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A case study of whistlers recorded at Varanasi ($L = 1.07$)

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Large number of high dispersion whistlers recorded at low latitude station Varanasi ($L = 1.07$) are analysed and it is find out that they have propagated along $L \simeq 2.12$–2.76. This is explained by considering the propagation of whistlers through the earth-ionosphere wave guide after exiting from the duct towards the equator. Using diffusive equilibrium model (DE-1), we have estimated equatorial electron density, total electron content in a flux tube and large scale convective electric fields which are in good agreement with the results reported by other workers from the analysis of mid latitude whistlers. The significance of this paper is to probe mid latitude plasmasphere using whistlers recorded at low latitudes. Further, an attempt has been made to study the propagation mechanism of low latitude whistlers.

1. Introduction

Whistlers, the dispersed form of electromagnetic signal propagating along geomagnetic field lines through the magnetosphere, yield information about medium parameters such as electron density, total electron content in a flux tube, electron temperature, electric field etc. In comparison to mid/high latitudes, the estimation of these parameters at low latitudes are not well documented, may be because the occurrence rate is large only during magnetic storm periods (when field aligned irregularities are enhanced) and they suffer from severe propagation conditions such as shorter path length, larger curvature gradients in the embedded magnetic field, duct excitation, trapping into and leakage from the ducts, duct spacings, ionospheric transmission and so on. In this paper an attempt has been made to probe mid latitude plasmasphere by analysing whistlers recorded at low latitude station Varanasi.

Park *et al.* (1978) analysed whistlers recorded at Siple ($L = 4$), Eights ($L = 4$), Byrd ($L = 7$) all in Antarctica and Stanford ($L = 2$) in California and studied diurnal and seasonal variation of electron density and associated total electron content. Tarcsai *et al.* (1988) processed whistler data collected at Tihany ($L = 1.9$) in Hungary and studied equatorial electron density distribution and total electron content in flux tubes between $L = 1.4$ and 3.2. As compared to mid/high latitudes (Sazhin *et al.*, 1992 and references there in), the exploitation of low latitude whistler data in the determination of equatorial electron density and total electron contents has been carried out in isolated cases only (Lalmani *et al.*, 1992, 1996; Singh, 1993a,b; Singh *et al.*, 1993, 1998).

Continuous whistler recording sometimes exhibits inward/outward drift of whistler path in the equatorial region of the plasmasphere. Considering this drift to be caused by large scale electric fields, the latter is evaluated from the analysis of whistlers (Bernard, 1973; Block and Carpenter, 1974; Park, 1976). Carpenter *et al.* (1972) and Sagredo *et al.* (1973) have shown that in an active period, if a large number of whistlers are analysed, the electric field can be estimated with a precision of 0.1 mV/m.

In this paper we report the results of analysis of whistlers recorded at low latitude station Varanasi (geomag. lat. $14°55'$N) whose path of propagation lies in the mid latitude magnetospheric region and it is assumed that they reached Varanasi through earth-ionosphere wave guide. The analysis show that the equatorial electron density and total electron content in a flux tube lies between 1.0×10^2–5.0×10^2 electrons cm^{-3} and 8.4×10^{12}–1.5×10^{13} electrons/cm^2-tube respectively for $L = 2.12$–2.76. The electric field comes out to be 0.2–0.3 mV/m and it is westward during post-midnight period. The results are for an isolated event but it is important as it provides an independent check and an extension to lower latitudes of the profiles published by workers at high and mid latitudes.

2. Observations and Analysis

At low latitudes whistler activity is usually low but it enhances during magnetic storm periods may be due to formation of additional ducts (Singh, 1993a,b). For the present study we have chosen whistlers recorded on 9th March 1991 between 0025 h and 0330 h IST. During this period K_p index varied between 3 and 4, and large number of good quality whistlers were recorded. Figure 1 shows a sequence of six sonograms of selected whistlers corresponding to different times of occurrence. All the whistlers have been arranged in such a way that the causative sferics lie on a single vertical line. W1, W2, . . . , W6 are labelled for identification of whistlers.

In the whistler analysis, frequency and corresponding arrival time are measured from the recorded spectrogram and dispersion is evaluated. The group travel time for the whistler wave from the source to the observer is written as

