Impulsive Energy Transfer from the Magnetosphere to the Ionosphere during Geomagnetic Storms

Lawrence Zanetti [1], Robert Robinson [2], Brian Anderson [3], Haje Korth [3]

[1] National Oceanic and Atmospheric Administration
[2] The Catholic University of America
[3] Johns Hopkins University Applied Physics Laboratory

E mail (Zanetti@noaa.gov).

Accepted: 31 August 2018

Abstract Data from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) have been used to study electric fields and currents for multiple magnetic storms. The calculation uses a high latitude conductivity model based on the field-aligned currents measured by AMPERE compared to measurements from the Poker Flat Incoherent Scatter Radar. The derivation of conductivities from field-aligned currents ensures spatial and temporal consistency in the calculated electrodynamic parameters. For all of the magnetic storms studied, the combined energy input from precipitating particles exhibits sharply-peaked maxima for small scale structures at the times of local minima in DsT, suggesting a close coupling between magnetospheric and/or ring current energy content and the high latitude currents driven by field-aligned currents. We speculate that these relatively rapid increases and decreases of the high latitude energy deposition may be a result of the variation of ionospheric conductance with field-aligned current strength, leading to a nonlinear relation between current and voltage, and impulsive transfer of energy from the magnetosphere to the ionosphere.

Introduction

Models of magnetosphere-ionosphere coupling at high latitudes are sensitive to the ionospheric electrical conductivity, which results both from solar illumination and auroral precipitation. While conductivities produced by solar EUV can be modeled with good accuracy, auroral conductivities exhibit high variability in space and time. Estimates based on empirical models typically fail to capture this variability. Also, it is important that auroral conductivities be consistent with the field-aligned currents calculated by the M-I coupling models.

Many years ago, Ahn et al. (1989) statistically related aurorally enhanced conductivities measured by incoherent scatter radars to local ground-based magnetometer measurements. This approach has the advantage of replicating local enhancements in conductivity that empirical models are unable to capture. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) model takes advantage of ground-based magnetometer and local measurements to produce an optimum specification of ionospheric conductivities (Richmond and Kamide, 1988; Richmond, 1992; Crowley and Hackert, 2001).

Here we focus on the recently observed increase of ionospheric conductances with field-aligned current using data from AMPERE and the Poker Flat Incoherent Scatter Radar (Figure 1). The data show that conductance increases with field-aligned currents in both upward and downward current regions, and that the relations between the two quantities vary with magnetic local time. We show that this behavior causes the relation between current and voltage in the magnetosphere-ionosphere electrical circuit to be nonlinear. The non-linear connection between the magnetosphere and the ionosphere can create runaway current conditions, leading to highly time varying and impulsive small scale currents.

Data

The procedure for calculating the field-aligned currents from the measured magnetic field perturbations is described in Anderson et al. (2000) and Waters et al. (2001). The field-aligned currents are computed from the horizontal magnetic perturbations at the satellite altitudes mapped to the ionosphere using a factor to account for the convergence of magnetic field lines. With the assumption that the horizontal magnetic field perturbations are poloidal (curl-free), the field-aligned currents can be computed from the associated potential function. To account for the uneven sampling of the Iridium magnetometer data, the data are fit by spherical harmonic expansion. Processed AMPERE data have been archived for the period between January 2010 and May 2013. The data consist of magnetic field measurements that have been adjusted for satellite attitude and rotated into geophysical coordinates. The Earth's main field has been removed using the IGRF, and long-period detrending performed to produce residuals as a function of Altitude Adjusted Corrected Geomagnetic (AACGM) coordinates.

Simultaneous and coincident measurements of height-integrated electrical conductivity were made by the Poker Flat Incoherent Scatter Radar (PFISR) located near Fairbanks, Alaska (Robinson et al., 2017). For each conductivity measurement made by PFISR at 10-minute intervals, the corresponding field-aligned current value from AMPERE was determined by a simple interpolation in space and time. Occasionally, the peaks in conductance align well with corresponding peaks in upward field-aligned currents, but more generally the correlation is not exact. To examine the correlation between field-aligned currents and ionospheric conductances, we used data from geomagnetically active days. We eliminated those data obtained when the solar zenith angle was less than 90 degrees. This was to ensure the observed conductances are produced by precipitating particles only.

