Extreme solar EUV flares and ICMEs and resultant extreme ionospheric effects: Comparison of the Halloween 2003 and the Bastille Day events

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Received 11 August 2005; revised 22 February 2006; accepted 22 March 2006; published 28 June 2006.

[1] Extreme solar flares can cause extreme ionospheric effects. The 28 October 2003 flare caused a ~25 total electron content units (TECU = 10^{16} el/m^2 column density), or a ~30%, increase in the local noon equatorial ionospheric column density. The rise in the TEC enhancement occurred in ~5 min. This TEC increase was ~5 times the TEC increases detected for the 29 October and the 4 November 2003 flares and the 14 July 2000 (Bastille Day) flare. In the 260–340 Å EUV wavelength range, the 28 October flare peak count rate was more than twice as large as for the other three flares. Another strong ionospheric effect is the delayed influence of the interplanetary coronal mass ejection (ICME) electric fields on the ionosphere. For the 28 and 29 October flares, the associated ICMEs propagated from the Sun to the Earth at particularly high speeds. The prompt penetration of the interplanetary electric fields (IEFs) caused the dayside near-equatorial ionosphere to be strongly uplifted by $\mathbf{E} \times \mathbf{B}$ convection. Consequential diffusion of the uplifted plasma down the Earth's magnetic field lines to higher magnetic latitudes is a major plasma transport process during these IEF (superstorm) events. Such diffusion should lead to inverted midlatitude ionospheres (oxygen ions at higher altitudes than protons). The energy input into the midlatitude ionospheres by this superfountain phenomenon could lead to local dayside midlatitude disturbance dynamos, features which cannot propagate from the nightside auroral zones.

Citation: Tsurutani, B. T., et al. (2006), Extreme solar EUV flares and ICMEs and resultant extreme ionospheric effects: Comparison of the Halloween 2003 and the Bastille Day events, *Radio Sci.*, *41*, RS5S07, doi:10.1029/2005RS003331.

1. Introduction

[2] We discuss the extreme solar flares of 28 and 29 October and 4 November of 2003 and 14 July 2000 (Bastille Day event) and their photoionization effects on the dayside ionosphere. *Meier et al.* [2002] modeled the ionospheric effects of the Bastille Day flare, prior to the use of GPS total electron content (TEC) measurements. In this paper we will show the GPS measurements and the dramatic ionospheric changes caused by the flare EUV photons. The flare-associated interplanetary coronal mass ejection (ICME) motional electric fields affected the Earth's equatorial and midlatitude dayside ionosphere as well. These delayed (by solar wind propagation) effects will be discussed. Figure 1 shows the SOHO Solar EUV Monitor (SEM) instrument 260–340 Å (EUV) count rates for all four extreme flares. An instrument description can be found in work by *Judge et al.* [2001]. The flares have been adjusted to their preflare baselines, so the relative count rate enhancements can be readily discerned. These flux increases are the factors that lead to enhanced photoionization of the

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0048-6604/06/2005RS003331

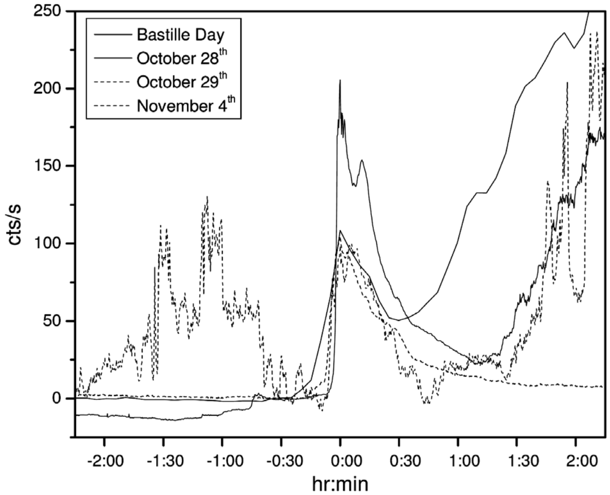

Figure 1. The 260–340 Å SOHO SEM (EUV) count rates for the 28 and 29 October and 4 November 2003 (Halloween events) and 14 July 2001 (Bastille Day) solar flares. The 28 October 2003 flare is the largest event by more than a factor of 2.

dayside upper atmosphere. See *Tsurutani et al.* [2005] for more details.

