Observations of deep ionospheric F-region density depletions with FPMU instrumentation and their relationship with the global dynamics of the June 22-23, 2015 geomagnetic storm

Victoria Coffey¹, Stan Sazykin², Michael O. Chandler¹, Marc Hairston³, Joseph I. Minow¹, and Brian J. Anderson⁴

¹ NASA Marshall Space Flight Center, Huntsville, AL 35812, USA (e-mail: Victoria.Coffey@nasa.gov)
² Rice University, Houston, TX 77251, USA (e-mail: Sazykin@rice.edu)
³ University of Texas at Dallas, Richardson, TX 75083 USA (email: Hairston@utdallas.edu)
⁴ The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (email: Brian.Anderson@jhuapl.edu)

I. INTRODUCTION

The magnetic storm that commenced on June 22, 2015 was one of the largest storms in the current solar cycle, resulting from an active region on the Sun that produced numerous coronal mass ejections (CMEs) and associated interplanetary shock waves. On June 22 at 18:36 UT the magnetosphere was impacted by the leading-edge shock wave and a sheath carrying a large and highly variable interplanetary magnetic field (IMF) Bz with values ranging from +25 to -40 nT. During the subsequent interval from 0000 to 0800 UT, there was a second intensification of the geomagnetic storm resulting from the impact of the CME.

We present dramatic responses of near-simultaneous particle measurements with the FPI instrument [Pollock et al., 2016] from the high-altitude MMS mission [Burch et al., 2016] in the near-Earth equatorial plane in the magnetosphere (~9-12 Re), and from the low-altitude F-region data from the Floating Potential Measurement Unit (FPMU, [Coffey et al., 2008; Wright et al., 2008]) on board the International Space Station (ISS), both in the evening local time sector. We analyze potential causes of the dramatic MMS particle flux dropouts and the ISS density depletions by putting them in the context of storm-time electrodynamics, and support our results with numerical simulations of the global magnetosphere and ionosphere. Additionally, we discuss the modeling results in comparison with observations from the Meteorological Satellite Program (DMSP) at low latitudes and the Birkeland currents from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE).

II. OBSERVATIONS

A. MMS in the Near-Earth Equatorial Plane

During the sheath phase of the storm, the MMS spacecraft in the equatorial plane observed a rapid reconfiguration of the magnetic field near 1923 UT. Initially in the warm plasmasheet, particle flux dropouts were observed as they tracked the plasma-sheet to lobe transitions with the stretching and thinning of the plasmasheet. Anti-sunward flowing O+ ions of ionospheric origin were also measured during this period, confirming that the MMS spacecraft temporarily was in a lobe [Reiff et al., 2016].

B. ISS FPMU in the Low Latitude Ionosphere

The FPMU is a suite of four plasma instruments on the ISS providing plasma densities, temperatures, and spacecraft charging potentials. The ISS orbits Earth approximately every 92 min or about 16 times per day. It has a varying altitude of about 400 km and a maximum latitude of about 52 degrees. Outside of the ISS engineering data [e.g., Fejer et al., 1999], on subsequent orbits, these regions of plasma instabilities evolve into more coherent wide density holes.
multiple depletions appear to coalesce into a single large depletion. The depletion after 22:40 UT is one of the largest depletions observed by FPMU. Bottom panel: Geodetic latitude (black) and longitude (blue) as a function of time obtained from Satellite Tool Kit (STK) propagation of ISS two-line element sets with CGM coordinates (dashed red) provided for geomagnetic context.

Both magnetospheric flux dropouts and onset of equatorial F-region instabilities are correlated. During the later (CME phase) period of the storm, both MMS and FPMU/ISS observe similar dropouts and instabilities, respectively, occurring approximately near the same times (Figures 3 and 4).

![Image](image1.png)

Figure 3. The MMS ion spectrometers observed particle flux dropouts during 3:20–3:30 and 5:11–5:45. These dropouts were representative of excursions from the plasmasheet to the lobe and return, resulting mostly from the thinning and expansion of the plasma sheet and also due to the flapping of the magnetotail.

