MAGNETOSPHERIC CONVECTION

AND THE HIGH LATITUDE F_2 IONOSPHERE

By

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ABSTRACT

Behavior of the polar ionospheric F-layer as it is convected through the cleft, over the polar cap and through the night side F-layer trough zone is investigated. Passage through the cleft adds of the order of 2×10^5 ions cm^{-3} in the vicinity of the F_2 peak and redistributes the ionization above approximately 400 km altitude to conform with an increased electron temperature. The redistribution of ionization above 400 km altitude forms the "averaged" Plasma ring seen at 1000 km altitude. The F-layer is also raised of the order of 20 km in altitude by the convection electric field. The time required for passage across the polar cap (25^o) is about the same as that required for the F-layer peak concentration to decay by e. The F-layer response to passage through the night side soft electron precipitation zone should be similar to but less than its response to passage through the cleft. The exception is that the layer will be lowered in altitude by the convection electric field. After leaving the night soft electron precipitation zone, the layer decays, primarily by chemical recombination, as it convects equatorward and around the dawn side of the earth. In the absence of ionization sources, decay by factors of the order of 10^2 to 10^3 could occur prior to entry into the sunlit hemisphere, thus forming the F-layer night trough.

INTRODUCTION

In an early study of the winter Arctic ionosphere Sato (1959) recognized in f_oF_2 contours the existence of a "tongue" of ionospheric plasma at F_2 peak heights extending from the dayside toward the night side ionosphere and suggested that ionospheric plasma was being driven across the polar caps by an electric field spread over the cap. In a later study of the winter Antarctic ionosphere Sato and Rourke (1964) noted some similarity between the current systems implied by magnetic variations and the f_oF_2 "tongue" distribution patterns and attempted to establish that the electric field responsible for the drift arose in the E-layer.

The principal objection to the suggestion that the "tongue" was formed by convection was that the convection velocity, then thought to be of the order of 0.1 km/sec, was too slow. At 0.1 km/sec the F-layer would decay in crossing the cap (cf Rishbeth, 1970).

More recently, electron concentration data obtained over the poles by satellite measurement at approximately 1000 km altitude has established the existence of a plasma ring or zone in which electron concentration enhancements frequently occur. The ring is poleward of the plasmapause, approximately coincident with the auroral oval, and presumably produced by precipitation of a component of the particles responsible for the auroral oval defined by all sky camera results (Thomas and Andrews, 1969; Sato and Colin, 1969; Pike, 1971a, b). Thomas and Andrews (1969) have suggested that the tongue of ionization observed by Sato (1959) and Sato and Rourke (1964) was basically the ring pattern made difficult to discern by scarcity of high latitude stations and perhaps by the solar cycle epoch difference.

The evidence for rapid antisunward convection of plasma across the geomagnetic poles at F_2 heights in response to the dawn to dusk magnetospheric electric field is now sufficiently conclusive that its existence is inescapable. The purpose of this study is to examine some of the implications of this convection for the high latitude ionospheric concentration and to attempt to reconcile some observations with the existence of both a strong antisunward convection and a ring of precipitating energetic particles.

A polar ionospheric convection pattern will first be suggested followed by semi-quantitative analysis of the expected changes in the F-layer ionosphere as it is convected from the dayside of the earth across the cleft, polar cap, night side auroral zone, into the F-layer nightside trough and back to the day side. The expected behavior of the

F-layer will then be compared with the observed behavior. Attention will be focussed on the F-layer behavior above about 200 km and below the altitude at which O^+ ceases to be the predominant ion. In the polar region this latter boundary is generally well above 1000 km.

F_2 Region Magnetospheric Convection

The dawn to dusk magnetospheric electric field when mapped down field lines to the polar regions by assuming the lines to be equipotentials produces convection of the F-layer ionospheric plasma shown schematically in Figure 1 (Axford, 1969; Maynard, 1972; Frank and Ackerson, 1972; Kavanagh et al., 1968). Above approximately 200 km altitude, the plasma may be considered attached to the magnetic field lines and these have a magnetospheric circulation pattern which maps at ionospheric altitudes into the two unequal convection cells illustrated when viewed from a non rotating magnetospheric coordinate system. Field lines originating at the cleft latitude ($\sim 76° \Lambda$) on the dayside of the earth connect with the solar wind magnetic field, convect over the magnetic poles to the tail of the magnetosphere, reconnect in the tail and then convect sunward as closed field lines within the magnetosphere until reaching the dayside magnetopause, and then repeat the process.

The precise convection pattern is unknown and a current topic of great interest. The pattern given in Figure 1 is presented as a necessary part of a general description of the polar F-layer behavior. The pattern may be in error in detail even as a "time average" pattern but it is generally consistent with current data as the steady non-substorm convection pattern.

The zone between the plasmapause and the equatorward boundary of the soft electron precipitation zone is that in which closed field tubes are convecting sunward after reconnection. The convection paths are those derived for the equatorial plane by Kavanagh et al., (1968) but which are mapped on a polar diagram. Time between dots, applicable only to the region equatorward of the closed field line boundary, is 1 hr. The most equatorward flow line shown is essentially the boundary between tubes which convect to the magnetopause and connect with the interplanetary magnetic field and those which do not. It is, therefore, the plasmapause except near the stagnation point (Nishida, 1966; Chappell, 1972). Equatorward of the plasmapause the field tubes circulate around Figure 1 counter clockwise at essentially co-rotation velocity except in the vicinity of the stagnation point. On the dawn side of the earth just poleward of the plasmapause the convection is only slightly faster than co-rotation with the earth. On the dusk side, the field tubes are essentially stationary near the stagnation point, and convect sunward poleward of the stagnation point.

In the immediate vicinity of the limit of closed field lines, the convection velocity is observed to be typically of the order of 1 km/sec and in the direction shown (Gurnett and Frank, 1973; Maynard, 1972).

The paths taken by the field tubes after connection with the inter planetary magnetic field is not known in detail either from theory or measurement. In Figure 1 I have simply connected the flow lines of closed field tubes across the cap with a suggestion of divergence around the pole. The electric field measurements of Gurnett and Frank (1973), Cauffman and Gurnett (1971), and Maynard (1972) suggest that the flow may be typically faster near the boundary of closed field lines (1 km/sec) and slower interior to the boundary (0.5 km/sec). On occasion the flow velocity is apparently uniform across the entire cap and may rise to 3 km/sec.

The boundary of closed field lines as defined by trapping of > 45 KeV electrons is evidently the boundary for reversal of the convection direction from sunward to antisunward and is also the equatorward boundary of the soft electron precipitation zone (Gurnett and Frank, 1973). Pike (1971b) has established the general coincidence of the plasma ring, polar F-layer irregularity zone, and zone of soft electron precipitation. Hence, the boundary of closed field lines is also the equatorward boundary of the plasma ring and polar F-layer irregularity zone.

The soft electron precipitation zone and character of the electron precipitation therein is reviewed by Paulikas (1971), Frank and Ackerson (1972), and Eather and Mende (1972).

DYNAMIC NATURE OF THE POLAR IONOSPHERE

Convection Through the Cleft

The convection velocity in the vicinity of the boundary of closed field lines is typically 1 km/sec as stated above. We have assumed that ionospheric plasma in the vicinity of the soft electron precipitation zone will be transported across the zone with the same velocity. The plasma velocity vector may not be "normal" to the boundary at all local times but it seems reasonable that it will be approximately so near local noon and midnight.

Convection transports F-layer plasma into and out of regions of ion production sufficiently rapidly that the conventional concept of a near-diffusive and thermal steady state F-layer appropriate to the mid-latitude ionosphere is misleading. The characteristic time required for establishment of a diffusive equilibrium F-layer peak at 280 km altitude is long compared with the time the plasma is within the cleft. On the other hand the electron temperature will be able to respond to the time varying electron heating rate and maintain an approximate conductive steady state as the cleft is traversed. The time constants required to establish these facts are evaluated and compared in the following discussion and a semi quantitative description of the F-layer as it convects through the cleft and over the cap is presented.

The time τ_c required for a field tube and the plasma contained therein to cross the cleft, which is typically 3^o wide, is

$$\tau_c \sim \frac{300 \text{ km}}{1 \text{ km/sec}} \qquad (1)$$

$$\sim 300 \text{ sec}$$

$$\sim 5 \text{ min.}$$

The time τ_d required for diffusive equilibrium to be established near the F_2 peak is

$$\tau_d \sim \frac{H^2}{D} \frac{T_e + T_i}{T_n} \qquad (2)$$

$$\sim 4.5 \times 10^3 \text{ sec}$$

$$\sim 75 \text{ min}$$

where the diffusion coefficient D has been evaluated at 280 km altitude; T_e, T_i, and T_n are the electron, ion and neutral temperatures respectively; and the scale height H is that of atomic oxygen at 1000°K (cf Whitten and Poppoff, 1971). Thus, the ionization added to the field tube at F-layer peak heights as the tube crosses the cleft will not have time during the passage to diffuse away from the altitude of production. The effect of particle precipitation on the F-layer at F peak altitudes as it crosses the cleft is to add a "blob" of ionization to the profile convected into the cleft.

