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# Behavior of the O+/H+ transition height during the extreme solar minimum of 2008

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[1] Typically the solar radio emission at 10.7 cm is used to scale the critical euv radiation that is absorbed by the Earth's neutral atmosphere. In the latter half of 2008 this radio emission from the Sun was at the lowest levels seen in the last 50 years and the persistence of these low levels has never been recorded before. Here we show that these uniquely low levels of solar radiation produce similarly unique behavior in the Earth's ionosphere and the upper atmosphere. Most remarkably, the altitude extent of the ionosphere is significantly smaller than our present reference models would predict for these levels of solar activity. The transition height resides near 450 km at night and rises to only 850 km during the daytime. At night, this unusually contracted ionospheric shell around the equator has a temperature of only 600 K and prior to sunrise the ion number densities at the transition height fall below $10^4$ cm$^{-3}$.

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## 1. Introduction

[2] The O+/H+ transition height is a sensitive indicator of solar euv ionizing flux and the dynamics of the topside ionosphere [*MacPherson et al.*, 1998]. It has long been recognized as an important specification parameter describing the topside ionosphere. and a number of studies have documented its variability [*Kutiev et al.*, 1994]. These studies generally involve the inspection of topside total ion concentration profiles obtained from topside sounders [*Kutiev and Marinov*, 2007] and combinations of total electron content (TEC) from GPS receivers and ionospheric density from ionosonde data [*Meza et al.*, 2008]. Many of the features of the transition height are revealed in ion composition measurements made from space [*Gonzalez et al.*, 1992] and from the ground [*Sulzer and Gonzalez*, 1996] and further descriptions of the O+/H+ transition height have been provided by *Antonova et al.* [1992], *Kutiev et al.* [1980] and *Miyazaki* [1979]. By accumulating topside sounder measurements over a 4-year period from 1962–1966 *Titheridge* [1976] was able to describe the global features of the transition height during solar minimum conditions, but generally the large daily altitude variation in the transition height makes it inaccessible, at some local times, to satellites that span a limited altitude range. The fortuitous combination of very low solar activity and the elliptical orbit of the Air Force Communications Navigation Outage Forecast System (C/NOFS) satellite overcomes this difficulty.

[3] The C/NOFS satellite was launched in April, 2008. The satellite is in a low inclination orbit (13°) with apogee near 850 km and perigee near 400 km. The orbit plane precesses 24 hours in local time in about 50 days. During this same period the line of apsides (line connecting apogee and perigee) moves almost 2 cycles around the orbit.

[4] The Coupled Ion Neutral Dynamics Investigation (CINDI) is a NASA sponsored project that includes a retarding potential analyzer (RPA) and an ion drift meter (IDM) that measure the temperature, velocity, major composition, and number density of the thermal ions in the ionosphere [*Heelis and Hanson*, 1998]. These instruments are carried as part of the payload on the C/NOFS satellite. Over a period of 2–3 months all latitudes at all altitudes accessible by the satellite are sampled at all local times and average properties of the ionosphere in this domain can be described. To accomplish this task it is necessary to average longitude variations that are known to exist but are generally much smaller than the local time and seasonal variations that we describe here [*West and Heelis*, 1996].

[5] Figure 1 shows the total ion number density, constituent ion composition and ion temperature that are measured by the RPA during an entire orbit of the C/NOFS satellite in June 2008. Figure 1 (top) shows the total ion concentration while Figure 1 (middle) shows the O+ and H+ concentrations as a fraction of the total. Figure 1 (bottom) shows the O+ temperature. The satellite crosses the geographic equator near apogee and perigee where the local times are near noon and midnight respectively. There are many features in the ion concentration, composition and temperature that are responsive to the dynamics in the topside ionosphere. Near apogee at local noon (0735 UT) H+ is the major ion and as the satellite moves to lower altitudes during the afternoon it crosses the O+/H+ transition height near 500 km at 1900 LT. In the post sunset hours at perigee O+ is the major ion and the ion temperature falls to levels below 600K in the presence of ionospheric density irregularities. As the satellite climbs in altitude during the night the satellite again crosses the transition height near 500 km. Prior to sunrise (0650 UT) the O+/H+ transition may appear below 500 km altitude where the total density can fall to levels below $10^4$ cm$^{-3}$.

