Whistler studies at low latitudes: A review*

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The information derived from whistler studies at low latitude Indian, Chinese and Japanese stations is reviewed. The enhanced occurrence rate during geomagnetic storm period at low latitudes has been interpreted in terms of formation of additional ducts which at low latitudes have a lifetime of less than an hour and during magnetic storm period they are frequently formed and destroyed. Dispersion analysis yields electron density and large scale electric field distribution in the inner plasmasphere which is comparable to that derived from mid-latitude whistlers. The characteristic properties of low latitude whistlers are explained in terms of ducted and pro-longitudinal mode of propagation whereas equatorial whistlers follow field-aligned path in the inner plasmasphere and Earth-ionosphere waveguide mode for subionospheric path.

1 Introduction

It is well established that the return strokes of lightning discharge radiate copious amount of energy spread over wide band of electromagnetic spectrum. The radiated spectral intensity peaks at approximately 5 kHz and varies either side as \( f^{-n} \), where \( n = 2 \) for \( f < 5 \) kHz and \( n = 1 \) for \( f > 5 \) kHz (Ref. 2); \( f \) is the wave frequency. Kawasaki et al.\(^1\) have obtained the Fourier spectra of positive lightning fields during winter thunderstorms, which show an \( f^{-1} \) dependence from 100 kHz and \( f^{-2} \) dependence between 400 kHz and 2 MHz. Part of this radiated energy penetrates the lower ionosphere and then traverses the outer ionosphere propagating along geomagnetic field lines in whistler mode (right hand polarized extraordinary mode) from one hemisphere to the other hemisphere. The signal during its propagation through the ionosphere and magnetosphere interacts with the ambient plasma in the presence of geomagnetic field and gets dispersed, i.e. different frequency components of the (echo) whistler wave travel with different velocities. The dispersion of signal results in a peculiar frequency-time spectrum which has a gliding tone usually descending in frequency, followed by ascending tones in some cases. Further, it should be noted that only a small part of the VLF energy radiated by return stroke is responsible for the observed whistler, major portion of it propagates in the Earth-ionosphere wave guide and is received as a “click” or a “tweak” preceding the whistler. The dispersion produced in the tweak is negligible and its frequency-time spectrum appears as a straight line on the sonagram (along with other sferics) and serves as an indication (accurate to within several milliseconds) of the time of origin of the whistler and is usually called as the causative sferic. Whistlers can be short or long depending upon whether they are observed in the opposite or same hemisphere in which they were originated. Unlike short whistlers at high latitudes, long whistlers are invariably preceded by the causative atmospherics. Short whistlers at low latitudes are sometimes preceded by tweaks. Various types of whistlers such as short, multiflash, multipath, sharp, diffuse, riser, twin, low dispersion, high dispersion, banded, hook, etc. have been observed at low latitude stations.\(^3\) Schematic dynamic spectra of some of these traces are shown in Fig. 1. The frequency spectra recorded at different stations differ primarily due to the sensitivity of the recording and analysis system, location of the station, background noise level, etc. The location of the station is controlled by the propagation path which is latitude/longitude dependent and thundercloud activity at the conjugate point of the station. The variation in frequency spectra recorded at different stations, is outside the perview of this paper.

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Storey\(^1\) gave the correct interpretation of whistler spectra in terms of magnetoionic theory.
and it stimulated worldwide interest in whistler studies. Whistlers propagate along the ducts, i.e. field-aligned crests or troughs of electron density\textsuperscript{12}, and this fact has been confirmed by observations in the magnetosphere\textsuperscript{13,14}. The ducted propagation is distinguished from the non-ducted propagation which is most common for whistlers observed in the magnetosphere\textsuperscript{15} and these whistlers are known as MR (magnetospherically reflected) whistlers. Usually non-ducted whistlers are not observed on the Earth's surface\textsuperscript{16,17}, although sometimes they have been observed following PL (pro-longitudinal) propagation\textsuperscript{18,19}. It is very difficult to distinguish between ducted and pro-longitudinal propagation based on ground-based observations only\textsuperscript{20}. The whistler wave propagation in the magnetospheric ducts has been theoretically studied by a number of workers\textsuperscript{21-26}. Singh and Tantry\textsuperscript{26} studied ducting of whistler waves at different latitudes using ray tracing computations for field-aligned columns of electrons and ions and showed that the density enhancement factors required to trap the whistlers at low latitudes are very high as compared to the corresponding values at mid- and high-latitudes. Hayakawa and Tanka\textsuperscript{27} reviewed the propagation characteristics of low latitude whistlers which suffer from severe propagation condition such as duct excitation, trapping into and leakage from the ducts, ionospheric transmission, and so on. The observation
of daytime whistlers at low latitudes and its explanation in terms of ducted mode propagation suggests close association between daytime whistlers and the equatorial anomaly of the ionosphere. Daytime whistlers have also been explained in terms of non-ducted propagation in the presence of equatorial anomaly.

Based on the dispersion analysis of whistlers, Storey for the first time estimated the ionization density to be 400 cm$^{-3}$ at an altitude of 2 $R_E$ from the surface of the Earth. Since then many workers have tried to determine magnetospheric electron plasma density (see reviews by Carpenter and Smith, Helliwell, Corcuff and references therein). Recently Sazhin et al. have reviewed the whistler diagnostics of magnetospheric parameters such as electron density in the equatorial magnetosphere, duct localization, and large scale magnetospheric electric field. Most of the analysis for magnetospheric electron density determination is for mid- and high-latitude whistlers. In this paper we shall be considering only the results available from low- and mid-latitude stations (Sofia $L=1.6$, Tihany $L=1.2$, Gulmarg $L=1.2$, Nainital $L=1.12$ and Varanasi $L=1.07$). Apart from the determination of electron density in the equatorial magnetosphere, low latitude whistlers have also been used to determine large scale electric field in the magnetosphere. Analysing whistler data recorded at Gulmarg, Nainital and Varanasi, Khosa et al. showed eastward electric field ($E \sim 0.3-0.7$ mV/m) in pre-midnight sector and westward field ($E \sim 0.1-0.7$ mV/m) in post-midnight sector.

