First observations of extremely small dispersion whistlers from Bhopal ($L \sim 0.96$), a low-latitude station

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First observations of extremely small dispersion (ESD) whistlers during night-time at low-latitude station, Bhopal (geomag. lat. 13°47′N) are reported. The propagation mechanism of these ESD whistlers has been investigated in some detail. ESD whistler data presented have been collected during quiet period of 19–20 March 1999, which is a rare event. Results of the study of the characteristics of ESD whistlers are strongly indicative of non-ducted propagation for low-latitude night-time whistlers. It is proposed that these ESD whistlers are VLF waves radiated from the return stroke of the lightning discharge launched at the ionosphere with different initial wave normal angles. They are propagated upwards under either quasi-longitudinal conditions or as pro-longitudinal whistler modes with the dispersion of the order of 3 to 5 $s^{1/2}$, and are in complete contrast to the earlier findings of ducted propagation of low latitude night-time whistlers in the presence of equatorial anomaly. These ESD whistlers observed at Bhopal are found to obey the Eckersley law.

Keywords: Electromagnetic waves, magnetic field, VLF emissions, whistler.

THE study of wave phenomena during quiet and disturbed periods of solar activity serves as useful diagnostic tool for detailed probing of microstructure and microphysical processes taking place in the earth's ionosphere and magnetosphere. The frequency spectrum from natural sources covers a wide variety of electromagnetic phenomena such as micropulsations, gyromagnetic resonance, solar whistlers, different types of very low frequency (VLF) emissions, terrestrial whistlers and spherics. A general survey of whistler research published so far indicates that the whistler observations at low-latitude stations are meagre in comparison with middle and high-latitude stations. Whistlers in relativity large numbers are observed only during periods of high geomagnetic activity. Lightning generates electromagnetic waves in a wide frequency range[1–3]. The broadband VLF (0.3–30 kHz) radiation from lightning propagates in the earth–ionosphere cavity as impulsive signals (spherics), and in the dispersive plasma regions of the ionosphere and magnetosphere it propagates as tones of descending or rising frequency (whistlers)[4]. The first correct interpretation of whistler spectra in terms of magnetospheric theory was given by Storey[5] in his pioneering work during 1953. Since then, there has been a flurry of research activity in this field[4,6–29]. Originally, whistlers were looked upon essentially as a high-latitude phenomenon. However, the pioneering work of Indian and Japanese scientists during the last three decades has not only detected whistler traces at much lower latitudes, but has also established many of their new morphological features. A wide variety of whistlers recorded during day and night-times at low-latitude ground stations are markedly different from those recorded at middle and high-latitudes. The propagation characteristics of these low-latitude whistlers are not yet properly understood. Some of these new types of whistlers are risers[30], low-dispersion whistlers[31,32], duplicate trace whistlers and hook whistlers[33].

Many experimental as well as theoretical investigations have been carried out during the last couple of decades to characterize and explain the properties of naturally occurring whistlers. The associated plasma behaviour of the inner plasmasphere has been extensively studied by Hayakawa and Tanaka[21]. They have stressed upon the importance of these low-latitude whistlers to general whistler studies. Unlike the middle and high-latitude whistlers, the propagation characteristics of low-latitude whistlers are not properly understood. Low-latitude whistlers are more susceptible to propagation conditions such as duct excitation, ionospheric transmission, etc. and therefore, are useful for studying mysterious problems, even for high and mid-latitude whistlers, as indicated by Walker[34] and Hayakawa and Tanaka[21]. As a result of the increasing importance and versatility of the whistler technique, it has become essential to understand whistler propagation mechanism at low latitudes.

Whistlers continue with the ionosphere and travel through the ionosphere – magnetosphere coupled system along the geomagnetic field lines to the magnetically conjugate point in the opposite hemisphere. During their propagation through the magnetosphere, these whistler waves acquire dispersion characteristics typical of their electron density inhomogeneities present along the whistler path. The dispersion of the whistler depends upon the length of the

