



AFRL-AFOSR-JP-TR-2018-0009

Multi-instrument investigation of ionospheric flow channels and their impact on the ionosphere and thermosphere during geomagnetic storms

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12/29/2017
Final Report

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REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 31-01-2018		2. REPORT TYPE Final		3. DATES COVERED (From - To) 30 Sep 2016 to 29 Sep 2017		
4. TITLE AND SUBTITLE Multi-instrument investigation of ionospheric flow channels and their impact on the ionosphere and thermosphere during geomagnetic storms				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER FA2386-16-1-4127		
				5c. PROGRAM ELEMENT NUMBER 61102F		
6. AUTHOR(S) Ildiko Horvath				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) THE UNIVERSITY OF QUEENSLAND UNIVERSITY OF QUEENSLAND BRISBANE, 4072 AU				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-JP-TR-2018-0009		
12. DISTRIBUTION/AVAILABILITY STATEMENT A DISTRIBUTION UNLIMITED: PB Public Release						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT During this 12-month project, we conducted detailed investigations on various processes occurring in the coupled system of Solar Wind, Magnetosphere, Ionosphere, and Thermosphere during geomagnetic storms/substorms. These efforts are documented in a series of journal articles [Horvath and Lovell, 2017A; 2017B; 2017C; 2017D]. Our findings contribute to the better understanding of some of the underlying physical processes. This improved understanding fills some existing gaps in the community knowledgebase, adds directly to the MURI-IT project and the ongoing sub-auroral and polar investigations carried out at AFRL, and thus provides advancement in the field of space science. Augmenting our data processing and computational capabilities, we developed two software packages to process GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite data. We also created a series of computer algorithms to compute the numerical values of (i) Poynting flux (S_{\parallel} ; mV/m ²) by utilizing DMSP data and (ii) field-aligned current (FAC) density (J_{\parallel} ; A/m ²) by employing solar wind and interplanetary magnetic field (IMF) data. We investigated a number of geomagnetic storms and some magnetically active and quiet periods.						
15. SUBJECT TERMS Magnetosphere, Ionosphere, Thermosphere, Flow Channel, Poynting flux, Sub-auroral polarization stream						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON WINDER, SHEENA	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) +81-42-511-2008	

Final Report for AOARD Grant FA2386-16-1-4127
Multi-instrument investigation of ionospheric flow channels and their impact on the
ionosphere and thermosphere during geomagnetic storms
Date: 29 December 2017

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Period of Performance: 30 September 2016 to 29 September 2017

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I.) Abstract:

During this 12-month project, we conducted detailed investigations on various processes occurring in the coupled system of Solar Wind, Magnetosphere, Ionosphere, and Thermosphere during geomagnetic storms/substorms. These efforts are documented in a series of journal articles [Horvath and Lovell, 2017A; 2017B; 2017C; 2017D]. Our findings contribute to the better understanding of some of the underlying physical processes. This improved understanding fills some existing gaps in the community knowledgebase, adds directly to the MURI-IT project and the ongoing sub-auroral and polar investigations carried out at AFRL, and thus provides advancement in the field of space science.

Augmenting our data processing and computational capabilities, we developed two software packages to process GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite data. We also created a series of computer algorithms to compute the numerical values of (i) Poynting flux (S_{\parallel} ; mV/m^2) by utilizing DMSP data and (ii) field-aligned current (FAC) density (J_{\parallel} ; $\mu\text{A/m}^2$) by employing solar wind and interplanetary magnetic field (IMF) data. We investigated a number of geomagnetic storms and some magnetically active and quiet periods.

Our investigations cover (A) the 24 August 2005 strong geomagnetic storm ($\text{Dst} \approx -180$ nT) when various types of localized neutral density increases or density spikes developed that had not been investigated by previous studies, (B) the 25 September 2000 medium geomagnetic storm ($\text{Dst} \approx -30$ nT) that is well known for its density spike development and that we compared with the magnetically quiet day of 2 March 2006 when the density spikes were absent, (C) the 18-23 September 2003 magnetically active period when, unusually, some inverted sub-auroral ion drifts (SAID) appeared repeatedly -called abnormal SAID or ASAI- of which development is still not clear, and finally (D) the 5-6 August 2011 geomagnetic storm ($\text{Dst} \approx -126$ nT) when energy deposition events occurring deep in the polar cap region, of which underlying physical processes are still unclear, led to the development of their resultant localized neutral density increases.

Our respective significant results (A) specify the density spikes related FAC systems, flow channel types and auroral forms, (B1) demonstrate the link between the density spike of interest and its underlying flow channel and divergent poleward-equatorward flows, (B2) confirm the absence of thermospheric upwelling events and resultant density spikes on 2 March 2006 based on CHAMP and GRACE observations, (B3) identify some characteristic chemical composition signatures related to the presence and absence of cusp enhancements/density spikes by employing NRLMSISE-00 simulations, (C) provide observational evidence that ASAI developed due to the northward IMF B_z or dominating B_y component creating overshielding conditions and that ASAI became enhanced by the westward travelling surge (WTS), and finally (D) demonstrate that Poynting flux increases occurred in a FC-2 type flow channel during magnetopause reconnection and in a FC-4 type flow channel during lobe reconnection.

II.) Investigations carried out:

(1) Investigating the development of localized neutral density increases during the 24 August 2005 geomagnetic storm. *Journal of Geophysical Research: Space Physics*, 122, 11,765–11,783. <https://doi.org/10.1002/2017JA024362>.