The increase of electron concentration $\Delta N_m F_2$ with time at the F-layer peak as a tube crosses the cleft may be approximated by

$$\Delta N_m F_2 \simeq \frac{\bar{p}}{\beta} (1-e^{-\beta t}) \qquad (3)$$

where β is the electron loss coefficient and $\bar{p}$ is the space average production rate due to cleft particle precipitation. Since at the F-layer peak

$$\tau_d \sim \frac{1}{\beta} \qquad (4)$$

and, as we have seen

$$\tau_c \ll \tau_d \quad ,$$

the value of $\Delta N_m F_2$ at the poleward edge of the cleft will be given by

$$\Delta N_m F_2 \simeq \bar{p}\tau_c \quad . \tag{5}$$

We may estimate $\bar{p}$ as follows. Heikkila and Winningham (1971) have reported the typical cleft energy flux as a few tenths erg cm^{-2} sec^{-1} $ster^{-1}$. Eather and Mende (1972) have inferred it to be 0.1 erg cm^{-2} sec^{-1} $ster^{-1}$ from air-glow observations. The cleft energy spectrum is typically peaked at an energy of the order of 100 eV (Heikkila and Winningham, 1971), and the ionization which it produces is centered in the vicinity of the F_2 peak (Rees, 1964). If we take as an average value for the energy flux $\sim$ 0.2 erg cm^{-2} sec^{-1} $ster^{-1}$ and assume that 35 eV per ion pair is absorbed throughout an altitude interval of 150 km, the increase in $N_m F_2$ as it crosses the cleft becomes

$$\Delta N_m F_2 \simeq \bar{p}\,\tau_c$$

$$\simeq 2 \times 10^5 \, cm^{-3} \quad .$$

Although the ionization added to the convecting field tube in the vicinity of 300 km altitude is unable to respond diffusively during passage through the cleft, the electron temperature within the tube is able to respond to heating by precipitating cleft electrons and heat conduction down the cleft and will maintain an approximate conductive steady state. The time constant τ_t for establishment of a conductive steady state is

$$\tau_t \simeq \frac{\text{Electron Heat Capacity} \times (\Delta T/e)}{\text{Heat Conductivity} \times (\Delta T/\Delta L)} \qquad (6)$$

$$\simeq \frac{N_m F_2 \times H_p^2 \times \frac{3}{2} k}{K_e \cdot e}$$

$$\simeq 40 \text{ sec}$$

$$\simeq 1 \text{ min.}$$

where $N_m F_2$ is the F_2 peak electron concentration taken to be $5 \times 10^5 \text{cm}^{-3}$, H_p is the plasma scale height taken to be 240 km, K_e is the electron heat conductivity for an electron temperature of 3000°K and e is the base of the natural logarithms. The heat capacity of the ions was neglected in this computation because the heat input to the thermal electrons will be removed predominantly by heat conduction to lower altitudes rather than by transfer to the ions. The electron thermal time constant is smaller than the time required for convection across the cleft and we may expect a conductive steady state to be approximately maintained.

Some time lag in electron temperature rise does exist so that the largest electron temperatures will tend to occur on the poleward edge of regions of uniform heat input. The plasma will convect approximately 1/2° in latitude in a time τ_t so that the electron temperature "latitudinal" variation will be displaced poleward of the latitudinal heat input variation.

Studies of electron concentration at 1000 km altitude at polar latitudes have established that concentration enhancements frequently occur at or near the cleft latitude during magnetic local daytime and presumably are produced by the cleft particles directly or indirectly (Thomas and Andrews, 1969; Sato and Colin, 1969). We have argued earlier that diffusion from 300 km altitude where production of ionization by cleft particles is greatest is too slow for this ionization to be distributed by diffusion and produce an enhancement at 1000 km altitude. In the following paragraphs we estimate the possible increase in electron concentration at 1000 km altitude produced by an increase in electron temperature as a tube of ionization enters and crosses the cleft. Above an altitude of approximately 400 km, ambipolar diffusion is sufficiently fast for the ionization above that altitude to diffuse upward in response to the increased electron temperature and produce an increase in electron concentration at 1000 km. The increase in concentration at 1000 km results both from redistribution of ionization present before the tube enters the cleft and also from the additional ionization produced in the vicinity of 400 km altitude. The latter becomes significant whenever $\Delta N_m F_2/N_m F_2$ approaches or exceeds one.

The time constant for diffusive equilibrium may be written as

$$\tau_d(h) = \tau_d(280 \text{ km})\, e^{-\frac{h-280 \text{ Km}}{53 \text{ Km}}} \qquad (7)$$

where h is the altitude in km and the neutral scale height is 53 km (Rishbeth and Garriot, 1969). At and above an altitude of approximately 400 km τ_d will be less than or equal to τ_c and significant redistribution of the plasma above this altitude can occur in response to the increase in electron temperature as the plasma passes through the cleft.

We desire to estimate the ratio of electron concentration at 1000 km altitude at the poleward edge of the cleft to that at 1000 km just prior to passage into the cleft. The ratio is

$$\frac{N^*(1000)}{N(1000)} \doteq \frac{N^*(400)\, e^{-\frac{600\ \text{km}}{H_p^*}}}{N(400)\, e^{-\frac{600\ \text{km}}{H_p}}} \tag{8}$$

where the asterisk refers to the heated electron gas condition at the poleward edge of the cleft, $N(h)$ is the electron concentration at altitude h in km, and the other symbols have been defined previously. The ionosphere prior to cleft entry is assumed to be in diffusive equilibrium above the F_2 peak altitude which we shall take to be 280 km. Consequently,

$$N(400) \doteq N_mF_2\, e^{-\frac{120\ \text{km}}{H_p}} . \tag{9}$$

The total electron content above 400 km after passage through the cleft will be that which entered, $H_p\, N(400)$, plus the additional ionization from cleft energetic particles. The latter should be approximately proportional to the neutral concentration above 400 km altitude. We have, therefore, that

$$H_p^*\, N^*(400) \doteq H_pN(400) + H_n\, \overline{p}(400)\, \tau_c \tag{10}$$

Using the relationships (5) and (9), we obtain

$$\frac{N^*(400)}{N(400)} \doteq \frac{H_p}{H_p^*}\left(1 + \frac{\Delta N_mF_2}{N_mF_2}\,\frac{\bar{p}(400)}{\bar{p}(280)}\,e^{\frac{120\ Km}{H_p}}\right)$$

$$\doteq e^{600\ km\,\frac{H_p^* - H_p}{H_p^*\,H_p}} \bullet \frac{H_p}{H_p^*}\left[1 + \frac{H_n}{H_p}\,\frac{\Delta N_mF_2}{N_mF_2}\,\frac{\bar{p}(400)}{\bar{p}(280)}\,e^{\frac{120\ Km}{H_p}}\right] \qquad (11)$$

The ratio $\bar{p}(400)/\bar{p}(280)$ will depend on the energy spectrum of the cleft electrons and should be less than one except for a very soft spectrum. By taking

$$\frac{H_n}{H_p}\,e^{\frac{120\ km}{H_p}}\,\frac{\bar{p}(400)}{\bar{p}(280)} \leq 1$$

we obtain

$$\frac{N^*(1000)}{N(1000)} \simeq e^{600\ km\,\frac{H_p^* - H_p}{H_p^*\,H_p}}\,\frac{H_p}{H_p^*}\left[1 + \frac{\Delta N_mF_2}{N_mF_2}\right] \qquad (12)$$

The term $\Delta N_mF_2/N_mF_2$ represents the contribution to the enhancement at 1000 km altitude of ionization produced by the cleft particles. Three possible cases are computed in Table I. Case 1 illustrates that a large increase in concentration at 1000 km altitude is possible from redistribution of ionization alone without any cleft particle production. Case 3 is likely to be the more representative case.

TABLE I

Case	T_e ($^\circ$K)	T_i ($^\circ$K)	N_mF_2 (cm^{-3})	ΔN_mF_2 (cm^{-3})	T_e^* ($^\circ$K)	T_i^* ($^\circ$K)	$\frac{N^*(1000)}{N(1000)}$
1	1000	1000	1×10^5	0	6000	2000	17
2	1000	1000	1×10^5	2×10^5	6000	2000	52
3	2000	1250	5×10^5	2×10^5	4000	1500	3.5

The largest electron concentration at 1000 km altitude may be expected toward the poleward edge of a cleft with uniform electron heating rate across it. The electron temperature will have achieved its largest value and the plasma will have had the longest time to diffuse upward in response to the increased electron temperature.