[3] In this EUV wavelength range, the 28 October 2003 event is by far the largest, with a peak count rate greater than twice that of the other three events. The 4 November, 29 October, and Bastille Day events were roughly comparable in peak intensity. The 28 October event had a secondary peak in the decay phase of the event that effectively "broadened" the flare width. This secondary peak was not detected in the 1–8 Å (GOES satellite) x-rays.

[4] The rise in EUV peak count rate was the sharpest in the 28 October event (~2.5 min 1/el risetime, measured backward from the peak), ~5 min for 29 October and 4 November, and unusually slow ~10 min for the Bastille Day event (B. T. Tsurutani et al., Rise and decay time-scales for SEM (SOHO) solar flares: Constraints of magnetic reconnection, unpublished manuscript, 2005).

[5] In all of the flare events except for 4 November, there was an increase in the SEM count rates after the flare had decayed away (however, on the Bastille Day event, the increase occurred during the flare decay phase). This increase is caused by solar flare energetic charged particles being detected by the SEM sensors. These increases occurred well after the flare peak count rates and therefore had negligible effects on the flare profiles. The 4 November flare was a limb event. Particles accelerated by the flare or ICME shock [*Tsurutani et al.*, 1982; *Pesses et al.*, 1984; *Tsurutani and Lin*, 1985] presumably did not have easy access to interplanetary magnetic fields that connected to Earth, thus the lack of an increase in SEM count rate after the flare.

[6] Figure 2 gives the "verticalized" TEC for a near-equatorial, local noon ground-based GPS receiver (Africa) for the 28 October 2003 flare. A total electron content unit (TECU) is 10^{16} el/m^2 column density. The TEC is determined by reduction of relative phase shifts between dual-frequency (~1.2 and ~1.5 GHz) signals transmitted from GPS satellites orbiting at 20,800 km altitude (see *Mannucci et al.* [1998], *Iijima et al.* [1999], *Afraimovich* [2000], and *Afraimovich et al.* [2002] for discussions of conversion of dual-frequency GPS signals to total electron content). The six GPS satellites tracked by the ground-based receiver are indicated in the insets. The TEC risetime was coincident with the flare onset, but the decay was far longer. The latter effect is due to photoionization occurring at high altitudes (>150 km) where the recombination rate is considerably lower than for lower altitudes. The increase in TEC from baseline to peak occurs within ~15 min (the vast majority of the rise occurs within 5 min) and has a magnitude of ~25 TECU. One hour prior to the flare, the dayside TEC at noon at the equator was ~82 TECU, so this flare caused an abrupt ~30% increase in the ionospheric TEC. The TEC increases for the 29 October, 4 November, and Bastille Day flares were all ~5 TECU. This apparent near equivalence of their ionospheric effects is consistent with their flare peak intensities being comparable. See also *Zhang and Xiao* [2005] for further ground-based TEC measurements of the 28 October flare event and *Afraimovich* [2000] and *Afraimovich et al.* [2002] for discussion of ionospheric effects of weaker flares.

[7] The 29 October flare onset occurred at ~2036 UT. After an initial increase of ~5 TECU, the ionospheric enhancement then increased further to much greater amplitudes. As will be shown later, this was coincident with the arrival at Earth of the ICME launched on 28 October. The interplanetary and ICME data for the Halloween events are shown in Figure 3. The plots, from top to bottom, are the solar wind speed, proton temperature, proton density, He^{++}/p^{+} number density ratio, magnetic field magnitude, B_z component (in solar magnetospheric coordinates), and the geomagnetic *Dst* index. The plasma data are from the ACE Solar Wine Electron, Proton, and Alpha Monitor (SWEPAM) instrument, and the magnetic field data are from the magnetometer. There are two extremely high solar wind speed events (top), one on 29 October (V_{SW} > 1850 km/s, with a most probable speed of ~2240 km/s), and a second event (V_{SW} = 1710 km/s) on 30 October [*Skoug et al.*, 2004]. There is a third (relatively) small event on 4 November. The first two ICMEs and leading shocks (denoted by the abrupt increases in V_{SW}, *T*, *B*, and *N* in Figure 3) are associated with the 28 and 29 October flares, respectively.

