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Whistler-Based Study of Electron Flux Transport in the Ionosphere–Plasmasphere System observed at Low-Latitude station Jammu (L = 1.17)

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Abstract

The downward flux of ionization was investigated using whistler-mode signals recorded at the low-latitude ground station Jammu (geomagnetic latitude 22°262 , L = 1.17) on 5 June 1997. The whistler observations exhibit a systematic temporal variation in dispersion. This decrease in dispersion is interpreted as a corresponding reduction in the electron content of ionization flux tubes and is compared with the mid-latitude results reported by Park (1972, Technical Report, Stanford University). Using Park's expressions, the equatorial electron density and total electron tube content (N_T) were computed. The whistler measurements indicate an average downward electron flux of 2.8×10^8 electrons cm^{-2} s^{-1}. The ionization gradient was also estimated using the simple diffusion equation that relates the particle flux to the ambipolar diffusion coefficient. The flux obtained from this diffusion model is found to be within an order of magnitude lower than that derived from the whistler dispersion analysis. This discrepancy suggests that, in addition to diffusion, other processes—such as (E ×B) drifts—play a dominant role in controlling ionospheric plasma transport at low latitudes.

Key words : flux of the ionization, equatorial electron density, electron tube content, Plasmasphere, Ionosphere, dispersion.

An important characteristic of low-latitude whistler propagation is the relatively low maximum height reached by the associated field lines. The L-values corresponding to low-latitude stations are quite small—for example, Gulmarg (L = 1.2), Nainital (L = 1.12), and Jammu (L = 1.17). This indicates that the propagation path of whistlers observed at Jammu remains within the upper boundary of the F-layer. Although this boundary is not sharply defined, it is generally considered to be the altitude at which light ions (hydrogen and helium) become more abundant than heavier ions, mainly oxygen. This upper boundary exhibits diurnal and geographical variations and is typically found between 600 and 2000 km [2,3,4]. For practical purposes, it is often identified near 1000 km, which is taken as the lower boundary of the plasmasphere. Thus, the study of whistlers at Jammu provides valuable information about the top of the ionospheric F-layer.

Apart from production and loss processes, a major concern in understanding the upper F-layer is the transport of ionization. In general, ionization transport in the topside F-region may result from:

(1) E × B drifts,

(2) ambipolar diffusion along magnetic field lines, and

(3) interaction between ionization and neutral winds.

At the magnetic equator, the combined effect of (1) and (2) explains the well-known equatorial anomaly.

A key question is the maintenance of the nocturnal F-layer. Several processes are believed to contribute to this. Neutral winds can transport ionization upward along magnetic field lines, where the dissociative recombination loss rate is reduced (Hansen and Patterson, 1964; Park, 1970; Carpenter and Bowhill, 1971; Rishbeth, 1968). A nighttime production rate of approximately 1 cm^{-3} s^{-1} is required to maintain the F-layer, supported by a critical downward flux of about 1.5×10^7 cm^{-2} s^{-1} (Rishbeth, 1968). It appears, however, that the nocturnal F-layer cannot be fully explained without invoking a downward diffusion flux of the order of 10^8 cm^{-2} s^{-1}, which is sufficient when combined with ionization produced by charge exchange involving Hz ions from the plasmasphere (Carpenter and Bowhill, 1971).

Whistler techniques are among the most reliable for studying the morphology and dynamics of the plasmasphere, magnetospheric electric fields, and coupling fluxes between the ionosphere and plasmasphere (Carpenter, 1966; Park, 1972). Mid-latitude whistler studies have reported upward daytime fluxes of approximately 3 × 10x electrons cm^{-2} s^{-1} across the 1000 km level, and nighttime downward fluxes of about 1.5 × 10x electrons cm^{-2} s^{-1}, sufficient to sustain the nocturnal F-layer[5].

Propagation characteristics of low-latitude whistlers and their association with plasma behaviour have been extensively studied by Hayakawa and Tanaka[9]. Low-latitude whistlers are particularly valuable for addressing unresolved problems in this region because they are highly sensitive to propagation conditions such as duct excitation and ionospheric transmission. Hayakawa *et al.*[10], studying nighttime low-latitude whistlers, pointed out that after ionospheric penetration the whistlers are more likely to propagate toward higher latitudes than toward the equator. Sub-ionospheric propagation also tends to exhibit horizontal beaming around the magnetic meridian plane. These observations have been interpreted in terms of either non-ducted or field-aligned propagation, with strong evidence favouring field-aligned propagation for very low-latitude whistlers localized around geomagnetic latitudes of 10°–14°.

In this paper, an attempt is made to determine the downward flux of ionization from whistler observations at low latitude. The data show a smooth variation in dispersion with time, which is interpreted as a corresponding decrease in the electron content of magnetospheric ionization tubes. A major difficulty in low-latitude whistler analysis is the precise determination of the nose frequency (f_n) and nose time delay (t_n).

