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Study of ionosphere–magnetosphere coupling using whistler data

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Abstract : The whistler mode wave propagation through the magnetosphere is facilitated by the formation of ducts caused by latitudinal variation (enhancement) of electron density through the process of interchange of flux tube or perturbation produced by electric field. The enhanced electron density decays by the process of diffusion across and along the magnetic field Charged particles have much greater mobility along the magnetic field lines as compared to that across the field line and hence diffuse along the field line from the magnetosphere to the ionosphere and as a result, coupling of magnetosphere to the ionosphere is established.

Whistler data is used to calculate the equatorial electron density and total electron content in a flux tube of unit cross section at the reference height. The time development of electron flux yields downward/upward movement of flux. The transported flux during geomagneticaly disturbed and quiet condition is evaluated. The whistler data recorded at Indian stations Varanasi and Gulmarg are used in the present study. The refilling of ionosphere by the flux transported from the plasmasphere is discussed in the light of other available measurements.

Keywords Whistler, ionosphere, magnetosphere.

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1. Introduction

The atmospheric whistler studies provided fruitful methods for diagnosing magnetosphere and upper ionosphere [1–6]. Attempts have been made to understand various features of magnetospheric plasma such as the structure and dynamics, magnetosphere-ionosphere coupling, *etc.* Park *et al* [3] analyzed whistler data acquired between 1959 and 1973 at Byrd ($L = 7.0$), Eights ($L = 4.0$) and Siple ($L = 4.0$) and gave a systematic description of the main features of the plasmaspheric electron density. Tarcsai *et al* [4] have processed whistlers recorded at Tihany (Hungary $L = 1.9$) between December 1970 and May 1975 and studied the distribution of equatorial electron density and total electron content in flux tubes having L-values in the range $L = 1.4$–3.2. At low latitudes, the exploitation of whistlers for electron density determination has been carried out by Lalmani *et al* [7], who have evaluated downward transport of ionization by analyzing whistlers recorded at Nainital. Singh *et al* [5] have also discussed the electron density, total electron content in a flux tube and downward transport of ionization by analyzing whistlers recorded at Varanasi, Nainital and Gulmarg.

The technique of electron density determination from whistler data assumes that the whistler wave has propagated along geomagnetic field lines. Singh *et al* [8] suggested that the whistlers received at Varanasi may have propagated in the Earth-ionosphere wave-guide in the lower ionosphere and followed field aligned path in the inner plasmasphere. Whistlers which have followed such propagation path when analyzed, yield information about mid latitude magnetosphere. Thus, whistlers recorded at low latitudes can be used to probe mid-latitude regions.

In this paper, an attempt has been made to determine the equatorial electron density and total electron content in a flux tube using whistlers recorded at low latitude stations Varanasi and Gulmarg. The results are quite important because it provides an extension to lower latitudes of the profiles

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published by workers at high and mid latitudes. The experimental data and the method of analysis are briefly discussed in Section 2. Results are discussed in Section 3. Finally, conclusions are summarized in Section 4.

2. Experimental data and method of analysis

The routine recording of whistlers at low latitude stations Varanasi (geomag lat. 14° 55' N) and Gulmarg (geomagnetic lat. 24° 10' N) shows that the whistler occurrence rate is low and sporadic. The occurrence probability enhances during magnetic storm period which may be due to additional duct formation. For the present study, we have chosen whistlers recorded on 9th March 1991 for Varanasi and 8th February 1986 for Gulmarg station. At Varanasi, on 9th March 1991 during 0030–0300 hrs IST, a large number of whistlers of good quality with sharp dynamic spectra (Figure 1) were recorded. At Gulmarg, whistlers in large numbers were

