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Cold plasma redistribution throughout geospace

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The redistribution of the electrically charged cold plasma of ionospheric origin involves the equatorial, low, mid, auroral, and polar-latitude regions in a multi-step, system-wide process linking the regions of geospace. Observations with ground and space-based instruments characterize the geospace plume-regularly occurring channels of enhanced plasma density flowing at both ionospheric and magnetospheric altitudes. Convection in the SAPS channel transports the eroded material to the noontime cusp in the ionosphere and to the dayside magnetopause at high altitudes. As the fluxes of cold plume plasma traverse the cusp and enter the polar cap, they form the polar tongue of ionization. At the cusp the plume plasma provides a rich source of heavy ions for the magnetospheric injection and acceleration via the mechanisms operative on those field lines.

plasmasphere, ionosphere, geospace, GPS TEC, ionospheric electric field, plume

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1 Introduction

The redistribution of cold plasma of ionospheric origin during major geomagnetic disturbances [1,2] is a multi-step, system-wide process involving the equatorial, low, mid, auroral, and polar-latitude regions. During disturbed conditions near solar maximum, IMAGE EUV space-based imagery [3] revealed dramatic tails or drainage plumes stretching sunward from the outer plasmasphere. These had been predicted in early studies modeling the interaction of disturbance electric fields with the plasmasphere (e.g. Chen and Grebowsky [4]). Mid-latitude ground-based observations revealed a number of related ionospheric phenomena (e.g. Mendillo [5]; Foster [6]), and the study by Su et al. [7] described the connection between the ionospheric observations, the plasmaspheric tails, and the large-scale redistribution of cold plasma in the magnetosphere.

Cold plasma disturbance effects in the ionosphere and magnetosphere often are driven by processes occurring in

the plasmasphere boundary layer (PBL) [8]. Magnetospheric electric field and ExB plasma convection extend deep into the mid-latitude ionosphere during storm conditions. At the PBL, strong electric fields contribute to the formation of the deep mid-latitude density trough that spans the nightside, while penetration electric fields uplift, destabilize, and perturb the low-latitude ionosphere. Large increases in the mid-latitude ionospheric F-region electron density and total electron content (TEC) often are observed in local dusk sector equatorward of the ionospheric trough during magnetic storms (e.g. Mendillo [9] and references therein).

Foster [6], using Millstone Hill incoherent scatter radar observations, found that recurring localized dusk-sector TEC enhancements observed at the PBL in disturbed conditions were associated with high-density plasma originating from lower latitudes convecting sunward (towards noon and poleward at ionospheric heights). That study defined the term storm enhanced density (SED) to refer specifically to the sunward-convecting density enhancements at the equatorward edge of the dusk-sector ionospheric trough [6]. Figure 1 presents a cross section of one such SED feature

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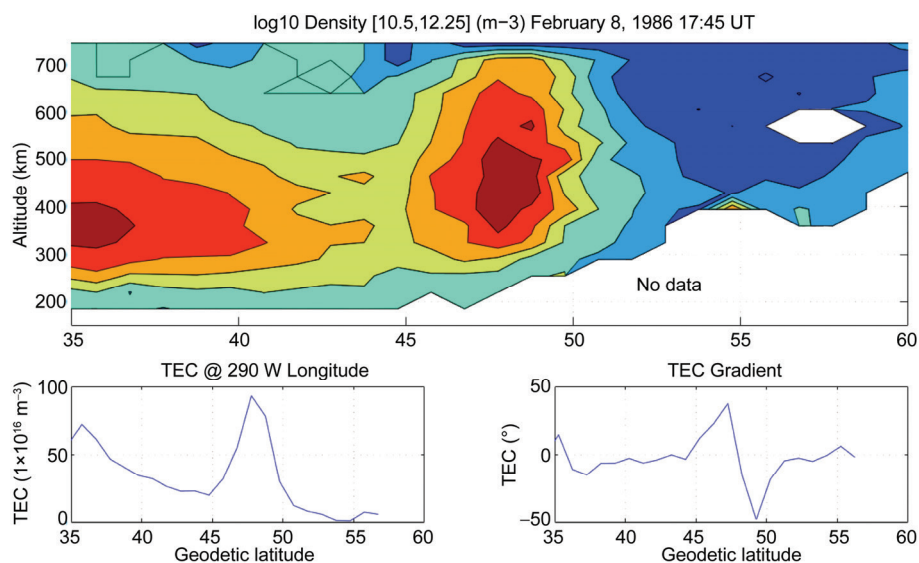