Very low frequency (VLF) emissions are the most popular wave phenomena associated with whistlers. Various types of low frequency emissions such as precursors, hiss, chorus, etc. have been observed at low latitude stations. VLF emissions can also be classified into two main types (i) unstructured hiss and (ii) structured discrete emissions including chorus and riser. Precursors are the rising tone preceding the originating whistlers. At low latitudes, precursors have been usually observed during magnetic storm periods. Discrete chorus emissions including the rising tone emissions have been frequently observed at low latitudes. The generation mechanisms of these emissions are supposed to be wave-particle interaction in the equatorial region. Sazhin and Hayakawa have reviewed chorus emissions observed on ground-based stations and in the Earth's magnetosphere. They have discussed different approaches used in modelling these emissions. Recently Hayakawa has reported the observation of whistler triggered VLF emissions at the low/mid latitude station Moshiri ($L=1.6$, geomagn. lat. 38°N). Apart from chorus emissions, VLF hiss emissions have also been observed at low latitudes. Lalmami et al. showed that the VLF hiss observed at low latitudes is a consequence of wave guide mode propagation of energy from sources located in the auroral zone. Jorgensen, summarizing ground observations of VLF hiss from 13 stations in both hemispheres ranging in geomagnetic latitudes from 34° to 89°, showed that the spectral densities in the frequency range 4-9 kHz vary from $10^{-19}$ to $10^{-14}$ Wm$^{-2}$Hz$^{-1}$ and concluded that hiss comes down through the ionosphere over the auroral zone and then propagates through the Earth-ionosphere wave guide to lower latitudes. The details of these VLF wave phenomena are outside the scope of the present paper, although their contributions are very much important in understanding the related phenomena.

It is known that the whistler activity varies with geomagnetic latitude showing higher occurrence rate at higher latitudes and low rate at lower latitudes. A part of the observed latitudinal variation of the whistler activity probably results from the difference in equipment (mainly the sensitivity of the equipment) and in the local noise level. But major part of the variation should be attributed to (i) global morphology of the thunderstorm occurrence and (ii) conditions conducive to the whistler mode propagation below, through and above the ionosphere. Rao et al. opined that the coupling between the ordinary and extraordinary magnetospheric wave is one of the factors which controls the dependence of whistler activity on the geomagnetic latitude. Lalmami and Singh studied the latitudinal variation of thunderstorm activity, density enhancement factor required to trap the whistlers in the duct, and coupling between ordinary and extraordinary mode and tried to explain the latitudinal variation of occurrence rate of whistlers. Recently, Ohta and Hayakawa have studied the correlation of whistler occurrence rate in January during one solar cycle (1977-87) at a low latitude station Yamaoka ($L=1.26$, geomagn. lat. 25°N) with thunderstorm activity near its conjugate region and have shown that there is no correlation between them. They have also shown that the occurrence rate is negatively correlated with solar activity. The statistical analysis of Ohta and Hayakawa has yielded that the ionospheric absorption effect is of major importance in determining the long term variation of whistler occurrence rate at low latitudes, while the duct formation is of
secondary importance. This is contrary to the whistlers at high latitudes where ionospheric absorption is low and duct formation is easier.

In this paper we have reviewed the present knowledge of low latitude whistlers which are poorly understood and also because Indian stations are distributed in this geomagnetic latitude range. The morphological features of geomagnetic storm period whistlers are used to derive information about duct width, duct life and the formation mechanism of ducts. The dispersion analysis has been used to derive information about electron density distribution and large scale magnetospheric electric fields. Propagation mechanisms of low- and equatorial-latitude whistlers have been pinpointed and their relative merits and demerits discussed.

2 Whistler ducts at low latitudes

At all low latitude Indian stations (Varanasi, Agra, Nainital and Gulmarg), consistently increased whistler activity almost simultaneously with increase in Kp index has been observed\(^4\). The marked enhancement in whistler activity has been understood in terms of formation of additional ducts during magnetic storm periods. It is known that during magnetic storm period, the electron density in the F2 region and in the exosphere region enhances and produces additional ducts in which whistlers are trapped and propagated to the conjugate hemisphere. Somayajulu et al., using whistlers recorded at Gulmarg, discussed with evidence the formation of additional ducts during magnetic storm period. Arranging the sonagrams in a time sequence, they discussed the formation, growth and decay of ducts. They showed that while for a duct to form it might require 30 min or even less time, but to grow to its full size it might take 3 h. The estimated duct life is from few hours to few days. Okuzawa et al.\(^5\) suggested that the duct formation and decay occur much more rapidly (within 30 min) and the cycle of formation and decay is continuous. Hayakawa et al.\(^6\), using real time whistler analyser at Moshiri (L=1.6), showed that it takes less than one hour for a duct to be formed and duct lifetime is of the order of one hour or less. They also suggested the successive growth and decay of ducts. Using cepstrum analysis of whistlers recorded at Moshiri, Shimakura et al.\(^7\) obtained the same results. Using power spectrum analysis of whistlers recorded at Gulmarg and Nainital, Rao and Lalmani\(^8\) evaluated duct lifetime of the order of one hour. Simultaneous observations of whistlers from adjacent station have yielded duct life as short as 30 min for mid-latitudes\(^9\). Using whistler data recorded at our low latitude stations Gulmarg, Nainital and Varanasi during magnetic storm period, Lalmani\(^10\) reported the duct lifetime of the order of 50 min.

The various whistler duct formation mechanisms are: (i) electric field duct formation mechanism, (ii) electron precipitation mechanism, and (iii) protonosphere-ionosphere plasma coupling mechanism. The radial electric field in the magnetosphere produces E x B drift of flux tubes. The flux tube interchange gives rise to enhancements and depressions in the electron plasma density. Park and Hellwell\(^11\) showed that an electric field of 0.1 mV/m in the equatorial plane can modulate the plasmasphere and give rise to enhancements and depressions of density of the order of 5% in 30 min and after one hour multiple peaks and valleys are formed. The source of electric field could be thundercloud electric field\(^12\), electrostatic polarization field in the ionosphere due to an unsymmetrical wind\(^13\), etc. The electron precipitation mechanism is based on the concept that magnetospheric plasma density enhancements would give rise to enhanced electron precipitation\(^14\). Thus a feedback mechanism involving magnetosphere-ionosphere plasma coupling and magnetosphere-ionosphere electrostatic coupling is set up which causes density enhancements and depressions\(^15\). The protonosphere-ionosphere plasma coupling mechanism is based on the concept that the irregular ionosphere-plasmasphere coupling fluxes would produce irregularities in magnetospheric electron density. This mechanism may operate during and following substorms. At other times, plasma flow is unlikely to contribute significantly for duct formation. From these brief discussions it is apparent that all ducts are probably not formed by the same mechanism. Further, the electric field perturbing the magnetospheric plasma plays a dominant role in duct formation.

