Indian J. Phys. **74B** (6), 449–454 (2000)

I J P B
an international journal

Quiet time average electron density profiles in the magnetosphere deduced from whistlers observed at a low latitude ground station Jammu

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Received 10 May 2000, accepted 16 October 2000

Abstract . New experimental data on whistler-triggered periodic VLF emissions observed during a quiet period at low latitude ground station Jammu (geomag. lat. 22°26' N; L = 1.17) is presented in this paper The present finding is believed to be the first such events reported from any of the low latitude ground stations during quiet times. The whistlers recorded during quiet times are one hop, or short type and the travel times of short whistlers at 4 kHz are found to lie in the range of 0.15–0.26 sec corresponding to dispersion in the range of 10–17 sec$^{1/2}$, a value typical of normal observation at low latitudes The short whistlers were observed continuously for a long period during quiet days in the frequency range normally between 2–5 kHz and are found to be triggered by periodic VLF emissions The observation of short whistlers during quiet times made at our low latitude ground station Jammu (geomag. lat. 22°26' N, L = 1.17) are used to deduce the average electron density profiles in the magnetosphere The electron density is computed by means of accurate curve fitting method and is in good agreement with the results reported by other workers at low latitudes

Keywords Whistlers, VLF periodic emissions electron density

PACS No. 94.30.Tz

1. Introduction

Whistlers, which are very low frequency (VLF) electromagnetic signals generated in the atmosphere during lightning discharges after being incident on the ionosphere travel through the ionosphere-magnetosphere coupled system along with geomagnetic field lines to the magnetically conjugate point in the opposite hemisphere [1]. During their propagation through the magnetosphere, these whistler waves acquire dispersion characteristics typical of the electron density inhomogenieties present along the whistler path. Whistlers have been used as an important diagnostic tool to probe the Earth's inner magnetosphere. Since the pioneering work of Storey [2], who was the first to give a correct interpretation of whistler spectra in terms of magneto-ionic theory, the observation of whistlers has been continued over a wide range of high to low latitudes [3–11]. Originally whistlers were looked upon essentially as high and mid latitude phenomena but the pioneering work of Indian and Japanese Scientists during the last three decades have not only detected whistler traces at much lower latitudes but have also established many of their new morphological features [3–11]. Whistler studies of India, which has been in progress since 1963, have made significant contribution to the propagation of low latitude whistlers and understanding

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of the structure and dynamics of the low latitude ionosphere. Recently, a co-ordinated ground based experimental study of low latitude whistlers has been initiated at three low latitude ground stations Varanasi, Agra, and Jammu under All India Co-ordinated Program of Ionosphere Thermosphere Studies (AICPITS). Under this program, we have conducted initial observations of whistlers and VLF emissions at the Jammu station and obtained some very interesting results for the first time during quiet periods.

In the present paper these results are presented. An attempt has been made to estimate the equatorial electron density and electron densities at an altitude of 1000 km, using whistlers recorded during quiet days at our low latitude ground station Jammu.

2. Experimental results

Using standard whistler observation equipments consisting of a T-type antenna 25 m high, suitably amplified by a transistorised pre- and main amplifiers having band pass of 500 to 15000 Hz, and a magnetic tape recorder, we conducted routine observation of whistlers at Jammu University Campus, a low latitude station Jammu (geomag lat., 22°26' N, geomag. long., 147°10' E) between January 1997 to June 1999. This station is located at a noise free area The observations were taken continuously during day and night hours. The accumulated data on magnetic tapes were analysed on a digital sonograph available at the Physics Department of Banaras Hindu University, Varanasi. The results of the analysis showed a number of whistlers and VLF emissions recorded at the station during various quiet periods Geomagnetically quiet periods were chosen for this study, with the aim of determining the quiet day behaviour of electron density distribution using whistler data recorded at our low latitude ground station Jammu At low latitudes, the whistler occurrence rate is low and sporadic But once it occurs, its rate of occurrence becomes comparable to that of mid latitudes [12] Similar behaviour has also been observed at Jammu. For the present study, we have chosen whistlers recorded during quiet periods of June 5, 1997; March 24, 1998; April 13, 1998; February 22, 1999 and March 29, 1999, magnetically quiet days with ΣKp values of 6, 13, 12, 12 and 13 respectively. Altogether more than a hundred whistlers were recorded at Jammu during these days and about 1000 whistlers were chosen for the present analysis The variation of whistler dispersion with local time is shown in Figure 1 for different quiet days. The whistler data are available in the form of spectrograms/sonograms, which show the variation of frequency with time The form of spectrogram is determined by the group delay time of the signal at different frequencies in the whistler mode from the source to the wave receiver.