Figure 1 (Color online) Iso-density contours observed by the Millstone Hill radar scanning N-S across a region of strong storm-enhanced density (SED) near local noon are presented with as a function of geodetic latitude (invariant latitude = geodetic latitude + 11°). F-region TEC and TEC gradient across the region are derived from the radar elevation scan and are shown in the bottom panels. The February 8, 1986 event represents a severe example of the ionospheric density perturbation that can occur over the continental US associated with SED plumes. TEC near 48° N geodetic latitude is ~100 TEC units with latitude gradient in TEC of ~50 TEC/deg [10].

observed with a Millstone Hill incoherent scatter radar (ISR) elevation-scan. Calculated from the ISR density-altitude profiles, F-region TEC approached 100 TECu within the SED plume while sharp TEC gradients (~50 TECu/deg latitude) were observed bordering the SED feature [10]. Such sharp spatial gradients pose significant space weather problems (1 TECu represents an integrated column density of 10^{16} electrons m^{-2}).

The enhancement of stormtime TEC at low and mid latitudes consists of two parts (as shown schematically in Figure 2 from Foster et al. [11]). Under the influence of the penetration electric field, TEC seen at and poleward of the crests of the equatorial anomalies increases associated with plasma uplift and redistribution from low to mid latitudes (e.g. Tsurutani et al. [12]). This occurs inside the plasmasphere boundary layer and serves as an enhanced source population for the second TEC feature. These are the plumes of storm enhanced density that are eroded from the lower-latitude ionosphere/plasmasphere by magnetospheric disturbance electric fields. This process results in narrow plasmasphere drainage plumes [3] whose extent along magnetic field lines stretches between the plasmasphere and the ionosphere (e.g. Chi et al. [13]).

Two-dimensional snapshots of the plasma distribution at ionospheric and plasmaspheric heights have been provided by global imaging from the ground using the distributed GPS observations of TEC [14] and from space by the IMAGE EUV instrument [15]. Incoherent scatter radar and overflights with the low-altitude DMSP satellites provide details of the related plasma convection velocities and the altitude-spatial distributions of the plasma. These important space weather phenomena are parts of a system perspective

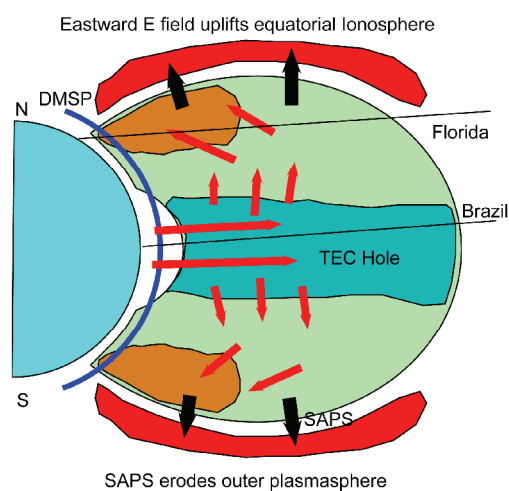


Figure 2 (Color online) The dual effects of disturbance electric fields are presented schematically. Penetration electric fields uplift the equatorial ionosphere redistributing equatorial plasma poleward, while Saps electric fields strip away the enhanced outer layers of the plasmasphere forming the SED plume [11].

involving the role of ionosphere-magnetosphere-heliosphere coupling in shaping and controlling such phenomena.