The dawn to dusk magnetospheric electric field at the local noon dayside cleft will impart a vertical drift to the plasma in the F-layer of amount

$$w = u_i \cos I$$

where w is the vertical drift velocity, u_i the ion velocity ($\bar{E} \times \bar{B}/B^2$) and I the magnetic dip. This electric-field-induced vertical drift will not have been cancelled by an ion-drag-induced horizontal wind of amount $u_i \csc I$ since the time constant for acceleration to this velocity is of the order of an hour (Rishbeth and Garriott, 1969). We expect a poleward directed neutral wind u_n at the cleft of 200-300 m/sec produced by solar heating (Challinor, 1970) which will impart a negative vertical drift. The resultant will be

$$\begin{aligned} w &= (u_i - u_n) \cos I \\ &\simeq 60 \text{ m/sec} \end{aligned} \quad (13)$$

In crossing the cleft, the F-layer will be raised

$$\begin{aligned} \Delta h &\simeq 60 \text{ m/sec} \cdot 300 \text{ sec} \\ &\simeq 18 \text{ km.} \end{aligned} \quad (14)$$

Only the F-layer entering the cleft will be raised this amount. The amount the cleft-produced ionization is raised will depend on where within the cleft latitude interval it is produced. In traveling to the magnetic pole the F-layer will be raised

$$\Delta h \simeq \frac{60}{2} \frac{\text{m}}{\text{sec}} \cdot 1 \times 10^3 \text{ sec}$$

$$\simeq 30 \text{ km}$$

where we have taken an average value for the cos I. As the plasma continues convecting over the cap on the night side, the difference in velocity between the neutral wind and plasma should decrease so that the layer will drop less than it is raised. The overall effect will be to raise the layer and, as a consequence, reduce the loss rate. The amount the F-layer is raised could be more than that indicated above by a factor of 3-5 during a substorm when the plasma velocities are greater than 1 km/sec and the cleft is at a lower latitude.

King et al. (1968, 1971) have attempted to explain high latitude ionospheric behavior in terms of vertical drift induced by solar-produced neutral winds. For stations within and poleward of the auroral oval, their conclusions must be re-examined, because the vertical drift induced by the convection electric field is larger and oppositely directed to that induced by the solar-produced wind field.

The change expected in the sunlit cleft F-layer as the plasma convects from just south of the cleft to the northern boundary is summarized qualitatively in Figure 2. Ionization is added to the F_2 peak in the vicinity of 300 km and the electron concentration at 1000 km altitude is increased by redistribution of ionization above approximately 400 km altitude. The decrease in concentration just above 400 km altitude shown in Figure 2 results from assuming for this example that no significant ionization is produced above 400 km altitude by particle precipitation.

Convection Over the Cap

After the plasma passes northward out of the cleft zone of particle precipitation, the heat input to electrons ceases - at least that from cleft soft electrons - and the electron temperature should drop back to an ambient value with time constant τ_t. This time corresponds to a convection distance of about $1/2^\circ$ in latitude. Thus, within about 1° of the northern cleft boundary defined by particle precipitation, the high electron temperature may be expected to decay and the plasma will diffuse back down the field line consistent with the reduced plasma scale height. Again, this redistribution of the plasma will be limited to altitudes above 400 km since only the time τ_t has elapsed.

As the plasma profile is convected on across the polar cap, the electron concentration bulge in the vicinity of 300 km altitude will decay with a time constant somewhat shorter than τ_d ($\simeq \beta^{-1}$) toward a level consistent with the local ion production rate. Diffusion of the concentration bulge and also loss of H^+ ions out of the open field tubes will tend to cause the decay time of N_mF_2 to be somewhat smaller than τ_d. At 0.5 - 1 km/sec the plasma will convect through about 27° of latitude which is the width of the polar cap in the time τ_d. We would expect in the winter hemisphere, therefore, that the electron concentration just poleward of the auroral oval on the night side of the polar cap will be reduced from that on the day side by a factor of the order of e.

Fedder and Banks (1972) have computed the temperature rise of ions at 300 km altitude resulting from a step function increase in electric field. Ions convecting into the cleft and on across the cap may experience a similar temperature rise. The ion temperature rise is not significant for our considerations however, for it is small ($\sim 300^{o}K$) compared to that expected for the electrons.

Convection Through the Nightside Precipitation Zones

After crossing the polar cap, in which little precipitation of particles occurs, the plasma will enter the low energy electron precipitation zone on the night side, be convected to and across the boundary of closed field lines and, then, convected sunward at a latitude below the boundary of closed field lines. The response of the plasma in crossing the night side low energy electron precipitation zone and the harder precipitation zone equatorward of the closed field line boundary will be, in a general way, similar to that described above for passage through the day side. We may expect some enhancement of concentration in the vicinity of 300 km and an increase in electron temperature with subsequent increase in scale height above about 400 km. However, the picture is more complicated for the night passage. The energy spectrum in the soft zone evidently hardens in the local evening and night sectors (Frank and Ackerson, 1972; Burch, 1970) which implies ion production at a lower altitude than that on the day side. The lifetime at low altitude will be correspondingly shorter, and the plasma will "slip" behind the field lines. In the hard or plasma sheet electron precipitation zone most of the energy will be deposited at still lower altitude in the E region. The convection paths are also more complicated in the night sector as inferred from electric field measurements and barium releases (Gurnett and Frank, 1973; Maynard, 1972).

Convection Around Night Side and Return to Cleft

I suggest that after the F-layer plasma crosses the nightside precipitation zone and is convected around the night sector toward the dawn, it decays and, in doing so, forms the F-layer trough. The flow lines of Figure 1 which are just poleward of the plasmapause and which circulate around the dawn side of the earth take several hours to reach the solar illuminated morning sector. F-layer plasma convected along these paths is expected to decay from recombination by a factor of ten for every two or three hours of travel time in the absence of any ionization source. Thus, the F-layer concentration at $60°\Lambda$ and in the midnight and post midnight sectors could be reduced below that in the soft electron precipitation zone and cap by a factor of 10^2 and more.

The explanation for the low electron concentration in the F-layer trough zone as compared with the F-layer concentration equatorward of the trough is incomplete and is intimately related to the problem of maintaining the night F-layer. I suggest that the night time maintenance mechanism is absent or weak poleward of an ebb and flow boundary located at about

$60^{\circ}\Lambda$ and that the "trough" zone is simply the region between the high concentration "tongue" of ionization filling the polar cap from the dayside and the ebb and flow boundary. As the "tongue" of ionization is convected below the trapping boundary on the night side and toward the sunlit region of the earth, the F-layer decays primarily from dissociative recombination and also to some extent from polar wind loss. The ebb and flow boundary is a magnetic latitudinal boundary equatorward of which the return flow of H^+ ions from the plasmasphere at night is adequate to maintain the F-layer against dissociative recombination (Park, 1970; Nagy and Banks, 1972; Rishbeth, 1968). It is approximately at the same latitude as the plasmapause.

The field tubes convecting across the polar caps are open and are expected to lose their light ions H^+ and He^+ to the solar wind. We may expect, therefore, a rather continuous upward flux of H^+ ions at 2000 km altitude of the order of 3×10^8 cm^{-2} sec^{-1} as a field tube crosses the cap, reconnects, and convects toward the sunlit region of the earth (Park, 1970; Banks et al., 1971; Chappell, 1972). This outflow of hydrogen ions diminishes the O^+ content through charge exchange and contributes to the rate at which the F-layer decays as it convects across the cap and around the nightside of the earth.

The time constant τ_p for this process acting alone to dissipate the topside F_2 layer for an N_mF_2 of 5×10^5 cm^{-3} is

$$\tau_p \simeq \frac{N_m F_2 \; H_p}{f} \tag{15}$$

$$\simeq \frac{5 \times 10^5 \times 150 \times 10^5}{3 \times 10^8}$$

$$\simeq 2.5 \times 10^4 \text{ sec}$$

$$\simeq 7 \text{ hr.}$$

where f is the upward flux of H^+ ions. Outflow of H^+ will thus contribute to the decay of the F-layer but the normal recombination decay is dominant since it reduces the concentration to 1/e in approximately 1.5 hours.

Equatorward of the ebb and flow boundary we envision that the field tubes are emptied at sufficiently infrequent intervals that the plasmasphere H^+ concentration is sufficient for a flow of ionization back into the F-layer at night to occur (Park, 1970; Nagy and Banks, 1972). This flow will contribute to, if not provide, the maintenance of the F_2 layer.

The lowest electron concentration at the F-layer peak should occur on those field tubes for which the time interval since passing the cleft and nightside soft electron precipitation zone is the greatest and which have not been exposed to solar radiation subsequently. Those tubes which circulate on the dawn side of the earth at the lowest latitude but which have not been exposed to solar radiation as they convect toward the stagnation point on the dusk side of the earth satisfy this criteria. From a consideration of Figure 1, we would expect that the trough would tend to be centered at about 55° - $60^\circ\Lambda$ and that it would be deepest (least concentration) toward the morning side of the earth. This last conclusion follows from the fact that the F-layer should continue to decay as the field tubes flow toward the morning side of the earth after crossing the night side soft electron precipitation zone and prior to being exposed to solar radiation on the morning side. A "rotation" of the trough toward the morning side is clearly evident in F-layer data as we shall see.