For the analysis of non-nose whistlers, the downward flux of ionization was computed using the accurate curve-fitting method developed by Tarcsai[11], applied to whistlers recorded on 5 June 1997 at Jammu. These results are compared with those reported by Park[1] for mid-latitudes. Magnetospheric electric fields and protonospheric coupling fluxes are also referenced based on simultaneous phase and group-path measurements of whistler-mode signals[19]. The ionization flux is further computed from the simple diffusion equation, which relates the flux to the ionization gradient via the ambipolar diffusion coefficient. The diffusion-derived flux is found to be within an order of magnitude smaller than the value obtained from dispersion data. This suggests that E × B drifts play a dominant role in regulating ionization transport at low latitudes.

Data Selection and Method of Analysis :

At low latitudes, the occurrence rate of whistlers is generally low and sporadic. However, once whistler activity begins, its occurrence rate often becomes comparable to that observed at mid-latitudes (Hayakawa et al., 1988). Similar behavior has been reported at Indian low-latitude stations. All Indian stations used for this study are well equipped for monitoring VLF waves from natural sources.

For the present work, whistler data recorded on 5 June 1997 at Jammu were selected. On this date, whistler activity at the Jammu station began around 2140 h IST (Indian Standard Time) and continued until 2245 h IST. During this period, approximately 100 whistlers were recorded (Lalmani *et al.*, 2001). In total, more than a hundred events were noted, and the occurrence rate exhibited a faint but distinct periodicity (Rao and Lalmani, 1975). Several whistlers recorded during this interval have also been reported by Singh e*t al.* (2000).

Figure 1(a) shows the dynamic spectrum of short whistlers (marked A, B, C, D, E, F, and G—selected for analysis) in the frequency range 3.0–4.5 kHz, recorded at 2212 IST on 5 June 1997 at Jammu. In the 1.7–3.0 kHz band, a large number of frequency components are missing, and the signals resemble emissions rather than true whistlers. Additionally, VLF waves in these two frequency bands do not appear simultaneously; instead, they occur alternately.

Figure 1(b) displays the dynamic spectrum of short whistlers (marked 1, 2, 3, and 4—selected for analysis) along with VLF emissions recorded at 2147 IST the same day. The whistlers appear banded and diffuse in the 2.7–3.7 kHz frequency range and repeat in time. The time intervals between consecutive events are irregular. Unusual VLF noise signatures are also visible in the spectrum.

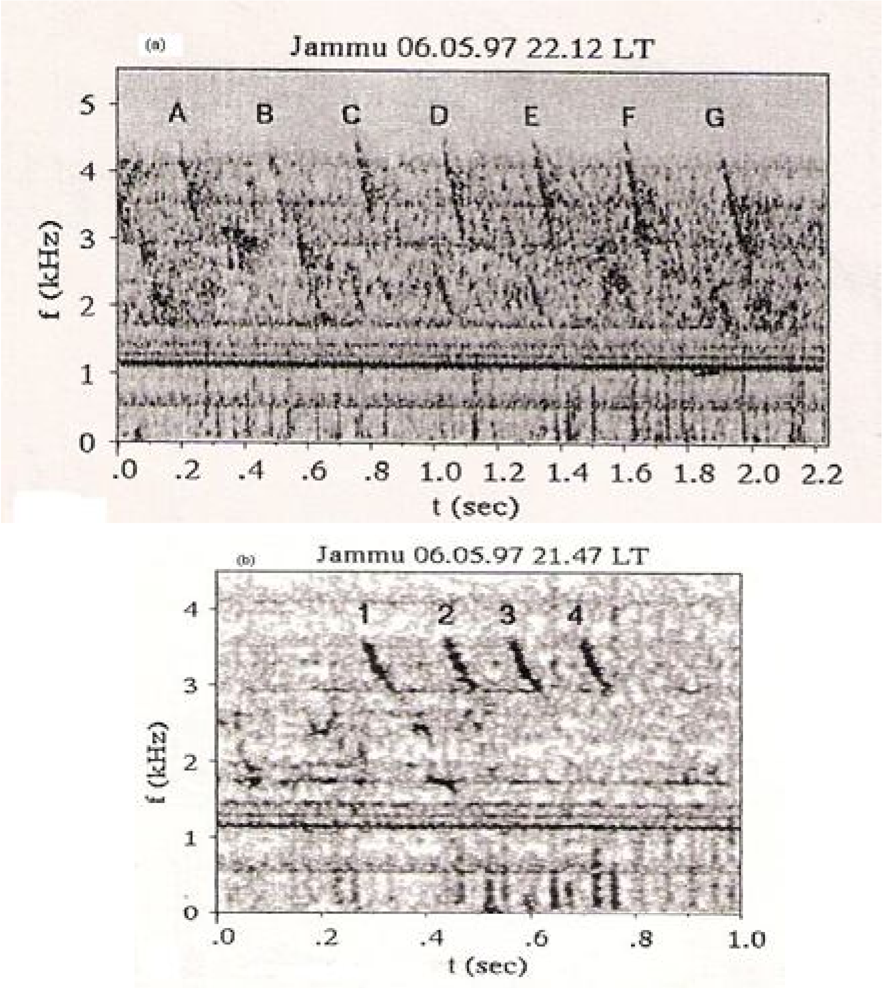

Fig. 1. (a) Dynamic spectrum of whistlers recorded at Jammu June 5, 1997. Whistlers are marked by A,B,C,D,E,F and G. (b) Dynamic spectrum of whistler recorded at Jammu June 5, 1997. Whistlers are marked by 1, 2, 3 and 4.

