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New understanding of the solar eclipse effects on geospace:The 21 August 2017 Solar Eclipse

Topside Ionospheric Electron Temperature Observations of the 21 August 2017 Eclipse by DMSP Spacecraft

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Key Points:
- Two DMSP spacecraft passing through the 21 August 2017 eclipse shadow detected decreases in the electron temperature in topside ionosphere
- The shapes of these decreases in the electron temperature were complex but showed a repeated pattern that was seen by both spacecraft
- The sporadic temperature decreases can best be explained by the nonuniform EUV solar illumination of the ionosphere during the eclipse

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Abstract

During the 21 August 2017 eclipse two separate DMSP spacecraft passed through the lunar penumbra at local afternoon (F16) and near local sunset (F17) in the topside ionosphere at an altitude of ~850 km. Measurements of the in situ electron temperature by the Langmuir probe on each spacecraft showed regions where the temperature decreased on the order of 500 to 1,000 K in the shadow. The patterns of these decreases were sporadic inside the shadow but generally showed the same overall shape in both passes. Comparing these patterns of temperature reductions with the projection of the gradient of the solar EUV radiation in the ionosphere suggests that these complex patterns are a result of the nonuniform distribution of the solar EUV radiation on the Sun at the time of the eclipse.

Plain Language Summary

As the shadow of the Moon moves across the Earth's upper atmosphere, the decrease in ultraviolet light from the Sun causes a cooling of the electrons in the ionosphere. Measurements during the 21 August 2017 eclipse from the DMSP spacecraft showed a complex and puzzling pattern of this temperature drop. The uneven distribution of the ultraviolet light sources from active regions on the Sun's surface is suggested as a possible explanation.

1. Introduction

The solar eclipse of 21 August 2017 crossed the northern hemisphere from the north Pacific Ocean, across the North American continent, and out into the Atlantic Ocean ending near Cape Verde off the western coast of Africa. During this nearly 4-hr eclipse, two of the four operational Defense Meteorological Satellite Program (DMSP) spacecraft passed through the lunar penumbra, though not the umbra, allowing us to make in situ measurements of the topside ionosphere's reaction to the eclipse at ~850-km altitude.

Solar EUV and X-rays ionize neutral particles in the upper atmosphere, causing an increase in the ionospheric plasma density during the day while the plasma density decreases at night when recombination processes become dominant. This diurnal hour daylight/darkness cycle has been well studied and understood for several decades, but the short period of darkness (~tens of minutes) during an eclipse provides us with a unique opportunity to study the short-term dynamics and responses of the ionosphere. Ground-based observations of the ionospheric response to eclipses have been done since the 1950s (Minnis, 1958) and spacecraft observations date back to at least 1980 (West et al., 2008). More recent spacecraft observations of ionospheric responses to eclipses have been performed by Tomas et al. (2007), Wang et al. (2010), and Maji et al. (2017). Predictions of the ionospheric response to this particular eclipse (Huba & Drob, 2017) provided the scientific community a guide to questions to be asked and observations to be made during this particular eclipse.

Observations of the electron temperatures during two separate DMSP spacecraft passes through the penumbral shadow during this eclipse showed sporadic regions of cooled and noncooled electrons rather than the smooth decrease and increase in temperature in the shadow predicted by Huba and Drob (2017). Mrak et al. (2018), who mapped the effects of two solar active regions producing excess EUV/X-ray irradiation onto the ionosphere, showed that this unevenness in the solar illumination produced a complex and structured ionospheric response rather than the smooth variation that was predicted. Comparing these results with the observed electron temperatures indicates that this is likely the cause of the sporadic cooling seen by the DMSP spacecraft.