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path over which it travels and on the electron density along the path. Hence at high latitudes where the paths are very long, dispersion is high and at low latitude, the dispersion is low. The dispersion is very small in satellites where the paths are much shorter than that observed between points on the ground. In fact, whistlers observed from satellites at heights of 1000 to 2000 km are too short to distinguish them from ordinary spherics. At low-latitude ground stations, whistlers with dispersions ranging from extremely small value of 5 $s^{1/2}$ to a value of about 90 $s^{1/2}$ have been observed[32]. They have been explained as originating at low latitude and following a hybrid path to the receiving latitude. Low dispersion whistlers with duplicate traces were also observed at geomagnetic latitude of 28°N. It was suggested that these duplicate whistlers are due to the electromagnetic waves radiated from a single source of lightning discharge and follow different hybrid paths between the source and the receiver on the ground. All these data of whistlers with dispersions ranging from 9 to 90 $s^{1/2}$ correspond to night-time observations. Recently, extremely small dispersion (ESD) whistlers varying from 5 to 10 $s^{1/2}$ have been recorded at low-latitude Indian ground station Jammu (geomag. lat. 19°26′N) during daytime by Lalmani *et al.*[35].

In order to explore the propagation mechanism of low-latitude whistlers, we have carried out whistler measurement at a newly installed ground-based station Bhopal (geomag. lat. 13°47′N; geomag. long. 148°36′E; $L \sim 0.96$) during 1999. Using an improved system we have succeeded in recording ESD whistlers during night-time, that are strongly indicative of non-ducted propagation for night-time whistlers at Bhopal. However, to our knowledge, such night-time ESD whistlers have not been reported from any of the low-latitude Indian ground stations so far during night-time. Observation of such ESD whistlers provides an indirect and strong evidence of non-ducted propagation of night-time whistlers at low latitudes.

Here, we have presented examples of whistlers observed at Bhopal and their characteristics along with their possible interpretation. Further, we have analysed critically the origin of the ESD whistlers, including the wave propagation mechanism of night-time whistlers and present arguments in support of non-ducted propagation at low latitudes.

Data selection and analysis

The recording of whistlers at Bhopal was started in the month of December 1998 on routine basis. The experimental set-up used for this purpose consists of *T*-type antenna 25 m height and 8 m long horizontally, pre/main amplifier and Digital Audio Tape Recorder (DAT). At low latitudes, the whistler occurrence rate is very low and sporadic. For the present study we have chosen some events recorded during night-time at our ground station Bhopal on 19 and 20 March 1999, as typically only a small number of whistlers were observed on these days.

Sample records of ESD whistlers observed on 19 and 20 March 1999 are shown in Figures 1 *a–f* out of a large collection of similar events recorded on these days. Figure 1 *a* shows a single trace of a short whistler (W_1) of dispersion ~ 3 $s^{1/2}$ with distinct causative atmospherics. Figure 1 *b* depicts two multiflash whistlers (W_2 and W_3) of dispersion 5 $s^{1/2}$ and 6 $s^{1/2}$. A trace of single short whistlers (W_4 and W_7) having the same dispersion of 3 $s^{1/2}$ is shown in Figure 1 *c* and *f*.

On 19 and 20 March 1999, the spurt in activity started around 0025 IST (Indian Standard Time), lasting for about 4 h, ending finally at 0425 IST. During this period, about 48 whistlers were observed. While 19 March was magnetically moderate with sum of total *Kp* index of 13, 20 March was magnetically quiet with sum of total *Kp* index of 10_0. From the detailed analysis, it was found that the measured values of all the recorded whistlers on this day have extremely small dispersions lying only in the range of about 3–6 $s^{1/2}$. For spectral analysis, the normal procedure of analysis by means of sonographic equipment was used. Detailed spectral analyses have been done for night-time whistlers on 19 and 20 March 1999, in order to study the propagation characteristics of these whistlers.

Figure 2 illustrates temporal distribution of the number of whistlers at Bhopal during night-time on 19 and 20 March 1999. The occurrence rate peaks at around about 0300 IST local time. This is in agreement with earlier results reported by other workers at low latitudes[8,10,12,16–18,22,25,26,29,36,37]. After detailed analyses of the whistlers at low latitude, observed on 19 and 20 March 1999, the characteristics of the whistlers are shown in Table 1.