The results are shown in Figure 2, which shows the correlation between Pedersen conductances and field-aligned currents in four magnetic local time intervals. In general, for positive (upward) field-aligned currents, the conductances are more likely to be larger than in downward current regions. The range in conductance values increases for larger parallel current densities for upward currents. Conductances also increase with field-aligned current in downward current regions, but the variation is not as strong. The increase in conductance with field-aligned current has a potential impact on magnetosphere-ionosphere coupling.

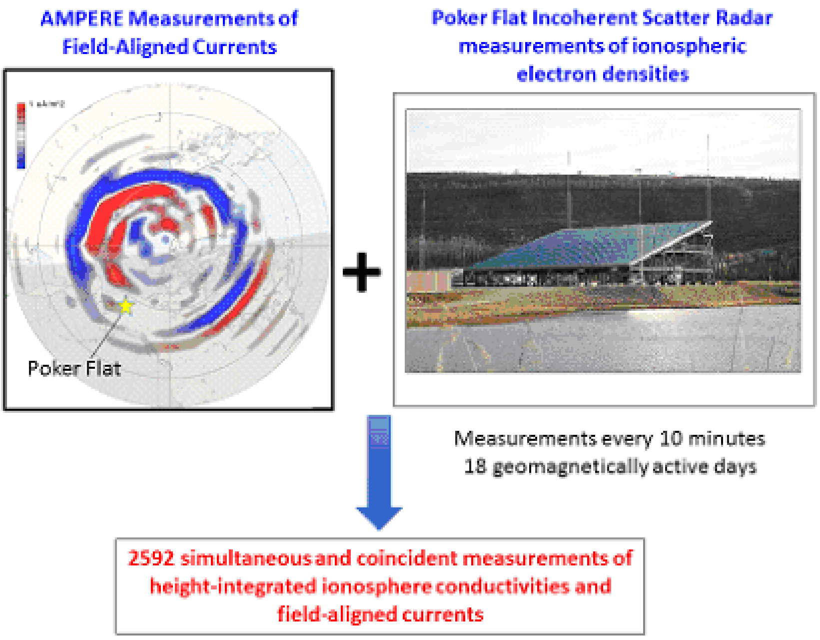


Figure 1 Comparison of Poker Flat observed ionospheric conductivity and magnetic field aligned currents from AMPERE

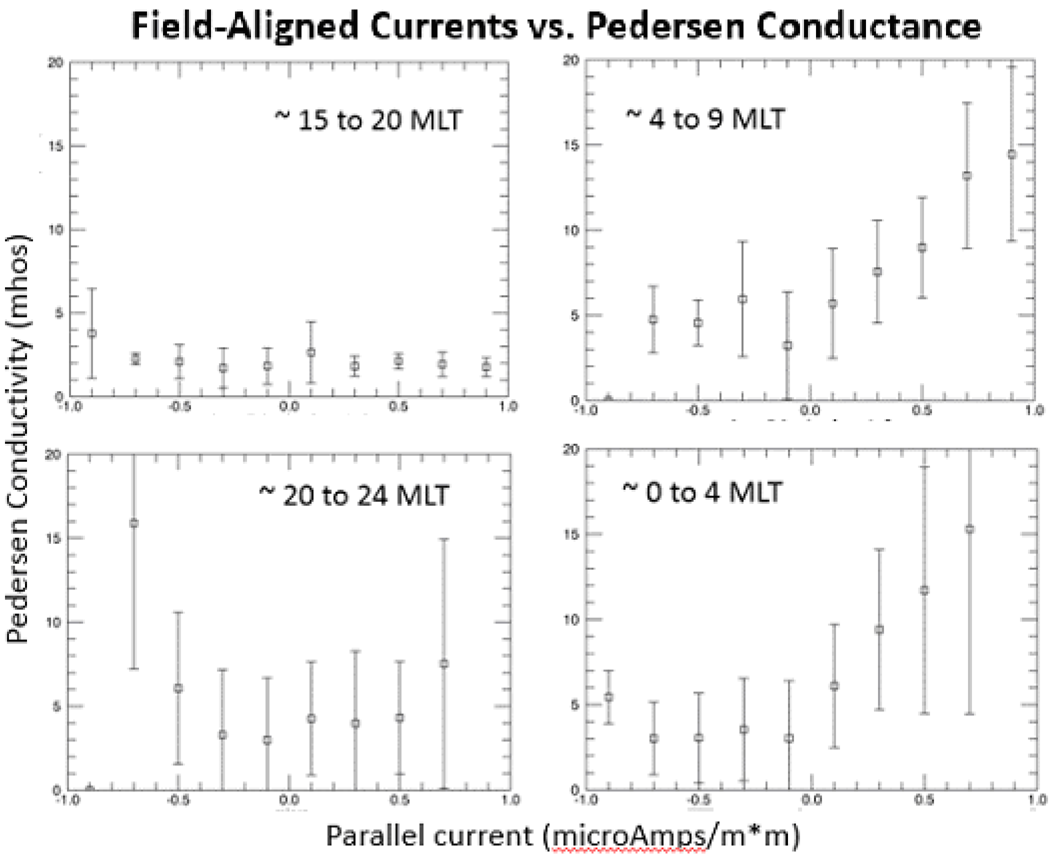
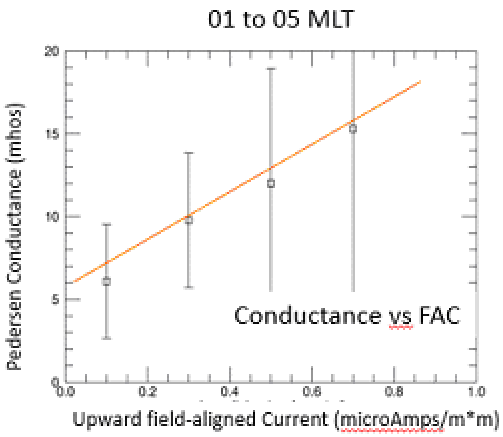