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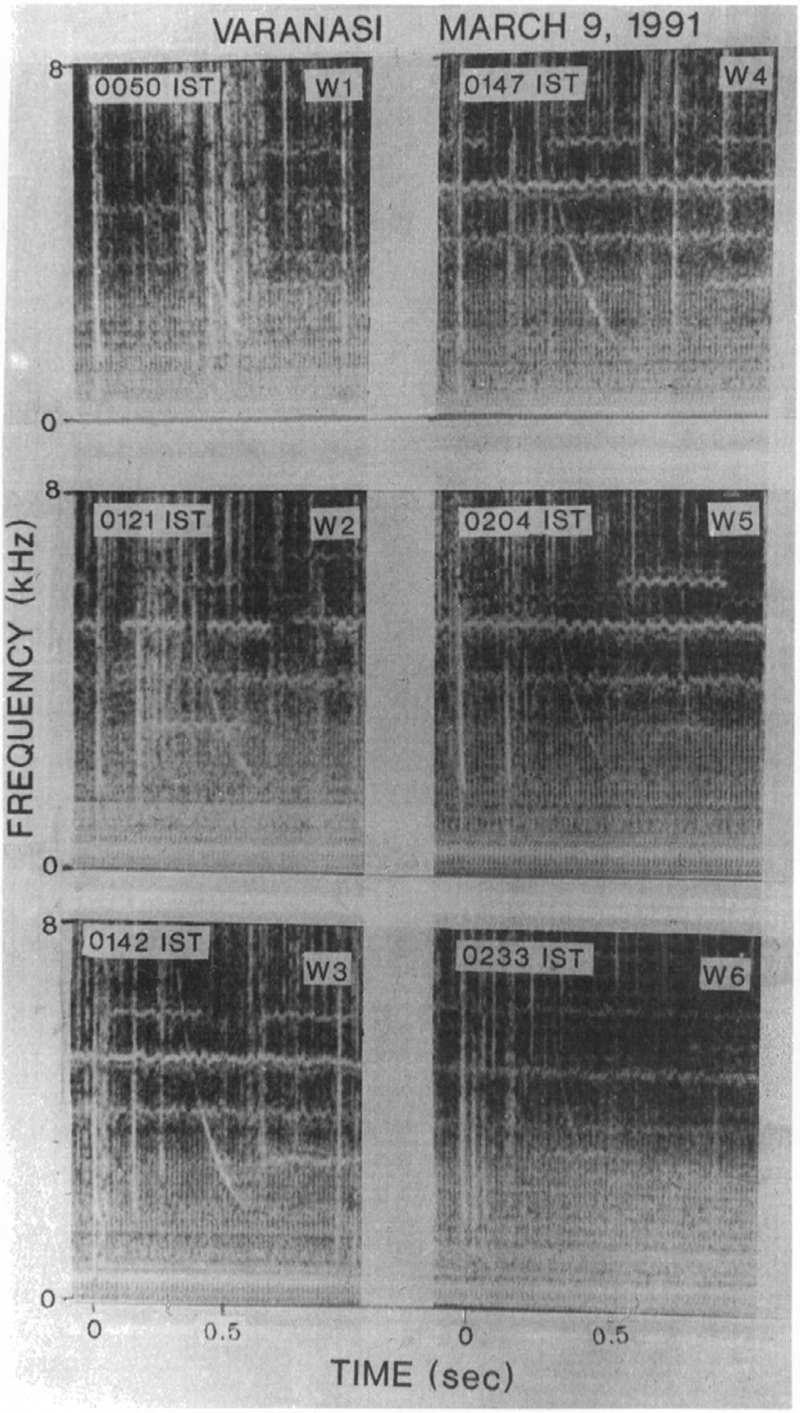

Fig. 1. Sonograms of whistlers observed at Varanasi.

$$t = t_s + t_w + t_{ion} + t_{mag} \qquad (1)$$

where t_s is the time taken by the sferics propagating through the earth-ionosphere wave guide from lightning source to the receiver, which is negligible small, t_w is the time taken by the whistler wave in the earth-ionosphere wave guide after exiting from the duct, t_{ion} is the time delay due to ionospheric path, t_{mag} is the time delay for magnetospheric path. The time t_w varies from event to event and can be evaluated only when ionospheric exit location from the duct are precisely known. In the absence of such information, Singh *et al.* (1993) have suggested an average value of $t_w \sim 10$ ms. In the evaluation of t_w it was assumed that the medium enclosed in the earth-ionosphere wave guide behaves like a free space.

The group delay time for ionospheric path is evaluated by using the formulation of Park (1972) which depends on critical frequency of the F_2-layer of the ionosphere. The critical frequency (f_0F_2) varies from place to place in the post-midnight period. Based on the measurement of f_0F_2 at the nearby station Ahmedabad, we consider its representative value for the present computation as 5 MHz. The t_{ion} for 5 kHz whistler wave frequency comes out to be 98 ms. Taking into account uncertainty in critical frequency of the F_2-layer, we have considered a representative value of $t_{\mathrm{ion}} \cong 100$ ms. Thus, with these corrections, we can write (Singh, 1993b, 1995; Singh *et al.*, 1993)

$$\begin{aligned} t - t_{\mathrm{w}} - t_{\mathrm{ion}} & \\ = t_{\mathrm{mag}} = \frac{R_{\mathrm{e}} L}{2c} \int_0^{\phi'} & \frac{f_{\mathrm{p}}(\phi)}{f^{1/2}} \\ \cdot \frac{f_{\mathrm{He}} \cos^6 \phi_0 (1 + 3\sin^2\phi)}{\cos^5\phi \left[f_{\mathrm{He}} \dfrac{\cos^6\phi_0}{\cos^6\phi} (1 + 3\sin^2\phi)^{1/2} - f \right]^{3/2}} & d\phi \end{aligned} \tag{2}$$

where f_{p} and f_{He} are local electron plasma frequency and equatorial electron gyrofrequency, respectively. ϕ' is the geomagnetic latitude at reference height 1000 km above the ionosphere, R_{e} is the earth's radius, L is McIlwain parameter and ϕ_0 is the geomagnetic latitude of the field line at the surface of the earth. To evaluate the integral in Eq. (2), out of various models, diffusive equilibrium (DE-1) model (Park, 1972) for the distribution of electron density along the field lines is considered. This model has been widely used in whistler analysis by earlier workers (Park, 1972; Tarcsai *et al.*, 1988; Sazhin *et al.*, 1992). According to this model at the level of 1000 km (reference height) temperature = 1600 K, concentration of $\mathrm{O}^+ = 90\%$, $\mathrm{H}^+ = 8\%$ and $\mathrm{He}^+ = 2\%$. Sazhin *et al.* (1992) have shown that in the diffusive equilibrium model we can write

