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Storm-Time Strong Field-Aligned Ion Upflow in Region of the SED Plume *

YUAN Zhi-Gang(袁志刚)[1,2**], DENG Xiao-Hua(邓晓华)[1], WANG Jing-Fang(王敬芳)[1]

[1]*School of Electronic Information, Wuhan University, Wuhan 430072*

[2]*Sate Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100080*

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We report the observations from the GPS TEC and DMSP F-13 satellites showing that very strong upward field-aligned (FA) ion velocity and flux in the outer region of the storm-enhanced density (SED) occurred in the event of the geomagnetic storm on 29–31 May 2003. By a method of coordinate transformation, upward FA ion velocities in excess of 250 m/s are obtained from the observations of the DMSP F-13 satellite. Further, an FA ion flux is estimated to be about 4.5×10^{13} *ions/*m^2*s in the dusk sector. The estimated FA ion velocity and flux provide a powerful direct proof to support the scenario that there is a strong coupling of particles between the ionosphere and plasmasphere in the region of the SED plume. In the process, FA ion flux transports from the ionosphere to the plasmasphere in the region of the SED plume. Therefore, the plume of SED in the ionosphere provides an important source to the enhanced density of* O^+ *in the storm-time plasmasphere.*

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The plasmasphere boundary layer (PBL) is a very important region of dynamic interactions between the plasma of the inner and outer magnetosphere at the outer extent of the plasmasphere.[1] During geomagnetic storms, a plasmaspheric drainage plume in the PBL is transported from the dusk sector to noon.[2,3] As a result, the cold and dense plasma in the plasmaspheric drainage plume have an important influence on the magnetic reconnection at the subsolar magnetopause or in the cusp.[4,5] With observations of the MIT Millstone Hill incoherent scatter radar near the ionospheric projection of the PBL, a storm-enhanced density (SED) regularly presents a plume which streams from the pre-midnight subauroral ionosphere towards the noontime cusp during the early stages of magnetic storms.[6] In fact, with combined observations from ground-based radars and space satellites, such an ionospheric SED is proven to be a low-altitude signature of the plasmasphere drainage plume.[7,8] At ionospheric heights, observations from the total electron content (TEC) map and the DMSP satellite have demonstrated that the equatorward extent of the sub-auroral polarization stream (SAPS) electric field overlaps the region of the SED. As a result, plumes of the SED are drawn noonward and poleward along the SAPS convectional channel.[9,10] In addition, narrow plasmasphere drainage plumes of cold plasma are produced by disturbance electric fields mapping from the ionosphere into the plasmasphere.[11,12] Associated with erosion of the outer plasmasphere/ionosphere in the dusk sector, the sunward flux of the thermal plasma has been estimated with observations of the Millstone Hill radar and satellites.[13] However, little attention has been paid to the observations, especially from space satellites, about the field-aligned (FA) plasma velocity and flux in the region of SED plumes, which is very important to reveal the particle coupling dynamics between the plasmasphere and ionosphere.

A modest geomagnetic storm occurred on 29–31 May 2003. As shown in Fig. 1, the disturbance storm-time index D_{st} sharply decreased at 2100 UT on 29 May 2003, and the main phase of the storm began. At 2300 UT it reached the minimum of −144 nT. Thereafter, a secondary minimum of −135 nT occurred at 0200 UT on 30 May 2003, and the recovery phase started. The interval of interest denoted by two vertical dashed lines extends from 0120 UT to 0140 UT on 30 May 2003. During the interval, the orbit of the DMSP 13 satellite just intersected an SED plume indicated in the GPS TEC map. The DMSP F-13 satellite passing through the region of the SED plume enables us to estimate the field-aligned (FA) plasma velocity and flux at F-region heights. In this Letter, by a method of coordinate transformation, we use the DMSP F13 in-situ observations of the ion density and three-dimensional ion velocities to determine the field-aligned (FA) ion velocity and flux in the region of SED plumes. In addition, we compare the estimated ion flux in the region of SED plumes with other results.

The GPS satellites are in 12-h circular orbits (about 20000 km altitude) with orbital inclination of 55°. After removing the biases from the GPS satellite and receiver hardware, the reliable vertical TEC can be derived from GPS observations. Since GPS satellites have apogee nearly 20000 km ($L = 4$), the derived

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**Email: y_zgang@vip.163.com

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TEC is a combined contribution of the ionosphere and overlying plasmasphere. Rideout and Coster have developed a software package known as MIT automated processing of GPS (MAPGPS) to automate the processing of GPS data into global TEC maps.[14] In this study, those GPS TEC data are derived by using MAPGPS. The data provide the estimated values of TEC in 1° by 1° bins every 5 min distributed over locations where the GPS data are available.