[6] During the months of June through August 2008 data from the CINDI RPA on C/NOFS has been taken almost

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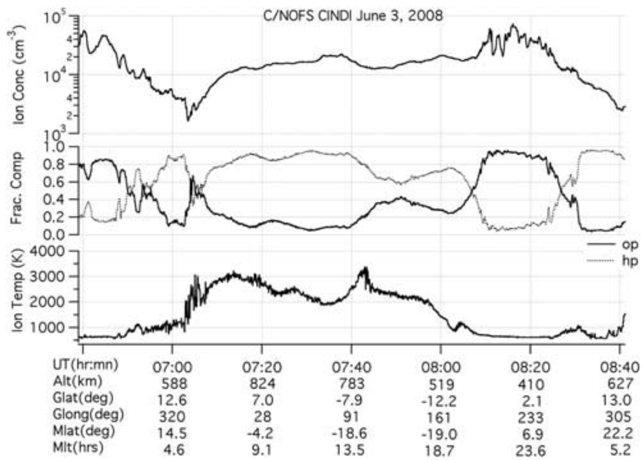


**Figure 1.** In-Situ measurements of thermal plasma parameters made by CINDI instrumentation allow the identification of the O+/H+ transition height and the ion temperature and total number density along the orbit.

continuously. Thus, for this time period a longitudinally-averaged description of the local time variation of the transition height surface around the equator can be constructed for the first time. Here we describe the major features of that surface when the solar F10.7 radio flux, typically used as a proxy for the solar ionizing radiation, is at the lowest levels ever recorded.

## 2. Observations

[7] Figures 2 provides a perspective view of the transition height surface constructed from the CINDI measurements for the northern summer months of June–August 2008, with a color scale indicating the O+ temperature on that surface in Figure 2 (top) and the logarithm of the total ion concentration in Figure 2 (bottom). The monthly average F10.7 cm solar flux for these months are respectively 68, 67.8 and 68 with only two days in the entire period with F10.7 in excess of 69. The CINDI data are used to construct a longitudinally averaged picture of ionospheric conditions around the equator during this prolonged period of extremely low solar activity. Thus, we emphasize only the large-scale features in the latitude and local time variations.

[8] The transition height is at it lowest just before sunrise where it appears near 450 km, just above the satellite perigee. It rises rapidly after sunrise reaching maximum altitudes during the daytime near 850 km. After sunset the transition height falls throughout the night. During the northern summer period shown here the transition height is asymmetrically distributed about the magnetic equator, being higher in the summer hemisphere than in the winter hemisphere by about 50 km. Such an asymmetry is consistent with the expectation that a wind, blowing in the upper