$$\begin{aligned} f_{\mathrm{p}}(\phi) = (f_{\mathrm{peq}}/\cos\phi) & \\ \cdot \left[\left(\sum_{\mathrm{i}} \xi_{\mathrm{i}} e^{-z/H_{\mathrm{i}}} \right) \Big/ \left(\sum_{\mathrm{i}} \xi_{\mathrm{i}} e^{-z_{\mathrm{eq}}/H_{\mathrm{i}}} \right) \right]^{1/4} & \end{aligned} \tag{3}$$

where summation is over the ionic species (O^+, He^+, H^+), ξ_{i}, the fractional concentration of ion specy, $H_{\mathrm{i}} = kT_{\mathrm{i}}/m_{\mathrm{i}} g_{\mathrm{ref}}$, k is Boltzmann's constant, g_{ref} is the acceleration due to gravity at the reference level, T_{i} is the ion temperature at the reference level (which is taken as equal to electron temperature) m_{i} is the mass of the ion and

$$z \equiv \frac{r_{\mathrm{ref}}}{2} \left(1 - \frac{r_{\mathrm{ref}}^2}{r_\phi^2} \right) \tag{4}$$

where r_{ref} is the geocentric distance of the reference level, r_ϕ is the distance from the earth's center to the given point in the magnetosphere corresponding to latitude ϕ, z_{eq} is the value of z corresponding to the equatorial point. Using Eqs. (2) and (3), t_{mag} is numerically evaluated and hence equatorial electron density is evaluated.

Before evaluating the integral, path of propagation is determined, which requires the estimation of nose frequency f_{n}. In an attempt to estimate f_{n} and group travel time, Dowden and Allcock (1971) introduced $Q(f) = 1/D(f)$ and suggested a linear relation $q(f) = q_0(1 - f/\alpha f_{\mathrm{n}})$ where $\alpha = 3.09 \pm 0.04$, $q_0 = 1/D_0$, D_0 is the zero frequency dispersion. Bernard (1973) discussed this assumption in detail and pointed out more consistent definition of $q(f)$, which is written as

$$q(f) = q_0 \frac{1 - \Lambda_{\mathrm{n}} f/f_{\mathrm{n}}}{1 - A\Lambda_{\mathrm{n}} f/f_{\mathrm{n}}} \tag{5}$$

where $\Lambda_{\mathrm{n}} = f_{\mathrm{n}}/f_{\mathrm{Heq}}$, $A = \frac{3\Lambda_{\mathrm{n}} - 1}{\Lambda_{\mathrm{n}}(1 + \Lambda_{\mathrm{n}})}$. From Eq. (5) we can write $q(f_{\mathrm{n}}) = \frac{1 + \Lambda_{\mathrm{n}}}{D_0}$. Using these relations and Eq. (2) we obtain

$$\frac{t_{\mathrm{mag}}}{t_{\mathrm{n}}} = \frac{1}{2(f/f_{\mathrm{n}})^{1/2}} \frac{[1 + \Lambda_{\mathrm{n}} - (3\Lambda_{\mathrm{n}} - 1) f/f_{\mathrm{n}}]}{(1 - \Lambda_{\mathrm{n}} f/f_{\mathrm{n}})}. \tag{6}$$

Thus using Eq. (6) and measuring frequency f and time t at any two points of the spectrum (when initiating sferic is known), f_{n} and t_{n} can be evaluated. In the absence of initiating sferics, group delays for different frequencies from a chosen sferic are measured and simultaneously a set of equations are solved to determine f_{Heq} and hence f_{n} ($f_{\mathrm{n}} = 0.4 f_{\mathrm{Heq}}$) and t_{n}. From the knowledge of f_{He}, the propagation path ($L = 95.6\, f_{\mathrm{He}}^{-1/3}$ (Hz)) along which the scaled whistlers have propagated is evaluated.

The knowledge of f_{Heq}, D_0 and group travel time are used to estimate equatorial electron density and its distribution along the geomagnetic field lines. Total electron contents in a magnetic flux tube of unit cross sectional area at the reference height is estimated by evaluating the integral (Park, 1972; Sagredo *et al.*, 1973; Singh *et al.*, 1993)

$$N_{\mathrm{T}} = \int_{\mathrm{ref}}^{\mathrm{Equator}} N(s) \frac{B_{\mathrm{r}}}{B(s)} ds \tag{7}$$

where B_{r} is the magnetic field at the reference level, $B(s)$ is the magnetic field strength at any other point "s" along the geomagnetic field line which is considered to be path of propagation for the ducted whistlers, and ds is elementary path length along the whistler path.

The knowledge of drift of whistler path is used to estimate the east-west component of electric field in the equatorial plane (Park, 1976). The whistler path is determined by the nose frequency, hence, any systematic increase or decrease in nose frequency with time can be interpreted as change of whistler path with time. The equatorial electric field is given by (Bernard, 1973; Park, 1976)

$$E_{\mathrm{w}} = 2.07 \times 10^{-2} \frac{d}{dt} (f_{\mathrm{n}})^{2/3} \ \mathrm{V/m} \tag{8}$$

where f_{n} is measured in Hz. The direction of electric field depends upon whether f_{n} increases or decreases with time. When $d(f_{\mathrm{n}})/dt$ is positive, then the electric field is directed from east to west.