![Image](image2.png)

Figure 4. ISS FPMU deep density depletions observed again at post-sunset equatorial latitudes on following day, June 23rd. These coincided with the flux dropouts observed by MMS near ~ 3:30 and 5:30 UT.

Putting these low-latitude measurements in context with the global dynamics of the storm, we use numerical simulations in our efforts to better understand the effects of this storm on the different regions of the coupled ionosphere-magnetosphere. We used the Space Weather Modeling Framework (SWMF, [Toth et al., 2005]) at the Community Coordinated Modeling Center (CCMC) to model the global magnetosphere-ionosphere system. This code is well suited to simulated global aspects of the solar wind-magnetosphere-ionosphere coupling, but does not have a first-principles ionosphere model or enough resolution to look at ionospheric effects. To model ionospheric response, we use the SAMI3-RCM ionosphere-magnetosphere coupled model [Huba et al., 2016].

III. GLOBAL MODELING AND AMPERE OBSERVATIONS

Figure 5 shows a time history of the total (integrated) field-aligned current in the northern hemisphere obtained from the SWMF simulations (red curve) and also estimated from the AMPERE experiment data. The strength of the total current is approximately proportional to the cross polar cap potential drop and is driven by the magnitude of the southward (negative) IMF Bz component. The AMPERE data is used to validate the simulations. At ionospheric altitudes, the integrated field-aligned currents inferred from the AMPERE data showed highly variable currents exceeding 20 MA after ~19:32 UT. The global simulations also showed large field-aligned currents and although accurate in timing, the magnitudes were 20-50% smaller in magnitude from AMPERE. Dramatic rise in the strength of the ionospheric convection was caused by a brief period of intense southward IMF Bz between 18:35 and 19:30 UT. A sudden reduction in current strength around 19:30 UT caused a large dipolarization (substorm) in the tail and put the MMS into the lobe environment. Therefore, our simulations confirm findings that MMS finds itself sampling the lobes during periods of northward IMF Bz [Reiff et al., 2016], accounting for observed flux dropouts and coconfirming IMF Bz northward turnings as their predictive parameter.

![Image](image3.png)

Figure 5. Total field-aligned current in the northern hemisphere estimated from AMPERE experiment on board Iridium spacecraft (black) and calculated from global magnetospheric simulations (red).
Figure 6. Same as Figure 5 but for the CME phase of the storm.

Figure 6 shows large increases in the total current during the later phase of the storm. The period between 01:40 UT and 05:30 UT on June 23, 2015 driven by a period of near-continuous large southward IMF Bz. Flux dropouts seen by MMS ion spectrometers at ~3:20 UT and ~05:20 UT were seen to coincide with sudden reduction in the total current strength. Simulations confirm (not shown here) that dipolarizations (substorms) occurred in the magnetotail during these times, resulting in the MMS being exposed to the lobe environment.

Thus, the global simulations in combination with AMPERE data confirm that sudden reductions in convection strength driven by northward IMF Bz turnings are responsible for magnetotail collapse putting MMS into low-density lobe environment, providing an explanation for observed flux dropouts.

IV. LOW-LATITUDE MODELING AND DISCUSSION

Large excursion of IMF Bz are also known to result in magnetospheric convection electric fields penetrating to the low-latitude ionosphere, where they affect ionospheric electrodynamics. Specifically, penetration electric fields during periods of southward IMF Bz result in enhancement of the pre-reversal vertical equatorial ExB plasma drift, resulting in increase likelihood of generation of spread-F instabilities [Fejer et al., 1999; Abdou, 2012; Huang, 2008; Huang et al., 2010]. We use simulations with the SAMI3-RCM code to investigate predicted penetration electric fields (ExB drifts) (the model does not have adequate spatial resolution to resolve plasma instabilities, but is capable of predicting the large-scale background conditions).