2 Cold plasma response to geospace electric fields

Early in a geomagnetic storm, plasmasheet particles are driven earthward by enhanced cross-tail electric fields. Before shielding fields can be set up on field lines in the outer

plasmasphere, the storm-induced electric field can penetrate deep into the inner magnetosphere. Penetrating eastward electric fields are observed at mid and low latitudes in the post-noon sector (e.g. Foster and Rich [16]), driving the F-region plasma upward and poleward in the $E \times B$ direction. For equatorial latitudes the ionosphere is lifted and spreads poleward along the field lines in both hemispheres under the influence of gravity and plasma pressure. This forcing drives the equatorial ion fountain and creates enhanced plasma density (or TEC) in the equatorial ionospheric anomaly (EIA) peaks.

In the inner magnetosphere, a shielding layer is set up at the PBL where the freshly-injected ring current particles abut the plasmapause. Region II field-aligned currents are driven into the sub-auroral ionosphere where the inward extent of the energetic ring current ions lies equatorward of the plasma sheet electrons [17]. Poleward-directed Pedersen closure currents in the low-conductivity ionosphere equatorward of the precipitating auroral electrons are accompanied by a strong poleward electric field that maps along magnetic field lines between the ionosphere and magnetosphere. This sub-auroral polarization stream electric field (SAPS) [14] overlaps the outer plasmasphere, drawing out the SED/ plasmasphere erosion plumes that stretch sunward from their dusk-sector source to the dayside cusp in the ionosphere and to the merging region at the high-altitude magnetopause [18,19].

3 Cold plasma redistribution

GPS TEC measures the column content of cold electrons integrated through the ionosphere and overlying plasmasphere to an altitude of ~ 20000 km (~ 4 Re) [20]. Foster et al. [18] combined ground- and space-based cold plasma imaging techniques demonstrating that the ionospheric SED

plume and the plasmasphere drainage plume spatially map to each other along magnetic field lines on a one to one basis associated with the stormtime erosion of the PBL. Direct observations of the sunward $E \times B$ advection were used by Foster et al. [19] to quantify the flux of ions carried by the SED plume to the noontime F-region cusp ionosphere. A typical value for the measured ion flux during disturbed conditions ($\sim 10^{26}$ ions/sec) amounts to a tenfold enhancement of the ionospheric source plasma available to cusp acceleration and injection mechanisms. Figure 3 (from Foster et al. [11]) presents a polar projection of the GPS TEC map indicating the spatial extent of storm enhanced density during the March 31, 2001 event discussed by Foster et al. [18]. Stretching from a region of enhanced TEC in the southeastern USA, the SED plume extends poleward to the limit of the GPS observations near the noontime cusp over north central Canada. Tsyganenko [21] magnetic field mapping is used at the right to project the ionospheric footprint of the TEC observations into the magnetosphere equatorial plane. The spatial extent and temporal variability of the ionospheric SED plume identifies the foot of the field lines mapping into a narrow drainage plume reaching sunward from the greatly eroded plasmapause position near $L=2$ to the dayside magnetopause (noon is at the right of the figure). The strength of the plume, its position, and related magnetospheric and ionospheric effects depend on both the cold plasma source of the SED material and the characteristics of the electric field that transports it.

Using these mapping techniques, Foster and Rideout [22] intercompared the ground-based GPS TEC observations of storm enhanced density (SED) and plasmasphere drainage plumes imaged from space by the IMAGE EUV imager, with observations of the SAPS electric field that couples and interconnects the inner magnetosphere and ionosphere during large storms. They found that the inner edge of the SAPS electric field overlaps the plasmasphere erosion plume

