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 Coffey (NASA Marshall Space Flight Center), Stan Sazykin (Rice University), Michael Chandler (NASA Marshall Space Flight Center), Marc Hairston (University of Texas at Dallas), Joseph Minow (NASA Marshall Space Flight Center), Brian Anderson (Johns Hopkins University Applied Physics Laboratory)

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 simultaneous particle measurements from the high-altitude Magnetospheric Multiscale Mission (MMS) at high altitudes in the magnetosphere (~9-12 Re) and from the low-altitude (F-region) Floating Potential Measurement Unit (FPMU) on board the International Space Station (ISS). We analyze potential causes of these dramatic particle flux dropouts by putting them in the context of storm-time electrodynamics, and support our results with numerical simulations of the global magnetosphere and ionosphere.

During the sheath phase of the storm, the MMS spacecraft in the near-earth 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.

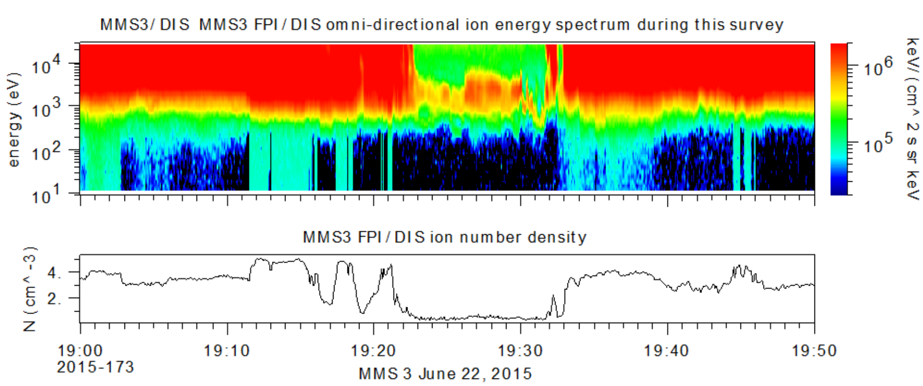

Figure 1. MMS FPI ion spectrometer flux (top) and number density (bottom) during the first phase of the June 22-23, 2015 magnetic storm.

The FPMU is a suite of four plasma instruments on the ISS providing plasma densities, temperatures, and spacecraft charging potentials. It includes a Wide Langmuir Probe (WLP), Narrow Langmuir Probe (NLP), Floating Potential Probe (FPP), and Plasma Impedance Probe (PIP). 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 needs, this instrument suite is powered on to obtain measurements for expected active space weather conditions and science campaigns. During the same sheath period of the storm as shown in Figure 1, FPMU measurements of F-region (~350-400 km altitude) density show dramatic depletions in the post-sunset (nighttime) local time sector at equatorial latitudes starting in the main phase of the storm and persisting on several subsequent orbits. We identify these depletions as equatorial spread-F. On subsequent orbits, these regions of plasma instabilities evolve into more coherent wide density holes.