Tarcsai[11] has developed a curve fitting technique for the analysis of middle and high latitude whistlers. This technique has also been applied successfully to those low latitude whistlers whose propagation path are low below L = 1.4 [15,16,18,11]. Further technique is found suitable not only for long and good quality whistlers but also for short and faint whistlers. The computer programme written for the purpose requires input data such as frequency time (f, t) values scaled at several points along whistler trace appropriate for F2, zero frequency dispersion (Do), and a suitable ionospheric model etc. The output results include the L-value of propagation, equatorial electron density, total tube content etc. we have adopted this programme for the analysis of nighttime whistlers recorded at our station Nanital, Varanasi and Jammu during quiet days.

At low L-values, the curve fitting method of Tarcsai[11] would not change too much the equatorial electron density and total electron content values compared to the systematic errors which are inherent in all of the existing nose extension methods. These systematic errors originate from the approximations used for the refractive index and for the ray path in the derivation of the analytic expressions for the dispersion and from the difference between the theoretical and actual distribution plasma along the field lines (Tarcsai et al., 1989). To examine its validity we analyzed few whistlers recorded at Jammu using this method as Dowden Allcock (1971) Q- technique. Both methods yielded results within ± 10%. Further, it is to be noted that the Tarcsai's method has successfully been used in the analysis of low latitude whistlers[14].

For the determination of D_o f_n and t_n Ho and Bernards (1973) approximate function for the dispersion of whistlers is given by [11]

$$D(f) = t(f) f^{1/2} = D_o \left[\frac{(f_{Heq} - Af)}{f_{Heq} - f} \right] \tag{1}$$

Where

D_o = zero frequency dispersion

f_{Heq} = equatorial electron gyrofrequency

f = Wave frequency

t(f) = travel time at frequency f, and

$$A = \frac{3\Lambda_n - 1}{\Lambda_n (1 + \Lambda_n)} \tag{2}$$

Here

$$\Lambda_n = \frac{f_n}{f_{Heq}}$$

Where f_n is the nose frequency for which travel time t_n is written as

$$t_n = \left[\frac{D_o}{f_n^{1/2}} \right] \left[\frac{2}{(1 + \Lambda_n)} \right] \tag{3}$$

If the causative sferic is unknown, and the travel times at different frequencies of the whistler traces are measured with respect to an arbitrary time origin, then it is necessary to introduce a new parameter T, which gives the difference in time between the chosen origin and the actual causative sferic. Using T and equation (1) the measured travel time $t^*(f)$ can be written as

$$t^*(f) = t(f) - T = \frac{D_o}{\sqrt{f}} \frac{(f_{Heq} - Af)}{(f_{Heq} - f)} - T$$

$$= \left[\frac{D_o}{\sqrt{f}} \frac{f_{Heq} f_n (f_{Heq} + f_n) - f(3f_n - f_{Heq})}{f_n (f_{Heq} - f)(f_{Heq} + f_n)} \right] - T \tag{4}$$

In this equation there are four unknown parameters; D_o, f_{Heq},T and f_n. In the following we proceed in two different ways; either we assume f_n to be an independent parameter or we adopt a model for the electron density distribution. This helps us in reducing the number of unknowns to three. In the present study, the latter procedure is followed. Thus those values of D_o, f_{Heq}, and T searched for, which fit best to the measurements in the least square sense, i.e, which minimize the sum of the weighted squares of residuals

$$M = \sum_{k=1}^{n} W_k \left[t^*_{mk} - t^*_{ck}(D_o, f_{Heq}, T) \right]^2 \tag{5}$$

Where the subscripts m and c refer to the measured and computed t^*values, respectively, w_k 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.

As is known from the theory of least squares estimation, in a nonlinear case the determination of the parameters which correspond to the condition M= minimum, can be accomplished through linearization by expanding the residuals into a Taylor series and then using an iteration procedure[11], we have done exactly this. Let us introduce the vector X whose components are

$$X_1 = D_o$$
$$X_2 = f_{Heq} \tag{6}$$
$$X_3 = T$$

Then assuming that the values of D_o , f_{Heq} and T are known at iteration
(i-1), the improved solutions at the ith step can be obtained as

$$X_I = X_{i-1} + \Delta X_I \tag{7}$$

Where the vector differential corrections ΔX_1 is given in each step of the iteration by

$$\Delta X = A' WY (A' WY)^{-1} \tag{8}$$

In equation (8) the prime indicates matrix transposition A is then n×3 matrix of the partial derivatives of t^* with respect to the unknown parameters, whose elements can be computed, using equation (4)

