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C/NOFS observations of deep plasma depletions at dawn

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[1] The Communication/Navigation Outage Forecasting System (C/NOFS) satellite was launched in 2008, during solar minimum conditions. An unexpected feature in the C/NOFS plasma density data is the presence of deep plasma depletions observed at sunrise at all satellite altitudes. Ionospheric irregularities are often embedded within these dawn depletions. Their frequencies strongly depend on longitude and season. Dawn depletions are also observed in coincident satellite passes such as DMSP and CHAMP. In one example the depletion extended 50° × 14° in the N-S and E-W directions, respectively. These depletions are caused by upward plasma drifts observed in C/NOFS and ground-based measurements. The reason for these upward drifts is still unresolved. We discuss the roles of dynamo electric fields, over-shielding, and tidal effects as sources for the reported depletions. **Citation:** de La Beaujardière, O., et al. (2009), C/NOFS observations of deep plasma depletions at dawn, *Geophys. Res. Lett.*, *36*, L00C06, doi:10.1029/2009GL038884.

1. Introduction

[2] The C/NOFS satellite was launched in April 2008 as an Air Force mission to forecast ambient plasma densities and irregularities in the equatorial ionosphere [*de La Beaujardière et al.*, 2004]. Instruments on the satellite measure electric fields, plasma characteristics, neutral winds, and the strength of scintillation-producing irregularities. The early phase of C/NOFS observations corresponds to the solar cycle minimum (F10.7 = 68). The pre-reversal enhancement in the vertical plasma drift, responsible for early-evening irregularities, rarely appears at such times. Instead, there is a high occurrence-rate of irregularities after midnight. In addition, distinctive deep plasma depletions are also observed at sunrise. This paper describes and analyzes these unexpected dawn depletions.

2. Observations of Dawn Depletions

[3] This paper focuses on data acquired by two C/NOFS sensors. The Planar Langmuir Probe (PLP) measures the ambient ionospheric densities and electron temperatures. It also provides high temporal (512 Hz) and spatial (~13 m) resolution measurements of density irregularities. The Vector Electric Field Instrument (VEFI) measures the AC and DC electric and magnetic fields. Electric fields are measured with three orthogonal 20 m tip-to-tip booms. Initial comparisons between VEFI and PLP with observations from the Jicamarca incoherent scatter radar (ISR) showed good agreement, supporting their validity.

[4] Figure 1 provides our first example of a deep plasma depletion observed at sunrise during C/NOFS orbit #915, on June 8, 2008 at 09:34 UT, while the satellite was at 410 Km altitude. Figure 2, bottom shows ion densities at finer (1-s) temporal resolution. At the western wall of the depletion, ion density decreased by four orders of magnitude from 5.10^4 to ~ 5 cm^{-3} in 30 seconds (~200 km in track). The locations of the dawn terminator at the altitudes of the satellite (09:32 UT), and the E-layer (~09:35 UT) are indicated. C/NOFS entered the depletion shortly before crossing the E-region terminator. Figure 2 also shows the presence of large-amplitude irregularities within the depletion. While the west wall is extremely sharp, the east side shows a gradual upward slope, due to progressive refilling of the ionosphere from below.

[5] The vertical component of the $\mathbf{V} = (\mathbf{E} \times \mathbf{B})/B^2$ plasma drift is also plotted in Figure 2. The drift turned upwards about 600 km to the west of where C/NOFS entered the depletion and remained so across it. Three large (~200 m/s) upward spikes appear. The first occurred ~1.3 minutes before the ion density minimum. The third is collocated with the depletion's west wall. The drifts presented in Figure 2 include the structured drifts associated with the dawn plasma cavity, and are enhanced compared to the background drift. During this period, we estimate that the peak background drift was ~80 m/s. This value was successfully used to model the background density depletion by *Su et al.* [2009]. Although we do not understand well the cause of these enhanced drifts and their relation to the density cavity, the drifts are not large compared to upward drifts of classical spread-F depletions, which sometimes are observed with speeds of 500 m/s or even 1 km/s. Note also that the conductivities during this period are so low that high electric fields can be maintained. There is no plasma to short them out. In addition, the reported E-fields are similar to the enhanced fields observed near sunrise and reported by *Aggson et al.* [1995] (see event C of *Aggson et al.* [1995, Figure 1]).

