

Global Ionospheric Storms

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THEME: Atmosphere-Ionosphere-Magnetosphere Interactions

EXECUTIVE SUMMARY

We discuss Global Ionospheric Storms as an important sub-field of study within solar and space physics. Significant science questions are discussed as well as methods to address them. Progress requires a robust observational approach that includes thermosphere/ionosphere imaging combined with in-situ measurements from space and ground-based measurements from globally distributed instruments. Because of the large-scale changes that occur over time scales of minutes, instruments operating continuously are needed to form the core observations. Small satellite constellations are also well suited to the study of GIS to characterize local time dependence of the ionospheric response.

1. Scientific Challenge

Understanding the storm-time ionosphere is fundamental to solar and space physics. Significant scientific attention and resources have been devoted to this topic over the last few decades, yet it remains fresh. Knowledge has been gained over the years, certainly a triumph for our field, yet this knowledge remains insufficient to predict how the ionosphere will behave during the next storm with a high level of confidence. We consider here “ionospheric behavior” in its broadest sense: behavior that spans time scales from minutes to days, and spatial scales from hundreds of meters to thousands of kilometers. The concerted effort of the past decades has provided an appreciation of the various physical phenomena that play a role in the ionospheric response to storms, yet we cannot pin down with confidence what will happen in any given event. The remaining gaps in our understanding are due to limited observations that are not up to the task of constraining the scientific hypotheses.

The concerted effort of scientists has provided a description of “qualitative” storm-time behavior, and our language used to describe these events is similarly qualitative: “positive phase” storm (increased electron density), “negative phase” (decrease), “prompt” (within minutes to a few hours) or “delayed” (response is delayed 12 hours or more). Yet, we do not have the ability to predict reliably which qualitative description will apply for a given storm, much less predict its quantitative magnitude. When considering the possible variations over a range of spatial and temporal scales, the limitations of the current state of knowledge are starkly revealed.

Recent research into the geospace response to coronal holes serves as a means to highlight today’s uncertainties. The “first cause” of an ionospheric storm is a change in solar wind conditions sunward of Earth, at the magnetopause. One expects that scientific descriptions of storm-time behavior must be closely tied to the categories of solar wind variation that cause the storm. The research literature is not particularly clear on this point. For example, although coronal holes as a heliospheric phenomenon have been known for at least three decades, the distinct ionospheric response to coronal holes is only now being characterized. Ionospheric storm phenomena have often been organized in terms of geomagnetic indices, e.g. the 3-hour Kp index. The problem is that a given Kp value can arise from a wide variety of solar wind conditions. Thus attempts to predict storm behavior based on Kp will suffer from ambiguities in working backwards from Kp to the solar wind causative factors.

Storm time response has also been described in terms of specific solar wind quantities (interplanetary magnetic field, plasma dynamic pressure or speed) that trigger the ionospheric response. For example, important high latitude drivers of storms are organized in statistical models according to the solar wind speed and magnetic field components (e.g. Weimer model). This naturally leads to a storm time description that *is* tied to the solar wind drivers. Yet, existing descriptions are insufficient because

they often ignore how the solar wind variation is itself organized according to phenomena originating near the Sun. A standard categorization of geoeffective solar surface phenomena identifies “coronal mass ejections” and “coronal holes.” In the interplanetary medium, these phenomena lead to “interplanetary coronal mass ejections” (ICME) and “high speed streams” (HSS). At 1 AU (at Earth), the solar wind characteristics of ICMEs and HSSs are generally quite distinct. Now consider that the ionospheric response depends critically on the detailed behavior of the solar wind, including correlations among the different solar wind variables (magnetic field, speed, density, temperature, etc.) and the time scales over which these variables change. It is natural to categorize storms as “HSS storms” and “ICME storms”, because these two distinct solar wind phenomena probably help organize the solar wind variation. Yet, the ionospheric characteristics of HSS storms are only now being explored as a distinct phenomenon, lagging by several decades the knowledge of HSS existence. This lag is due to limited physical understanding of ionospheric storms, and the fact that it has been a struggle simply to identify the general characteristics and basic physical processes at play during storms, much less understand how those processes are tied to the solar wind.