$$a_{kj} = \left(\frac{\partial t^*}{\partial x_j} \right)_{f=f_k} \tag{9}$$

W is n×n square matrix of the measurement weights, which is diagonal for uncorrected measurement errors, and Y is the column vector of residuals with elements

$$Y_k = t^*_{mk} - t^*_{ck} \tag{10}$$

In evaluating the matrix formula of equation (8), those values of D_o , f_{Heq} and T are to be used, of course, which have been obtained in the previous step of the iteration. No weighting has been used in general ($w_{kk} = 1$, $w_{kj} = 0$, $k \neq j$). The value of f_n has also been improved in each step, in the following manner. According to Park (1972) for typical diffusive equilibrium model, (DE-1) of the electron density distribution, Λ_n can be calculated from f_n as

$$\Lambda_n = (3.5475 - 0.47351F + 0.065879F^2)^{-1} \tag{11}$$

Where $F = \log_{10} f_n$

Also as $\Lambda_n = f_n/f_{Heq}$, we can write

$$f_{n,i+1} = \Lambda_{ni} \ f_{Heq,i+1} \tag{12}$$

Where, Λ_{ni} is computed from equation (11) with f_{ni} obtained in the preceding step of the iteration. Thus, for a converging, $f_{ni,}$ the nose frequency also converges. From this it is clear that in the course of iteration the value of A is also changed successively but in general rather weakly, and it converges very fast.

The iteration procedure outlined can be stopped, if the magnitude of the corrections decreases below a certain fixed level, or the sum of weighted squares of the residuals stabilizes. After the criterion of convergence has been fulfilled, i.e., the iteration has been finished, t_n can be computed from equation (3)

In order to ensure the procedure against divergence it is necessary to introduce a multiplicater m into equation (7) we have

$$X_1 = X_{i-1} + m\Delta X_1 \tag{13}$$

Where $0 < m \leq 1$ and the actual value of m is properly varied in the course of iteration. Generally $m \leq 0.1 - 0.3$ at the first two steps and it is increased to unity.

Using values of D_o and f_{Heq} (or f_n and t_n) obtained by the curve fitting method, we can compute the equatorial radius of the whistler duct (L) the local electron density at the geomagnetic equator (n_{eq}) and at a height of 1000km (N) ; and the tube electron content (N_T). After Park (1972) and Tarcsai (1975), and using equation (3) for t_n we can write

$$L = 8.735 \times 10^5 f_{Heq}^{-1/3} \tag{14}$$

Where f_{Heq} is in *Hz*

$$n_{eq} = K_e f_n t_n^2 L^{-5} = K_e^{/} D_o^2 f_{Heq}^{5/3} \tag{15}$$

$$N_T = K_T f_n t_n^2 L^{-1} = K_T^{/} D_o^2 f_{Heq}^{1/3} \tag{16}$$

$$N = K_1 f_n t_n^2 L^{-5} = K_1^{/} D_o^2 f_{Heq}^{5/3} \tag{17}$$

Where the constants $K^{/}_e$ and $K^{/}_T$ are weakly dependent on f_n and Λ_n Tracsai (1975).

Table 1. Parameters of whistlers observed at Jammu ground station estimated from the whistler dispersion analysis using accurate curve fitting technique. W is the whistler number, IST is the Indian Standard Time, D_o is the dispersion of whistler, f_n is the whistler nose frequency, f_{Heq} is equatorial gyro frequency, L-value is in earths radii, n_e is the equatorial electron density.

W	Station	Dates&Year	IST	D_o ($sec^{1/2}$)	f_n (KHz)	f_{Heq} (KHz)	L Value	n_e(cm^{-3})	N_T(cm^{-2})
1	Jammu	05June1997	21:40:25	65.5±1.0	4.2±0.03	11.37±0.07	4.25±0.01	159±3	1.9×10^{13}
2	Jammu	05June1997	21:47:42	81.9±1.1	3.39±0.013	10.59±0.034	4.35±0.005	220±5	2.9×10^{13}
3	Jammu	05June1997	22:47:50	88.9±1.8	3.82±0.02	10.27±0.05	4.39±0.07	247±8	1.9×10^{13}
4	Jammu	05June1997	22:47:55	87.6±1.4	3.85±0.01	10.37±0.03	4.38±0.00	244±6	3.4×10^{13}
5	Jammu	05June1997	22:12:20	28.8±1.2	8.15±0.72	21.98±1.95	3.41±0.10	93±6	3.3×10^{12}
6	Jammu	05June1997	22:12:51	28.9±0.9	6.29±8.21	16.96±0.55	3.72±0.04	61±1	4.5×10^{12}
7	Jammu	05June1997	22:13:22	35.5±1.7	6.13±0.25	16.51±0.66	3.75±0.05	88±2	4.2×10^{12}
8	Jammu	05June1997	22:13:53	38.3±1.9	4.61±0.10	12.42±0.28	4.12±0.03	63±4	6.3×10^{12}
9	Jammu	05June1997	22:14:24	26.1±0.6	5.76±0.13	15.53±0.35	3.83±0.02	43±4	3.3×10^{12}
10	Jammu	05June1997	22:14:55	22.8±1.7	5.99±0.41	16.17±1.10	3.78±0.08	35±1	2.6×10^{12}
11	Jammu	05June1997	22:15:26	38.9±1.2	5.06±0.09	13.62±0.24	4.00±0.02	76±3	7.1×10^{12}