Results and discussion

It is clearly seen that good quality ESD whistlers are recorded at Bhopal at night-time during magnetically quiet periods only. Further, these ESD whistlers are characterized by consistently good whistler intensity and rate with well-defined components. From the detailed spectrum analysis, it is found that all the ESD whistlers observed during 19–20 March 1999 have extremely small dispersion of 3–6 $s^{1/2}$, and are strictly found to obey Eckersley law, thereby indicating that presumably these whistlers had a quasi-longitudinal propagation with a right-handed circular polarization or pro-longitudinal whistler mode of propagation. Hayakawa and Tanaka[21] have found an empirical relation between dispersion and geomagnetic latitude of propagation, based on night-time whistler data obtained at the Japanese ground station. This relation is $D = 1.22\ (\phi - 0.72)$, where D is the dispersion in $s^{1/2}$ and ϕ is the geomagnetic latitude in degrees. From this relation the maximum dispersion observed[37] at Bhopal latitude should be about 16 $s^{1/2}$. Hence the occurrence of ESD whistlers observed at Bhopal cannot be explained on the basis of whistler mode propagation along the magnetic lines of force. The field-aligned propagation

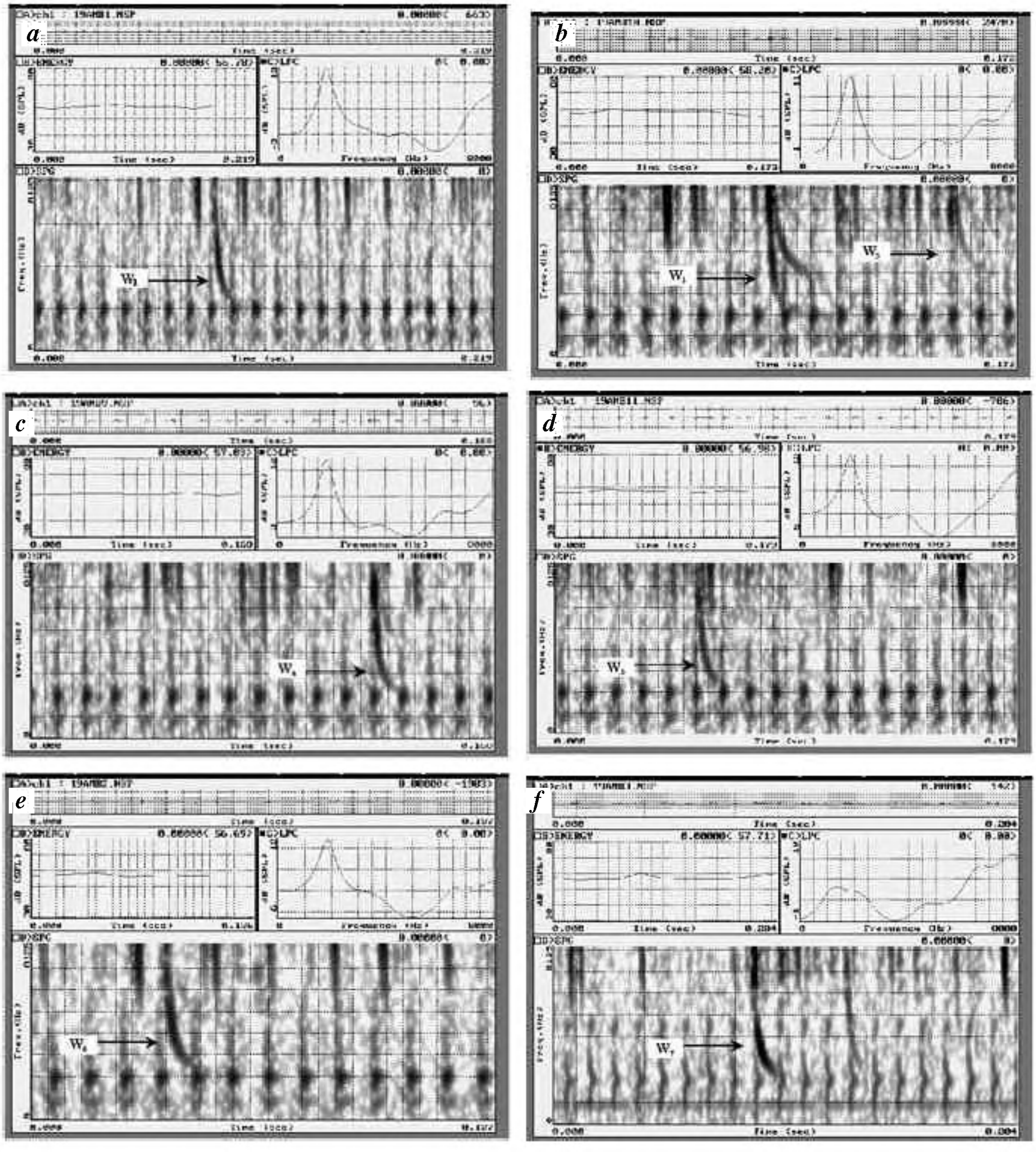

Figure 1. Single trace (***a***) and multiflash (***b***) whistler observed at Bhopal station on 19 March 1999. Single trace whistler observed at Bhopal station on (***c***) 19 March 1999 and (***d***) 20 March 1999. ***e***, ***f***, Single trace whistlers observed at Bhopal station on 20 March 1999.

