Journal of Atmospheric and Solar-Terrestrial Physics 95-96 (2013) 96–101

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Ionospheric characteristics associated with wave–particle interactions in a SED plume during a super geomagnetic storm

Zhigang Yuan [a,b,*], Ying Xiong [a,c], Shunrong Zhang [d], Xiaohua Deng [e], Jingfang Wang [a]

[a] School of Electronic Information, Wuhan University, Wuhan 430072, China
[b] State Key Laboratory of Space Weather, Chinese Academy of Sciences, Beijing 100080, China
[c] School of Computer Science, Hubei University of Technology, Wuhan 430068, China
[d] MIT Haystack Observatory, Westford, MA, USA
[e] Institute of Space Science and Technology, Nanchang University 330031, China

ARTICLE INFO

Article history:
Received 8 September 2012
Received in revised form
21 December 2012
Accepted 25 January 2013
Available online 13 February 2013

Keywords:
Wave–particle interaction
SED plume
Ionogram
Plasmaspheric plumes

ABSTRACT

We report some interesting ionospheric characteristics associated with wave–particle interactions with observations of the ionosonde and co-located incoherent scatter radar (ISR) at Millstone Hill in a storm-enhanced density (SED) plume identified from two-dimensional GPS TEC maps during a super geomagnetic storm on Nov. 20, 2003. Firstly, the digisonde ionogram only contained echoes for scanning frequencies from 6.2 MHz to 9.3 MHz. The lack of echoes at frequencies below 6.2 MHz is attributed to enhancements of sub-ionospheric absorption caused by precipitating RC electrons in the SED plume. Secondly, there was an obvious F_1 layer, as well as an Es layer, appearing on the ISR profile, that was not observed by the digisonde due to strong sub-ionospheric absorption. For echoes at frequencies from 6.2 MHz to 9.3 MHz, a comparison of the virtual height obtained from the digisonde ionogram and that derived from the ISR electron density profile, demonstrated that an Es layer appeared with a peak altitude of 123 km. The occurrence of the Es layer is attributed to enhancements of precipitating energetic ion fluxes in the SED plume. Our result suggests that the ionospheric behavior in the SED plume is controlled not only by ionospheric dynamical process but also by precipitating energetic RC ions/ electrons as a consequence of wave–particle interactions in the plasmaspheric plume.

1. Introduction

It is well known that a plasmaspheric drainage plume can be formed and can extend from the main plasmasphere in the dusk sector to the dayside magnetopause during geomagnetic storms (Elphic et al., 1997; Sandel et al., 2001). The shape and location in magnetic local time of a given plume can be described in terms of phases that follow the rise and fall of the convection strength (Goldstein and Sandel, 2005). Empirical models of the subauroral polarization stream (SAPS) have achieved reasonable success at reproducing the plasmapause and plume locations observed by IMAGE and Los Alamos National Laboratory (LANL) geostationary satellites (Goldstein et al., 2003, 2005a, 2005b). At ionospheric heights, combined observations from ground-based radars, in situ satellites, and the GPS receiver network have shown a plume of storm-enhanced density (SED) streaming from the pre-midnight sub-auroral ionosphere towards the noontime cusp during the early stage of magnetic storms (Foster, 1993; Foster et al., 2004, 2005). In fact, such a SED plume is considered to be the low-altitude signature of the plasmaspheric drainage plume (Foster et al., 2002; Yizengaw et al., 2008). A SED plume with a narrow latitude extent drawn noonward and poleward is easily recognized on two-dimensional GPS TEC maps (Foster et al., 2002; Yuan et al., 2008a,b).

In the presence of cold dense ions of plasmaspheric plumes, the electromagnetic ion cyclotron (EMIC) waves are easily generated by a resonant interaction with anisotropic ring current (RC) ions (Gary et al., 1995; Fraser and Nguyen, 2001). As a consequence of the RC-EMIC interaction, ring current protons can be scattered into the loss cone and cause detached subauroral arcs (Immel et al., 2002; Spasojević et al., 2004; Yuan et al., 2010, 2012b). On the other hand, the precipitating RC protons have influence on the ionospheric electron density mainly in the *E* or lower *F* region (Fang et al., 2007).

