The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille Day event

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[1] Some of the most intense solar flares measured in 0.1 to 0.8 nm x-rays in recent history occurred near the end of 2003. The Nov 4 event is the largest in the NOAA records (X28) and the Oct 28 flare was the fourth most intense (X17). The Oct 29 flare was class X7. These flares are compared and contrasted to the July 14, 2000 Bastille Day (X10) event using the SOHO SEM 26.0 to 34.0 nm EUV and TIMED SEE 0.1–194 nm data. High time resolution, ~30s ground-base GPS data and the GUVI FUV dayglow data are used to examine the flare-ionosphere relationship. In the 26.0 to 34.0 nm wavelength range, the Oct 28 flare is found to have a peak intensity greater than twice that of the Nov 4 flare, indicating strong spectral variability from flare-to-flare. Solar absorption of the EUV portion of the Nov 4 limb event is a possible cause. The dayside ionosphere responds dramatically (~2.5 min 1/e rise time) to the x-ray and EUV input by an abrupt increase in total electron content (TEC). The Oct 28 TEC ionospheric peak enhancement at the subsolar point is ~25 TECU (25×10^{12} electrons/cm^2) or 30% above background. In comparison, the Nov 4, Oct 29 and the Bastille Day events have ~5–7 TECU peak enhancements above background. The Oct 28 TEC enhancement lasts ~3 hrs, far longer than the flare duration. This latter ionospheric feature is consistent with increased electron production in the middle altitude ionosphere, where recombination rates are low. It is the EUV portion of the flare spectrum that is responsible for photoionization of this region. Further modeling will be necessary to fully understand the detailed physics and chemistry of flare-ionosphere coupling. **Citation:** Tsurutani, B. T., et al. (2005), The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille Day event, *Geophys. Res. Lett.*, *32*, L03S09, doi:10.1029/2004GL021475.

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1. Introduction

[2] In this paper, we will examine the October 28, 29, November 4, 2003 and Bastille Day flares and their ionospheric effects. Prior flare-ionosphere studies have identified sudden ionospheric disturbances, or SIDs [*Thome and Wagner*, 1971; *Mitra*, 1974; *Donnelly*, 1976]. The impulsive ionization of the flare radiation causes enhanced ionization over a broad altitude range from the D region (80–100 km altitude) all the way to the F region (the F peak is at ~300 km altitude). However *Meier et al.* [2002], in attempting to do detailed ionospheric modeling, have noted that previous ionospheric measurements made by ground-based single point measurements (ionosondes and other techniques), have typical cadences of 15 to 60 min, too slow to capture the details of the flare effects. In this study we will use ~30s resolution ground-based global positioning system (GPS) receiver data. To obtain global coverage, approximately 100 ground stations are included. The receivers track some of the 28 GPS satellites simultaneously at two frequencies (~1.2 and ~1.5 GHz). Processing of the dual frequency data yield the total electron content (TEC) along the line-of-sight between the GPS satellite and the receivers. The relative accuracy of TEC determination by GPS measurements is ~0.01 TECU, with an absolute accuracy of 1–3 TECU (a TEC unit is 10^{12} electrons/cm^2) [*Mannucci et al.*, 1998]. As another measure of the ionospheric photoionization rate, we also include far ultraviolet (FUV) dayglow irradiance measured by the Global UltraViolet Imager (GUVI) instrument. For the flare profiles we will use the SOHO Solar EUV Monitor (SEM) 26.0–34.0 nm 15 s resolution data and the GOES x-ray (0.1–0.8 nm) data.

2. Data Analyses

[3] The SOHO SEM instrument description is given by *Judge* [1998]. Because of the extreme intensity of these

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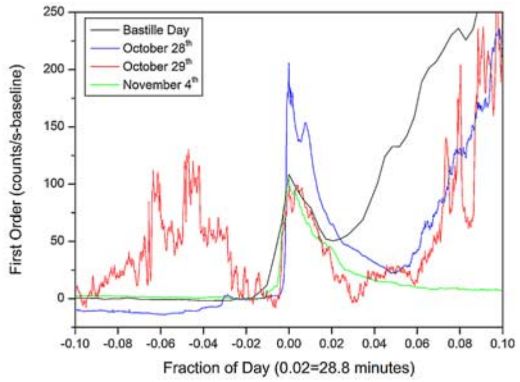

Figure 1. The Oct 28, Oct 29, Nov 4 and Bastille Day solar flare count rates in 26.0–34.0 nm EUV wavelengths. The full disc solar background has been removed from each event. The Oct 28 solar flare is largest by more than a factor of two.

solar flares, the SOHO SEM 1.0 to 50.0 nm and the GOES 0.1 to 0.8 nm channels were often saturated near their peak count rates. In this paper we use the SEM 26.0 to 34.0 nm channel data for two reasons. First, because solar EUV photons (not x-rays) are the most important contributor to the lengthy (~hrs) ionospheric TEC enhancements, we focus on this wavelength band (discussed further in the body of the paper). Secondly, because of the narrowness of the band, the two 26.0–34.0 nm channels were never saturated for any of the four flares, giving accurate profiles (onsets, peak count rates and decays) of the flares. This is important to make an accurate comparison to ionospheric TEC measurements.