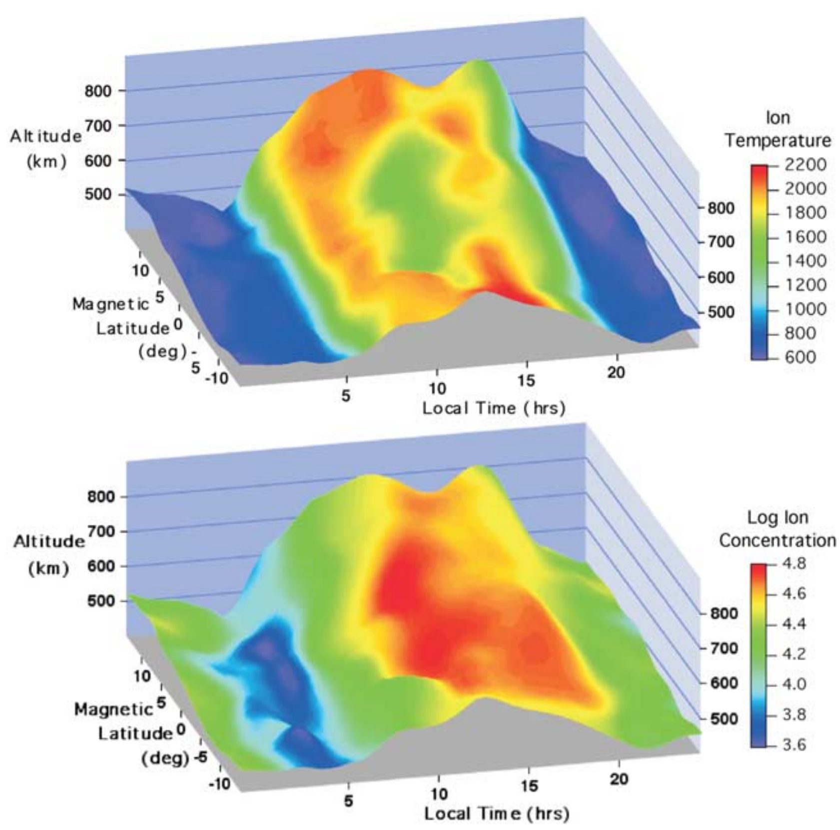


**Figure 2.** In these perspectives the altitude of the O+/H+ transition surface is described by averaging the CINDI measurements over the period June–August 2008. Both (top) the temperature and (bottom) the log of the total ion concentration are described by the color shading of the surface.

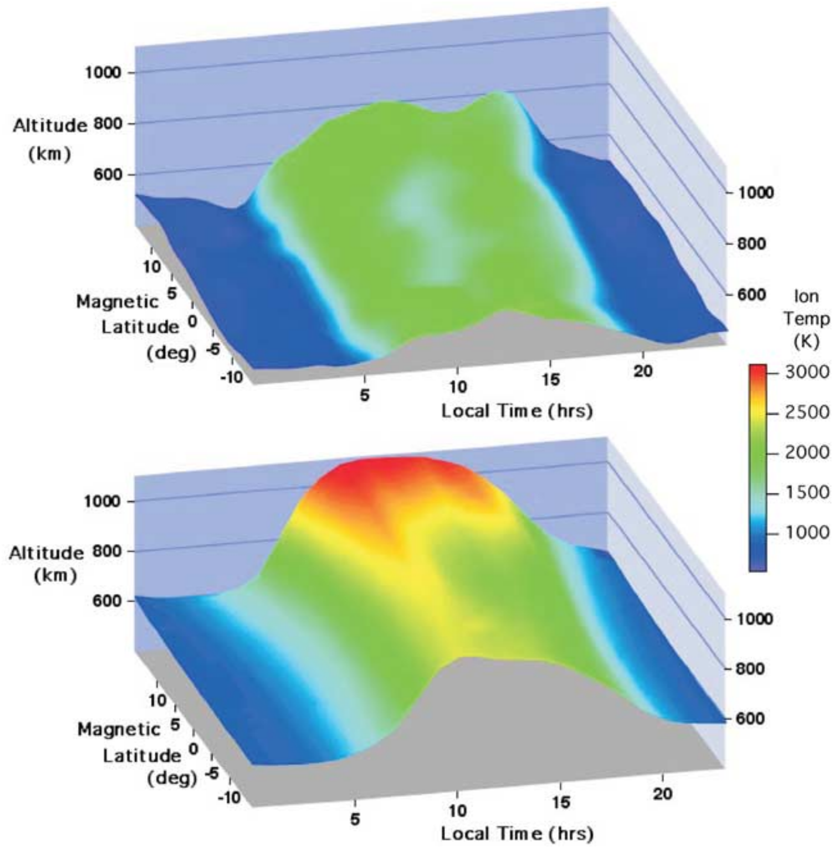


**Figure 3.** Comparison of (top) CINDI measurements and (bottom) the predictions from the IRI model highlight the difference in the altitude of the transition surface and the ion temperature at the surface. The surface is much lower and much cooler than expected.