2. Observations

The DMSP spacecraft are in circular Sun-synchronous, polar orbits at altitudes between 820 and 860 km. During 2017 there were four operational spacecraft: DMSP F15–F18. Since the launch of DMSP F8 in 1987 all DMSP spacecraft have carried the special sensor-ion, electron, scintillation (SSIES) package of thermal plasma instruments consisting of a retarding potential analyzer, an ion drift meter, a scintillation monitor, and a Langmuir probe. With these four instruments the SSIES package is able to take in situ measurements of the three components of the thermal ion flow, the ion density, the ion composition, and the separate temperatures of both the ions and the electrons (see Heelis and Hanson, 1998 for the retarding potential analyzer, ion drift meter, and scintillation monitor background; Rich, 1994 for more background and operational information on all the SSIES-3 [F16 through F19] instruments; and Brace, 1998 for the background and operation of the Langmuir probe).

During the 21 August 2017 eclipse there were two spacecraft tracks (one by F16 and one by F17) that passed deep into the eclipse penumbra. F16 passed through the lunar penumbra between about 19:10 and 19:26 UT, while the spacecraft was northbound over the Atlantic at a local time of roughly 15:35 hr. The maximum occultation of the Sun was 55% at around +31.5° latitude. Later, F17 passed through the lunar penumbra between about 20:17 and 20:35 UT, while the spacecraft was northbound over the Atlantic at a local time of roughly 18:24 hr. Note that even though this local time indicates that this spacecraft is over the nightside of the Earth, because of its altitude, it was in sunlight and/or the Moon's shadow throughout this period. The maximum occultation of the Sun during the F17 pass was 78% at around +3.7° latitude. There were two other DMSP passes (F17 and F18) that skimmed the edge of the penumbra earlier over the Pacific during the southbound legs of their orbits, but neither of them penetrated far enough into the shadow to show any results in the observed plasma data.

For the afternoon and sunset passes of F16 and F17 described above we examined the full set of ion and electron parameters from SSIES comparing them to both the previous and subsequent orbital passes, and in some cases to passes at the same UT on previous and subsequent days. Most of the parameters either showed no response to the eclipse or were ambiguous and are still being analyzed. The only clear response to the eclipse appeared as puzzling sporadic decreases in the electron temperature (T_e) data rather than the expected parabolic decrease in T_e in the topside ionosphere observed by radar during an eclipse by Evans (1965) and predicted by Huba and Drob (2017). The similarity between the overall shape of the T_e decreases in both passes from different spacecraft strongly suggested that this response was real and not an instrument artifact.

The T_e from DMSP is determined using a Langmuir probe that measures the collected electron current while the potential on the sensor is varied over a 2-s sweep. (Note there is a 2-s rest period between each sweep resulting in a 4-s cadence to the T_e data.) The T_e is determined by finding the maximum gradient in the measured current during the sweep. Normally, this is done by an on-board algorithm and these are the data presented in the public DMSP data set. This simple calculation assumes that the electron plasma conditions are constant during the 2-s sweep as this is the case for the vast majority of measurements. But for these suspect temperature decreases during the eclipse, we reanalyzed the full set of the sweep current data during these two passes.

On the edges of the two eclipse passes the current data during the sweeps were smooth as expected and the newly calculated T_e matched the onboard calculations. But within the eclipse region the current sweeps were somewhat noisy resulting in the large decreases in T_e reported by the automatic algorithm. We smoothed the current data using a fifth-order Savitzky-Golay filter with a 13-point window that significantly reduced the noisiness, then reanalyzed them to find the maximum gradient and the corresponding electron temperature. The reanalyzed T_e data showed that the decreases in the temperature were not as large as the on-board T_e calculation showed. For example, the onboard T_e values for F16 originally showed a decrease from the baseline of as much as 1,700°, while the largest decrease in the reanalyzed T_e values was about 900°. Even after smoothing the current data, the sporatic regions of cooler T_e remained and the temperature decreases were significantly larger than the background variations during the pass.

