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Latitudinal Patterns in Plasma Scale Heights & Ion Transition Altitudes in the Low Latitude Topside Ionosphere

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Trans-equatorial passes of the Alouette-2 satellite covering $\pm 60°$ dip are examined for latitude and altitude variations of electron density during typical solstice and equinox periods. Clear seasonal differences are seen between dip-conjugate locations in the two hemispheres up to an altitude of 1200 km, very pronounced in the solstices and milder in equinox. Above 1200 km, altitude profiles of N_e from all latitudes within $\pm 40°$ merge into uniformity. Interpolated *N-h* data at closely spaced height intervals are used to compute scale heights, and hence to compute ion change-over altitudes at these low latitudes. The O^+-He^+ change-over altitude seems to occur at 600-800 km with higher values in the summer hemisphere. The He^+-H^+ change-over shows more variability ranging between 1200 and 2000 km. Field-aligned values of electron density show a smooth variation with considerable symmetry about the equator even during solstices. These features are interpreted in terms of physical processes in the topside.

1. Introduction

In the topside ionosphere above the F2 peak, collisions of charged particles with neutrals are greatly reduced, and the dominance of the geomagnetic field on plasma motion is complete. At most latitudes (except for the plasma trough region where Torr[1] shows loss through recombination with atomic N is of importance), production and loss of ionization is almost nil, and the only chemical process is charge exchange between ions and neutrals. At low latitudes the electrons and ions take up a diffusive equilibrium distribution along the geomagnetic flux tubes; plasma transport is governed by gravity, electric fields, neutral thermospheric winds and field-aligned flow due to differing plasma pressure gradients as discussed by Banks and Kockarts[2]. At higher latitudes, this condition of diffusive equilibrium is frequently perturbed by magnetospheric convection processes. The phenomenon of ionosphere-protonosphere flow is a strong coupling factor between the topside and the bottomside. Hence some factors such as seasonal variations in ionization, ion-drag due to neutral winds and low-latitude **E** × **B** drifts, which directly affect the F-region, would be expected to reflect on particle distributions in the topside.

With increasing altitude the heavier O^+ ions give way to He^+ ions and then to H^+ ions and hence the scale height of plasma changes with altitude. This ion-transition altitude varies in a systematic manner with latitude providing clues to the physical processes at work in the topside. The advent of polar-orbiting satellites in the last two decades has greatly added to knowledge of these latitudinal patterns, and hence to the structure of the topside. The earliest observations of heavy ions increasing in concentration with increasing latitude were taken by Istomin[3] from the Sputnik-3 satellite. Latitudinal patterns in O^+ and H^+ distributions were shown by Barrington *et al.*[4] from the Alouette-1 and by Bowen *et al.*[5] from the Ariel satellite, while detailed descriptions of these were given by Taylor *et al.*[6] from the OGO-2 ion mass spectrometer. More recent works on the composition structure are those of Titheridge[7] and Miyazaki[8].

In this work, interpolated *N-h* data from the Alouette-2 topside sounder (published by the Communications Research Centre of Canada) are utilized to understand the latitudinal patterns in plasma scale height and ion change-over altitudes, and to see how these respond to changing season. The Alouette-2 satellite was of polar-orbiting type with inclination $\approx 80°$, apogee 3000 km and perigee 500 km. This work consequently concerns plasma behaviour in the 500-3000 km altitude region.

2. Latitudinal Variations and Altitude Profiles of N_e

Trans-equatorial passes with fairly extensive latitude coverage were selected for solstice and equinox periods during the years 1966-69. Passes occurring within 60 to 150° geographic longitude are classified as the East Zone, within 150 to 225° as the Pacific Zone, 225 to 330° as the West Zone, 330 to 60° as the Inter Zone.

Shown in Fig. 1 are the latitudinal variations of N_e for constant altitudes lying within 500-2600 km for

