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varying, horizontal E X B drift patterns are imposed and subsequent ionospheric responses are calculated to determine how enhanced plasma densities in the dark polar cap could result from extended transit of relevant flux tubes through regions of significant solar production. This would occur south of the cusp prior to convection as patches across the polar cap. It is found that a density enhancement in NMAX from 7×10^4 to 5×10^5 el/cm^3 occurs at Thule when a time-varying convection pattern is included in the simulation. The "patch of ionization" is generated when an initial convection pattern characterized by an 80 KV crosstail potential and a 12° polar cap radius is abruptly changed to a 100 KV crosstail potential and a 15° polar cap radius. The horizontal extent of the patch is related to the length of time the new convection pattern remains "turned-on".

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ORIGIN OF DENSITY ENHANCEMENTS IN THE WINTER POLAR CAP IONOSPHERE

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ABSTRACT

Coherent and incoherent ground-based radar measurements of the winter polar cap ionosphere at Thule and Sondrestrom, Greenland, have established the existence of "patches" of enhanced ionization which drift across the polar cap in an antisunward, noon-midnight direction. Associated with these patches is strong radio scintillation activity which severely disrupts ground-to-satellite communication systems and interferes with the operation of space surveillance radar at high latitudes. Several recent studies have shown that the source of enhanced ionization is the sunlit sub-cusp ionosphere rather than production by precipitating energetic particles. However, the question of what causes the "patchiness" has not been addressed. We study this problem by solving the time-dependent plasma continuity equation including production by solar ultraviolet radiation, loss through charge exchange, and transport by diffusion and convection E X B drifts. Time and spatially varying, horizontal E X B drift patterns are imposed and subsequent ionospheric responses are calculated to determine how enhanced plasma densities in the dark polar cap could result from extended transit of relevant flux tubes through regions of significant solar production. This would occur south of the cusp prior to convection as patches across the polar cap. It is found that a density enhancement in NMAX from 7 X 10^4 to 5 X 10^5 el/cm^3 occurs at Thule when a time-varying convection pattern is included in the simulation. The "patch of ionization" is generated when an initial convection pattern characterized by an 80 KV crosstail potential and a 12^o polar cap radius is abruptly changed to a 100 KV crosstail potential and a 15^o polar cap radius. The horizontal extent of the patch is related to the length of time the new convection pattern remains "turned-on".

INTRODUCTION

Substantial evidence exists, both observational and theoretical, which suggests that enhanced "patches" of ionization, 200 to 1000 km in horizontal extent, are associated with a southward directed Interplantary Magnetic Field (IMF) orientation (B_z < 0). During winter hours (1000-2000 CGLT), these patches are observed to drift in an anti-sunward direction over Thule, Greenland with speeds ranging from 300 to 1000 m/sec. Recent observations carried out simultaneously from Thule and Sondrestrom, Greenland (Weber et al, 1986) have traced the trajectory of a single enhancement for over 3000 km. Figure 1 presents observed f_oF_2 values as a function of Universal Time at Thule (86^o CGL) for the period 4 Dec to 10 Dec, 1983 (Buchau et al., 1985). The "patches" of ionization are evidenced as ionization enhancements normally observed between 1400 and 2200 UT and may be broad patches as on 5 Dec or "spikey" patches as on 7 and 10 Dec.

A number of different studies have demonstrated that the plasma within the enhanced region is produced by solar ultraviolet radiation in flux tubes located equatorward of the subcusp region before convecting over Thule. Buchau et al. (1985) have presented quantitative arguments which demonstrate that the observed diurnal variation in NMAX (F2) at Thule in December cannot be accounted for by local production due to precipitating energetic electrons and qualitatively show that the source of plasma is equatorward of the cusp region.