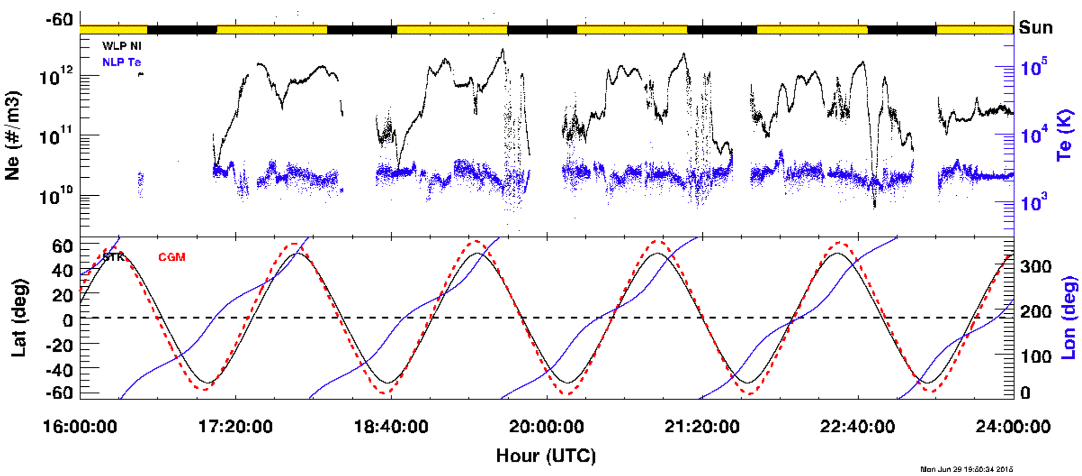

Figure 2. Top panel Density (left): Three developing post sunset, equatorial plasma depletions are initially sampled by ISS starting ~19:40 UT. ISS encounters the depletions on two subsequent orbits where multiple depletions appear to coalesce into a single large depletion. The depletion after 22:40 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 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, seemingly occurring around the same times (Figures 3 and 4).

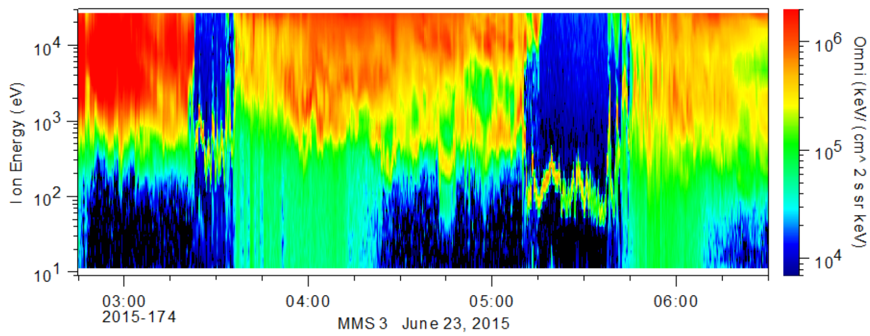

Figure 3. The MMS ion spectrometers observed particle flux dropouts during 3:20-3:30 and 5:11 – 5:45. These dropouts were representative of excursions from the plasmasheet to the lobe and return. These treansitions of MMS from the plasma sheet to the lobe resulted primarly from the thinning and expansion of the plasma sheet and partially because of the flapping up and down of the magnetotail.

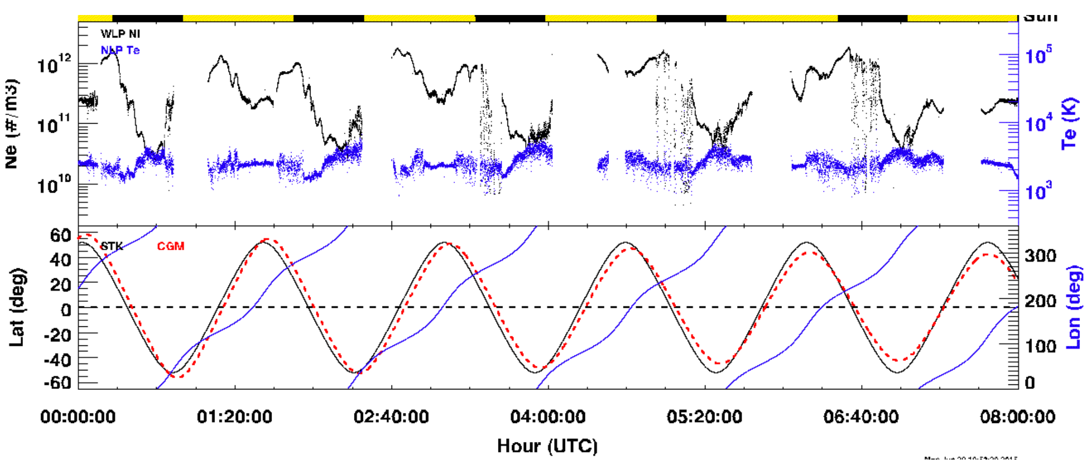

Figure 4. ISS FPMU deep density depletions observed again at post-sunset equatorial latitudes on following day, June 23rd. These coincided with the flux dropouts observed by MMS near ~ 3:30 and 5:30 UT.