In Figure 1 the corrected T_e observations for the F16 (a) and F17 (b) eclipse passes are shown as heavy black lines and compared to the T_e observations from the passes closest in time and longitude to the eclipse pass

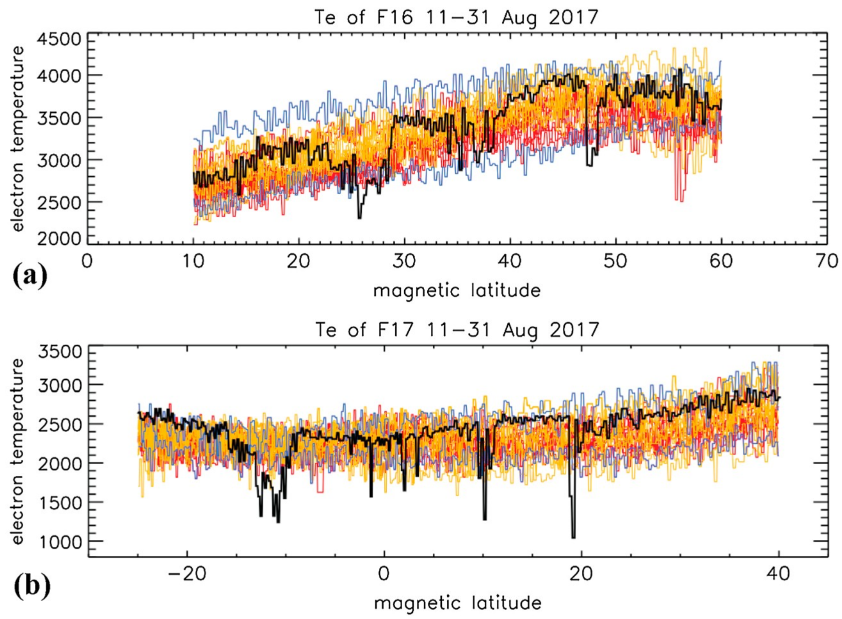

Figure 1. The electron temperature observed by (a) DMSP-F16 and (b) DMSP-F17 during their eclipse pass (heavy black lines) compared to the electron temperature observed during the previous 10 days (red lines) at the closest time/longitude to the eclipse pass and subsequent 10 days (yellow-orange lines) at the closest time/longitude to the eclipse pass. Two of these control passes are plotted in blue to show the normal variability of the temperature.

from the prior 10 days (red lines) and subsequent 10 days (yellow-orange lines) to serve as control data. In addition, two noneclipse passes on each plot are plotted in dark blue to show the typical variation of T_e during a noneclipse pass. Note that the Langmuir probe current sweeps taken during the noneclipse control passes were not as noisy as the current sweeps taken while the spacecraft was in the eclipse. For several control passes the onboard calculated T_e were compared to the T_e calculated after smoothing the sweeps and reanalyzing. These comparisons showed that the overall values were essentially unchanged by the smoothing, so comparing the reanalyzed T_e from the eclipse passes with the onboard calculated T_e from the control passes was judged to be valid. The maximum occultation of the Sun occurred at +37° magnetic latitude for F16 and at +2° magnetic latitude for F17.

The control passes show that there is a variation in the baseline T_e over the 21 days that ranges about 1,000 K for both spacecraft, while the variation within a single pass compared to its running mean is generally less than 250 K. Examining the eclipse pass T_e traces of F16 and F17 shows a wide region (~6° for F16, ~4° for F17) of low temperatures on the southern portion of the eclipse, a narrower region (~2° for F16, 3° for F17) of decreased temperature on the north end of the eclipse, and a region of multiple and short (~0.5° to 1° for both) dips in temperature in the middle. Comparing the eclipse traces to the control passes shows that (a) the baseline values of the eclipse passes outside of the eclipse region fall within the overall variance of the control baselines seen here, (b) the dips in temperature within the eclipse regions are greater than what is observed in the variation seen in the control passes, and (c) much of the temperature drops in the eclipse region, especially for F17, are outside the even the baseline variation. Thus, we conclude that these T_e drops are real and caused by the eclipse. Out of all the control passes only one from F16 on 19 August shows any T_e drop comparable to the eclipse passes. In this case the drop was about 1,000 K and occurred at 55° magnetic latitude. Based on its high latitude this drop is most likely a result of some polar ionospheric phenomenon.