[6] Ionosonde measurements on this day from Jicamarca corroborate the C/NOFS VEFI measurements. The low plasma density precluded using ISR measurements, but the ionosonde data can be used to estimate upward drifts.

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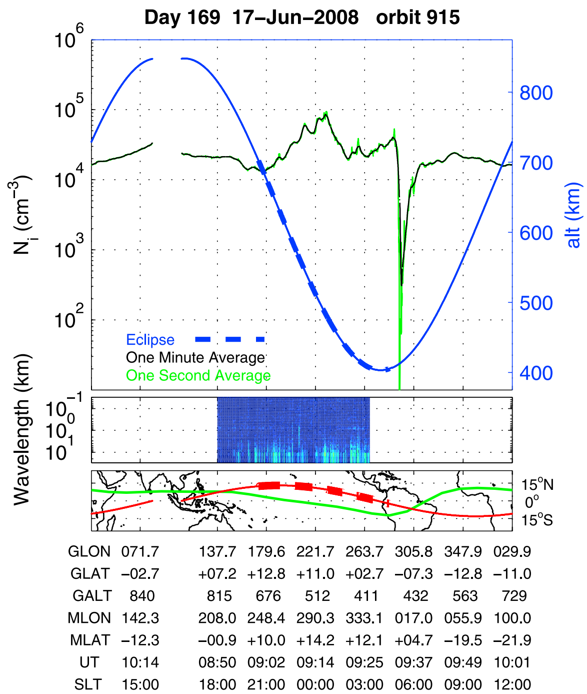

Figure 1. Dawn plasma depletion, orbit 915, Jun 17, 2008. (top) 1-min integrated ionospheric density (black), 1-s integrated density (green), satellite altitude (blue). Middle panel: FFT from the 512 Hz PLP data. (bottom) Map with satellite trajectory (red) and magnetic equator (green). Thicker dotted lines indicate when C/NOFS was in darkness.

Between 09:45 and 10:00 UT (~05 LT), the F-layer peak altitude increased. The velocity inferred from this rise was ~15 m/s. Then, between 10:00 and 10:05, the upward velocity abruptly increased to 125 m/s. After 10:05, it was not possible to accurately measure the F peak, because the density was too low to allow for the o-mode return to be seen. Using he x-mode return, we infer that the upward drift may have remained high, possibly reaching 50 m/s, until 10:35 UT. The ionosonde return is an average over the large region covered by the antenna beam, necessarily much lower than a point measurement from a satellite. Therefore the ionosonde data confirm the presence of large upward drifts at dawn on that day and are consistent with the C/NOFS satellite VEFI in situ measurements.

[7] Figure 3 displays ion densities sampled during a nearly simultaneous pass of the Defense Meteorological Satellite Program (DMSP) satellite F17 at 850 km near the dawn meridian. F17, a sun-synchronous satellite, crossed the magnetic equator at ~09:24 UT, about 10 minutes before C/NOFS' first encounter with the dawn depletion. The plotted measurements show that F17 detected a latitudinally broad depletion with embedded irregularities. An examination of DMSP passes reveals that encounters with similar depletions at dawn are not unusual during this period.

[8] C/NOFS crossed similar depletions at all altitudes between perigee and apogee. Figure 4 provides a second example of a dawn plasma depletion. It occurred at 23:09 UT while the satellite was at 650 km in the Indian longitude sector. A Fast Fourier Transform (FFT) of ion densities sampled at 512 Hz, represented as color spectrograms in the middle panel, indicates that irregularities appeared within the dawn depletions but not elsewhere during this pass.