[4] The GUVI instrument is described by *Christensen et al.* [2003]. GUVI is onboard the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) satellite. TIMED is in a 625 km, 74.1° inclination orbit.

3. Results

3.1. October 28, 2003

[5] Figure 1 shows the SOHO SEM 26.0–34.0 nm (EUV) count rates for all four flares. The full disc solar backgrounds have been subtracted out for each flare. This was done to be able to intercompare flare enhancements over background for the four events. It also allows a direct comparison to ionospheric total electron content (TEC) enhancements caused by the flares. It should be noted that (unpublished) studies of the multiyear daily SEM 26.0–34.0 nm time series have shown that this channel is not sensitive to x-rays.

[6] In this EUV wavelength range, the Oct 28, 2003 flare peak count rate is by far the largest, with a value greater than twice that of the other 3 events. This is in sharp contrast to the situation for the 0.1 to 0.8 nm x-ray range (Nov 4 is almost twice [28/17] as intense as Oct 28). This clearly indicates that there is a large spectral difference between the Oct 28 flare and the Nov 4 flare [*Thomson et al.*, 2004] have argued from VLF phase change measurements, that the Nov 4 event magnitude was perhaps as large as X45 ±5, making this spectral contrast even greater). The Nov 4, Oct 29 and Bastille Day events were roughly comparable in peak EUV count rate.

[7] The rise in EUV peak count rate in the Oct 28 event had the sharpest (~2.5 min 1/e rise time, measured from the peak), ~5 min for Oct 29 and Nov 4, and unusually slow ~10 min for the Bastille Day event. This is discussed in more detail by B. T. Tsurutani et al. (Characteristics of solar flare EUV time scales: Constraints and implications for models, manuscript in preparation, 2005, hereinafter referred to as Tsurutani et al., manuscript in preparation, 2005).

[8] In all of the flare events except for Nov 4, there are large increases in SEM count rates after the flares had decayed away (however, for the Bastille Day event the increase in count rate occurred during the flare decay phase). These post-flare increases are due to solar flare energetic particles impinging upon the SEM detectors. This was confirmed by examination of the GOES energetic particle data. These increases occur well after the flare peak count rates and have negligible effects on the flare profiles. The Nov 4 flare erupted on the solar limb. Particles accelerated by the flare or by the related ICME shock presumably did not have easy access to interplanetary magnetic fields that connect to the Earth, thus resulting in a lack of particle contamination at SOHO SEM for this event.

[9] VUV flare irradiances have been reported for times near the peaks of the Oct 28 and Nov 4 flares [*Woods et al.*, 2004]. This TIMED Solar EUV Experiment (SEE) 0.1–194 nm spectral data indicate that the variations between ~20–110 nm are very similar to that of the SOHO SEM EUV profile. This 1 nm spectral resolution information will be extremely useful for future modeling of the ionospheric effects of the Oct 28 event.

[10] Figure 2 shows the global ionospheric response to the Oct 28, 2003 flare event. The time of measurement is from 1100 to 1108 UT, at the onset of the flare. A quiet day "background" of 27 Oct 2003 was subtracted out to obtain this "difference" plot, yielding the ionospheric effects due to the solar flare. The subsolar point is located at the center

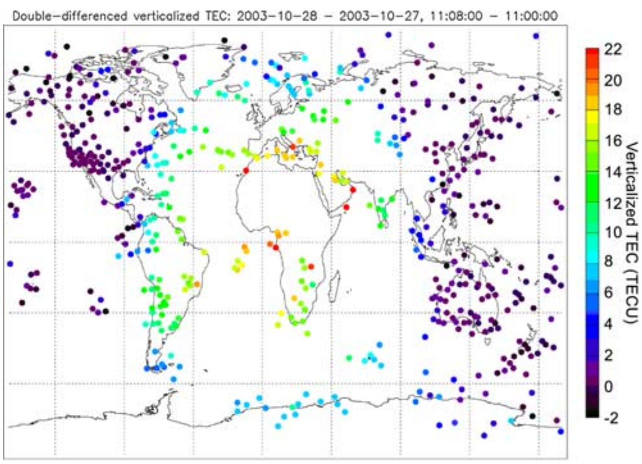

Figure 2. The TEC enhancement for the Oct 28 solar flare. ~100 ground-based GPS receivers were used in this figure. The subsolar point is at the center of the figure, in Africa. The greatest enhancement occurs near the subsolar point and decreases with increasing latitude and longitude away from this point.