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) 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.

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.

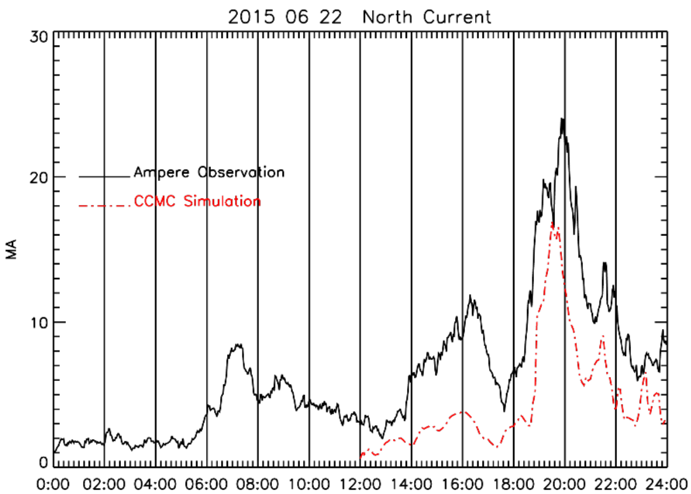

Figure 5. Total field-aligned current in the northern hemisphere estimated from AMPERE experiment on board Iridium spacecraft (black) and calculated from global magnetospheric simulations (red).

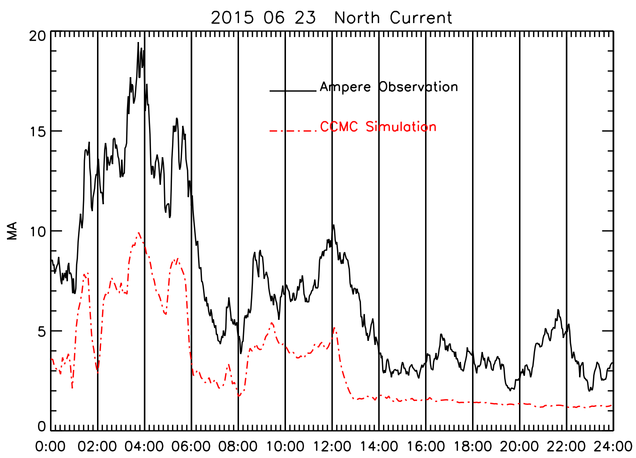

Figure 6. Same as Figure 5 but for the CME phase of the storm.

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.

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. The consequences of the magnetospheric penetration electric field and their role in the occurrence of these equatorial spread F observations will be investigated through the results of the SAMI3-RCM numerical model, a coupled ionosphere-magnetosphere model with self-consistent large-scale electrodynamics.

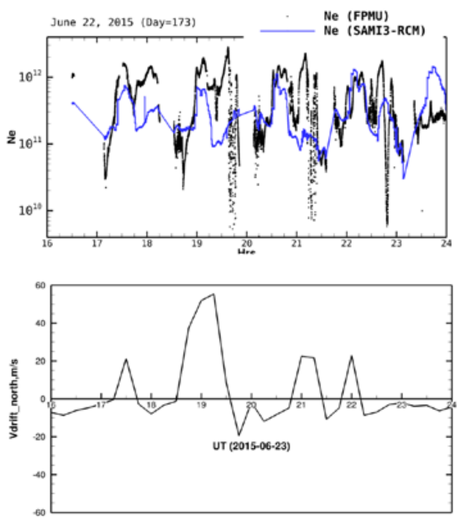

Figure 7. Results from preliminary study of simulating the June 22-23, 2015 geomagnetic storm with SAMI3-RCM with the FPMU data. The model illustrates good agreement along satellite trajectory. Small-scale depletions observed by ISS are not reproduced and is likely due to the courser spatial resolution in the model.