In Fig. 2, sonagrams are arranged in a sequence of increasing time from 0048 to 0238 hrs IST. The path latitudes travelled by the whistler along the ducts lies between 24° and 30°N geomagnetic latitudes. During this period Kp index varied between 8 and 7, showing the recovery phase of the magnetic storm period. It is clearly seen that as time passes from 0048 to 0114 hrs IST [trace (a) to (f)], second duct starts developing and becomes matured at 0058 hrs IST and remains intact till 0114 hrs IST. At 0114 hrs IST a third duct initiates which is clearly visible at 0141 hrs IST and all the three ducts exist till 0238 hrs IST. If we carefully see the traces from (g) to (l), the
intensity of different spectrograms seems to be modulated. For example, the whistler traces in (h) are less intense as compared to those in (g) or (i), whereas relative intensity (darkness) of (j) is more than that of (i) and (k). The traces in (l) are more intense than those in (k). This gives an indication of duct intensity modulation, i.e. the electron density forming the duct is being modulated. Further, three ducts are existing simultaneously for ~1 h, leading to the fact that the duct life is of
the order of 1 h. This is in agreement with the duct life derived by Lalmani for Indian stations from altogether different sets of whistler data.

The observations of whistlers at low latitudes exhibit pure gliding tone frequency time spectrum during quiet days (Fig. 3), while majority of the whistlers recorded during the disturbed days show a large amount of diffuseness (Fig. 2) which can be either due to source effect or propagation effect or both. Since whistlers are generated during return stroke which lasts for milliseconds and the spread in whistler trace at a given frequency is much large, source effect is ruled out. The diffuseness could be due to VLF energy propagating within the wide area of the ducts having diffused boundary. Measuring the time spread at a given frequency (5 kHz), Somayajulu and Tantry evaluated the effective duct width from 15 to 25 km for normal days whistlers and from 40 to 180 km for magnetically disturbed days whistlers. The main results of low latitude ducts are summarized in Table 1.

3 Electron density and electric field determination using low latitude whistlers

The main interest in whistler research lies in interpreting the data to obtain the ionization in the protonosphere, its coupling with the ionosphere, and to understand the propagation mechanism at different latitudes. The main data available are in the forms of spectrograms/sonograms, which show the variation of frequency with time and form the bed-rock on which the analysis of whistler data is based. The form of the spectrogram is determined by the group delay time of the signal propagating at different frequencies in the whistler mode from the source to the wave receiver,

\[ r(f) = \frac{1}{2c} \int \frac{\delta(s) f_h(s) ds}{f \sqrt{f^2 - f_h(s)^2} + T} \]  

where \( c \) is the velocity of the electromagnetic wave in free space, \( f_h \) and \( f \) are the electron plasma and gyrofrequency respectively, \( f \) is the wave frequency, \( \delta \) is the frequency of the whistler, and \( T \) is the time delay.
frequency, \( ds \) is the path element along the path \( s \), and \( T \) is the time difference between chosen origin and actual causative atmospherics. The integral is to be evaluated along the whistler wave path which is assumed to coincide with the magnetospheric magnetic field. At the ionospheric height where signal either enters the duct or emerges from the duct, the path deviates from the field line. Ionospheric correction has been discussed by Sazhin et al.\textsuperscript{33} who have discussed various methods and extrapolations used to evaluate the integral in Eq. (1). They have also discussed in detail whistler diagnostics of magnetospheric parameters such as electron density, electron temperature, and large scale electric field.

Eq. (1) is rewritten as

\[
\tau(f) = D(f) f^{-1/2} + T
\]  

\[ ... (2) \]

where \( D(f) \) is the dispersion at frequency \( f \). To evaluate \( D(f) \), Bernard\textsuperscript{24} expressed it as

\[
D(f) = D_0 \frac{f_{he}}{f_n} \left[ f_n (f_{he} + f_n) - f (3 f_n - f_{he}) \right] \frac{1}{(f_{he} - f)(f_{he} + f_n)} \]  

\[ ... (3) \]

where \( D_0 \left( = \int_0^\infty \frac{f(s)ds}{2 \pi c f_{he}(s)} \right) \) is the zero frequency dispersion and is obtained from the intercept of \( D(f) \) versus \( f \) plot on \( D \) axis, \( f_{he} \) is the equatorial electron gyrofrequency, and \( f_n \) is the nose frequency of whistler wave. Using Eqs (2) and (3), we can write

\[
\frac{D_n}{D_0} = \frac{2}{1 + f_n/f_{he}}
\]

\[ t_n = \frac{D_n}{f_n^{1/2}} \]  

\[ ... (4) \]

where \( D_n \) and \( t_n \) are the whistler dispersion and travel time at nose frequency \( f_n \) respectively.

In the case of nose whistler, \( f_n, D_n \) and \( D_0 \) are measured from the spectrogram (frequency versus time curve) and equatorial electron gyrofrequency \( f_{he} \) is determined using Eq. (4) which fixes the propagation path for the whistler wave. In the case of non-nose whistler, which is usually the case at low latitudes, one introduces the function