3. Results and Discussions

The whistler dispersion depends upon electron/ion density, geomagnetic field and their distribution along the path of propagation, hence it varies from station to station and also from event to event. Based on detailed analysis Somayajulu *et al.* (1972) showed that the dispersion of whistlers which followed field lines of Gulmarg (geomag. lat. 24°10′N) and Nainital (geomag. lat. 19°1′N) should be of the order of 24 and 19 $\mathrm{sec}^{1/2}$ respectively, whereas for Varanasi station it should be $\sim$12 $\mathrm{sec}^{1/2}$ (Singh, 1993a). These values of dispersion are without any correction for ionospheric and wave guide path. If these corrections are taken into account then these values would further reduce to 17, 11 and 5 $\mathrm{s}^{1/2}$. Figure 2 shows that the whistler dispersion (after ionospheric and wave guide propagation corrections are made) recorded at

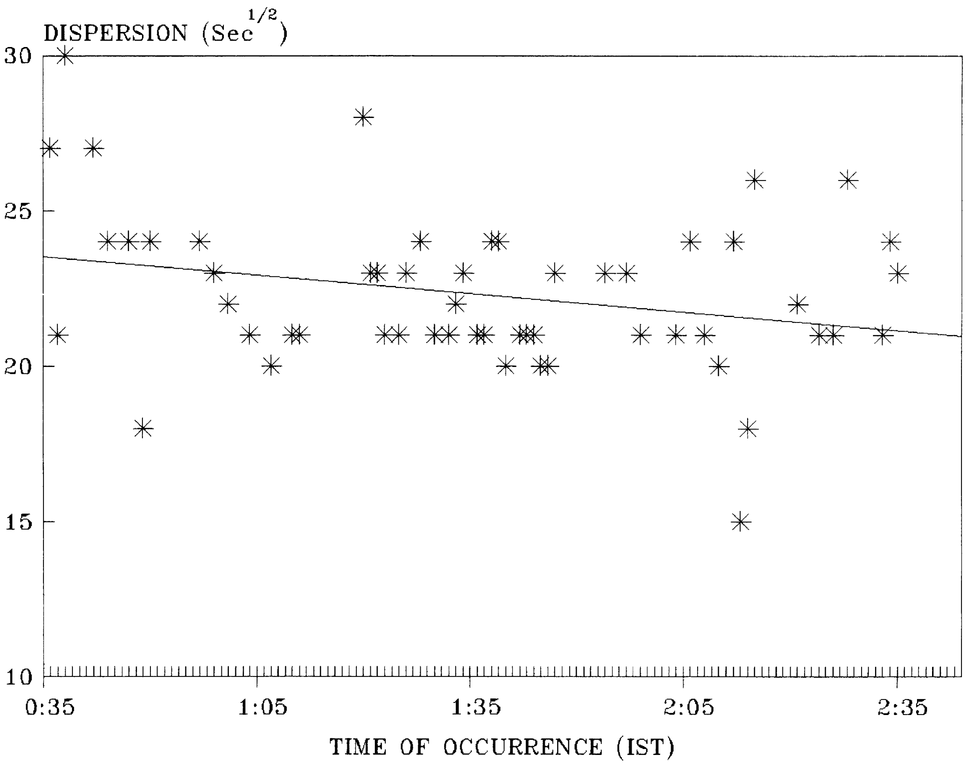

Fig. 2. Variation of whistler dispersion with time.

Varanasi are greater than 15 sec$^{1/2}$, which for low/equatorial latitude stations could be called as high dispersion whistlers.

The nose extension method applied to these data yield the path of propagation lying between L = 2.12–2.76 although the L-value of receiving station (Varanasi) is 1.07. Few whistlers from the reported data were also analysed using matched filtering and parameter estimation technique (Hamar *et al.*, 1990) and the determined path is within 10% of the value reported in this paper. The matched filtering technique has better resolution. Singh *et al.* (1993) have shown that the L-values derived from whistler analysis using Dowden and Allcock's (1971) method and Tarcsai's (1985) curve fitting method lie within ±10%. Tarcsai *et al.* (1989) have shown that the error in L-value may be less than 1%. The variation in path during the recording period $\Delta L \approx 0.64$. Thus, it is seen that the whistlers propagated along higher L-values in the magnetosphere and after exit from the ionosphere are received at ground station corresponding to lower L-value. This is only possible if the wave after exiting from the ionosphere propagated through the earth-ionosphere wave guide towards the equator without attenuation. Such propagation mechanism was discussed by Singh *et al.* (1992). The lower cut-off frequency for all the recorded whistlers lies between 1.7 and 3.9 kHz (Fig. 3) and are higher than the fundamental cut-off frequency of the earth-ionosphere wave guide (~1.67 kHz). Figure 3 shows that the large number of whistlers have lower cut-off frequencies lying between 1.9 and 2.5 kHz. The propagation of whistlers in the earth-ionosphere wave guide has also been confirmed using dynamic spectra containing additional traces (Shimakura *et al.*, 1991). The whistler wave entering into the earth-ionosphere wave guide may propagate either towards equator or towards pole depending upon the wave normal angle of the whistler wave at the time of entrance into the wave guide. Figure 2 shows that the whistler dispersion decreases with time although the data are quite scattered. The change in dispersion

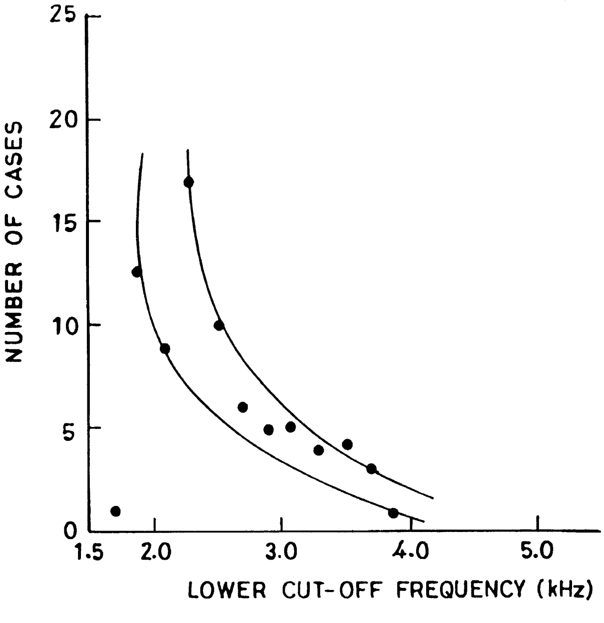

Fig. 3. Distribution of whistlers with lower cut-off frequency.