Plasmaspheric hiss is a broadband, structureless, extremely low frequency (ELF) electromagnetic emission in the frequency range from ~100 Hz to several kHz (Meredith et al., 2006). Besides in the Earth's main plasmasphere (Russell et al., 1969; Thorne et al., 1973; Cornilleau-Wehrlin et al., 1993), ELF hiss have been observed in plasmaspheric plumes (Chan and Holzer, 1976; Cornilleau-Wehrlin et al., 1978; Parrot and Lefeuvre, 1986; Summers et al., 2008;

---

[*] Corresponding author at: Wuhan University, School of Electronic Information, Luo-jia-shan, BaYi road, Wuhan 430072, China. Tel.: +86 027 68754720.
E-mail address: y_zgang@vip.163.com (Z. Yuan).

1364-6826/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jastp.2013.01.015

Yuan et al., 2012a). One of the consequences of interactions between ELF hiss and energetic electrons is the precipitation of energetic electrons into the atmosphere due to pitch angle diffusion (Titova et al., 1998; Yuan et al., 2011). The increase of precipitating energetic electron fluxes can lead to enhancements of ionospheric absorption of HF radio waves in the SED plume (Yuan et al., 2011).

As a powerful tool for the study of the midlatitude/subauroral ionosphere during magnetic storms (e.g., Buonsanto, 1995, 1999; Huang et al., 2003), the Millstone Hill incoherent scatter radar (42.6° N, 288.5° E, invariant latitude$=$55°) can provide ionospheric electron density profiles $N(h)$ from 100 km up to a few hundred kilometers. On the other hand, as a routine ground-based ionospheric observation instrument, the digital ionosonde is another type of radar used to measure the ionospheric electron density profile below the peak of the F_2 layer by transmitting HF radio pulses, a technique widely used to document and monitor ionospheric storms (e.g., Prölss, 1997; Lee et al., 2002; Yuan et al., 2003). Therefore, it is interesting to study ionospheric characteristics associated with wave–particle interactions by these two different kinds of co-located ground-based radars for SED plume conditions.

A super geomagnetic storm occurred during Nov. 20–21, 2003 with a minimum of the Dst index equal to -422 nT. During the main phase of this super storm, the Millstone Hill incoherent scatter radar (ISR), located in the SED plume region, measured the electron density profiles $N(h)$. In an earlier paper (Yuan et al., 2009), we have discussed the relationship between the shape of the profile $N(h)$ observed by the ISR and TEC enhancements in the SED plume. In this paper, we focus on the ionospheric characteristics associated with wave–particle interactions with simultaneous observations of the ISR and co-located digisonde in the SED plume. In Section 2, we present observations of the ISR and co-located digisonde at Millstone Hill during a passage of a SED plume identified from two-dimensional GPS TEC maps. In Section 3, we discuss the observations from those two ground-based radars. Finally, a summary is given in Section 4.

2. Observations

In this paper, data of the GPS TEC are generated by MAPGPS which is a software package developed by Rideout and Coster (2006). MAGGPS provides estimated values of TEC in 1° by 1° bins every 5 min, distributed over locations where GPS data are available. Those data of GPS TEC are provided from the MIT Haystack Observatory Madrigal database. The ISR data for the event we are discussing, however, were obtained from experiments with an interleaved long-pulse and alternating coded scheme. The alternating coded data provided a height resolution of a few km, best suited for the $E-F_1$ region investigations. With observations of the zenith, the ISR can provide the ionospheric electron density profiles $N(h)$. The ISR profile at 17:45 UT that we will be focusing on was from such alternating coded measurements. Since the integration time for an ISR profile and an ionogram of the digisonde is 2 min and 1.3 min for the case respectively, it is reasonable to consider that the ISR and co-located digisonde simultaneously observed the ionosphere in the SED plume.

As shown in Fig. 1(b), a SED plume, denoted by the black arrow, extends poleward and sunward. Such a SED plume is considered as a signature of a plasmaspheric drainage plume (Foster et al., 2004). Fig. 1(b) indicates that the SED plume originates from the region of enhanced mid- and low-latitude TEC below 30° latitudes. The poleward and sunward SED plume is transported into the noontime cusp by the $\boldsymbol{E}\times\boldsymbol{B}$ convection as discussed by Foster et al. (2004). The "*M*" in Fig. 1(b) indicates the location of the Millstone Hill ISR, which is right in the plume. Fig. 1(a) displays the averaged GPS TEC in the range of $-71°$ to $-74°$ longitudes in the meridional sector of the Millstone Hill ISR. As shown in Fig. 1(a), there is an obvious mid-latitude trough poleward of the ISR.