A quantitative comparison of calculated and observed NMAX (F2) values at Thule has been carried out by Anderson et al (1986) and by Buchau et al (1985) and it was shown that indeed, plasma convecting over Thule during winter, daytime hours (1000 to 2000 CGLT) spends about 3 to 5 hours in the sunlit region under B_z south conditions. Magnetic flux tubes arriving over Thule between the hours 2000 and 1000 CGLT, along their respective trajectories never enter the sunlit region (see fig 10, Buchau et al., 1987, IES Proceedings) and ionization production is due entirely to precipitating energetic electrons. The purpose of this paper is to present a possible mechanism for creating the

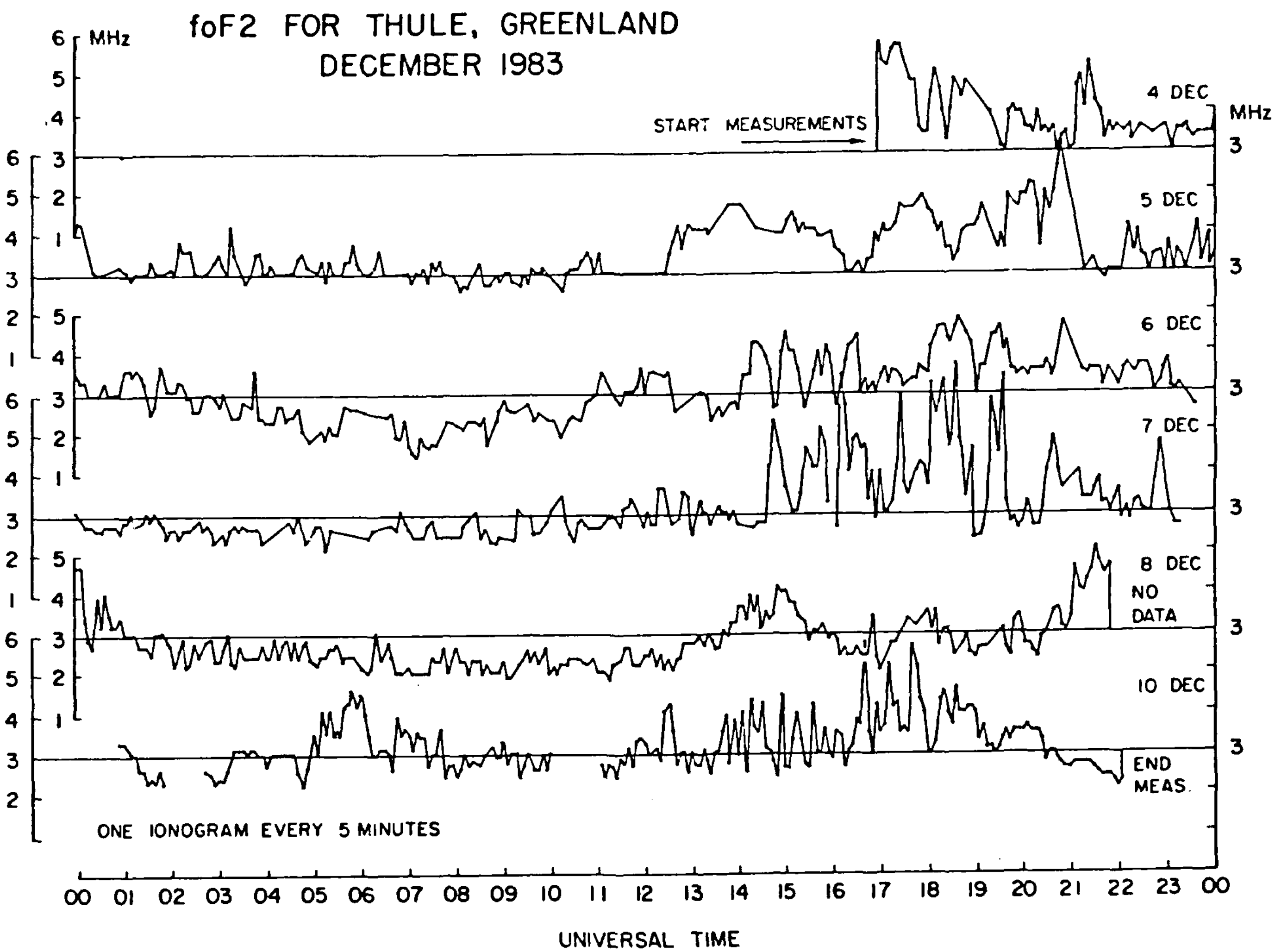

Figure 1. Observed f_oF_2 values as a function of Universal Time at Thule, Greenland from Dec 4 to Dec 10, 1983. (From Buchau et. al., 1985).

"patchiness" in the plasma observed between 1400 and 2000 UT and to answer the question "where are the patches formed?"