The elapsed travel time of a plasma tube after it leaves the night side precipitation zone decreases rather rapidly poleward of the plasmapause at a fixed magnetic time meridian. At the 02 hr meridian of Figure 1, for example, the difference in elapsed time between the two lowest latitude paths is 12 hours and between the next two paths is about 4 hours. The paths are approximately 3^{o} apart in latitude. With the plasma decaying an order of magnitude about every three hours, we may expect the electron concentration to increase rapidly - orders of magnitude within 3^{o} - toward the pole from the position of the minimum concentration.

If the plasmapause location did not move in response to magnetic storms, we would expect a very abrupt discontinuity in F-layer electron concentration in crossing the plasmapause toward the equator. Occurrence of magnetic storms will smooth out the discontinuity, however, by removing the magnetospheric plasma on tubes normally closed (Chappell, 1972). Park (1970) and Banks et al., (1971) have established that several days are required to refill a tube at $L = 5$ once emptied and that the diurnal ebb and flow of H^{+} ions does not recommence until the concentration near the equator reaches a dynamic steady state. We may expect the time of recovery to be a strong function of L because the tube volume varies strongly with L. During a storm, for example, the plasmapause may be shifted to $50^{o}\Lambda$ and following the storm return to $65^{o}\Lambda$. Return flow of plasma to the F-layer at night at $65^{o}\Lambda$ will require some days to be reestablished but will continue uninterrupted at $50^{o}\Lambda$. In between these latitudinal limits the return flow at night will be intermediate to these two flow extremes.

The interpretation of the trough given here differs from that outlined by Nishida (1967) in that the maintenance of the polar cap ion concentration by strong convection was not recognized by Nishida. It also differs in recognition that the low concentration at night in the trough region is probably less a direct consequence of polar wind loss of plasma poleward of the ebb and flow boundary than it is an absence of the mechanism that maintains the ionosphere equatorward of the boundary.

COMPARISON WITH OBSERVATIONS

In Figure 3 electron concentration profiles reduced from topside and bottom side ionograms within and near the cleft are shown. The topside and bottomside ionograms were recorded on the ISIS II satellite and AFCRL Flying Ionospheric Observatory, respectively, during the AFCRL Airborne Auroral Expedition (Pike, 1972). The aircraft flew along the satellite track under the cleft shortly after the satellite passed over the cleft on May 28, 1971 at approximately 17:55 UT. The electron concentration profile at 74^{o} invariant latitude (Λ) is that produced by solar photons without contribution from the cleft soft electrons. The soft particle spectrometer (SPS) on ISIS II recorded the presence of cleft electrons from 74 to $77^{o}\Lambda$ (Winningham, 1973). The electron concentration profile measured for $76^{o}\Lambda$ shows an increase of electron concentration of about 4×10^{5} at an altitude of approximately 275 km. Above approximately 350 km the concentration drops back to values typical of the undisturbed ionosphere measured south of the cleft but with a somewhat greater scale height.

For comparison, two computed electron concentration profiles obtained with and without the soft electron flux from the cleft affecting the model are shown. The profiles represent steady state solutions to the continuity, momentum and energy equations governing the ionospheric plasma. The soft particle spectrum used as input for the cleft profile was that measured by the ISIS II SPS. Diffusive equilibrium exists in the computed profile and is clearly not present in the observed profile.

Further details of the modelling of the cleft ionosphere will be given in a later publication. Our interest herein is to emphasize the apparent lack of diffusive equilibrium in the absserved profiles.

The lack of diffusive equilibrium at $76°\Lambda$ in the observed profile is not the result of polar wind flow, evidently. The flow of H^+ ions into the magnetosphere can reduce the scale height of the F-layer above the F-layer peak provided the flow is sufficiently large (Holzer, 1970). However, comparison of the two experimental profiles and the diffusive equilibrium profiles suggests strongly that the bulge is the result of ionization having been added between 200 and 300 km altitude which has not diffused into an equilibrium profile. Furthermore, Alouette 2 topside ionosonde profiles from low latitude to high latitude at night show a large reduction in electron concentration at 3000 km altitude as the plasmapause is crossed, but no obvious change in the low altitude top side F-layer is evident (Nelms and Lockwood 1967). In passing from a region of no expected polar wind flow to one of expected polar wind flow no significant change in the low altitude F-layer is evident.

Although time variation in the cleft input electron energy spectrum and energy flux could produce a non-diffusive equilibrium profile, the most probable cause - or at least a contributory cause - is rapid relative motion of the cleft ion production zone and the F-layer plasma.

A large increase in concentration at high altitude toward the poleward edge of the cleft is not evident in the experimental profiles of Figure 3. An increase is evident in statistical results as we shall see.

A tongue of ionization extending from the day side toward the night side of the polar caps has been reported previously as described in the introduction. More recently Pike (1971a) has plotted in corrected geomagnetic latitude and time (Hakura, 1965) the monthly median f_oF_2 data from ionospheric stations in the Arctic for Dec. 1958 at 1800 UT. The contours are reproduced in Figure 4 with the convection pattern of Figure 1 superimposed. Since the contours are of monthly median values for the universal time of 1800, the result represents a typical condition for the Arctic polar winter during sun spot maximum. The tongue of ionization transported across the polar cap from the dayside by the magnetospheric electric field is clearly evident.

The plasma ring at F-layer altitudes is not strongly evident, if at all, in the bottom side data. The only suggestion is that on the night side at about 74° corrected geomagnetic latitude indicated by the two adjacent 6 MHz contours. Failure to see an increase in foF_2 across the day side cleft (~ 76° CGL) could result from lack of stations or difficulty in reading ionograms in the vicinity of the cleft. A large increase in foF_2 is not expected since an increase of N_mF_2 by 2×10^5 cm^{-3}, which we have seen is the typical increase to be expected, would increase f_oF_2 only from 8 MHz to 9 MHz ($N_mF_2(cm^{-3}) = 1.24 \times 10^4\ foF_2^2\ (MHz)$).

The slight depression near the center of the cap suggests a polar cavity in which the concentration at F-layer height is reduced (Pike, 1971a). If this feature is real it could result from the slower convection velocity interior to the cavity and consequent longer decay time. The reduced particle precipitation in the center of the cap may also contribute to a lower concentration.

Duncan (1962) has demonstrated that the monthly median value of N_mF_2 has a diurnal maximum at approximately 0600 UT in the Antarctic at all seasons. In the Arctic the maximum is observed to occur at approximately 1800 UT (Duncan, 1962; Pike, 1971a). Sato and Rourke (1964) observed that the tongues in the Antarctic were most prominent between

0400 and 0900 UT and in winter. These latter two authors recognized that the universal time dependence and seasonal appearance had a simple explanation if ionization were being transported across the cap from the dayside ionosphere. The solar zenith angle at local magnetic noon and at the cleft latitude goes through a diurnal cycle and is a minimum at all seasons at approximately 1700 UT in the Arctic and 0400 UT in the Antarctic. We would thus expect that the solar produced F-layer just equatorward of the cleft, which is that being convected across the cap, would have the largest concentration at these universal times in the respective hemispheres. This universal time variation may be visualized as a receding of the dayside contours of Figure 4 to a lower latitude by approximately 20^{o} for a universal time of 0500 and return to that shown at 1800.

The actual universal times of maximum f_oF_2 in the two polar regions correspond to approximately two hours past local noon in magnetic local time (Pike, 1971a). The local time at which the convection velocity switches from eastward to westward at the cleft is also in the afternoon (Figure 1 and Gurnett and Frank, 1973) and suggests that the ionization convected across the cap is being drawn primarily from this local time sector.

Nishida (1967) has presented average electron concentrations over the north polar area for the low sunspot years 1962, 1963 and 1964 obtained from Alouette topside ionograms during geomagnetically quiet periods. The results for an altitude of 350 km plotted in corrected geomagnetic coordinates are reproduced in Figure 5 together with the convection paths of Figure 1. These data represent a universal time average, evidently, for the autumn (equinox) season. A suggestion of a small ridge at the dayside cleft is present in these data but an enhancement at the nightside soft electron precipitation zone is not evident. The "tongue" is clearly evident as well as the F-layer trough of low electron concentration on the night side. The contours again suggest that the ionization is being drawn from a local time position of 13-14 CGT.

The enhancement at 18 CGT equatorward of the stagnation point suggests that it is related to the plasmaspheric bulge. It could be the result of neutral winds and westward declination of the magnetic field lines, however, since the data were obtained around 85°W longitude as noted by Nishida (1967).

