Direct EUV/X-ray modulation of the ionosphere during the August-21, 2017 total solar eclipse

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Introduction

A total solar eclipse traversed the continental United States on August 21, 2017, entering in Oregon ~17:15 UT and exiting South Carolina at ~18:50 UT. The eclipse offered a fortuitous opportunity to study ionospheric response by virtue of myriad ground based instrumentation. In particular, we focused the investigation on highly transient phenomena, associated with the supersonic pass of the penumbra. We utilized a dense GPS receiver network in the continental U.S., and topside measurements of two DMSP spacecraft.

The eclipse leftover an unexpected and unpredicted imprint in the ionosphere. First, we show evidence for a rapid response in the ionization due to a non-uniform EUV/X-ray illumination. A data fusion approach of calculated EUV occultation mask and the differential TEC maps reveal four large scale TEC perturbations, strikingly similar and matched with regions of irregular illumination. Second, the DMSP spacecraft measured sporadic depletion in electron temperature, exceeding 1000 K. Likewise, we show a great spatial correlation between the regions of irregular illumination and the sporadic drops in the electron temperature profile.

The Eclipse

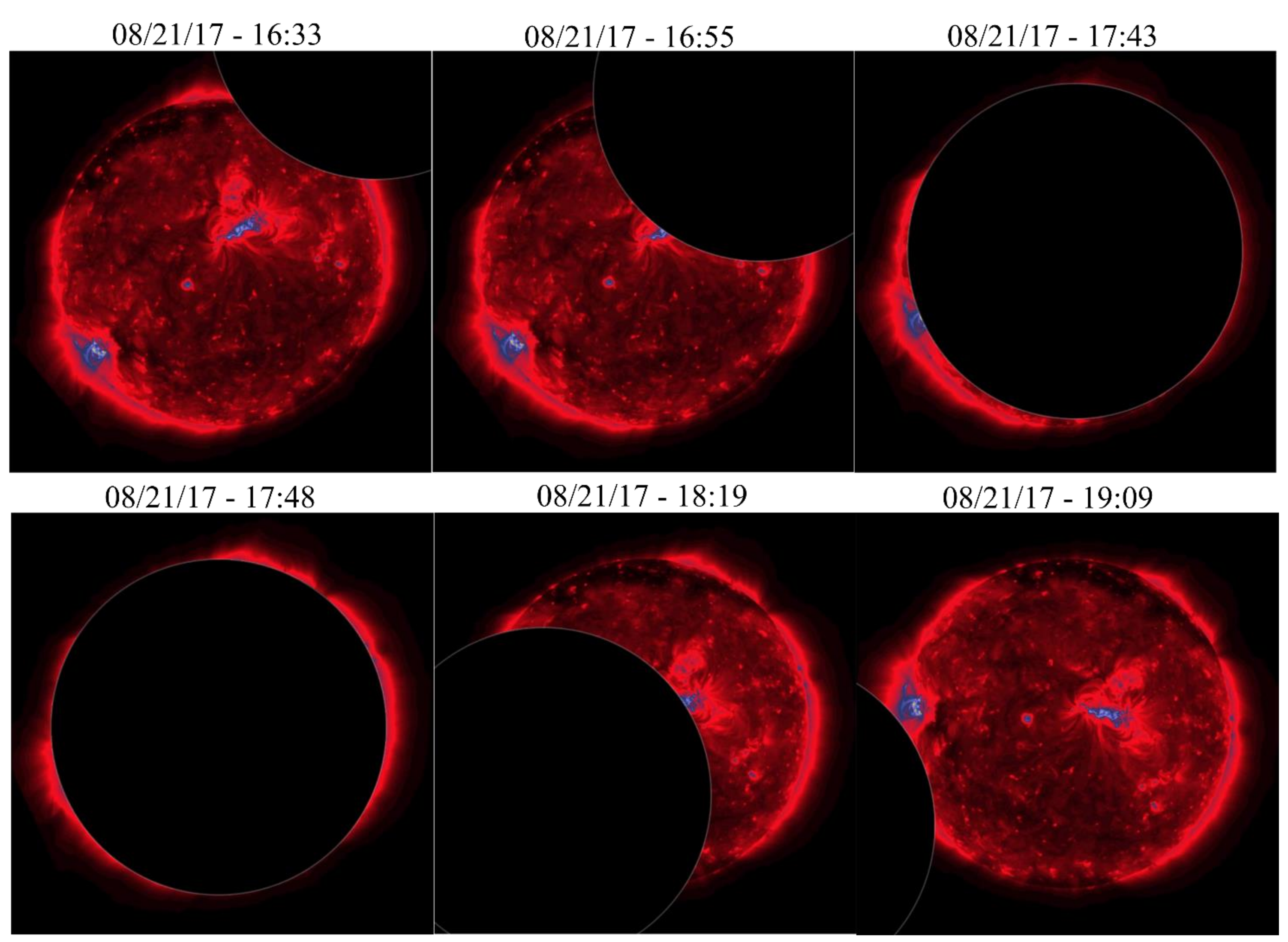

Figure 1: Solar Dynamics Observatory (SDO) observations of the solar disk at EUV - 19.3 nm wavelength. The transition of the moon was calculated to mimic a ground based observation from Luck, Wyoming. Six consecutive snapshots representing a transition of the moon across the sun, emphasizing the profound effect of the two sunspot at the time of the eclipse.

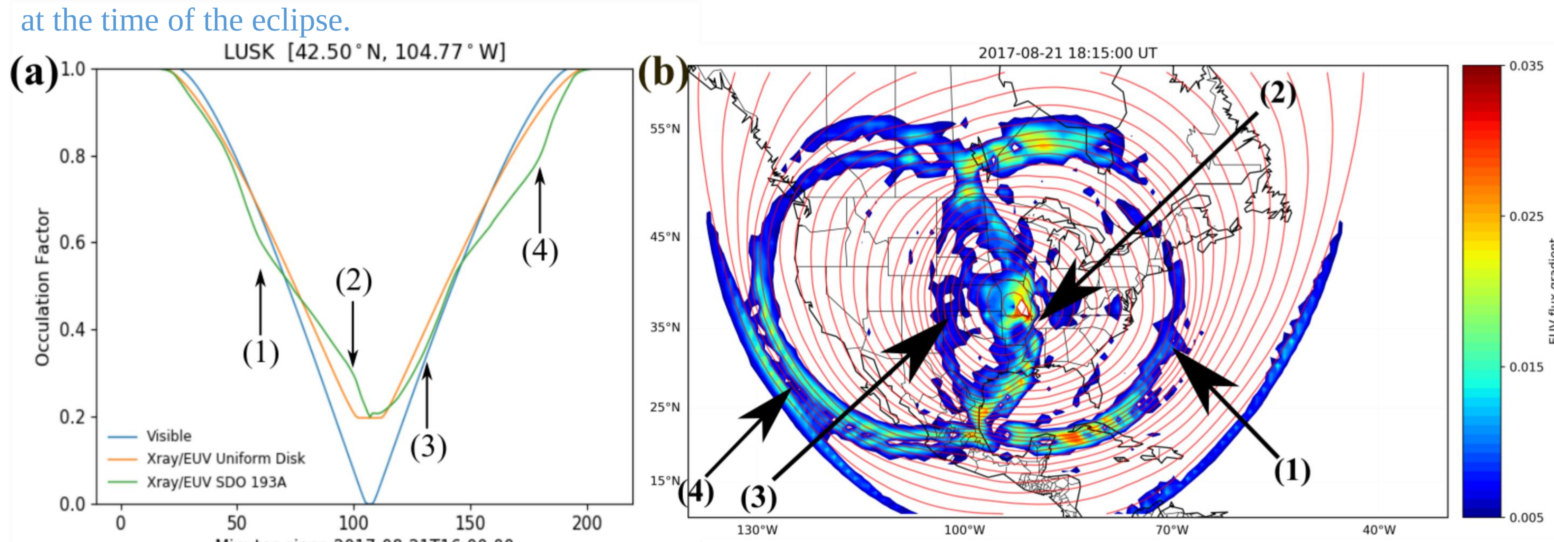

Figure 2: **(a)** Ground based occultation factors, at visible wavelengths, modeled uniform disk at EUV, and an actual occultation factors from Lusk, Wyoming. (b) Projection of EUV-19.3 nm occultation mask: red contour lines are occultation factor, colormap are deviations from uniform disk model, i.e. the Laplacian of the obscuration mask.