Introduction:

During the evolution of 24 August 2005 intense geomagnetic storm ($Dst \approx -175$ nT), some intensive localized coupling events occurred in the dayside ionosphere under northward and southward B_Z conditions and continuous B_Y domination. These had been investigated by various studies such as (1) Li et al. [2011] reporting high-latitude hemispheric Joule heating differences, (2) Wilder et al. [2012] describing some strong sunward drifts and associated FAC/Joule heating increases, (3) Crowley et al. [2010] observing some isolated heating occurring near the northern magnetic pole, and (4) Peng et al. [2011] suggesting the association of auroral brightening and density spike.

Crowley, G., D. J. Knipp, K. A. Drake, J. Lei, E. Sutton, and H. Lühr (2010), Thermospheric density enhancements in the dayside cusp region during strong BY conditions, *Geophys. Res. Lett.*, 37, L07110, doi:10.1029/2009GL042143.

Li, W., D. Knipp, J. Lei, and J. Raeder (2011), The relation between dayside local Poynting flux enhancement and cusp reconnection, *J. Geophys. Res.*, 116, A08301, doi:10.1029/2011JA016566.

Peng, Z., C. Wang, Y. Q. Hu, J. R. Kan, and Y. F. Yang (2011), Simulations of observed auroral brightening caused by solar wind dynamic pressure enhancements under different interplanetary magnetic field conditions, *J. Geophys. Res.*, 116, A06217, doi:10.1029/2010JA016318.

Wilder, F. D., G. Crowley, S. Eriksson, P. T. Newell, and M. R. Hairston (2012), Ionospheric Joule heating, fast flow channels, and magnetic field line topology for IMF By-dominant conditions: Observations and comparisons with predicted reconnection jet speeds, *J. Geophys. Res.*, 117, A11311, doi:10.1029/2012JA017914.

Results and Conclusions:

In this study, reported in Horvath and Lovell [2017A], we focused on the 24 August 2005 storm ($Dst \approx -175$ nT) in order to provide some detailed experimental observations by utilizing CHAMP and GRACE neutral wind data plus correlated DMSP F13 and F15 multi-instrument measurements and Wide-Band Imaging Camera (WIC) images taken by the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite. We investigated a number of scenarios that show (1) a northern density spike associated with enhanced antisunward polar flows driven by dayside merging along old-open field lines during the storm initial phase, (2) some southern density spikes associated with enhanced sunward auroral flows caused by auroral brightening events during the storm initial phase and main phase (see Figure 1), (3) a dayside-nightside density spike configuration associated with enhanced eastward (or antisunward) polar flows caused by their respective dayside merging and nightside magnetotail reconnection occurring commonly along old-open field lines during the underlying substorm activity (see Figure 2), and (4) a series of enhanced polar sunward flows developed in the polar cap driven by different process during the recovery phase.

From the results obtained we concluded that (1) the hemispheric differences observed were due to the different underlying magnetic activity producing different types of flow channels and FACs. (2) The pulsed sunward flows appearing during the recovery phase were related to (i) a polar FC-4 type flow channel associated with L1-L2 FACs and polar arcs originating from the morning oval at $B_Z > 0$, and to (ii) a combined FC-1—FC-2 flow channel associated with R0-R1 FACs and prenoon poleward moving auroral forms at $B_Z \leq 0$. (3) There was significant energy/momentum deposition along both newly-open and old-open magnetic field lines leading to density spike development at auroral latitudes and in the polar cap including its central region near the magnetic pole. (4) The various density spikes investigated were associated with various auroral/polar forms (auroral brightenings, auroral arcs/polar arcs, prenoon poleward moving auroral forms) via the oppositely directed and enhanced FACs connecting in various types of flow channels above/within which these density spikes developed.