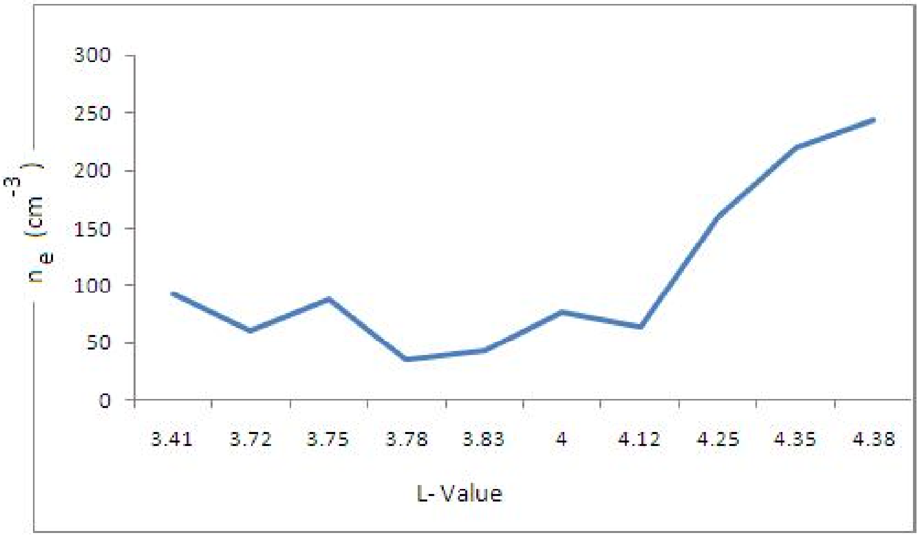

Fig. 2. Variation of equatorial electron density (n_e) with L.

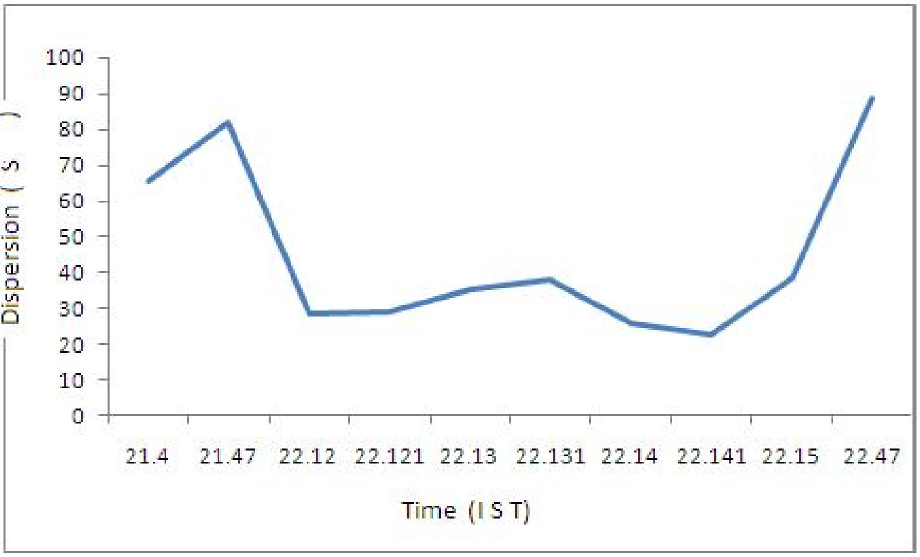

Fig. 3. Variation of dispersion with time.

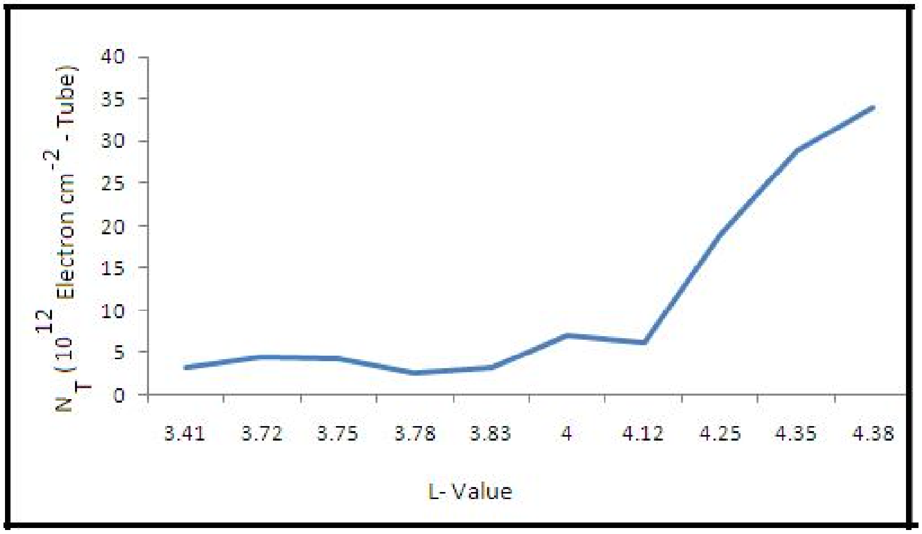

Fig. 4. Variation of Electron tube content with L- Value

Transport of Ionization and Ambipolar Diffusion :