Observations: GNSS

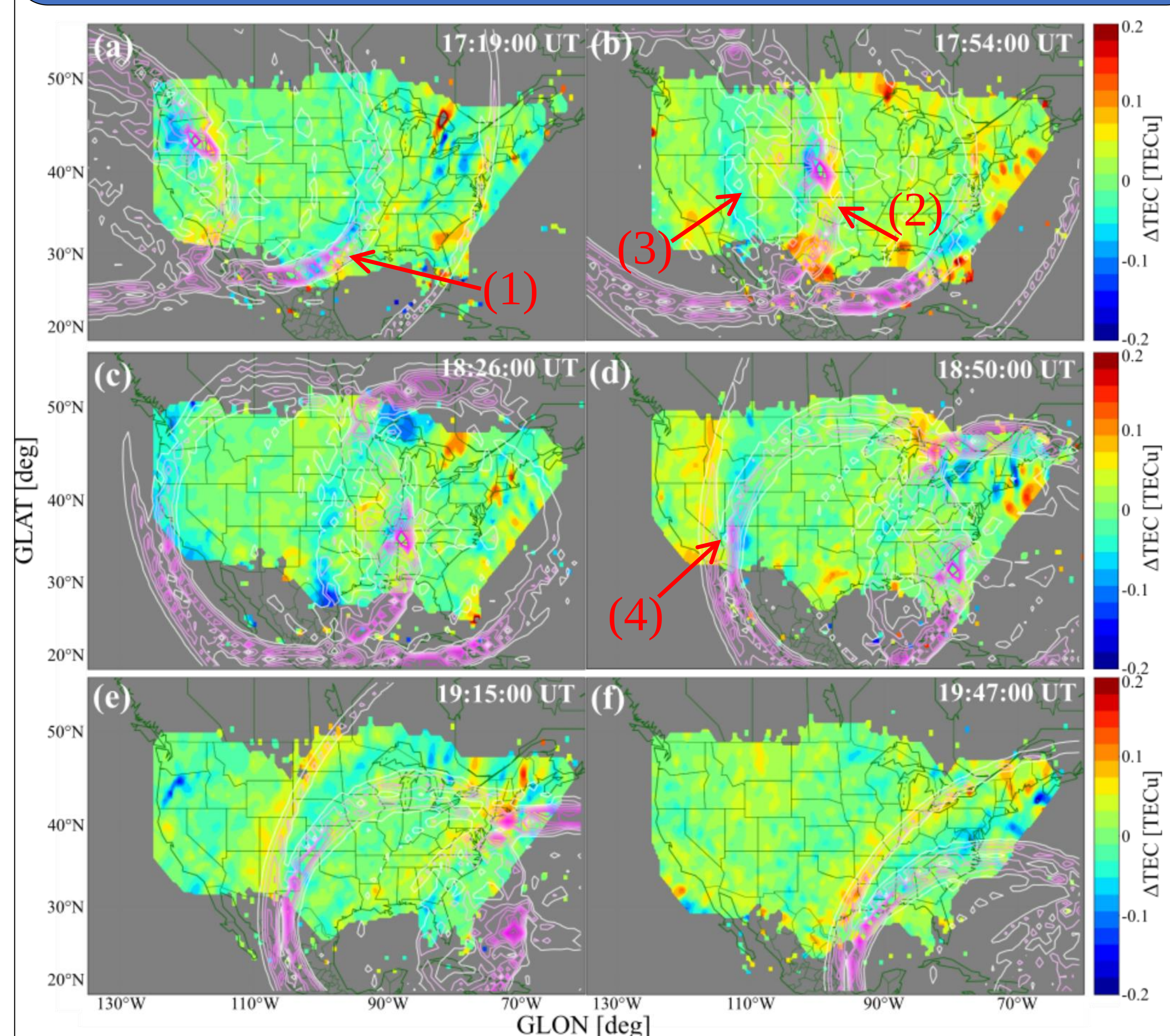

Figure 4: Imaged TEC perturbation on a regular grid (0.3°lon x 0.3°lat) at 300 km altitude. The overlay is a contour plot of the Laplacian of the obscuration mask at 19.3 nm EUV.