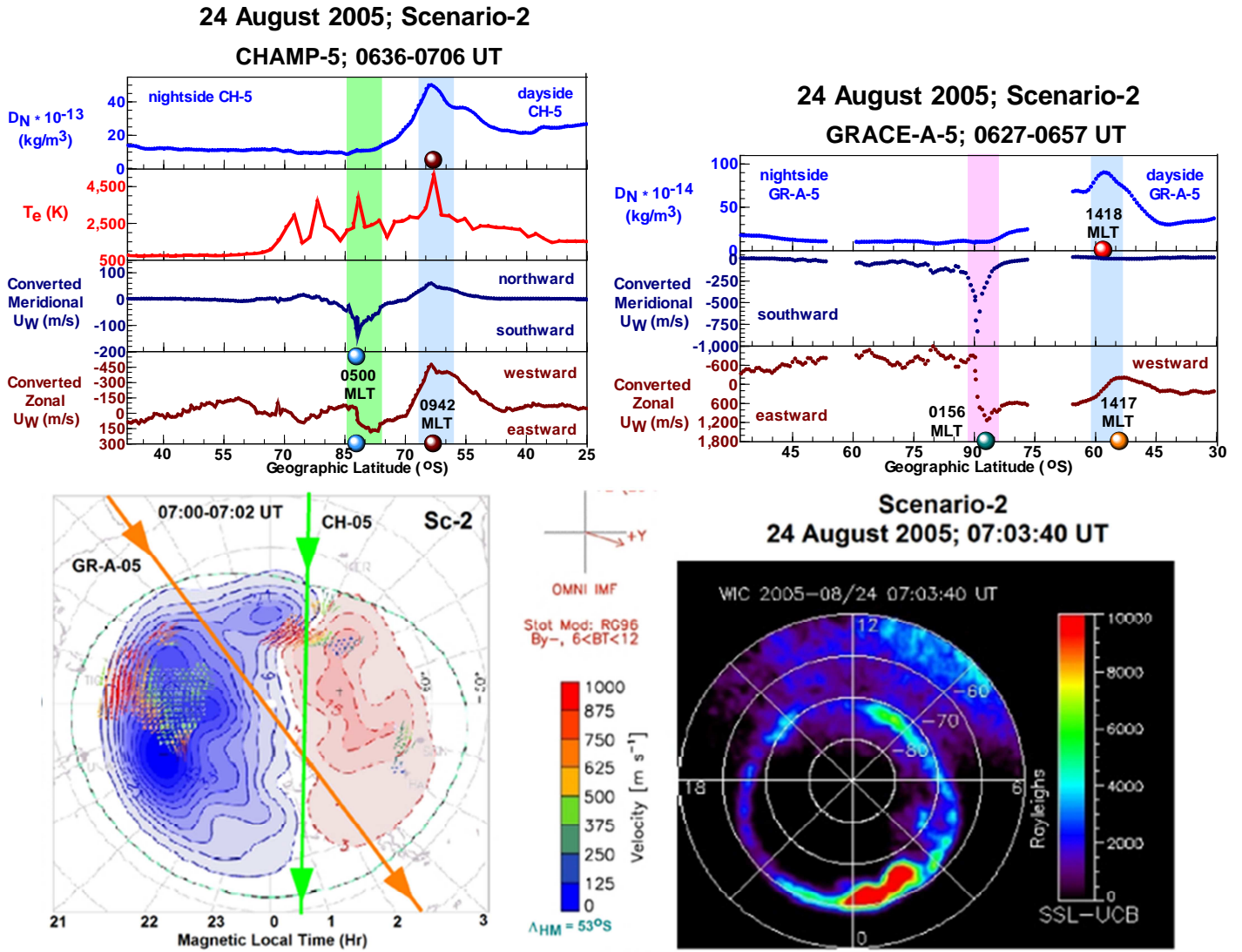


Figure 1: The multi-instrument [top left panel] CHAMP and [top right panel] GRACE observations show two density spikes (indicated as shaded intervals in blue) at 0942 and 1417 MLT respectively with their underlying westward (or sunward) flow channels. [bottom left panel] The Super-DARN convection map shows the ground tracks of these CHAMP and GRACE passes, and the enhanced sunward flows (indicate in red) underlying the density spikes. [bottom right panel] The IMAGE WIC picture shows the associated auroral brightening event.

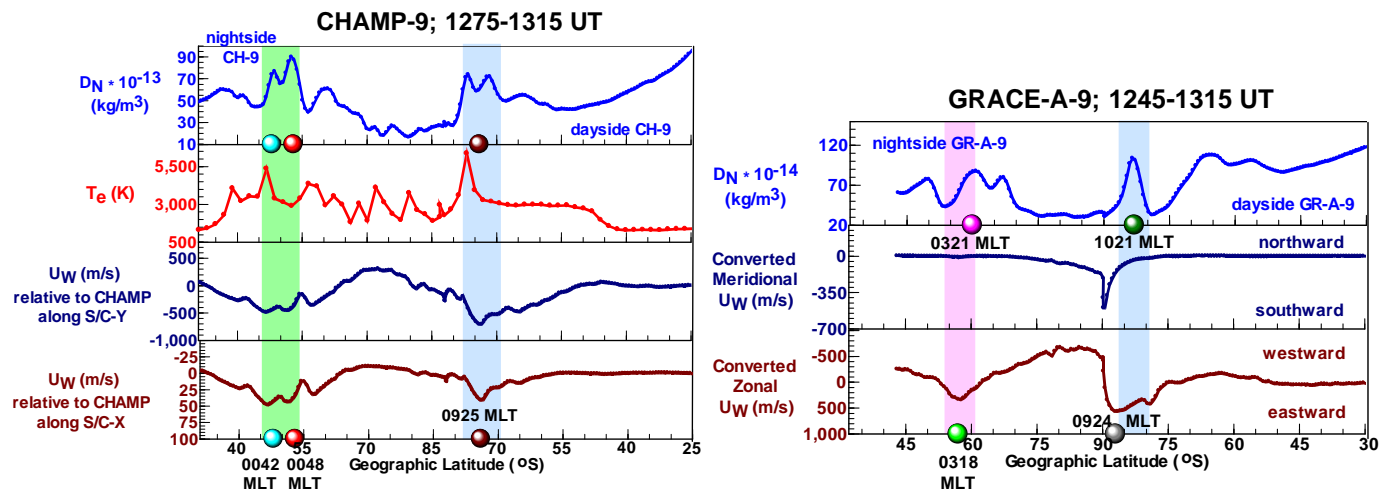


Figure 2: Correlated [left panel] CHAMP and [right panel] GRACE multi-instrument observations show a dayside-night-side density spike configuration and the underlying eastward (or antisunward) flow channels that are the signatures of dayside magnetopause and nightside magnetotail reconnections respectively. The daytime density spikes (indicated as shaded intervals in blue) occurred at 0925 and 1021 MLT, while the nighttime density spikes (indicated as shaded intervals in green and magenta) appeared at around magnetic midnight and ~0318 MLT respectively.

(2) High-latitude neutral density structures investigated by utilizing multi-instrument satellite data and NRLMSISE-00 simulations (J. Geophys. Res. Space Physics; doi: 2017JA024600; under review)

Introduction:

For magnetically quiet conditions, Clemmons et al. [2008] investigated the thermosphere over the southern dayside cusp by utilizing Streak data collected at ~250 km altitude, but Streak did not detect large (~30%) cusp enhancements, like CHAMP did at ~400 km altitude on the moderately active day of 25 September 2000 [Lühr et al., 2004]. Streak detected minor (~2%) cusp enhancements and depletions on 2 March 2006. These 2 March 2006 Streak observations appeared to be a major challenge to the Lühr et al. [2004] given explanation of the 25 September 2000 density spike development based on neutral gas upwelling due to Joule heating fueled by ionospheric currents in the E-region. However, no 2 March 2006 CHAMP/GRACE observations are shown by Clemmons et al. [2008] to justify this challenge with direct high-altitude observations and to compliment the lower-altitude Streak detections.