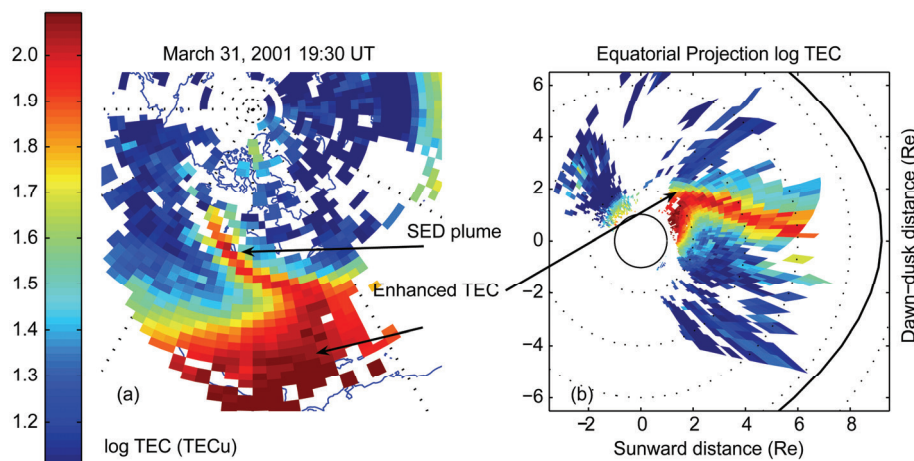


Figure 3 (Color online) (a) A region of enhanced GPS TEC was observed at the base of the plume of storm enhanced density seen over North America during the March 31, 2001 event. (b) Projecting the GPS TEC observations into the magnetospheric equatorial plane using Tsyganenko mapping (with the sun at the right) indicates that the SED plume maps to field lines extending to the dayside magnetopause [11].

and that cold plume material from the outer plasmasphere is carried sunward in the SAPS overlap region. Figure 4, taken from Foster and Rideout [22], characterizes the overlap regions of SAPS and SED observed in the topside ionosphere by DMSP. The separately-observed phenomena, SED in the ionosphere and the erosion plume at magnetospheric heights, define a common trajectory for the sunward transport of cold plasma fluxes across the midnight-dusk-postnoon sector. For cold plasmas originating in the outer plasmasphere, $E \times B$ redistribution entrains both low- altitude ions (O^+ in the ionospheric F region) and high-altitude ions (plasmaspheric and topside H^+ , He^+) to move in unison on the same magnetic field line. In this way these plasmas convect together from the PBL to the ionospheric cusp at low altitudes and at high altitude to the dayside magnetopause.

Simultaneous magnetically conjugate observations in the ionosphere and in the magnetosphere equatorial plane (cf. Figure 5) with the DMSP and Van Allen Probes spacecraft reported by Foster et al. [23] found close similarities at high and low altitudes between the SAPS channel in magnitude and invariant latitude spatial extent and location. From pre-midnight sector through post-noon local times, the SAPS electric field overlaps both the plasmasphere boundary layer and the plasmasphere erosion plume. The SAPS channel at ionospheric heights as projected into the equatorial plane defines the sharp outer boundary of the plasmasphere erosion plume.

Combining observations from the high latitude incoherent scatter radars with SuperDARN HF radar mapping and DMSP simultaneous observations, Foster et al. [24] described the trajectory of the SED plume carrying low-latitude

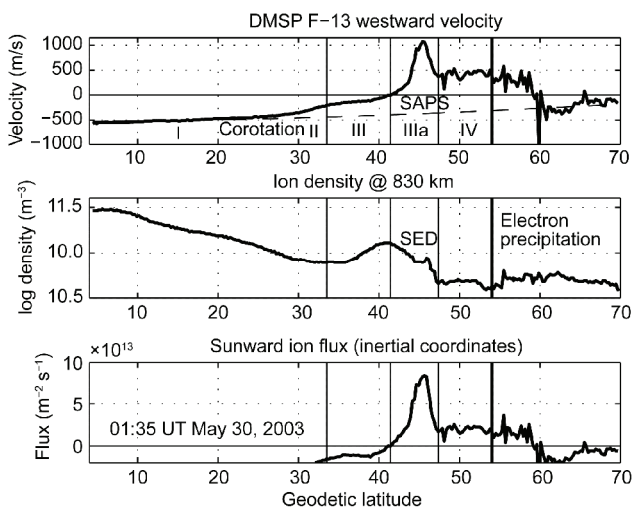


Figure 4 DMSP F-13 observations of plasma density (middle panel) and cross-track velocity (top panel; positive westward) are shown. The equatorward limit of electron precipitation is indicated by vertical lines near 54° N. An extensive region of SAPS convection extends inward to $< 35^\circ$. The lower panel presents sunward ion flux calculated as the product of density times velocity. The westward ion flux exceeds $8 \times 10^{13} \text{ m}^{-2} \text{ s}^{-1}$ in the topside F region ($\sim 830 \text{ km}$) in the outer portion of the SED plume [22].