The observed flux of ionization at an altitude of 500 km can, in principle, be explained by ambipolar diffusion. The ambipolar diffusion coefficient (δ_a), the gradient of electron density (∇n), and the downward ionization flux (F) is related by (Carpenter and Bowhill, 1971):

$$F = \delta_a \cdot \nabla n \tag{18}$$

Derivation of Electron density gradient :

Let n(r, t) be the electron number density. The gradient is $\nabla n = \frac{\partial n}{\partial x}, \frac{\partial n}{\partial y}, \frac{\partial n}{\partial z}$

Electron current density has two contributions: Drift and Diffusion

$J_{drift} = q\, n\, \mu\, E$

$J_{diff} = q\, D\, \nabla n$

Hance total current $J = q\, n\, \mu\, E + q\, D\, \nabla n$

Charge conservation gives $\frac{\partial n}{\partial t} = -\nabla.(qn\mu E) - \nabla.(qD\nabla n)$

The electron density gradient appears naturally from diffusion

$$\nabla n = \frac{1}{qD}(J_n - qn\mu E)$$

The ambipolar diffusion coefficient δ_a (parallel to the magnetic field) is approximately given by:

$$\delta_a \approx \delta_i \left(1 + \frac{T_e}{T_1}\right) \qquad (19)$$

Where δ_i = diffusion coefficient of ions = $K(T_i/m_i\, \nu_{in})$, Here T_e = electron Temperature, T_i = Ion temperature, K = Boltnman Constant, m_i = mass of ion and ν_{in} = collision frequency between ions and neutral particles.

The value of δ_a can be computed using reasonable estimates of T_e , T_i, and ν_{in}. At a height of 500 km, δ_a has been determined to be approximately 2×10^{11} cm^2 s^{-1} (Okuzawa et al., 1971, P. Coisson, *et. al* 2025).

To calculate the flux, the magnitude of the electron density gradient ∇n is required. This gradient can be obtained from electron density profiles derived from whistler observations. At 500 km altitude, the gradient is approximately 5.4×10^{-3} cm^{-3} cm^{-1}. Thus the magnitude of flux is about 14.6×10^7 cm^{-2} s^{-1} which is within one order of magnitude less than the value of 2.8×10^8 cm^{-2} s^{-1} obtained earlier.

Discussion of Results

It is instructive to compare the present results for total electron content and ionization flux with those obtained by Park (1970, 1972), whose computations apply to L-values between 3.5 and 5. According to Park, the total electron content of ionization tubes in this L-range is of the order of 10^{13} electrons cm^{-2}. Our results, summarized in Table 1, cannot be directly compared with Park's values because the L-values for our observations (3.8–4.4) differ from those used in his studies. For these L-values, the equatorial electron density (n_e) and electron tube content (N_T) obtained in the present analysis lie in the ranges of 2×10^2 electrons cm^{-3} and 10^{12}–10^{13} electrons cm^{-2} $tube^{-1}$, respectively.

The discrepancy between low-latitude and mid-latitude results may be attributed to the use of the nose extension method for analyzing non-nose whistlers, which dominate at our low-latitude station, Jammu. During night-time, interchange processes between the ionosphere and protonosphere and the downward flux of ionization (from about 500 km to 1000 km) are well established at mid-latitudes. Our low-latitude results indicate a similar downward flux, consistent with these observations.

Low-Latitude versus Mid-Latitude Behaviour :

One important source of uncertainty in the present analysis arises from the dominance of non-nose whistlers at the low-latitude station Jammu. The use of the nose-extension method, while necessary under such conditions, introduces additional assumptions regarding duct geometry and propagation paths. In contrast, mid-latitude studies benefit from a larger number of well-defined nose whistlers, leading to more precise estimates of plasma parameters.

Despite these limitations, the low-latitude results clearly indicate a persistent downward flux of ionization during night-time conditions. This behaviour mirrors well-established mid-latitude observations, where ionosphere–protonosphere interchange and downward plasma transport from altitudes of 500–1000 km are commonly observed. The present findings therefore suggest that similar coupling processes occur at low latitudes, although their manifestation may differ due to magnetic field geometry and electric field configurations.