Clemmons, J. H., J. H. Hecht, D. R. Salem, and D. J. Strickland (2008), Thermospheric density in the Earth's magnetic cusp as observed by the Streak mission, *Geophys. Res. Lett.*, 35, L24103, doi:10.1029/2008GL035972.

Lühr, H., M. Rother, W. Köhler, P. Ritter, and L. Grunwaldt (2004), Thermospheric up-welling in the cusp region: Evidence from CHAMP observations, *Geophys. Res. Lett.*, 31, L06805, doi:10.1029/2003GL019314.

Results and Conclusions:

In order to fill this gap in observational evidence, we conducted a detailed study reported in Horvath and Lovell [2017B]. Our aim was to conduct a detailed investigation regarding the neutral density features developed in the cusp region on the active day of 25 September 2000 and quiet day of 2 March 2006, particularly focusing on the role of Joule heating in their development.

Our observations demonstrate the relations of flow channels (FCs), density spikes (see left panel of Figure 1), and upwelling-related divergent flows on 25 September (Figure 2), and their connections to the underlying (1) dayside reconnection depositing magnetospheric energy into the high-latitude region and (2) Joule-heating-driven disturbance dynamo effects. The absence of such relations and connections on 2 March implies direct heating by weak particle precipitations that did not lead on this quiet day to flow channel development and divergent flows (see right panel of Figure 1). Chemical compositions related to these density features were modeled by NRLMSISE-00. Composition outputs generated for the density spike's plasma environment -since NRLMSISE-00 could not reproduce the density spike itself, only its baseline approximating its plasma environment- depict some characteristic upwelling signatures. Inversely, in the case of low cusp-densities, composition outputs show opposite characteristics due to the absence of upwelling (see Figure 3).

From the results obtained we concluded that minor direct heating by weak particle precipitations, occurring under magnetically quiet conditions on 2 March 2006, did not lead to the development of any density spike, flow channel, and divergent flow.

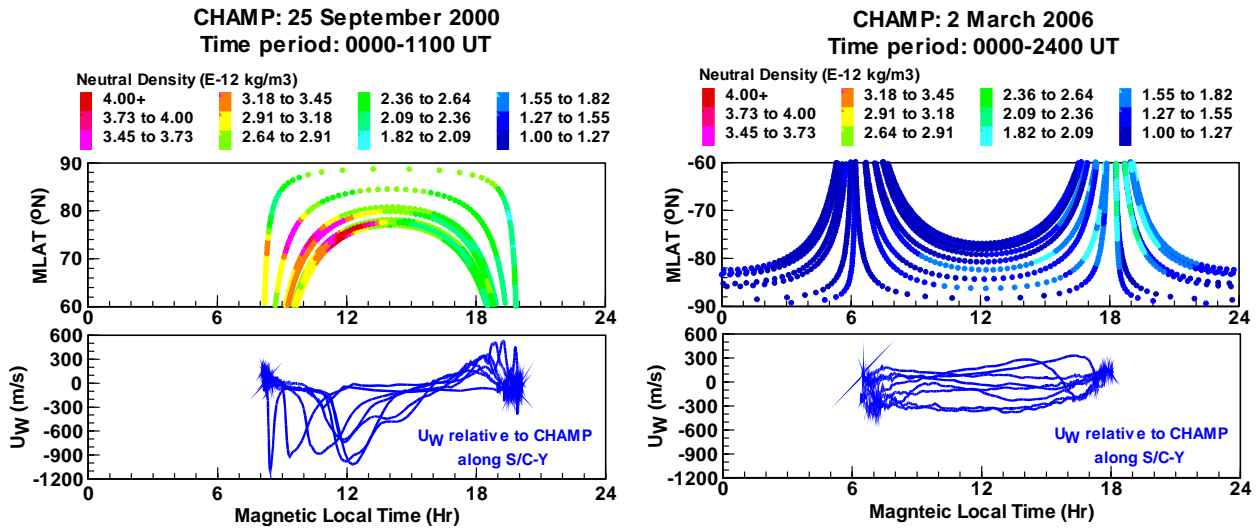


Figure 1: The MLAT vs MLT maps illustrate the spatial variations of neutral density [left panel] on the active day of 25 September 2000 and [right panel] quiet day of 2 March 2006. The presence of cusp enhancements/density spikes at around local midday in MLT is indicated by the maximum neutral density values (in red and orange), while their absence is evidenced by the minimum values (in dark and light blue). The neutral wind speed (U_W) line plots show [left panel] wind surges associated with the density spikes on the active day and [right panel] constant winds related to the minimum cusp densities on the quiet day.