<table>
<thead>
<tr>
<th>Stations of whistler registration</th>
<th>Main results</th>
<th>Ref. No.</th>
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<tbody>
<tr>
<td>Gulmarg ((L=1.2))</td>
<td>It takes much less than 30 min for duct formation. Duct grows to its full size within 3h and it may persist for 2-3 days. The duct width for 5 kHz varies from 15 to 25 km for normal days and from 40 to 180 km for magnetically disturbed days.</td>
<td>58</td>
</tr>
<tr>
<td>Nainital ((L=1.12))</td>
<td>Power spectrum analysis yields duct lifetimes of the order of 1h.</td>
<td>62</td>
</tr>
<tr>
<td>Varanasi ((L=1.07))</td>
<td>Power spectrum analysis of the whistler data yields 50min for the growth and decay of ducts.</td>
<td>70</td>
</tr>
<tr>
<td>Gulmarg ((L=1.2))</td>
<td>Duct lifetime is of the order of 50 min. Electric field plays dominant role in the duct formation which is found to be (-0.1-0.7 \text{ mV/m}).</td>
<td>64</td>
</tr>
<tr>
<td>Nainital ((L=1.12))</td>
<td>Ducts are formed in less than 1h and they may persist for the same time period. The distribution of occurrence data suggests the successive growth and decay of ducts.</td>
<td>60</td>
</tr>
<tr>
<td>Varanasi ((L=1.07))</td>
<td>The apparent lifetimes of ducts are found to be 1-2 h. Temporal movement of the ducts have been demonstrated. The simultaneous presence of few ducts at the same latitude is also seen.</td>
<td>71</td>
</tr>
<tr>
<td>Moshiri ((L=1.6))</td>
<td>Cepstrum analysis of the data yields cyclic occurrence of whistler ducts at 2h and 4h.</td>
<td>61</td>
</tr>
<tr>
<td>Moshiri ((L=1.6))</td>
<td>Ducts are formed in less than 1h and they may persist for the same time period. The distribution of occurrence data suggests the successive growth and decay of ducts.</td>
<td>60</td>
</tr>
<tr>
<td>Kagoshima ((L=1.22))</td>
<td>The apparent lifetimes of ducts are found to be 1-2 h. Temporal movement of the ducts have been demonstrated. The simultaneous presence of few ducts at the same latitude is also seen.</td>
<td>71</td>
</tr>
<tr>
<td>Ohgata ((L=1.25))</td>
<td>The apparent lifetimes of ducts are found to be 1-2 h. Temporal movement of the ducts have been demonstrated. The simultaneous presence of few ducts at the same latitude is also seen.</td>
<td>71</td>
</tr>
<tr>
<td>Sakushima ((L=1.28))</td>
<td>Whistler observation during and after the storm period suggests duct life of the order of 1-2 days. Duct width for the enhancement factors of 0.25 and 0.50 varies between 25 and 200 km.</td>
<td>72</td>
</tr>
<tr>
<td>Okinawa ((L=1.08))</td>
<td>Duct life is of the order of 2h. Numerical computation suggests ( \Delta N/N ) of (-0.27 ) for whistler trapping which may be produced by (0.29 \text{ mV/m} ) electric field. Duct formation and decay is a cyclic phenomenon.</td>
<td>73</td>
</tr>
</tbody>
</table>
$Q(f) = 1/t(f)f^{1/2} = 1/D(f)$, which is more convenient for approximating the whistler dispersion. A plot between $Q(f)$ and $f$ comes out to be a straight line, whose intercept on the $f$ axis is $f_0 = (3.09 \pm 0.04) f_e$ (Ref. 75). From the intercept $f_0$, the nose frequency $f_n$ is determined. Thus $D_0$ and $f_n$ are derived from whistler $f-t$ curve and $f_{He}$ is evaluated.

To locate causative atmospherics on the $f-t$ spectrum, time $t$ is measured with respect to some arbitrarily chosen atmospherics and $f^{-1/2}$ as a function of time $t$ is plotted. This plot is usually a straight line. If is passes through the origin, then the chosen sferics is the causative sferics, otherwise the intercept with the time axis determines the required shift in the location of causative sferics. One should make some allowance (of the order of a few milliseconds) for the propagation in the Earth-ionosphere wave guide.

It is seen that $D_0$ is a function of $f_e$ and $f_{He}$. For dipolar magnetic field, the variation of $f_{He}$ is known. Thus $D_0$ is a function of $f_e$ and hence a function of electron density. Irrespective of the chosen model of electron density distribution along the field line, for a given model and $L$, we can write

$$D_0 = \text{constant} \times N_{eq}^{1/2} \quad \ldots (5)$$

where $N_{eq}$ is the equatorial electron density in the magnetosphere for the considered $L$ value. The constant depends on the electron density model used in the computation and $f_{He}$. The total electron content in a magnetic flux tube of unit cross-sectional area at the reference height is written as

$$N_T = \int N dv = \int N(s) [B_v/B(s)] ds \quad \ldots (6)$$

where $v$ is the volume of the flux tube, $B_v$ is the magnetic field at the reference point $r$ where cross-sectional area of the tube is taken as $1 \text{ cm}^2$, $B(s)$ is the magnetic field at any other point $s$ along the geomagnetic field line, and $ds$ is the path length. The integral is evaluated from the reference height to the equator.

In another approach, the equatorial electron density has been computed by means of accurate curve fitting method\textsuperscript{76} based on the least squares estimation of three parameters $D_0$, $f_{He}$ and $T$. Equations (2) and (3) show that there are four unknown parameters $D_0$, $f_{He}$, $T$ and $f_n$ and hence one has to estimate four parameters. The problem becomes simple if we can find a relation between any two parameters, say between $f_n$ and $f_{He}$. For example, in diffusive equilibrium model\textsuperscript{77} (DE-1, $T_{eq} = 1600 \text{ K}$, $n_{O_r} = 90\%$, $n_{H_r} = 8\%$, $n_{He_r} = 2\%$), the nose frequency $f_n$ can be expressed as\textsuperscript{74} 

$$f_n = f_{He} \left[ 3.5475 - 0.4735 \log_{10} f_n + 0.06588 \left( \log_{10} f_n \right)^2 \right]^{-1} \quad \ldots (7)$$

Expressing $f_n$ as a function of $f_{He}$, the remaining three parameters $D_0$, $f_{He}$ and $T$ are estimated by the least squares technique in which the following function is minimized

$$M = \sum_{k=1}^{n} W_k \left( t_{m_k} - t_{c_k}(D_0, f_{He}, T) \right)^2 \quad \ldots (8)$$

where the subscripts $m$ and $c$ refer to the measured and computed $t^*$ values respectively, $W_k$ are the weights given to the individual measurements, and the summation is to be taken over the points of the whistler trace scaled at frequency $f_k$.

Detailed analysis shows that for diffusive equilibrium model\textsuperscript{76} 

$$L = 8.736 \times 10^5 f_{He}^{-1/3}, \text{ where } f_{He} \text{ is in Hz}$$

$$N_{eq} = K_{eq} D_0^2 f_{He}^{1/3}$$

$$N_T = K_T D_0^2 f_{He}^{1/3} \quad \ldots (9)$$

The constants $K_{eq}$ and $K_T$ are weakly dependent functions of $f_{He}$ and $f_n$ respectively.

The large scale magnetospheric electric field has been determined using continuous whistler data. The method is simple and based on the change in nose frequency of successive whistlers with time. Since the nose frequency is related to the equatorial electron gyrofrequency, it is argued that the change in nose frequency amounts to change in whistler path in the equatorial plane which is supposed to be caused by the electric drift of magnetic field line [drift velocity $= \mathbf{E} \times \mathbf{B}_{eq} / B_{eq}^2 = d(R_e L_{eq})/dt]$. The magnitude of this electric field (assuming $\mathbf{E}$ is perpendicular to $\mathbf{B}_{eq}$) is given by\textsuperscript{74} 

$$|E| = 2.07 \times 10^{-2} \frac{d(f_{n}^{1/3})}{dt} \text{ V/m} \quad \ldots (10)$$

where $f_n$ is measured in Hz. If $f_n$ increases with time, then electric field is directed from east to west and in the reverse case it is directed from west to east. $|E|$ can be determined with a precision of typically 0.1 mV/m. The electric field determination is almost independent of the model of electron distribution assumed.

