Mid-Latitude Electron Density Enhancement in the Nocturnal Topside Ionosphere and Its Longitudinal Inequalities

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A study of data from the cylindrical electrostatic probe and the topside sounder aboard the Alouette 2 satellite reveals the existence of nighttime N_e enhancements at mid-latitudes, at altitudes 1,000–3,000 km. The peaks seem to approach the equator with increasing altitude, and appear to lie on a specific set of geomagnetic field lines. The intensity and location of these nocturnal N_e peaks, as well as the electron density in the entire low- to mid-latitude range, show a marked dependence on geomagnetic longitude. These observations are interpreted in terms of field-aligned flow of thermal plasma from the protonosphere above 3,000 km in the presence of a westward electric field at $L \approx 2$.

1. Introduction and Observations

The occurrence of an enhanced electron density peak at $\pm 40^\circ \phi$ (geomagnetic latitude) in the 1,000 km altitude region at night has been reported by BRACE *et al.* (1967) from observations of the Explorer 22 satellite. MATUURA and ONDOH (1969) also observed a similar N_e peak from their study of nighttime Alouette 2 topside ionograms; they reported it to be visible only up to the altitude of 1,500 km.

The present work shows that these nocturnal mid-latitude N_e peaks are seen at altitudes up to at least 3,000 km (the apogee height of the Alouette 2 satellite). The feature exhibits a marked dependence on equatorial geomagnetic longitude (λ), the intensity of the N_e peak being strongest in the vicinity of $180^\circ \lambda$ and weakest around $0^\circ \lambda$. This geomagnetic longitude dependence is also seen in the electron density values at the lower latitudes of 10° , 20° , and $30^\circ \phi$. The data used is from the topside sounder and the *in situ* cylindrical electrostatic probe aboard the Alouette 2 satellite. Figure 1 shows the latitudinal variation of electron density at constant heights ranging from 400 km to 2,800 km, over

Fig. 1. Latitudinal variation of electron density at constant heights ranging from 400 to 2,800 km for a May midnight pass of the Alouette 2.

the Europe-Africa sector, for a May night. The N_e distribution between 400 and 1,000 km is characterised by sharp irregularities which smooth out at higher altitudes. Above 1,200 km a smooth trough in the electron density forms at the low latitudes, with N_e enhancements at around $\pm 55^\circ$ dip angle. These mid-latitude N_e peaks seem to approach the equator with increasing altitude, moving in from about 60° dip angle at the 1,600 km level to about 40° dip angle at higher altitudes.

It was decided to plot the height contours of constant electron density for the same satellite pass together with the geomagnetic lines of force, as shown in Fig. 2. The field lines with feet at 16, 23, 31, 36, and 41° dip latitude are marked as M_{16} , M_{23} , M_{31} , M_{36} , and M_{41} respectively, and are shown by the dashed curves. They are derived on the assumption of a dipole field model from the equation

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

Fig. 3. Mid-latitude N_e peaks observed by Alouette 2 electrostatic probe in various sectors in the night time hours, and the corresponding T_e latitudinal variations.

The N_e variations of Fig. 3 and other Alouette 2 passes examined showed a dependence of the N_e peak formation on the longitude sector of observation. The equatorial trough and mid-latitude N_e peak features showed most prominently in the East, i.e., Asia-Australia zone (130 to $250^\circ \lambda$ where λ is the equatorial geomagnetic longitude). It was least pronounced in the West, i.e., American zone (280 to $40^\circ \lambda$), and occupied intermediate values in the Inter, i.e., Europe-Africa zone (30 to $130^\circ \lambda$). These observations are based on the N_e

Fig. 4. Topside sounder observations of electron density at various altitudes ranging from 800 to 2,800 km in the various zones. For both local summer and local winter conditions, the N_e mid-latitude peak is most prominent in the East zone.

variations shown in Fig. 4 from the topside sounder data over the different geographic sectors. All these passes are for the nighttime hours, the majority of them being for magnetically quiet intervals of quiet days. The latitudinal variation of electron density at representative heights, ranging from 800 to 2,800 km is shown by the curves. The N_e peak at around 50° dip is very marked in the East zone during both local summer and local winter months. For the

Fig. 5. Latitudinal position of the mid-latitude N_e peak, and its intensity as compared to equatorial N_e , as a function of geomagnetic longitude during local midnight.

same local season, it is less pronounced in the Inter zone, and is almost absent in the West zone.