The meridional profiles of average electron density for corrected geomagnetic times of 12 and 24 hr at equinox are reproduced in Figure 6(after Nishida, 1967). The 12 CGT profile illustrates the enhancement of electron concentration at high altitude expected from our foregoing analysis. No significant enhancement in electron concentration at the cleft is indicated at 350 km altitude in this profile although one is evident for the winter season in a profile to be reproduced shortly. Similarly, no electron concentration enhancement is evident in the nightside soft electron precipitation zone (~ 70-80° CGL) although a steep gradient to lower values occurs just south of the zone.

In Figure 7 we reproduce the meridional profiles for 1000 and 0200 CGT for three seasons. In winter, at 350 km altitude a definite enhancement at the dayside cleft from ~ 1 x 10^5 to 2 x 10^5 cm^{-3} occurs but is not evident during the summer. The concentration at 350 km altitude drops by about a factor of e in crossing the cap (80° Day ~ 75° night) in all seasons. The largest concentration both at 350 and 950 km altitude in winter evidently occurs at or poleward of 80° CGL which is consistent with the electron temperature and concentration being largest at the poleward boundary of the cleft. The data were averaged in 4° latitude intervals, however, so that a strong case for the location of the maximum cannot be made. A small enhancement at night and in winter does appear at both 350 and 950 km altitude at about ~ 67° CGL. This may be the signature of the plasma passing the night side soft electron precipitation zone since we would expect on the night side that the largest enhancement in electron temperature and concentration at 950 km and also electron concentration at 350 km would be on the equatorward edge of the zone.

A zone exists equatorward of the nightside auroral oval referred to as the trough in which the F-layer concentration is low (Muldrew, 1965;

Sharp, 1966; Nishida, 1967; Thomas and Andrews, 1968; Bowman, 1969). The electron concentration increases rather abruptly in the poleward direction by orders of magnitude from its minimum value and increases more slowly toward the equator (Sharp, 1966; Bowman, 1969). This behavior is consistent with that outlined previously. The average position of the trough as derived from Muldrew's 1965 data and plotted by Bowman (1969) is shown in Figure 5. This position follows rather well the lowest latitude convection flow line and also the center of the electron concentration trough derived by Nishida. The trough is rotated toward the morning hours in both Figures 4 and 5 which is consistent with the expected behavior.

The troughs in the averaged data presented in Figures 4 and 5 are broader and not as low in concentration as those observed within a short time period. Concentrations as low as 1-2 x 10^3 cm^{-3} have been reported (Sharp, 1966; Bowman, 1969; Hultqvist and Liszka, 1972). The concentration increases from 10^3 to 10^6 cm^{-3} within a degree or two of latitude on occasion (Hultqvist and Liszka, 1972). Changes in concentration and latitude of the instantaneous trough with time in response to changes in the solar wind presumably produce the averaged troughs illustrated.

SUMMARY

It is suggested that convection of F-layer plasma over the polar caps in response to the magnetospheric electric field plays a profound role in the behavior of the layer - particularly in winter when solar illumination is absent. Plasma equatorward of the dayside cleft is convected through the cleft typically in 5 minutes. During cleft passage, ionization is added to the layer - principally in the altitude interval 250-350 km. The amount of ionization added is typically $1 - 2 \times 10^5 \ cm^{-3}$ which is relatively insignificant in comparison with the solar maintained F-layer concentration in the summer hemisphere. The amount added is significant in the winter hemisphere - particularly at universal times when the solar zenith angle at the day side cleft is largest. Also during cleft passage the electron gas is heated - largely independently of the ions - but is maintained in a conductive steady state. The F-layer plasma above approximately 400 km altitude adjusts itself into a diffusive equilibrium consistent with the increased electron temperature and produces the "averaged" enhanced electron concentration seen at 1000 km altitude coincident with the cleft. Some lifting of the F-layer ($\sim$ 18 km) resulting from the magnetospheric electric field will occur.

After passage through the cleft, the electron temperature drops and the ion concentration at 1000 km decreases as the top side ionosphere "slumps" back down the field tube. This drop in temperature should occur within about 1° of the poleward boundary of the cleft.

At a convection velocity of 0.5-1 km/sec, the F-layer is convected from $80^{\circ}\Lambda$ on the day side to $75^{\circ}\Lambda$ on the night side (across the cap) in a time approximately equal to that required for the layer to decay by a factor of e.

In crossing the night side soft electron precipitation zone, the F-layer will respond qualitatively in a similar manner to that described above for the dayside except that the layer will be lowered in altitude. The generally harder electron spectrum on the night side implies that the F-layer will respond less on the nightside than on the dayside.

After passage across the night soft electron precipitation zone, the F-layer will convect toward lower latitude and around the dawn side of the earth (Figure 1). As it does so at a latitude of $\sim 60^{\circ}\Lambda$, a decay in concentration through recombination of the order of 10^2 - 10^3 is expected in the absence of any maintenance sources and the night side F-layer trough is thus formed. The outflow of H^+ poleward of the plasmapause is evidently not the major loss mechanism for the F-layer. It does provide during sunlit hours the plasma on closed field lines which returns to the F-layer at night to contribute to the maintenance of the F-layer equatorward of the plasmapause.

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FIGURE CAPTIONS

FIGURE 1 Convection paths of F layer plasma implied by models of the magnetospheric electric field. The convection paths and time intervals in the region between the plasmapause and closed field line boundary were derived from the computed motion of plasma in the equatorial plane (Kavanagh et al., 1968) for a dawn to dusk electric field of 0.3 mV/m and a zero potential plasmasphere equal to one earth radius. Flow lines over the polar cap are joined to the intersection of the closed magnetospheric flow lines with the expected boundary of closed field lines. Plasma convects across the cap at a rate of 32°/hr for a convection velocity of 1 km/sec.

FIGURE 2 Schematic representation of the expected change in the solar exposed F layer as it convects through the cleft.

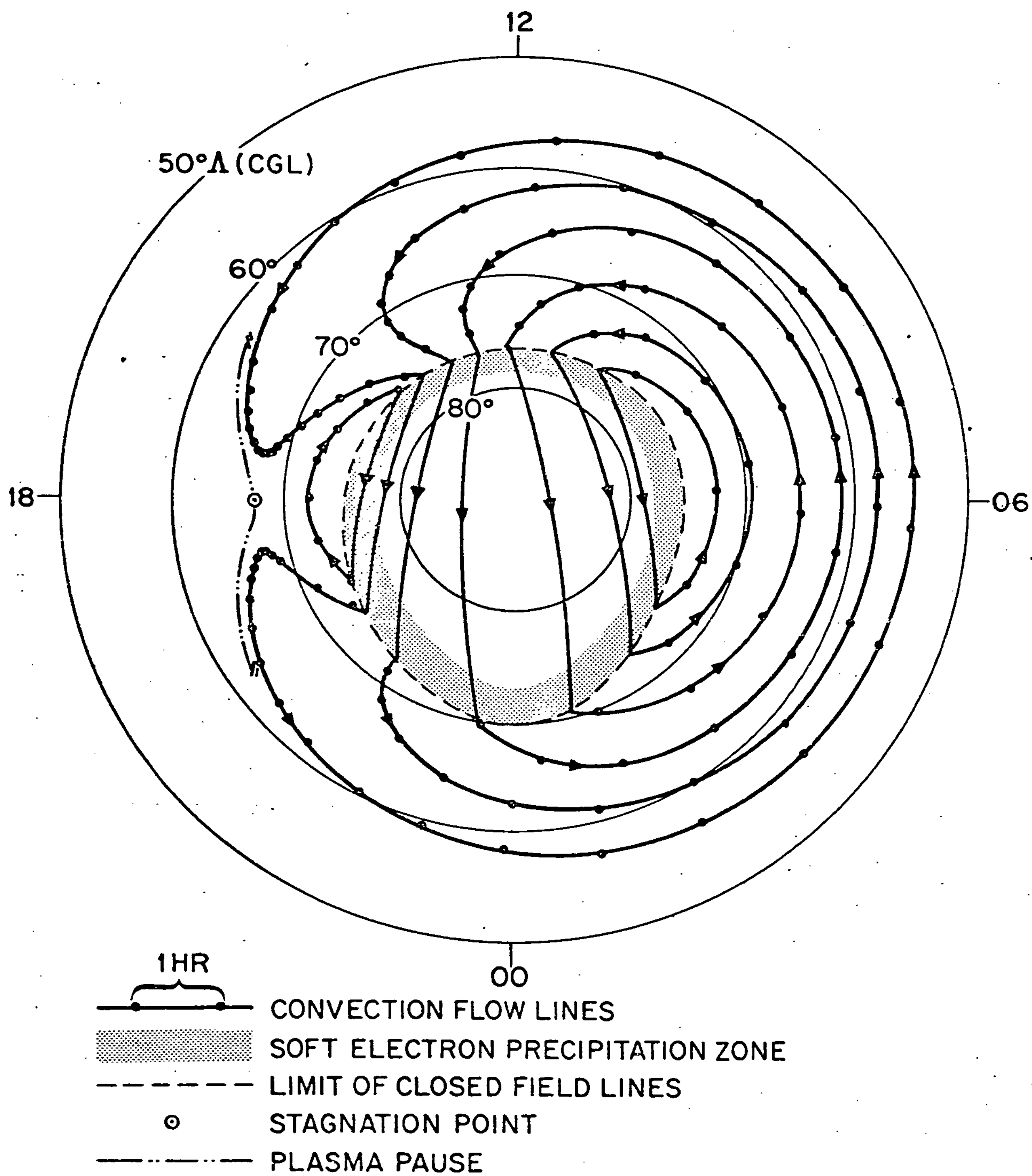
FIGURE 3 Comparison of observed and modelled F-layer profiles for the day side cleft. The observed ionosphere at 74°Λ is just equatorward of the cleft and that at 76°Λ close to the poleward edge (Winningham, 1973, and Pike, 1972). The modelled ionospheres are in diffusive equilibrium with no flow of plasma out the top. S.Z.A. is the solar zenith angle.