was suggested by Tsuruda *et al.*[31], in order to explain ESD whistlers. They have speculated a hybrid propagation in which they assumed that the source region is around the magnetic equator and the field-aligned mechanism is present at latitudes as low as 10^0. However, Tsuruda *et al.* had not observed any traces of hybrid whistlers. This problem was re-examined by Okuzawa and Horita[38], wherein they concluded that the field-aligned propagation model does not apply to ESD whistlers.

In order to arrive at the best plausible propagation mechanism for ESD whistlers, observed at Bhopal, some explanations have been cited below:

Sub-protonospheric whistlers

Sub-protonospheric (SP) whistlers[39] with extremely small dispersion of the order of 5 $s^{1/2}$ have been observed at Suffield and Great Whale River ground stations, in the Allouette satellite at an altitude of about 1000 km and on Aerobee rocket in the height range of 100–200 km. SP whistler energy echoes back and forth between 100 and 1000 km ionosphere heights with increasing dispersions corresponding to the increase in number of reflections, as depicted in Figure 3. One of the interesting features of SP-whistlers is that they are found to obey Eckersley law within experimental error. Since the observations of SP-whistlers correspond to IQSY period, the maximum electron number density of F2-layer and beyond may be smaller. Thus if SP-whistlers are recorded at a low-latitude ground station, during maximum solar activity period, the dispersion of SP-whistlers will be higher and may be even as high as 10 $s^{1/2}$. However, SP-whistlers are not observed at low latitudes even by satellites. Therefore, the possibility that ESD whistlers observed at Bhopal could be the once and twice reflected SP-whistlers is ruled out due to the fact that the ratio of dispersions of ESD whistlers observed at Bhopal is not an even integer. Hence, possibility of occurrence of ESD whistlers with dispersions ranging from 3 to 6 $s^{1/2}$ may not probably be explained in terms of different SP-whistlers.

ESD whistlers with hybrid paths

Whistlers with low dispersions have also been earlier observed[31,32,40] at Kakioka (geomag. lat. 26°N) and Tohakatta (geomag. lat. 28°N). These workers have attributed the recordings of low-dispersion whistlers to the hybrid paths followed by the whistlers, as shown in Figure 4 *a* and *b*.

According to their hypothesis, VLF waves radiated by the return stroke of the lightning discharges propagate initially in the waveguide mode from their source and later penetrate the ionosphere in whistler mode. Then they propagate to the other hemisphere along the geomagnetic lines of force not corresponding to the observing station. After reaching the opposite hemisphere, the VLF waves again traverse in the waveguide mode to reach the observing station. Thus, they have adopted the complicated waveguide mode path in order to explain the occurrence of low-dispersion whistlers. There seems to be some difficulty for the whistlers in adopting the combined propagation paths of waveguide mode and whistler mode because there will be a good amount of energy loss in transforming the energy of VLF waves from whistler mode to waveguide mode and vice versa. Another plausible explanation for such ESD whistlers is perhaps much simpler. Shawhan[33] from his ray-tracing computations, has shown that the ray paths of VLF wave propagation in the magnetoionic medium depend much on the initial wave normal angle and wave frequency. Almost the same viewpoint was expressed by Kimura[41], and later by Storey and Cerisier[42]. Further, Shawhan[33] has shown that VLF waves of frequencies less than f_{LHR} (lower hybrid resonance) and launched at 300 km, with some initial wave normal angle with respect to magnetic lines of force, have propagated upwards, had transverse propagation and turned around at 670 km. On the other hand, another VLF wave falling in the same frequency range and launched at the same height but with initial

Table 1. Details of night-time whistlers observed at low latitude ground Indian station Bhopal ($L \sim 0.95$) as shown in Figure 1 *a–f*

Day	Time (IST)	Dispersion	Lower cut-off
19 March 1999	0205 IST	3	1.92
	0208 IST	6} multiflash	2.96
	0350 IST	5	3.32
20 March 1999	0200 IST	3	1.36
	0320 IST	3} multiflash	3.32