Among the data, some very interesting and unusual one-hop multiflash whistlers triggered by periodic VLF emissions were also observed for the first time in the ground data at such a low latitude station The frequency time spectrograms

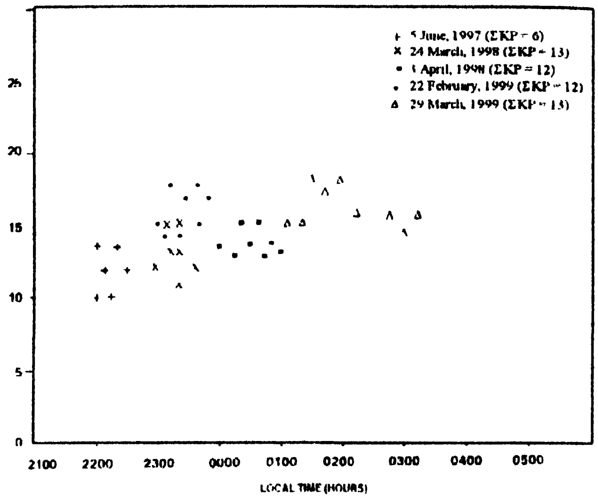

Figure 1. Variation of whistler dispersion with time for different quiet days

of these whistlers are shown in Figures 2(a–c) which are photographed from the monitor of the sonograph computer due to nonavailability of the printer of the sonograph. The date and time of the observation of whistlers are mentioned on the top of the figure.

