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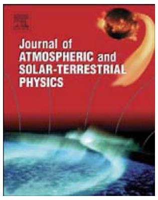

The temporal evolution of the large equatorial plasma depletions observed during the 29–30 October 2003 storm

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ABSTRACT

This study investigates the temporal evolution of the large plasma depletions observed by ROCSAT-1 and DMSP near 295°E during the 29–30 October 2003 storm. The presence of a penetration electric field around the detection time of the large plasma depletions is supported by the observation of high upward ion drift velocity and formation of an intense equatorial ionization anomaly in the American sector. However, these ionospheric disturbances occur in broad longitude regions; a short-range polarization electric field may adequately explain the creation of the large plasma depletions. The penetration electric field may trigger the Rayleigh–Taylor instability and produce abnormally large plasma depletions during the storm. The TIMED/GUVI and CHAMP observations provide an insight for the evolution of the large depletions several hours after their formation. The large depletions appear as arch-shaped emission depletions in the TIMED/GUVI image and as symmetric depletions paired in the magnetic north and south in the CHAMP observation. These characteristics can be explained by the "plasma depletion shell" phenomenon (Kil et al., 2009) produced by the westward shear flow of the ionosphere during the storm.

1. Introduction

The occurrence of large equatorial plasma depletions at night is one of the most fascinating features during very large geomagnetic storms. The depth and width of these storm-time plasma depletions are much greater than those observed in normal equatorial plasma bubbles during magnetically quiet periods. The formation of these large depletions is believed to be driven by a penetration electric field (Tanaka, 1986; Greenspan et al., 1991; Basu et al., 2001; Su et al., 2002). The observations of increased upward ion velocity in the equatorial plasma and the uplift of the bottom-side F layer to high altitudes during intense geomagnetic storms (Basu et al., 2001, 2007; Sahai et al., 2005) support the association of these large depletions with the occurrence of a penetration electric field.

Kil and Paxton (2006) reported observations of multiple plasma depletions at lower altitudes at the same location as that of large depletions, an observation that may support the association of the large depletions with plasma bubbles. The authors called the large depletion a "storm-induced big bubble" (SIBB) because of the similarity between SIBBs and bubbles in all characteristics except size. Basu et al. (2007) suggested that the enhancement of the longitudinal conductivity gradient in the F region induced by the energetic particle precipitation is responsible for the development of an intense post-sunset eastward electric field. Kil et al. (2008) explained the development of the post-sunset eastward electric field by the accumulation of positive charges at the terminators by the penetration electric field. Uplift of the ionosphere by the post-sunset eastward electric field provides a preferred condition for the development of the Rayleigh–Taylor instability (Kelley, 1989) and may create the abnormally large plasma depletions during very large geomagnetic storms (Kil and Paxton, 2006; Kil et al., 2006; Basu et al., 2007).

In this paper, we investigate the temporal evolution of the large plasma depletions during the 29–30 October 2003 superstorm by considering additional observations from the Global Ultraviolet Imager (GUVI) (Christensen et al., 2003) onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite and the Planar Langmuir Probe (PLP) (McNamara et al., 2007) onboard the CHAllenging Minisatellite Payload (CHAMP) satellite. The CHAMP/PLP and TIMED/GUVI observations provide the morphology of the large plasma depletions several hours after their formation. Kil et al., (2009) suggested the formation of a "plasma depletion shell" in low latitudes by the zonal shear plasma flow. Through the investigation of the temporal evolution of the large plasma depletions, we examine the effect of the zonal shear flow on the morphology of plasma depletions.

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2. Characteristics of the large plasma depletions

Fig. 1 shows the SYM-H index during 28–31 October 2003 obtained from the World Data Center, Kyoto, Japan. The vertical arrow indicates the occurrence time of the large plasma depletion near 295°E, and the small box on the bottom left shows the large plasma depletion observed by the Special Sensor-Ions, Electrons, and Scintillation (SSIES) sensor (Hairston and Heelis, 1996) on the Defense Meteorological Satellite Program (DMSP) F15 satellite at that time. A few large plasma depletions were also observed near 295°E by the Ionospheric Plasma and Electrodynamics Instrument (IPEI) sensor (Su et al., 1999) on the first Republic of China satellite (ROCSAT-1). Our investigation focuses on the evolution of the plasma depletions and ionospheric conditions around 295°E. The TIMED/GUVI images have not been used to investigate the morphology of the large plasma depletions; the primary reason was that the emission depletions were not distinguishable during super-storms because of strong emissions caused by particle precipitation. The TIMED/GUVI observation near 295°E during the 29–30 October 2003 storm was made a few hours after the particle precipitation and provides a unique emission depletion image near the location of the large plasma depletions.

The DMSP spacecraft have sun-synchronous circular polar orbits (98° inclination) at a mean altitude of 840 km. The magnitude of the fountain effect over the American sector was investigated by using the measurements of the ion density from F13 at 1800 LT and F15 at 2130 LT. ROCSAT-1 had a circular orbit with a mean altitude of 600 km with an orbital inclination of 35°. The occurrence of plasma depletions and the magnitude of the vertical plasma drift at the location of the large plasma depletion were investigated by using the ROCSAT-1 data. The TIMED spacecraft is in a 625-km circular polar orbit with an orbit inclination of 74.1°. The TIMED orbit precesses 360° in 120 days so that each local time is sampled every 60 days. At the time of the October storm, CHAMP was at an altitude of 400 km with an orbital inclination of 87.3°. CHAMP covers 24-h local time every 4 months. The optical signatures of plasma depletions observed by TIMED/GUVI and plasma depletions observed from CHAMP/PLP provide useful tools in identifying the evolution of the large plasma depletions.