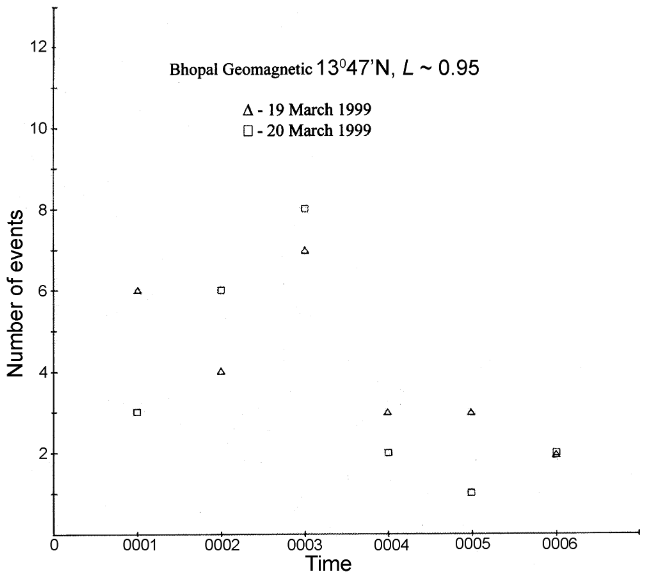

Figure 2. Temporal evolution of the events rate of whistlers at low-latitude ground station Bhopal observed on 19–20 March 1999.

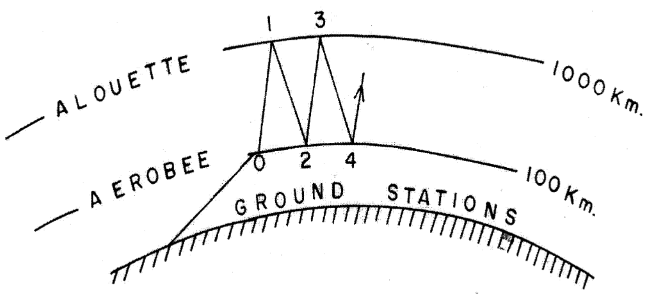

Figure 3. Paths of sub-ionospheric whistlers (after Carpenter *et al.*[39]).

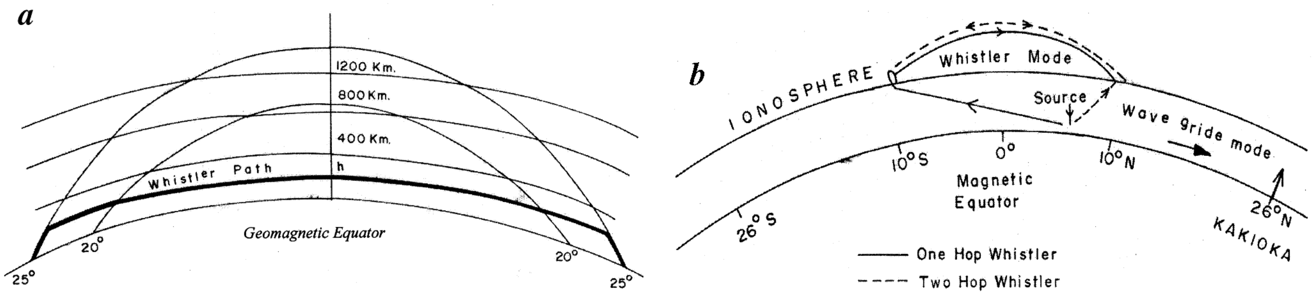

Figure 4. *a*, Paths of ESD whistlers (after Takuda[40]). *b*, Hybrid paths of low dispersion whistlers (after Tsuruda *et al.*[31]).

wave normal angle zero with respect to the magnetic lines of force, continued to propagate along the geomagnetic lines of force up to 4000 km and above.

Shawhan[33] has also shown that VLF waves are reflected at a height of 2800 km by his ray-tracing computations. Ohtsu[43] has explained whistlers with a small dispersion of 5 $s^{1/2}$ in terms of oblique propagation effect arising from the large angle between wave normal and geomagnetic field direction at low latitudes. Dikshit *et al.*[44] have suggested that the low-dispersion whistlers (15 and 10 $s^{1/2}$) recorded simultaneously at Gulmarg (geomag. lat. 24°10′N) and Nainital (geomag. lat. 19°01′N) are VLF waves radiated from the return stroke of lightning discharge launched at the ionosphere with different initial wave normal angles, propagated upwards under either quasi-longitudinal conditions or pro-longitudinal (PL) whistler mode. Similar mechanism has also been proposed by Singh *et al.*[45], who have carried out ray-tracing of non-ducted whistlers in the realistic ionospheric model, to explain the small-dispersion whistlers observed simultaneously at two stations of Gulmarg and Nainital[44].