In view of this longitudinal effect on the N_e peak, it was thought reasonable to plot the latitudinal position and intensity of the peak as a function of the equatorial geomagnetic longitude. Figure 5 shows the longitude dependence of the mid-latitude N_e peak; in the upper curve is shown its location in dip latitude and the second curve expresses the ratio of the crest N_e (value of N_e at the mid-latitude peak) to the trough N_e (value of N_e at the equator). The trend of the curves clearly suggests that the maximum of both parameters would occur in the vicinity of $180^\circ \lambda$. The local time of observation for all the points shown is around midnight hours.

The *in situ* electron density observed by the Alouette 2 probe, at 0, 10, 20, 30, and 40° dip latitude during local midnight hours were also plotted as a function of geomagnetic longitude as shown in Fig. 6. The satellite altitude for these data remained in the vicinity of 2,500 km. Using the information from Fig. 5, namely that the N_e crest maximum is likely to be in the vicinity of $180^\circ \lambda$, sine curves are fitted to the data points for the different latitudes using

Fig. 6. Electron density at 0, 10, 20, 30, 40° dip latitude, as a function of geomagnetic longitude during midnight hours for the altitude range $2,750 \pm 250$ km.

the method of least squares. At most latitudes, the best-fitting sine curve has its maximum at $160^\circ \lambda$. The curves show that for any latitude between 0 and $40^\circ \lambda$, namely in the entire low-latitude belt, the electron density at local midnight hours is largest in the vicinity of $180^\circ \lambda$ and smallest around $360^\circ \lambda$. Examined critically, the figure suggests that the largest electron densities occur at 30° dip latitude.

Assuming symmetry about the dip equator, the global configuration of N_e and T_e during midnight hours for the low latitudes within $\pm 40^\circ \phi$ was obtained from the electrostatic probe observations at different longitudes. These contours correspond to the 2,500–3,000 km observations of the satellite, and are shown in Fig. 7; the units of N_e are 10^3 el/cm³ and those of T_e are degrees Kelvin. The N_e contours show a region of high electron density around $180^\circ \lambda$, with low values around 0 and $360^\circ \lambda$. The dashed line depicts the variation of maximum N_e with geomagnetic longitude. The T_e contours show considerable longitudinal asymmetry in electron temperature within $\pm 40^\circ \phi$. Two regions of low T_e (less than 1,750 K) are conspicuous at the 0 and $360^\circ \lambda$ low-latitude regions, corresponding to low values of N_e in the upper contours. At latitudes beyond $\pm 40^\circ$ however, no marked longitudinal asymmetry is seen in the T_e distribution.

Fig. 7. Low-latitude configuration of N_e and T_e at altitudes $2,750 \pm 250$ km, as a function of geomagnetic longitude, during midnight hours.

2. Discussion

It appears that the formation of an equatorial trough in electron density, with its peaks at $\pm 40^\circ \phi$ is a characteristic of the nighttime exosphere above 1,000 km. This feature is not to be confused with the equatorial F region anomaly in the bottomside below 1,000 km, in which by daytime a low-latitude trough of N_e forms with crests at around $\pm 20^\circ \phi$. The nighttime equatorial trough discussed here gains prominence above 1,000 km.

The gradual increase of ionisation from the equator to $40^\circ \phi$ at 2,500 km altitude suggests that the plasma in the protonospheric regions above 3,000 km flows down along the magnetic flux tubes by nighttime. For some reason, this field-aligned plasma flow maximises at $30^\circ \phi$, and fails to be effective in enhancing N_e beyond $40^\circ \phi$. Since the plasma content of the geomagnetic field tube increases with the volume of the tube (PARK, 1972), it seems reasonable that the contribution from the region above 3,000 km will increase with geomagnetic latitude till plasma removal processes set in.