THEORETICAL CALCULATIONS

Calculated electron density profiles as a function of latitude, longitude and local time are found by numerically solving the time dependent ion (O^+) continuity equation given by expression (1).

$$\frac{\partial N_i}{\partial t} + \nabla \cdot (NV_i) = P_i - L_i \qquad (1)$$

Here N_i is the ion density ($=N_e$); V_i, the ion velocity; P_i, the production rate and L_i, the ion loss rate. To solve equation (1) requires transforming the independent variables from a spherical r, θ, ϕ coordinate system to one which defines directions parallel and perpendicular to B. After some rearrangement, equation (1) takes the form

$$\frac{\partial N_i}{\partial t} + \overline{V}_{i\perp} \cdot \nabla N_i = P_i - L_i - \nabla \cdot (N\overline{V}_{i\parallel}) - N_i \cdot \overline{V}_{i\perp} \qquad (2)$$

The left hand side of expression (2) gives the time-rate-of-change of ion density in a reference frame which drifts with the $V_{i\perp}$ convection velocity where $V_{i\perp} = E \times B/B^2$. A detailed description of the numerical solution of expression (2) can be found in Anderson (1973) or Moffett (1979).

We assume that ionization is produced by solar ultraviolet radiation of wavelength less than 911A and neglect the contribution by precipitating energetic electrons. Neglecting particle precipitation is justified, since flux tubes convect across the cusp at speeds of 500 to 1000 m/sec^{-1} (Heelis, 1984), and during the short time spent within the high-flux region of the cusp, the expected contribution to the resulting electron density from particle precipitation is approximately 2.4 X 10^4 cm^{-3} (Knudsen et. al., 1977). This is an order of magnitude less than the densities typically observed within the patches (3 X 10^5 cm^{-3}, or foF2 = 5 MHz). Loss of O^+ ions is through charge exchange with N_2 and O_2 where the loss rate coefficients depend on the relative velocities between ions and neutrals. Plasma transport is due to ambipolar diffusion, neutral winds and convection E X B drift velocities. Various input parameters must be specified in order to solve equation 2. These models are now described briefly.

1. Neutral atmospheric densities of N_2, O_2 and O and the neutral temperature, T_n, as a function of altitude, latitude and local time are obtained from the MSIS neutral atmosphere model. (Hedin et al., 1977). An F10.7 cm flux value of 120 is chosen to represent a moderate solar active period and an A_p value of 10 represents quiet conditions in January.

2. For production by solar ultraviolet radiation, the photoionization coefficient at the top of the atmosphere, P_∞ is chosen to be 5 X 10^{-7} sec $^{-1}$. Plasma diffusion rates are similar to those used by Buchau et al (1985) and the loss rates due to charge exchange with N_2 and O_2 are taken from Torr and Torr (1979). The appropriate volume rate coefficients are dependent on effective ion temperatures which depend on the relative motion between ions and neutrals.

3. Horizontal $\overline{E} \times \overline{B}$ convection velocities are obtained from the Heelis (1984) model. The model specifies the geomagnetic coordinates (latitude and local time) where the plasma drifts to after a specified Δt. If $\Delta t < 0$ then the model specifies where the plasma came from Δt seconds earlier. Input parameters to the Heelis model include the crosstail potential, the width of the "throat" region, its angular displacement relative to the noon-midnight direction and other parameters specifying the fall-off of potential with latitude on the day and night side.

4. For this particular study, neutral wind velocities are assumed to be zero since they are of secondary importance in actually creating the "patches". In reality, however, they will have a moderating effect on calculated ion and electron density values.

Plasma which crosses over Thule at a specified geomagnetic local time is assumed to originate six hours earlier in elapsed time. The initial location in geomagnetic coordinates is found by tracing backwards along the trajectory established (by Heelis) for a given set of input parameters. After each time step (300 sec), the appropriate geographic coordinates and solar local time are calculated corresponding to the established geomagnetic coordinates and geomagnetic local time. Initial locations are found for trajectories which pass over Thule (six hours later) at hourly intervals between 0800 and 2100 CGLT. The calculations are begun at these initial locations.

RESULTS AND DISCUSSION

Two convection patterns were chosen for this study. The basic differences between the two are characterized by the radius of the polar cap region and the magnitude of the crosstail potential. For both, the throat region is aligned in the noon-midnight direction. One pattern possesses a crosstail potential of 80KV and a polar cap radius of 12° while the other is represented by a 100KV crosstail potential and a 15° polar cap radius.

