Density enhancement in plasmasphere-ionosphere plasma during the 2003 Halloween Superstorm: Observations along the 330th magnetic meridian in North America

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[1] On October 29–31, 2003, the ground observations of field line resonance signals and the total electron content (TEC) along the 330th magnetic meridian recorded extraordinary density variations in both the magnetosphere and the ionosphere. In the magnetosphere, the density decreased at outer f shells due to strong convection, whereas it increased significantly in the afternoon sector at E ≤ 4. In the ionosphere, a strong positive storm occurred at low latitudes, and storm enhanced density was also observed at approximately 1400 LT in mid-latitude regions. The density enhancements in both the magnetosphere and ionosphere coincided with intervals of southward IMF and high-speed solar wind, consistent with the scenario that the eastward electric field imposed on the ionosphere led to a positive storm which might contribute to the dense plasmaspheric drainage plume. These results demonstrate that the ionosphere can be an important factor modulating the density variations in a storm-time plasmasphere. Citation: Chi, P. J., C. T. Russell, J. C. Foster, M. B. Moldwin, M. J. Engebretson, and I. R. Mann (2005), Density enhancement in plasmasphere-ionosphere plasma during the 2003 Halloween Superstorm: Observations along the 330th magnetic meridian in North America, Geophys. Res. Lett., 32, L03S07, doi:10.1029/2004GL021722.

1. Introduction

[1] The zeroth-order model of the plasmasphere describes a plasmasphere that is determined by the balance between the corotation and the solar-wind-driven sunward convection [e.g., Nishida, 1966]. During magnetic storms the sunward convection increases, and the plasmasphere undergoes erosion as the plasmasphere moves closer to the Earth. The research that provides observational evidence for this paradigm as well as more complicated characteristics of the plasmasphere has been pioneered by studies using whistler propagation and sawtooth measurements [see Lamoure and Gringauz, 1998, and references therein]. In recent years, in addition to the new insights of the global plasmasphere provided by the IMAGE satellite mission [Borovsky et al., 2000], ground observations of the plasmasphere were revisited by the advent of the gradient method that uses ground magnetometer observations of field line resonance (FLR) signatures to infer the magnetospheric density [see, e.g., Russell et al., 1999, and references therein] as well as the fast-growing array of GPS receivers that can be used to deduce the total electron content (TEC) [e.g., Foster et al., 2002]. Previous observations have demonstrated that the plasmasphere can undergo severe depletion even at low L shells [Chi et al., 2000, Vellante et al., 2002].

[2] In this letter we present a case in which, in addition to the depletion in the outer magnetosphere, the storm-time plasmasphere experienced an unusually significant enhancement in its density. This event occurred during October 29–31, 2003, the first three days of the “2003 Halloween Superstorm,” which was induced by multiple interplanetary shocks. This storm event was also accompanied by some of the most intense X-ray emissions and strongest proton events in recent history [see other papers in this special issue for details]. Using the FLR-inferred magnetospheric density and TEC, assisted by the observations in the solar wind during the same time interval, we conclude that the extraordinary electric field imposed by the solar wind resulted in the increase in the content of the ionosphere, which might lead to the density enhancement in the plasmaspheric drainage plume.

2. Observations

[4] To investigate the latitudinal profile of the plasma density, we used the ground magnetometers at the same longitude to remove the local time effects. The gradient technique [Borovsky et al., 1985] for identifying FLR frequencies also requires a close separation in the north-south direction between adjacent stations. Therefore, we studied the data collected from nine stations that were located roughly along the 330th magnetic meridian (see Figure 1). These stations are located at L-values ranging from 2.4 to 9.5, and their local time is approximately 6.3 hours behind Universal Time. The variations in the ionospheric density is inferred from the vertical TEC values calculated from more than 450 GPS sites in North America and the Caribbean region using the standard ionospheric mapping function [Foster et al., 2003]. In this study we present the TEC results at the same longitude as that of the magnetometer observations for the purpose of comparison. The complete TEC data have coverage in other local times, providing us with the information about the shape of the storm enhanced density structure.
In addition to ground observations, the solar wind data from the ACE spacecraft are also studied for comparison, as shown in the top panel of Figure 2. The solar wind speed exceeded 1000 km s\(^{-1}\) from 0630 UT on October 29 for 26 hours as well as from 1630 UT on October 30 for 17.5 hours. The velocity even topped 1700 km s\(^{-1}\) at 1800 UT on October 29 and at 1800 UT on October 30. The solar wind density was low during the interval of high-speed solar wind, and thus the dynamic pressure only increased moderately from its already high values [Shue et al., 2004]. Also important was the interplanetary magnetic field (IMF), which turned northward briefly at the arrival of the high-speed solar wind plasma, as well as during two longer intervals starting at 1600 UT on October 29 and 1800 UT on October 30 for 10 hours and 4 hours, respectively. When the solar wind speed was higher than 1000 km s\(^{-1}\), the interplanetary medium took less than 40 min to travel from the ACE spacecraft to the subsolar region of the Earth’s magnetosphere. The IMF index shows that the magnetic storm started at 1600 UT on October 29, and the main phase consisted of three stages before it dropped to a very low value of -401.