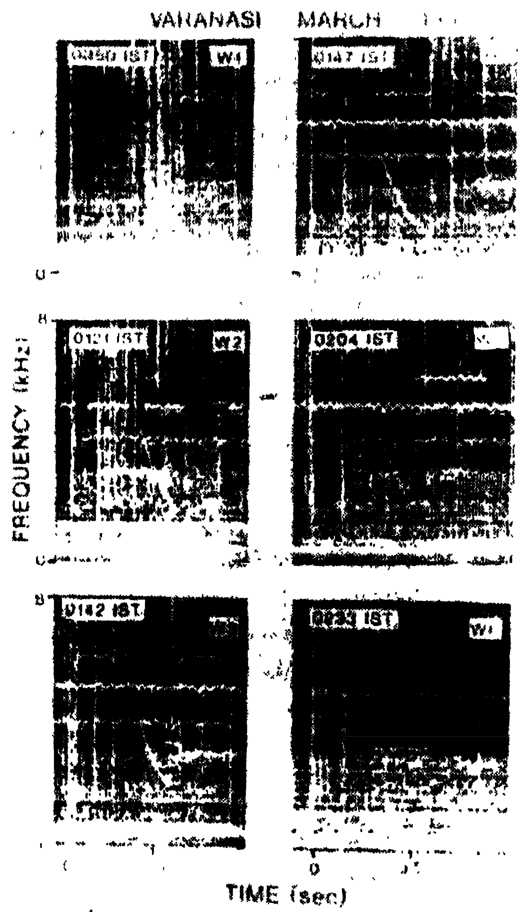

Figure 1. Sonogram of whistlers recorded at Varanasi on 9th March, 1991.

observed on 8th February 1986 between 0254-0650 hrs IST. A sequence of sonograms is shown in Figure 2, which are diffuse in nature. It may be noted here that for the present study, the selected data correspond to different time periods and also to different levels of magnetic activity. These periods are chosen because very large number of whistlers were recorded which is necessary for morphological studies. In our data bank, we could not get data simultaneously recorded at two stations which would have been an ideal situation.

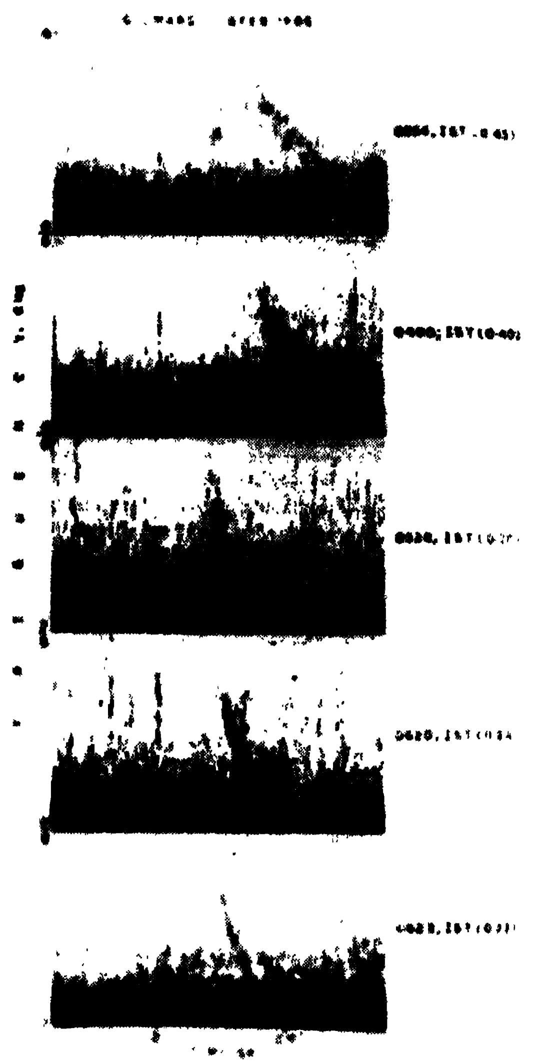

Figure 2. Sonogram of whistlers recorded at Gulmarg on 8th February 1986.

In the whistler analysis, frequency and corresponding arrival time are measured from the dynamic spectrogram and dispersion is evaluated. Dispersion of the wave in terms of frequency and travel time is $D = t f^{1/2}$. The group travel time for the whistler wave from the source to the observer is written as

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

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 negligibly small and is taken as origin for time measurements, t_w is the time taken by the whistler wave in the Earth-ionosphere wave-guide after exiting from the lower ionosphere, 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* [5] have suggested an average value of $t_w \sim 10$ ms for whistlers recorded at low latitude Indian stations.