Figure 2 (from Robinson et al., 2017) Correlation of field aligned currents vs. Pedersen conductivities as a function of local time sectors

Figure 3 shows the current-voltage relationship for a circuit where the conductivity increases with current. In the ionosphere, the rapid increase in voltage with increasing current means that the horizontal electric field grows at a faster rate than the current. Because Joule heating is proportional to the square of the electric field, the amount of energy lost to the ionosphere by Joule heating increases even more rapidly. The explosive loss of energy from the magnetosphere to the ionosphere cannot be sustained indefinitely. At some point, the loss of electrical energy will discharge the magnetospheric generator driving the potential and field-aligned currents. This process will be reflected in the field-aligned current densities as a sharp increase followed by a similarly sharp decrease. We expect this process will be localized spatially to regions where the rate of change of conductivity with field-aligned current is greatest.



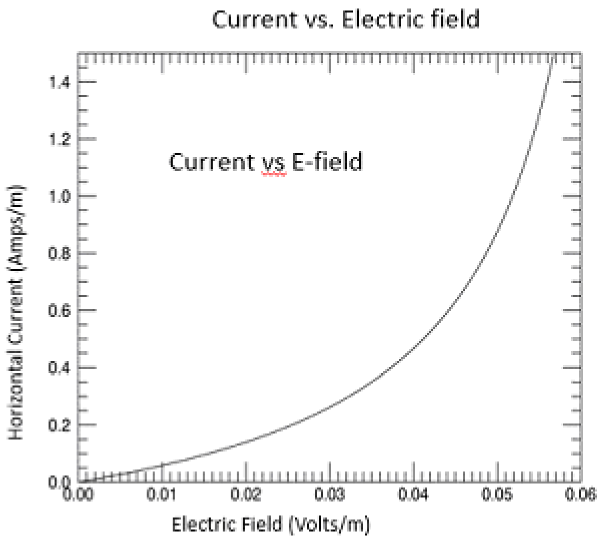


Figure 3 (from Robinson et al., 2017) Conductance vs. upward field aligned current; variable resistance implies runaway current for moderately increasing electric field

To illustrate the impulsive nature of the process, we show in Figure 4 an indicator of the global field-aligned current strength as a function of time for a geomagnetically active day. The indicator is simply the absolute magnitude of the field-aligned current in Amps. The top of each panel shows the DsT and the Sym-H index. The correlation between the field-aligned current strength and the indices could be interpreted as the impulsive discharge of the magnetospheric/ring current energy due to runaway current conditions. This global indicator shows the impulsive nature of the magnetospheric drivers for field-aligned currents. Whereas some portion of the variability may reflect structure in the solar wind density and magnetic field direction, the non-linear relation between currents and voltage caused by variable conductance in the ionosphere can be an important contributor to the observed impulsive nature of M-I coupling.