FIGURE 4 Contour lines of monthly median f_oF_2 for 1800 UT, December 1958 in the Arctic drawn in corrected geomagnetic latitude and time coordinates (After Pike 1971a). The convection flow lines of Figure 1 are also shown.

FIGURE 5 Average electron concentration for the autumn season at the 350 km altitude level obtained from Alouette I profiles during geomagnetically quiet times in 1962 and 1963 (After Nishida, 1967). The coordinates are corrected geomagnetic latitude and time. The mesh size for averaging was 4° by 2 hr. The average trough position is derived from Muldrew (1965) and Bowman (1969).

FIGURE 6 Meridional profile of the average density in autumn for the 1200 and 2400 CGT meridians (After Nishida, 1967). Units are 10^{4} electrons/cm^{3}.

FIGURE 7 Latitudinal variation of the average electron concentration in summer, autumn and winter in the 10 and 02 CGT meridians at 350 and 950 km altitude (After Nishida, 1967). The coordinates are corrected geomagnetic latitude and time.



12
50°Λ (CGL)
60°
70°
80°
18
06
00
1 HR
CONVECTION FLOW LINES
SOFT ELECTRON PRECIPITATION ZONE
LIMIT OF CLOSED FIELD LINES
STAGNATION POINT
PLASMA PAUSE

Figure 1

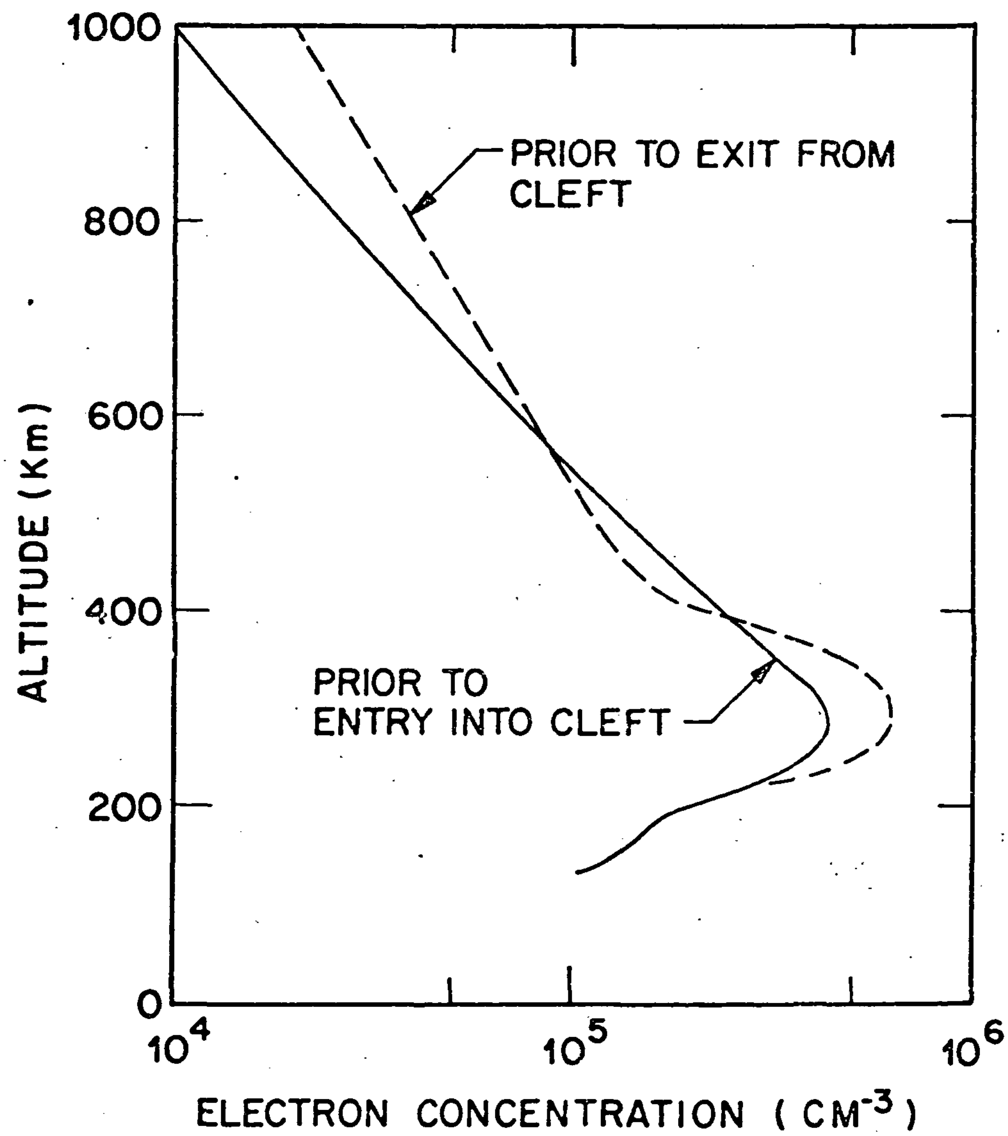
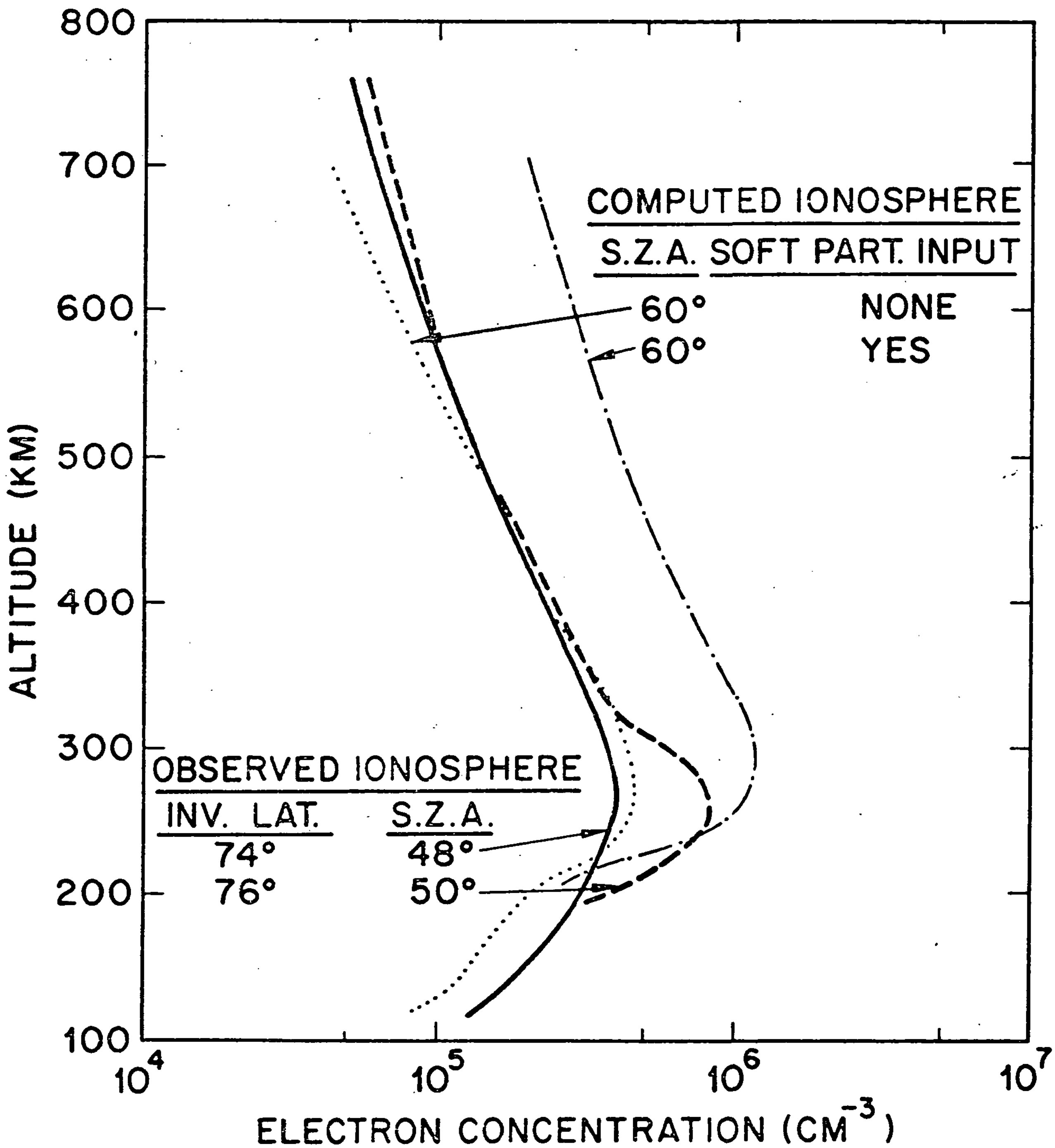