atmosphere from summer to winter, will raise the ionospheric layer in the summer and lower it in the winter [*Heelis and Hanson*, 1980]. At the transition height the O+ and H+ concentrations are, of course equal. However, the constituent temperatures may be quite different especially during the day when the thermal contact between the electrons and the H+ is more efficient than between the electrons and O+. Under the conditions of equal constituent concentrations, analysis of the CINDI RPA data delivers the temperature of the O+ ions. As the sun rises the ion temperature rises rapidly with temperatures near the equator that are higher than those seen at local noon. This sunrise surge in temperature is produced by photoelectron heating in the initially low plasma content of the magnetic flux tubes [*Schunk and Nagy*, 1978]. However it is quickly suppressed as the plasma content rises during the daytime.

[9] At night the ion temperature falls to unprecedented low levels reaching values of 600K by local midnight. At this local time the transition height has fallen to near 450 km altitude and we expect that the O+ ions are in good thermal contact with the neutral gas. In this case the neutral temperature can be no greater that 600K.

[10] Examination of the total ion concentration shows maximum levels a little before local noon. The presence of peaks in the ion concentration near 10 degrees magnetic latitude in the northern and southern hemispheres indicates the formation of a weak equatorial anomaly that extends only to about 1500 local time. In the afternoon and throughout the night, the ion concentration decreases to reach levels significantly below $10^4$ cm$^{-3}$ just before sunrise.

[11] The observed behavior of the transition height and the plasma properties in the topside ionosphere stand in significant contrast to those predicted using the international reference ionosphere (IRI) [*Bilitza*, 2001]. Figure 3 compares the height of the transition surface and the total ion concentration at that surface observed by CINDI and predicted by the IRI model. By both day and night the transition height is over 200 km lower than predicted by the model and the peak daytime ion concentration is over a factor of 5 lower than expected. While a well-formed equatorial anomaly is present in the model it is largely absent in the observations and the minimum ion concentration observed just before sunrise is almost a factor of 10 lower than expected. Figure 4 indicates that similar deviations from our expectations occur in the ion temperature. During the daytime, peak ion temperatures are nearly 1000 K cooler than expected while during the nighttime, the minimum temperature before sunrise is nearly 200K lower than expected.

## 3. Discussion

[12] Observations for the very low levels of solar activity prevailing during 2008 have never before been taken. Thus it is perhaps not surprising to see significant deviations from the observations and model results that must be extrapolated from higher solar activity levels. The lack of good agree-