A particularly fruitful area of research is the spatially localized responses (~100-200 km) that occur in the midst of a major global scale ionospheric perturbation. The last decade has witnessed a significant focus on localized storm-enhanced density effects that appear at sub-auroral latitudes. Quasi-imaging observational approaches based on dense networks of ground-based GPS receivers have revealed these features, but considerable controversy exists over the physical processes at work. This leads to an important question: are poorly understood fundamental physical processes involving plasma and ion-neutral physics playing a role in the formation and evolution of stormtime structures? The easy answer to this question is “yes”, yet the scientific questions regarding these localized processes have yet to be crisply identified.

2. Phenomena

Figure 1 can help motivate the idea of a global ionospheric storm (GIS), although it should not be interpreted as to restrict what a global ionospheric storm might be. This figure shows the large plasma redistribution and creation that occurred rapidly after storm onset for the Halloween storm of October 2003, as observed by total electron content (TEC) measurements above the CHAMP satellite orbiting at 400 km altitude. The following questions remain to be answered about such “superstorm” events:

- What are the relative roles of winds and electric fields in creating the storm time response?
- To what degree is the acting electric field solely of magnetospheric origin, or could there be a dynamo component also (the latter would generally counteract the magnetospheric component during daytime).
- What physical processes lead to the large electric field magnitudes that were estimated for this event (> 4 mV/m at the equator)?
- What is the impact of plasma transport across latitudes?
- What determines the latitudinal extent and structure of the prompt ionospheric response? What is the longitudinal profile of the response? Is there a dependence of the response on the UT onset of the storm? What is the local time response of the storm? What role do seasons play? If multiple storms occur in succession (e.g. October 29 and 30, 2003) is there a significant preconditioning effect? Will preconditioning increase or decrease the ionospheric response?
- How and why do significant mid-latitude plasma gradients form, and what are physical processes at play?
- What is the extended (multiday) response of the thermosphere and ionosphere to intense ICME generated storms. What tends to suppress the response (e.g. November 10, 2003; see Mannucci et al., 2009)? What determines time scales for recovery? How does the recovery phase vary globally? What role is played by the plasmasphere during the storm recovery phase.
- What is the influence of solar EUV flux on the stormtime response?

Of course, a major overarching question is: what solar wind characteristics determine the observed responses (e.g. Figure 1)?

Figure 1 illustrates the daytime GIS response. Nighttime phenomena have recently been discovered over Puerto Rico and Japan, which show the existence of mesoscale propagating irregularity waves and areas of ionospheric depletions with widths of a few hundred kilometers. These mid-latitude features are a few thousand kilometers in length with strong electron density gradients occurring over dimensions of 10 km. Nighttime features during superstorms deserve further study.