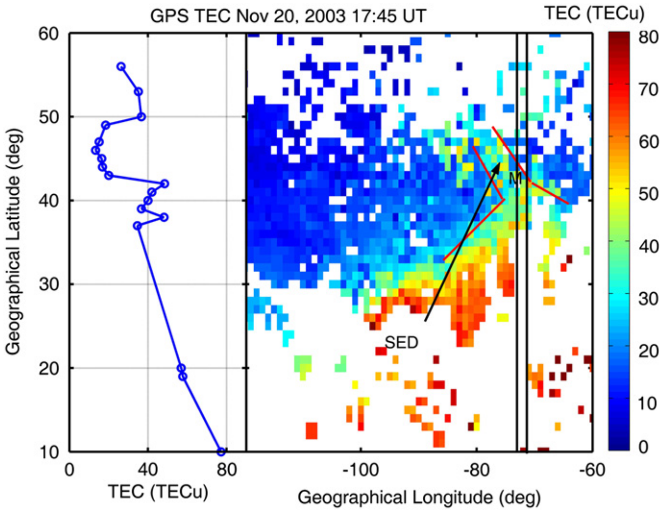

Fig. 1. GPS vertical total electron content (TEC) observations over the continental USA for 17:45 UT on Nov. 20, 2003. In panel (a), the averaged GPS TEC corresponds to the range of $-71°$ to $-74°$ longitudes as denoted by the two vertical solid lines in panel (b). In panel (b), a narrow plume of storm-enhanced density (SED), denoted by the black arrow, extends sunward and poleward. The uppercase letter '*M*' near 43° latitude is used to indicate the location of the Millstone Hill incoherent scatter radar.

Since ISR profiles were only available from 1430 UT on 20 Nov. to 1500 UT on 21 Nov., the digisonde observation at 17:45 UT on 19 Nov. is used as the quiet-time reference. The right panel in Fig. 2 presents a typical quiet-time ionogram. Red and green traces denote the vertical ordinary (O) and extraordinary (X) polarization echoes, respectively. The traces below 450 km belong to 1-hop echoes, while the traces of 2-hop echoes exceed 450 km in height. The black line on the red traces is used to precisely define the 1-hop O echo trace, from which the electron density profile is calculated (Reinisch and Huang, 1983, 2001). Since the well-defined F_2 layer critical frequency (foF$_2$) and complete visibility of E-layer and F-layer echo traces lead to a high-quality ionogram, the derived electron density profile $N(h)$ can be reliably used as the quiet-time reference. In the right panel of Fig. 2, for routine operation the digisonde profile above the F_2 layer peak is approximated by an α-Chapman function with a constant scale height that is derived from the bottomside profile shape near the F_2 peak [Reinisch and Huang, 2001]. However, on the disturbed day only those O echoes reflected in the F layer, starting in 6.2 MHz and ending in 9.3 MHz, are visible in the left panel in Fig. 2. On the ionogram, the value of foF$_2$ cannot be precisely determined. Since the derived F-region electron density profile is greatly sensitive to the foF$_2$ value, the lack of O echoes with frequencies above 9.3 MHz is mainly responsible for underestimated values of the foF$_2$, the F_2 layer peak height (hmF$_2$) and the derived profile $N(h)$ only below 403 km altitude with a routine profile inversion algorithm (Reinisch and Huang, 1983). In addition, the lack of O echoes with frequencies below 6.2 MHz can also lead to underestimated values of hmF$_2$ and the derived profile $N(h)$ only below 403 km. As a result, the profile $N(h)$ and the values of the foF$_2$, hmF$_2$ derived from the digisonde in the SED plume are not reliable.

Fig. 3 presents the electron density profile $N(h)$ observed with the Millstone Hill ISR at 17:45 UT when the ISR is located in the SED plume. As a reference, the profile $N(h)$ derived from the co-located digisonde at Millstone Hill at 17:45 UT on the quiet day is also shown. For the electron density profile of the ISR, there was an obvious F_1 layer with the F_1-layer peak height (hmF$_1$) of