The FLR frequencies observed by ground magnetometers are estimated through the amplitude-phase gradient method (APGM) that has recently been tested by Kurokawa et al. [2002]. One advantage of using the APGM is that the FLR frequency can be estimated as a continuous function of latitude. The results of the fundamental mode FLR frequencies during the Holloween event are plotted as a function of time and the geographic magnetic (GOM) latitude in the second panel of Figure 2. The coverage in the dayside region is generally good except for the regions near the prenoon or noon sectors. The trend of decreasing FLR frequencies in the daytime is caused by the gradual lifting of the magnetospheric flux tubes by the ionosphere. The coverage in the nighttime is expectedly limited, possibly due to the low ionospheric conductivity that can reduce the quality of FLR to the magnetosphere as well as the magnitude of the FLR-driven atmospheric effects. However, it is worth noting that some FLR signatures can still be found in the nighttime, and more studies are needed to understand the cause of their occurrence. The FLR frequencies for October 28 and November 1–2 are basically consistent with the values observed in the quasi-steady conditions. However, the FLR frequencies at low latitudes on October 29–30 were unusually low, and they continued to be below average on October 31.

The unusual FLR frequencies observed on October 29–31 indicate the disturbed conditions of magnetospheric density during the period. Because the fundamental mode frequency constitutes most of the ground FLR observations, the density at the magnetospheric equator is estimated under two assumptions. First, the deviation of FLR frequencies from values obtained with a dipole field due to the realistic magnetospheric field was calculated in the same fashion as in the work by Singer et al. [1981]. Second, the density distribution along a field line is assumed to be constant for simplicity as well as for being in close agreement with the empirical studies using satellite observations of plasma density [e.g., Tsurutani et al., 2004]. In general, a moderate deviation from this assumption would not alter the conclusions of this study because the fundamental mode of FLR is most sensitive to the plasma near the equator. For example, if a density function proportional to \(r^{-1}\) were used, the estimated equatorial
density could have been reduced by only 5% at L = 4. The estimated density at the magnetosphere equator is plotted against time and the L-value as shown in the third panel of Figure 2. Also noted in the plot is the contour line of 200 amu cm⁻³ approximately represent the plasmapause location during moderately active times. During the main phase of the magnetic storm, the plasmasphere was eroded progressively by the enhanced convection, and clear changes in plasma density could take place within 2 or 3 hours. The same result of the equatorial density was also observed in time series in the bottom panel, where the density variations at L-values ranging from 2.5 to 8.5 are plotted. In the outer magnetosphere, the strong convection resulted in a lower level of density as plasma moved toward the dayside magnetopause. In contrast, the most distinguishing features for the density at inner L shells are the very high peaks at the end of October 30, as well as the less substantial enhancements on October 29. In particular, the maximum density on October 30 reached an unusually high level that is 4-5 times larger than the typical density observed at the same local time. At middle L shells, the density increased severely during October 29-31, a likely phenomenon when the plasmasphere moves inward and outward.