In this paper we have given in very brief the method of determination of equatorial electron density, electron content in a magnetic flux tube of $1 \text{ cm}^2$ cross-sectional area at the reference
height, and the large scale magnetospheric electric field. Different approximations and limitations of these techniques have not been discussed. For details, readers are suggested to see the recent review paper of Sazhin et al.\textsuperscript{33}

Using Eq. (9) and analysing a large number of whistlers recorded at Nainital on 25 Mar. 1971, Lalmani et al.\textsuperscript{34} have discussed the computed profile of $N_T$ and $N_{eq}$ versus $L$. Singh et al.\textsuperscript{35} have computed the profile of $N_{eq}$ and $N_T$ for Varanasi and Gulmarg using the whistler data of 19 Mar. 1977 and 8 Feb. 1986 respectively. These dates have been chosen to evaluate downward transport of ionization during magnetic storm period. Figure 4(a) shows the variation of equatorial electron density $N_{eq}$ and total electron content $N_T$ in the tube for all the three stations. From the distribution of $N_{eq}$ it is seen that the whistlers received at Varanasi, Nainital and Gulmarg have travelled along different $L$ values which are widely dispersed. The equatorial electron density decreases systematically with the increase in $L$ value. The values of electron density derived from whistlers recorded at low latitude Indian stations are slightly smaller than those derived from whistler data recorded at mid-latitude station Tihany, Hungary ($L=1.9$) and high latitude station Siple, Antarctica\textsuperscript{76} [Fig. 4(b)]. The Siple data represent only a portion of the density profile which extends to higher $L$ values. At lower $L$ values ($L \leq 2$), there is an increasing tendency to underestimate the electron densities due to unavoidable approximations in the whistler analysis. Contrary to this, an unrealistic steep rise in the equatorial electron densities at lower $L$ values ($L \leq 2$) has been reported\textsuperscript{35} which does not follow the diffusive equilibrium models\textsuperscript{27} DE-1 to DE-4 (DE-1: $T_{e,\text{eff}} = 1600 \text{ K, } n_{\text{O}_2} = 90\%, \, n_{\text{He}} = 2\%, \, n_{\text{H}_2} = 8\%$; DE-2: the same as DE-1 but with $T_{e,\text{eff}} = 3200 \text{ K}$; DE-3: $T_{e,\text{eff}} = 1600 \text{ K, } n_{\text{O}_2} = 50\%, \, n_{\text{He}} = 10\%, \, n_{\text{H}_2} = 40\%$; and DE-4: the same as DE-3 but with $T_{e,\text{eff}} = 800 \text{ K}$). The total electron content $N_T$ shows a slight increase at lower $L$ values ($L \leq 2$) in spite of the rapidly decreasing volume of geomagnetic field line tubes. This is because of the higher electron densities at lower $L$ values. Such behaviour of electron density profiles can be understood in terms of higher electron density enhancements required for the ducting of low latitude whistlers. At mid- to high-latitudes 10% of density enhancement is sufficient for whistler ducting, whereas at low latitudes ($L < 2$) enhancement factors of $\sim 100\%$ are required\textsuperscript{25,26,77}. These higher enhancement factors may be causing the systematic errors in $N_{eq}$ and $N_T$ at low latitudes derived from whistler analysis. Further, these higher values of $N_{eq}$ may be considered as an indirect support of theoretically evaluated higher enhancement factors required for the ducting of whistlers at low latitudes.

The change in flux tube content with time is evaluated using the formula

$$\frac{dN_T}{dt} = \frac{N_{T_2} - N_{T_1}}{t_2 - t_1} \quad \cdots (11)$$

![Fig. 4(a) Total electron content in a flux tube as a function of local time derived from whistlers recorded at Varanasi ($L=1.07$), Nainital ($L=1.12$) and Gulmarg ($L=1.2$).](image1)

![Fig. 4(b) Variation of equatorial electron density as a function of $L$ value derived from whistler data recorded at Nainital ($L=1.12$; 25 Mar. 1972), Tihany ($L=1.9$; March-August 1972-75), and Siple ($L=4.0$; June 1973).](image2)
where $N_{T_1}$ and $N_{T_2}$ are the tube contents derived from whistler observations at times $t_1$ and $t_2$ respectively. The change in tube content with time at any particular location is equivalent to the transport of ionization flux from that region. Flux transport is upward when $N_{T_2} > N_{T_1}$, and downward when $N_{T_2} < N_{T_1}$. The transport of ionization flux as derived from whistlers comes out to be $10^9 \text{ cm}^{-2} \text{s}^{-1}$ for Varanasi, $3 \times 10^9 \text{ cm}^{-2} \text{s}^{-1}$ for Nainital, and $\sim 3.2 \times 10^9 \text{ cm}^{-2} \text{s}^{-1}$ for Gulmarg. These results are in agreement with those reported by Park\textsuperscript{79} for high latitude whistlers and Lalmani \textit{et al.}\textsuperscript{38} for low latitude whistlers. The large downward flux from the plasmasphere into the ionosphere causes enhancements in critical frequency of F2 layer, which was confirmed by simultaneous ionosonde records\textsuperscript{79}.

The transported electron flux computed above are the coupling fluxes between ionosphere and plasmasphere. Using whistler observation at Tihany, Tarcsai\textsuperscript{76} demonstrated the systematic dependence of coupling fluxes on the $L$ values of coupled plasma regions. The average coupling fluxes at the base of 1000 km were below $6 \times 10^8 \text{ el. cm}^{-2} \text{s}^{-1}$ while fluxes up to $3 \times 10^9 \text{ el. cm}^{-2} \text{s}^{-1}$ were occasionally also measured\textsuperscript{76}. The reported fluxes were directed mainly towards the ionosphere except at some occasions when upward fluxes were also reported\textsuperscript{76}. Tarcsai\textsuperscript{76} also studied day-to-day filling of the plasmasphere for some days but no saturation of plasmasphere filling at higher $N_T$ values could be observed. Based on low latitude whistlers recorded at Varanasi, Nainital and Gulmarg, the coupling fluxes of $\sim 3 \times 10^9 \text{ el. cm}^{-2} \text{s}^{-1}$ towards the ionosphere were observed. The base heights used in the computation of tube content for Varanasi, Nainital and Gulmarg have been taken as 400, 500 and 600 km respectively. These results are based for whistlers recorded during geomagnetic storm periods. Thus it is observed that the fluxes during geomagnetic storm move from plasmasphere to ionosphere. Since the data are limited for small time duration, the present study cannot be used for the diurnal variation of fluxes.