Figure 7 (top) shows a comparison of FPMU ion densities (black dotted line) with model-predicted total ion densities (blue/continuous line) along the ISS trajectory. We use this comparison to confirm the ability of the model to predict large-scale changes in the ionosphere in response to high-latitude changes in the convection. The model-computed vertical ExB drift velocity at a fixed location in the region of pre-reversal enhancement (18 MLT, near magnetic equator) is shown in the bottom panel in the meridional plane (positive up/north) at the equator near the dusk terminator (19 MLT). A large penetration electric field is seen at the equator at dusk starting ~19:00 UT and lasting over an hour. On the first subsequent orbit crossing the post-sunset equatorial ionosphere (~19:35 UT), FPMU detected onset of large depletions. Our simulations thus support the idea that it is a penetration electric field caused by a southward IMF Bz turning that is the primary factor in triggering growth of plasma instabilities seen by FPMU.
Another period of penetration electric field was predicted by the simulations between ~02:00 UT and 05:30 UT, during a period of southward IMF Bz. A new onset of depletions was subsequently detected by FMPU on the orbit crossing equatorial post-sunset ionosphere at ~3:35 UT.

Similar conclusions can be seen during the CME phase of the storm (Figure 8). A good overall agreement between the simulated and measured ion densities confirms validity of the model results. A period of penetration electric field at the dusk equatorial sector is predicted between 02:00 and 05:30 UT, and FMPU indeed sees a new onset of irregularities on the first subsequent orbit that samples this region (~3:30 UT).

To further confirm the role of penetration electric fields in the equatorial ionosphere, we present measurements of the ion drift velocity on board the Defense Meteorological Satellite (DMSP) F19 taken within 5 degrees latitude of the magnetic equator and between the hours of 17 and 19 local time (Figure 9). While the absolute values of the drift velocity are uncertain due to offsets in determining the sensor pointing direction, relative changes over short (a few hours) intervals are used as an indicator of penetration undershielding (upward drift) or overshielding (downward drift) electric field. A positive increase in response to the southward IMF Bz turning (second orbit since 1700 UT) and a subsequent negative change in response to the subsequent northward turning on the third orbit are consistent with model-predicted drifts.

V. CONCLUSIONS

We presented observations of dramatic responses of spacecraft plasma environment during a large geomagnetic storm simultaneously happening in the F-region equatorial ionosphere and in the near-Earth (9-12 Re) magnetosphere at approximately same local times. We find that both responses seem to coincide with large and rapid changes in the IMF Bz component. Using a combination of data analysis and first-principles simulations, we find that (1) At magnetospheric distances, large dropouts in kilovolt particle fluxes are due to rapid magnetic field reconfigurations, resulting in spacecraft being exposed intermittently to the magnetotail lobe environment; (2) Southward IMF Bz turning cause temporary penetration of the high-latitude convection electric field to the equatorial ionosphere, resulting in enhanced vertical drift velocity near dusk equator; (3) Enhanced equatorial vertical drift is likely the primary factor triggering onset of observed irregularities. Both MMS flux dropouts and new onsets of ionospheric FPMU-observed equatorial instabilities can be explained in terms of electrodynamic response of the magnetosphere-ionosphere system to large and abrupt changes in the IMF Bz component. Simulations support the role of the penetration electric field in triggering the onset of spread F at dusk and are consistent with DMSP vertical ion drift data, providing each region’s context to the global dynamics and time evolution of the storm.
VI. REFERENCES


Huang, C., Continuous penetration of the interplanetary electric field to the equatorial ionosphere over eight hours during intense geomagnetic storms, *J. Geophys. Res.*, 113(A11305), 2008.


ACKNOWLEDGMENT

We thank the Space Physics Data Facility for the interplanetary and ISS FPMU data from the CDAWeb at https://cdaweb.sci.gsfc.nasa. We thank the providers at the Madrigal Database, http://cedar.openmadrigal.org, for the DMSP data.