Naively, it would be assumed that the T_e would show a roughly linear response to the amount of sunlight blocked by the Moon, thus forming a parabolic-shaped curve in the T_e data. Both Wang et al. (2010) and Maji et al. (2017) observed the T_e in the topside ionosphere during eclipses using the DEMETER at altitudes of about 660 km, and they also found complex temperature responses that did not match this simple parabolic decrease corresponding to the shadow. Since the T_e decreases observed here are indeed

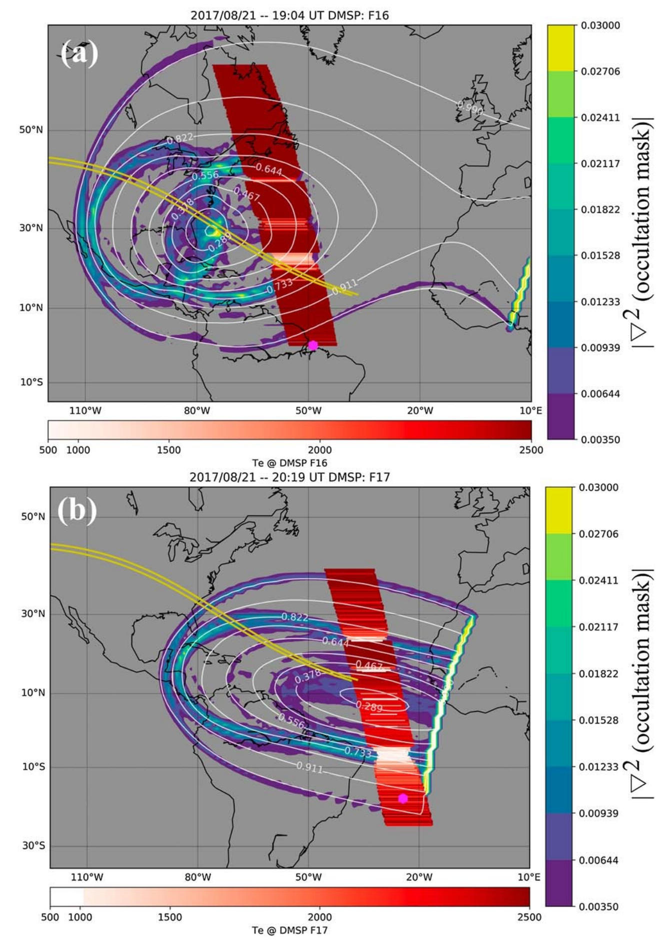

Figure 2. The mask of the absolute value of the EUV gradient at (a) 19:04 UT and at (b) 20:19 UT 21 August 2017 with the ground track of the F16 and F17 (respectively) eclipse passes overlaid and color coded to show the observed electron temperatures. The yellow lines denote the path of the eclipse totality. The white lines and values denote the solar occultation at the time of the mask. The pink dots indicate the location of each spacecraft at the time of this mask. The yellow-white lines on the right indicate the sunset terminator at 300-km altitude.

real we are left with the question: How can a smooth change in the radiation from the Sun produce sporadic changes like this in the electron temperature?