The dispersion produced for ionospheric path is evaluated by using the formulation of Park [9] which depends on critical frequency of the F-layer of the ionosphere. The critical frequency ($f_0\ F_c$) varies from place to place in the post-mid night period. Based on the measurement of $f_0\ F_c$ at nearby station, 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 $t_{ion} \cong 100$ ms. Thus, with these corrections, we can write [5,10]

$$t - t_w - t_{ion} = t_{mag} = \frac{R_e L}{2C} \int_0^{\phi'} \frac{f_P(\phi)}{f^{1/2}} \frac{f_{He} \cos^6 \phi_0 (1 + 3\sin^2 \phi)}{\cos \phi \left[f_{He} \frac{\cos^6 \phi_0}{\cos^6 \phi} (1 + 3\sin^2 \phi)^{1/2} - f \right]^{3/2}} d\phi, \quad (2)$$

where f_p and f_{He} are local electron plasma frequency and equatorial electron gyro-frequency, respectively. φ' is the geomagnetic latitude at reference height, R_e is the earth's radius, L is the McIlwain parameter and φ_0 is the geomagnetic latitude of the field line at the surface of the Earth. At low latitudes, $f_{He} >> f$ and considering electron density distribution along dipolar geomagnetic field line to be $N = K^2 R^{-3}$ [11] (where K is a constant), eq. (2) in terms of dispersion is written as

$$D_0 = D_{obs} - D_{ion} = (9 L R_e^{-1/2} K / 2C f_{He}^{1/2}) \int^{\varphi'} \cos\varphi (1 + 3\sin^2 \varphi)^{1/4}\, d\varphi, \quad (3)$$

where $D_{obs} = (t - t_w) f^{1/2}$ is the measured dispersion with correction, $D_{ion} = t_{ion} f^{1/2} \cong 7.0\ \sec^{1/2}$. D_{obs} was obtained from the slope of $t - t_w$ *versus* $f^{1/2}$ plot. Thus, for a given station, K is determined by integrating eq. (3) and using measured dispersion of the recorded whistler. Once K is known, the electron density distribution along a geomagnetic field line is determined.

In eq. (3), the integral has to be evaluated along the whistler path in the magnetosphere. The whistler path is determined from the nose frequency on the dynamic spectrograph. At low latitudes, the nose frequency is not observed which is estimated by extrapolation technique [12,13]. In this approach, $Q(f)$ [$= 1/D(f)$] *versus* f is plotted, which results in a straight line whose intercept on the f axis is $f_0 = (3.09 \pm 0.04) f_n$. Thus, f_n is determined from f_0. The group propagation time T_n at the nose frequency f_n is estimated from

$$T_n = -\{2.1 f_n^{3/2} (dQ / df)\}^{-1}. \quad (4)$$

The maximum error introduced in the evaluation of f_n and hence in T_n in the present case, comes out to be within 10–14%. Although this method gives good results at mid-latitudes, its validity at low latitude may be questioned. Singh *et al* [5] analyzed few whistlers both by this method and Tarcsai's method [4] and noted that both methods yielded results within $\pm 10\%$. Tarcsai's method for low latitude whistlers was successfully used by Lalmani *et al* [7].

Using $f_{Heq} = f_n / 0.4$ [12,13], the L value along which whistler wave has propagated is estimated by

$$L = 9.56 / f_{Heq}^{1/3}, \quad (5)$$

where f_{Heq} is measured in kHz.

The electron density distribution along geomagnetic field line is used to determine the total electron content in a magnetic flux tube of unit cross sectional area at the reference height, which is written as

$$N_T = \int_{ref}^{equator} N(s) \{B_r / B(s)\} ds, \quad (6)$$

where B_r is magnetic field at the reference level and $B(s)$ is magnetic field at any other point s along the field line and ds is elementary path length. Using continuous whistler observation, the time development of electron content of the flux tube is monitored and the change in flux tube content is evaluated using the formula

$$dN_T / dt = (N_{t2} - N_{t1}) / (t_2 - t_1), \quad (7)$$

where N_{t1} and N_{t2} are the tube content derived from whistler data 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. If $N_{t2} > N_{t1}$, flux transport is upward whereas for $N_{t2} < N_{t1}$, flux transport is downward.