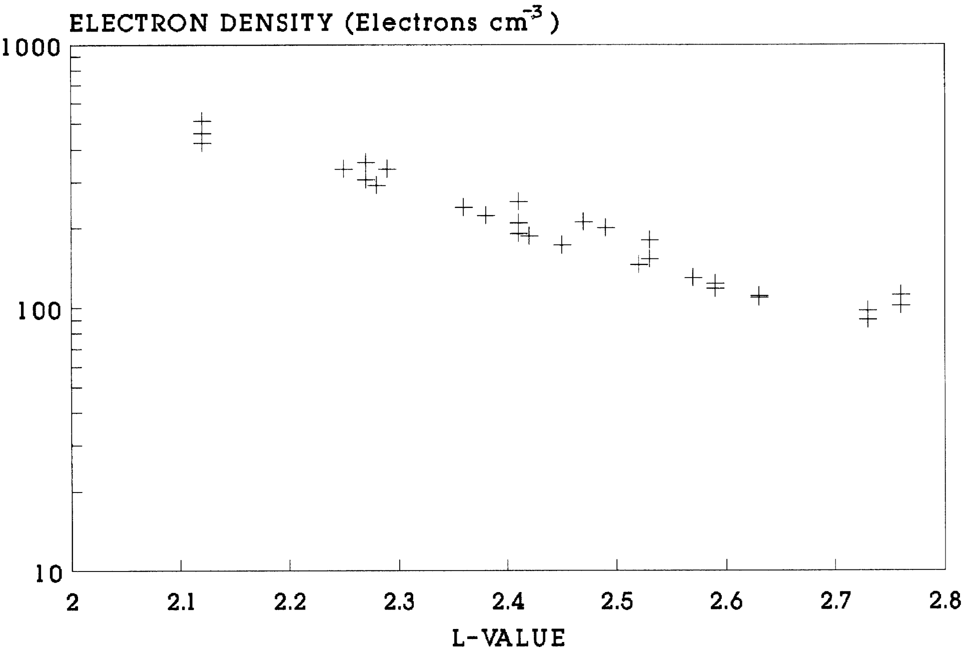

Fig. 4. Distribution of electron density in the equatorial region of L-value.

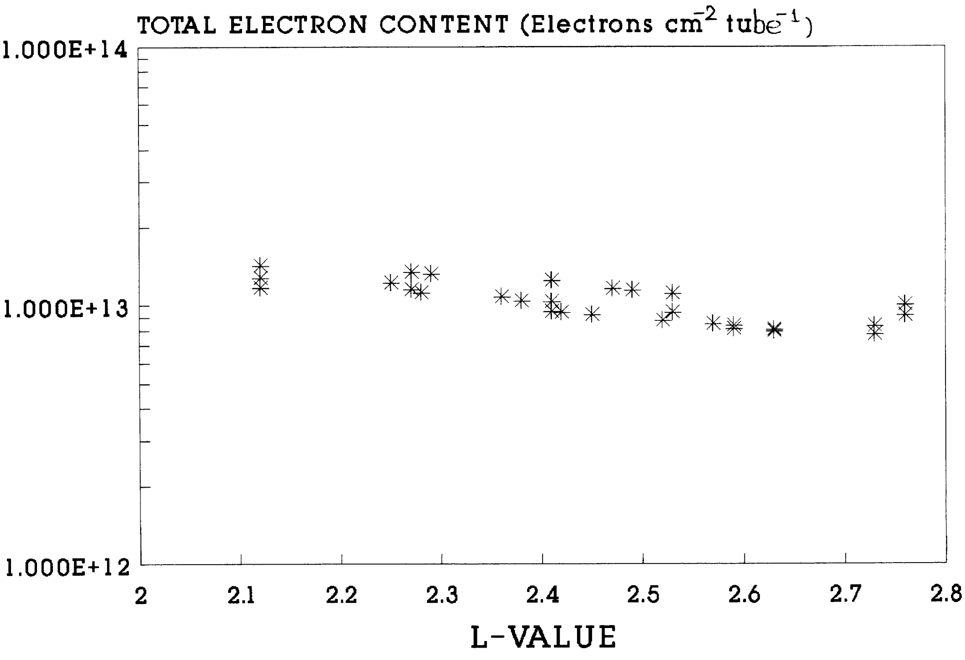

Fig. 5. Distribution of total electron content in a flux tube of different L-values.

could be either due to change in electron density distribution in the duct or due to change in the location of the duct through which whistlers have propagated or it may be due to both. For a fixed path, variation of dispersion with time yields information about variation in electron density distribution and hence changes in total electron flux. On the other hand, the change in path yields information about east-west component of electric field.