Discussion

Sergeev et al. (1996) and Pulkkinen et al (2006) have shown that geomagnetic responses to external solar wind forcing can only be explained if an internal mechanism of magnetospheric origin is also taken into account (structure less than 4 hours which is the outer limit of this study). Sergeev et al. (1996) referred to these as impulsive dissipation events (IDE). Alternate internal processes of note include the substorm magnetospheric energy release mechanism, also generating impulsive current circuits although the substorm process is a larger scale phenomena. Shown here is that ionospheric conductance variability caused by field-aligned currents may explain this internal process. The process is analogous to terrestrial lightning, as the increasing conductivity with field-aligned current allows for runaway current conditions and impulsive energy transfer from the magnetosphere to the ionosphere.

Careful analysis of the spatial distribution of these impulsive events shows that they are localized in both magnetic latitude and local time. This emphasizes the importance of being able to monitor small-scale processes to better understand solar wind-magnetosphere-ionosphere coupling. Although global context is critical to universal understanding and theory comparisons, the typical regional averaging envelops small-scale phenomenon. Observational scientific space measurements on small scales cannot be properly registered just given the practical limits on measurement performance, data storage and downlink capability, followed by limited successive analysis and computing capability. Kappenman, et al. (1998) and references therein discussed field-aligned current region identification utilizing small scale fluctuations; identification algorithms to register these field-aligned current regions were implemented for space weather interests but may align well with the subject of this paper. These indicators may well have been registering similar small scale structures which may have had similar intense, lightning-like consequences at these disruptive boundaries or within current regions. There may be many examples of boundaries of extreme transition regions, e.g. tail reconnection regions, magnetopause reconnection, solar transition edges, solar system - interplanetary boundaries. It is suggested that standard magnetospheric MHD modelling should strive to include smaller scale structure. The non-linear relation between current and electric field described here may act across many spatial and temporal scales.

Certainly the solar wind provides the energy responsible for the large scale ring current, magnetospheric and field-aligned current variations, but there is not a one-to-one correlation between the two. If the large variation behavior of the field-aligned currents in Figure 4 is solely caused by southward and northward turnings of the IMF, then it is difficult to account for the similar durations of these events over the two-day course of this storm example. What is suggested is that the solar wind drives the high latitude electric field, which produces intensifying field-aligned currents. The consequent increase in conductivities results in a rapid discharge of electrical energy into the ionosphere on small spatial scales and rapid temporal scales. The overall result is an increase followed by a precipitous decrease in field-aligned current intensity. The charging and discharging cycle is analogous to the processes taking place in terrestrial lightning. Another analog is a simple florescent light without controls and without current-limiting devices. Without ballast to control electric current, the conductivity within the simple plasma light fixture increases with the current, which in turn allows the current to grow, enhancing the conductivity even more. With no current control, the voltage applied across the tube would explosively discharge.