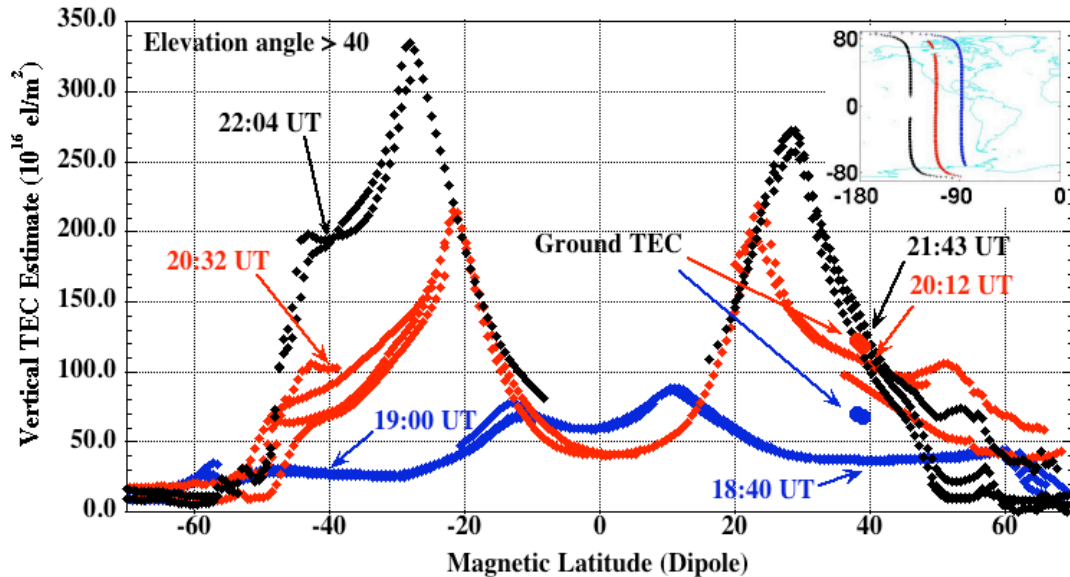


Figure 1: Global scale response to a super storm. The plotted quantity is total electron content (approximately vertical) above the CHAMP satellite orbiting at 400 km altitude. Three daytime passes are shown. The local time near the equator for all three passes is 1300. The blue trace precedes the storm. The red trace occurs after a large B_z southward excursion has reached the magnetopause. The black trace is the next pass. The ground track of the satellite is shown in the upper right. From Mannucci et al., 2005.

There have been relatively few reports of the characteristics of middle-latitude auroras that accompany superstorms. The characteristics and consequences of such large auroral zones should be studied. The enlarged auroral oval could significantly change the physics of penetration electric fields of magnetospheric origin. In fact, the entire structure of the magnetosphere is likely altered significantly during these events. What is the characteristic of “monster auroras” and do they modify the ionosphere on global scales? Little is known. In the boundary region between the auroral zone and middle latitudes, strong gradients form in electron density, conductivity, and temperature, likely altering significantly the global scale thermospheric circulation and ionosphere-magnetosphere interactions

Middle Latitude Structuring

A remarkable feature of GIS is the structures that form at middle to low latitudes that have yet to be explained. Unusually large (factor of 10 TEC increase) localized midnight electron density enhancements at mid-latitudes have been reported. One of these events occurred over Florida during the local nighttime of October 30-31, 2003 [Mannucci et al., 2005; Datta-Barua et al., 2008]. See Figure 2. Preliminary evidence suggests that other superstorms have produced similar events. The following science questions should be addressed:

- 1) What is the electron density structure and time evolution for these events?
- 2) What types of geospace conditions and prior storm conditions are necessary for these enhancements to occur?

- 3) What are the occurrence statistics of these events? Do they occur in areas other than Florida? Are there always conjugate enhancements in the Southern Hemisphere?
- 4) What are the physical mechanisms that lead to these nightside enhancements? Is there any connection between these events and equatorial ionospheric phenomena? Why do the events co-rotate and appear to remain earth-fixed over several hours?

The question arises of where such mid-latitude structuring occurs during superstorms. It is certainly the case that the effects of global ionospheric storms are easier to observe over North America, where GPS receiver chains are quite dense. Satellite observations are needed to answer the global question. Figure 3 shows a pass of the JASON satellite over the Pacific Ocean and the corresponding vertical TEC measured below the satellite by the altimeter system, for the October 30, 2003 superstorm. The ground track of the JASON satellite is shown in the insert. During this global ionospheric storm mid-latitude TEC values increased by up to a factor of ten (point A) and elevated TEC values extend poleward beyond 50° south latitude where there is an extraordinarily sharp gradient in TEC (point B). JASON transited local times of roughly 1100 LT to 1400 LT during this pass. The black trace shows a typical quiet time electron density distribution for the same local time as the storm time pass, and a similar longitude. This example demonstrates a high degree of mid-latitude structuring during the storm, the cause of which is unknown.