3. Analysis

The expectation of a parabolic-shaped T_e observation during the eclipse is based on the assumption that the EUV radiation from the Sun that affects the ionosphere is uniformly distributed across the solar disk. Moreover, a smooth penumbra should produce a decrease in electron temperature of about 500 K in the totality (Huba & Drob, 2017). However, Mrak et al. (2018) showed that this was not the case. On 21 August 2017 observations from the Solar Dynamics Observatory Atmospheric Imaging Assembly showed that there were two active regions on the side of the Sun facing the Earth, one near the center and one near the edge. As each active region produced excess EUV and X-ray emissions compared to the main solar disk, the illumination in these wavelengths at a given point on the Earth would undergo sharp changes when the lunar limb obscured these active regions rather than the smooth changes expected from a uniformly illuminated disk. Utilizing the Solar Dynamics Observatory observations at 19.3 nm in conjunction with Naval Observatory Vector Astrometry Software (Kaplan et al., 2011), Mrak et al. (2018) showed that a projection of the actual penumbra consists of regions of steep changes in gradients, manifesting themselves as overlapping circles moving eastward with the eclipse (see Figure 1b of Mrak et al., 2018). Further, they compared the time sequence of the locations of these EUV gradients with the measured total electron content (TEC) perturbations during the eclipse and found they matched, thus indicating that the source of the TEC perturbations was the uneven EUV illumination from the Sun.

Since the shapes of the electron temperature distributions observed by both DMSP were defined by temperature decreases on the north and south ends of the passes, we considered the possibility that, like the TEC perturbations, the T_e temperatures were somehow also driven by these EUV gradients. Figure 2 shows the still 1-min patterns (at 19:04 UT [a] and 20:19 UT [b], respectively) of the absolute value of the second derivative of the penumbra occultation factors (i.e., the Laplacian of the EUV mask) at 300 km, referred elsewhere here as the EUV gradients (see Mrak et al., 2018 for more details on the work creating this mask). The space between the thin yellow lines indicates the path of totality, while the thin white lines show the occultation values of the total solar disk. The DMSP tracks (of F16 and F17, respectively) are overlaid on each figure and are color-coded to show the electron temperature with the lighter colors indicating the lower temperatures. The pink dots indicate the positions of the spacecraft at the instant of this pattern, and the yellow-white lines on the right indicate the sunset terminator at an altitude of 300 km. The two passes show a general, but not exact, match between the change in the EUV gradient and the electron temperature decrease. This is not surprising since the EUV gradient images are 1-min snapshots of the moving pattern, while the electron temperature plots cover the 18- and 19-min long spacecraft passes (F16 and F17, respectively).

To correlate the EUV gradient mask properly with the T_e observations the data from the EUV gradient mask during the first minute of the DMSP pass were sampled along that portion of the spacecraft's track during that minute and saved. This process was then repeated for the EUV gradient mask for the second minute of the DMSP track, and the data from that portion of the DMSP track were added to the data from the first minute. This process was repeated for the entire pass, thus creating a running sample of all the EUV gradient masks to match what the spacecraft would see over the time period during its pass. The initial comparisons of