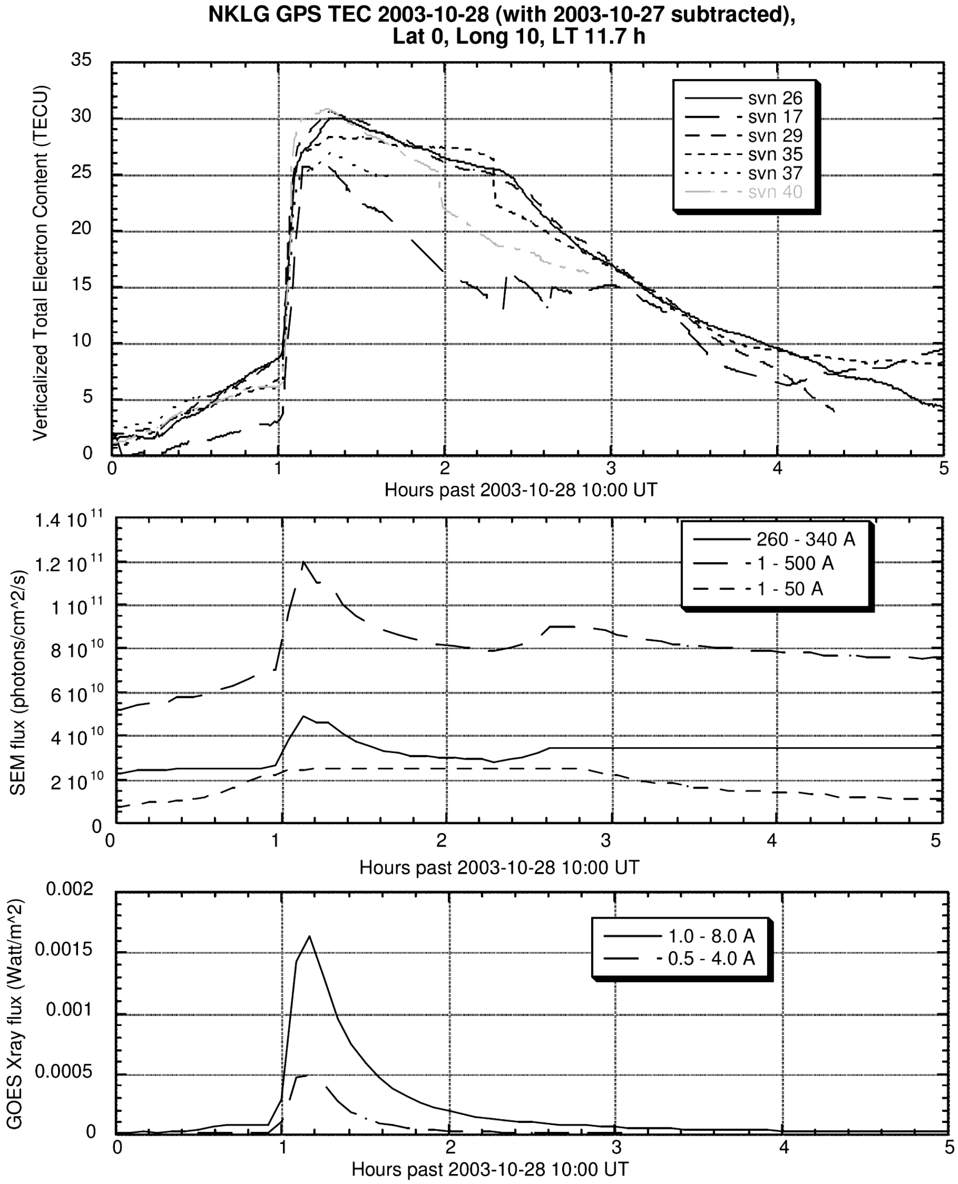

Figure 2. Ionospheric response to the 28 October 2003 solar flare: (top to bottom) ground-based TEC measurements, SOHO SEM EUV flare profiles, and GOES flare x-ray profiles.

[8] There is a large interplanetary negative B_z event (~-30 nT) at the shock ahead of the 30 October ICME. This is caused by shock compression of preexisting magnetic cloud material [*Mannucci et al.*, 2005]. This negative IMF B_z event is responsible for the magnetic storm on 30–31 October (*Dst* decrease). The *Dst* index, an indicator of the intensity of the storm time ring current, is well correlated with the IMF B_z event (see discussion by *Gonzalez et al.