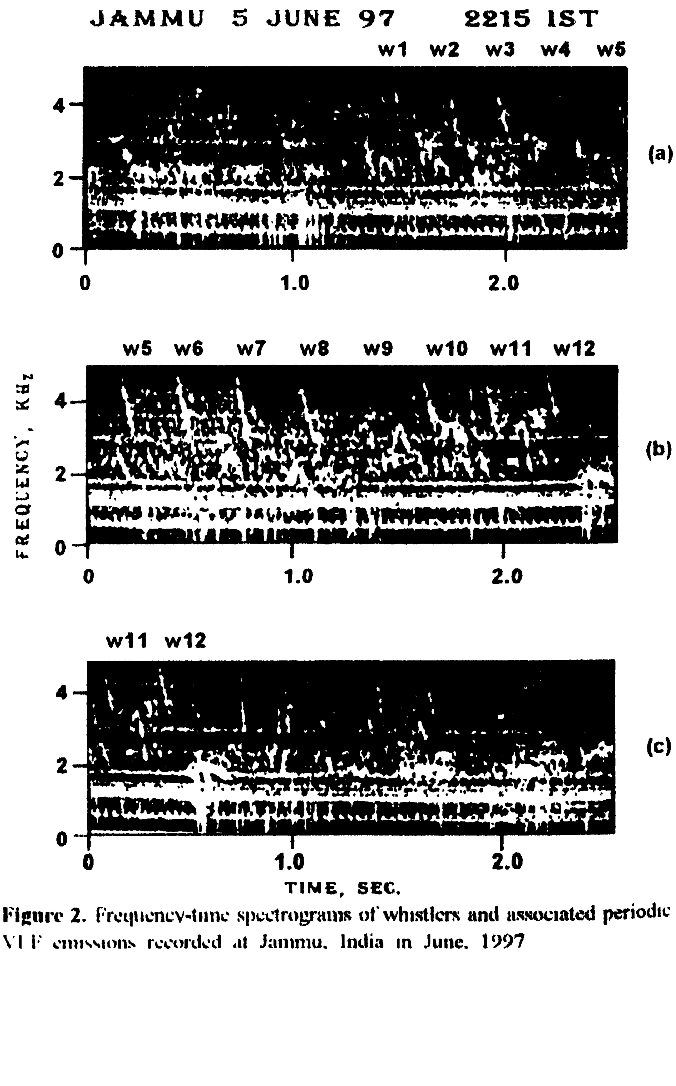

Figure 2. Frequency-time spectrograms of whistlers and associated periodic VLF emissions recorded at Jammu, India in June, 1997

In Figures 2(a–c), we show a group of whistlers (dispersion ~10 $s^{1/2}$) which show a temporal fine structure in occurrence at a regular time interval of about 0.28 s. From the detailed analysis of these whistlers, it is found that these are multiflash whistlers observed in the frequency range 2–5 kHz which occurred at almost constant time interval of about 0.28 s. The multiflash whistlers shown in Figures 2 (a-c) are clearly detected upto about 15 in numbers continuously and triggered by periodic VLF emissions. Such multiflash whistlers triggered by the periodic VLF emissions observed during a quiet period have never been reported from any of the low latitude ground stations. These multiflash whistlers are clearly seen to be triggered by periodic VLF emissions lying in the frequency range of about 1.5–3 kHz and to a lesser extent in the range about 2–3.5 kHz. The spurt in periodic VLF emission activity on June 5, 1997 started around 2140 IST (Indian Standard Time) and lasted for about 2 hours ending finally at 2340 IST. The period of observation was magnetically quiet with $\Sigma Kp = 6$ only but was preceeded by magnetic disturbance on the preceeding five days. The periodic emissions recorded on this day are of non-dispersive type having different spectral forms (falling tones, inverted hooks and complex combination of rising and falling tones) The measured period of these periodic emissions lies typically in the range of 0.1–0.7 s, which is much smaller in comparison to that reported from higher latitudes. One of the most remarkable and important features of the observed VLF data at Jammu is that we have succeeded in recording periodic VLF emissions at a surprisingly high rate during a quiet period along with whistler-triggered periodic VLF emissions on June 5, 1997. The present finding as shown in Figure 2 is the first such event reported from any of the low latitude ground stations.

3. Method of analysis

At low latitudes the main difficulty in whistler analysis is to obtain the nose frequency (f_n) and nose time delay (t_n) with a reasonable degree of precision. This is because of the fact that whistler spectrograms do not exhibit the portion of the whistler near nose frequency at low latitudes. Such a nose frequency will have to be inferred by extrapolation techniques. For the analysis of non-nose whistlers, a number of methods have been proposed [12–16]. The nose frequency of the whistler data used in estimating equatorial electron density n_{eq}, and electron density at an altitude of 1000 km has been computed by means of accurate curve fitting method developed by Tarcsai [16]. Tarcsai [16] 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 paths are below $L = 1.4$ [9–17]. Further, the technique is found suitable not only for long and good quality whistlers but also for short and faint whistlers. The computer program written for the purpose requires input data such as frequency, time (f,t) values scaled at several points along whistler trace, appropriate f_0F_2, Zero frequency dispersion (D_0), and a suitable ionospheric model *etc*. The output results include the L value of propagation, equatorial electron density, total tube content *etc*. We have adapted this programme for the analysis of the nighttime whistlers recorded at our station Jammu during quiet days.

At low L-values, the curve fitting method of Tarcsai [16] 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 [18,19]. To examine its validity, we analysed few whistlers recorded at Jammu using Dowden-Allcock Q-technique [13]. 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 [9,17,20].