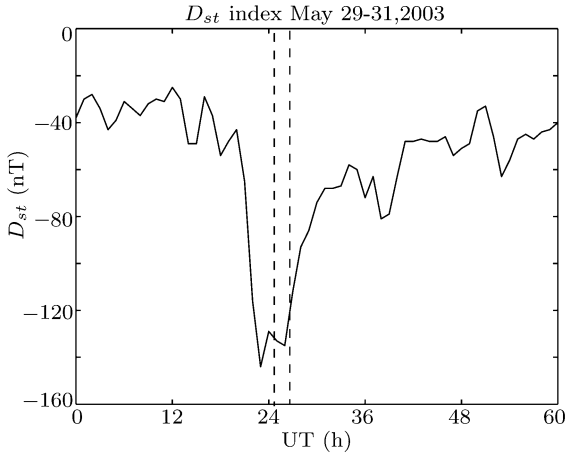


Fig. 1. D_{st} index in the event of 29–31 May 2003. The interval of interest denoted by two vertical dashed lines extends from 0120 UT to 0140 UT on 30 May 2003.

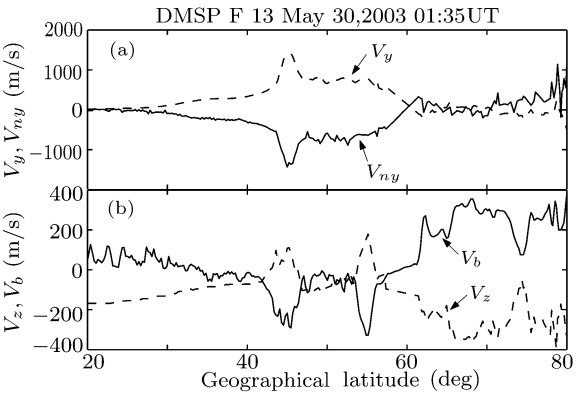


Fig. 2. Observed and derived ion bulk velocities from the DMSP F-13 satellite between 20° N and 80° N on 30 May 2003. (a) Directly observed cross-track horizontal ion velocity V_y (dashed lines) and derived eastward convection velocity V_{ny} (solid lines). (b) Directly observed vertical ion velocity V_z away from the centre of the Earth (dashed lines) and the derived field-aligned velocity V_b (solid lines). The time resolution is 4 s for the data of ion velocities.

The DMSP F-13 satellite flies in a sun-synchronous dawn-dusk orbit at about 840 km altitude. The ion density and three-dimension ion velocities can be observed by a retarding potential analyser (RPA), an ion drift meter (IDM), and a scintillation meter. The data with time resolution of 4 s are used in this study. Three-dimensional ion velocities are supplied in the local coordinate of the satellite. V_x denotes the ion velocity in the flight direction of the satellite. V_y and V_z are used to indicate the cross-track horizontal and vertical ion flow away from the centre of the Earth, respectively. At high latitudes, it is reasonable to consider V_z as the field-aligned (FA) ion velocity.[15] However, as shown in the following, it is not the case at sub-auroral latitudes. In order to derive plasma convection and FA velocities at sub-auroral or middle latitudes, it is necessary to adopt a method of coordinate transformation. Firstly, ion velocities can be derived in the geographical coordinate by using the data of the satellite position and ion velocities in the local coordinate of the satellite. Secondarily, the IGRF2005 model is used to obtain the geomagnetic field where the DMSP F-13 satellite is located. After projecting the derived ion velocity in the geographical coordinate along the direction of above the calculated magnetic field, the FA ion velocity V_b can be calculated. The convection velocity is also derived by subtracting V_b from three-dimensional ion velocity in the geographical coordinate. Finally, the northward convection velocity V_{nx} and the eastward convection velocity V_{ny} have been derived by projecting the convection ion velocity along the direction of geographical north and east, respectively. Figure 2 presents the ion bulk velocities in different frames. Since DMSP F13 flies from equator to high latitudes in the northern hemisphere during the interval, as shown in Fig. 2(a), the positive V_y denotes a westward ion velocity. In fact, in addition to nearly the same amplitude, a positive V_y, as well as a negative V_{ny}, indicates a westward component of ion bulk velocity between 30° N and 60° N. However, as shown in Fig. 2(b), there are two positive (upward) impulses between 40° N and 60° N, superimposed on a negative (downward) shift of V_z between 30° N and 60° N. In the northern hemisphere, the negative V_b indicates an up-flow ion velocity along the downward-declining geomagnetic field. In comparison with V_z, here V_b also shows two negative (FA upward) impulses between 40° N and 60° N, but superimposed on a nearly zero shift between 30° N and 60° N. The negative velocity shift of V_z should be attributed to the plasma convection velocity ($\boldsymbol{V} = \boldsymbol{E} \times \boldsymbol{B}/B^2$). Between 60° N and 80° N, the amplitude of V_z is almost the same as that of V_b. Therefore, at high latitudes, it is reasonable to consider V_z as the FA ion velocity V_b. On the other hand, instead of V_z, it is essential to adopt a method of coordinate transformation to obtain an accurate value of V_b at sub-auroral or middle latitudes.