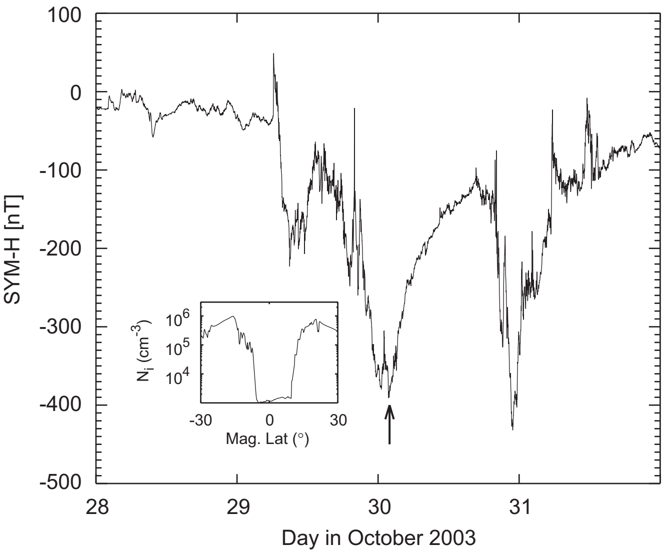

Fig. 1. SYM-H index during 28–31 October 2003. The large plasma depletion inside the small box is observed by DMSP F15 near 295°E at 0157 UT. The vertical arrow on the SYM-H index indicates the observation time of the depletion.

Fig. 2 shows the observations of ion density from ROCSAT-1 and F15 in the American sector on 30 October 2003. Fig. 2a shows the satellite orbits with the locations of plasma depletions (thick lines). Figs. 2b–e show the F15 and ROCSAT-1 data in the geomagnetic coordinate. The locations of plasma depletions identified by horizontal bars in the density plots are indicated by thick lines in the map. The plasma depletion shown in the F15 orbit (Fig. 2b) is the same as the depletion shown in Fig. 1. The location of the plasma depletion in the F15 orbit coincides with the westernmost large plasma depletions in ROCSAT-1 orbits 1 and 2 (Figs. 2c and d). The longitudinal width of the plasma depletion in the F15 orbit is comparable to the two large plasma depletions in ROCSAT-1 orbit 2. The polar orbit of F15 detects a wide plasma depletion in the north–south direction due to the elongation of the plasma depletion along the magnetic field. The plasma depletions are shifted westward in ROCSAT-1 orbit 3 (Fig. 2d). We can identify the three plasma depletions in ROCSAT-1 orbit 3 that may correspond to the plasma depletions in ROCSAT-1 orbit 2. The locations of the plasma depletions appear to be stationary between 0157 and 0253 UT, a finding that seemingly contradicts the observation of the large westward drift of the ionosphere at night (see Fig. 6). To explain the locations of the depletions at different latitudes/apex heights at different times, we need to understand the depletion structure and the zonal plasma flow. As we explain later, the coincidence of the locations of the depletions in the F15 orbit and ROCSAT-1 orbits 1 and 2 and the westward shift of the plasma depletions in ROCSAT-1 orbit 3 indicate the variation of the zonal plasma drift with latitude and apex height.

Before we further investigate the characteristics of the storm-time plasma depletions, we examine the ionospheric perturbations in the American sector around the detection time of the large plasma depletions. Fig. 3a shows the DMSP and ROCSAT-1 orbits. Figs. 3b and c show the density profiles observed from the F13 and F15, respectively, with the density profiles from different orbits distinguished by color. The black dashed lines in the density plots are the observations from the previous day for the orbit path closest to orbit 2. The equator-crossing UTs of orbits 1–3 were 2135, 2316, and 0058 UT for F13 and 0016, 0157, and 0339 UT for F15. F13 flies over a given region 3.5 h before F15 does. The significant enhancement in the plasma density at low to middle latitudes and the occurrence of an ionization trough at the magnetic equator support the interpretation that a severe fountain effect has acted over the American sector. In normal conditions, the equatorial ionization anomaly (EIA) does not develop at the altitude of 840 km, as shown by the black dashed curves in DMSP density plots. If we ignore the plasma depletions detected by F15, the background density profiles are almost identical over the American sector in the three orbits. Fig. 3d shows an observation of large upward ion drift, a finding that is consistent with our interpretation that a severe fountain effect was present in the American sector. The increase in upward drift velocity during the main phase of this storm is attributed to the penetration electric field (Kil et al., 2008). On the basis of the observation of an equatorial ionization trough at 1800 LT by F13, the large upward drift must have been present before 1800 LT over the American sector. The mean vertical drift velocity on ROCSAT-1 orbit 2 (Fig. 3e) is near zero. Therefore, the penetration electric field was observed to be gone before 2050 LT. A digisonde observation on the ground in the Brazilian sector also supports the occurrence of large upward plasma flow during the storm (Sahai et al., 2005). We emphasize that the penetration electric field acted in broad longitude regions. The penetration electric field may affect the generation of the large plasma depletions, but detailed illustration is required to determine why the large depletions occur in the narrow longitude region.