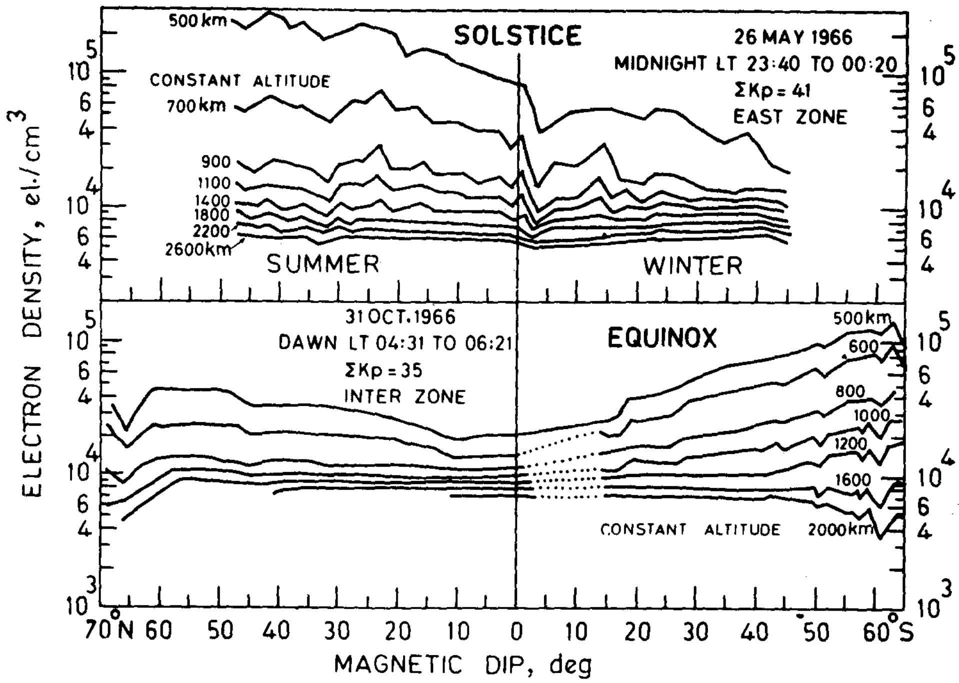

Fig. 1—Latitudinal variation of N_e at various altitudes for solstice and equinox conditions (Latitudinal gradients in N are considerably smoothened out above 1200 km altitude.)

typical solstice and equinox conditions. The local time, magnetic activity conditions, and longitude zone of the respective passes are indicated against the variations. These latitudinal profiles show considerable inter-hemispheric asymmetry, more pronounced in the solstice and less in the equinox. Summer hemisphere electron densities exceed those in the winter hemisphere for the midnight pass of 26 May 1966. This is true even for the dawn pass of 31 Oct. 1966 with higher N_e values in the southern hemisphere with "near summer" conditions. The interhemispheric asymmetry disappears around 1000 km and above this altitude it is practically absent. It is not possible to comment on the absolute N_e values as the local times for the two passes are different. There are clear undulations in the profiles which are more prominent during solstice than during equinox, indicating irregular latitudinal gradients in the electron density. These irregularities too disappear with increasing altitude.

From these latitudinal variations of N_e, dip-conjugate points on either side of the equator were selected in such a way that they did not lie in a sharp latitudinal gradient of N_e. Altitude profiles of N_e at the equator and at these dip-conjugate locations were compared, and these are shown in Figs. 2 and 3. Fig. 2 shows these vertical altitude profiles of N_e for typical solstice months, viz. May and February; both the passes occurred at midnight and the magnetic activity conditions were similar, although the solar cycle epochs and the longitude zones were not. Full lines show profiles for the northern hemisphere and dashed lines for the southern hemisphere. The magnetic dip location of the observation is also shown against each profile. Clearly there is considerable difference in N_e at different locations at altitudes below 1200 km. Above 1200 km the N_e profiles at all latidues within $\pm 45°$ dip merge together. Below 500 km, at dip-conjugate locations, N_e differs by almost an order of magnitude, with the equatorial profile clearly separating the higher summer values from the lower winter ones. The gradient of the N-h profile changes with altitude, indicating a change in the dominant ion species. This change occurs at higher altitudes in the summer hemisphere as compared to the winter hemisphere. In Fig. 2, in the pass for 11 Feb. 1969 the satellite was nearer perigee and hence N_e values above 1500 km are not available; still the merging of all N_e profiles above 1200 km is clearly seen. The N_e profile for + 39° dip is an unusual one, with scale height being uniformly large right from 400 km altitude itself.