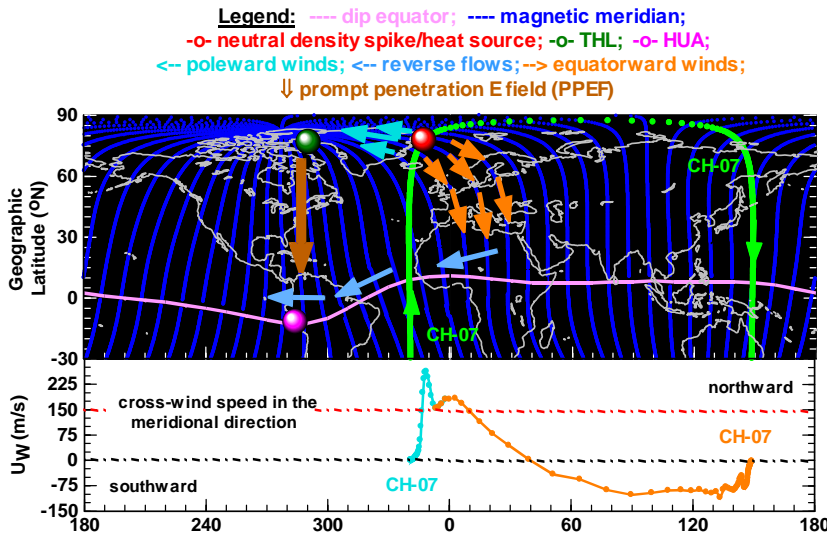


Figure 2: The map shows the ground track of CHAMP pass-07 (in green) detecting a Joule heating source (indicated as dot in red). The resultant divergent flows progress poleward (indicated as arrows in cyan) and equatorward (indicated as arrows in orange), while the reversed Sq currents (indicated as arrows in light blue) follow the dip equator (indicated as line in magenta). The CHAMP meridional wind line plot (U_W) tracked these divergent flows propagating poleward (or northward) and equatorward (or southward).

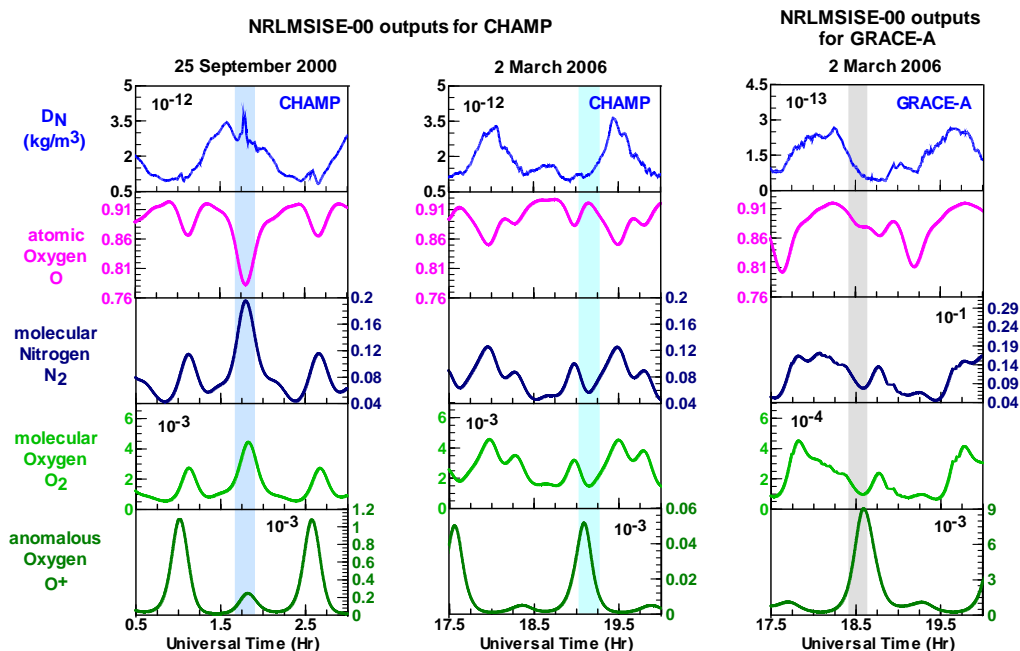


Figure 3: NRLMSISE-00 simulations generated for [left column] the active day of 25 September 2000 when CHAMP detected a density spike and for the quiet day of 2 March 2006 when [middle column] CHAMP and [right column] GRACE detected low neutral densities. The composition elements selected show the depletion of atomic O and elevated N_2 , O_2 and O^+ on the active day. Opposite trends are evident on the quiet day.

(3) Investigating the development of abnormal sub-auroral ionization drift (ASAIID) and abnormal sub-auroral polarization stream (ASAPS) during the magnetically active times of September 2003 (*J. Geophys. Res. Space Physics*; doi: 2017JA024870; under review)

Introduction:

According to the traditional view, the development of sub-auroral ion drift (SAID) is driven by a poleward or northward directed polarization electric (\mathbf{E}) field (\mathbf{E}_p). Based on traditional theories, this \mathbf{E}_p can be produced by a magnetospheric (1) current or (2) voltage generator system or by a magnetospheric (3) voltage difference. However, according to recent studies, SAID development can rather be explained with a short-circuiting model regarding SAID as part of a turbulent plasmaspheric boundary layer wherein the near-tail sub-storm injected plasma jets (or plasmoids) with a cross-tail width move across the magnetic field (\mathbf{B}) near the magnetic equator at around midnight [Mishin, 2013]. Although none of the traditional and newly developed theories expects SAID flow eastward, some recent studies report such observations. Eastward sub-auroral flows had been observed by Voiculescu and Roth [2008] in DMSP F15 satellite data during some moderately disturbed and quiet periods and in the 0600-0900 MLT and 2000-2130 MLT sectors. In the more recent modeling study of Ebihara et al. [2014], global magnetohydrodynamic (MHD) model simulations demonstrate the appearance of SAID ($\sim 66^\circ$ MLAT) with an equatorward shielding electric (\mathbf{E}) field ($\sim 64^\circ$ MLAT) at ~ 1800 MLT creating a shielding- \mathbf{E} —SAID structure.

Ebihara, Y., T. Tanaka, and T. Kikuchi (2014), Counter equatorial electrojet and overshielding after substorm onset: Global MHD simulation study, *J. Geophys. Res. Space Physics*, 119, 7281–7296, doi:10.1002/2014JA020065.

Mishin, E. (2013), Interaction of substorm injections with the subauroral geospace: 1. Multispacecraft observations of SAID, *J. Geophys. Res. Space Physics*, 118, 5782–5796, doi:10.1002/jgra.50548.