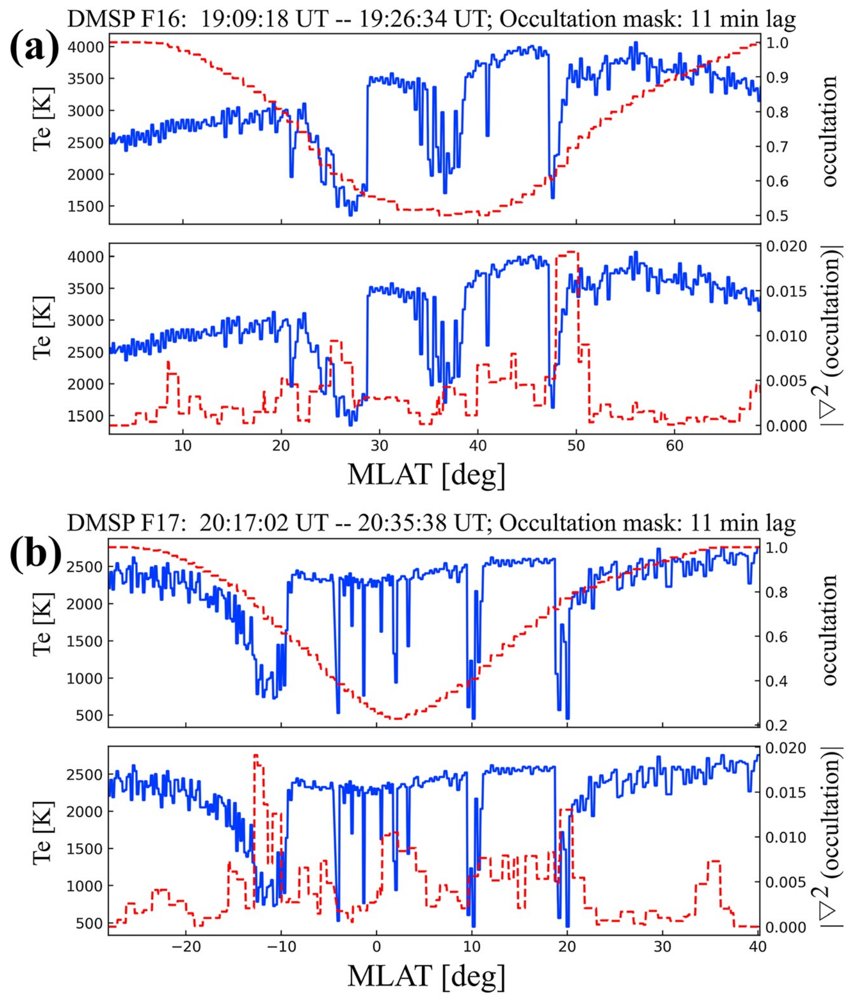

Figure 3. The (a) DMSP-F16 and (b) F17 electron temperature in blue during their respective eclipse passes compared to the occultation of the Sun at 300-km altitude in red (top panel of each) and the running absolute value of the EUV gradient occultation mask along the spacecraft's track also in red (bottom panel of each) with an 11-min lag.

the running EUV gradient masks to the electron temperature were somewhat mismatched, indicating that there was a time lag between the EUV gradient mask at 300 km and the resulting electron temperatures measured at ~850 km. Comparing various time lags showed that the F16 and F17 electron temperature observations best matched the running EUV gradients from 11 min earlier. Figure 3 shows the T_e observations from F16 (a) and F17 (b) plotted in blue compared to the occultation of the Sun at 300-km altitude (upper panels) and compared to the EUV gradient mask from 11 min earlier (lower panels).

4. Conclusions

While the matches in Figure 3 are not exact, they do indicate the presence of a probable connection between the EUV gradient and the electron temperature cooling seen by the two DMSP spacecraft. But there remain two unanswered questions. The first question is why is there a time lag between the gradient EUV mask and the resulting electron temperatures? The most plausible explanation is that this is a result of an altitude difference. The location of the gradient EUV masks here is calculated at an altitude of 300 km to match the F layer peak where most of the heating and cooling of the electrons occurs, while the DMSP measurements are taken in the topside at about 850 km. The lag indicates that there is delay in the vertical transport of thermal energy of electrons from the F peak to 850 km of about 11 min. The second question is that why should the electron temperature respond to the gradient of the EUV radiation rather than intensity of the

EUV itself? This question remains unanswered, although the work here and in Mrak et al. (2018) clearly show that the gradient of the EUV radiation has a significant effect on the ionosphere.

There is still work to be done on the DMSP SSIES data with regards to this eclipse. While the T_e data showed the clearest, though puzzling, response to the eclipse, several other plasma parameters, notably the ion density, the ion temperature, and the vertical ion flow, also showed intriguing responses. Work analyzing these parameters that compared them to the values of the control passes is ongoing to determine if their variations indeed prove to be significant. We are planning a longer and more comprehensive report that will tie all these results together.

This work points up importance and usefulness of exploring the ionospheric response to solar eclipses to gain a better understanding of the physical dynamics of the upper atmosphere. There are several eclipses in the historical DMSP database that we are planning to explore in hopes of building on this work and achieving a better understanding of the relationship between the gradient EUV, the electron temperatures, and other plasma parameters in the ionosphere.

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