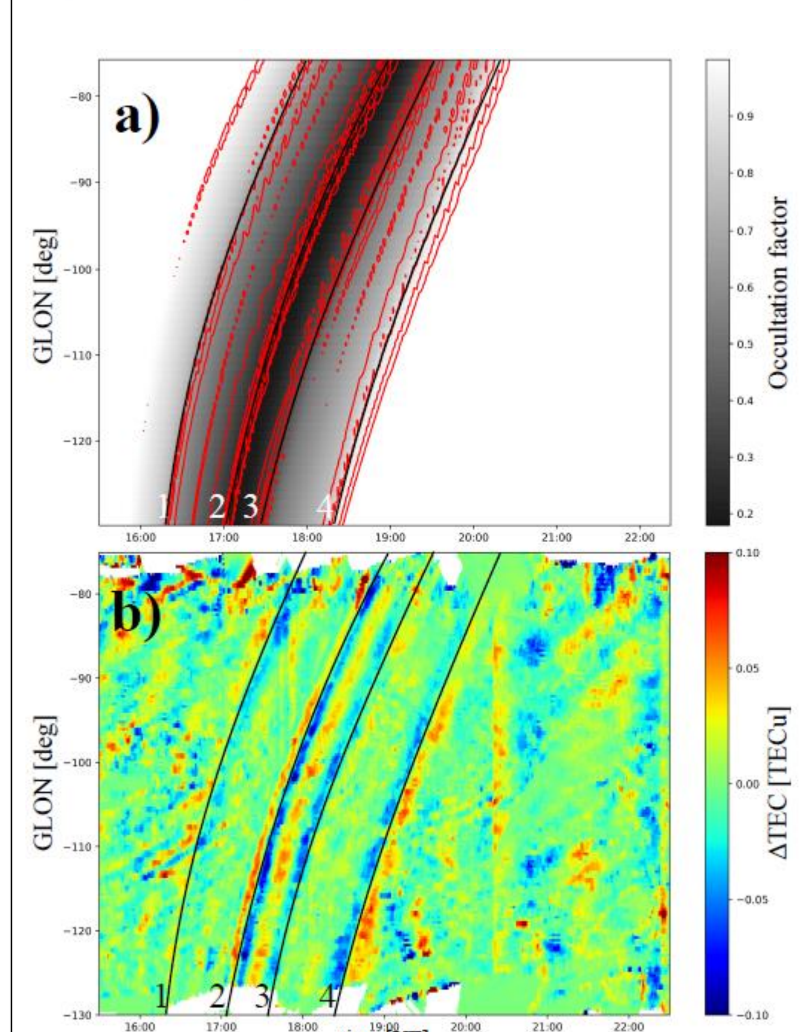

Figure 4: (a) Keogram of the obscuration mask and its Laplacian in its frame of reference. The fiducial lines are lines of maximum Laplacian. (b) Totality-aligned ΔTEC keogram, averaged along ±1.5° glat (dashed line in panel (a))

- The sun had two discrete active regions during the time of the eclipse, shown in the Figure 1. The sunspots caused four distinct deviations in the eclipse occultation mask, as illustrated in Figure 2a.
- The deviations in the occultation mask manifested themselves as double ring pattern in the 2D projection, depicted in Figure 2b. The double ring pattern represent the solar surface projection on the ionosphere, obtained by virtue of the Laplacian filter of the occultation mask.
- We identify and enumerate four deviations in the occultation mask, whose pattern resembles again in the differential TEC (ΔTEC) maps, shown in Figure 3.
- Figure 3 consists of six snapshots of the ionospheric response in ΔTEC. The overlaying contours is the Laplacian introduced in Figure 2b. The TEC perturbations and the Laplacian are in a great spatiotemporal agreement. Likewise, the amplitudes of the TEC perturbations follow values of the Laplacian. Namely, we are seeing a direct modulation of the plasma production function.