For the determination of D_0, f_n and t_n, Ho and Bernard [14] approximation function for the dispersion of whistlers is given by [16]

$$D(f) = t(f)\sqrt{(f)} = D_0(f_{He} - Af)/(f_{He} - f), \quad (1)$$

where D_0 is zero frequency dispersion, $t(f)$ travel time at frequency f, and

$$A = 3A_n - 1/A_n(1 + A_n) \text{ and } A_n = f_n / f_{He}, \quad (2)$$

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

$$t_n = \frac{D_0}{\sqrt{(f_n)}\,(1 + A_n)}. \quad (3)$$

Sometimes the causative atmospherics is not known. In such cases the travel time is measured from a chosen origin and a correction parameter T, is introduced (which gives the time difference between the chosen origin and the actual sferic). Using eqs. (1) and (2), the measured travel time $t^*(f)$ is written as

$$t^*(f) = t(f) - T$$

$$= \frac{D_0}{\sqrt{f}} \cdot \frac{f_{He}}{f_n} \cdot \frac{f_n(f_{He} + f_n) - f(3f_n - f_{He})}{(f_{He} - f)(f_{He} + f_n)} - T, \quad (4)$$

where f_{He} is equatorial electron gyro frequency.

Using values of D_0, f_n and t_n obtained by the curve fitting method as developed by Tarcsai [16], we can compute the equatorial radius of the whistler path (L) or the local electron density at the geomagnetic equator (n_{eq}) and at a height of 1000 km (N). In this method, those values of D_0, t_n and f_n are searched which give best fit to the measured parameters. After Tarcsai, and using eq. (3) for t_n, we can write

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

$$n_{eq} \doteq K_e f_n t_n^2 L^{-5} = K_e' D_0^2 f_{He}^{5/3}, \quad (6)$$

$$N = K_1 f_n t_n^2 L^{-5} = K_1' . D_0^2 . f_{He}^{5/3}, \quad (7)$$

where the constants $K'_{\perp}$, K and K'_1 are weakly dependent of f_n and A_n. Using eqs (5–7) and analysing a large number of whistler recorded during the quiet period at Jammu, equatorial electron density n_{eq} and electron density N at an altitude of 1000 km have been evaluated.

4. Results and discussion

In order to determine the equatorial electron density and electron density at an altitude of 1000 km using nighttime whistlers observed during quiet periods at Jammu, we applied the curve fitting technique of Tarcsai [16]. We scaled down the frequency-time spectrograms of these whistlers and determine f, t values at a number of points along their traces. The value of f_0F_2 in the curve fitting technique was taken to be 7.8 MHz which was the same as that taken by Chauhan and Singh [21], Lalmani *et al* [17] and Singh [9]. A diffusive equilibrium model shown similar to that adopted by Park [22], Tarcsai [16], Chauhan and Singh [21], Lalmani *et al* [17] and Singh [9], was employed which was represented at a height of 1000 km by an electron density of 10^3 electrons/cm^3, O^+ = 90%, H^+ = 8% and He^+ = 2% and temperature of 1000°K. Figure 1 shows the variation of dispersion of whistlers observed over a span of three years at Jammu during quiet periods with time. From Figure 1 it is clearly seen that whistlers during quiet periods are normally observed around midnight hours and there is no perceptible change in the whistler dispersion with time. The dispersion of the majority of whistlers lie in the range of 13–17 sec$^{1/2}$. However dispersion of some of the whistlers are exceptionally low and lie between 10 and 12 sec$^{1/2}$. Such small dispersion whistlers observed at low latitudes have also been reported earlier by Lalmani *et al* [17].