From our calculations, the downward ionization flux is of the order of 2×10^8 electrons cm^{-3} s^{-1}, which agrees reasonably well with Park (1970). The major source of uncertainty arises from the fact that only non-nose, low-latitude whistlers were available for analysis. Nevertheless, studies of topside F-region ionization transport remain valuable. The results would be even more significant if simultaneous measurements from other techniques, such as incoherent scatter radar, were available for validation.

Importance of $E \times B$ Drifts :

The inability of ambipolar diffusion to fully explain the observed ionization flux strongly points to the importance of electrodynamic transport mechanisms, particularly drifts. Numerous mid-latitude whistler studies (Angerami and Carpenter, 1966; Park, 1970, 1972) have demonstrated that these drifts play a dominant role in redistributing plasma across magnetic field lines.

In the present low-latitude context, the observed downward movement of ionization implies the presence of westward electric fields in the morning sector. Such electric fields produce vertical plasma drifts that can effectively transport ionization downward along field-aligned ducts. To account for the observed variations in tube content, a westward electric field of the order of 1 mV m^{-1} is required.

The flux of ionization estimated through the ambipolar diffusion mechanism is approximately

1.44×10^8 electrons cm^{-2} s^{-1}, about one order of magnitude smaller than our whistler-derived value of 2×10^8 electrons cm^{-2} s^{-1}. This suggests that ambipolar diffusion alone cannot account for the observed flux, consistent with the findings of Okuzawa *et al.*[21], who attempted to explain duct spreading through diffusion processes.

Most mid-latitude whistler observations strongly indicate that E × B drifts play a major role in ionization transport (Angerami and Carpenter, 1966; Park, 1970, 1972). Our low-latitude results also support this conclusion. In the context of E × B drifts, the observed downward movement of ionization implies the presence of westward electric fields in the morning sector (Park and Meng, 1971; Altaf and Ahmad, 2014). Rapid and complex variations in tube content during substorms (Park, 1970, 1971, 1972) are likely caused by the combined effects of E × B drifts and field-aligned fluxes. To explain these variations, a westward electric field of approximately 1 mV m^{-1} is required.

Westward electric fields of this magnitude have indeed been inferred from whistler observations[25,20], based on radial motions of discrete field-aligned ducts and associated changes in nose frequency (Block and Carpenter, 1974; Hayakawa and Tanaka, 1978). Theoretical and experimental evidence supports ducted propagation of low-latitude whistlers, particularly within geomagnetic latitudes of 10°–14°, as confirmed by the direction-finding studies of Hayakawa *et al.* (1990).

The computed results reported by various researchers (Carpenter *et al.*, 1972; Block and Carpenter, 1974; Andrews *et al.*, 1978; Park, 1978,), though pertaining to higher latitudes, fall well within the expected range when extrapolated to lower latitudes. The present study highlights the significant relationship between vertical plasma drifts and protonospheric fluxes, demonstrating that both mechanisms play important roles in the nighttime ionosphere. Hence, it is concluded that E × B drifts are essential in controlling the transport of ionization at low latitudes.

Effects and Temporal Variability :

Rapid and complex variations in electron tube content, particularly during substorm periods, are likely caused by the combined action of drifts and field-aligned plasma fluxes. Park (1970, 1971, 1972) showed that such variations cannot be explained by diffusion alone and require time-dependent electric fields associated with magnetospheric dynamics.

The present low-latitude observations are consistent with this interpretation, suggesting that substorm-related electric fields penetrate to low latitudes and significantly influence topside ionospheric plasma transport.

Supporting Evidence from Whistler Observations :

Independent support for the presence of westward electric fields comes from whistler-based studies of duct motion. Radial displacements of discrete field-aligned ducts and corresponding changes in nose frequency have been used to infer electric field strengths of the order of 1 mV m^{-1} (Misra, 1979; Altaf and Ahmad, 2014, D Ravindra Patel 2021). These observations are consistent with the electric fields required to explain the present results.

Furthermore, both theoretical and experimental studies confirm that ducted propagation of low-latitude whistlers is feasible, particularly within geomagnetic latitudes of 10°–14°. Direction-finding measurements by Hayakawa *et al*. (1990, 2024) provide strong evidence for such ducted propagation, lending further credibility to the present analysis.

Implications and Future Work :

Overall, the present study demonstrates that while ambipolar diffusion contributes to downward ionization transport, it is insufficient to explain the observed fluxes at low latitudes. Electrodynamic processes, particularly drifts driven by westward electric fields, play a dominant role. The results highlight the importance of combining whistler observations with independent measurement techniques such as incoherent scatter radar or satellite-based plasma diagnostics. Such coordinated observations would significantly reduce uncertainties and provide a more comprehensive understanding of topside ionospheric transport processes.

Limitations of the Present Study :

The results presented in this study are subject to several limitations that arise primarily from the case-study nature of the dataset, which is based on whistler observations recorded at the low-latitude ground station Jammu ($L = 1.17$) on 5 June 1997.