1000
800
600
400
200
0
ALTITUDE (Km)
PRIOR TO EXIT FROM
CLEFT
PRIOR TO
ENTRY INTO CLEFT
10^4
10^5
10^6
ELECTRON CONCENTRATION (CM^-3)

Figure 2



800
700
600
500
400
300
200
100
ALTITUDE (KM)
COMPUTED IONOSPHERE
S.Z.A. SOFT PART. INPUT
60° NONE
60° YES
OBSERVED IONOSPHERE
INV. LAT. S.Z.A.
74° 48°
76° 50°
10^4
10^5
10^6
10^7
ELECTRON CONCENTRATION (CM^-3)

Figure 3

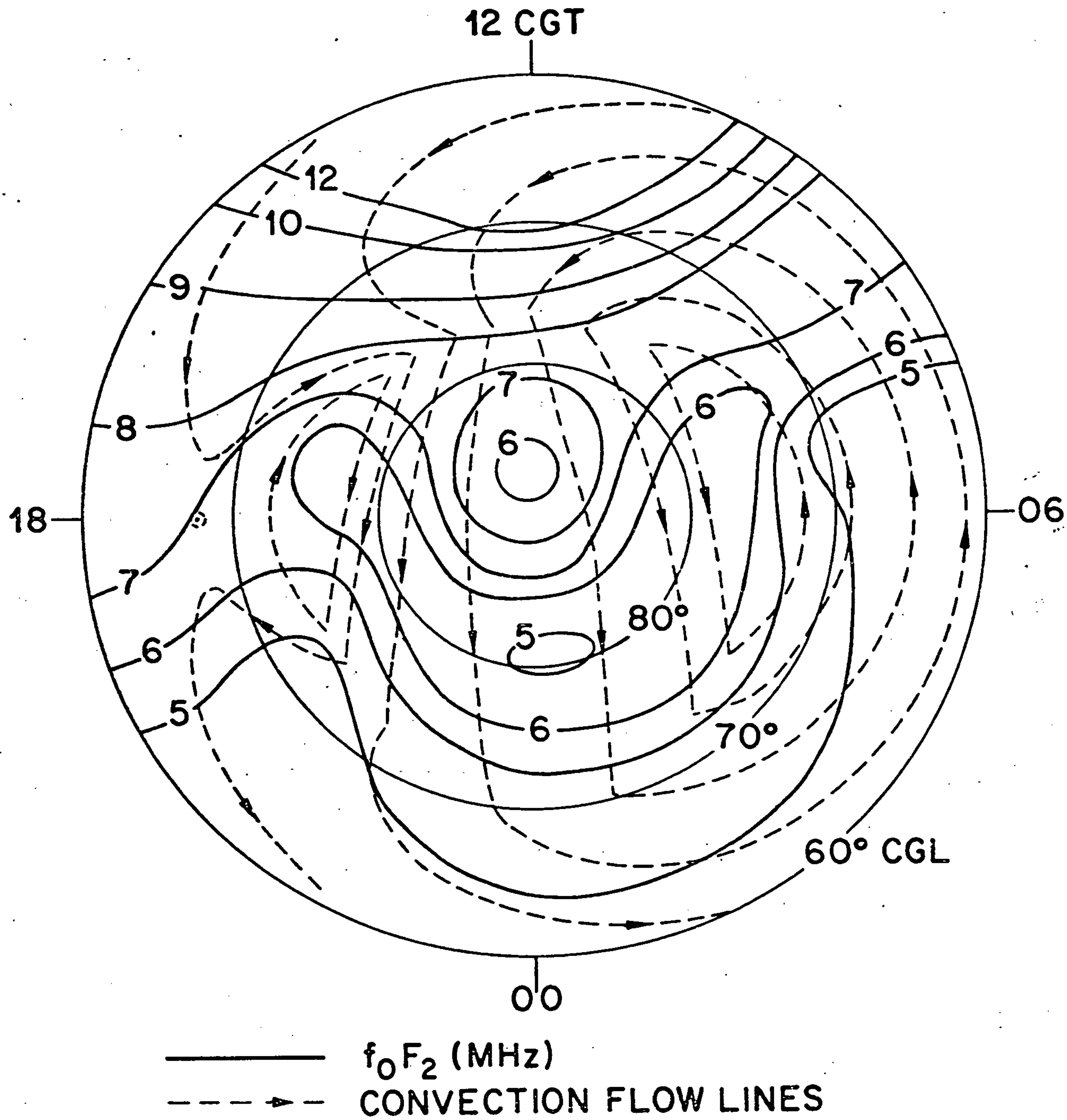

12 CGT
18
06
00
12
10
9
8
7
6
5
7
6
5
7
6
6
5
80°
70°
60° CGL
f0F2 (MHz)
CONVECTION FLOW LINES

Figure 4

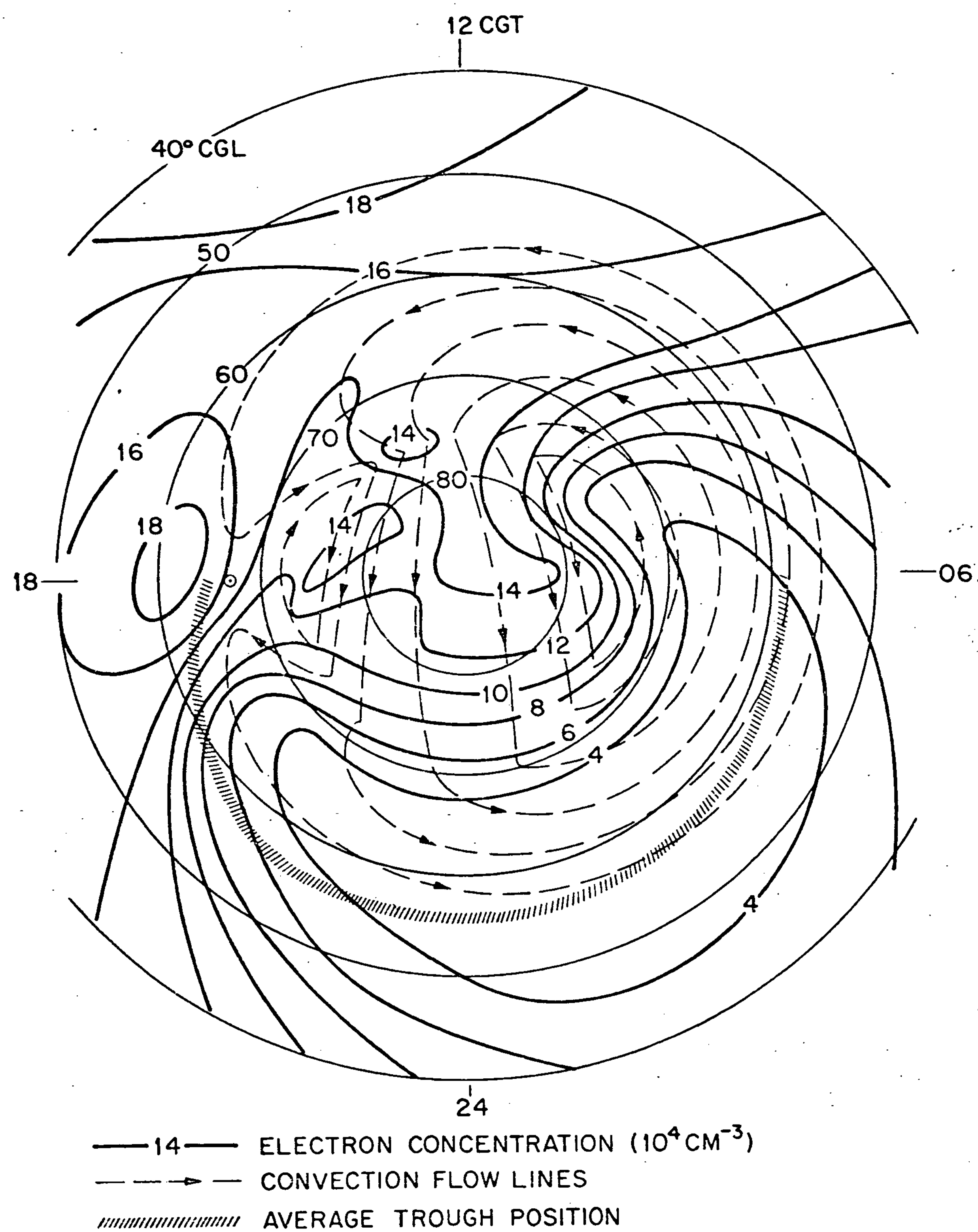

12 CGT
40° CGL
18
50
16
60
16
18
70
14
80
14
18
06
14
12
10
8
6
4
4
24
14 ELECTRON CONCENTRATION (10⁴ CM⁻³)
CONVECTION FLOW LINES
AVERAGE TROUGH POSITION