Figure 3 shows the variation of equatorial electron density n_{eq} and electron density N at 1000 km altitude with time. It is clearly seen that the equatorial electron density

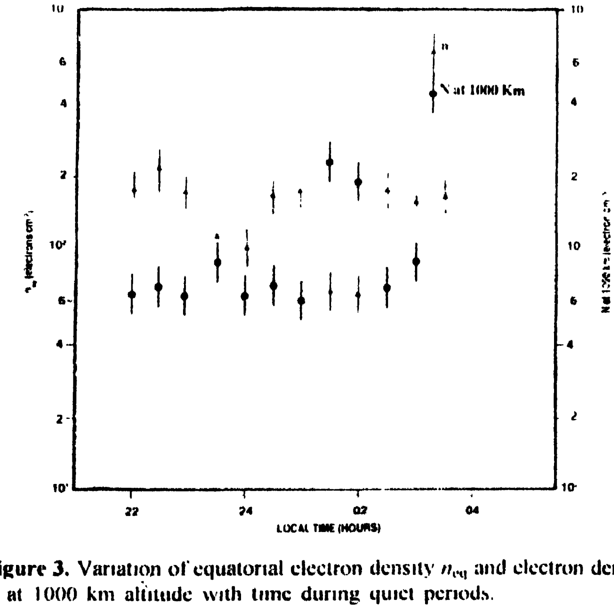

Figure 3. Variation of equatorial electron density n_{eq} and electron density N at 1000 km altitude with time during quiet periods.

during quiet periods derived from the whistler data observed at Jammu varies between 2.67 × 10^3 cm^{-3} and 6.4 × 10^1 cm^{-3}. From the curve fitting technique it is also found that the majority of the whistlers of dispersion between 14–16 sec$^{1/2}$ have propagated in the ducts located between the L range of 1.4–1.8. The results derived from quiet time whistlers recorded at Jammu using curve fitting technique are in remarkable agreement with those reported by Saxton and Smith [23], and Lalmani *et al* [17] during quiet period. The electron density derived from whistlers observed during magnetic storm periods at high, mid and low latitudes have also been reported by various workers [24–27]. But it is not meaningful to compare these results with ours.

It is worthwhile to mention here that although a number of nose extension methods developed to analyse the middle and high latitude whistlers [13–15,28–31], the one given by Tarcsai [16] has some advantages over the others. For example, it can be applied for the analysis of low latitude whistlers successfully and errors in the analysis of whistlers related to the equatorial electron density are much low [9,17].

Whistler-triggered periodic VLF emissions shown in Figure 2 have been recorded for the first time on the ground at low latitudes. The presence of such types of whistler-triggered periodic emissions at high latitudes have been known from the beginning of whistler studies recorded first at ground station of Seattle, Washington (54° N geomagnetic latitude), and Wellington, New Zealand (45° S geomagnetic latitude) [32–34]. The experimental data on whistler triggered periodic VLF emissions observed simultaneously at Seattle, Washington and Wellington have shown that a sequence of periodic emissions is initiated or triggered by a whistler, and then period between emission is the same as the whistler-mode echoing period at some frequency within the range of periodic emission. To explain these results, Helliwell [32], has proposed that generation or triggering of the emissions is controlled by packets of electromagnetic waves echoing in the whistler mode. Further Helliwell and Brice [33], have also shown that periodic emissions are generated through by emissions echoing the whistler mode and not by mirroring bunches of particles.

Since the dispersion of the whistlers usually recorded in various low latitude ground stations in India during quiet periods are less than 25 s$^{1/2}$ [17], it may be inferred that multiflash whistlers shown in Figures 2 are low latitude whistlers. At the first glance, these whistlers appear to be falling tone multiphase VLF emissions similar to those usually observed at high latitudes [1]. However, these whistlers and periodic emissions were recorded simultaneously at our latitude in different frequency ranges on June 5, 1997 and moreover these whistlers obey perfectly Eckersley law and hence this possibility is ruled out. It is also not possible that these whistlers are first, third and fifth hops of multipath whistlers generated from the successive strokes of a lightning discharge because no increase in dispersion is observed between hop to hop. Whereas the measured dispersion of these whistlers remains constant and hence whistlers shown in Figures 2 (a-c) are one-hop multiflash whistlers caused by return strokes of a lightning discharge. The measured period of VLF periodic emission is found to lie in a range from 0.1–0.7 s and this clearly shows that these are generated at low latitudes. This period of emission matches perfectly with that of whistler time delays between the two consecutive hops. This period information of the emissions provide important information about path latitude of whistlers observed at Jammu without the use of direction finding.