The possibility of a field-aligned flow of thermal plasma from the nighttime protonosphere into the lower ionosphere was first pointed out by HANSON and ORTENBURGER (1961), and developed later by several workers (HANSON and PATTERSON, 1964; GEISLER and BOWHILL, 1965; NAGY *et al.*, 1968; MOFFETT and MURPHY, 1973). PARK and BANKS (1974) have solved the continuity and momentum equations for H^+ and O^+ with appropriate boundary conditions, using various working models of the thermosphere taken from Tables B of BANKS and KOCKARTS (1973). They clearly show that the nighttime protonosphere above 3,000 km is a thermal plasma reservoir, whose content is hardly depleted by plasma flow into other regions. For a mid-latitude magnetic field tube, a plasma flow of 5×10^8 ion/cm² sec sustained over 4 hr depleted the tube plasma content by only 10%. MARUBASHI and GREBOWSKY (1976) also show that the time constant N_T/F (where N_T is the tube plasma content above 3,000 km, and F is the H^+ ion flux at 3,000 km for a given H^+ ion density at 3,000 km for nighttime hours) is 10^5 to 10^6 sec.

Apparently there is a critical value of H^+ ion density at 3,000 km (denoted by $n(H^+)_{3000}$) which decides whether the H^+ plasma flow is upwards into the protonosphere or downwards into the ionosphere. This critical value is given by BANKS and DOUPNIK (1974) as 9×10^3 ions/cm³. When $n(H^+)_{3000}$ is less than this value, the plasma flow is upwards into the protonosphere; for values exceeding this it is downwards into the ionosphere, with the magnitude of the flow increasing rapidly as $n(H^+)_{3000}$ increases. The observations in this paper then can be explained by a field-aligned flow of thermal plasma from the region above 3,000 km, into the lower regions between 0 and $30^\circ \phi$. The requirement of $n(H^+)_{3000}$ exceeding the critical value of 9×10^3 ions/cm³ for a downward plasma flow is satisfied, as the N_e density in Fig. 3 shows values of 1 to 2×10^4 electrons/cm³ at 2,500 km; this of course is on the assumption of the plasma being electrically neutral and the major ion being H^+ . The OGO-4 observations of CHEN *et al.* (1973) clearly reveal an equatorial trough and enhancements of H^+ ion density at $\pm 40^\circ \phi$ during midnight hours very similar to the N_e pattern seen in Fig. 3.

The observations of Fig. 2 also suggest that the mid-latitude N_e peaks follow some specific field tubes which converge over the equator at around 4,000–5,000 km, i.e., at almost $L=2$. This suggests the presence of a westward electric field at this altitude which gives rise to a cross L drift of the magnetic field tubes through an $\mathbf{E} \times \mathbf{B}$ drift; this would enhance the plasma density in the concerned field tube. The origin of this westward electric field is still elusive. It seems presumptuous to associate this with the dawn to dusk convection electric field as normally one expects this only beyond the plasmapause at $L=4$. However the steep decrease in N_e beyond $40^\circ \phi$ in the observations cited here suggests

that the mechanism responsible for the formation of the mid-latitude plasma-trough starts from $L \approx 2$ itself.

Other workers have explored the effect of electric fields inside the plasmasphere on plasma flow. PARK and BANKS (1974) show that for $n(\text{H}^+)_{3000}$ of 1 or 2×10^4 ions/cm³ there is an H^+ flux of 3 to 5×10^8 ions/cm² sec downwards into the mid-latitude ionosphere, for zero electric field. In the presence of a westward electric field, the downward flux along the field tube increases in proportion to the intensity of the electric field; an eastward electric field tends to reduce the downward plasma flow. The model calculations of MARUBASHI and GREBOWSKY (1976) show that altitudes below 1,000 km are not affected by such electric fields; higher altitudes respond with a change in ion density, and plasma tube content above 3,000 km changes to some extent. Their work shows that the rate of change of the plasma tube content in a specific field tube due to the convection electric field is

$$\frac{\partial}{\partial t} N_T \approx \left(\frac{L}{L_{\text{stag}}} \right)^2 \omega N_T,$$

where

$L = L$ value of concerned field tube,

$L_{\text{stag}} = L$ value of stagnation point, generally at dusk with a quiet time value of 7,

$\omega =$ angular velocity of corotation in radians,

$N_T =$ plasma tube content above 3,000 km in ions/tube.