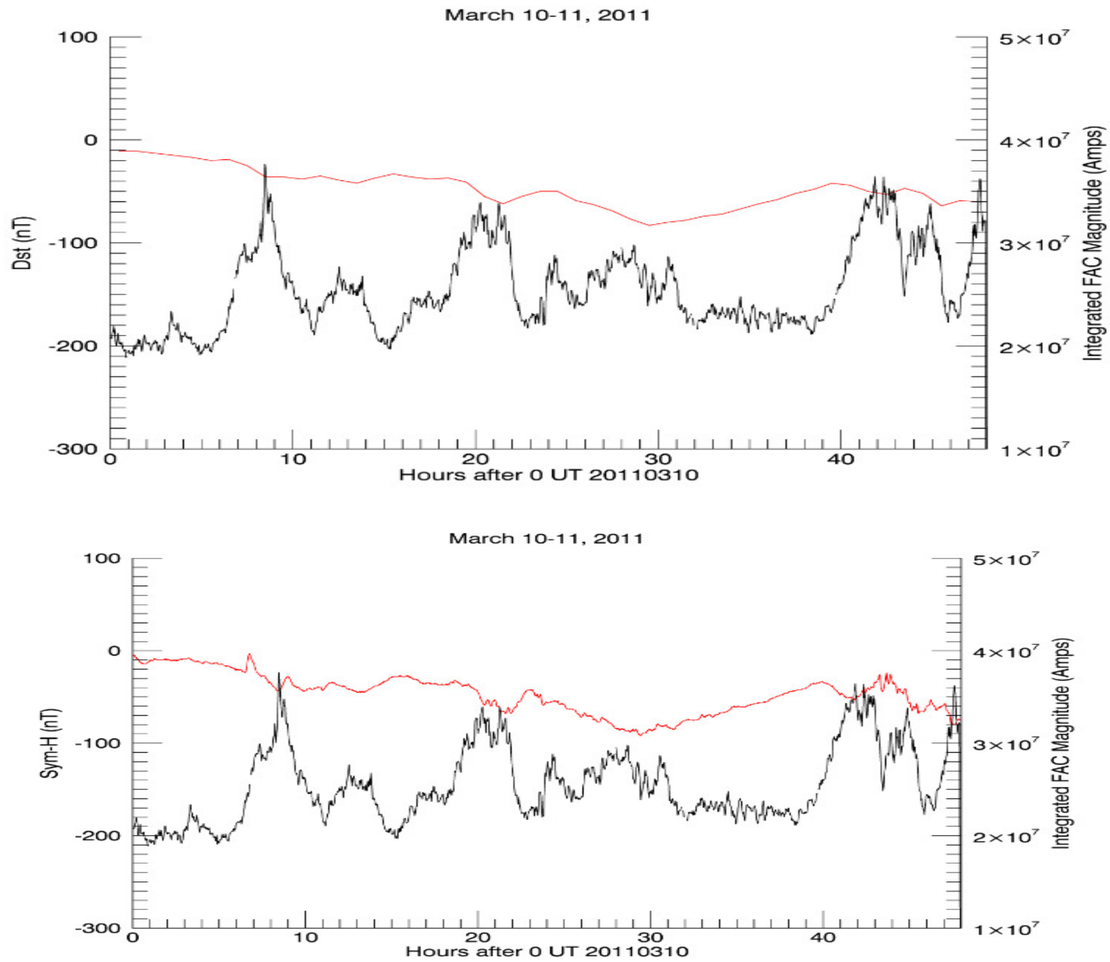


Figure 4 Example comparison of DsT and Sym-H magnetospheric/ring current with impulsive field aligned current growth, then reversal of current and the restoration of magnetospheric current

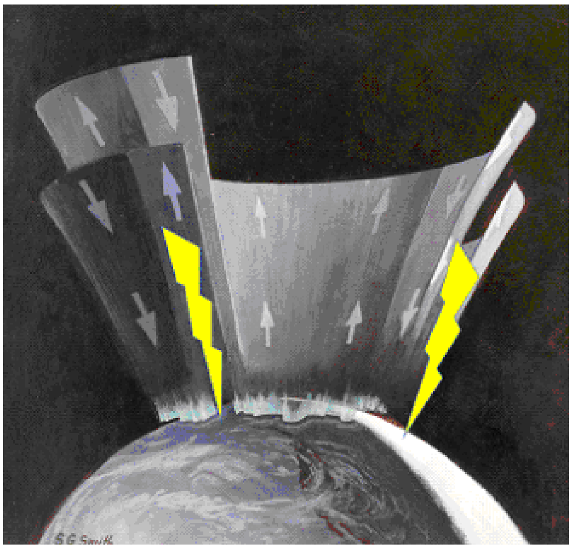


Figure 5 – graphic depiction of “lightning” analog of high intensity, small scale magnetospheric - ionospheric impulsive current discharge

The primary point here is that the process is conductivity controlled at this very small scale. The energy content of the ring current is the result of solar wind energy input and loss of energy through various processes. One of those processes may be the impulsive energy discharge into the ionosphere caused by the variation of conductivities with field-aligned currents. The non-linear connection between the magnetosphere and the ionosphere can create runaway current conditions, leading to highly time varying and impulsive changes in current circuits (Figure 5). In the magnetosphere-ionosphere circuit there are no current-limiting processes. The current could grow rapidly, resulting in impulsive electrical discharge into the ionosphere in a process very similar to terrestrial lightning.

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