* [1994]). The solar wind convection of southward magnetic fields creates a dawn-to-dusk (motional) electric field as viewed from the Earth. *Kelley et al.* [2003] have noted that these electric fields can ‘‘promptly penetrate’’ to the equatorial ionosphere.

[9] The ionospheric effects (in TECU) during the 30–31 October 2003 (Halloween) interplanetary dawn-to-dusk electric field event are shown in Figure 4. Three CHAMP satellite passes are shown in Figure 4. CHAMP

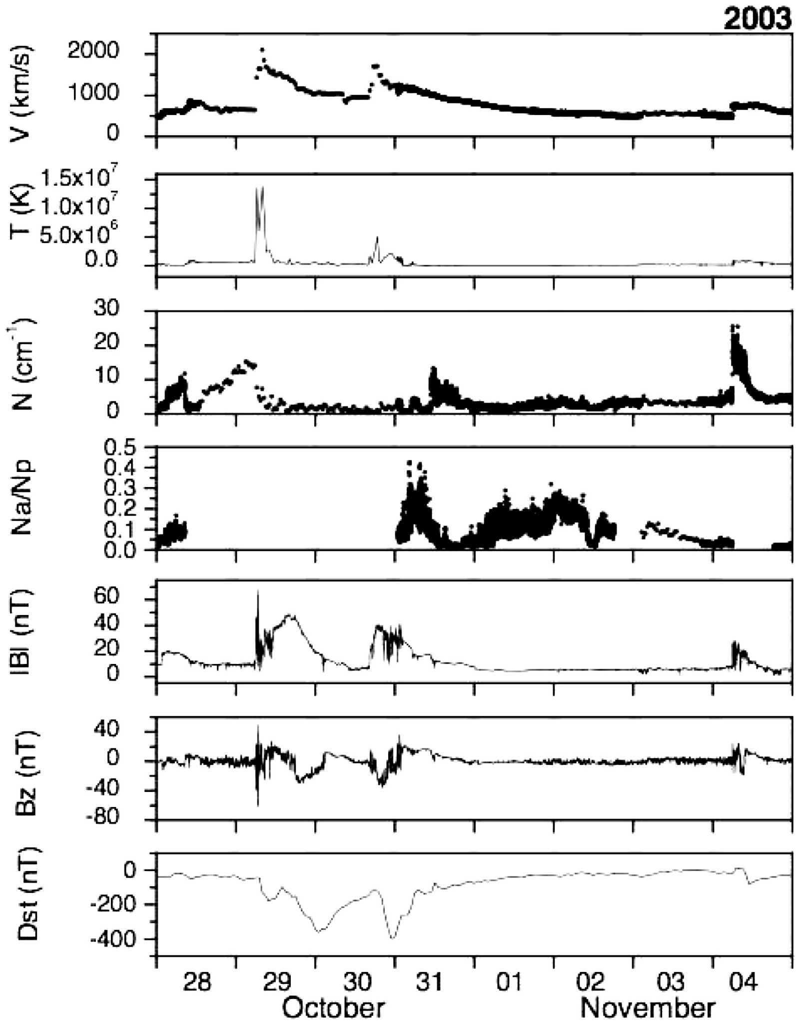

Figure 3. ACE solar wind parameters and geomagnetic *Dst* indices for the 28 and 29 October and 4 November 2003 Halloween ICME events.