A comparison of FPMU ion densities (black dotted line) with simulated densities (blue/continuous line). Also shown is the simulated vertical ExB drift velocity component in the meridional plane (positive up/north) at the equator near the dusk terminator (19 LT). Onset of enhanced depletions follows periods of large vertical drift excursions. This is the sheath period of the storm.

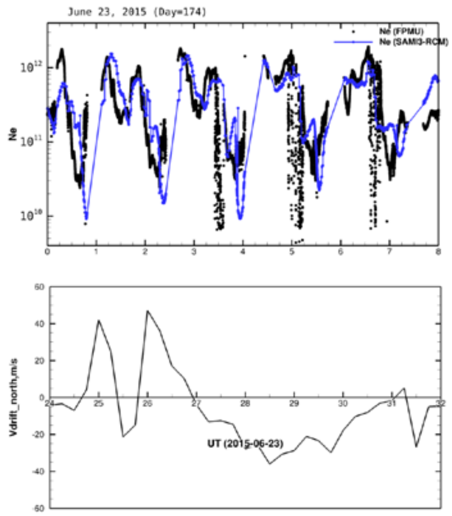

Figure 8. Same as Figure 7 but for the CME phase of the storm.

Similar conclusions can be seen during the CME phase of the storm (Figure 8).

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 Spacecraft (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.

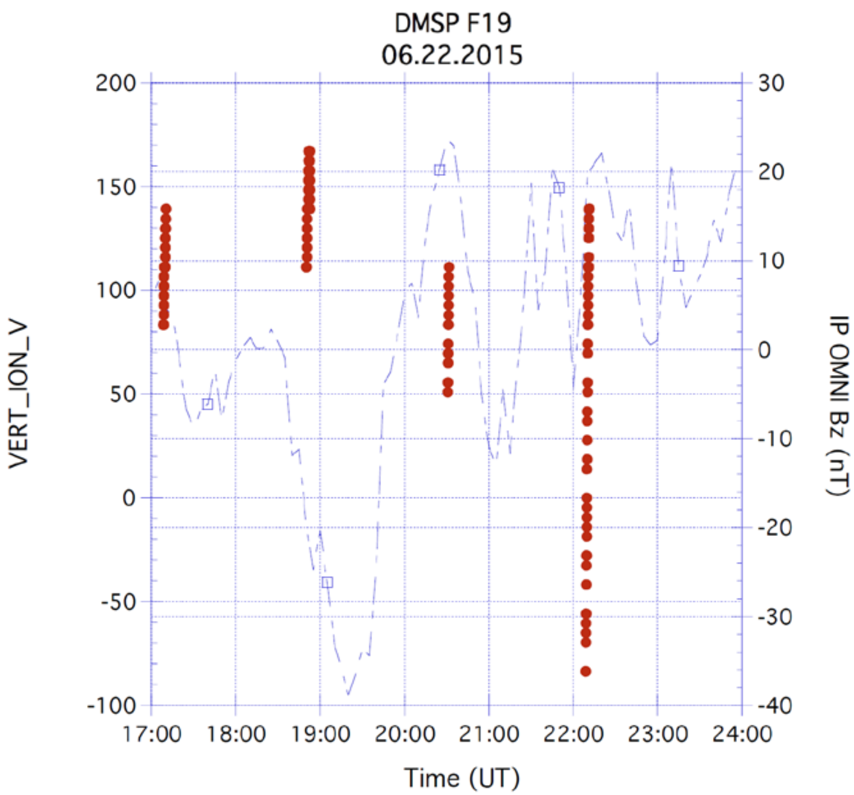

Figure 9. DMSP F19 ion drift velocities (red symbols) plotted within 5 degrees latitude of the magnetic equator and between 17 and 19 hours of local time. Blue curve is the IMF Bz component.

In conclusion, the observations indicate that both MMS flux dropouts and new onsets of ionospheric FPMU-observed equatorial instabilities are electrodynamic responses 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.