Voiculescu, M. and M. Roth (2008), Eastward sub-auroral ion drifts or ASAIID, *Ann. Geophys.*, 26, 1955–1963, <https://doi.org/10.5194/angeo-26-1955-2008>.

Results and Conclusions:

In our study, reported in Horvath and Lovell [2017C], we investigated the development of these recently described phenomena (i.e. ASAIID and shielding- \mathbf{E} —SAID). As our results show, these features appeared on the magnetically active day of 19 September 2003. Our main aim was to obtain more detailed observations that could provide more observational evidence shedding light on the development of ASAIID and the shielding- \mathbf{E} —SAID structure during the moderately active time period of 18-25 September 2003. We investigated the state of the sub-auroral region, auroral zone, and polar cap in order to find the link between these unusual sub-auroral processes producing ASAIID or a shielding- \mathbf{E} —SAID structure, and their associated auroral and polar processes. With a series of 19 September 2003 observations, our results show the development of ASAPS that is an inverted SAPS (see left panel in Figure 1), shielding- \mathbf{E} —SAID structure (see middle panel in Figure 1) and a wider ASAPS encompassing a narrow ASAIID (see right panel in Figure 1) during overshielding ($R2 > R1$ FACs) events. We observed also SAPS development during undershielding ($R1 > R2$ FACs), and the absence of any sub-auroral flow during perfect shielding ($R2 = R1$ FACs).

According to our observational evidence, the ASAIID features of interest developed due to the overshielding conditions created by the northward IMF \mathbf{B}_z component or the dominating \mathbf{B}_y component under southward IMF conditions. Furthermore, ASAIID became enhanced by the westward travelling surge (WTS) and related substorm current wedge (SCW) via the strong downward $R2$ FAC-style return currents generated enhancing $R2$ -FACs and therefore strengthening overshielding. As well known, overshielding provides the particular configuration required for the development of a plasmaspheric shoulder structure. We concluded from our observational results, which did not include any northern-hemisphere plasmaspheric shoulder detection since the IMAGE satellite provided southern-hemisphere observations at that time when ASAIID develop only in the northern hemisphere, that the development of ASAIID during the magnetically active time period investigated was possibly due to this shoulder structure creating a cold-plasma-shoulder—hot-ring-current interface in the turbulent plasmaspheric boundary layer.