was at an altitude of ~400 km and crossed the magnetic equator at ~1300 local time for each of the three passes. The onboard GPS receiver measured the TEC at altitudes above the satellite. The first pass starting at 1825 UT occurs before the negative IMF B_z event (note that several GPS satellites were tracked simultaneously; verticalized TEC values are shown for all satellites at greater than 40° elevation angle relative to CHAMP). The second pass at ~2000 UT occurs ~1 hour 15 min after the negative IMF B_z event had impinged upon the magnetosphere, and the third pass at 2145 UT occurs ~2 hours 45 min after the start of the interplanetary electric field event.

[10] In the prenegative IMF B_z interval, the dual peak "fountain effect" is noted. The ionospheric peaks are located at ±10° magnetic latitude (MLAT). The cause of the fountain effect is the $\mathbf{E} \times \mathbf{B}$ force due to the ionospheric dynamo eastward electric field. This convection produces vertical plasma drift of the postdawn equatorial ionospheric plasma and the eventual diffusion of this plasma down the magnetic lines of force to higher latitudes on either sides of the equator. At 2000 UT, after the imposition of the negative IMF B_z fields, the TEC above CHAMP (~400 km altitude) was ~210 TECU at ±20°–25° MLAT. At 2145 UT, the TEC became even higher, reaching peak values of ~330 TECU at 28° MLAT. This effect has been called the "dayside

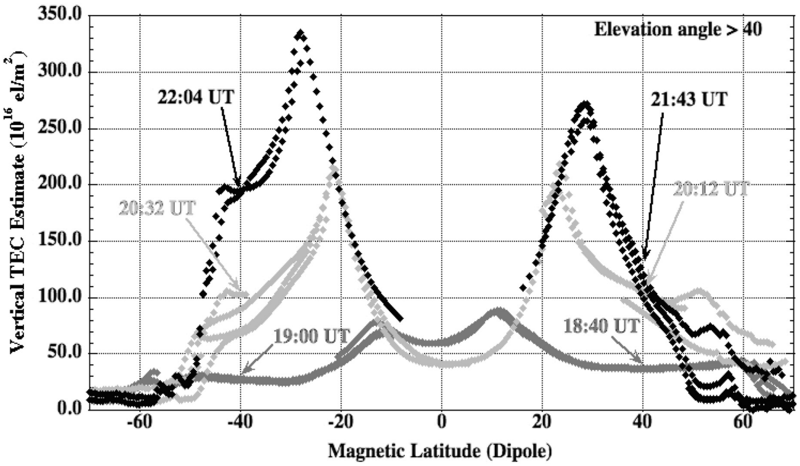

Figure 4. TEC above CHAMP (~400 km altitude) for three different passes, before and during an interplanetary electric field event. Taken from *Mannucci et al.* [2005].

superfountain effect" [*Tsurutani et al.*, 2004; *Mannucci et al.*, 2005]. See also related results of *Tanaka* [1981], *Greenspan et al.* [1991], and *Basu et al.* [2001].