The above observations from ground magnetometers can be more illuminating when they are compared with the TEC observations at the same event. The comparison during the disturbed period October 29-31 is presented in Figure 3, where the top panel shows the IMF electric field in the equatorial plane deduced from the IMF B, and solar wind speed. The middle panel shows the vertical TEC observed at 255° longitude, approximately where the low-latitude ground magnetometers are located. The ionospheric storm positive phase occurred in the daytime region at low latitudes during the time interval on October 29 and 30 when the IMF electric field was eastward. The presence of positive storms is consistent with the scenario in which an eastward electric field and the close-to-horizontal magnetic field result in an uplifting of the F layer via the B x E drift. The upward displacement of the F layer then leads to an event increase in the ionization density as the lower less decreases much faster than the production rate [Pudovik, 1991]. The presence of electric fields and the uplifting F layer during the October 2003 storms have also been confirmed by the DMSP satellite observations [Juhng and others, 2004]. Each of the high TEC regions on October 29 and 30 has a very steep gradient on the right hand side, indicating that the plasmapause moved rapidly from higher latitudes to latitude below 35° UL. 195]. This is consistent with the Carpenter and Anderson [1993] empirical formula that predicts a plasmapause at L = 1.6 starting from 0900 UT on October 29 for more than 2 days. The time series of TEC at 40° and 45° latitude, corresponding to L-values at 2.5 and 3.0, are also plotted. The data show two events of storms enhanced density (SED) at these latitudes, and both events occurred during the geomagnetic storm phase. The TEC values for these SED events are significant at the maximum TEC value at 40°-55° latitude is about 80 TEC units during quiet days. These SED events occurred at approximately 1400 UT and had shorter durations, suggesting that they were connected to the plasmaspheric drainage phase in the magnetosphere [Fontes and others, 2002].

The bottom panel of Figure 3 shows the FLL inferred equatorial densities at L = 2.5 and 3.0 during the same time interval. The sharp increase in the density at the magnetospheric equator correlated with the TEC SED event on October 30, although with a slight time delay. The coarse FLL data for the October 29 SED event also hint at the same pattern of correlation. The enhanced magnetospheric density took place outside the new plasmasphere, as the FLL observations here were taken at L-values > 2.5. The enhancement in magnetospheric density on October 30 occurred very quickly, suggesting that the magnetospheric field lines involved rotated the drainage phase, but the density fell off to the previous level 11 hours after TEC dropped to low values because of the low ionosphere content in the nighttime. The comparison between the increase in magnetospheric density at L = 2.5 and that at L = 3.0 on October 30 also implies that the density enhanced more significantly at the inner part of the drainage phase.

3. Discussion

[5] The 2003 Halloween storm is certainly an extreme case of magnetic storms, and it challenges our conventional wisdom with its extreme conditions. This layer is formed on the density variations in the magnetosphere and their relationships with ionospheric conditions. Further details regarding the dynamics of the ionosphere during this disturbed period are reported by Fontes and Rabinov [2005]. Although both ground magnetometer data and TEC observations clearly show density enhancements at low latitudes during the first three days of the Halloween storm, the same does not apply to many other magnetic storms for which a depiction of the plasmasphere is more common. A very strong contrast to the Halloween storms is the September 25, 1998 magnetic storm, during which the
plasma sphere as well as the TEC under very strong deploration at L-value as low as 2 [Chl et al., 2000]. The key difference in the September 1998 storm might be that the IMF was generally northward except in the first 6 hours when the ground observations in North America that found deploration were in the nighttime. There is also a difference in the magnitude of convection: The solar wind during the Halloween storm carried an eastward electric field that is up to 4 times as strong as that during the September 1998 storm. Whether or not the electric field is strong enough to penetrate through to the low-latitude ionosphere may be critical in uplifting the ionospheric F layer. Despite all these differences, the Halloween storm demonstrates again that not only is connection in the magnetosphere important in determining how much plasma the plasma sphere can retain, but also can the variations in the ionosphere affect the tube content significantly during magnetic storms.

[11] There are remaining issues to resolve with regard to the detailed interplay between the ionosphere and plasma sphere during the SID events. For example, the filling of plasmapheric flux tubes was unusually fast after the SID event on October 30. If we assume that the density enhance- ments happened after the IMF electric field turned eastward, the density at the magnetospheric equator at L = 2.5 increased 6-7 times within as short as 2 hours. An O+ rich outflow from the ionosphere could possibly contribute to part of the increase, but the diffusion process alone may not be enough to explain the observations. Another possible source of dense plasma is that from inner L shells. However, the sunward convection tends to deplete all L shells involved. Further numerical modeling studies of the iono- sphere-plasma sphere system could provide valuable insights to the observed density enhancements during the Halloween storm.

In this letter we present the observations that show the significant increase in both magnetospheric equatorial density and TEC at approximately 330 magnetic longi- tudinal. The FLR observation at other longitudes also reported a similar increase in the equatorial density at low L shells [Takahashi et al. 2004]. The convection in the magnetosphere creates a local time asymmetry in the plasmasphere, and the ionosphere has even greater local time dependence as its plasma content is strongly controlled by solar EUV emissions. The IMF and solar wind can also impose local time dependence on both the plasmasphere and the ionosphere. Further studies that combine the observations at different longitudes would be very valuable in understanding how all these physical mechanisms influence the behavior of the storm-time plasmasphere-ionosphere system.

References
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