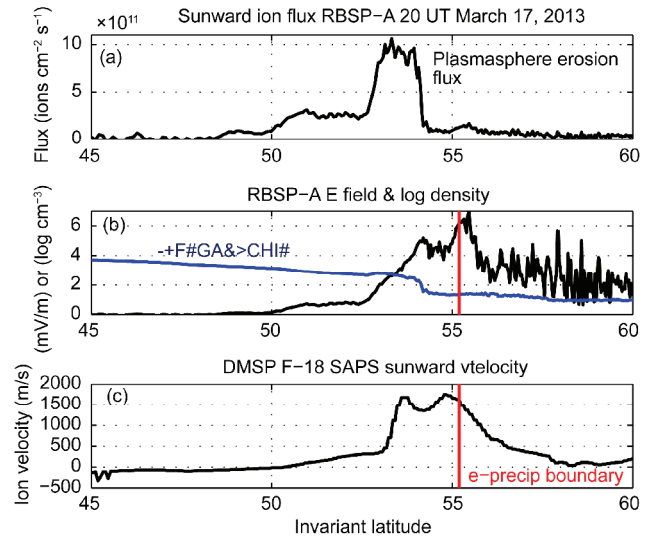


Figure 5 (Color online) (a) Plasmasphere erosion flux derived from in-situ observations as RBSP-A exited the outer plasmasphere near the apex of the $L=3 R_E$ field line on 17 March 2013. Sunward flux is calculated as the product of density and $E \times B$ velocity. (b) Outward radial electric field magnitude and log electron density at $\sim 20 \text{ UT}$ on 17 March 2013. Sunward erosion flux maximizes in the region where the SAPS electric field overlaps the outer plasmasphere. (c) DMSP F-18 sunward ion velocity at $\sim 830 \text{ km}$ altitude, showing close similarity in position and shape with the outer plasmasphere SAPS in-situ electric field. The red fiducial line indicates the equatorward extent of the DMSP observed precipitation of 100 eV plasma sheet electrons [23].

material across the cusp and into the polar cap forming a high-TEC tongue of ionization (TOI) spanning polar latitudes from noon to midnight (cf. Figure 6 from Foster et al. [24]). Cold plasma following the plume trajectory is streaming sunward across magnetic field lines towards the cusp at low altitudes (e.g. Foster et al. [19]) and to the dayside magnetopause at high altitudes (e.g. Walsh et al. [25]). The stream of the enhanced F region plasma on field lines passing through the dayside cusp on field lines associated with magnetic merging results in the elevated TEC polar tongue of ionization [24,26,27]. At polar latitudes the TOI is associated with the F region patches (e.g. Weber et al. [28]) that pose a scintillation space weather hazard.

4 Magnetic conjugacy

Electric fields are responsible for the redistribution of cold ionospheric and plasmaspheric material. Foster et al. [29] intercompared simultaneous observations of the ground-based TEC in the northern and southern hemispheres with Jason and TOPEX satellite TEC observations taken over the oceans to investigate the magnetic conjugacy characteristics of the plumes and related TEC enhancements. They found that the SED plumes streaming toward noon and poleward closely follow magnetic conjugate paths. This confirms that electric field-driven convection is dominant in driving the