Figure 2 plots, in corrected geomagnetic latitude and lo l time, the trajectories of the plasma which cross Thule at 1400 CGLT for each pattern. When the 80KV pattern is assumed plasma comes from later local times and from latitudes of 70° or higher. In contrast, when the 100KV, 15° radius pattern is assumed, plasma originates from earlier local times and at lower latitudes in the subcusp region. The time between points on each trajectory represents one half hour elapsed time.

From the standpoint of plasma production by solar radiation, however, the important coordinate system is geographic latitude and local solar time. Figure 3 replots the trajectories pictured in Figure 2 in this coordinate system. The solar terminator for January 1 is also drawn in the figure to make it easier to see which parts of the trajectory enter the sunlit region. The 80Kv, 12° radius trajectory remains essentially in darkness the entire time, barely approaching the terminator before crossing over Thule. The 100KV, 15° radius path, on the other hand, spends more than five hours in the sunlit region before reaching Thule. This is due to the fact that at the longitude of Thule (and west) a lower geographic latitude is reached for a given geomagnetic latitude. For longitudes east of Thule at later local times, a given geomagnetic latitude corresponds to higher and higher geographic latitudes.

We now calulate electron density profiles as a function time by solving equation (2) numerically beginning six hours before the plasma reaches Thule. Figure 4 plots calculated NMAX values at Thule as a function of magnetic local time for the two assumed convection patterns. It is emphasized that this is not the density variation along the path traced out by the convecting plasma, but is rather the calculated density when the plasma reaches Thule at these various magnetic local times having traveled along different trajectories.

The solid-lined curve gives the local time variation of NMAX for the 80KV, 12° radius convection pattern and demonstrates that calculated densities in the neighborhood of 1 X 10^5 el/cm^3 are obtained between 1200 and 1900 magnetic local time. Between 1900 and 2200 CGLT, plasma crossing Thule has entered the sunlit region for a brief time. Before 1100 and after 2300 CGLT, plasma densities all fall below 2 X 10^4 el/cm^3 indicating that the convection paths remain totally in darkness. If ionization production by precipitating energetic electrons had been included, NMAX values would have been maintained above 5 X 10^4 el/cm^3 (Buchau et al, 1985) during this time.

In contrast, calculated NMAX values given by the dashed-line curve for the 100KV, 15° radius pattern reach a maximum value of 5 X 10^5 el/cm^3 between 1500 and 1900 CGLT and remain above 1 X 10^5 el/cm^3 from 1100 to 2200 magnetic local time. These trajectories remain in the sunlit region a significant amount of time which accounts for the larger density values. In fact, the difference between the two trajectories is most sensitive to the polar cap radius. An 80KV, 13° radius trajectory is very similar to the 12° radius path, while the 14° radius trajectory is very similar to the 15° radius pattern. If the calculated density at Thule is so sensitive to the polar cap radius, what is the effect on NMAX of incorporating a time varying convection pattern, one that is more realistic than the steady-state pattern? Specifically, we want to answer the question can "patches" of enhanced ionization be formed by a time-varying convection pattern?

We have calculated values of NMAX at Thule as a function of magnetic local time from 1100 to 2300 CGLT where the convection pattern is initially assumed to be the 80KV, 12° radius pattern. At 1700 UT (1430 CGLT at Thule) the convection model is suddenly switched to the 100KV, 15° radius pattern and maintained for two hours until 1900 UT at which time it is switched back to the original one. In the second case, the convection pattern is changed for one hour from 1700 to 1800 UT. Figure 5 displays the resulting calculated NMAX values at Thule for the two cases. When the 100KV, 15° radius pattern is maintained for two hours, the change in NMAX is given by the solid-lined curve and when the pattern is maintained for one hour, the change is denoted by the dotted-lined curve. For both cases, the change in NMAX beginning at 1430 CGLT is dramatic. Within 15 minutes the density increases from 7 X 10^4 to 5 X 10^5 el/cm^3. Keeping the 100KV connection pattern "on" for two hours causes the ionization patch to last about one hour at Thule before decreasing to the density value characteristic of the 80Kv pattern at 1700 CGLT. When convection is changed for only one hour, a "spike" in NMAX occurs between 1430 and 1530 magnetic local time.