Using Eq. (10), Misra \textit{et al.}\textsuperscript{40} derived electric field from the whistler data recorded at Nainital ($L=1.12$) between 0130 and 0500 hrs IST on 25 Mar. 1971 which lies in the range 0.1-0.5 mV/m. The electric field causes plasma drift towards smaller $L$ values. Khosa \textit{et al.}\textsuperscript{19} determined electric field from the whistlers recorded at Gulmarg ($L=1.2$), Nainital ($L=1.12$), and Varanasi ($L=1.07$). Their study reveals that the electric field is directed eastward in the pre-midnight sector and the magnitude is about 0.33-0.7 mV/m in the equatorial plane of Gulmarg and 0.3 mV/m in the equatorial plane of Nainital. The electric field is westward in the post-midnight sector whose magnitude is 0.2-0.7 mV/m for Gulmarg, 0.3-0.5 mV/m for Nainital, and 0.1-0.3 mV/m for Varanasi. Ralchovski\textsuperscript{41}, analysing whistler data recorded at Sofia ($L=1.6$) between 1500 and 1800 hrs LT, reported eastward electric field having magnitude 0.44-0.54 mV/m which is in close agreement with those reported for Indian stations.

4 Propagation of low latitude whistlers

It is generally accepted that the ground-based whistlers at high- as well as low-latitudes are trapped in field-aligned ducts through the magnetosphere and propagate back and forth along geomagnetic field lines. The presence of ducts has been inferred from a large number of ground-based measurements\textsuperscript{80-82}. Direct evidence has also been obtained from \textit{in situ} observations on-board satellite OGO3\textsuperscript{13}, ISIS\textsuperscript{93} and on a rocket\textsuperscript{29}. At high latitudes long whistlers are invariably preceded by the causative atmospherics whereas the short-whistlers are not. The detection of whistlers and not the causative sferics clearly shows that the whistler energy traverses without much spreading and absorption. Hayakawa and Tanaka\textsuperscript{27} reviewed the observations and theories of the propagation of low latitude whistlers and showed that the propagation characteristics differ with the change of latitudes. They classified the whole low latitude range into three zones occurring (i) above 30°, (ii) between 30° and 20°, and (iii) below 20° geomagnetic latitudes.

The whistlers observed at the ground stations lying in the first category (geomagn. lat. $>30°$) have morphological features nearly the same as those of mid-latitude and high-latitude. These whistlers propagate along geomagnetic field lines in ducted mode. Singh and Tantry\textsuperscript{26} studied ducting of whistlers at different latitudes for two different field-aligned column models, one of which contained only electrons and the other contained both the electrons and ions. Using ray tracing computations they showed that the enhancement factors ($\Delta N/N$), where $N$ is the background plasma density and $\Delta N$ is the increment in the density at the duct boundary, required to trap the whistler waves in the two models at high latitudes are almost the same. As latitude decreases, the enhancement factor required to trap the whistler in the model containing ions increases markedly. At low latitudes for the electron-ion model, the enhancement factor required for whistler ducting
becomes unrealistically very high and pro-lon-
tudinal (PL) mode of propagation has been evoked for nighttime whistlers, assuming a suit-
able negative horizontal gradient at the iono-
sphere of wave incidence. In the PL mode the ray paths need not align along geomagnetic field line, instead the wave normal should lie inside a cone around geomagnetic field line and produce travel time and downgoing wave normals that are typical of pure longitudinal propagation along the field lines. Ishikawa et al., using two-dimensional ray-
tracing computations for inhomogeneous magne-
tospheric plasma model, have shown that the strongest ray focussing occurs at a frequency slightly below the half electron gyrofrequency in the vicinity of the geomagnetic equator. This ray focussing helps in PL mode propagation.

Another question which is of importance for low-mid latitude whistler is the whistler wave energy leakage into and from field-aligned electron density ducts; this question has been treated by a number of workers. Earlier treatment has considered uniform duct structure along its length. However, Strangeways and Rycroft considered the variation of refractive index along the length of a duct which resulted in the trapping and loss through the side of the duct. Considering tapered and more complicated duct structure, Strangeways et al. provided an explanation for the discrepancy between the $L$ values of the exit points of some whistlers and their $L$ values calculated from their nose frequency. The discrepancy has been explained in terms of refraction during the whistler’s non-ducted path after leakage from the duct. For field-aligned propagation of VLF waves, the wavelength at any given wave frequency increases with decreasing altitude (as wave travels from equator towards the Earth surface). Due to the divergence nature of geomagnetic field, the duct width decreases with decreasing altitude. The wave leaks out from the duct whenever wavelength becomes approximately equal to duct width. As a result of the combined effect of duct width and wavelength variation, there is a progressive leakage of downcoming ducted wave which can explain the high dispersion whistlers observed at low latitudes. Such whistlers after emerging from the duct may either propagate to the receiving site in non-ducted mode or penetrate the ionosphere and reach the observation site in wave guide mode propagation through Earth-ionosphere wave guide.

In the second category, whistlers received on the ground stations between 20° and 30° geomag-
etic latitudes are considered and are called low

latitude whistlers which are characterized by a sharp occurrence peak of duration 1-2 h in the daytime, around sunset (called daytime whistlers) and a broad maximum in the early morning (called nighttime whistlers). Daytime whistlers occur in the form of multiflash type with highly concentrated dispersion and propagate in ducted mode with daytime ducts located at the high altitude flank of the equatorial anomaly. An association between equatorial anomaly and daytime whistler has been evoked based on (i) a close relationship between the occurrence peak of daytime whistler with the local time behaviour of equatorial anomaly, (ii) the position of the ducts at high latitude edge of the equatorial anomaly, and (iii) the density enhancement factor derived from dispersion analysis for ducted propagation including the effect of equatorial anomaly and that derived from wave normal direction measurement on rockets which are of the same order of magnitude. Hasegawa and Hayakawa, taking realistic models of equatorial anomaly, performed ray tracing computation of non-ducted whistler mode propagation and showed that two different non-ducted modes are able to reach the ground. One is whispering gallery mode guided by the anomaly and trapped by its outer edge. This whistler closely obeys Eckersley’s law and is a very pure tone whistler and usually it cannot be distinguished from ducted mode. Another is the pro-longitudinal (PL) mode which is supported by the horizontal gradient in the tail of the anomaly. A downgoing whistler in PL mode can excite the Earth-ionosphere wave guide modes propagating both poleward and equatorward. Analysing multistation network data, Hayakawa and Ohtsu confirmed only the poleward propagation of low latitude whistlers in the Earth-ionosphere wave guide. Thus, PL mode propagation becomes unimportant for explaining daytime whistlers at low latitudes even though the dispersion of PL mode whistler follows Eckersley’s law. Singh and Singh used the longitudinal dependence characteristics of equatorial anomaly to explain the diurnal variation in the occurrence number and rate of occurrence of whistlers at Sakushima ($L=1.2$) and Gulmarg ($L=1.2$) (both stations are approximately at the same latitude but at different longitudes).