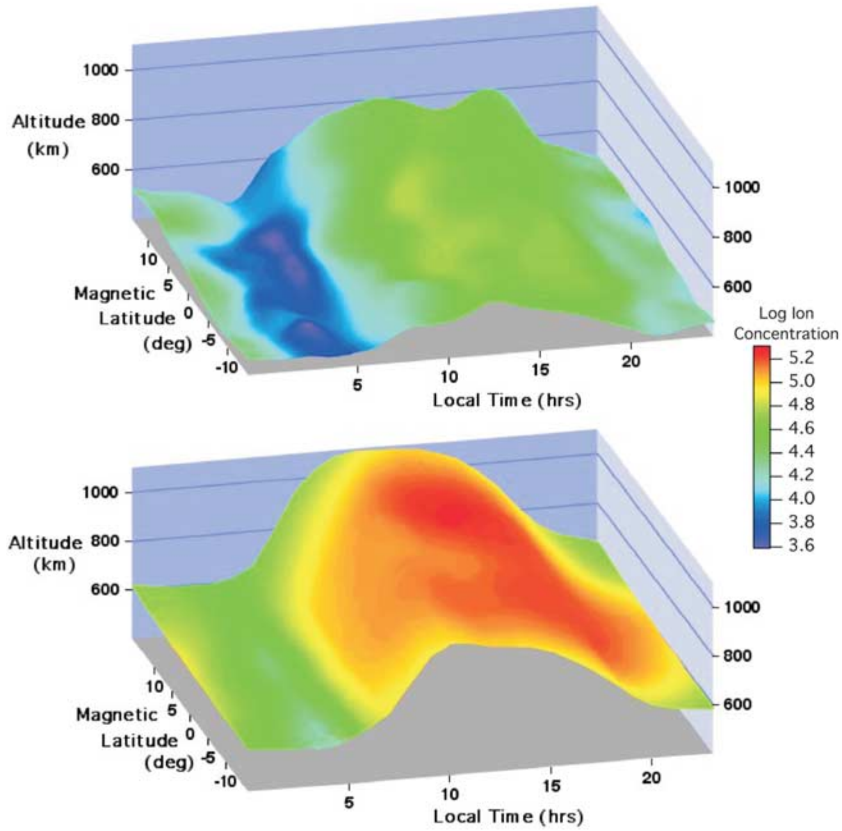


**Figure 4.** Comparison of (top) CINDI measurements and (bottom) the predictions from the IRI model highlight the difference in the altitude of the transition surface and the total ion concentration at the surface. The total ion concentration is also much lower than expected even as the surface itself is lower than expected.

ment between the model and data in the topside ionosphere during these extreme conditions does not reflect on the well-recognized ability of the model to describe the F-peak density and the F-peak height during more moderate levels of solar activity. The observations of ion temperatures during the daytime and the nighttime indicate that the overall heating rate to the upper atmosphere, due to the absorption of euv radiation, may be significantly smaller than expected. For example, the observations shown here suggest that the nighttime neutral atmosphere temperature is near 600 K or below and thus the neutral atmosphere density near 400 km will be at much lower levels than usually seen. The appropriateness of using the 10.7 cm solar flux to estimate the ionization and heating rates is clearly in doubt and direct observations of the solar euv spectrum during this period suggest that these rates should be much smaller than those derived using the reported 10.7 cm flux levels (Woods, private communication). With lower temperatures in the charged and neutral gases the atmospheric and ionospheric scale heights will be correspondingly lower with the transition height surface showing the very limited variations that are observed. It appears that during the daytime and the nighttime the ionosphere and the upper atmosphere are contracted closer to the surface of the Earth than they have ever been before.

[13] The fact that the very low levels of solar activity have existed for an unprecedented long period may also lead to significantly different behavior in the dynamics of the ionosphere. The evidence for a prevailing summer to winter wind in the upper atmosphere is strongly supported by the hemispherical asymmetry in the transition height surface. However, the distribution of the total ion concentration at the transition surface shows only a very weak equatorial anomaly suggesting that the dynamics of the ionosphere is significantly different from our expectations. Based on the observations of ionospheric concentrations we might expect upward drifts that drive the anomaly formation in the daytime to be weaker and of more limited duration. It seems likely that the dependence of both the photochemistry and the electrodynamics of the equatorial ionosphere need to be understood to explain the observed behavior in the transition height during this extreme solar minimum period. More extensive studies of the entire data set available from the C/NOFS satellite should also provide a direct and more definitive analysis.

## 4. Conclusions

[14] In the latter half of 2008 the upper atmosphere was exposed to extremely low and prolonged levels of solar extreme ultraviolet radiation. Observations in the ionosphere have never before been taken during such conditions and they have provided a unique opportunity to describe the O+/H+ transition surface in the equatorial ionosphere. This surface is much closer to the planet than expected, it is much cooler than expected and the ion concentration at the

surface is lower than expected. All these parameters indicate that both the photoionization and extreme ultra violet heating rates are much lower than is indicated by the 10.7 cm radio flux that is usually used as a proxy for these rates. In addition the distribution of ionization in latitude and local time suggests that the ionospheric dynamics may also be significantly modified during this period. Finally we point out that the unusual behavior of the near-space environment of the Earth during this solar quiet period is just one feature of the Sun-Earth coupled system. In addition to the very low levels of euv radiation, the community also reports the lowest levels of solar wind density and solar wind speed that have been observed in the space age [*McComas et al.*, 2008].

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