[9] This orbit was selected because CHAMP, a polar-orbiting satellite at 325 km altitude, traversed the same dawn depletion ~20 min earlier. Figure 5a displays *in-situ* ion densities measured by CHAMP during ~1 orbit (red line). International Reference Ionosphere (IRI) plasma densities along the CHAMP trajectory are also shown (green line) for comparison. CHAMP crossed the magnetic equator at ~05 and 17 LT. The pronounced density minimum at the center of Figure 5a coincides with the satellite's crossing of the magnetic equator on the morning side at 22:47 UT. The density fell from 10^5 to 2×10^3 cm^{-3}. Note that IRI failed to reproduce this depletion, predicting densities well above all measured values.

[10] Figure 5b summarizes characteristics found in the present example. The depletion is located just to the west of the E-region terminator. The dimensions of this dawn depletion deduced from the roughly orthogonal C/NOFS and CHAMP orbits are 14° in longitude and 50° in latitude. The oval sketched in this map approximates the size of the depleted ionosphere, and illustrates its large extent.

[11] Almost identical dawn depletions were seen by CHAMP during seven consecutive orbits on this day. Each time, the depletion occurred as the satellite crossed the magnetic equator and very close to the E-region terminator. Electron temperatures (not shown) measured by CHAMP within these depletions were 1,000°, as predicted by IRI. Several days earlier, when the satellite's orbit was near the 06 LT meridian, electron temperatures peaked near 3100° during the equatorial crossing.

[12] Ion densities measured by CHAMP at the magnetic equator were averaged in one-hour bins, from 03 to 07 LT (L. McNamara, private communication, 2009). Morning side density depletions are deepest in the 05 LT bin. In

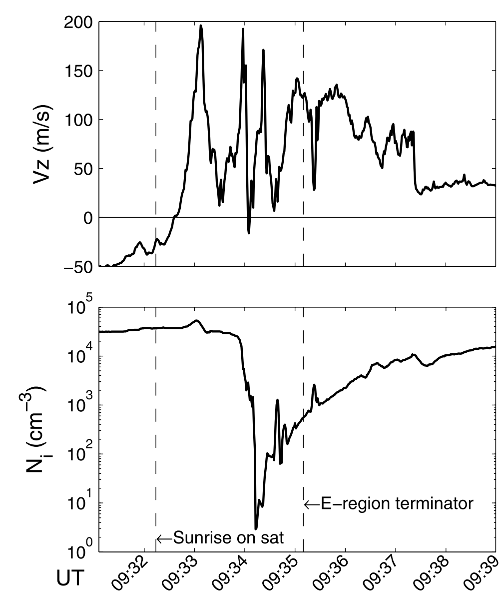

Figure 2. High time-resolution ion density and plasma drift, 17 June 2008.

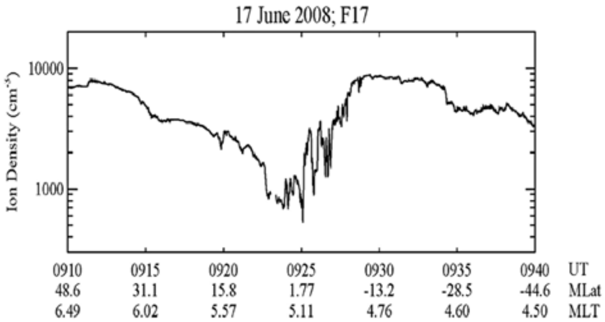

Figure 3. DMSP F17 ion density, 17 June 2008.

September 2008 they were deepest in two longitude sectors: 30° to 110°, and 310° to 350°.

3. Discussion

[13] To recapitulate, the C/NOFS satellite repeatedly observed deep plasma density depletions close to its crossings of the E-layer terminator. They are associated with irregularities and were observed at all C/NOFS altitudes (400 to 850 km). Similar depletions were crossed by the polar-orbiting DMSP and CHAMP spacecraft. Closely coincident passes of C/NOFS and DMSP/CHAMP indicate that the depletions cover about 14° in longitude and 50° in latitude.