The equatorial electron density for diffusive equilibrium model (DE-1) is estimated by analysing all the recorded whistlers. Figure 4 shows the variation of equatorial electron density as a function of L-value. The electron density reported in this paper in general is of the same order of magnitude as that derived from whistler data recorded at mid latitude station Tihany ($L = 1.9$), Hungary and high latitude station Siple ($L = 4$) and follows the same trend as far as variation with L-value is concerned (Park *et al.*, 1978; Tarcsai *et al.*, 1988). The equatorial electron density derived

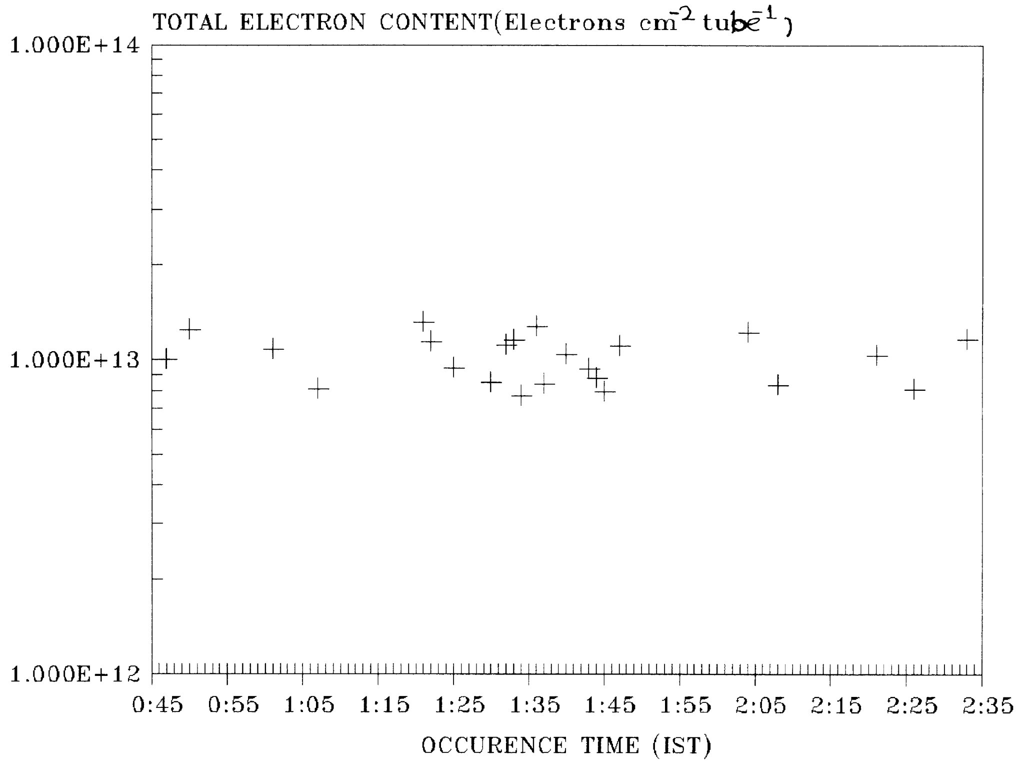

Fig. 6. Distribution of total electron content in a flux tube with observation time.

from whistlers W1 and W2 is 253 and 336 electrons cm^{-3} respectively. Whistlers W1 and W2 have followed the path $L = 2.4$ and 2.3. The minimum and maximum value of the equatorial electron density for the whistlers recorded on 9th March, 1991 comes out to be 1.0×10^2 and 5.0×10^2 electrons cm^{-3}. Park *et al.* (1978) has reported electron density 3.0×10^3 electrons cm^{-3} at $L = 2$ whereas Tarcsai *et al.* (1988) has reported 2.0×10^4 electrons cm^{-3} at $L = 1.4$ and 5.0×10^2 electrons cm^{-3} at $L = 3.2$. Thus numerically our results are not far away from the previously reported values by other workers. Singh *et al.* (1993) reported average equatorial electron density for Varanasi ($L = 1.07$) $\approx 5.5 \times 10^4$, for Nainital ($L = 1.12$) $\approx 12.0 \times 10^4$ and for Gulmarg ($L = 1.2$) $\approx 16 \times 10^4$ electrons cm^{-3}. These are in increasing order contrary to the observed decreasing electron density with increasing L-value. They have explained that the recorded data were for different time periods and the level of magnetic activity during the observation period varied. At low L-values ($L < 2$), there is an increasing tendency to underestimate the electron densities due to unavoidable approximations in the whistler analysis (Tarcsai, 1981; Tarcsai *et al.*, 1989; Singh *et al.*, 1993; Singh and Singh, 1997).

The total electron content (Fig. 5) shows slight decrease with L-value although all the values lie between 8.4×10^{12} and 1.5×10^{13} electrons/cm^2-tube. The total electron content reported in this paper is of the same order as reported by other workers (Park *et al.*, 1978; Tarcsai *et al.*, 1988; Lalmani *et al.*, 1992; Singh *et al.*, 1993). Singh *et al.* (1993) have reported total electron contents for Varanasi, Nainital and Gulmarg to be 2.1×10^{13}, 4.5×10^{13} and 7.5×10^{13} electrons/cm^2-tube respectively. This increase in tube electron content with increase in L-value has been attributed to severe magnetic activity which was prevailing during the period of collection of data. The activity was maximum for Gulmarg ($K_p = 7$–9), followed by Nainital ($K_p = 2$–5) and Varanasi ($K_p = 1$–4). The total electron contents for whistlers W1 and W2 comes out to be 1.24×10^{13} and 1.31×10^{13} electrons/cm^2-tube respectively. The change in total electron content may be due to change in path of propagation of whistlers. We may also look at change in total electron content with time. We have plotted the variation of total electron content as a function of time which is shown in Fig. 6. Here, it may be remembered that the evaluated total electron flux is for different L-value. We observe that the ionization flux varies with time. The rate of change of electron flux distributed over $\Delta L = 0.64$, is found to be 1.1×10^9 electrons $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. We can not compare these results with the previous works (Singh *et al.*, 1993; Singh and Singh, 1997) because they have evaluated transport of ionization flux for almost fixed L-values, where as in the present case the recorded whistlers were distributed over L-values lying between 2.12 and 2.76.