Recently, Ohta et al., using digital recorder and a fast Fourier transform (FFT) analyser for direction measurements, have shown that the ionospheric exit point and polarization of daytime whistlers are almost frequency independent. The results have been interpreted in terms of ducted
mode propagation. The diameter of the duct is less than 60 km. The sharp peak in occurrence with a duration of 1-2 h is thought to be the consequence of the formation and decay of single ducts. The high stability of exit point during the occurrence periods strongly favours the ducted mode of propagation. While the waves are transmitted downward through the ionosphere, the F-layer irregularities modulate the transmission coefficient over wide frequency range\(^1\) which results into the patched structure of whistlers often observed (both during day and night) at low latitude stations\(^2\). To understand the ionospheric transmission mechanism of low latitude whistlers, Shimakura et al\(^9\) have separated the contribution of waves which arrive at the antenna directly after emerging from the lower edge of the ionosphere and the other which reach the antenna after multiple reflections in the Earth-ionosphere waveguide. They have found that the energy of reflected waves is greater than those of direct waves. This suggests that at low latitudes, whistler propagation path combines propagation along field lines and propagation through Earth-ionosphere waveguide\(^9\). Singh and Jain\(^4\), using ray path computation, showed that small scale irregularities responsible for spread-F (irregularity of 10 km thickness and $\Delta N/N = \sim 5\%$) bring the wave normal direction of downcoming waves almost vertical at the base of the F-region ionosphere. These waves penetrate the lower ionosphere and reach the ground. Tanaka and Hayakawa\(^5\) reported a low latitude cut-off around $-20^\circ$ geomagnetic latitude for daytime whistlers. The absolute intensity of daytime whistlers derived from direction-finding measurements at low latitude station Yamaoka (geomagn. lat. 25°N) is found to be more than that of nighttime whistlers. The absolute intensity of the maximum occurrence is 100-125 $\mu$V/m and the peak value is 225-250 $\mu$V/m during daytime, while the corresponding peak value at night is 150-175 $\mu$V/m (Ref. 95) which has been explained in terms of average source intensity around the conjugate region and ionospheric absorption during propagation. This has been explained by noting that the conjugate region of Yamaoka is located just in the centre of the most active thunderstorm region, so strong VLF waves are the origin of daytime whistlers overcoming the high ionospheric absorption at daytimes. On the other hand the active thunderstorm region at night is generally far away from the conjugate region and hence VLF energy is forced to propagate in the Earth-ionosphere wave guide followed by the oblique incidence into the ionosphere, hence resulting in relatively weak nighttime whistlers.

Singh et al\(^9\) have proposed hybrid mode propagation for low latitude whistlers where propagation path is the combination of ducted mode along geomagnetic field line and a guided mode in Earth-ionosphere wave guide. Analysing the accompanying tweeks the sources of whistlers have been located, which are widely distributed and are away from the conjugate points of Varanasi. This shows that whistlers have propagated in the Earth-ionosphere wave guide before following the field-aligned path. Shimakura et al\(^9\) have presented whistler traces which support the hypothesis that whistlers after field-aligned mode follow the Earth-ionosphere wave guide mode after leaving the ionosphere and before being received on the ground. In Fig. 5 we have reproduced the whistlers recorded at Sakushima and Kagoshima. The additional traces of the Earth-ionosphere wave guide propagation on the spectrogram is clearly seen. Shimakura et al\(^9\) have simultaneously located the exit region of the whistler and their causative atmospherics and have found that the causative atmospherics are located exactly at the duct entrance. This shows that a large amount of radio energy from the return stroke of lightning is directed nearly vertical to the ionosphere, is trapped in a field-aligned duct, and propagates in ducted mode in the magnetosphere. The simultaneous presence of the first and second order modes suggests that (a) ionospheric exit regions of these whistlers must be located far from the observing station leading to the fact that after ionospheric exit whistlers must have propagated in the Earth-ionosphere wave guides and (b) wave energy is radiated widely over all exit angles, which together with the extremely small divergence loss results in an efficient wave interference. As a consequence of wave interference, additional traces of first and second order mode cut-offs appear on the spectrogram. Recently, Chinese scientists\(^9\) using multistation observations in China (Wuchang (geomagn. lat. 19.4°), Guangzhou (geomagn. lat. 11.9°), Zhanjiang (geomagn. lat. 10.0°), Yulin (geomagn. lat. 7.0°), and Yongxiang (geomagn. lat. 5.5°)), have shown that there exists a preferred whistler path at a very low latitude of $\sim 10^\circ$. They have suggested that this preferred path is attributed to the non-ducted propagation. However, the whistlers having the features of strong intensity as well as the existence of echoes have also been explained in terms of ducted propagation for which it was supposed that the observed whistlers have
excited the ionosphere very close to the observatory, which may not be valid in all cases.

The propagation of nighttime whistlers in the second category (geomagn. lat. 20°-30°) and whistlers in third category (geomagn. lat. < 20°) is identical. The whistlers observed at ground stations lying between equator and 20° geomagnetic latitudes are called as equatorial whistlers. The Indian stations Varanasi (geomagn. lat. 15°N) and Bhopal (geomagn. lat. 13.47°N) lie in this range, whereas Agra (geomagn. lat. 17.20°N) is at the outer edge of this zone. Whistler observations are being monitored at Varanasi for the last two years and at Bhopal for the last one year. Second and third harmonics of tweeks along with atmospherics have been recorded at Bhopal. Based on whistler observations at Indian, Chinese and Japanese ground-based stations spread over in this latitude range, general features of whistlers are summarized below in order to facilitate the discussion of propagation mechanism of equatorial whistlers:

(i) Whistlers have not been observed in daytime. They are observed in the post-midnight sporadically with low activity, but once they occur the occurrence rate becomes comparable to the low latitude region (geomagn. lat. 20°-30°).