[14] Preliminary results show that occurrence rates of these dawn depletions depend on season and longitude. For example, between September 10 and 15, 2008, dawn depletions were seen in 77% of C/NOFS passes. However, significantly fewer events were observed between November 1 and 6, 2008 when dawn depletions were recorded in only 15% of the orbits. In all seasons, depletions appear more frequently and are deeper in the America-Africa and India-Indonesia longitude sectors. The presented data were acquired during magnetically quiet times. The Kp index was 2+ and 1−, for the June and September examples, respectively, and remained low throughout the entire two days. Conditions were generally quiet from 10 to 15 Sept with Kp $\leq$ 3, except for the last 9 hours of the 15th when Kp = 4.

[15] *Scherliess and Fejer* [1999] indicate that upward plasma drifts appeared in their recorded satellite and ground data and were subsequently incorporated into their climatological model. For example, scatter plots in their Figures 1 and 2 show many instances of upward drifts in the dawn LT sector. Their plots show peaks of 20 and 40 m/s, respectively. These represent background drifts and are of similar magnitude as the C/NOFS drifts reported here. Interestingly, their Figure 4 shows large discrepancies between the model and average drift values at night after ~20:00. As indicated above, large upward drifts at dawn were also deduced from the Jicamarca ionosonde. Thus, the C/NOFS measurements are not unique in showing significant upward drifts around 05 LT.

[16] *Retterer et al.* [2005] developed the Physics Based Model (PBMod) to assist C/NOFS analysis. *Su et al.* [2009] ran PBMod twice for the entire June 17day: first, using VEFI measurements and then, using the climatological electric fields of *Scherliess and Fejer* [1999] as drivers. As mentioned above, the PBMod simulation using VEFI inputs reproduced the observed dawn density depletion. It also showed the height of maximum density H_mF_2 reaching ~900 km with well separated Appleton anomaly peaks. The climatological-driven simulation reproduced neither feature.

[17] This paper is not the first to report dawn depletions. *Burke et al.* [1979] described dawn-sector depletions observed by the DMSP F2 satellite under solar minimum conditions. However, electric fields were unavailable at that time. *Oya et al.* [1986] inferred plasma density depletions at dawn from responses of an impedance probe on the Hinotori satellite during the 1981–1982 solar maximum. ROCSAT-1 also crossed density reductions near sunrise during solar maximum storms [*Su et al.*, 2009]. *Fejer et al.* [1999] mention density depletions close to sunrise and attribute them to the stormtime disturbance-dynamo.

[18] We are now left with the challenge of explaining the presence of an eastward E field at dawn. The electric field could be generated by a dynamo mechanism driven by winds and/or gravitational drifts [*Eccles*, 2004], or could be due to over-shielding by region 2 Birkeland currents. The winds that drive the dynamo could be due to geomagnetic-disturbance dynamo or a traveling atmospheric disturbance triggered by the passage of the terminator [*Fujiwara and Miyoshi*, 2006]. Non-migrating tides in the equatorial ionosphere [*Immel et al.*, 2006] and the strength of the geomagnetic field may explain part of the longitudinal variation. If the ultimate cause is a dynamo produced by a zonal flow, then, in a way similar to the pre-reversal enhancement that occurs at dusk, we can invoke the requirement for current continuity across the discontinuity of conductivity at dawn to explain the generation of electric fields in the orthogonal direction, leading to vertical plasma drifts.

[19] Concerning the generation of these fields by geomagnetic activity, *Burke et al.* [2009] and *Su et al.* [2009]