3. Results and discussion

The thermal plasma interacting with whistler wave in the presence of geomagnetic field causes dispersion of the wave which is recorded at Varanasi and Gulmarg. The dispersion has been evaluated from the dynamic spectra for different time period and is shown in Figure 3. It is seen that the dispersion decreases with the increase in time for both the stations, although the data are quite scattered. If the whistlers follow the same path, it can be safely assumed that the electron density distribution along the field line has changed and hence, total electron flux has changed with time. Using the extension method, nose frequency for each whistler has been determined which is used to determine the path of propagation of whistlers. It is found that for Varanasi data,

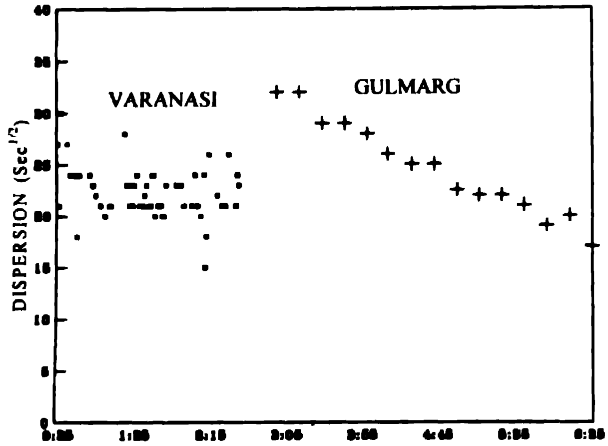

Figure 3. Variation of dispersion of whistlers with time recorded at Varanasi.

the propagation path varies from $L = 2.1$ to $L = 2.7$ whereas the L-value of Varanasi is 1.07. Thus, it is found that the whistler have propagated along higher L-values in the magnetosphere and after exiting from the ionosphere followed the Earth-ionosphere wave-guide and propagated towards equator to be received at Varanasi.

The equatorial electron density is estimated by analyzing all the recorded whistlers. The variation of equatorial electron density as a function of L-value is shown in Figure 4. It is

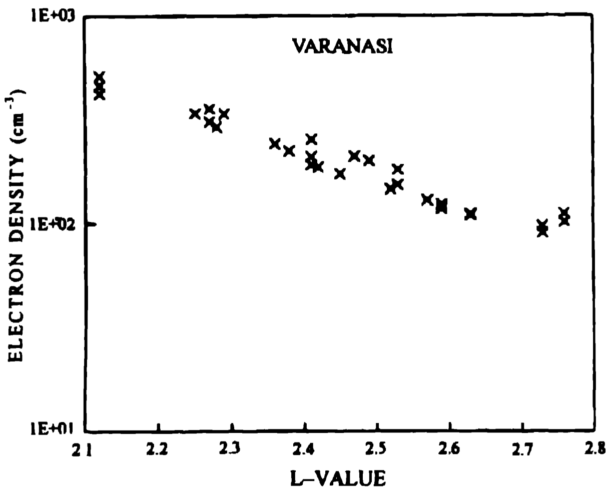

Figure 4. Distribution of electron density in the equatorial region of L-value for the whistler data recorded at Varanasi.

observed to decrease with the increase in L-value. The minimum and maximum values of the electron density for the whistlers recorded at Varanasi on 9th March 1991 come out to be 1×10^2 and 5×10^2 electron cm^{-3}, whereas for Gulmarg on 8th February 1986, the minimum and maximum values of the electron density come out to be 2×10^4 and 16×10^4 electrons cm^{-3} respectively. Since the magnetic activity for Gulmarg data is greater ($K_p = 7$–9) than Varanasi ($K_p = 3$–4), the increase in electron density with equatorial altitude may be attributed to the difference in magnetic activity. The results derived from our observations are in agreement with those reported by Park *et al* [3] and Tarcsai *et al* [4]. Park *et al* [3] have obtained average density of 3×10^3 electron cm^{-3} at $L = 2.0$, whereas Tarcsai *et al* [4] have reported 2×10^4 electron cm^{-3} at $L = 1.4$ and 5×10^2 electron cm^{-3} at $L = 3.2$. Apart from comparing the magnitudes of the electron density, we can not discuss the time and height variation of electron density using the data obtained from whistlers recorded at Varanasi and Gulmarg, because the observations at these two stations were not carried out simultaneously. This time gap forbids us from microscopic comparison.