2. Dayside Superfountain Effect

[11] The enhanced TEC above CHAMP shown in Figure 4 implies that the dayside ionosphere was significantly uplifted. A dawn-to-dusk directed equatorial dayside ionospheric electric field would cause such an uplift. This electric field would be of the same sense as the interplanetary electric field and as the magnetospheric storm time convection electric field. How do these electric fields penetrate to the dayside equator? There are two (considerably different) possibilities. First, magnetic reconnection between the interplanetary magnetic field and the Earth's magnetic field [*Dungey*, 1961] will lead to a magnetospheric dawn-to-dusk electric field. For timescales shorter than ~30 min, this electric field may penetrate to low-latitude regions. However, after this interval, "shielding" is expected to reduce this effect significantly [*Wolf*, 1975]. On the other hand, *Kikuchi and Araki* [1979] have shown from studies of sudden impulses that polar ionospheric electric fields can penetrate to the equatorial ionosphere via near-instantaneous propagation through the Earth-ionospheric waveguide. At this time, we do not know whether strong magnetospheric electric fields (such as this case) can cause the breakdown of shielding, or if the *Kikuchi and Araki* [1979] mechanism is the correct explanation. Further research is needed to resolve this important issue.

[12] After the plasma is lifted to higher altitudes, it will diffuse down the magnetic fields to higher latitudes. This uplift followed by downward diffusion will lead to conversion of gravitational potential energy into kinetic energy (see discussion by *Mannucci et al.* [2005]). If the energy input into the middle-latitude ionosphere is sufficient, twin dayside disturbance dynamos would be created. This is currently being studied both experimentally and also by modeling. If the heavy (oxygen) ions that exist at the bottom of the ionosphere are also uplifted by this process, then this plasma will then be at the top of the ionosphere as the plasma diffuses to middle latitudes. The transported plasma will have an inverted profile, with the oxygen ions on top. The ionosphere will also have an older oxygen ion layer at the bottom, giving a double oxygen ion layered ionosphere. We are currently searching experimentally for such middle-latitude ionospheric features.

[13] Why are the midlatitude superfountain column plasma densities so high for the event of Figure 4, higher than the normal full ionospheric column densities (~100 TECU)? The reason is that when a portion of the dayside ionosphere is uplifted to high altitudes, the plasma is brought to a region where the electron-ion recombination timescales are much longer, hours to days. Solar photoionization will produce new ion-electron pairs at lower altitudes, replacing the uplifted plasma. This gradual process of plasma uplift and production at lower altitudes is the physical process that leads to the abnormally high dayside ionospheric plasma densities during interplanetary dawn-to-dusk electric fields. Much of this plasma will come down the Earth's magnetic lines of force to middle latitudes, as discussed previously.

3. Conclusions

[14] The extreme Halloween solar flares are shown to have extreme ionospheric effects. Enhancements in iono-

spheric total electron content of ~30% nominal values were noted for the 28 October 2003 event. These changes occurred on timescales of ~5 min. The enhanced ionospheric TEC lasts for hours after the flares. The 260–340 Å portion of the flare spectra through photoionization creates electron-ion pairs at altitudes >~160 km, where the recombination rates are long. The x-ray portion of the flare spectra, on the other hand, creates ionization at ~95–110 km altitude, where the recombination timescales are only approximately tens of seconds. The latter ionospheric effects are therefore short lived (further discussion can be found in the work by *Tsurutani et al.* [2005]). There is a wide variation in flare spectra from event to event. It was shown that although the 4 November flare (X28) was almost double the intensity of the 28 October flare (X17) in 1–8 Å x-rays (28/17; the flare magnitudes are scaled linearly), the 28 October flare was more than double the 4 November flare peak intensity in the 260–340 Å EUV wavelength band. If this ratio is even larger at longer, ~500 Å, wavelengths, this may explain the factor of ~5 greater photoionization for the 28 October event. However, other possible contributions may exist. This event is currently being modeled.

[15] Even larger ionospheric effects are caused by the prompt penetration of the interplanetary electric field to the dayside equatorial ionosphere. These ionospheric events are more gradual (approximately hours) but can lead to ~400% increases in TEC column densities at middle latitudes, strong variations in height and latitude distributions, potential heating, and possibly even neutral particle uplift. These storm time phenomena warrant further studies.

[16] **Acknowledgments.** Portions of this research were performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. BTT wishes to thank T. Tsuda of RISH, Kyoto University, for hosting him during the writing of portions of this paper.

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