Fig. 3 shows similar vertical profiles of N_e for equinox dawn conditions. The case of 23 Mar. 1968 is a perfect equinox example. In contrast to the solstice conditions of Fig. 2, dip-conjugate locations here show very little asymmetry in N_e even at lower altitudes and all asymmetry evens out completely at 900 km itself. The case of 31 Oct. 1966 is not a true equinox, tending to lean towards northern winter conditions. This is seen from the difference in N_e exhibited by dip-conjugate locations at lower altitudes and the

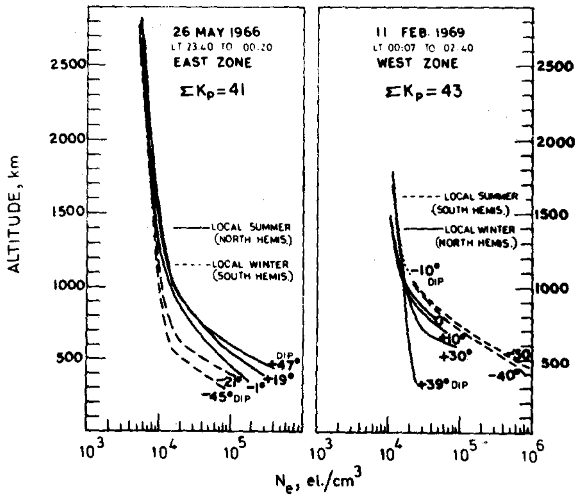

Fig. 2—Altitude profiles of N_e for midnight solstice conditions at equatorial and low-latitude dip-conjugate locations (Note the vastly different electron densities in the summer and winter hemisphere below 1200 km.)

differences even out only above 1300 km. The profiles marked as + 68° and − 65° stand apart from the others. They characterize the midlatitude plasma trough region and their small-scale heights persisting to high altitudes, speak of possibly O^+ as the dominating ion.

3. Latitudinal Variation of Ion Change-over Altitudes and Plasma Scale Heights

Because of gravity, the mean ionic mass is expected to decrease with altitude. Also, since charge neutrality is believed to be preserved at the high altitudes, the electron density profiles are interpreted in terms of ion density profiles of the dominant ions expected at the relevant heights. Using this concept, the change-over altitudes of the dominant ion species O^+, He^+ and H^+ are obtained from the vertical profiles of Figs. 2 and 3. This was done by extrapolating height regions with predominantly similar gradients or, by drawing tangents at these regions and then obtaining the intersection heights of these extrapolations or tangents