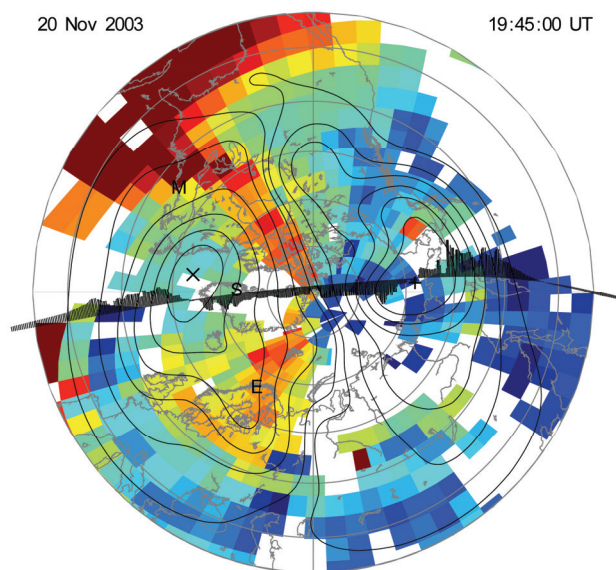


Figure 6 (Color online) Combined GPS TEC and convection observations are displayed in polar projection (mag lat/MLT coordinates; 10-deg latitude circles; with noon at the top). \log_{10} vertical TEC observations binned by lat/long at 350 km altitude are displayed with the simultaneous, independent convection pattern derived from the combined SuperDARN and DMSP observations. Ion drift meter cross-track velocity data from a trans-polar cap DMSP pass are shown, indicating anti-sunward convection above 60 deg latitude spanning the polar region. A plume of elevated TEC follows the convection contours back across the polar cap from the dayside cusp forming the polar tongue of ionization [24].

formation and location of the SED plume, although a combination of local ionospheric effects with recent past history determines the TEC content of the plume at any location and time. In this way, the location and flow of the SED plumes are useful as a tracer of the extent and strength of disturbance electric fields.

5 Recent observations

The redistribution of the ionosphere/plasmasphere cold plasma has significant consequences for geospace processes. The cold, dense plasmaspheric plume can substantially impact the coupling of the geomagnetic and solar magnetic fields at the dayside reconnection region. Walsh et al. [25] described the extension of the plume of plasmaspheric ions to the dayside magnetopause. Using the ground-based TEC maps and measurements from the THEMIS spacecraft, Walsh et al. [30] investigated simultaneous ionosphere/magnetosphere observations of the plasmaspheric plume and its involvement in unsteady magnetic reconnection. The observations characterize the full circulation pattern of the plume from its plasmaspheric source to the magnetopause. That study also validated the connection between signatures of variability in the dense plume and reconnection at the magnetopause as measured in-situ and through the TEC measurements in the ionosphere.

Magnetic merging of the solar and geomagnetic fields on field lines threading the cusp carries the low-altitude field lines into the polar cap (e.g. Zhang et al. [31]) forming the TOI and polar cap patches. The TEC and DMSP satellite observations regularly observe this plasma redistribution extending anti-sunward across polar latitudes to field lines involved in magnetic field (X-line) reconnection on the nightside. Using observations with the Van Allen Probes spacecraft in conjunction with the ground-based TEC observations of the TOI, Foster et al. [32] reported direct observation of the plume material at 5.5 Earth radii altitude in the midnight sector magnetosphere and its involvement in substorm injection into the inner magnetosphere. Adiabatic acceleration of the plume plasma to keV energies in such events contributes to the population of the inner magnetosphere plasma sheet and ring current populations.

6 Summary and conclusions

During large storms plasma redistribution is seen as a multi-step system-wide process involving and coupling processes and regions at equatorial, low, mid, auroral, and polar latitudes acting under the influence of storm time drivers of the coupled system. Penetration electric fields enhance the uplift and redistribution of the equatorial ionosphere to form enhancements of the equatorial ionization anomaly peaks at low latitudes. Energetic particle injection into the storm time ring current leads to the formation of strong poleward-directed sub-auroral polarization stream (SAPS) electric fields in the evening to postnoon sector. The SAPS electric fields overlap the outer plasmasphere and the TEC enhancements formed by the low-latitude redistribution effects drawing out plumes of storm enhanced density (SED). Convection in the SAPS channel transports the eroded material to the noontime cusp in the ionosphere and to the dayside magnetopause at high altitudes. These greatly-enhanced fluxes of cold plasma traverse the cusp and enter the polar cap forming the polar tongue of ionization and providing a rich source of heavy ions for the magnetospheric injection and acceleration mechanisms which operate in these regions.

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