In the present computation we have used diffusive equilibrium model DE-1, although more recent and modified model incorporating temperature gradients which has produced results consistent with satellite measurements (Strangeways, 1986) is available. The model with temperature gradient is complicated to handle and provides the refinements on the available results. The contribution of temperature gradient at mid latitudes is much smaller than at low latitudes and the whistlers which we are analysing belong to mid latitudes, although they are recorded at low latitude. Further, the assumption that the contribution of ionosphere to the total observed dispersion does not change with the progress of time during night hours is strictly not valid because even critical frequency of F_2-layer changes with time during post-midnight. Apart from this, even the location of F_2 peak varies with time and with magnetic activity. These effects will cause some changes in the ionospheric dispersion which will change the equatorial electron density and total electron content in the flux tube. In spite of these limitations, the present effort to study mid latitude electron density profile using whistlers recorded at low latitude is scientifically important.

Using Eq. (8) equatorial electric fields corresponding to $L = 2.12$–2.76 during post-midnight sector come out to be ~0.2–0.3 mV/m in close agreement with those reported by other workers (Block and Carpenter, 1974; Andrews *et al.*, 1978; Park, 1978; Mishra *et al.*, 1980; Saxton and Smith, 1989; Singh *et al.*, 1998). Khosa *et al.* (1982) evaluated electric fields from whistlers recorded at Gulmarg ($L = 1.2$) and Nainital ($L = 1.12$) showed that the electric fields during the observation periods in the equatorial plane of the recording station was directed eastward in the pre-midnight sector with the magnitude of 0.33–0.70 mV/m and 0.3 mV/m respectively. Further, They also found westward field in the post-midnight sector with magnitudes of 0.2–0.7 mV/m, 0.3–0.5 mV/m and 0.1–0.3 mV/m in the equatorial plane of Gulmarg, Nainital and Varanasi respectively. Ralchovski (1981), analysing whistler data recorded at Sofia ($L = 1.6$) between 1500 h and 1800 h LT, reported eastward electric field having magnitude 0.44–0.54 mV/m. Carpenter (1978) using whistler data recorded on four consecutive magnetically quiet days estimated westward component of the magnetospheric electric field at the equator ($L = 4$) ~ 0.1 mV/m and showed that the electric field decreased rapidly as $L^{-3/2}$ with increasing distance. The analysis strongly supported the concept that the observed electric fields originated at middle to low latitudes, apparently in an ionospheric dynamo process (Carpenter, 1978).

In the determination of electric field, dipolar geomagnetic field has been assumed. This assumption is valid as long as the ring current is weak and the geomagnetic condition is quiet. On such occasions the electric field is also weak (Carpenter, 1978). However, both the ground-based and in-situ measurements show fast changes in the magnetic field, particularly during sudden commencements and substorm expansion and recovery phases. Thus, there is deviation from dipole geometry during severe magnetic activity, which introduces certain systematic errors in the estimation of electric field. The temporal fluctuations in magnetic field induces electric field and hence a suitable correction is also required to the westward electric field deduced from the total change in the nose frequency (Block and Carpenter, 1974). In fact, the inter-relations between the magnetic field dynamics, electric fields and plasma movements in the plasmasphere are to be solved, in order to understand the problems related with electric fields.

4. Conclusions

The mid latitude whistler data recorded at Varanasi ($L = 1.07$) on March 9, 1991 during post-midnight period are analysed to study the propagation characteristics, the equatorial electron density, total electron content and electric field. We have shown that whistlers recorded at Varanasi have actually travelled along L-values lying in the range 2.12 to 2.76 in the hybrid mode. The electron density in the equatorial region varied between 100 and 500 electrons cm^{-3} as L varied from 2.76 to 2.12. The equatorial electron density decreases with altitude as is expected. The total electron content slightly decreases with L-values, although all the values lie in the range 8.4×10^{12} and 1.5×10^{13} electrons/cm^2-tube. The calculated value of electric field is found to be in the range of 0.2–0.3 mV/m. The electron density and electron flux derived from whistler data usually show upper limits but these results are very much useful in comparing the electron density measurements obtained by other techniques. Sometimes these results are used in planning the experiments to measure them by in-situ probes. The significance of the present study is that we are able to evaluate the electron density, total electron content and the electric field in the equatorial region of $L = 2.12$–2.76 by recording whistlers at low latitude station Varanasi ($L = 1.07$).

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References

Andrews, M. K., F. B. Knox, and N. R. Thomson, Magnetospheric electric fields and protonospheric coupling fluxes inferred from simultaneous phase and group path measurement on whistler-mode signals, *Planet. Space Sci.*, **26**, 171–183, 1978.

Bernard, L. C., A new nose extension method for whistlers, *J. Atmos. Terr. Phys.*, **35**, 871–880, 1973.

Block, L. P. and D. L. Carpenter, Derivation of magnetospheric electric fields from whistler data in a dynamic geomagnetic field, *J. Geophys. Res.*, **79**, 2783–2789, 1974.

Carpenter, D. L., New whistler evidence of a dynamo origin of electric fields in the quiet plasmasphere, *J. Geophys. Res.*, **83**, 1558–1564, 1978.

Carpenter, D. L., K. Stone, J. C. Siren, and T. L. Crystal, Magnetospheric electric field deduced from drifting whistler paths, *J. Geophys. Res.*, **77**, 2819–2836, 1972.