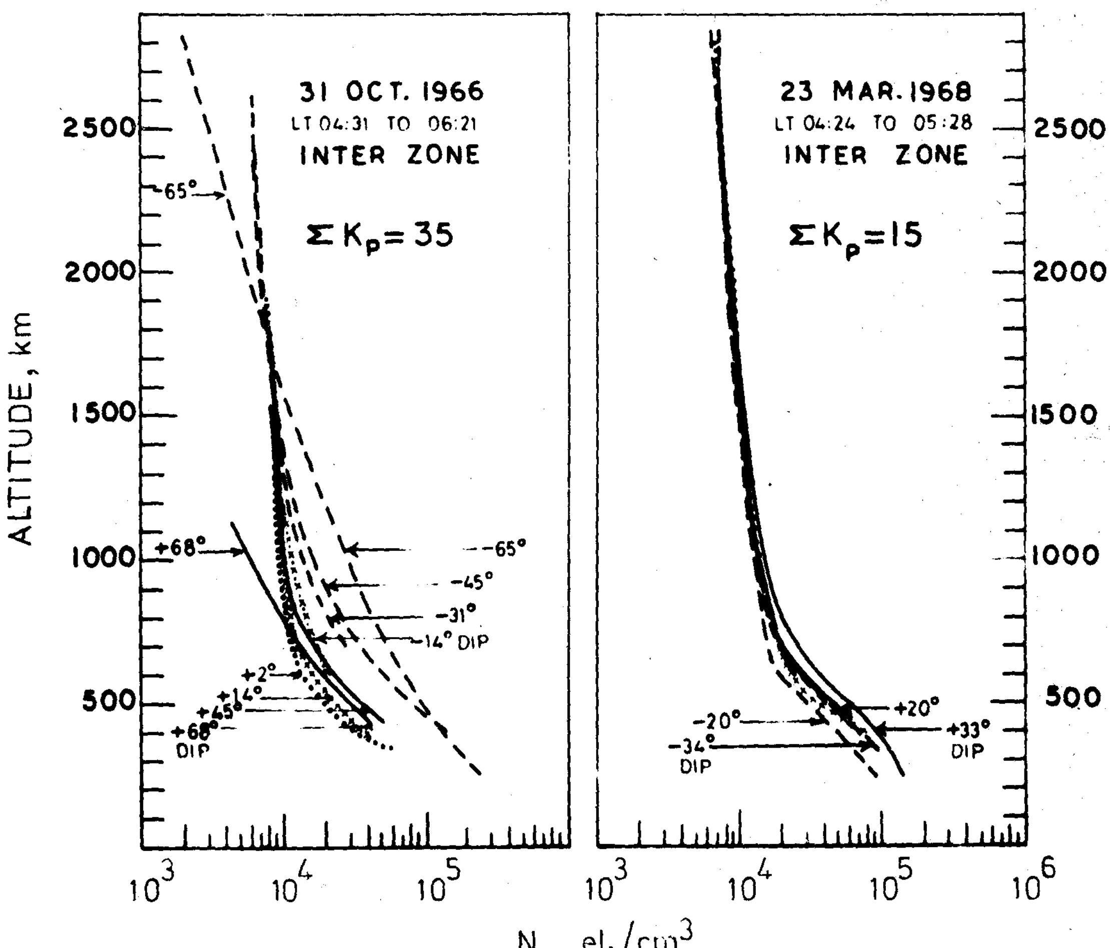

Fig. 3—Altitude profiles of N_e for dawn equinox conditions at equatorial and low latitude dip-conjugate locations (For the true equinox condition of 23 Mar. 1968, there is practically no interhemispheric asymmetry in N_e even below 1000 km.)

as the case might be. These two intersection heights were treated as the change-over altitudes of O^+ to He^+ dominance and He^+ to H^+ dominance, respectively. The term "change-over altitude" is used rather than the conventional term "transition altitude", which by definition is the altitude where the two ion species are each 50% in proportion.

The O^+-He^+ and He^+-H^+ change-over altitudes obtained thus are shown in Fig. 4. The best cases for checking seasonal and north-south asymmetry are the midnight pass of 26 May 1966, and the dawn pass of 23 Mar. 1968, respectively. In both passes the O^+-He^+ change-over altitude lies between 600 and 800 km which is in agreement with the transition-altitude observations of Bowen *et al.*[5] from the Ariel satellite. The solstice month clearly shows higher values in the local summer hemisphere. This feature agrees with the observations of Watt[9] for midlatitudes in the West Zone. This feature is also repeated to a lesser extent in the 31 Oct. 1966 pass which tends towards southern hemisphere summer conditions. The He^+-H^+ change-over altitudes in Fig. 4 tend to show more variability than the O^+-He^+ change-over levels, ranging between 1200 and 2000 km. These values agree with the O^+-H^+ transition altitudes obtained by Brinton *et al.*[10] from the Explorer-32 spectrometer data for the year 1966. The equinox results in the lower part of Fig. 4 differ significantly from the solstice results. The equinoctial dawn-time Inter Zone passes show, instead of an equatorial dip, a north-south asymmetry with higher He^+-H^+ change-over altitudes in the southern hemisphere. For the West Zone Titheridge[7] pointed out lower ion transition heights in the southern hemisphere as compared to the northern hemisphere.

The plasma scale height is a parameter which is defined as $\left[-\frac{\partial}{\partial h}\left(\ln N_e\right)\right]^{-1}$. Fig. 5 shows these scale heights computed as a function of latitude at selected altitudes (marked against the respective profiles). The plasma scale height is small at the lowest altitudes and is also constant with latitude. This indicates a heavy ion predominance at these altitudes within these latitudes. The plasma scale height increases considerably at the higher altitudes with a tendency to form a peak over the equator, and to decrease gradually towards higher latitudes. This would indicate light ions being abundant over the equator at high altitudes but gradually getting contaminated by heavy ions with increasing latitude. At 60° dip and beyond, scale height has low values at all altitudes (even up to 2000 km). This suggests that heavy ion dominantes at all altitudes within the plasma trough region and beyond.

The solstice pass of 26 May 1966 clearly shows considerable seasonal asymmetry in scale heights below 2000 km with winter hemisphere values