The density enhancement at Thule responds very quickly to the change in the convection pattern primarily because the convection velocity is so high. As shown in Figure 3, it takes plasma only 1/2 hour to travel from 60° geog. latitude to Thule (76° geog. lat.) when the crosstail potential is

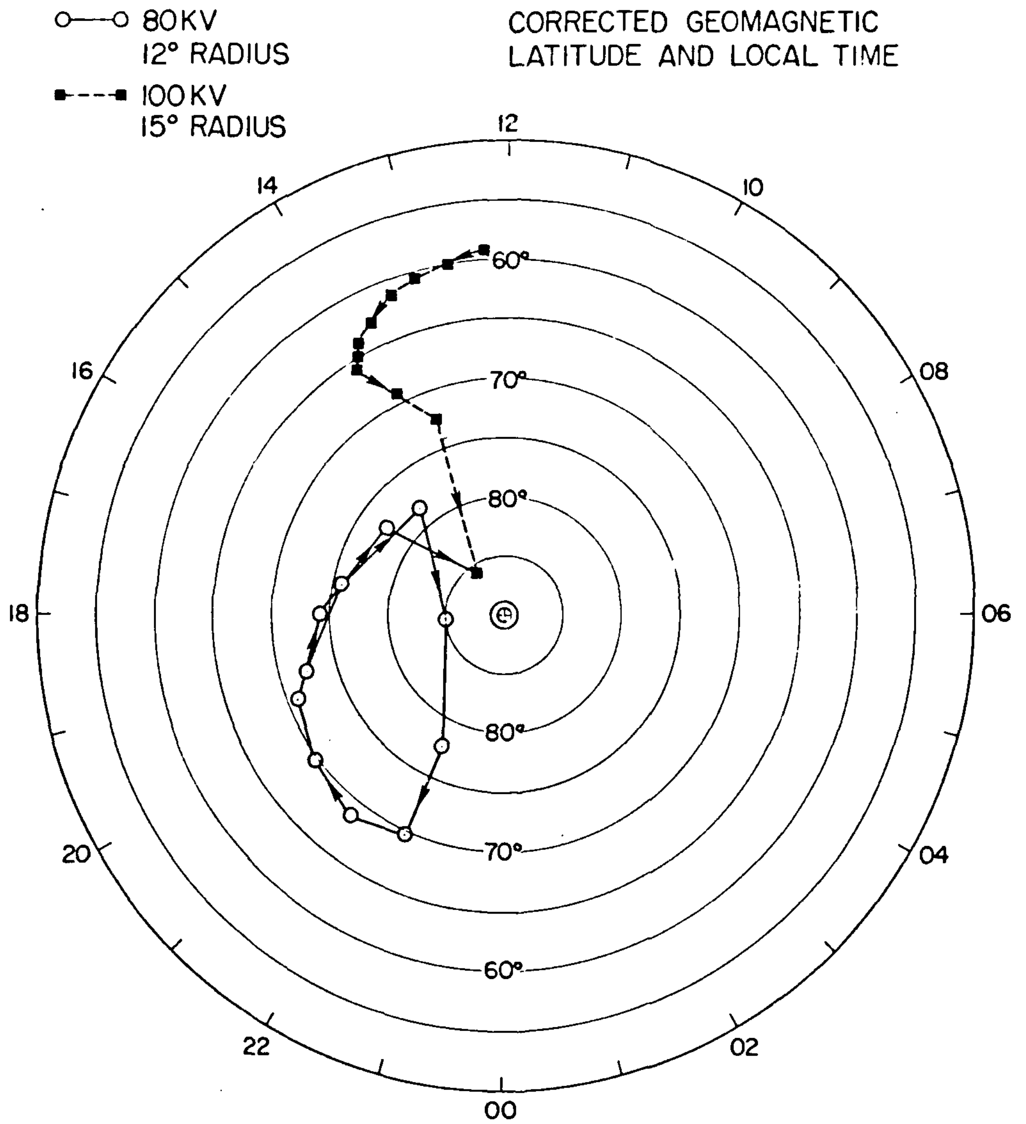

Figure 2. Plasma trajectories in a corrected geomagnetic latitude and local time coordinate system for two Heelis convection patterns characterized by respective crosstail potential and polar cap radius values of 80KV, 12° and 100KV, 15°.