Figure 5

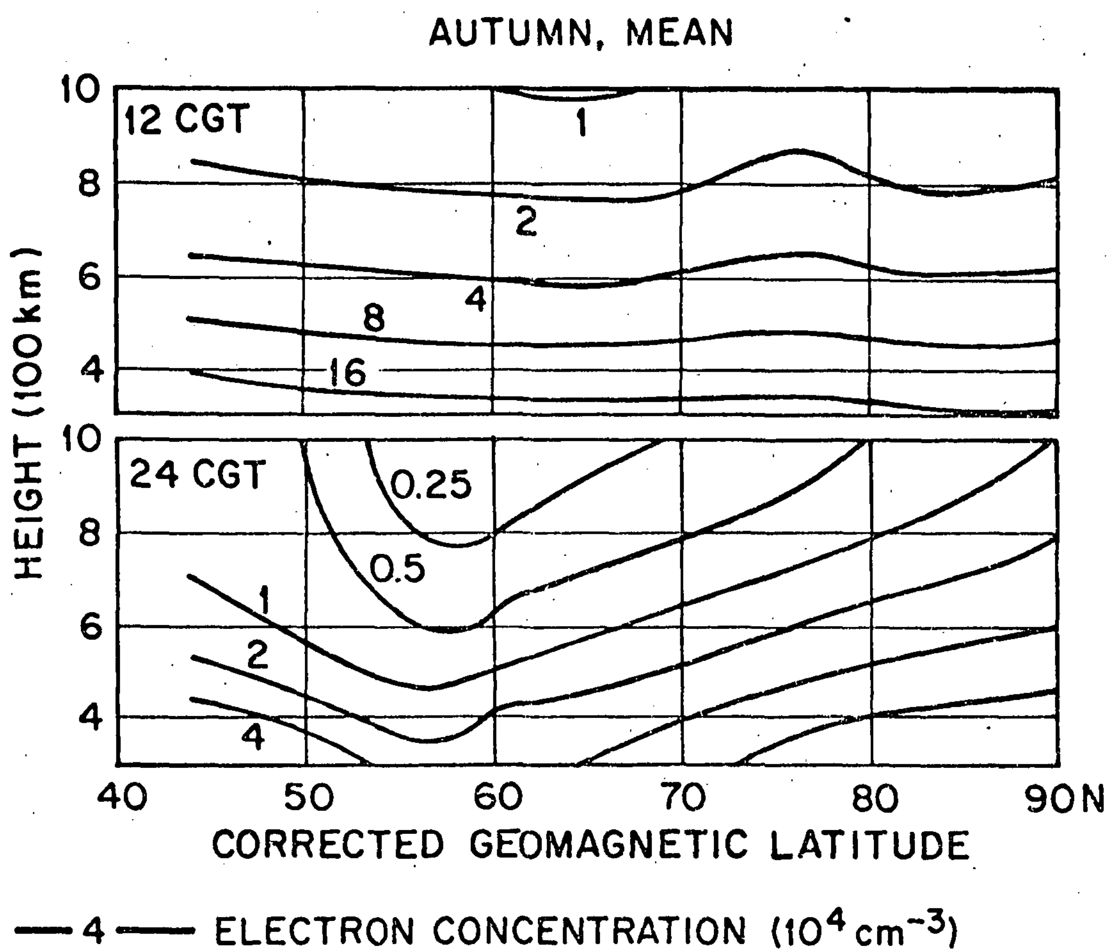

AUTUMN, MEAN
12 CGT
24 CGT
HEIGHT (100 km)
10
8
6
4
1
2
4
8
16
0.25
0.5
40
50
60
70
80
90N
CORRECTED GEOMAGNETIC LATITUDE
— 4 — ELECTRON CONCENTRATION (10^4 cm^{-3})

Figure 6

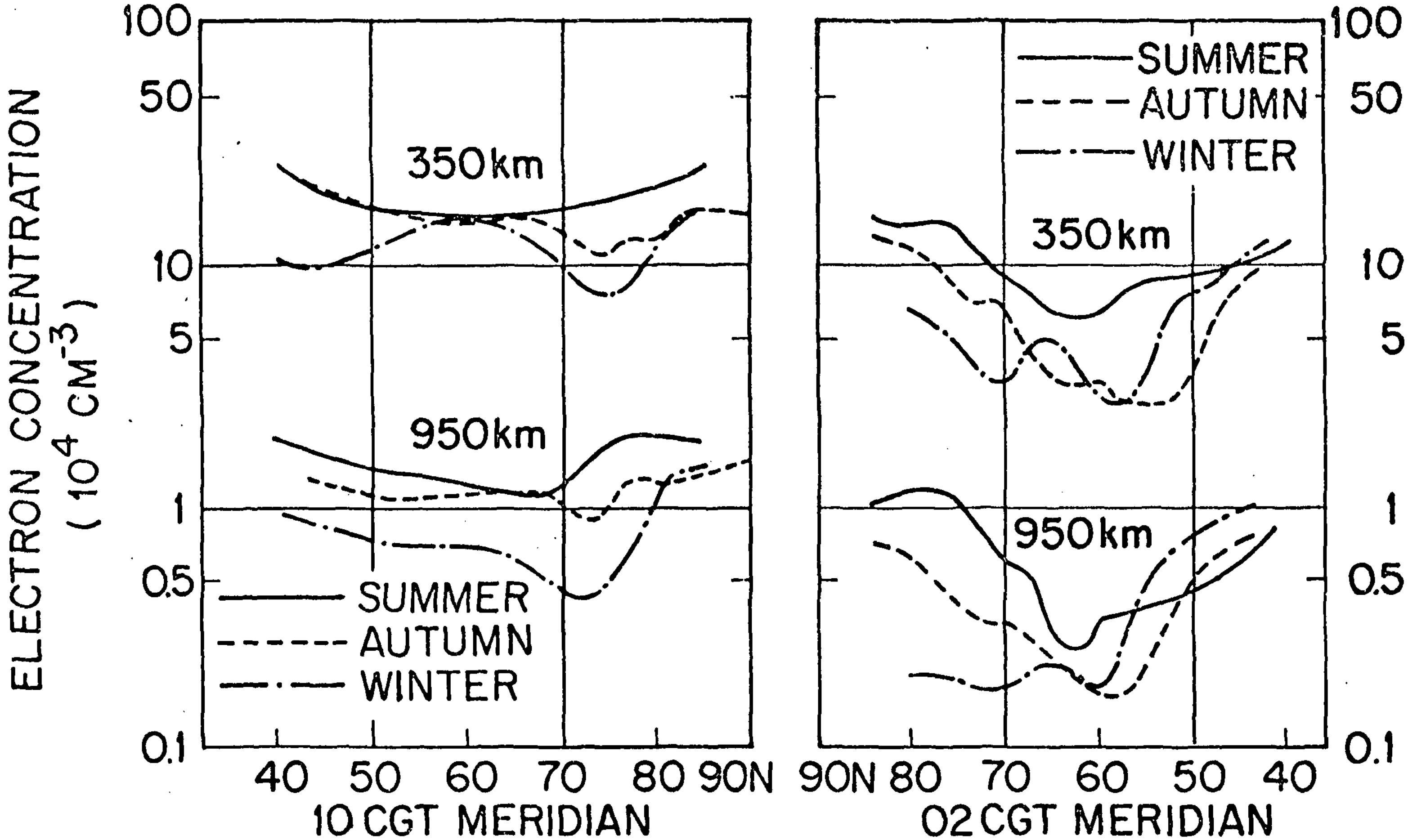

ELECTRON CONCENTRATION
(10^4 CM^{-3})
100
50
10
5
1
0.5
0.1
350km
950km
SUMMER
AUTUMN
WINTER
40 50 60 70 80 90N
10 CGT MERIDIAN
90N 80 70 60 50 40
02 CGT MERIDIAN

Figure 7