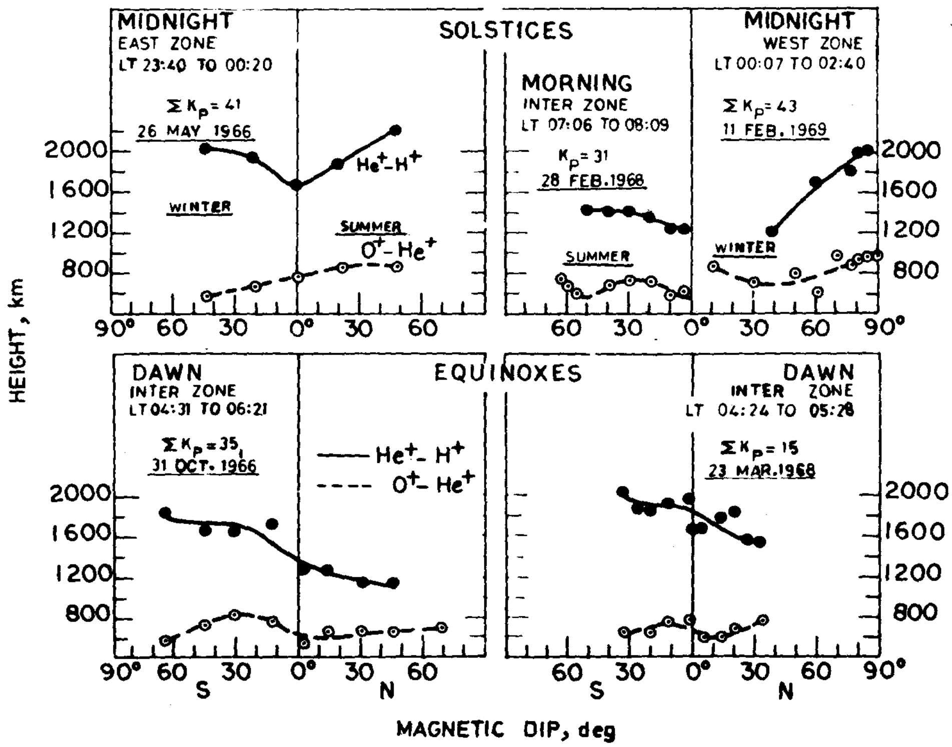

Fig. 4—Latitudinal variations of O^+-He^+ and He^+-H^+ change-over altitudes for midnight solstice and dawn equinox conditions