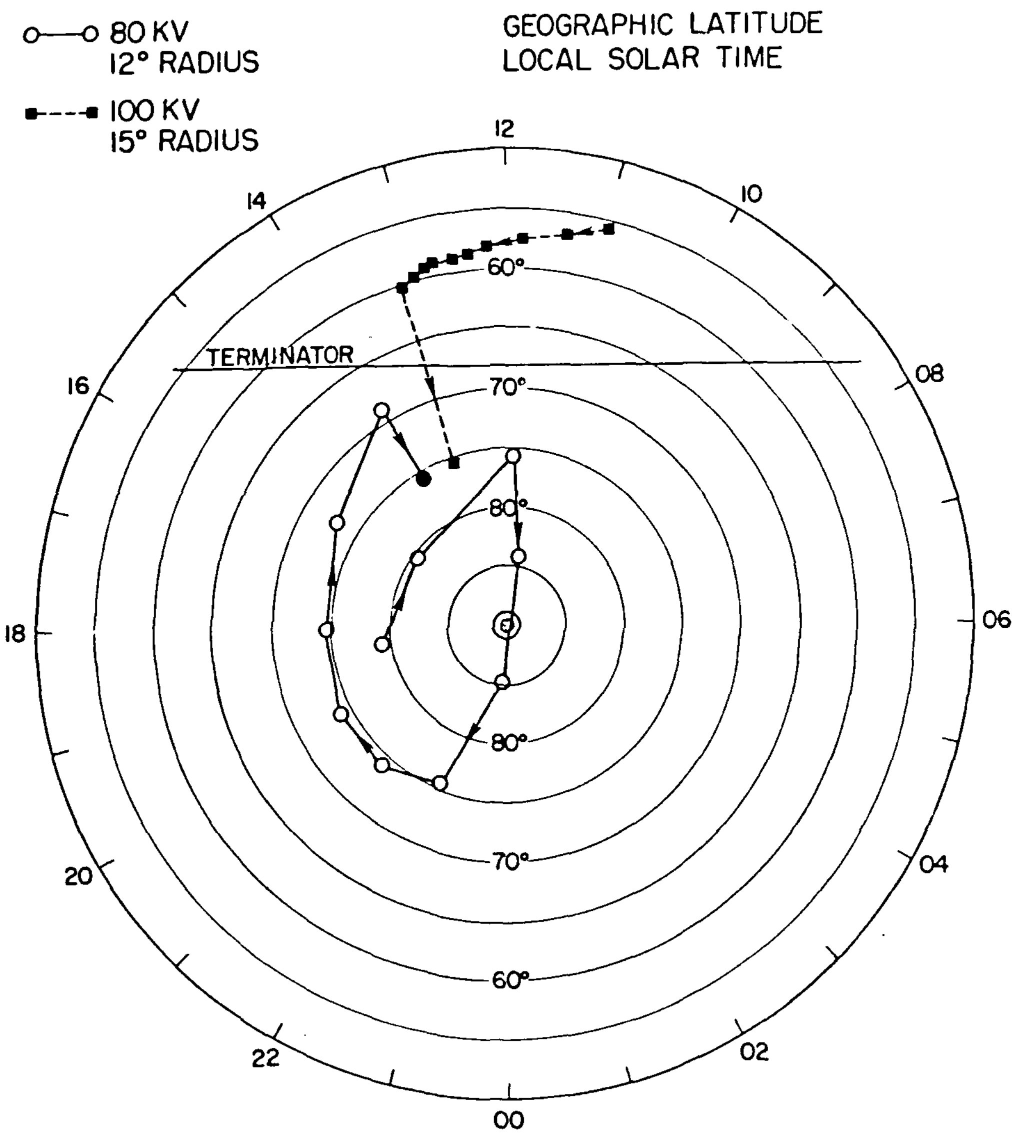

Figure 3. Same as Figure 2 except in a geographic latitude, local solar time coordinate system. The time between the points on each curve represent 1/2 hour elapsed time.