The total electron content in a flux tube of unit cross sectional area has been obtained by numerically integrating eq. (6). The time development of total electron content in a flux tube of unit cross section for Varanasi and Gulmarg are shown in Figure 5. It varies between 8.4×10^{12} and 1.5×10^{13} electrons/cm^2-tube at Varanasi and between 2.1×10^{13} and 1.3×10^{14} electrons/cm^2-tube at Gulmarg.

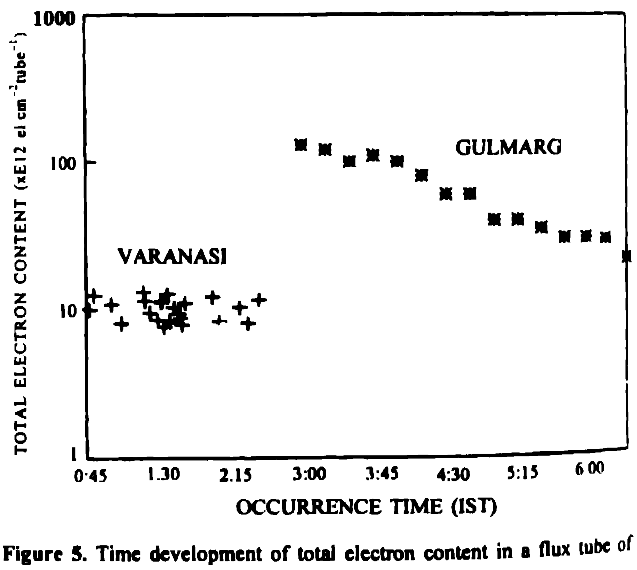

Figure 5. Time development of total electron content in a flux tube of unit cross section for Varanasi and Gulmarg.

The higher tube electron content at Gulmarg may be due to severe magnetic storm ($K_p = 7$–9) condition during which data were collected. Another reason may be that the flux tube length corresponding to Gulmarg is large compared to that of Varanasi. The tube electron contents as determined at these stations are of the same order as reported by other workers [3,4,7,13].

From Figure 5 and using eq. (7), we have computed the ionization flux transported downward for Varanasi as 1.1×10^9 electrons cm^{-2} sec^{-1} and for Gulmarg as 8.8×10^9 electrons cm^{-2} sec^{-1}. These results are in agreement with those reported by Lalmani *et al* [7] and Singh *et al* [5]. These results clearly show that the downward transported flux increases with the increase in magnetic activity. This again supports that the large magnetic activity causes movement of plasmapause closer to the surface of the Earth. During magnetic disturbances, the size of the plasmasphere is reduced and the density levels inside the reduced plasmasphere is also reduced [3]. Subsequent recovery takes place by refilling from the underlying ionosphere which is slow and requires many days [14].

4. Conclusions

The whistler data recorded at Varanasi and Gulmarg at different times and for different magnetic activities have been analyzed to study the downward transport of flux. The computed electron densities in the equatorial region lies in the range 1×10^2–5×10^2 electrons cm^{-3} for Varanasi and 2×10^4–16×10^4 electrons cm^{-3} for Gulmarg. The computed electron content lie in the range 0.84×10^{13} and 1.5×10^{13} electrons/cm^2-tube for Varanasi and 2.1×10^{13} and 1.3×10^{14} electrons/cm^2-tube for Gulmarg. The downward transport of ionization flux is of the order of 10^9 electrons cm^{-2} sec^{-1}. These results are in good agreement with the results reported by other workers. It is also shown that the transported flux increases with the increase in magnetic activity. These transported fluxes couple the ionosphere and the lower part of the inner magnetosphere and form the basis for the study of the magnetosphere-ionosphere coupling mechanism.

Acknowledgment

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