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Editor's Note:

After Vol.15 Issue 1 was distributed, it was pointed out that the final report from the Tail/Substorm campaign, submitted to NSF in September 2003, had not yet been distributed. Herein we publish that report.

Report Upon The End Of The GEM Tail-Substorm Campaign

Introduction

Disturbances of the space environment are a critical aspect of Space Weather and of the NSF Geospace Environment Modeling (GEM) program. Other than for the stormtime ring current, which forms within the inner magnetosphere, the primary space weather disturbances occur within the plasma sheet of the magnetotail and couple along magnetic field lines to the auroral ionosphere. At the time of inception of the GEM Tail-Substorm (TS) campaign, the substorm was the primary type of plasma sheet disturbance that was generally recognized. Hence, the Strategies for the Tail-Substorm Campaign (ed. by W. J. Hughes, Published by Boston University), completed in July 1993, emphasized the study of substorms, though it was also recognized that there are large temporal variations in plasma sheet flow, which were thought to play an important aspect of tail dynamics.

During the first phase of the TS campaign (1994-1997), it became apparent that substorms were not the only type of important disturbance of the nightside plasma sheet and auroral oval. It was found that the there are several different types of disturbances, each

being an important and distinct type of disturbance and each reflecting fundamentally different dynamical processes within the magnetosphere-ionosphere system. This represented a major breakthrough in our understanding, being as important to Space Weather as the distinction between mid-latitude cyclones, hurricanes, and tornadoes is to tropospheric weather. In addition, the full compliment of NASA ISTP spacecraft became available, and capabilities for ground observations of ionospheric manifestations of disturbance phenomena dramatically improved. This greatly added to our ability to observe tail dynamics and its relationship to the solar wind and to Space Weather disturbances. To take advantage of our developing knowledge and of the new observational opportunities, and to satisfy the evolving needs of the community, the magnetotail-substorm campaign was restructured in 1997.

The restructured GEM TS campaign had the broader goal of understanding the dynamics of the tail and its relationship to geomagnetic disturbances and was active from 1998-2003. It

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focused significant community effort on identifying and developing understanding of the important types of distances of the magnetotail and nightside auroral oval. As a result, our understanding of Space Weather advanced dramatically. The discussion below focuses on four fundamentally different types of disturbances that were found to be important and are related to large-scale disturbances of the magnetosphere-ionosphere system: substorms, poleward boundary intensifications (PBIs), effects of solar wind dynamic pressure enhancements referred to here as "dynamic pressure disturbances," and morningside, convection driven disturbances. Of these, only the substorm was generally recognized as being important prior to the GEM TS campaign. Each of these types of disturbance has unique characteristics and reflects distinctly different physical processes occurring within the magnetosphere. Since these disturbances couple to the auroral ionosphere, auroral emissions provide an invaluable two-dimensional image of each disturbance. Spacecraft auroral images are shown in Figure 1 which illustrate optical signatures of the disturbances described below.

Substorms

Substorms are a dramatic and large-scale disturbance. The substorm occurrence rate is highly variable, but there are typically several per day. Auroral activity during substorms typically initiates within a ~1-2 hr in local time sector near the equatorward boundary of the nightside auroral oval and then expands both poleward and azimuthally. Very intense discrete aurora lies along the poleward and westward boundaries of this expanding region. The poleward expansion can bring strong aurora well into the region that is normally occupied by the polar cap, forming what is known as the auroral "bulge". An example of a spacecraft image of a well-defined auroral bulge during a substorm is shown in the upper left-panel of Figure 1. The westward expanding region of strong discrete

aurora is referred as the "westward traveling surge" and can continue for up to ~30 min after the substorm onset. Ground magnetic disturbances associated with substorms are typically a few hundred nT, but can range from ~50 nT to ~2000 nT.