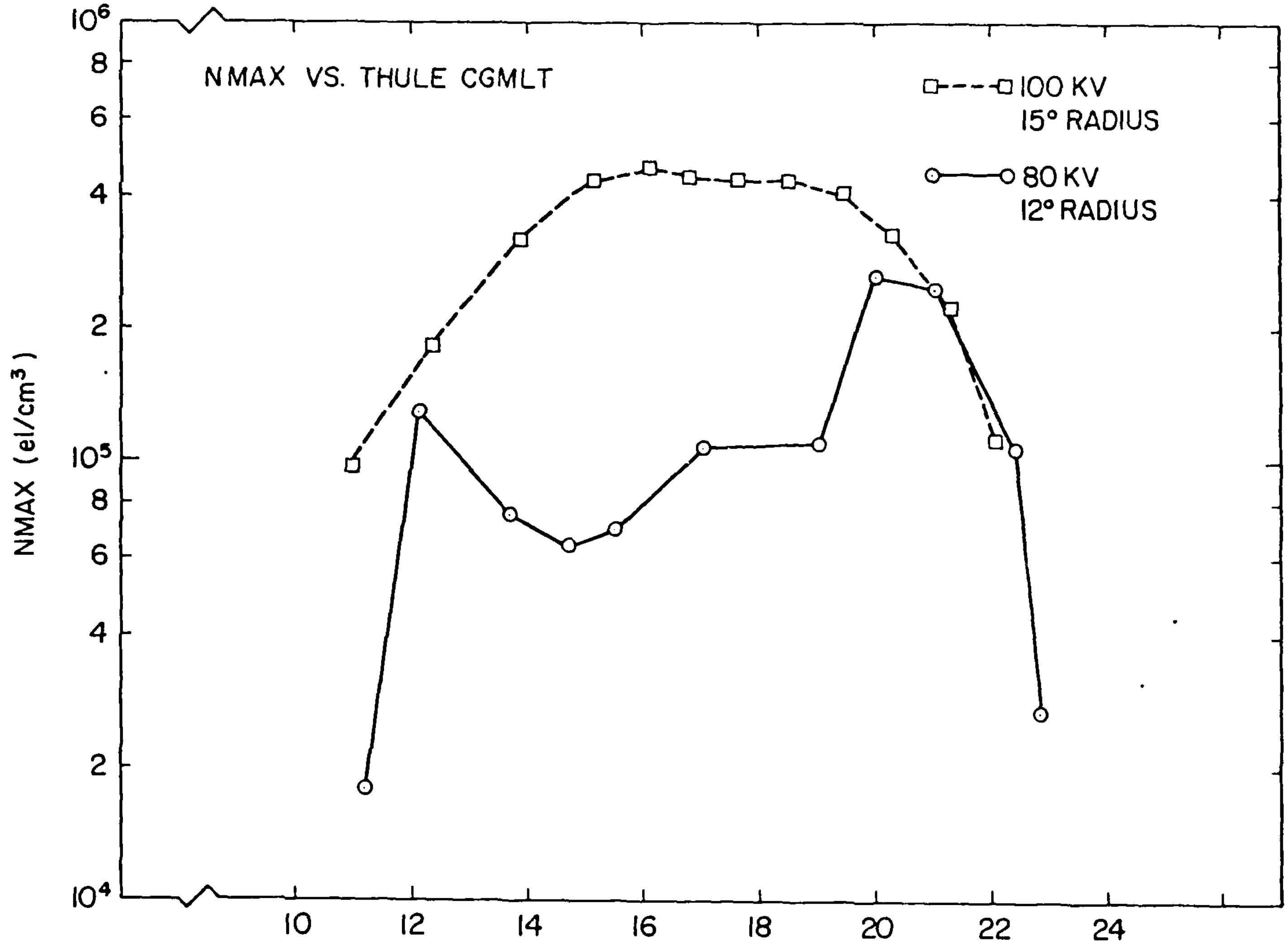

Figure 4. Calculated NMAX values at Thule as a function of corrected geomagnetic local time for the two convection patterns. The solid-lined curve represents the 80KV, 12° radius and the dashed-lined curve, the 100KV, 15° radius pattern.