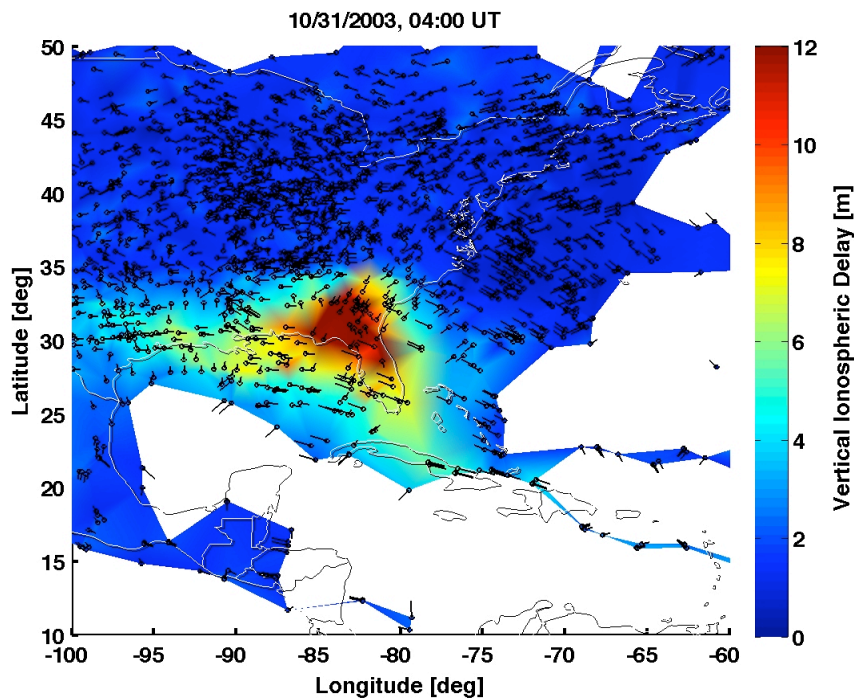


Figure 2. TEC over the eastern US and Caribbean at 2300 LT. GPS measurements (black circles with a ray pointing back toward the GPS receiver) from about 400 stations, converted to an equivalent vertical TEC assuming a 500 km ionospheric shell, and linearly interpolating TEC between nearest measurements. One meter of ionospheric delay corresponds to 6.13 TECU. [after Datta-Barua, 2004].

Plasma Gradients

Generally nature abhors strong gradients and tries to eliminate them with a combination of diffusion, instabilities, and mixing. Yet uncharacteristically large ionospheric electron density/TEC gradients are obvious in previous figures. For example, Figure 3 shows a change of nearly 200 TECU in one degree of latitude. Figure 4 illustrates how the ionosphere can change significantly from the viewpoint of three nearby GPS receivers in the US (Pittsburgh, Hawk Run, PA and USNO in DC). The

plot is position error caused by excess ionospheric delay above the receiver. The large change in range error occurs rapidly at each site, but is clearly distinct among the sites. This suggests sharp TEC gradient scale lengths of a few tens to hundreds of km and that the gradients are moving horizontally relative to the site locations. Large gradients have been observed to persist over the US heartland for 2-3 hours and are 30 to 100 times more intense than gradients produced by diurnal solar illumination.