Dowden, R. L. and G. M. Allcock, Determination of nose frequency of non-nose whistlers, *J. Atmos. Terr. Phys.*, **33**, 1125–1129, 1971.

Hamar, D., G. Tarcsai, J. Lichtenberger, A. J. Smith, and K. H. Yearby, Fine structure of whistler recorded digitally at Halley, Antarctica, *J. Atmos. Terr. Phys.*, **52**, 801–810, 1990.

Khosa, P. N., M. M. Ahmad, and Lalmani, Whistler observation of magnetospheric electric field in the night side plasmasphere at low latitudes, *The Moon and Planet*, **27**, 453–462, 1982.

Lalmani, A. Ahmad, and M. M. Ahmad, Ionosphere plasmasphere coupling electron fluxes from low latitude whistler studies at Nainital during geomagnetic storm, *Planet. Space Sci.*, **40**, 1409–1418, 1992.

Lalmani, A. Ahmad, and R. Singh, An estimate of quiet time plasmaspheric electric fields from whistler observations at low latitude, *J. Geomag. Geoelectr.*, **48**, 211–220, 1996.

Mishra, K. D., Lalmani, and B. D. Singh, Magnetospheric electric field from low latitude whistlers during magnetic storm, *Planet. Space Sci.*, **28**, 449–452, 1980.

Park, C. G., Methods of determining electron concentration in the magnetosphere from nose whistlers, Tech. Report No. 3454-1, Radioscience Lab., Stanford University, Stanford, 1972.

Park, C. G., Substorm electric fields in the evening plasmasphere and their effects on the underlying F-layer, *J. Geophys. Res.*, **81**, 2283–2288, 1976.

Park, C. G., Whistler observations of substorm electric fields in night side plasmasphere, *J. Geophys. Res.*, **83**, 5773–5777, 1978.

Park, C. G., D. L. Carpenter, and D. B. Wiggin, Electron density in the plasmasphere: whistler data on solar cycle, annual, and diurnal variations, *J. Geophys. Res.*, **83**, 3137–3144, 1978.

Ralchovski, T. M., Electric field in the inner plasmasphere obtained from whistlers daytime observations, *Rep. Bulg. Acad. Sci.*, **34**, 1503–1504, 1981.

Sagredo, J. L., I. D. Smith, and K. Bullough, The determination of whistler nose-frequency and minimum delay and its implication for the measurements of the east-west electric field and tube content in the magnetosphere, *J. Atmos. Terr. Phys.*, **35**, 2035–2046, 1973.

Saxton, J. M. and A. J. Smith, Quiet time plasmaspheric electric fields and plasmasphere, ionosphere coupling fluxes at $L = 2.5$, *Planet. Space Sci.*, **37**, 283–293, 1989.

Sazhin, S. S., M. Hayakawa, and K. Bullough, Whistler diagnostics of magnetospheric parameters: A review, *Ann. Geophys.*, **10**, 293–308, 1992.

Shimakura, S., M. Moriizumi, and M. Hayakawa, Propagation mechanism of very unusual low latitude whistlers with additional traces of the earth-ionosphere waveguide propagation effect, *Planet. Space Sci.*, **39**, 611–616, 1991.

Singh, A. K., Study of inner magnetosphere by VLF waves, Ph.D. Thesis, Banaras Hindu Univ., India, 1995.

Singh, R. P., Whistler studies at Low Latitudes: A review, *Ind. J. Rad. Space Phys.*, **22**, 139–155, 1993a.

Singh, R. P., Lalmani, and U. P. Singh, Electron density distribution derived from low latitude whistler studies, *Ann. Geophys.*, **11**, 1011–1017, 1993.

Singh, R. P., A. K. Singh, and D. K. Singh, Plasmaspheric parameters as determined from whistler spectrograms: a review, *J. Atmos. Solar Terr. Phys.*, **60**, 495–508, 1998.

Singh, U. P., Whistlers/VLF Emissions and Related phenomena, Ph.D. Thesis, Banaras Hindu Univ., India, 1993b.

Singh, U. P. and R. P. Singh, Study of plasmasphere ionosphere coupling fluxes, *J. Atmos. Solar Terr. Phys.*, **59**, 1321–1327, 1997.

Singh, U. P., A. K. Singh, Lalmani, R. P. Singh, and R. N. Singh, Hybrid-mode propagation of whistlers at low latitudes, *Ind. J. Rad. Space Phys.*, **21**, 246–249, 1992.

Somayajulu, V. V., M. Rao, and B. A. P. Tantry, Whistlers at low latitude, *Ind. J. Rad. Space Phys.*, **1**, 102–118, 1972.

Strangeways, H. J., A model for the electron temperature variation along geomagnetic field lines and its effect on electron density profiles and VLF paths, *J. Atmos. Terr. Phys.*, **48**, 671–683, 1986.

Tarcsai, G., Candidate of science thesis, Hungarian Academy of Sciences, Budapest, 1981.

Tarcsai, G., Ionosphere-plasmasphere electron fluxes at middle latitudes observed from whistlers, *Adv. Space Res.*, **5**, 155–158, 1985.

Tarcsai, G., P. Szemeredy, and L. Hegymegi, Average electron density profiles in the plasmasphere between $L = 1.4$ and 3.2 deduced from whistlers, *J. Atmos. Terr. Phys.*, **50**, 607–611, 1988.

Tarcsai, G., H. J. Strangeways, and M. J. Rycroft, Error sources and travel time residuals in plasmaspheric whistler interpretation, *J. Atmos. Terr. Phys.*, **51**, 249–258, 1989.

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