As shown in Fig. 3, the ionospheric footprint of an overflight of the DMSP F-13 satellite is denoted by the solid lines on the TEC frame. A SED plume denoted by a black arrow extends poleward and sunward. The DMSP satellite passes through the SED plume nearly at 40° N latitude and 115° W longitude (1800 LT).

Therefore, observations from DMSP F13 provide a good opportunity to study the plasma coupling in the region of SED plumes between the ionosphere and plasmasphere.

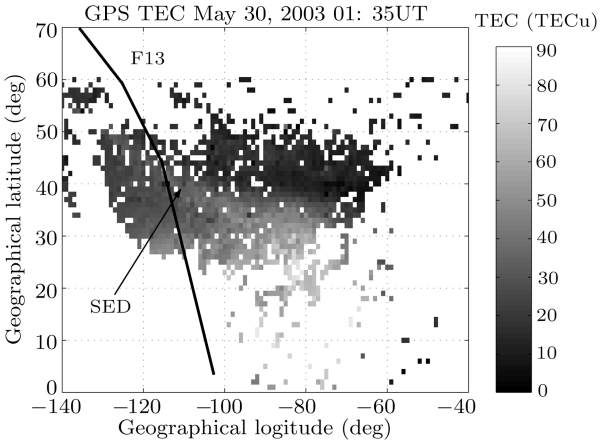


Fig. 3. GPS vertical total electron content (TEC) observations over the continental USA for 01:35 UT on 30 May 2003. A narrow plume of storm-enhanced density (SED) denoted by the black arrow extends sunward and poleward. An overflight of the DMSP F-13 satellite crossing the SED plume is indicated by the solid lines.

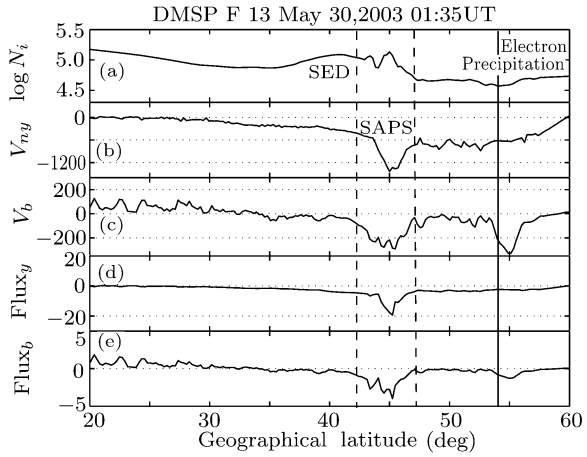


Fig. 4. (a) Ion density (cm^{-3}), (b) derived westward convectional velocity (m/s), (c) field-aligned ion velocity (m/s), (d) westward ion flux (10^{13} ions/m^2s), and (e) field-aligned ion flux (10^{13} ions/m^2s) from observations of DMSP F-13 at the time of TEC images in Fig. 3. The equatorward extent of electron precipitation is indicated by vertical lines near 54° N. A strong upward field-aligned ion velocity between 42° N and 47° N denoted by two vertical dashed lines.

Figure 4 presents the in-situ observations of the ion density and derived sunward convection velocity V_{ny}, FA ion velocity V_b, sunward ion flux (fluxy), and FA ion flux (fluxb) from DMSP-13. Between 35° N and 47° N. Figure 4(a) indicates an enhancement of the ion density, consistent with the SED plume indicated by GPS TEC map in Fig. 3. The equatorward extent of electron precipitation observed by the particle spectrometer (not shown) is indicated by vertical solid lines near 54° N. Between 42° N and 47° N denoted by two vertical dashed lines, as shown in Fig. 4(b), V_{ny} presents a very strong sunward SAPS. The SAPS electric field extends poleward to 54° N and equatorward to 30° N. As shown in Figs. 4(a) and 4(b), it is obvious that the SAPS overlaps the SED plume, especially, between 42° N and 47° N. During the interval, Fig. 4(c) presents a strong negative FA ion velocity V_b, reaching -250 m/s. Since the negative V_b indicates an upward FA ion velocity in the northern hemisphere, there is a very strong upward FA ion flow from the ionosphere to the plasmasphere in the outer region of the SED plume. As shown in Fig. 4(d), a peak sunward flux (20×10^{13} ions/m^2s) was observed where the strong SAPS peak overlapped the outer region of the SED plume near 45° N. The sunward ion flux is comparable to another estimated value (5×10^{13} ions/m^2s) from the DMSP F-12 satellite in the region of SED plumes for the event on 11 April 2001.[12] It is more important that Fig. 4(e) presents a strong FA upward ion flux, reaching 4.5×10^{13} ions/m^2s, which is attributed to the strong upward FA ion velocity and SED plume between 42° N and 47° N. As shown in Fig. 3, the plume of SED should originate from the region of enhanced mid- and low-latitude TEC below 30° latitudes caused by penetration eastward electric fields during geomagnetic storms.[12] Such a plume of SED is also considered as a signature of the erosion of the dusk-sector plasmasphere by strong SAPS electric fields.[10] Since the ion upflow occurred in the region of strong SAPS electric fields, the frictional ion heating can be considered as an important candidate in triggering the ion upflow.[16]

