PROBING TOPSIDE IONOSPHERE/PLASMASPHERE STRUCTURE DURING GEOMAGNETIC DISTURBANCES

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ABSTRACT

Radar, satellite, and GPS/TEC observations are combined to identify the source and significance of ionospheric storm enhanced density (SED). We find that SED is the ionospheric signature of the erosion of the outer plasmasphere by ring current-induced disturbance electric fields. The SED/TEC plumes identified at low altitude map closely onto the direct magnetospheric identification of the plasmapause and plasmaspheric tails determined by EUV imaging from the IMAGE spacecraft. These patches and plumes of greatly-enhanced TEC perturb GPS and other trans-ionospheric radio propagation, and are responsible for the unexpected occurrence of mid and high-latitude radio scintillation.

INTRODUCTION

Severe space weather effects have been observed at mid latitudes over the continental US during the strong magnetic storms of the current solar cycle. Large-scale enhancements of total electron content (TEC), steep spatial gradients in ionospheric plasma parameters and TEC, and the occurrence of strong radio scintillation occur in the sub-auroral region which usually is free from such disturbances. These phenomena are the effects of magnetosphere-ionosphere coupling associated with the penetration of storm-induced electric fields into the inner magnetosphere, the injection of energetic ring-current particles, and the rapid erosion of the outer plasmasphere.

Incoherent scatter radar (Millstone Hill) and in situ satellite (DMSP) observations of plasma density and convection are used to characterize the ring current-produced sub-auroral polarization stream (SAPS) electric field which spans the low-conductivity region between the plasmapause and the equatorward extent of plasma sheet precipitation. The continental array of GPS observing sites is used to map total electron content (TEC) with 5 or 15-min temporal resolution and clearly identifies the temporal/spatial evolution of the plumes of storm-enhanced density (SED) [1] which surge across mid latitudes from their plasmaspheric source. These patches and plumes of greatly-enhanced TEC perturb GPS and other trans-ionospheric radio propagation, and are responsible for the unexpected occurrence of mid-latitude radio scintillation.

A number of important magnetospheric boundaries are found near the auroral/sub-auroral transition, nominally near 60˚ invariant latitude (Λ), and these result in the ionospheric structure and dynamics which characterize the local ionospheric observations made from MIT's Millstone Hill Observatory research facility, located near 54˚Λ in eastern Massachusetts. The high-altitude plasmapause [2] maps down to the region near the equatorward edge of the (mid-latitude) ionospheric trough and is associated with the transition between the corotating inner magnetosphere and the strong convection electric fields which drive the ionospheric circulation at auroral latitudes. As the level of geomagnetic disturbance increases, the electric fields and particle populations which characterize the auroral region expand equatorward and their effects are felt at previously sub-auroral latitudes. These often-intense electric fields serve to deepen the trough [3] and redistribute the ionospheric plasma through advection from one local time region to another. The equatorward extent of the plasma sheet particle population lies on field lines near the plasmapause and precipitation from the plasma sheet alters the ionospheric conductances, currents, and fields. Important to the current study is the fact that ionospheric conductance is very low in the region of the deep night time ionospheric trough between the equatorward limit of plasmasheet particle precipitation and the elevated *F*-region densities of the plasmasphere.

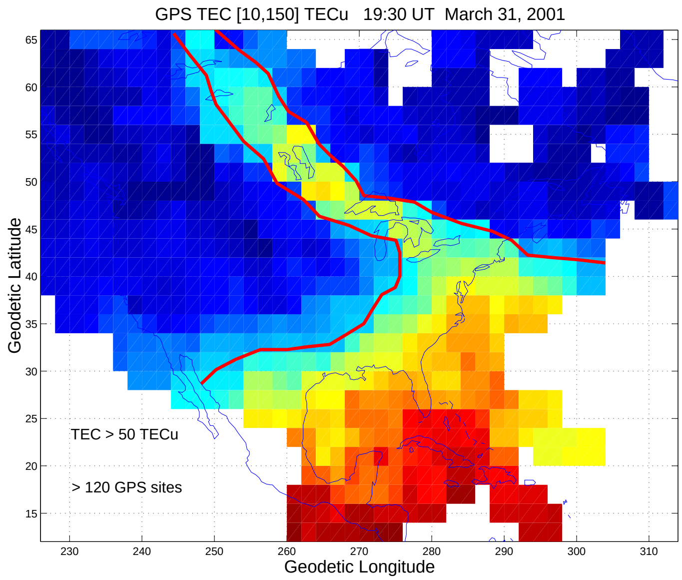

Fig. 1. Snapshot of SED plume in the post-noon sector obtained by plotting vertical TEC obtained from > 120 GPS receiving sites during a 15-min interval. The 50 TECu contour is outlined in red and defines the instantaneous position of the SED/TEC enhancement.