For $L = 3.2$, and $N_T \approx 10^{13}$ ions/tube, MARUBASHI and GREBOWSKY (1976) show that the rate of change of N_T is between 10^8 to 10^9 ions/sec/tube. Substitution of $L = 2$ yields the rate of change to be $\approx 10^8$ ions/sec/tube. In either case this change in tube content almost matches the normal H^+ flux along the magnetic field tubes existing in the absence of electric field.

The strong geomagnetic longitude dependence shown by this N_e peak feature also suggests that an $\mathbf{E} \times \mathbf{B}$ drift mechanism is involved in its formation. The vicinity of $180^\circ \lambda$ is the region where the earth's equatorial magnetic field has the largest intensity (0.40 Gauss), while $0^\circ \lambda$ is the sector with the smallest equatorial field intensity (0.26 Gauss). Any phenomenon involving the equatorial field intensity would show a sharp contrast between the 0 and $180^\circ \lambda$ sectors as is suggested by the results in this paper.

The role played by T_e in the formation of this N_e peak is not clear and requires further study. Averaged values of nighttime N_e at the 2,500 km altitude region suggest that the mid-latitude N_e peak gains prominence in solstitial months and is flattened out in equinoctial months (RAJARAM and OBAYASHI, 1977). Some investigation is also required on the seasonal dependence of the N_e

peak. It appears that field-aligned diffusion of plasma from the protonosphere above 3,000 km, together with a westward electric field in the region of $L \approx 2$ can cause the formation of this mid-latitude N_e peak, and its geomagnetic longitude inequality.

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REFERENCES

- BANKS, P.M. and J.R. DOUPNIK, Thermal proton flow in the plasmasphere: The morning sector, *Planet. Space Sci.*, **22**, 79–94, 1974.
- BANKS, P.M. and G. KOCKARTS, *Aeronomy*, Part B, p. 311, Academic Press, New York, 1973.
- BRACE, L.H., B.M. REDDY, and H.G. MAYR, Global behaviour of ionosphere at 1,000 km altitude, *J. Geophys. Res.*, **72**, 265–283, 1967.
- CHEN, A.J., J.M. GREBOWSKY, and H.A. TAYLOR, Jr., Light ion trough structure—A combination of orbital geometry and plasmasphere dynamics, presented at Chapman Memorial Symposium, Boulder, Colorado, June, 1973.
- GEISLER, J.E. and S.A. BOWHILL, An investigation of ionosphere-protonosphere coupling, Aeron. Rep. 5, Univ. of Ill., Urbana, 1965.
- HANSON, W.B. and I.B. ORTENBURGER, The coupling between the protonosphere and the normal F region, *J. Geophys. Res.*, **66**, 1425–1435, 1961.
- HANSON, W.B. and T.N.L. PATTERSON, The maintenance of the night-time F layer, *Planet. Space Sci.*, **12**, 979–997, 1964.
- MARUBASHI, K. and J.M. GREBOWSKY, A model study of diurnal behaviour of the ionosphere and the protonosphere coupling, *J. Geophys. Res.*, **81**, 1700–1706, 1976.
- MATUURA, N. and T. ONDOH, The structure of the topside ionosphere deduced from Alouette data, *Proc. IEEE*, **57**, 1150–1154, 1969.
- MOFFETT, R.J. and J.A. MURPHY, Coupling between the F region and protonosphere: Numerical solution of the time-dependent equations, *Planet. Space Sci.*, **21**, 43–52, 1973.
- NAGY, A.F., P. BAUER, and E.G. FONTHEIM, Night-time cooling of the protonosphere, *J. Geophys. Res.*, **73**, 6259–6274, 1968.
- PARK, C.G., Methods of determining electron concentrations in the magnetosphere from nose whistlers, Tech. Rep. 3454-1, Radio Sci. Lab., Stanford Univ., Stanford, Calif., 1972.
- PARK, C.G. and P.M. BANKS, Influence of thermal plasma flow on the mid-latitude night-time F_2 layer: Effects of electric fields and neutral winds inside the plasmasphere, *J. Geophys. Res.*, **79**, 4661–4668, 1974.