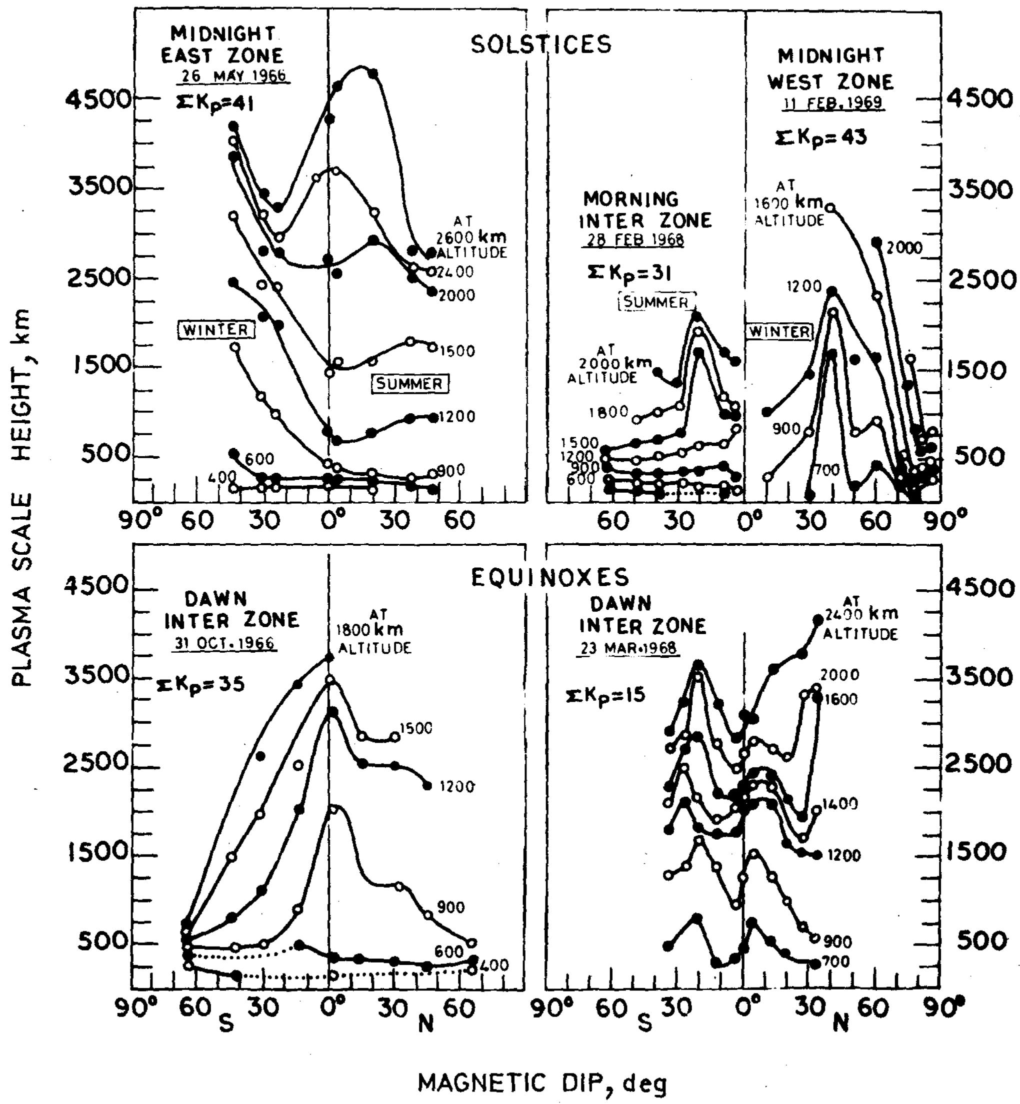

Fig. 5—Latitudinal variation of plasma scale heights at various altitudes for midnight solstice and dawn equinox conditions

exceeding those in the summer hemisphere. This observation would indicate a larger proportion of light ions in the winter hemisphere which is in conformity with the works of Taylor[11] and Breig and Hoffman[12]. Above 2000 km, this seasonal asymmetry evens out and scale heights at the equator increase sharply. These features of enhanced equatorial scale height and enhanced winter scale heights below 2000 km are also seen for 31 Oct. 1966 (with southern hemisphere having "near summer" conditions). The true equinox case of 23 Mar. 1968 does not show much north-south asymmetry in scale height but it shows, at all altitudes, sinusoidal variations with a systematic periodicity, the reason for which is not clear. The summer morning pass of 28 Feb. 1968 shows a highly compressed set of profiles with comparatively low scale heights at all latitudes and altitudes.

4. Geomagnetic Field-Aligned Electron Density Distributions

A symmetric dipole magnetic field model given by

$$r = r_0 \cos^2\theta$$

where

- r Radial distance of any point of field line from centre of earth
- θ Latitude of the point on field line with respect to the centre of the earth
- r_0 Radial distance of field line from centre of earth in equatorial plane

was used to obtain the altitudes at which various low-latitude field lines intersect different latitudes.

The electron densities observed by the satellite at the altitudes where each field line cuts the different latitudes, are read from the interpolated N-h data for each of the passes chosen for this study. This in an approximate way gives the field-aligned electron densities; the term approximate is used because the actual geomagnetic field is known to deviate from the symmetric dipole field, more at some longitudes and less at others. If plasma in the topside tends to distribute itself in hydrostatic equilibrium along the flux tubes, as is presently believed, the electron densities read from the interpolated *N-h* data should decrease from lower altitudes to higher altitudes in a steady manner along the heights demarcating the field lines at different latitudes. The results of this exercise are shown in Fig. 6. The field lines along which the electron densities are read, have values near them indicating at which geomagnetic latitude their feet lie, i.e. the φ value at which they meet earth surface. The first point that strikes one is that the electron densities are well aligned along each field line, and show hardly any scatter about it; this is in spite of these symmetric dipole field lines only being a rough approximation to the real field. The alignment is remarkable, and it rather confirms the presence of field-aligned diffusion of ionization. Lowest values of electron density are found at the equator where the field line has highest altitude, and N_e gradually increases with increasing latitude as the altitude of the field line gradually reduces.

The second point is that in the lower two blocks for the equinoxes the electron density distributions along the field lines are quite symmetrical about the equator even at the lower heights associated with the $10°\varphi$ and the $15°\varphi$ magnetic field lines. In the first block of Fig. 6 for the solstice period (26 May 1966), there is a perfect symmetry of N_e for the higher field lines. Some asymmetry is seen for the lower field lines ($15°\varphi$ and $20°\varphi$) but it is far less than the interhemispheric asymmetry observed in the latitudinal variations of N_e at the altitudes depicted in Fig. 1. In fact Fig. 1 also