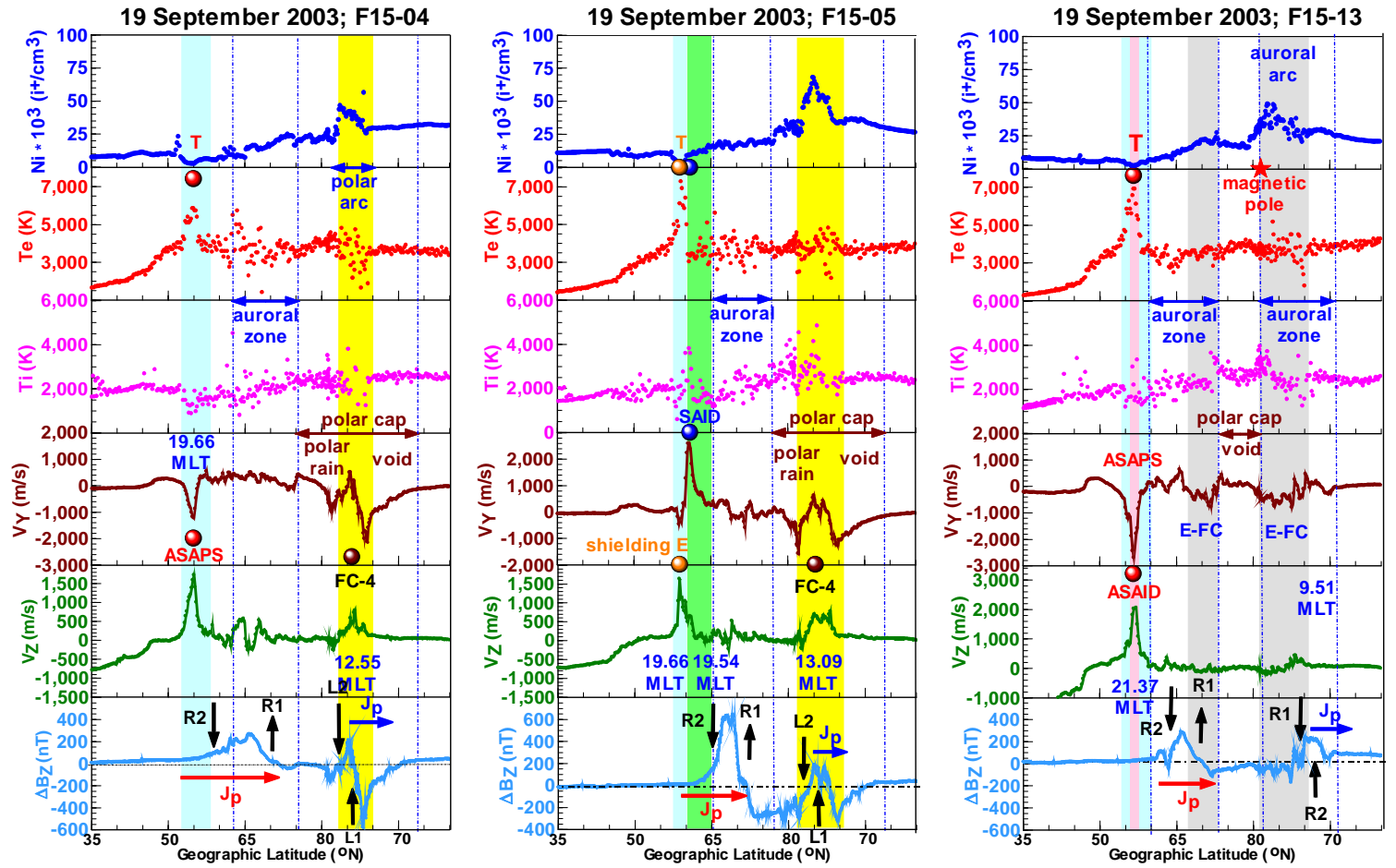


Figure 1: On 19 September 2003, the various F15 passes detected [left panel] an ASAPS feature (indicated as shaded interval in cyan) and [middle panel] a shielding-E—SAID structure (indicated as shaded intervals in cyan and green) during overshielding conditions evidenced during each event by the cross-polar sunward flows appearing as a FC-4 type flow channel (indicated as shaded interval in yellow). [right panel] A wider ASAPS flow channel (indicated as shaded interval in cyan) encompassing a narrow ASAPD (indicated as shaded interval in magenta) appeared at the arrival of the westward travelling surge (WTS) indicated by the eastward flow channels (E-FC; marked as shaded intervals in grey) enhancing overshielding conditions. Overshielding in the polar cap is evidenced during this event by the close to zero cross-polar flow near the magnetic pole (indicated as symbol star in red).

(4) Polar cap energy deposition events during the 5-6 August 2011 magnetic storm (J. Geophys. Res. Space Physics; doi:10.1002/2017JA025102; under review)

Introduction:

More recently Huang et al. [2014a; 2014b] investigated energy transfer from the magnetosphere to the coupled I-T system during geomagnetic storms by utilizing Poynting flux measurements. According to their northern-hemisphere results, Poynting flux enhancements at polar and auroral latitudes were similar. Furthermore, the primary location of thermospheric heating by Joule heat was located at $\sim 83^\circ\text{N}$ (magnetic) latitude in the central polar cap. These new results of Huang et al. [2014a; 2014b] demonstrate that the polar cap plays a key role in various M-I-T coupling processes, particularly during magnetic storms.

Huang, Y., C. Y. Huang, Y.-J. Su, Y. Deng, and X. Fang (2014a), Ionization due to electron and proton precipitation during the August 2011 storm, *J. Geophys. Res. Space Physics*, 119, 3106–3116, doi:10.1002/2013JA019671.

Huang, C. Y., Y.-J. Su, E. K. Sutton, D. R. Weimer, and R. L. Davidson (2014b), Energy coupling during the August 2011 magnetic storm, *J. Geophys. Res. Space Physics*, 119, 1219–1232, doi:10.1002/2013JA019297.

Results and Conclusions:

In our study, reported in Horvath and Lovell [2017D], we focused on the 5-6 August 2011 storm ($\text{Dst} \approx -180$ nT) and its energy deposition events occurring deep in the polar cap region in order to unravel the underlying physical processes. We investigated the relations among Poynting flux intensifications and flow channels (FCs) and localized neutral density enhancements often appearing as density spikes, plus the nature of the underlying reconnection events.

Our observational results provide new insights into the development of elevated Poynting flux in the polar cap region and its association with the localized neutral density increases. We demonstrated that (1) the pulsed nature of this 5-6 August 2011 magnetic storm (see Figure 1) and the resultant pulsed polar convection strongly controlled the polar cap neutral wind circulation by large-scale FACs that connected via ionospheric Pedersen currents in various types of flow channels. (2) The polar cap Poynting flux intensified in flow channels specified as FC-2 (see Figure 2) and FC-4 (see Figure 3) above/within which neutral density increases developed due to upwelling fueled by FACs powering Joule heating. (3) These flow channels appeared deep in the polar cap, within the 83°N (magnetic) region, defined by the above-mentioned previous studies as the region of energy deposition during this storm. Both the prevailing IMF \mathbf{B}_Y domination and the pulsed nature of this storm created favorable conditions for the development of these FC-2 and FC-4 types flow channels in the sunlit northern summer hemisphere, and caused the observed Poynting flux intensifications deep in the polar cap.

From our observational results we concluded that the solar wind source of these magnetopause (associated with FC-2) and magnetotail (associated with FC-4) reconnections taking place along old-open field lines was situated in the high-latitude boundary layer (HBL). Thus, the HBL dynamo provided a vigorous source of energy/momentum transfer during the latter-stage reconnections unfolding along old-open field lines. Consequently, the source of the Poynting flux intensification observed within/above FC-2 and FC-4, deep in the polar cap, was the HBL dynamo.