The interesting point in Figure 2 is that the time intervals between the consecutive periodic emissions are almost same with the time delays between any of the two successive hops of multiflash whistlers. Further, the time period between any of the periodic VLF emissions and one-hop whistler traces is almost half of the time delay of a one-hop whistler of dispersion ~10 $s^{1/2}$ (as shown in Table 1). We interpret the

Table 1. A comparison of time period between different periodic VLF emissions and time delays between different multiflash whistlers of dispersion 10 $s^{1/2}$ of Figure 2

Periodic Emissions			Whistlers		Time period between successive periodic emissions and one-hop whistler traces (between 2–4 kHz range)	
Traces	Time period (s)	At frequency (kHz)	Hops	Time delay at 4 kHz		
1-2	0.28	2.5	1-2	0.28	1-1	0.13
2–3	0.29	2.5	2-3	0.28	2-2	0.14
3-4	0.29	2.5	3-4	0.29	3-3	0.14
4–5	0.28	2.5	4-5	0.28	4-4	0.13
5–6	0.29	2.5	5–6	0.28	5-5	0.12
6-7	0.28	2.5	6-7	0.27	6-6	0.13
7–8	0.28	2.5	7-8	0.29	7-7	0.13
8–9	0.28	2.5	8-9	0.28	8-8	0.14
9–10	0.28	3.3	9–10	0.29	9-9	0.13
10–11	0.29	3.3	10–11	0.28	10-10	0.14

unusual relationship between the time intervals of these periodic VLF emissions and one-hop whistlers as follows. We assume that the consecutive periodic VLF emissions of these events were generated as a result of interactions between the trapped energetic particles and the various hops of multiflash whistlers near the equatorial region under cyclotron resonance mechanism and propagated to our field station in whistler mode of propagation. Under this assumption, we measure the time intervals between the consecutive periodic emissions at the frequency of 3 kHz and then match them with delays at 3 kHz between various hops of whistlers. We find that the observed time intervals of periodic emissions match closely with those of different hops of on observed whistler dispersion of ~10 $s^{1/2}$. The interesting point in Figure 2 is that the time period between any of the two successive periodic emissions and one-hop whistlers of the event are almost half of the time delay of a one-hop whistler of dispersion ~10 $s^{1/2}$ within about 12% of the measurement error. This shows that time taken by both of the one-hop whistler and the periodic VLF emissions is same to reach the receiving ground station Jammu from the equatorial region. The detailed results are presented in Table 1. Our results summarized in Table 1 clearly depict that the periodic VLF emissions observed at Jammu on June 5, 1997 are generated near the equatorial region as a result of interaction between trapped energetic particles and one-hop whistlers under cyclotron resonance mechanism and propagated to our ground station Jammu in whistler mode of propagation. This provides a possible explanation to the observed characteristics of whistler-triggered periodic VLF emissions recorded at Jammu shown in Figure 2.

The possibility that the occurrence of these whistler-triggered periodic emissions was just a coincidence, does not seem to be likely because a large number of periodic emissions occurred one after the other during the same night of observation. Thus results presented in Table 1, give a strong experimental evidence of wave-particle interaction taking place in the equatorial heights of low latitude inner magnetosphere.