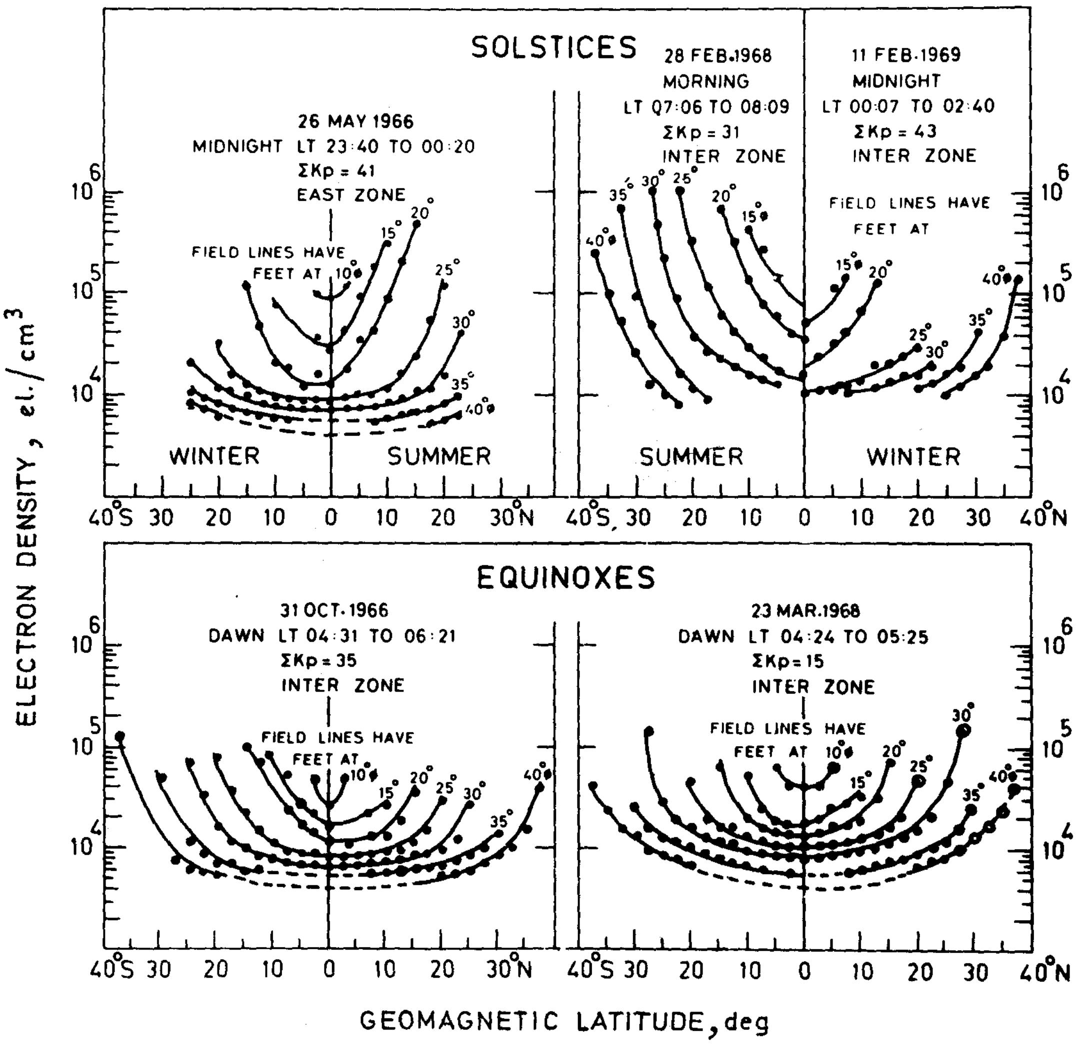

Fig. 6—Plots of electron densities observed by the Alouette-2 satellite along the geomagnetic field lines $\pm 10°\varphi$ to $\pm 40°\varphi$

showed some interhemispheric asymmetry during the equinox case of 31 Oct. 1966 which is totally absent in Fig. 6. All these features confirm the powerful role of the geomagnetic field in plasma diffusion and the hydrostatic diffusive equilibrium distribution of plasma in the low latitude topside. No comments can be made about the second solstice pass in Fig. 6, because the two hemispheres correspond to different satellite passes in different zones at different periods. The respective passes, however, clearly demonstrate the alignment of N_e along the magnetic field lines with hardly any scatter.

A third point which is striking in all the passes is that the gradient of N_e along neighbouring magnetic flux tubes is much less at the equator and gradually increases with increasing distance away from the equator. Latitudinal gradients in N_e along the low latitude field lines (marked $\pm 10°\varphi$, $\pm 15°\varphi$, $\pm 20°\varphi$, $\pm 25°\varphi$) are far sharper in the solstice months as compared to equinox months. Fig. 6 also indicates that above 1000 km altitude and within $\pm 20°\varphi$, electron density along any magnetic field line is practically unchanged, at least during the dawn and midnight conditions considered here.