Substorm onsets are preceded by a $\gtrsim 30$ min growth-phase period of enhanced convection that is typically associated with a moderate to large southward-directed IMF. During the growth phase, the plasma sheet moves earthward and particle energization increases leading to an increase in the cross-tail current. This increase is particularly strong within the earthward portion of the plasma sheet. In addition to being associated with auroral activity, the expansion phase is associated with a reduction in strength of the cross-tail current and a displacement of the inner edge of the plasma sheet and the cross-tail current away from the Earth, and thus with a large release energy from the inner portion edge of the plasma sheet.
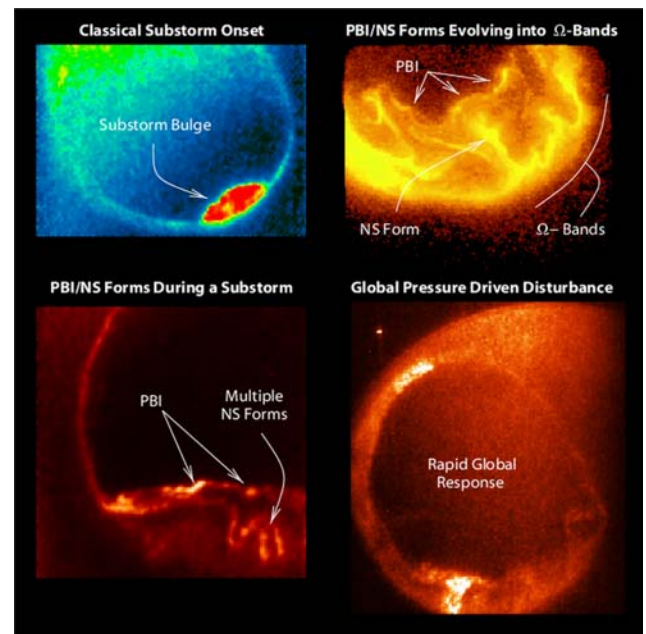

Figure 1: Viking and POLAR spacecraft images of the auroral oval showing different types of disturbance.

The reduction of cross-tail current during a substorm is initially localized and does not extend across a large distance of the tail. The edges of the current reduction region are connected to field-aligned currents extending to the ionosphere. These currents are upward and large on the dusk side of the current-reduction region. The large upward currents connect along magnetic field lines to the strong discrete aurora that forms the intense, active aurora that characterizes the substorm expansion phase. Within the inner plasma sheet, large increases in plasma energy density occur during the substorm growth phase and large increases in energetic particle fluxes occur during the expansion phase. Rapid changes in ground magnetic fields also occur.

The above aspects of substorms were all known prior to the TS campaign. However, two major changes in our understanding of substorms have occurred during the course of the campaign. First, prior to the campaign is was believed by most of the community that substorms were the result of a internal magnetospheric instability that occurred as the energy stored in the tail magnetic field and plasmas increased during periods of strong magnetospheric convection. However, early GEM TS campaign studies indicated, to the surprise of many, that substorms often occur in response to IMF changes that lead to reductions in the strength of convection, and thus can be viewed as being caused by appropriate IMF changes. This suggested that the substorm energy release is associated with a decrease in the input of solar wind energy, and not a direct response to energy build up, a concept that that is now a mainstream aspect of substorm research. Later GEM studies showed that the majority of substorms occur in this way. It is also known that substorm are infrequent during periods of steady enhanced convection. However, it has not yet been determined whether or not all substorms result from reductions in the strength of convection driven by the solar wind.

The second major GEM accomplishment on substorms concerns a long-term controversy as to whether substorm onset processes initiate first within the inner plasma sheet ~10 R_E from the Earth or in the mid-tail ~20-30 R_E. A significant number of studies have been completed on this topic, all indicating that onset initiates within the inner plasma sheet. These studies indicate, however, that the mid-tail region also plays an important role in expansion phase dynamics.

Poleward boundary intensifications

During the TS campaign, it was found that by far the most common type of auroral-zone disturbance is the PBI. PBIs occur repetitively with a period on the order of 10-15 min. They can occur independently from other types of disturbances and concurrently with other disturbances, and their intensity and frequency of occurrence tends to increase with the strength of convection and following substorm onsets. They have an auroral signature that often can be seen to move equatorward from the poleward boundary of the auroral oval, which, on the nightside, lies very near the boundary between open and closed fields. Individual PBIs are longitudinally localized, and there can be several such disturbances within the nightside auroral oval at one time. Disturbances typically occurr from near dusk to a hour or two past midnight. They also extend varying distances through the auroral oval, some staying confined to very near the polar cap boundary and others extending through a large portion of the auroral oval and becoming elongated in the north-south direction. The lower left panel of Figure 1 shows a detailed view of auroral emissions with a substorm bulge. PBIs can be seen as auroral brightenings along the poleward boundary of the bulge and extending as approximately north-south aligned auroral structures within the bulge itself. PBIs are typically associated with ground magnetic perturbations of a few tens of nT, but perturbations can be as high as ~500 nT during periods of strongly enhanced convection. The

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time scale for individual intensifications is typically a few minutes.