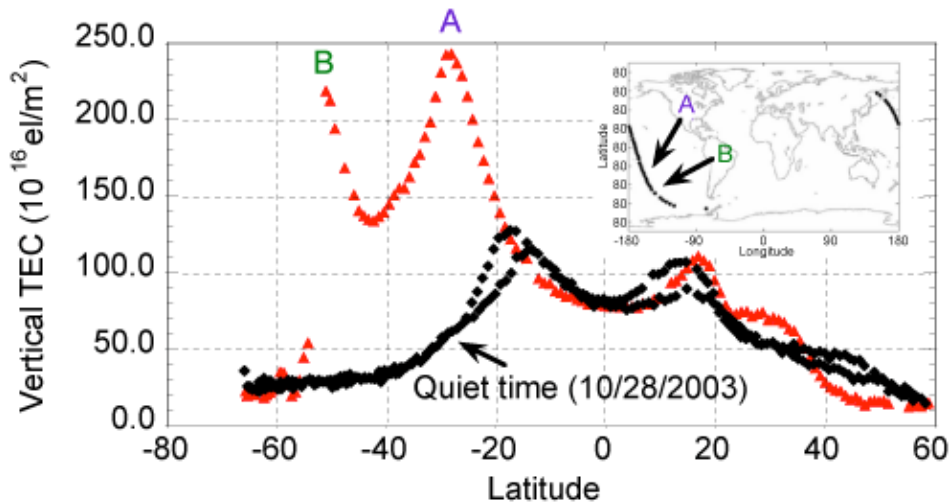


Figure 3. VTEC as measured from the JASON S/C during the October 30, 2003 super-storm. The large VTEC value of nearly 250 TECU was measured over the South Pacific at about 1400 LT.

In contrast to both high and low latitude ionospheric gradients that exist during quiet times, there is limited scientific understanding of what produces and maintains these very large mid-latitude gradients, how often such sharp gradients occur, their full spatial extent, or their temporal evolution. Previous research has provided some hints at the physics involved in generating ionospheric gradients, which are, broadly speaking, the result of either enhanced plasma production, enhanced plasma erosion, or a combination of the two. For example, upward plasma drift caused by electric fields can increase the total plasma quantity during daytime conditions as solar production is maintained and plasma loss is reduced at higher altitudes (Figure 1). Alternatively, significant plasma erosion is thought to occur along the edges of the mid-latitude ionospheric trough through heating associated with fast plasma drifts [Schunk et al., 1976]. This gradient might be associated with the boundary of the high-latitude convection pattern, or due to SAPS electric fields [Foster et al., 2002].

Global (geostationary) imaging is needed to characterize the creation and stability of hemispheric-scale severe density gradients during magnetic storms. Imaging will determine how these structures are interconnected across latitudes and whether they interact with the different geophysical phenomena that they may connect with, such as the equatorial anomaly, auroral oval, plasmaspheric drainage plumes, the high-latitude convection pattern, and inner magnetospheric penetrating electric fields.

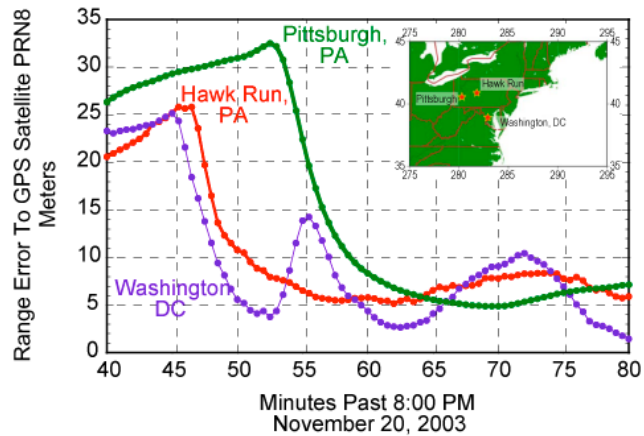


Figure 4. GPS position error and three nearby sites in the US during the November 2003 superstorm. The position error is caused by ionospheric delay. The rapid changes with time indicate significant ionospheric gradients drifting rapidly above each site.