1. Single-Event Analysis :

The analysis relies on whistlers recorded during a single geomagnetic event, which restricts the ability to generalize the inferred electron fluxes and ionosphere–plasmasphere coupling characteristics. While the event provides valuable insight into low-latitude plasma transport processes, it may not be fully representative of typical background conditions or other geomagnetic scenarios such as storm-time or quiet-time variability.

2. Short Duration of Observations :

The whistler dataset spans a relatively short time interval, limiting the investigation of longer-term temporal variations in electron density, tube content, and fluxes. As a result, processes operating on longer timescales—such as diurnal, seasonal, or solar-cycle-dependent variations—cannot be adequately assessed within the present framework.

3. Limited Statistical Significance :

Due to the small number of usable whistler traces, statistical averaging is limited. This increases uncertainty in the derived parameters such as equatorial electron density, total electron tube content ((N_T), and downward electron flux. Consequently, the results should be interpreted as indicative rather than definitive.

4. Assumptions in Whistler Inversion Techniques :

The derivation of electron density and flux from whistler dispersion relies on model-dependent assumptions, including field-aligned propagation, ducted whistler paths, and the applicability of Park's (1972) expressions—originally developed for mid-latitude conditions—to a low-latitude environment. Any deviation from these assumptions may introduce systematic errors.

5. Absence of Complementary Measurements :

The study lacks simultaneous supporting measurements, such as in situ satellite observations, ionosonde data, or electric field measurements near the magnetic equator. The absence of these independent datasets limits the validation of the inferred ionization gradients and the relative contributions of diffusion and electrodynamic processes.

6. Uncertainty in Transport Mechanisms :

Although the diffusion-based flux estimates are compared with whistler-derived values, the role of electrodynamic processes such as (E ×B) drifts cannot be directly quantified due to the lack of concurrent electric field data. This restricts the ability to conclusively identify the dominant transport mechanism.

Concluding Remark on Limitations :

Despite these limitations, the present study provides a valuable low-latitude case study high lighting discrepancies between diffusion-based and whistler-inferred electron fluxes. The results underscore the need for multi-event analyses and coordinated ground-based and satellite observations to better understand ionosphere–plasmasphere coupling at low latitudes.

Here is a well-structured section you can directly add to your research paper under the heading:

Scope and Future Research Prospects :

The present study of whistler-based electron flux transport in the ionosphere–plasmasphere system at the low-latitude station Jammu (L = 1.17) opens several promising directions for future investigation.

1. Long-Term Solar Cycle Dependence :

Future studies may focus on examining whistler-derived electron flux variations over complete solar cycles. A comparative analysis during solar minimum and solar maximum conditions would help in understanding the influence of solar activity on ionosphere–plasmasphere coupling at low latitudes.

2. Multi-Station Conjugate Observations :

Extending observations to a network of low- and mid-latitude stations, along with geomagnetically conjugate stations, would improve spatial understanding of electron transport processes.

Coordinated measurements could help quantify longitudinal and hemispheric asymmetries in plasmaspheric flux distribution.

3. Integration with Satellite Data :

Future research can integrate ground-based whistler observations with satellite missions such as:

- Van Allen Probes
- Swarm
- DEMETER

Such combined studies would allow validation of flux estimates, improve inversion techniques, and provide better insight into wave–particle interactions and energy transport mechanisms.

4. Storm-Time and Geomagnetic Disturbance Studies :

Detailed investigations during geomagnetic storms and substorm events are essential. Future work may examine how disturbed electric fields, plasma convection, and enhanced wave activity modify electron flux transport at L = 1.17. This would significantly contribute to space weather modeling efforts.

5. Wave–Particle Interaction Modeling :

Advanced numerical simulations incorporating VLF/ELF wave propagation and resonant wave–particle interactions could refine theoretical models of electron precipitation and pitch-angle diffusion. Coupling observational data with physics-based models would strengthen understanding of radiation belt dynamics at low L-shells.

6. Artificial Intelligence and Machine Learning Applications :

Application of machine learning techniques for automatic whistler detection, classification, and parameter extraction from large datasets could enhance accuracy and reduce manual processing time. Predictive modeling of electron flux variations using AI-based approaches may also be explored.

7. Coupling with Ionospheric Parameters :

Future work may correlate whistler-derived electron flux with:

- Total Electron Content (TEC)
- Ionosonde measurements
- GPS-based ionospheric scintillation data

Such integrated studies would improve understanding of electrodynamic coupling between the lower ionosphere and plasmasphere over low-latitude regions.

8. Regional Importance of Jammu (L = 1.17) :

Since Jammu lies at a low L-value, future research can investigate the role of inner plasmaspheric dynamics and its response to equatorial electrodynamics. This location provides a unique opportunity to study electron transport mechanisms closer to the Earth, where observational data remain comparatively limited.

Concluding Perspective

Overall, continued whistler-based investigations at Jammu can significantly contribute to global understanding of ionosphere–plasmasphere coupling, inner radiation belt dynamics, and space weather processes. With coordinated ground-based networks, satellite validation, and advanced modeling techniques, future research can establish more accurate quantitative relationships governing electron flux transport at low latitudes.

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