STORM ENHANCED DENSITY

In the low-altitude ionosphere, the process of stormtime erosion of the plasmasphere is evidenced by the appearance of sunward-convecting regions of enhanced plasma density at mid latitudes. For many years, the Millstone Hill incoherent scatter radar has observed storm enhanced density (SED) in the pre-midnight sub-auroral ionosphere during the early stages of magnetic storms [1]. These high-TEC plumes of ionization appear at the equatorward edge of the mid-latitude ionospheric trough and stream sunward driven by poleward-directed electric fields at the equatorward limit of region of sunward convection. TEC in excess of 200 TECu (1 TECu =10^{16} el m^{882}) was observed at L=2 in northern Florida during the July 15, 2000 Kp=9 event, while 100 TECu over the north-central USA is more typical of pre-midnight SED events for Kp=5 or 6. We find that SED is the ionospheric signature of the erosion of the outer plasmasphere by ring current-induced disturbance electric fields.

SAPS ELECTRIC FIELD

We find that the strong polarization electric fields which develop across the sub-auroral ionosphere during disturbed conditions [4] is responsible for the erosion of the outer plasmasphere and the formation of SED and plasmaspheric tails. Solar wind-driven convection electric fields energize ring-current particles and transport them into the inner magnetosphere. Nightside pressure maxima develop cause field-aligned currents (FACs) to flow into the evening sector ionosphere. Portions of these FACs flow into regions of low ionospheric conductivity at sub-auroral latitudes. Large polarization electric fields, needed to maintain current continuity, drive rapid plasma drift in the sub-auroral polarization streams (SAPS) which play an important role in determining the characteristics of the magnetosphere/ionosphere thermal plasma distribution and related space weather effects. The SAPS electric field is strongest near 22 MLT and near this point the SAPS abuts and overlaps the high-density, high-TEC region of the enhanced outer plasmasphere. In this region, the outer plasmasphere is stripped away, producing plasma tails (or detached plasmas) in the inner magnetosphere, and drastic enhancements of TEC in the sub-auroral ionosphere where the GPS ray paths intersect the SED flux tubes.

PLASMASPHERIC TAILS

An exciting recent capability is the direct observation of the extent and dynamics of the plasmasphere by the IMAGE satellite [5]. EUV images using resonantly-scattered sunlight from plasmaspheric helium depict the evolution of the plasmapause across wide swaths of MLT. For the first time dayside plasmaspheric tails are seen stretching sunward from the perturbed afternoon-sector plasmasphere. For the March 31, 2001 event, we make direct comparisons between GPS maps of total electron content (TEC) over the North American continent with Millstone Hill radar observations of storm enhanced density and low and high-altitude satellite measurements of the perturbation of the outer plasmasphere

We have calculated vertical TEC at each satellite ionospheric pierce point determined from > 120 GPS sites in North America and the Caribbean We use the standard ionospheric mapping function [6], bin TEC in 2˚x2˚ latitude/longitude bins, and generate maps of TEC over the North American continent at 5-min intervals as presented in Fig. 1. We find a pronounced band of storm enhanced density with TEC in the range 70 - 100 TECu extending from the New England coast across the Great Lakes region and into central Canada. This large-scale ionospheric feature directly maps into an extended plasmaspheric tail which was observed simultaneously by the IMAGE EUV sensor [7].

The Millstone Hill incoherent scatter radar observed high speed sunward ion motion associated with the SAPS region. A radar scan map of sunward ion flux is presented in Fig. 2. The ion flux was greatly enhanced at the equatorward extent of the region of rapid sunward ion motion, where the SAPS electric fields overlapped the low-latitude edge of the trough near the plasmapause projection. The radar and concurrent DMSP observations indicate that the TEC plumes mapped by GPS were convecting sunward (i.e. along the plume) at speeds >1000 m/s.