3. Systems Science

The large increase in energy input leading to Global Ionospheric Storms also creates coupling between different regions of geospace that might be obscured during more quiet times. The AIM community has been increasingly focused on the “systems science” perspective as reflected in the CEDAR Strategic Plan (CEDAR, 2010). *The focus on systems science is needed because a strongly interacting system cannot be described or understood by studying its components in isolation from the larger system.* An example of system interactions that are hypothesized to occur during GIS is shown in Figure 5. The diagram schematically illustrates how low-to-middle latitude plasma transport, caused by penetrating magnetospheric electric fields and solar EUV production, leads to increased plasma outflow into the magnetosphere, in turn producing ring current energization and additional electric field penetration as well as plasmaspheric changes and changes to the dayside reconnection rate. This complex web of interactions is only in the initial stages of being understood.

4. Missions And Concluding Remarks

Unraveling the complex phenomena that constitute Global Ionospheric Storms requires a robust observational approach combining space-based observations with globally distributed ground-based observations. This scientific problem is certainly worthy of a flagship-class mission, although alternative strategies are certainly possible. It is necessary to combine full Earth-disk imaging from geostationary orbit if possible, with in-situ observations that measure the forces undergoing dynamic changes. In-situ sampling of the boundary region between the auroral and middle latitudes as the auroral zone expands rapidly is a high scientific priority. Small satellite constellations are well suited to GIS science also because of the need to sample multiple local times simultaneously. Ionosphere focussed missions should be combined with magnetospheric and solar wind data to address interactions at the systems level.

5. Acknowledgement

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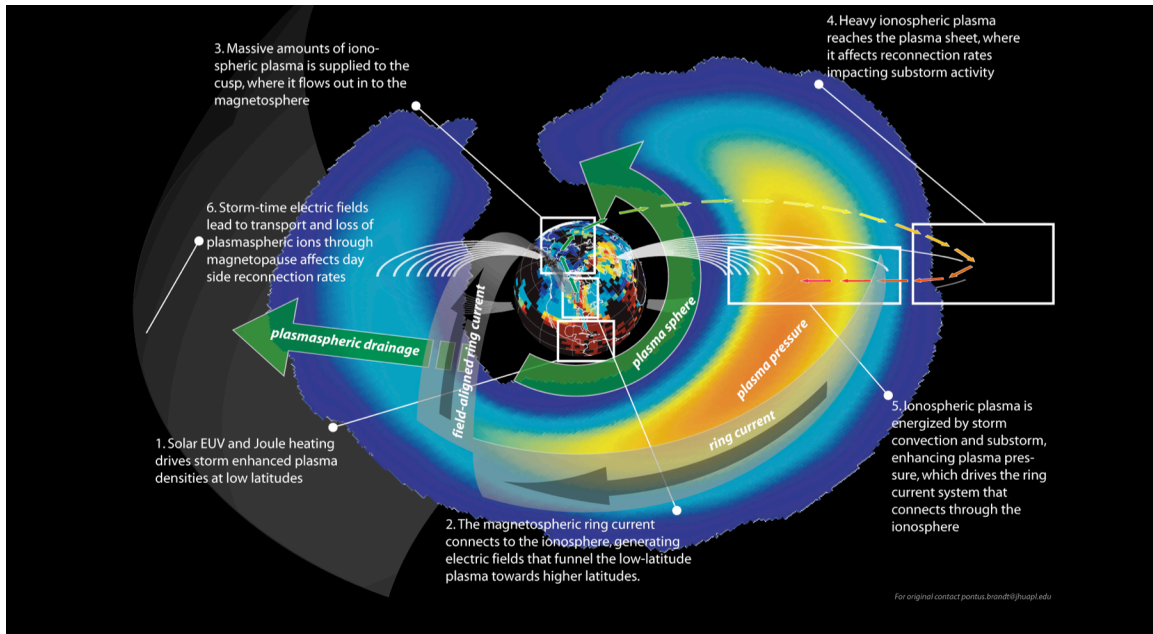


Figure 5. The systems view of outflow and ionosphere-magnetosphere interactions during a Global Ionospheric Storm. What are roles of magnetospheric dynamics, plasmaspheric dynamics and structuring? From Tim Fuller-Rowell's presentation of the Living With A Star Focused Science Team, AGU Fall Meeting, 2008.

6. References

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