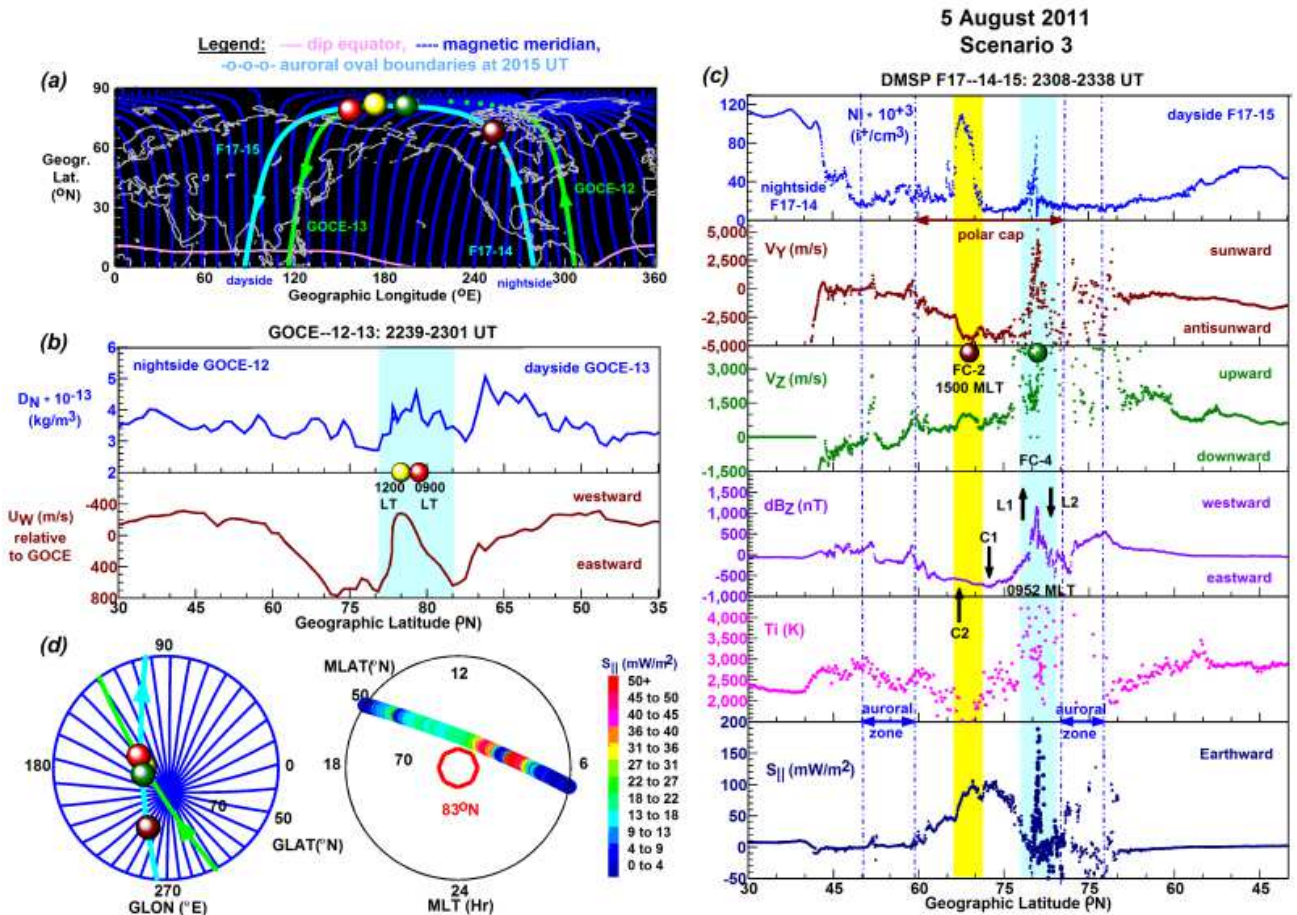


Figure 3: [a]-[b] GOCE detected multiple neutral density peaks (indicated as dots in yellow and red) and their underlying cross-polar sunward flow (indicated as shaded interval in cyan) deep in the polar cap. [c]-[d] Based on the matching DMSP F15 plots, we specified this cross-polar sunward flow as a FC-4 type flow channel (indicated as dot in green and shaded interval in cyan) wherein the Poynting flux ($S_{||}$) locally maximized deep in the polar cap (MLAT~83°N). There were also Poynting flux increases in the polar cap region peaking in a FC-2 type flow channel (indicated as dot in dark red and shaded interval in yellow).

III.) List of publications funded by AOARD Grant FA2386-16-1-4127:

a) Papers published in peer-reviewed journals:

1. Journal Name: J. Geophys. Res. Space Physics, 121, doi:10.1002/2015JA022057.

Title: Investigating the development of localized neutral density increases during the 24 August 2005 geomagnetic storm.

Date of online publication: 24 NOV 2017

Authors: Horvath, I., and B. C. Lovell

b) Papers published in peer-reviewed conference proceedings:

None

c) Papers published in non-peer-reviewed journals and conference proceedings:

None

d) Conference presentations without papers:

None

e) Manuscripts submitted to peer-reviewed journals but not yet published:

1. Journal Name: J. Geophys. Res. Space Physics, doi: 2017JA024069.

Title: High-latitude neutral density structures investigated by utilizing multi-instrument satellite data and NRLMSISE-00 simulations.

Date received: 22 February 2017

Authors: Horvath, I., and B. C. Lovell

2. **Journal Name:** J. Geophys. Res. Space Physics, 121, doi: 2017JA024870.
Title: Investigating the development of abnormal subauroral ionization drift (ASAIID) and abnormal subauroral polarization stream (ASAPS) during the magnetically active times of September 2003.
Date received: 10 October 2017
Authors: Horvath, I., and B. C. Lovell
3. **Journal Name:** J. Geophys. Res. Space Physics, doi: 2017JA025102.
Title: Polar cap energy deposition events during the 5-6 August 2011 magnetic storm.
Date received: 06 December 2017
Authors: Horvath, I., and B. C. Lovell

f) List any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

IV). Seminars presented

1. **Even Name:** AOARD/AFOSR GRANT REVIEW MEETING
The University of Queensland, Brisbane, QLD, Australia
Title: Investigating ionospheric and thermospheric variations during geomagnetic storms
Date: 23 February 2017
Presenters: Dr Ildiko Horvath and Prof Brian Lovell
2. **Even Name:** 2017 Joint CEDAR-GEM Workshop,
Keystone Conference Center and Lodge, Keystone CO
Sunday-Friday at noon, 18-23 June 2017
Title: Polar ionosphere and dayside cusp enhancements on 25 September 2000
Date: 18-23 June 2017
Presenter: Dr Cheryl Huang, Senior Research Physicist
AFRL/RVBXP, Kirtland AFB, NM, USA

V). Award for best paper, poster:

None

VI.) Award of fund received related to your research efforts:

None

VII). Attachments: Publications a)