Acknowledgments

The authors are grateful to Principal, Regional Engineering College, Srinagar, Kashmir and Principal, Government College of Engineering and Technology, Jammu, Old University Campus, Canal Road, Jammu for their constant encouragement and providing necessary facilities. The financial support by Department of Science and Technology, Government of India, New Delhi, India under Grant No FSS/75/028/93 dated 10.03.95 is gratefully acknowledged. Thanks are due to the unknown referee for his constructive comments and suggestions.

References

[1] R A Helliwell *Whistlers and Related Ionospheric Phenomenon* (Stanford, USA Stanford Univ Press) (1965)

[2] L R O Storey *Phil Trans Roy Soc* **A246** 113 (1953)

[3] G McK Allcock *IGY Whistler Results, paper presented at 13th General Assembly, Union Radio Sci Int* (London) (1960)

[4] A Iwai and J Ohtsu *Denki Tsushin Gakkai Zasshi* (Japan) **45** 556 (1962)

[5] V V Somayajulu, M Rao and B A P Tantry *Indian J Rad Space Phys* **1** 102 (1972)

[6] S S Sazhin and M Hayakawa *Planet Space Sci* **40** 681 (1992)

[7] M Hayakawa and Y Tanaka *Rev Geophys Space Phys* **16** 111 (1978)

[8] R P Singh *Indian J Rad Space Phys* **22** 139 (1993)

[9] B Singh *Ann Geophysicae* **15** 1005 (1997)

[10] V S Sonwalkar and U S Inan *J. Geophy Res* **100** 7783 (1995)

[11] K Ohta, Y Nishimura and T Kitagawa *J Geophys. Res.* **102** 7537 (1997)

[12] M Hayakawa, Y Tanaka, S S Sazhin, M Tixier and K Okada *J. Geophys Res.* **93** 5685 (1988)

[13] R L Dowden and G McK Allcock *J Atmos Terr Phys* **33** 1125 (1971)

[14] D Ho and L C Bernard *J. Atmos. Terr Phys* **35** 881 (1973)

[15] *private communication*

[16] G Tarcsai *J Atmos Terr Phys* **37** 1447 (1975)

[17] Lalmani, R P Singh, Rajesh Singh and Altaf Ahmad *Earth Moon & Planets* (Netherlands) **74** 7 (1996)

[18] G Tarcsai *Thesis (Hungarian Academy of Sciences, Buda Pest)* (1981)

[19] G Tarcsai, H J Strangeways and M J Rycroft *J Atmos Terr Phys* **51** 249 (1989)

[20] Lalmani, Altaf Ahmad and M M Ahmad *Planet Space Sci* **40** 1409 (1992)

[21] P Chauhan and B Singh *Planet Space Sci.* **40** 873 (1992)

[22] C G Park *Radio Sci Lab (Standford Univ.) Tech. Rep.* **No. 3454-1** (1972)

[23] J M Saxton and A J Smith *Planet. Space Sci.* **37** 283 (1989)

[24] T M Ralchovski *Rep Bulg Acad Sci.* **29** 351 (1976)

[25] C G Park, D L Carpenter and D B Wiggin *J. Geophys Res.* **83** 3137 (1978)

[26] G Tarcsai, P Szemeredy and L Hegygmegi *J. Atmos. Terr. Phys* **50** 607 (1988)

[27] R P Singh, Lalmani and U P Singh *Ann. Geophys* **11** 1011 (1993)

[28] L C Bernard *J Geophys Res* **78** 2201 (1973)

[29] P Corcuff and Y Corcuff *Ann Geophys* **29** 273 (1973)

[30] A J Smith, I D Smith and K Bullough *J. Atmos Terr Phys.* **37** 1179 (1975)

[31] G F Stuart *J Atmos Terr. Phys.* **39** 433 (1977)

[32] R A Helliwell *J Geophys Res.* **68** 5975 (1963)

[33] R A Helliwell and N M Brice *J Geophys. Res.* **69** 4704 (1964)

[34] S S Sazhin and M Hayakawa *J Atmos Terr Phys* **56** 735 (1994)