(ii) The dispersion values of most whistlers are concentrated between 10 s^{1/2} and 15 s^{1/2} (Fig. 6) and dispersion at a particular local time is single valued.
Lower Cut-off Frequency (kHz)

Fig. 7—Distribution of extremely small dispersion whistlers as a function of lower cut-off frequency. Whistlers were recorded at Varanasi \((L=1.07,\text{ geomagn. lat. } 15°N)\) during the periods Jan. 1976-Aug. 1978 and Jan.-Apr. 1990.

(iii) Whistlers with lower cut-off frequency lying in the range 1.70-2.50 kHz (Fig. 7) are frequently observed, which indicates that there exist some stationary and recurrent paths of whistler propagation near 10° geomagnetic latitude\(^9\).

(iv) The extent of ionospheric exit region \((30-40 \text{ km})\) is very stable on different days\(^9\) and it is localized in the 10°-14° geomagnetic latitude. The exit region is frequency independent.

(v) Surprisingly high occurrence of echo train whistlers is observed. More than 10% of whistlers are accompanied by three-hop whistlers.

(vi) After ionospheric transmission, whistler propagation in Earth-ionospheric wave guide is more likely towards higher latitudes than towards the equator\(^9\). Further, the subionospheric propagation exhibits a horizontal beaming around the magnetic meridian plane.

The above mentioned characteristics of equatorial whistlers have been interpreted either in terms of non-ducted propagation\(^7\) or ducted propagation\(^3/field-aligned propagation\(^8\). The whistlers and their echoes observed at Varanasi are found to obey Eckersley’s law and dispersion value computed along geomagnetic field lines passing through Varanasi fits well with the observed one. These results along with the direction-finding measurements suggest ducted propagation mode\(^23/39\) for which the required density enhancement is greater than 100%, which has not been observed experimentally. The required enhancement factor contradicts the ducted propagation mode. On the other hand, all these features which are in favour of ducted propagation mode are easily explained by field-aligned propagation either in surface wave mode\(^102\) or in whispering gallery mode\(^103\).

Now let us compare the observational features which are predicted from non-ducted propagation. Liang \textit{et al.}\(^98\) carried out three-dimensional ray tracing considering a realistic ionospheric model including the effect of equatorial anomaly and showed that whistler waves launched at 9°-14° geomagnetic latitude can penetrate on to the ground in a region of 7°-10°N. The computed dispersion is around 12 s\(^1/2\). Using two-dimensional ray tracing, Andrews\(^104\) estimated a non-ducted propagation channel to be around 10° geomagnetic latitude. Thus non-ducted propagation seems to be consistent with the observational facts (ii) and (iii). On the other hand, following points are against non-ducted propagation mode: (a) for non-ducted whistlers, the exit point and its extent will vary greatly on different days due to dynamically different density profile which is contrary to the observed features (iv), (b) in the non-ducted propagation, horizontal beaming of the subionospheric propagation is not allowed and hence high occurrence of echo trains is not explained \[(v)\] and \[(vi)\], and (c) three-hop waves in non-ducted mode must suffer from an additional four times absorption in the lower ionosphere and due to extremely high attenuation it is improbable to receive three-hop whistler, which on the other hand has been frequently observed (v).

The reception of two-hop/three-hop whistlers support the field-aligned propagation. On the basis of multiple-hop whistler observation on a rocket \((L=1.06)\), Anderson \textit{et al.}\(^105\) interpreted their results in terms of field-aligned propagation. Two-hop whistler is supposed to be the one which has entered the ionosphere near the receiving station after Earth-ionosphere wave guide propagation over a great distance from the source, probably near the conjugate of the station. The frequent observation of two-hop/three-hop whistlers strongly indicate the existence of an extremely stable propagation path which shows that the ionosphere exit region will be frequency independent. Thus the observed features (ii), (iii), (iv), (v) and (vi) are consistent with the field-aligned
propagation either in ducted mode or in pro-longitudinal non-ducted mode. Field-aligned irregularities support the propagation along a field line. The electric field from upward lightning discharge causes the formation of field-aligned irregularities which may provide a field-aligned path for the whistlers. Such field-aligned structures with small enhancement factor and with small width can support surface wave mode or whispering gallery mode.

5 Conclusions

General features of low latitude whistlers have been studied with special reference to (i) characterization of ducts during normal days and during geomagnetic storm period, (ii) dispersion analysis and computation of magnetospheric electron density and electric field, and (iii) propagation mechanisms of low latitude and equatorial latitude whistlers. Whistlers at low latitude stations show enhanced occurrence rate during geomagnetic storm period which has been explained in terms of formation of additional ducts during storm period. At equatorial and low latitudes, the duct develops within less than an hour and duct life is of the order of 1 h or less. The duct width on the normal days is of the order of 25 to 30 km, whereas during geomagnetic storm period it can grow up to 200 km. Analysing the whistlers recorded at Varanasi, Nainital and Gulmarg, the electron density distribution as a function of $L$ value has been determined which compares well with the reported value based on mid- and high-latitude whistlers. Total electron content in a flux tube of 1 cm$^2$ cross-sectional area at the base of reference height has been computed from which downward transport of ionization has been evaluated, which comes out to be $\sim 10^7$ cm$^{-2}$ s$^{-1}$. This is in agreement with those reported for mid-latitude whistlers. The large scale magnetospheric electric field derived from the variation of whistler noise frequency with time at low latitudes comes out to be $\sim 0.5$ mV/m which is directed eastward in the pre-midnight and westward in the post-midnight.

The propagation mechanism of low latitude whistlers is quite complicated and to understand it three zones of geomagnetic latitude ranges ($> 30^\circ$, $20^\circ$-$30^\circ$, $< 20^\circ$) have been considered. Whistlers observed at geomagnetic latitudes $> 30^\circ$ are explained by considering usual ducted mode propagation although some of the whistlers have been explained using PL mode of propagation. The daytime whistlers observed at stations lying in the geomagnetic latitude range $20^\circ$-$30^\circ$ are understood in terms of ducted mode propagation with the duct lying at the high altitude flank of the equatorial anomaly. The propagation of nighttime whistlers observed at stations lying at geomagnetic latitudes less than $30^\circ$ are explained in terms of field-aligned propagation in the inner plasmaphere and Earth-ionosphere wave guide mode propagation in the subionospheric path.

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