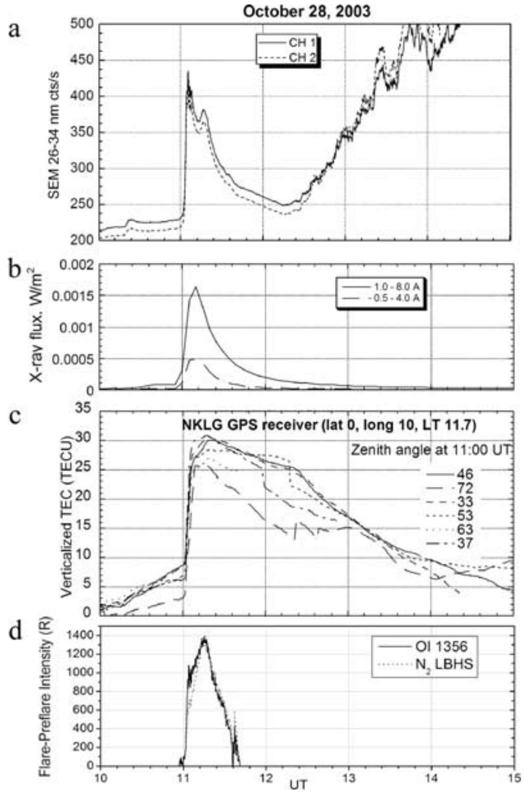

Figure 3. (a) The SOHO SEM EUV count rate, (b) the GOES x-ray flux, (c) the Libreville, Gabon TEC data, and (d) the GUVI FUV O and N_2 dayglow data.

of the graph (Africa). The largest TEC enhancement occurs at the subsolar region, with an electron column density increase of ~22 TECU. This increase in TEC is less at local times away from noon and at higher and lower latitudes away from the subsolar point, as expected. There is essentially no TEC change in the nightside ionosphere.

[11] Figure 3 compares the flare, ionospheric TEC, and dayglow time sequences for the Oct 28, 2003 event. Figure 3a is the SOHO SEM 26.0–34.0 nm channel count rates (here, two separate channel data are shown; the responses are essentially identical). Figure 3b contains the GOES 0.1–0.8 nm and 0.5–4.0 nm x-ray fluxes. Figure 3c is the Libreville, Gabon TEC data, and Figure 3d is the FUV dayglow measurements. The Libreville station was chosen because it is an equatorial station that was close to local noon at the time of the flare (11.7 LT, 0.4° latitude). The Libreville receiver tracked six different GPS satellites simultaneously. Each data track was "verticalized", assuming an ionospheric spherical shell extending from 450 to 650 km altitude. The satellite position relative to the station zenith angle given in Figure 3d.

[12] The figure shows the simultaneous onset of the flare (detected at SOHO and GOES at ~1 AU), and the Libreville ionospheric TEC enhancement and the dayglow enhancement at ~1100 UT. The SEM data shows a double peak structure. The EUV first, larger peak occurred at ~1105 UT and the secondary peak at ~1116 UT (the GOES relativistic electron data was used to verify that the secondary peak was not caused by particles). The ionospheric TEC enhancement rose most rapidly from ~1100 UT to ~1105 UT, and then less rapidly from 1105 to ~1118 UT. A peak value of ~25 TECU above background was reached at ~1118 UT. The ionospheric "background" level was 82 TECU at the subsolar point one hr prior to the flare onset. Thus the flare caused a ~30% increase in the ionospheric electron content in this region. The dayglow increased most rapidly from ~1100 to ~1104 UT with a peak at ~1115 UT.

[13] The flare EUV/x-ray intensities decayed more slowly than the initial intensity increases (in the impulsive phase), in accord with typical flare profiles/characteristics [*Sturrock*, 1980; Tsurutani et al., manuscript in preparation, 2005]. It is noted that the SOHO SEM count rates decreased slightly more gradually than did the GOES x-ray fluxes. The ionospheric TEC values decreased slowest of all, taking ~3 hrs to reach background levels.

[14] Figure 3d shows the FUV dayglow measurements during the daytime portion of the TIMED orbit encompassing the Oct 28 flare. Two GUVI channels are shown, one for the O emission at 135.6 nm and one for N_2 LBH short wavelength bands between 141.0 and 152.8 nm. The irregular structure detected between ~1100 UT and ~1112 UT is due to the different character of the aurora between the two orbits. The O and N_2 FUV dayglow is produced by prompt photoelectrons with $E > 9$ eV. Consequently the dayglow change from the preflare to postflare state is a direct measure of the column photoionization rate. The small differences between the O and N_2 emissions are caused by compositional differences. The net increase in the ionospheric photoionization rate at the peak of the flare is about a factor of 3 times the nominal rate and is approximately consistent with combined factor of 2+ SEM EUV increase and the orders of magnitude x-ray flux increase.