Enhancements of the TEC in the event of the geomagnetic storm on 29–31 May 2003 have ever been reported. Since the spectrographic imaging component of the FUV instrument can obtain simultaneous 2D images of terrestrial FUV emission,[17] the intensity of FUV emission have been compared with GPS TEC observations on 29–31 May 2003.[18] In the report, a plume of SED stretches poleward across the western US and Canada from a source of enhanced TEC over the Caribbean. In our study, data of GPS TEC and DMSP F-13 are combined to study the SED event. With those observations, we estimate the FA ion velocity, sunward and upward FA ion flux in the region of SED plumes in the geomagnetic storm event on 30 May 2003. The upward FA ion velocity reaches 250 m/s. Furthermore, FA ion flux is estimated to about 4.5×10^{13} ions/m^2s. Compared the enhanced GPS TEC with plasmaspheric drainage plume during the 2003 Halloween superstorm, Chi *et al.*, have concluded that the extraordinary electric field imposed by the solar wind results in the increase of content of

the ionosphere, which can lead to the density enhancement in the plasmaspheric drainage plume.[19] In our study, the estimated FA ion velocity and ion flux provide a powerful direct proof to support the scenario.

With ground-based observations of the Millstone Hill incoherent scatter radar, Yeh and Foster have calculated an upward flux of oxygen ions in excess of 3.0×10^{13} ions/m^{2}s at 42° geodetic latitude over 3 h around 18 MLT during the very large magnetic storm on 8 February 1986.[16] Their estimated value of the upward ion flux is comparable to those obtained from observations of the DMSP satellite in this study.

In conclusion, in order to obtain the FA ion velocity and flux in the region of SED plumes, it is necessary to adopt a method of coordinate transformation from DMSP observations of three-dimensional ion velocities. The SAPS electric field causes a narrow channel of sunward-propagating cold plasma in the midnight-dusk-postnoon sector not only for the SED in the ionosphere but also for the erosion plume in the plasmasphere. With the sunward ion flux caused by SAPS electric fields, the observations of the DMSP satellite in this study suggest that there are strong coupling of particles between the ionosphere and the plasmasphere in the region of SED plumes. The FA ion flux transports from the ionosphere to the plasmasphere in the region of SED plumes. When those ionospheric ions are transported into the storm-time magnetosphere, they will alter concentrations of the inner magnetosphere. Therefore, the SED in the ionosphere provides an important source to the enhanced density of O^+ in the storm-time plasmasphere.

References

[1] Carpenter D L and Lemaire J 2004 *Ann. Geophys.* **22** 4291
[2] Elphic R C et al 1996 *Geophys. Res. Lett.* **23** 2189
[3] Elphic R C et al 1997 *Geophys. Res. Lett.* **24** 365
[4] Su Y J et al 2000 *J. Geophys. Res.* **105** 7591
[5] Su Y J et al 2001 *J. Geophys. Res.* **106** 6085
[6] Foster J C 1993 *J. Geophys. Res.* **98** 1675
[7] Sandel B R et al 2001 *Geophys. Res. Lett.* **28** 1439.
[8] Su Y J et al 2001 *Geophys. Res. Lett.* **28** 111
[9] Anderson P C et al 1991 *J. Geophys. Res.* **96** 5785
[10] Foster J C et al 2002 *Geophys. Res. Lett.* **29** 1623
[11] Foster J C et al 2005 *Geophys. Monograph.* **159** 277
[12] Foster J C et al 2007 *J. Atmos. Solar Terr. Phys.* **69** 303
[13] Foster J C et al 2004 *Geophys. Res. Lett.* **31** L08809
[14] Rideout W and Coster A 2006 *GPS Solutions* **10** 219
[15] Coley W R et al 2003 *J. Geophys. Res.* **108** 1441
[16] Yeh H C and Foster J C 1990 *J. Geophys. Res.* **95** 7881
[17] Mende S B et al 2000 *Space Sci. Rev.* **91** 287
[18] Immel T J et al 2005 *Geophys. Res. Lett.* **32** L03808
[19] Chi P J et al 2005 *Geophys. Res. Lett.* **32** L03S07