynamic simulations of transient transpolar potential responses to solar wind density changes, *J. Geophys. Res.*, *112*, A10212, doi:10.1029/2006JA012169.

Palmroth, M., N. Partamies, J. Polvi, T. I. Pulkkinen, D. J. McComas, R. J. Barnes, P. Stauning, C. W. Smith, H. J. Singer, and R. Vainio (2007), Solar wind-magnetosphere coupling efficiency for solar wind pressure impulses, *Geophys. Res. Lett.*, *34*, L11101, doi:10.1029/2006GL029059.

Richmond, A. D., and Y. Kamide (1988), Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique, *J. Geophys. Res.*, *93*, 5741–5759.

Ridley, A. J., G. Lu, C. R. Clauer, and V. O. Papitashvili (1998), A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique, *J. Geophys. Res.*, *103*, 4023–4039.

P. C. Anderson, Center for Space Sciences, University of Texas at Dallas, Richardson, TX 75080, USA.

A. Boudouridis, L. R. Lyons, and E. Zesta, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095, USA. (thanasis@atmos.ucla.edu)

A. J. Ridley, University of Michigan, Ann Arbor, MI 48109, USA.