[15] One important difference in the GUVI and the TEC data is while the OI 135.6 nm and LBHS emission track the flare EUV, the elevated TEC persists for several more hrs (for all four cases studied). The dayglow emissions are produced during the thermalization of fast photoelectrons. Once the photoelectrons are thermalized, the optical emissions terminate. In contrast, the enhanced TEC persists for many hrs.

3.2. Nov 4, Oct 29, 2003 and the Bastille Day Events

[16] The flare onsets and the ionospheric TEC enhancements were simultaneous for the Nov 4, Oct 29 and Bastille Day events (not shown), similar to the results shown in Figure 3. The TEC peaks were slightly delayed from the flare peaks. The SOHO SEM EUV and GOES x-ray profiles exhibited a similar behavior, with the EUV count rates having slightly longer decay times than that for the x-rays. The ionospheric TEC decay times were considerably (~hrs) longer than the flare decay times, similar to the Oct 28 flare event. The Nov 4 event had a peak TEC increase of ~5–7 TECU and the Oct 29 and Bastille Day events had peak TEC increases of ~5 TECU. The subsolar point backgrounds (one hr prior to the flare onsets) were approximately 102 TECU, 90 TECU and 69 TECU, respectively. The strong variability of the background of the Halloween events (82, 102 and 90 TECU for Oct 28, 29 and Nov 4, respectively) was partially due to the solar EUV active

regions being highly asymmetrically located on the solar disc and partially due to magnetic storm ionospheric effects. The latter topic is discussed in a companion paper by A. J. Mannucci et al. (Prompt dayside global ionospheric response to the major solar events of October 29–30, 2003 ''Halloween Storms'', submitted to *Geophysical Research Letters*, 2004). The Bastille Day ionospheric TEC background level was low, presumably due to the different (ascending) phase of the solar cycle for that event.

4. Discussion

[17] It has been shown that the Oct 28, 2003 event was by far the most intense flare of the four events, when measured in EUV wavelengths. In contrast, the Nov 4 event was the largest in the x-ray regime. This implies that there is a large spectral difference between the two flares. *Donnelly* [1976] has shown that the solar flare EUV spectra have strong center-to-limb effects, while there is essentially none for x-rays. His arguments are that solar EUV is produced lower in the solar atmosphere (than x-rays) and the further the flare site is away from (solar) disc center, the greater the EUV solar absorption. It is noted that the Nov 4 flare was a limb event, consistent with this possible explanation.

[18] We have shown that for extreme EUV solar flares, there is a sudden, intense, long-lasting dayside ionospheric TEC increase effect. The increase can be up to $\sim$25 TECU, reaching a near-peak value within $\sim$5 min.

[19] The duration of the enhanced TEC due to the flare was $\sim$3 hours, much longer than the EUV flare duration. The GOES x-rays (0.1–0.8 nm) have a 1/e penetration depth to altitudes of $\sim$95–110 km. The SEM EUV photons (26.0–34.0 nm) have a 1/e penetration to altitudes of $\sim$160–175 km. For longer wavelengths, the stopping height is higher. Assuming O_2^+ ion production at $\sim$100 km altitude, the recombination timescale is $\sim$70 s. Thus photoionization by x-rays is not effective in producing the long lasting TEC effects ($\sim$3 hrs) noted in this paper. In the F_2 region ($\sim$300 km), the dominant ion is O^+. Electron loss by direct recombination is very slow compared with flare timescales. For example, typical time scales are of order $\sim$4 hrs or faster below 200 km for the reaction $O^+ + [O_2, N_2] \rightarrow [O_2^+, NO^+] + [O, N]$, followed by rapid dissociative recombination of the molecular ion. Although this timescale matches reasonably well with the GPS TEC observations, it is clear that the TEC change is a height-integration of ionization plus loss including both chemistry and neutral wind dynamics. The full (assumed) flare spectrum plus loss processes will have to be modeled in some detail in order to better understand the underlying physics and chemistry.

5. Concluding Comments

[20] This represents an initial look at extreme solar flare events and their ionospheric effects. Although the Oct 28 flare peak EUV irradiance was much greater (more than double) that of the other 3 events, a TEC enhancement ratio of $\sim$5:1 is not easy to understand. Inclusion of other data sets and detailed modeling including ionospheric dynamics will have to be undertaken to better understand this difference. It is likely that continuous full solar flare spectra will be necessary to resolve this issue. Although reasonable models of flare spectra can be produced [*Meier et al.*, 2002], actual measurements will not be available until the Solar Dynamics Observatory (SDO) mission gets launched.

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