PBIs were also found to be associated with the bursts (~few min in duration) of enhanced plasma flow that where know before the TS campaign to be dynamically important within the tail plasma sheet. The flow bursts are longitudinally localized, extending only a small distance across the tail, and they lead to enhance auroral emissions because they are associated with localized enhancements in electric fields across the tail. The mapping of these electric fields to the ionosphere results in longitudinally localized regions of enhanced dawn-to-dusk directed electric fields, which on their western edge give rise to converging Pedersen currents. These converging ionospheric currents are connected to upward field-aligned currents which are often sufficiently strong to lead to the formation of the discrete auroral forms which are observed as the PBIs. Sometimes individual PBI structures observed at low altitudes traverse essentially the entire latitudinal extent of the plasma sheet, which would correspond to flow bursts that extend from the distant tail plasma sheet (~50-100 R_E) all the way to the vicinity of synchronous orbit. PBIs have also been found to be associated with significant enhancements in energetic particle fluxes and magnetic variations within the plasma sheet.

Morningside, convection driven disturbances

Also during the campaign, large enhancements in auroral emissions were identified at midnight to dawn MLTs during prolonged periods of strongly enhanced convection, which can include the growth phase of some substorms, SMCs, and magnetic storms. These morning auroral enhancements are believed to result from plasma sheet electrons that are strongly energized as they convect earthward during periods of strongly enhanced convection. As the electrons reach the inner region of the plasma sheet, magnetic

drift carries them around the dawn side of the Earth where strong pitch angle diffusion causes their precipitation and the resulting intense diffuse aurora. At times the morning side auroral enhancements develop waves along their poleward boundary that are know as "omega bands". These waves have periods similar to those of PBIs. An auroral image showing omega bands on the dawn side of the auroral oval during a period of enhanced convection is shown in the upper-right panel of Figure 1. This image also shows strong north-south oriented auroral structure, which when viewed as a time sequence, appear to develop into the omega bands. This indicates that there may be a physical connection between there two different repetitive phenomena.

Only limited attention has yet been paid to the morningside enhancements driven by enhanced convection. Thus much needs to be done to determine the simultaneous ionospheric and field-aligned currents and electric fields associated with the enhancements, their overall contribution to magnetospheric dynamics, and a more precise description of conditions for when they are important.

Dynamic pressure disturbances

Finally, it was found during the TS campaign that enhancements in solar wind dynamic pressure can cause large disturbances during periods of strong magnetospheric convection. Dynamic pressure enhancements affect the entire auroral oval nearly simultaneously, unlike substorms and PBIs. Within a few minutes of the time an enhancement in dynamic pressure hits the magnetopause, the poleward boundary of the auroral oval moves poleward and the intensity of auroral emissions increases throughout essentially the entire auroral oval. The equatorward boundary of the oval is not significantly affected, so that the latitudinal width of the auroral oval increases. The poleward motion of the poleward boundary of the oval can be as much as 10° in latitude, which corresponds to a large broadening of the auroral

oval. It also corresponds to a large reduction in the area of open, polar-cap magnetic field lines, since, except near local noon, the poleward boundary of the oval lies at the boundary between open and closed field lines. Most of the increase in auroral intensity is in the diffuse aurora, but increases in discrete aurora most likely also occur. An image showing global bright aurora following the impact high solar wind dynamic pressure upon the magnetosphere is shown in the lower right panel of Figure 1.

Dynamic pressure enhancements compress the entire magnetosphere. The compression heats the plasma sheet plasma, which enhances auroral emissions, and causes significant enhancements of fluxes of trapped energetic particles. The compression also enhances the larges-scale magnetospheric current system. Increases in the current within the dayside magnetopause can be over a factor of three. It is also know that the global field-aligned current system that lies along the open-closed field-line boundary, the ionospheric current system driven by magnetospheric convection, and the cross-tail current significantly increase in response to enhancements in solar wind dynamic pressure. Magnetospheric convection and the cross-polar cap potential drop were also found to increase following an increase in solar wind dynamic pressure, suggesting that the strength of coupling between the solar wind and the magnetosphere increases with increasing solar wind dynamic pressure. The causes of the current system, convection, and polar cap area responses to solar wind dynamic pressure changes are not currently well understood.

Concluding statement

The GEM TS campaign has stimulated major changes in our understanding of Space Weather disturbances of the nightside magnetosphere. Prior to GEM, only substorms were generally considered to be significant. Now all four types of disturbance described above are known to be important and are being actively studied throughout the international community. While much has been learned, much more needs to learned before these disturbances can be realistically included in dynamic models of the near-Earth space environment.

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