The daytime ESD whistlers observed at Jammu[35,37] during March 1998 were explained on the basis of similar mechanism given by Dikshit *et al.*[44] and Singh *et al.*[45]. Similar type of ESD whistlers were observed at our low-latitude station Bhopal in the early morning hours from 2400 to 0400 IST during 19 and 20 March 1999. The whistler waves radiated from the return stroke of the lightning discharges launched at the ionosphere with different initial wave normal angles propagated upwards and turned around at different heights, are then received at Bhopal with dispersions ranging from 3 to 6 $s^{1/2}$. The question then arises whether such ESD whistlers observed at Bhopal obey Eckersley's law or not. It is well known that SP-whistlers reflected at 1000 km altitude have constant dispersion, from high frequency up to 2 kHz at least. Further, Scarabuchi[46] has shown through rigorous calculations and analysis that VLF waves can propagate in the PL-whistler mode and they need not necessarily be ducted along the magnetic lines of force; but during propagation, the wave normal directions of the ray path must lie within the transmission cone. However, PL-mode whistlers usually resemble normal whistlers that actually obey Eckersley dispersion law. If there is transverse or quasi-transverse propagation, there can be a time delay which is constant with frequency. In such case, the Eckersley law may be violated. However, if VLF waves have spent only a small amount of time in transverse propagation, the additional time delay due to quasi-transverse propagation can be small and thus be ignored provided that the wave frequency is less than f_{LHR}, as pointed out by Smith[47]. Further, if reflection takes place during transverse propagation at $f = f_{LHR}$, the whistler will have an increasing time delay with increasing frequency thereby exhibiting riser characteristics[30]. Our detailed spectral analyses have shown that ESD whistlers observed at Bhopal obey Eckersley law. Therefore, it is suggested that these whistlers are due to reflections at different altitudes of VLF waves radiated from the return strokes of lightning discharge and received at Bhopal with effective propagation similar to whistler mode obeying Eckersley's law.

From satellite measurements, Cerisier[14,15] proposed an altogether different model for non-ducted propagation and has shown that non-ducted propagation is possible at L values less than 1.7. However, no information is given on the detailed local time dependence of the propagation characteristics. Thus night-time ESD whistlers observed at Bhopal are consistent with the suggestion of non-ducted propagation at low latitudes given by various workers[14,15,26,29,30,35,37,43,45,47–53].

ESD whistlers observed at Bhopal could well be explained with the help of ray-tracing studies, similar to that given by Lalmani *et al.*[35], where they have explained the daytime ESD whistlers observed at Jammu (L = 1.17). They have also suggested that the low-latitude VLF waves are propagated to the ground station in the PL mode under the influence of negative horizontal density gradient existing in the low-latitude ionosphere around the equator.

Lalmani *et al.*[35] have calculated ray-paths of ESD whistler waves of frequencies from 1 to 8 kHz using ray-tracing equation and computer program of Taylor and Shawan[54]. They have adopted the diffusive equilibrium model for the background electron density, similar to that adopted by Chauhan and Singh[55], Singh and Singh[56], Singh[57], which was represented at the height of 400 km by an electron density of 1.5×10^5 el per cc, $O^+ = 95\%$, He = 4.75%, H = 0.25% and temperature of 1000 K. Since the computations are done down to 120 km, the ionosphere–exosphere model similar to that of Singh[58] is also employed. From their ray-tracing studies, the lower and upper cut-off frequencies and dispersions of ESD whistlers observed at Jammu have been successfully explained[35].

Similar ray-tracing studies are required to explain ESD whistlers observed at low-latitude station Bhopal to come to a definite conclusion regarding their propagation mechanisms. However, in spite of our limitations, the present exercise is still worthwhile.

Conclusion

Based on whistler wave observations at Bhopal, we have studied the detailed characteristics of ESD whistlers. From the limited observational results, including the occurrence rate, we have found non-ducted propagation of ESD whistlers in the faromud mechanism. ESD night-time whistlers observed at Bhopal having dispersions in the range of 3–6 $s^{1/2}$, can be successfully explained through the mechanism given by several workers[30,35,37,43,59]. It is therefore, concluded that the night-time whistlers may be observed at low latitudes both due to ducted as well as non-ducted propagation. A large database needs to be generated alongwith substantial theoretical investigation to substantiate our viewpoint.

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