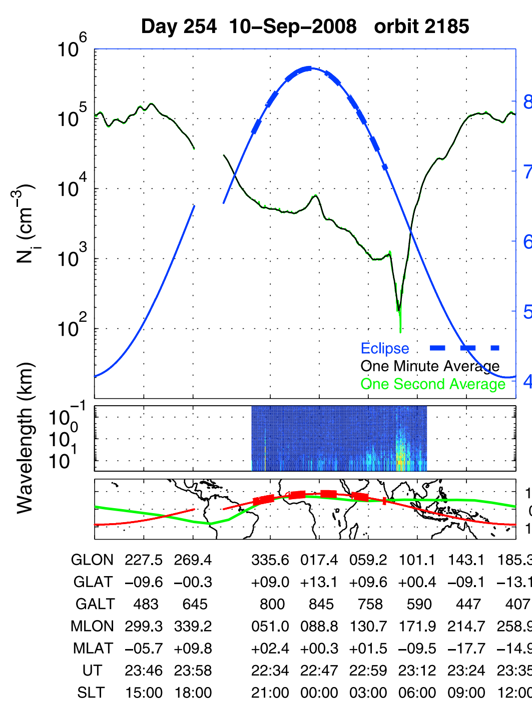

Figure 4. Same as Figure 1, but for 10 September 2008.

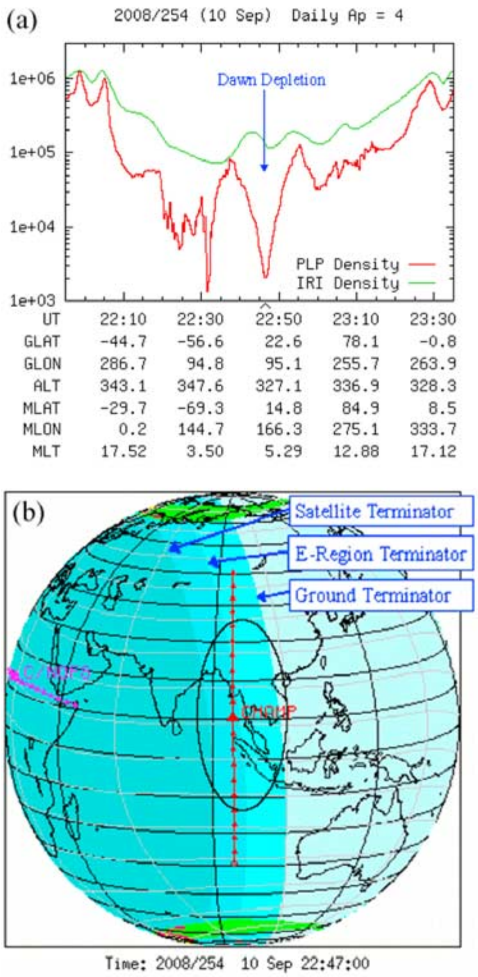

Figure 5. (a) CHAMP data, 10 September 2008 with density (red) and IRI model (green). (b) Sketch of the depleted ion density region in the dawn depletion, 10 September 2008. Both CHAMP and C/NOFS see dawn depletions when the E region below the satellite is still in darkness, but very close to the terminator. Oval illustrates the depletion size ~50° × 14°.

argue that the event of June 17 may be due to the disturbance dynamo or over-shielding by Region 2 currents. A solar wind disturbance reached the Earth on June 14. Although it did not drive a magnetic storm, it did cause irregular increases in the AE index during the following days. AE reached ~700 nT at 05 UT on June 16. The authors of these two papers regard the Figure 1 depletion as a remnant of a wider depletion that had formed earlier. Nevertheless, this remnant cannot be considered a dead depletion. It was kept alive and nurtured by continuing large upward drifts. It is clear, however, that many dawn depletions observed during C/NOFS passes cannot be regarded as remnants of prior geomagnetic activity. They appear spontaneously as isolated events that start at about 05 LT, with no discernible antecedent signatures.

4. Conclusion

[20] We have shown that deep pre-sunrise depletions associated with upward plasma drifts were frequently observed by C/NOFS. Coincident DMSP and CHAMP data provide an estimate of the extent of these depletions. Using the electric field measured by VEFI, PBMod has reproduced the observed features of the depletions. We considered several possible reasons for the generation of the observed upward drifts. As part of our future work we plan to investigate in more detail possible explanations for these depletions at 05 LT. In addition, as C/NOFS measurements accumulate, we will derive statistical models of this effect in order to understand how and why the dawn depletions and corresponding E-fields vary with longitude, local time, season, magnetic activity and solar flux.

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