Observations: DMSP

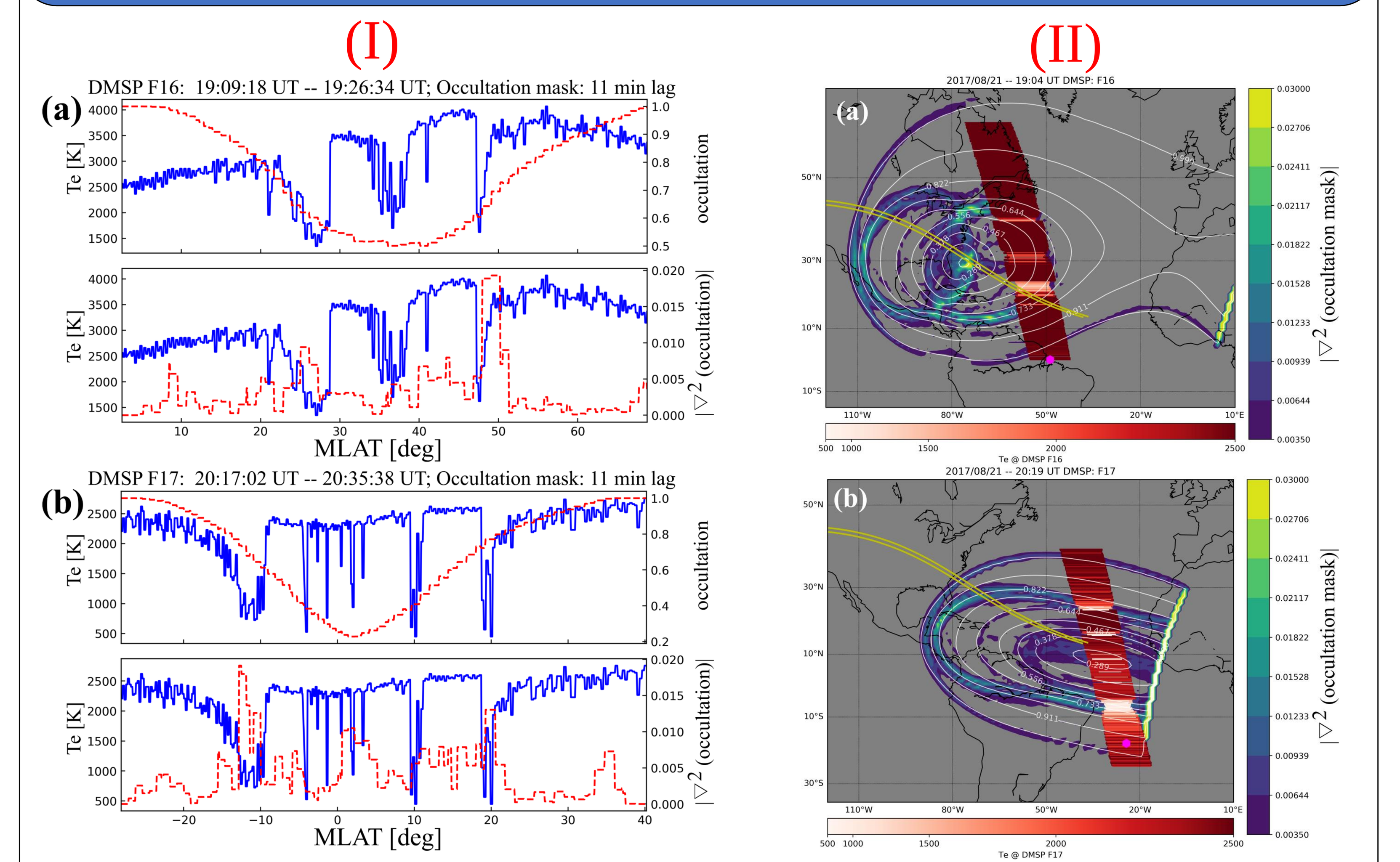

Figure 5: DMSP measurements of the electron temperature profile through the penumbra. Panels (I) show the electron temperature and its relation to the occultation mask in magnetic latitude coordinates. Panels (II) show the spatial association between the cooling region and the irregular penumbra.

- Keograms of the TEC perturbations in Figure 4 bolster the spatiotemporal correlation between uneven EUV illumination function and the TEC perturbations. The keograms show a persistent pattern, following the exact line of the irregular occultation mask. The temporal/latitudinal speed dependence is presented in the natural frame of reference.
- Furthermore, the irregular penumbra severely perturbed the topside ionosphere. Namely, *in situ* measured electron temperature (Te) by two independent DMSP spacecraft passes show intriguing and totally unexpected sporadic cooling regions. The cooling regions and their relationship with the penumbra is illustrated in Figure 5.
- Panels (I) of the Figure 5 show the Te time series measurements as a function of the magnetic latitude, in conjunctions with the values of the occultation mask and its Laplacian. It is evident that the cooling regions spatiotemporally coincide with the steepest changes in the EUV illumination. However, there is a ~10 min time lag in-between.
- Further, panels (II) of the Figure 5 show spatial relationship between the penumbra and the DMSP measurements mapped on the geographical map. The spatial agreement between the double ring regions and the cooling regions is striking, and shockingly conspicuous.
- The observations are entirely unexpected, and intriguing by the fact they are the first of its kind. The physical explanation for the cooling regions is yet unknown.

Conclusions

- Solar active regions are the source of statistically most significant transient ionospheric perturbations via direct modulation of the plasma production function.
- The large scale TEC perturbations match the regions of steepest deviation in occultation function, namely the Laplacian of the EUV occultation mask. Namely the ionosphere act as a sensor, being a projection of the solar surface. The spatial appearance, the intensity of the perturbations is proportional to the value of the EUV occultation mask Laplacian.
- The steep changes in EUV illumination also affected the electron temperature, causing abrupt cooling regions of yet unknown physical mechanism.
- The novel observations are a catalyst for further examination of undelaying physical processes, highlighting a gap in understanding of transient solar-terrestrial interaction.

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