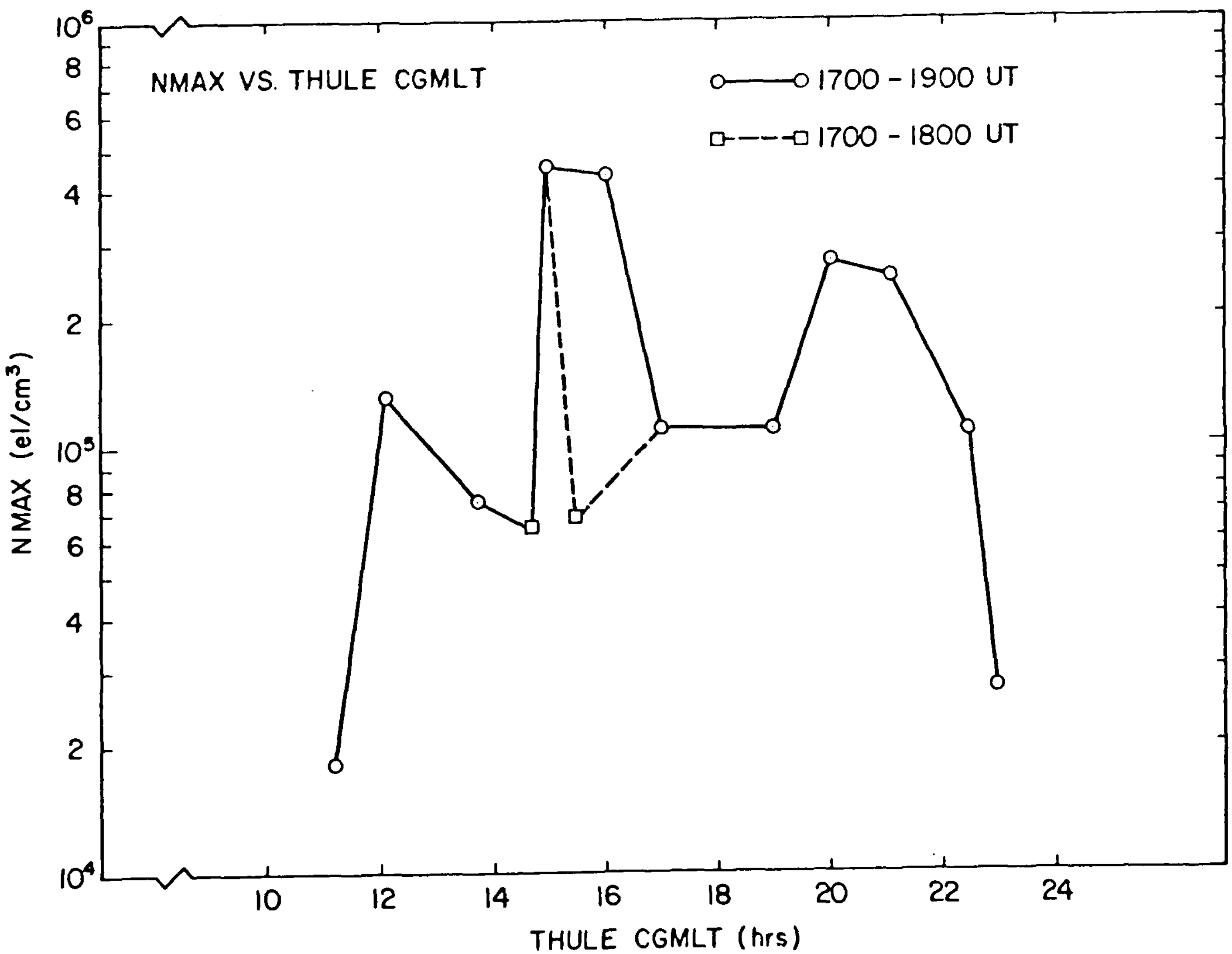

Figure 5. Calculated NMAX values at Thule as a function of corrected geomagnetic local time for a time-varying convection pattern. At 1700UT, convection model was changed from 80KV, 12^{0} to 100KV, 15^{0} and maintained for either two hours or one hour (see text for details).

100kV. This is equivilent to a convection velocity of 900 m/sec. It appears, therefore, that a viable candidate for creating and orginizing polar cap patches is a time-varying convection pattern. The patch is formed simply by allowing plasma, normally found in the sunlit, sub-cusp region, access to the polar cap region for short periods of time. The most sensitive convection parameter which permits this transition to occur appears to be the polar cap radius. The angle the "throat" makes with the noon-midnight direction does not seem to be a critical parameter. It has also been demonstrated that the longer the convection pattern change has been turned "on", the larger the patch region becomes and the longer it takes to convect over a given location in the polar cap. Ionization patches which are more "spikey" in nature seem to represent a more rapid time-variation in the convection pattern.

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