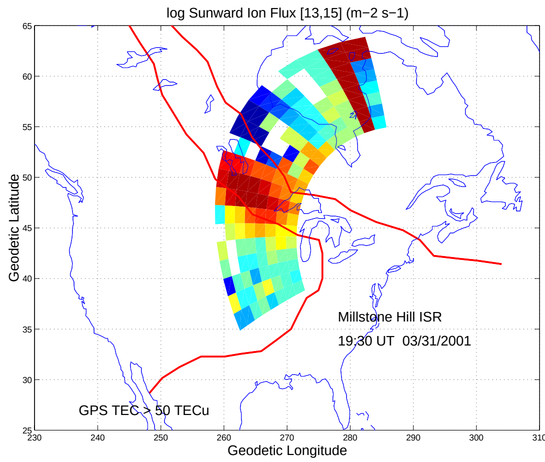

Fig. 2. Intense sunward ion flux (density x velocity) was observed with Millstone Hill radar azimuth scans across the region of the SED plume. Ion flux ~10^{15} $m^{-2}s^{-1}$ was observed coincident with the GPS TEC/SED feature of Fig. 1.

DISCUSSION

The sub-auroral electric field plays an important role in determining the characteristics of the magnetosphere/ionosphere thermal plasma distribution and related space weather effects. The steep disturbed-time plasmapause and spectacular plasmaspheric tails are formed where SAPS overlaps the outer plasmasphere [7]. As the polarization stream sweeps sunward, entrained plasmaspheric material is observed at high altitudes near the dayside magnetopause as plasmaspheric drainage plumes [8] and at low altitudes as regions of storm enhanced density [1] and elevated total electron content (TEC). The dramatic, dynamic plasmaspheric and ionospheric structure which accompanies these processes produces severe mid-latitude space weather consequences during moderate and large disturbances. Plasma density (TEC) gradients on the edges of the regions of SED [9] result in GPS loss of lock and strong trans-ionospheric radio scintillations occur in their vicinity. SED plumes sweep high-TEC plasma from low latitudes to the dayside auroral region, and hence into the polar cap where they have been termed tongues of ionization. These topside F-region patches in the polar regions are strong sources of ion outflow (polar wind) and lead to polar cap irregularities and radio scintillation. Strong mid-latitude scintillation was observed at Hanscom AFB in the early post-noon sector during the March 31, 2001 event [Sa. Basu, private communication, 2002] during the interval when the SED plume/plasma tail discussed in this paper was passing over the Boston/Millstone/Hanscom area. Scintillation also occurred in the center of the polar cap at this time, as a dense tongue of ionization appeared at polar latitudes (Fig. 3).

The structuring of the outer plasmasphere by the penetration jet electric field is a major contributor to ionosphere-magnetosphere coupling and space weather phenomena across the span of latitudes from L=2 to the poles. Coordinated ground-based and satellite investigations of these related phenomena are characterizing these processes and their effects for incorporation into descriptive and predictive models of earth's plasma environment.

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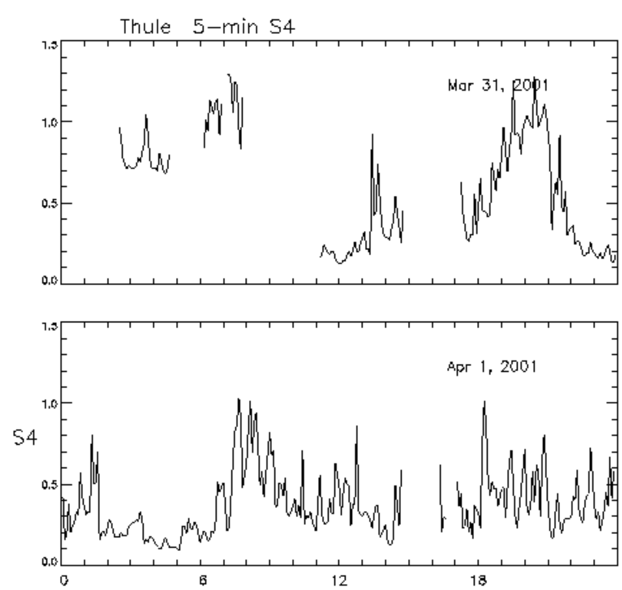

Fig. 3. Strong scintillation was observed at Thule near 20 UT on March 31st in conjunction with the formation of the SED/plasma tail and a tongue of ionization over the polar cap which was observed during DMSP satellite overflights.