5. Discussion

Distinct seasonal differences are seen in electron density at heights below 1500 km during solstice months. These are less pronounced during equinox months. At all seasons, above 1500 km altitude, vertical profiles of N_e within $\pm 45°$ dip merge into uniformity. Field-aligned proton flux between the hemispheres can explain this uniformity at dip-conjugate locations, but it is difficult to understand why the N_e values should be equal over the entire belt of $\pm 45°$ at altitudes exceeding 1500 km. Latitudinal gradients in N_e also vanish at altitudes exceeding 1200 km. This possibly indicates the reduced effect of the neutral particles on ions. Some of the irregularities at altitudes below 1000 km could be the manifestations of the effect of acoustic gravity waves. Testud and Francois[13] have shown these to get diminished considerably at higher altitudes where the time constant for diffusion is smaller than the time constant for wave perturbations.

Longitudinal differences in the electron density distributions and ion change-over altitudes are not discussed here because that needs comparison under identical conditions unlike what is shown here. The presence of longitudinal effects has been brought out by Taylor[11]. The Explorer-32 study by Brinton *et al.*[14] also shows the effect of longitude on the O^+-H^+ transition level. The He^+-H^+ change-over altitude in Fig. 4 shows considerable dependence on the local time and season of observation. One reason for this could be that plasma densities at ionospheric heights which are greatly dependent on local time and season determine the direction and intensity of the geomagnetic field-aligned ionosphere-protonosphere flux, and this in turn would determine the altitude region where protons begin to dominate. Neutral winds arising from seasonal asymmetries between the two hemispheres have been observed to set up field-aligned fluxes, and thereby cause differences in the O^+-H^+ transition levels in the two hemispheres[10,15]. In the solstices, the He^+-H^+ change-over altitude has minimum values near the equator and increases towards higher latitudes. This result agrees with the observations of Titheridge[7], and those of Miyazaki[8] from the TAIYO satellite, although the altitude values differ. Two other points require special mention. Firstly the predictions of Nicolet[16] and Bauer[17] and the observations of Taylor *et al.*[6] indicate He^+ to be a very minor constituent during sunspot minimum, but it starts increasing in the ascending part of the solar cycle. In the present study for portions of 1966-69, most altitude profiles of N_e showed three distinct slope regions which have been interpreted as regions of O^+, He^+ and H^+ dominance. Secondly, it seems reasonable to interpret the change in slope at any particular latitude as due to the change in the ionic mass, ignoring temperature as the causative factor. The reason for this is that at the low latitudes and for the night hours (2305) during the period 1968-69 considered in this paper, the altitude variation of T_e is rather small. A recent work by Köhnlein[18] combines incoherent backscatter data and ISIS-1 data to show, for the 1967-70 period, that the typical nighttime variation of T_e at Jicamarca ($+1°\varphi$) is from 1000 K at 500 km to 1250 K at 3000 km, and at Arecibo ($+30°\varphi$) from 1250 K at 500 km to 1600 K at 3000 km. Hence our interpretation of the change in slope as the change in ion species.

The alignment of electron density along the magnetic field lines, and the clear symmetry about the equator shown in Fig. 6, even during solstices (unlike the N_e at constant altitudes in Fig. 1) point to physical situations in the topside ionosphere. These features show the equilibrium attained by plasma along the field tubes, and the complete dominance of the geomagnetic field on plasma motion. The field-aligned scale length (i.e. the latitudinal spacing along field lines in which N_e falls to $1/e$ of its value) is much smaller at latitudes away from the equator, and increases considerably near the equator. Similarly, the rate of decrease of N_e in adjacent magnetic field tubes is far less in the vicinity of the equator within $\pm 20°\varphi$ and increases rapidly with latitude in the region outside $\pm 20°\varphi$. Thomas *et al.*[19] (using Alouette-1 data) have pointed out the validity of considering field-aligned scale heights in the topside equatorial region rather than vertical scale heights. This was in view of horizontal field-aligned diffusion likely to be the dominant process at the equator rather than vertical transport. These large low latitude scale-lengths along field lines indicate that a uniform ion species (possibly) light ions) dominates at low latitudes ($\pm 20^\circ \varphi$) unaffected by local perturbations. The light species gives way to a different ion species (possibly heavy ions) with increasing latitude. These conclusions based on Fig. 6 tally with our conclusions from the scale height variations of Fig. 5.

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